South Washington Watershed District

Erosion Potential by Shear Stress Analysis of

Cottage Grove Ravine Regional Park

EMMONS & OLIVIER RESOURCES

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I. Introduction

Included in the storm water management strategy developed by the South Washington Watershed District (SWWD) is the option of routing storm water piped from regional detention/infiltration areas through the county park ravine in Cottage Grove. As part of an Environmental Assessment of the County Road 19 Corridor, EOR conducted a preliminary erosion analysis of the Cottage Grove Ravine. Erosion potential along the ravine for assumed flow rates was determined from channel velocities and stream power. FIScH Engineering, a national consultant with expertise in channel stability analysis, assisted in quantifying the effects of duration and potential erosive power exerted on the channel, and identified potential stabilization measures. Results from the velocity analysis were summarized in EOR's Environmental Assessment Phase I Report, EOR memo to the SWWD dated 2/7/01, and the FIScH Engineering Erosion Assessment Report (see References). The shear stress analysis provided here is a more in-depth and accurate means of assessing erosion potential.

Maximum permissible velocity is useful as a cursory analysis of erosion potential. The approach, while relatively easy to conduct, has some limitations, as it does not consider channel shape and flow depth, which can have an impact on the forces acting on the boundaries. We have supplemented here the velocity analysis with a shear stress analysis, which has a stronger basis in fluid mechanics and channel stability assessment.

For the velocity analysis, erosion potential was determined in the main channel of the ravine as well as the west branch ravine. Results from the velocity analysis for the west ravine clearly indicated a high potential for erosion. Since flow through the west ravine is through an already confined channel, the recommendation from the velocity analysis would be to armor most of the channel. The velocity analysis provided sufficient information regarding the stabilization measures needed for the west ravine, therefore, shear stresses were analyzed for the main channel only. A shear stress analysis of the west branch ravine could be completed in the future if desired.

EOR performed the shear stress analysis with in collaboration with FIScH Engineering. The XP-SWMM ravine model developed as part of the Environmental Assessment for County Road 19 Corridor was used to evaluate shear stresses in the ravine for the same flows used in the velocity analysis: 90, 120, 150 and 180 cfs. The shear stress analysis was then used to develop recommended methods of stabilization for various reaches of the ravine. This report describes the process used to perform the shear stress analysis including the methodology to determine the shear stresses, evaluation of the erosion potential, and the results of modeling the channel with stabilization measures in place.

II. Technical Criteria for Evaluating Erosion Impacts

The following process, based on the steps outlined by FIScH Engineering (Fischenich, 2001), was used to perform the shear stress analysis for each ravine section. Additional detail on the methodology can be found in FIScH Engineering's Erosion Assessment Report (Fischenich, 2001), included in Appendix A.

Erosion Analysis Process

1. **Shear stress** was calculated from the mean hydraulic conditions (hydraulic radius and slope of the energy grade line) obtained at each cross section from the XP-SWMM model developed for the velocity analysis of the main channel of the ravine. The methodology used to calculate the shear stresses is summarized in Appendix B.

2. **Maximum shear stress** was estimated by multiplying the shear stress from step 1 by a factor of 1.5 (Chang, 1988) to account for variations in local and instantaneous velocities.

3. The **erosion potential** was determined by comparing the shear stress values calculated in step 2 with the shear stress threshold values of the existing conditions listed in Table 1. The threshold values were based on the vegetation and soil descriptions from the Environmental Assessment (Emmons & Olivier Resources, 2000), and developed through correspondence with FIScH Engineering. Erosion potential was categorized into four levels of low, medium, high, and excessive and assigned to each section based on the following criteria:

Low	Below the lower limit of the shear stress threshold range
Medium	Between the lower limit and midpoint of the shear stress threshold range
High	Between the midpoint and upper limit of the shear stress threshold range
Excessive	Above the upper limit of the shear stress threshold range

4. **Stabilization measures** were then selected based on the erosion potential rating determined in step 3, information from permissive shear stress thresholds in Table 2, and with input from FIScH Engineering. The following measures are recommended for stabilization of the ravine. Stabilization measures were not assigned for sections with a low erosion potential rating since the calculated shear stress was below the threshold limit for the existing channel conditions.

Vegetation Management

Restore ravine sections to more open oak savanna habitat through removal and control of invasive shrubs (e.g. buckthorn), removal of deadfall, and thinning of the tree canopy. This will facilitate the establishment of a more stable ground cover of native grasses and forbs. Vegetation management was selected for sections with a medium erosion potential rating. A shear stress threshold of 1.2 lb/ft^2 was established for this measure based on the lower limit for long native grasses in Table 2. A schematic view showing a typical reach based on existing conditions is found in Figure 1. For comparison, vegetation management of the same cross-section is depicted in Figure 2. This approach emphasized bio-stabilization measures that better integrate into the natural character of the county park.

Check Dams

Install check dams less than three feet high, spanning the section reach. Check dams were selected for sections with a high or excessive erosion potential rating. While check dams do not provide direct protection of channel slopes, they reduce shear stresses by reducing the effective slope of the channel and concentrating energy losses in a specific location that can be protected. Figure 3 shows a schematic of a check dam in a typical ravine section. This configuration can provide additional water quality and flow control benefits by forming temporary pools that will increase infiltration and ponding.

New Lined Channels

Construct and line channels to concentrate the flow in channels designed to withstand higher shear stresses. Channels would typically be less than 2.5 feet deep and 20 feet wide. Channels were selected for the sections where it would be difficult to establish a ground cover (e.g. under the dense canopy of evergreens) and where disturbance of the existing vegetation and tree cover was undesired (e.g. oak forest). A shear stress threshold of 3.0 lb/ft^2 was established for this measure based on the limit for unvegetated non-degradable rolled erosion control product (RECP). Non-degradable RECP provides protection from erosion with or without the presence of vegetation and is usually less expensive than riprap. Unvegetated, non-degradable RECP was used in the analysis as a conservative estimate of permissible shear stress to account for areas of the ravine where shade may impede the establishment of vegetation. Other available options include vegetated, non-degradable RECP and riprap (9-inch diameter or greater), both which have higher shear stress limits. Figure 4 shows a schematic view of a lined channel within the ravine.

Table 1. Shear Stress Threshold Limits

Cross Sections	Existing Vegetative Cover	Estimated Shear Threshold (lb/sf)
0+00 - 2+00	Unmaintained old field grass. High grass	1.5 – 2.5
2+00 - 9+00	Wooded forest. Wooded areas not covered with deadfall. Good ground cover (80%-90%).	1.0 – 2.0
9+00 - 20+00	Mowed grass on the trail (approx. 12 feet wide). Wooded side slopes, no dead fall.	1.0 – 1.5
20+00 - 24+00	Wooded forest floor. Good ground cover. Grass cover, trail on channel's right bank.	0.8 – 2.0
24+00 - 28+00	Wooded forest floor. Good ground cover. Grass cover, trail on channel's left bank.	0.8 – 2.0
28+00 - 35+00	Grass cover. Maintained.	1.0 – 1.5
35+00 - 39+00	All wooded with debris and significant amount of fallen trees.	0.3 – 1.0
39+00 - 48+00	Pine and spruce plantation. No significant ground cover (only pine needles and pine cones).	0.25 – 0.7
48+00 - 54+00	Clean oak forest, no fallen trees. Medium density underbrush. Medium tree density.	0.4 – 1.0
54+00 - 61+00	Unmaintained excavated channel filled with high to medium density forbs and shrubs.	0.3 – 1.0
61+00 - 68+00 (Pond)	Weedy area. Reed canary grass and stingy nettles and forbs.	0.4 – 0.9
68+00 - 81+00	Wooded (medium density) with heavy deadfall. Low to medium density under-brush.	0.4 – 1.0
81+00 - 85+00	Bare channel, unmaintained. Fairly clean bottom with roots. Brush on the side slopes.	0.2 – 0.7
85+00 - 95+00	Pasture - Dense, short grass. Mowed.	0.4 – 1.0

Note: All soils are sandy loam.

Table 2. Permissible shear or tractive stresses for selected lining materials[1]

From Erosion Assessment Report (FIScH Engineering, 2001)

Boundary Category	*Boundary Type*	*Permissible Shear Stress (lbs/sq.ft)*	*Permissible Velocity (ft/s)*
Soils	Fine colloidal sand	.02 - .03	1.5
	Sandy loam (noncolloidal)	.03 - .04	1.75
	Alluvial silt (noncolloidal)	.045 - .05	2
	Silt loam (noncolloidal)	.045 - .05	1.75 – 2.25
	Firm loam	.075	2.5
	Fine gravels	.075	2.5
	Stiff clay	.26	3 – 4.5
	Alluvial silt (colloidal)	.26	3.75
	Graded loam to cobbles	.38	3.75
	Graded silts to cobbles	.43	4
	Shales and hardpan	.67	6
Gravel/Cobble	1-inch	0.33	2.5 – 5
	2-inch	0.67	3 – 6
	6-inch	2.0	4 – 7.5
	12-inch	4.0	5.5 – 12
Vegetation	Class A Turf	3.7	6 – 8
	Class B Turf	2.1	4 - 7
	Class C Turf	1.0	3.5
	Long Native Grasses	1.2 – 1.7	4 – 6
	Short Natives & Bunch Grass	0.7 - .95	3 – 4
	Reed Plantings	0.1-0.6	N/A
	Hardwood Tree Plantings	0.41-2.5	N/A
Temporary Degradable RECP's	Jute Net	0.45	1 – 2.5
	Straw with Net	1.5 – 1.65	1 – 3
	Coconut Fiber with Net	2.25	3 – 4
	Fiber Glass Roving	2.00	2.5 – 7
Non-Degradable RECP's	Unvegetated	3.00	5 – 7
	Partial Establish	4.0-6.0	7.5 – 15
	Fully Vegetated	8.00	8 – 21
Riprap	6 – inch d_{50}	2.5	5 – 10
	9 – inch d_{50}	3.8	7 – 11
	12 – inch d_{50}	5.1	10 – 13
	18 – inch d_{50}	7.6	12 – 16
	24 – inch d_{50}	10.1	14 – 18
Soil Bioengineering	Reed fascine	0.6-1.25	5
	Coir Roll	3 - 5	8
	Vegetated Coir Mat	4 - 7	9.5
	Live Brush Mattress (initial)	0.4	4
	Live Brush Mattress (grown)	3.90-4.60	12
	Brush Layering (initial/grown)	1.1-6.25	12
	Live Fascine	1.25-3.10	6 – 8
	Live Willow Stakes	2.10-3.10	3 – 6
Hard Surfacing	Gabions	10	14 – 19
	Concrete	12.5	>18

[1] Ranges of values generally reflect multiple sources of data or different testing conditions.

Lining Existing Channels

Line the channel to withstand higher shear stresses where more well defined channels already exist. The same shear threshold was used for new and existing lined channels (3.0 lb/ft^2). Again, other lining materials could be considered and can provide higher shear stress tolerances. A schematic view of lining of an existing channel reach is shown in Figure 5. Lining a channel is a fairly invasive technique, but is needed in particularly erosive conditions.

Stabilization measures can be used alone or in combination depending on their effectiveness in meeting the shear stress thresholds. For example, check dams are used in combination with channel lining some reaches to reduce the permissible shear stress to a level that is below the threshold for channel lining.

5. **Channel stability was verified** through repeating the analysis. The stabilization measures were added to the XP-SWMM model and steps 1-5 repeated until the calculated shear stresses were below the shear stress thresholds for all sections.

6. A **safety factor** was determined for each ravine section by dividing the permissible shear stress by the calculated maximum shear stress. A minimum safety factor of 1.2 was considered in the analysis. Stabilization measures would be increased to a higher level if the safety factor is not maintained.

XP-SWMM Modeling of Stabilization Measures for 90 cfs Flow Rate

Stabilization measures were selected based on shear stress calculations for the 90 cfs flow rate. The measures were modeled in XP-SWMM by modifying the original ravine model. The following changes were made to the model to simulate the stabilization measures:

Vegetation Management

Changes to the model for the sections with vegetation management consisted of changing the Manning's roughness coefficient to 0.075 based on the Manning's coefficients tables (Chow, 1959).

Check Dams

The check dams were modeled using a weir with a maximum height of 3 ft and a width corresponding to the cross-section width. The energy dissipation downstream of the check dam was modeled by setting the discharge coefficient of the weir to 2.4. Table 3 contains the check dam dimensions for the affected sections.

New and Existing Lined Channels

New lined channels were modeled by modifying the ravine's cross-section geometry to include the channel dimensions. A maximum channel depth of 2.5 ft and channel top-width of 20 ft were used as limits. Channel dimensions for each affected section were determined for the 90 cfs flow rate and are listed in Table 4. The lining for both the new and existing channels was modeled by using a Manning's roughness coefficient of 0.03.

Preliminary Findings on Additional Stabilization Measures for Higher Flow Rates and Safety Factors

To determine what additional stabilization measures would be needed at 120, 150, and 180 cfs, the XP-SWMM model developed for 90 cfs with associated stabilization measures was run at the higher flow rates. Shear stresses were calculated from the model output and compared to the shear stress thresholds. Erosion potential ratings were then determined. Stabilization measures were selected by the same methodology used for the 90 cfs flow rate. Where new lined channels and the lining of existing channels had already been selected for a reach, the suggestion is to increase the size of the channel, or line the existing channel further up the banks. The XP-SWMM modeling was not conducted to confirm the additional stabilization measures, but the model could be modified and rerun in the future once a flow rate is established.

Additional measures to achieve higher safety factors were also selected for the 90 cfs flow rate, following the same selection methodology as above. In reaches where check dams were already selected, additional or higher check dams are proposed to increase the safety factor. XP-SWMM modeling was not used to confirm the additional measures for increased safety factors, but additional modeling and analysis could be performed to confirm these preliminary findings. Safety factors were not developed for the higher flow rates as the additional stabilization measures would need to be modeled to determine corresponding shear stresses.

Table 3. Check Dam Dimensions

Section Number	Height (ft)	Length (ft)
4+00	1.5	85
7+00	3	120
8+00	3	70
10+00	2.0	130
13+00	2.5	53
14+00	2.5	86
21+00	2.5	140
23+00	2	90
27+00	2	17
54+00	3	40
55+50	3	40
57+00	2	30
70+00	2	55
72+00	1	30
75+00	3	75
76+25	3	75
78+50	3	60
81+00	3	17
82+50	3	17
84+00	2	15

Table 4. New Lined Channel Dimensions

Section Number	Top Width (ft)	Bottom Width (ft)	Depth (ft)
39+00	17	5	2
40+00	17	5	2
41+00	17	5	2
42+00	17	5	2
43+00	17	5	2
44+00	17	5	2
45+00	14	5	2.5
46+00	20	5	2.5
48+00	15	5	2
49+50	12.5	5	1.5
50+00	20	5	3
52+00	17.5	5	2.5

Note: Channel dimensions can be adjusted and still maintain the same channel effective flow dimensions.

III. Results

The results of the shear stress analysis for the Cottage Grove Ravine are summarized in Table 5. The table shows the erosion potential rating for each section, with approximately 60% of the total length of the ravine exceeding the shear stress threshold at a flow rate of 90 cfs (see Table 6). This is an increase from the previous flow velocity-based analysis, where 43% of the ravine sections exceeded the low erosion category at the 90 cfs flow rate.

Table 5 also lists the stabilization measures selected for each section for the 90 cfs flow rate. With the stabilization measures incorporated into the XP-SWMM model, the calculated shear stresses were below the shear stress threshold for each section at 90 cfs. For the 150 and 180 cfs flow rates, stabilization measures in addition to those used for 90 cfs would be required for approximately 30% of the total length of the ravine. Possible stabilization measures for the higher flow rates are listed in Table 5. Additional modeling would be required to incorporate the stabilization measures and verify that the shear stresses are below the threshold. The maps in Figures 6A, 6B, and 6C identify the station locations, corresponding erosion potential ratings, and stabilization measures for 90, 120, 150, and 180 cfs flow rates.

The safety factor analysis for the 90 cfs flow rate indicates that some of the reaches fell below the accepted limit of 1.2, as indicated in Table 7. Additional stabilization measures would be required to increase the safety factor above 1.2. Suggested measures are also included in Table 7. Additional modeling would be required to incorporate the stabilization measures and confirm that all safety factors exceeded 1.2 with the proposed measures.

Table 5. Shear Stress Analysis Results

Existing Conditions													
						90 cfs		120 cfs		150 cfs		180 cfs	
Section Number	Station Number From	Station Number To	Length (ft.)	Existing Vegetation Cover	Estimated Shear Threshold	Maximum Shear Stress	Erosion Potential	Maximum Shear Stress (lb/sq.ft.)	Erosion Potential	Maximum Shear Stress	Erosion Potential	Maximum Shear Stress	Erosion Potential
0+00	-2+50	1+00	350	Unmaintained	1.5 - 2.5	0.17	Low	0.16	Low	0.14	Low	0.14	Low
1+00	1+00	2+00	100	field grass	↓	0.43	Low	0.51	Low	0.55	Low	0.62	Low
2+00	2+00	3+00	100	Wooded forest,	1.0 - 2.0	0.36	Low	0.42	Low	0.49	Low	0.54	Low
3+00	3+00	4+00	100	good ground cover		0.46	Low	0.50	Low	0.54	Low	0.58	Low
4+00	4+00	5+00	100		↓	1.25	Medium	1.47	Medium	1.67	High	1.85	High
5+00	5+00	6+00	100	Pond									
6+00	6+00	7+00	100	Wooded forest,	1.0 - 2.0	0.88	Low	0.99	Low	1.08	Medium	1.15	Medium
7+00	7+00	7+50	50	good ground cover		2.40	Excessive	2.51	Excessive	2.70	Excessive	2.92	Excessive
7+50	7+50	8+00	50			0.30	Low	0.46	Low	0.61	Low	0.80	Low
8+00	8+00	9+00	100		↓	1.57	High	1.83	High	1.90	High	2.55	Excessive
9+00	9+00	10+00	100	Wooded forest,	1.0 - 1.5	0.95	Low	0.72	Low	0.82	Low	0.90	Low
10+00	10+00	10+60	60	good ground cover,		1.83	Excessive	2.04	Excessive	2.09	Excessive	1.33	High
10+60	10+60	11+00	40	mowed grass on		0.63	Low	0.70	Low	0.75	Low	0.70	Low
11+00	11+00	12+00	100	trail		0.28	Low	0.35	Low	0.43	Low	0.48	Low
12+00	12+00	13+00	100			0.88	Low	1.05	Medium	1.20	Medium	1.35	High
13+00	13+00	14+00	100			1.65	Excessive	1.79	Excessive	1.90	Excessive	1.98	Excessive
14+00	14+00	15+00	100			1.43	High	1.58	Excessive	1.72	Excessive	1.85	Excessive
15+00	15+00	16+00	100			1.19	Medium	1.30	High	1.39	High	1.47	High
16+00	16+00	17+00	100			0.72	Low	0.84	Low	0.95	Low	1.06	Medium
17+00	17+00	18+00	100			0.53	Low	0.61	Low	0.68	Low	0.76	Low
18+00	18+00	19+00	100			0.96	Low	1.09	Medium	1.20	Medium	1.29	High
19+00	19+00	20+00	100		↓	0.85	Low	1.00	Low	1.14	Medium	1.27	High
20+00	20+00	21+00	100	Wooded forest,	0.8 - 2.0	0.48	Low	0.58	Low	0.67	Low	0.76	Low
21+00	21+00	22+00	100	good ground cover,		1.45	High	1.68	High	1.89	High	2.08	Excessive
22+00	22+00	23+00	100	trail on channel's		0.79	Low	0.91	Medium	1.02	Medium	1.12	Medium
23+00	23+00	24+00	100	right or left bank		1.39	Medium	1.65	High	1.87	High	2.07	Excessive
24+00	24+00	25+00	100			0.95	Medium	1.06	Medium	1.16	Medium	1.25	Medium
25+00	25+00	26+00	100			1.09	Medium	1.30	Medium	1.49	High	1.66	High
26+00	26+00	27+00	100			0.73	Low	0.85	Medium	0.95	Medium	1.04	Medium
27+00	27+00	28+00	100		↓	3.14	Excessive	3.41	Excessive	3.67	Excessive	3.91	Excessive
28+00	28+00	29+00	100	Wooded forest,	1.0 - 1.5	0.08	Low	0.10	Low	0.12	Low	0.14	Low
29+00	29+00	29+50	50	good ground cover,		0.37	Low	0.14	Low	0.16	Low	0.17	Low
29+50	29+50	30+00	50	grass on trail		0.36	Low	0.33	Low	0.34	Low	0.42	Low
30+00	30+00	31+00	100			0.03	Low	0.05	Low	0.06	Low	0.08	Low
31+00	31+00	32+00	100			0.65	Low	0.74	Low	0.72	Low	0.66	Low
32+00	32+00	36+00	400		↓	0.53	Low	0.61	Low	0.68	Low	0.75	Low
36+00	36+00	37+00	100	Wooded with deadfall	0.3 - 1.0	0.25	Low	0.29	Low	0.33	Medium	0.36	Medium
37+00	37+00	38+00	100			0.70	High	0.87	High	1.01	Excessive	1.16	Excessive
38+00	38+00	39+00	100		↓	1.12	Excessive	1.26	Excessive	1.39	Excessive	1.51	Excessive
39+00	39+00	40+00	100	Pine and spruce	0.25 - 0.7	0.54	High	0.54	High	0.57	High	0.60	High
40+00	40+00	41+00	100	plantation, no ground		0.88	Excessive	1.00	Excessive	1.07	Excessive	1.13	Excessive
41+00	41+00	42+00	100	cover		0.57	High	0.64	High	0.71	Excessive	0.75	Excessive
42+00	42+00	43+00	100			0.63	High	0.72	Excessive	0.78	Excessive	0.85	Excessive
43+00	43+00	44+00	100			0.64	High	0.75	Excessive	0.85	Excessive	0.94	Excessive
44+00	44+00	45+00	100			1.75	Excessive	2.02	Excessive	2.25	Excessive	2.45	Excessive
45+00	45+00	46+00	100			1.09	Excessive	1.14	Excessive	1.17	Excessive	1.21	Excessive
46+00	46+00	48+00	200		↓	0.32	Medium	0.37	Medium	0.42	Medium	0.46	Medium
48+00	48+00	49+00	100	Clean oak forest,	0.4 - 1.0	0.30	Low	0.32	Low	0.34	Low	0.36	Low
49+00	49+00	50+00	100	medium density		1.18	Excessive	1.30	Excessive	1.52	Excessive	1.62	Excessive
50+00	50+00	52+00	200	underbrush		0.58	Medium	0.71	High	0.81	High	0.94	High
52+00	52+00	54+00	200		↓	0.51	Medium	0.58	Medium	0.65	Medium	0.71	High
54+00	54+00	58+00	400	Unmaintained	0.3 - 1.0	2.58	Excessive	2.93	Excessive	3.23	Excessive	3.48	Excessive
--	--	--	--	channel with medium		--	--	--	--	--	--	--	--
--	--	--	--	density forbs/shrubs		--	--	--	--	--	--	--	--
58+00	58+00	68+00	1000	Pond									
68+00	68+00	69+00	100	Wooded with deadfall,	0.4 - 1.0	0.85	High	0.71	High	0.42	Medium	0.25	Low
69+00	69+00	70+00	100	low-medium density		1.18	Excessive	1.47	Excessive	1.57	Excessive	1.88	Excessive
70+00	70+00	71+00	100	underbrush		2.06	Excessive	2.28	Excessive	2.65	Excessive	2.80	Excessive
71+00	71+00	72+00	100			0.81	High	0.96	High	1.12	Excessive	1.24	Excessive
72+00	72+00	73+00	100			1.28	Excessive	1.43	Excessive	1.57	Excessive	1.69	Excessive
73+00	73+00	75+00	200			1.20	Excessive	1.24	Excessive	1.45	Excessive	1.55	Excessive
75+00	75+00	80+00	500		↓	1.71	Excessive	1.94	Excessive	2.08	Excessive	2.24	Excessive
--	--	--	--		--	--	--	--	--	--	--	--	--
--	--	--	--		--	--	--	--	--	--	--	--	--
80+00	80+00	81+00	100		0.4 - 1.0	1.12	Excessive	1.06	Excessive	1.12	Excessive	1.10	Excessive
81+00	81+00	85+00	400	Bare channel,	0.2 - 0.7	2.69	Excessive	3.08	Excessive	3.40	Excessive	3.72	Excessive
--	--	--	--	Unmaintained	--	--	--	--	--	--	--	--	--
--	--	--	--		--	--	--	--	--	--	--	--	--
85+00	85+00	91+00	600	Mowed pasture	0.4 - 1.0	1.41	Excessive	1.09	Excessive	1.67	Excessive	1.49	Excessive
91+00	91+00	95+00	400		↓	1.58	Excessive	2.06	Excessive	1.92	Excessive	2.58	Excessive

Stabilization Measures for 90 cfs														Additional Possible Stabilization Measures for Higher Flow Rates		
						90 cfs		120 cfs		150 cfs		180 cfs				
Section Number	Station Number From	Station Number To	Length (ft.)	Stabilization Measures	Estimated Shear Threshold (lb/sf)	Maximum Shear Stress	Erosion Potential	Maximum Shear Stress	Erosion Potential	Maximum Shear Stress	Erosion Potential	Maximum Shear Stress	Erosion Potential	Additional Stabilization Measures for **120 cfs**	Additional Stabilization Measures for **150 cfs**	Additional Stabilization Measures for **180 cfs**
0+00	-2+50	1+00	350	N/A	1.5 - 2.5	0.17	Low	0.16	Low	0.15	Low	0.13	Low	N/A	N/A	N/A
1+00	1+00	2+00	100	N/A	↓	0.44	Low	0.51	Low	0.58	Low	0.64	Low	N/A	N/A	N/A
2+00	2+00	3+00	100	N/A	1.0 - 2.0	0.36	Low	0.43	Low	0.48	Low	0.52	Low	N/A	N/A	N/A
3+00	3+00	4+00	100	N/A	↓	0.45	Low	0.50	Low	0.53	Low	0.56	Low	N/A	N/A	N/A
4+00	4+00	5+00	100	Check Dam/Veg. Mgmt.	1.2	0.30	Low	0.34	Low	0.37	Low	0.40	Low	N/A	N/A	N/A
6+00	6+00	7+00	100	N/A	1.0 - 2.0	0.91	Low	1.02	Medium	1.12	Medium	1.21	Medium	Veg. Mgmt.	Veg. Mgmt.	Check Dam
7+00	7+00	7+50	50	Check Dam/Veg. Mgmt.	1.2	0.03	Low	0.09	Low	0.19	Low	0.28	Low	N/A	N/A	N/A
7+50	7+50	8+00	50	N/A	1.0 - 2.0	0.37	Low	0.56	Low	0.73	Low	0.91	Low	N/A	N/A	N/A
8+00	8+00	9+00	100	Check Dam/Veg. Mgmt.	1.2	0.61	Low	1.25	Excessive	1.48	Excessive	1.58	Excessive	New Lined Channel	New Lined Channel	New Lined Channel
9+00	9+00	10+00	100	N/A	1.0 - 1.5	0.72	Low	0.65	Low	0.48	Low	0.36	Low	N/A	N/A	N/A
10+00	10+00	10+60	60	Check Dam/Veg. Mgmt.	1.2	0.47	Low	1.19	Low	1.27	Excessive	1.34	Excessive	N/A	Check Dam	Check Dam
10+60	10+60	11+00	40	N/A	1.0 - 1.5	0.44	Low	0.67	Low	0.71	Low	0.76	Low	N/A	N/A	N/A
11+00	11+00	12+00	100	N/A		0.90	Low	0.35	Low	0.42	Low	0.49	Low	N/A	N/A	N/A
12+00	12+00	13+00	100	N/A		0.85	Low	1.01	Medium	1.16	Medium	1.29	High	Veg. Mgmt.	Veg. Mgmt.	Check Dam
13+00	13+00	14+00	100	Check Dam		0.03	Low	0.05	Low	0.06	Low	0.07	Low	N/A	N/A	N/A
14+00	14+00	15+00	100	Check Dam	↓	0.48	Low	0.55	Low	0.60	Low	0.65	Low	N/A	N/A	N/A
15+00	15+00	16+00	100	Veg. Mgmt.	1.2	1.15	Low	1.25	Excessive	1.35	Excessive	1.43	Excessive	Check Dam	Check Dam	New Lined Channel
16+00	16+00	17+00	100	N/A	1.0 - 1.5	0.74	Low	0.87	Low	0.99	Low	1.10	Medium	N/A	N/A	Veg. Mgmt.
17+00	17+00	18+00	100	N/A		0.52	Low	0.60	Low	0.66	Low	0.74	Low	N/A	N/A	N/A
18+00	18+00	19+00	100	N/A		0.96	Low	1.09	Medium	1.20	Medium	1.29	High	Veg. Mgmt.	Veg. Mgmt.	Check Dam
19+00	19+00	20+00	100	N/A	↓	0.85	Low	1.00	Low	1.14	Medium	1.26	High	N/A	Veg. Mgmt.	Check Dam
20+00	20+00	21+00	100	N/A	0.8 - 2.0	0.65	Low	0.78	Low	0.90	Medium	1.01	Medium	N/A	Veg. Mgt.	Veg. Mgmt.
21+00	21+00	22+00	100	Check Dam		0.52	Low	0.59	Low	0.66	Low	0.71	Low	N/A	N/A	N/A
22+00	22+00	23+00	100	N/A		0.78	Low	0.92	Medium	1.04	Medium	1.16	Medium	Veg. Mgmt.	Veg. Mgmt.	Veg. Mgmt.
23+00	23+00	24+00	100	Check Dam	↓	0.32	Low	0.39	Low	0.47	Low	0.55	Low	N/A	N/A	N/A
24+00	24+00	25+00	100	Veg. Mgmt.	1.2	0.85	Low	0.95	Low	1.04	Low	1.10	Low	N/A	N/A	N/A
25+00	25+00	26+00	100	Veg. Mgmt.	1.2	0.92	Low	1.09	Low	1.37	Excessive	1.40	Excessive	N/A	Check Dam	Check Dam
26+00	26+00	27+00	100	Veg. Mgmt.	1.2	0.82	Low	0.96	Low	1.06	Low	1.18	Low	N/A	N/A	N/A
27+00	27+00	28+00	100	Check Dam	0.8 - 2.0	0.75	Low	0.79	Low	0.63	Low	0.76	Low	N/A	N/A	N/A
28+00	28+00	29+00	100	N/A	1.0 - 1.5	0.12	Low	0.15	Low	0.17	Low	0.19	Low	N/A	N/A	N/A
29+00	29+00	29+50	50	N/A		0.12	Low	0.46	Low	0.18	Low	0.18	Low	N/A	N/A	N/A
29+50	29+50	30+00	50	N/A		0.79	Low	0.40	Low	0.41	Low	0.45	Low	N/A	N/A	N/A
30+00	30+00	31+00	100	N/A		0.01	Low	0.05	Low	0.07	Low	0.08	Low	N/A	N/A	N/A
31+00	31+00	32+00	100	N/A		0.70	Low	0.74	Low	0.82	Low	0.75	Low	N/A	N/A	N/A
32+00	32+00	36+00	400	N/A	↓	0.46	Low	0.53	Low	0.60	Low	0.66	Low	N/A	N/A	N/A
36+00	36+00	37+00	100	Deadfall/Veg. Mgmt.	1.2	0.30	Low	0.35	Low	0.39	Low	0.43	Low	N/A	N/A	N/A
37+00	37+00	38+00	100	Deadfall/Veg. Mgmt.		0.16	Low	0.20	Low	0.24	Low	0.28	Low	N/A	N/A	N/A
38+00	38+00	39+00	100	Deadfall/Veg. Mgmt.	↓	0.29	Low	0.36	Low	0.42	Low	0.48	Low	N/A	N/A	N/A
39+00	39+00	40+00	100	New Lined Channel	3.0 in channel	0.74	Low	0.91	*Low / Exc.	0.81	*Low / Exc.	0.78	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
40+00	40+00	41+00	100	New Lined Channel	0.25 - 0.7 outside	1.44	Low	1.48	*Low / Exc.	1.84	*Low / Exc.	1.91	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
41+00	41+00	42+00	100	New Lined Channel	of channel	1.04	Low	1.28	*Low / Exc.	1.24	*Low / Exc.	1.19	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
42+00	42+00	43+00	100	New Lined Channel		1.15	Low	1.09	*Low / Exc.	1.22	*Low / Exc.	1.18	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
43+00	43+00	44+00	100	New Lined Channel		1.22	Low	1.63	*Low / Exc.	1.30	*Low / Exc.	1.30	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
44+00	44+00	45+00	100	New Lined Channel		1.39	Low	1.09	*Low / Exc.	1.09	*Low / Exc.	1.27	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
45+00	45+00	46+00	100	New Lined Channel		1.13	Low	1.17	*Low / Exc.	1.13	*Low / Exc.	1.04	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
46+00	46+00	48+00	200	New Lined Channel	↓	0.72	Low	0.83	*Low / Exc.	1.03	*Low / Exc.	1.27	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
48+00	48+00	49+00	100	New Lined Channel	3.0 in channel	1.33	Low	1.82	*Low / Exc.	1.40	*Low / Exc.	0.90	*Low / Exc.	Larger Channel	Larger Channel	Larger Channel
49+00	49+00	50+00	100	New Lined Channel	0.4 - 1.0 outside	1.87	Low	1.99	*Low / Exc.	2.51	*Low / Exc.	3.65	*Exc. / Exc.	Larger Channel	Larger Channel	Check Dam/Larger Chan.
50+00	50+00	52+00	200	New Lined Channel	of channel	0.28	Low	0.13	*Low / Low	0.18	*Low / Low	0.01	*Low / Low	N/A	N/A	N/A
52+00	52+00	54+00	200	New Lined Channel	↓	0.49	Low	0.34	*Low / Low	0.28	*Low / Low	0.12	*Low / Low	N/A	N/A	N/A
54+00	54+00	55+50	150	Check Dam/Line Existing Channel	3.0 in channel	0.54	Low	0.58	*Low / Med	0.61	*Low / Med	0.63	*Low / Med	Additional Channel Lining	Additional Channel Lining	Additional Channel Lining
55+50	55+50	57+00	150	Check Dam/Line Existing Channel	0.3 - 1.0 outside	0.60	Low	0.65	*Low / Med	0.69	*Low / High	0.72	*Low / High	Additional Channel Lining	Additional Channel Lining	Additional Channel Lining
57+00	57+00	58+00	100	Check Dam/Line Existing Channel	of channel	0.59	Low	0.58	*Low / Med	0.54	*Low / Med	0.48	*Low / Med	Additional Channel Lining	Additional Channel Lining	Additional Channel Lining
68+00	68+00	69+00	100	Deadfall/Veg. Mgmt.	1.2	1.03	Low	1.13	Low	1.17	Low	1.19	Low	N/A	N/A	N/A
69+00	69+00	70+00	100	Deadfall/Veg. Mgmt.		1.04	Low	1.22	Excessive	1.31	Excessive	1.45	Excessive	N/A	Check Dam	Lined Channel
70+00	70+00	71+00	100	Check Dam/Veg.Mgmt.		0.45	Low	0.53	Low	0.60	Low	0.63	Low	N/A	N/A	N/A
71+00	71+00	72+00	100	Deadfall/Veg. Mgmt.		0.77	Low	0.88	Low	0.98	Low	1.07	Low	N/A	N/A	N/A
72+00	72+00	73+00	100	Check Dam/Veg.Mgmt.		0.50	Low	0.54	Low	0.57	Low	0.59	Low	N/A	N/A	N/A
73+00	73+00	75+00	200	Deadfall/Veg. Mgmt.		0.96	Low	1.03	Low	1.10	Low	1.14	Low	N/A	N/A	N/A
75+00	75+00	76+75	175	Check Dam/Veg.Mgmt.		0.56	Low	0.65	Low	0.74	Low	0.81	Low	N/A	N/A	N/A
76+25	76+75	78+50	175	Check Dam/Veg.Mgmt.		0.78	Low	0.88	Low	0.98	Low	1.06	Low	N/A	N/A	N/A
78+50	78+50	80+00	150	Check Dam/Veg.Mgmt.		0.72	Low	0.80	Low	0.89	Low	0.94	Low	N/A	N/A	N/A
80+00	80+00	81+00	100	Deadfall/Veg. Mgmt.	↓	1.09	Low	1.13	Low	1.14	Low	1.15	Low	N/A	N/A	N/A
81+00	81+00	82+50	150	Check Dam/Line Existing Channel	3.0 in channel	0.62	Low	0.59	*Low / High	0.54	*Low / High	0.42	*Low / Med	N/A	Additional Channel Lining	Additional Channel Lining
82+50	82+50	84+00	150	Check Dam/Line Existing Channel	0.2 - 0.7 outside	0.56	Low	0.51	*Low / High	0.42	*Low / Med	0.28	*Low / Med	N/A	Additional Channel Lining	Additional Channel Lining
84+00	84+00	85+00	100	Check Dam/Line Existing Channel	of channel	0.13	Low	0.11	*Low / Low	0.11	*Low / Low	0.10	*Low / Low	N/A	N/A	N/A
85+00	85+00	91+00	600	Class B Turf	2.1	1.16	Low	1.26	Low	1.33	Low	1.38	Low	N/A	N/A	N/A
91+00	91+00	95+00	400	Class B Turf	↓	1.41	Low	1.61	Low	1.80	Low	1.98	Low	N/A	N/A	N/A

Low - Below lower limit of threshold
Medium - Between lower limit and midpoint range of threshold
High - Between midpoint range and upper limit of threshold
Excessive - Above upper limit of threshold

1.2 based on lower limit for long native grasses
2.1 based on Class B turf
3.0 based on unvegetated non-degradable RECP

* First erosion potential classification is for shear stress with respect to in-channel threshold, second classification is with respect to outside of channel. Channel designed for 90 cfs so all shear stresses for 90 cfs compared to threshold in channel.

Note: Decreasing shear stresses with increasing flow for a few sections is likely due to unique channel geometry, transitions, and backwater effects

Table 6. Levels of Stabilization Needed in the Ravine

Flow Rate (cfs)	**90**	**120**	**150**	**180**
Length of ravine requiring stabilization (ft)	5,560	5,960	6,260	6,260
% of total ravine length requiring stabilization	59	63	66	66

Table 7. Safety Factor Analysis for 90 cfs

Section Number	Station Number From	Station Number To	Existing Vegetation Cover	Stabilization Measures for 90 cfs	Estimated Shear Threshold (lb/sf)	Maximum Shear Stress (lb/sq.ft.)	Safety Factor (SF)	Additional Possible Stabilization Measures for Safety Factor < 1.2
0+00	-2+50	1+00	Unmaintained	N/A	1.5 - 2.5	0.17	8.81	N/A
1+00	1+00	2+00	field grass	N/A	↓	0.44	3.41	N/A
2+00	2+00	3+00	Wooded forest,	N/A	1.0 - 2.0	0.36	2.76	N/A
3+00	3+00	4+00	good ground cover	N/A	↓	0.45	2.22	N/A
4+00	4+00	5+00		Check Dam/Veg. Mgmt.	1.2	0.30	4.04	N/A
5+00	5+00	6+00	Pond					
6+00	6+00	7+00	Wooded forest,	N/A	1.0 - 2.0	0.91	1.10	Veg. Mgmt.
7+00	7+00	7+50	good ground cover	Check Dam/Veg. Mgmt.	1.2	0.03	40.00	N/A
7+50	7+50	8+00		N/A	1.0 - 2.0	0.37	2.70	N/A
8+00	8+00	9+00		Check Dam/Veg. Mgmt.	1.2	0.61	1.97	N/A
9+00	9+00	10+00	Wooded forest,	N/A	1.0 - 1.5	0.72	1.39	N/A
10+00	10+00	10+60	good ground cover,	Check Dam/Veg. Mgmt.	1.2	0.47	2.55	N/A
10+60	10+60	11+00	mowed grass on	N/A	1.0 - 1.5	0.44	2.27	N/A
11+00	11+00	12+00	trail	N/A		0.90	1.11	Veg. Mgmt.
12+00	12+00	13+00		N/A		0.85	1.18	Veg. Mgmt.
13+00	13+00	14+00		Check Dam		0.03	30.04	N/A
14+00	14+00	15+00		Check Dam	↓	0.48	2.06	N/A
15+00	15+00	16+00		Veg. Mgmt.	1.2	1.15	1.04	Check Dam
16+00	16+00	17+00		N/A	1.0 - 1.5	0.74	1.36	N/A
17+00	17+00	18+00		N/A		0.52	1.91	N/A
18+00	18+00	19+00		N/A		0.96	1.04	Veg. Mgmt.
19+00	19+00	20+00		N/A	↓	0.85	1.18	Veg. Mgmt.
20+00	20+00	21+00	Wooded forest,	N/A	0.8 - 2.0	0.65	1.24	N/A
21+00	21+00	22+00	good ground cover,	Check Dam		0.52	1.54	N/A
22+00	22+00	23+00	trail on channel's	N/A		0.78	1.02	Veg. Mgmt.
23+00	23+00	24+00	right or left bank	Check Dam	↓	0.32	2.53	N/A
24+00	24+00	25+00		Veg. Mgmt.	1.2	0.85	1.41	N/A
25+00	25+00	26+00		Veg. Mgmt.	1.2	0.92	1.31	N/A
26+00	26+00	27+00		Veg. Mgmt.	1.2	0.82	1.46	N/A
27+00	27+00	28+00		Check Dam	0.8 - 2.0	0.75	1.06	Add'l or Higher Check Dam
28+00	28+00	29+00	Wooded forest,	N/A	1.0 - 1.5	0.12	8.26	N/A
29+00	29+00	29+50	good ground cover,	N/A		0.12	8.65	N/A
29+50	29+50	30+00	grass on trail	N/A		0.79	1.27	N/A
30+00	30+00	31+00		N/A		0.01	70.01	N/A
31+00	31+00	32+00		N/A		0.70	1.42	N/A
32+00	32+00	36+00		N/A	↓	0.46	2.16	N/A
36+00	36+00	37+00	Wooded with deadfall	Deadfall/Veg. Mgmt.	1.2	0.30	4.00	N/A
37+00	37+00	38+00		Deadfall/Veg. Mgmt.		0.16	7.49	N/A
38+00	38+00	39+00		Deadfall/Veg. Mgmt.	↓	0.29	4.08	N/A
39+00	39+00	40+00	Pine and spruce	Lined Channel	3.0 in channel	0.74	4.05	N/A
40+00	40+00	41+00	plantation, no ground	Lined Channel	0.25 - 0.7 outside	1.44	2.09	N/A
41+00	41+00	42+00	cover	Lined Channel	of channel	1.04	2.87	N/A
42+00	42+00	43+00		Lined Channel		1.15	2.61	N/A
43+00	43+00	44+00		Lined Channel		1.22	2.46	N/A
44+00	44+00	45+00		Lined Channel		1.39	2.16	N/A
45+00	45+00	46+00		Lined Channel		1.13	2.64	N/A
46+00	46+00	48+00		Lined Channel	↓	0.72	4.16	N/A
48+00	48+00	49+00	Clean oak forest,	Lined Channel	3.0 in channel	1.33	2.25	N/A
49+00	49+00	50+00	medium density	Lined Channel	0.4 - 1.0 outside	1.87	1.60	N/A
50+00	50+00	52+00	underbrush	Lined Channel	of channel	0.28	10.64	N/A
52+00	52+00	54+00		Lined Channel	↓	0.49	6.07	N/A
54+00	54+00	58+00	Unmaintained	Check Dam/Channel Lining	3.0 in channel	0.54	5.60	N/A
--	--	--	channel with medium	Check Dam/Channel Lining	0.3 - 1.0 outside	0.60	4.99	N/A
--	--	--	density forbs/shrubs	Check Dam/Channel Lining	of channel	0.59	5.12	N/A
58+00	58+00	68+00	Pond					
68+00	68+00	69+00	Wooded with deadfall,	Deadfall/Veg. Mgmt.	1.2	1.03	1.17	Check Dam
69+00	69+00	70+00	low-medium density	Deadfall/Veg. Mgmt.		1.04	1.16	Check Dam
70+00	70+00	71+00	underbrush	Check Dam/Veg.Mgmt.		0.45	2.68	N/A
71+00	71+00	72+00		Deadfall/Veg. Mgmt.		0.77	1.56	N/A
72+00	72+00	73+00		Check Dam/Veg.Mgmt.		0.50	2.42	N/A
73+00	73+00	75+00		Deadfall/Veg. Mgmt.		0.96	1.25	N/A
75+00	75+00	80+00		Check Dam/Veg.Mgmt.		0.56	2.16	N/A
--	--	--		Check Dam/Veg.Mgmt.		0.78	1.55	N/A
--	--	--		Check Dam/Veg.Mgmt.		0.72	1.67	N/A
80+00	80+00	81+00		Deadfall/Veg. Mgmt.	↓	1.09	1.10	Check Dam
81+00	81+00	82+50	Bare channel,	Check Dam/Channel Lining	3.0 in channel	0.62	4.82	N/A
--	--	--	Unmaintained	Check Dam/Channel Lining	0.2 - 0.7 outside	0.56	5.33	N/A
--	--	--		Check Dam/Channel Lining	of channel	0.13	23.27	N/A
85+00	85+00	91+00	Mowed pasture	Class B Turf	2.1	1.16	1.81	N/A
91+00	91+00	95+00		Class B Turf	↓	1.41	1.49	N/A

SF < 1.2

Figure 1. Existing Vegetation Coverage

View at section 10+00

Drawn by Ingraham & Associates

Figure 2. Vegetation Management

Restore to oak savanna

View at section 10+00

Drawn by Ingraham & Associates

Figure 3. Check Dam

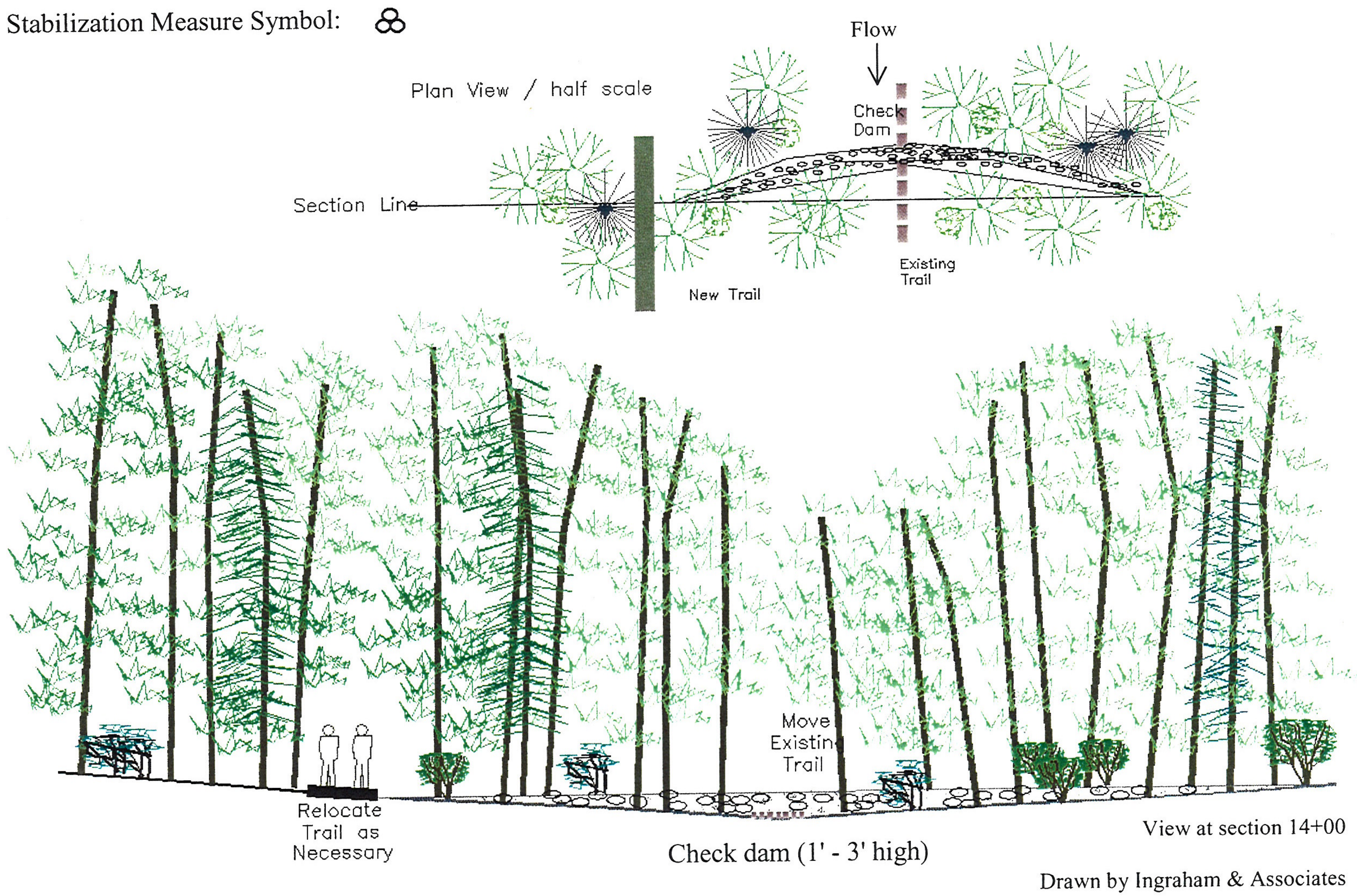
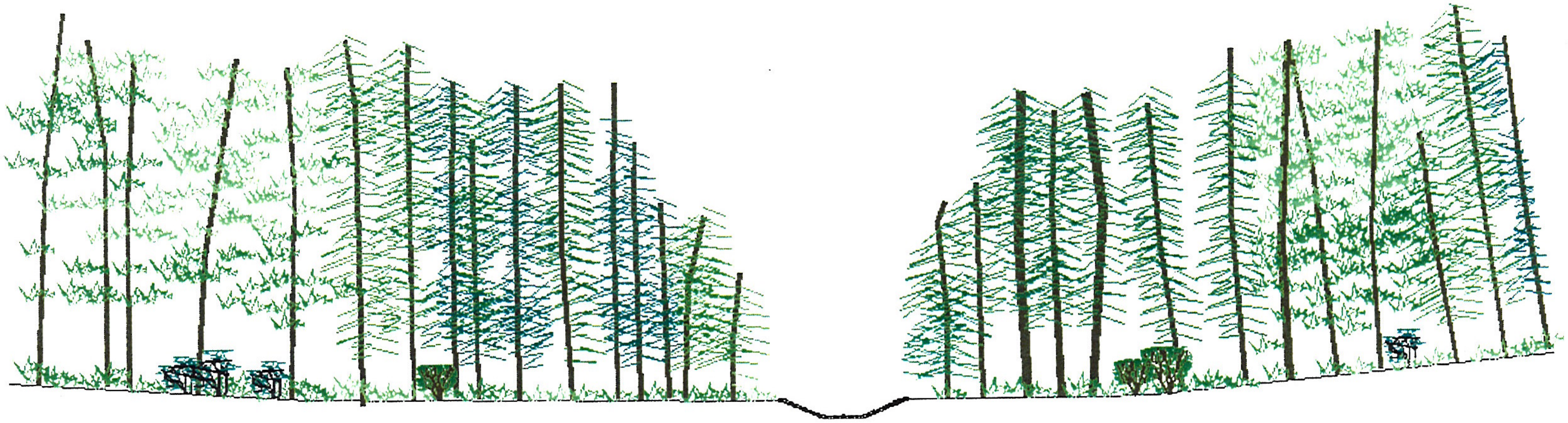


Figure 4. New Lined Channel

Stabilization Measure Symbol: 



Channel

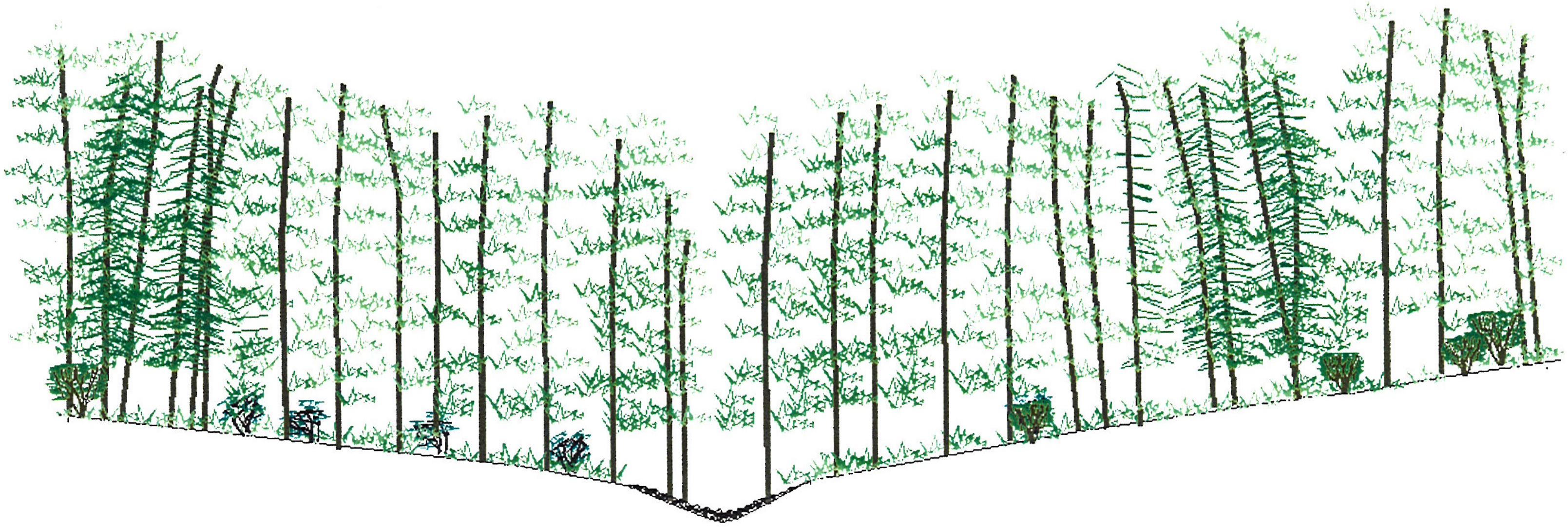
- 15'-20' top width
- 5'-8' bottom width
- Approximately 2' deep

View at section 43+00

Drawn by Ingraham & Associates

Figure 5. Line Existing Channel

Stabilization Measure Symbol: 



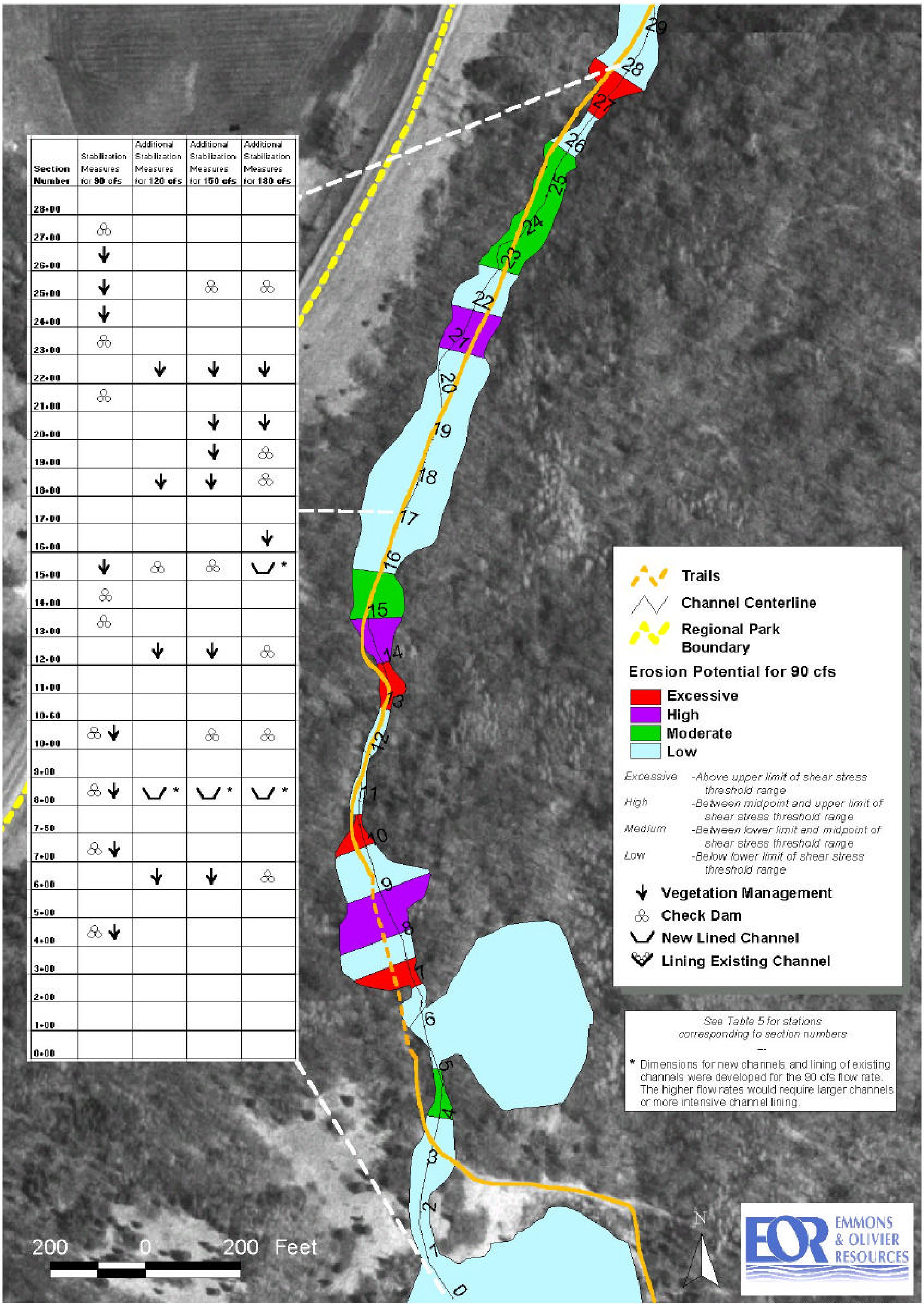
View at section 56+00

Drawn by Ingraham & Associates

Figure 6A

Erosion Potential Based on Shear Stress for 90 cfs and Stabilization for Flows from 90 cfs to 180 cfs

South Washington Watershed District
SWWD



Section Number	Stabilization Measures for 90 cfs	Additional Stabilization Measures for 120 cfs	Additional Stabilization Measures for 150 cfs	Additional Stabilization Measures for 180 cfs
28+00				
27+00	∴			
26+00	↓			
25+00	↓		∴	∴
24+00	↓			
23+00	∴			
22+00		↓	↓	↓
21+00	∴			
20+00			↓	↓
19+00			↓	∴
18+00		↓	↓	∴
17+00				
16+00				↓
15+00	↓	∴	∴	⊔ *
14+00	∴			
13+00	∴			
12+00		↓	↓	∴
11+00				
10+60				
10+00	∴ ↓		∴	∴
9+00				
8+00	∴ ↓	⊔ *	⊔ *	⊔ *
7+50				
7+00	∴ ↓			
6+00		↓	↓	∴
5+00				
4+00	∴ ↓			
3+00				
2+00				
1+00				
0+00				

Trails
Channel Centerline
Regional Park Boundary

Erosion Potential for 90 cfs

🟥 Excessive
🟪 High
🟩 Moderate
▢ Low

Excessive	*-Above upper limit of shear stress threshold range*
High	*-Between midpoint and upper limit of shear stress threshold range*
Medium	*-Between lower limit and midpoint of shear stress threshold range*
Low	*-Below lower limit of shear stress threshold range*

↓ Vegetation Management
∴ Check Dam
⊔ New Lined Channel
⋎ Lining Existing Channel

See Table 5 for stations corresponding to section numbers

--

* Dimensions for new channels and lining of existing channels were developed for the 90 cfs flow rate. The higher flow rates would require larger channels or more intensive channel lining.

EOR EMMONS & OLIVIER RESOURCES

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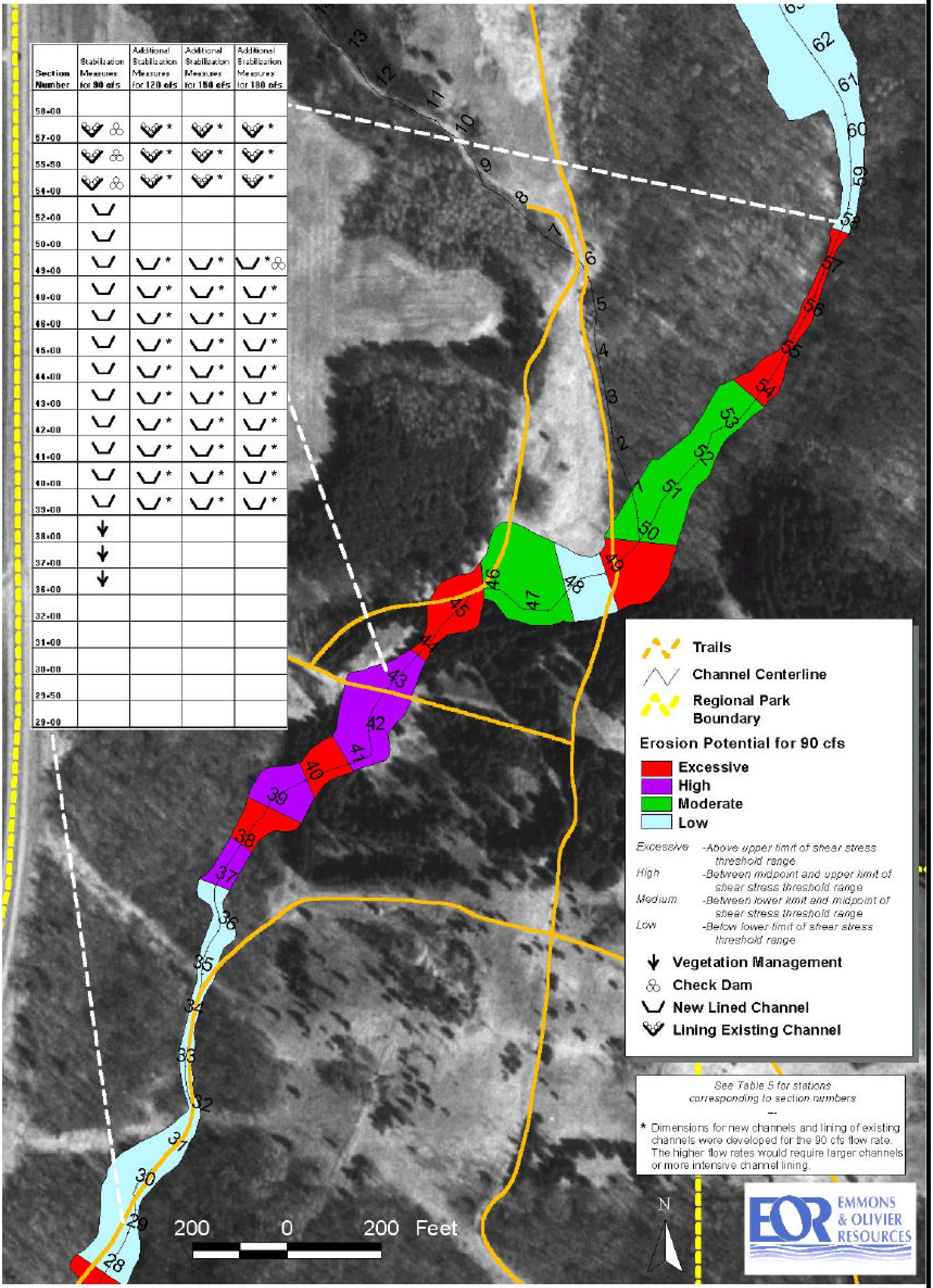
Figure 6B

Erosion Potential Based on Shear Stress for 90 cfs and Stabilization for Flows from 90 cfs to 180 cfs



Section Number	Stabilization Measures for 90 cfs	Additional Stabilization Measures for 120 cfs	Additional Stabilization Measures for 150 cfs	Additional Stabilization Measures for 180 cfs
58+00				
57+00	▽ ∴	▽ *	▽ *	▽ *
55+50	▽ ∴	▽ *	▽ *	▽ *
54+00	▽ ∴	▽ *	▽ *	▽ *
52+00	⊔			
50+00	⊔			
49+00	⊔	⊔ *	⊔ *	⊔ * ∴
48+00	⊔	⊔ *	⊔ *	⊔ *
46+00	⊔	⊔ *	⊔ *	⊔ *
45+00	⊔	⊔ *	⊔ *	⊔ *
44+00	⊔	⊔ *	⊔ *	⊔ *
43+00	⊔	⊔ *	⊔ *	⊔ *
42+00	⊔	⊔ *	⊔ *	⊔ *
41+00	⊔	⊔ *	⊔ *	⊔ *
40+00	⊔	⊔ *	⊔ *	⊔ *
39+00	⊔	⊔ *	⊔ *	⊔ *
38+00	↓			
37+00	↓			
36+00	↓			
32+00				
31+00				
30+00				
29+50				
29+00				

Trails
Channel Centerline
Regional Park Boundary

Erosion Potential for 90 cfs

🟥 Excessive
🟪 High
🟩 Moderate
⬜ Low

Excessive	*-Above upper limit of shear stress threshold range*
High	*-Between midpoint and upper limit of shear stress threshold range*
Medium	*-Between lower limit and midpoint of shear stress threshold range*
Low	*-Below lower limit of shear stress threshold range*

↓ Vegetation Management
∴ Check Dam
⊔ New Lined Channel
▽ Lining Existing Channel

See Table 5 for stations corresponding to section numbers

* Dimensions for new channels and lining of existing channels were developed for the 90 cfs flow rate. The higher flow rates would require larger channels or more intensive channel lining.

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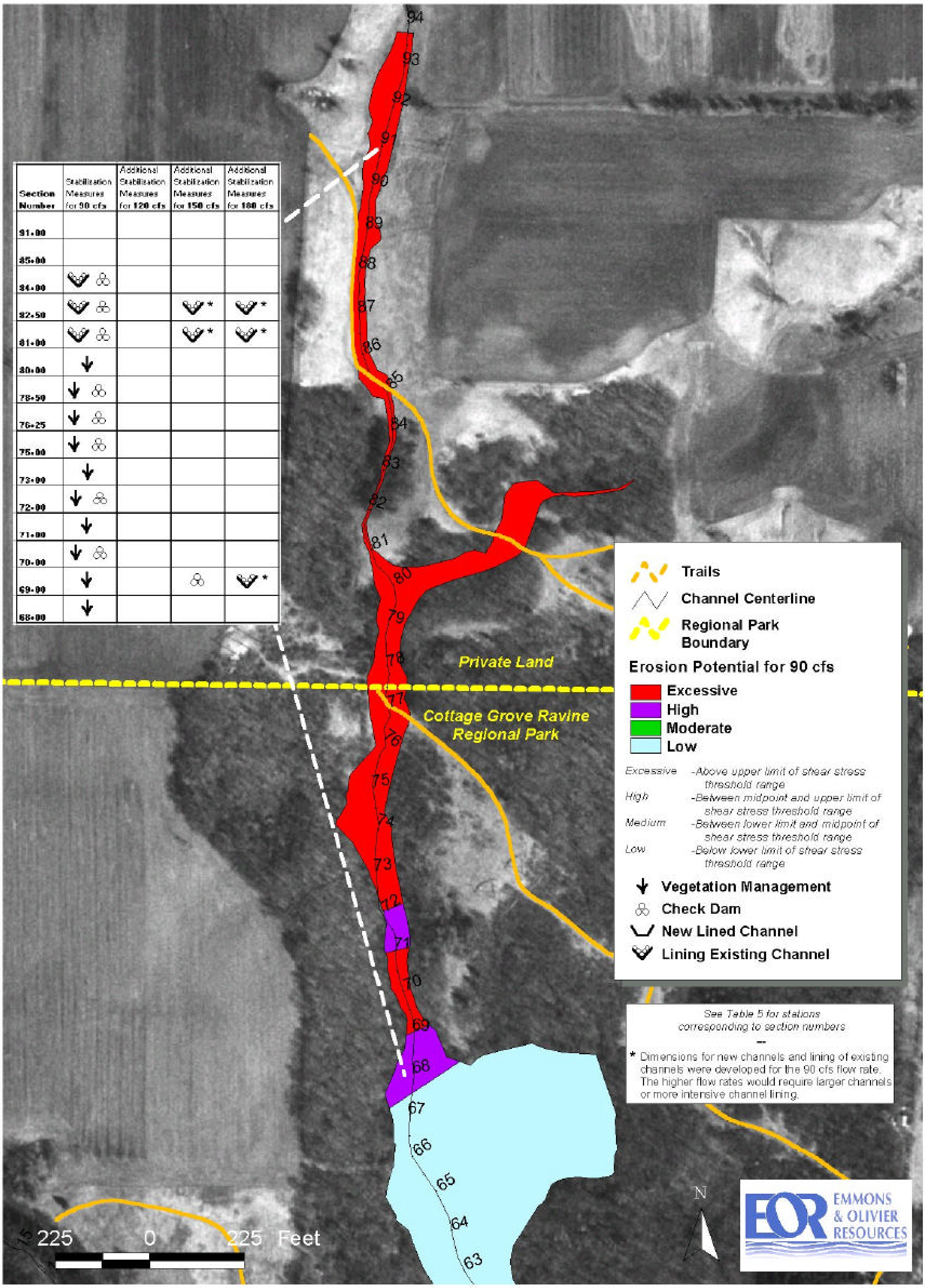
Figure 6C

Erosion Potential Based on Shear Stress for 90 cfs and Stabilization for Flows from 90 cfs to 180 cfs

South Washington Watershed District
SWWD



Section Number	Stabilization Measures for 90 cfs	Additional Stabilization Measures for 120 cfs	Additional Stabilization Measures for 150 cfs	Additional Stabilization Measures for 180 cfs
91+00				
85+00				
84+00	⋁ ∴			
82+50	⋁ ∴		⋁ *	⋁ *
81+00	⋁ ∴		⋁ *	⋁ *
80+00	↓			
78+50	↓ ∴			
76+25	↓ ∴			
75+00	↓ ∴			
73+00	↓			
72+00	↓ ∴			
71+00	↓			
70+00	↓ ∴			
69+00	↓		∴	⋁ *
68+00	↓			

Trails
Channel Centerline
Regional Park Boundary

Erosion Potential for 90 cfs

- 🟥 Excessive
- 🟪 High
- 🟩 Moderate
- ▭ Low

Excessive	*-Above upper limit of shear stress threshold range*
High	*-Between midpoint and upper limit of shear stress threshold range*
Medium	*-Between lower limit and midpoint of shear stress threshold range*
Low	*-Below lower limit of shear stress threshold range*

- ↓ Vegetation Management
- ∴ Check Dam
- ∪ New Lined Channel
- ⋁ Lining Existing Channel

See Table 5 for stations corresponding to section numbers

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* Dimensions for new channels and lining of existing channels were developed for the 90 cfs flow rate. The higher flow rates would require larger channels or more intensive channel lining.

EOR EMMONS & OLIVIER RESOURCES

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ravine_new_flow_rates.apr aps_1/30/02

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Appendix A

FIScH Engineering
Erosion Assessment Report

EROSION ASSESSMENT

South Washington Watershed District
County Road 19 Corridor
Minneapolis/Saint Paul, MN

February 7, 2001

FIScH Engineering

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FIScH Engineering
1100 Newit Vick Dr.
Vicksburg MS, 39183

Background

The South Washington Watershed District (SWWD) has identified in its 1997 Watershed Management Plan the need to address storm water issues in the northern half of the District due to the potential for problems resulting from increased urbanization. The District has studied the various options for managing storm water in the watershed for the past few years, and has developed a management strategy that includes the potential to route storm water through a ravine in a county park in the southeastern portion of the Twin Cities (Minneapolis/St. Paul) Metropolitan area in Minnesota. An assessment of the potential for erosion in this ravine and the development of preventive or mitigative measures are needed before pursuing this option further.

Scope of Service

Emmons & Olivier Resources sought the assistance of FIScH Engineering in the conduct of a stability assessment for the ravine. Specifically, FIScH Engineering was tasked with answering the following questions:

1. How to quantify different stream power forces on the existing channel comparing short-duration, local flows with long-duration, regional flows. Put another way, do impacts from 180 cfs to 230 cfs of local flows equal 180 cfs of regional flows (no additional impact of adding upstream flows on system already experiencing high peak flow rates)?
2. What are the appropriate protective measures (in general terms) for different velocity ranges along the channel? This could range from no action or softer (bio) solutions at lower velocities to hard surface (structural) solutions at higher velocities.

Representatives of FIScH Engineering have not conducted an on-site assessment of the conditions at the project site. The evaluation furnished in this report is based upon information furnished by Emmons & Olivier Resources, and includes the following:

1. SWWD Environmental Assessment - County Road 19 Corridor, Draft Phase I Report (October 23, 2000)
2. Copy of the XP-SWMM 2000 Ravine model input and output files for the various flow rates and tables with summaries of the flow velocities and depths
3. Survey information – AutoCAD files of the channel cross-sections generated for input into the model
4. Representative hydrographs along the ravine for simulated (un-calibrated) local flows (100-year, 10-day spring runoff event - frozen soil conditions) and the corresponding XP-SWMM model which includes the local drainages

Stability Criteria

The stability of a stream, or any channel for that matter, refers to how it accommodates itself to the inflowing water and sediment load. In general, stable streams may adjust their boundaries, but do not exhibit trends in changes to their geometric character. One form of instability occurs when a stream is unable to transport its sediment load - sediments deposit within the channel, leading to the condition referred to as aggradation. When the ability of the stream to transport sediment exceeds the availability of sediments within the incoming flow, and stability thresholds for the material forming the boundary of the channel are exceeded, erosion occurs. This paper deals with the latter case of instability, and distinguishes the presence or absence of erosion (threshold condition) from the magnitude of erosion (volume).

Erosion occurs when the hydraulic forces in the flow exceed the resisting forces of the channel boundary. The amount of erosion is a function of the relative magnitude of these forces and the time over which they are applied. The interaction of flow with the boundary of open channels is only imperfectly understood. Adequate analytical expressions describing this interaction have not yet been developed for conditions associated with natural channels. Thus, means of characterizing erosion potential must rely heavily upon empiricism. Traditional approaches for characterizing erosion potential can be placed in one of two categories: maximum permissible velocity, and tractive force (or critical shear stress). The former approach is advantageous in that velocity is a parameter they can be measured within the flow. Shear stress cannot be directly measured but must be computed from other flow parameters. On the other hand, shear stress has a better basis in fluid mechanics. Moreover, conventional guidelines, including ASTM standards, rely upon the use the shear stress as a means of assessing the stability of erosion control materials. Both approaches are presented in this paper.

Incipient Motion (Threshold Condition)

As the flow over the bed and banks of a stream increases, a condition is reached when the forces tending to move materials on the channel boundary are in balance with those resisting motion. This is referred to as the threshold state. The forces acting on a non-cohesive soil particle lying on the bed of a flowing stream include hydrodynamic lift, hydrodynamic drag, and the submerged weight ($F_w - F_b$), and a resisting force F_r. as seen in Figure 1. The drag is in the direction of the flow and the lift and weight are normal to the flow. The resisting force depends on the geometry of the particles. At the threshold of movement, the resultant of the forces in each direction is zero. Two related approaches for defining the threshold state are discussed herein, initial movement being specified in terms of either a critical velocity (v_{cr}) or a critical shear stress (τ_{cr}).

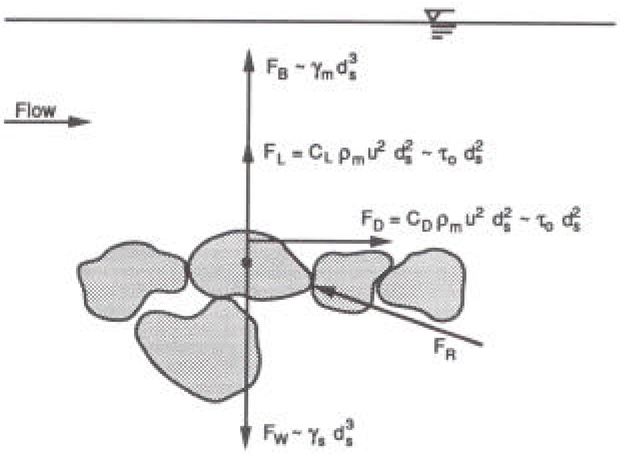

Figure 1. Forces acting on the boundary of a channel (adapted from Julien, 1995).

Critical Velocity

Figure 1 shows that both the lift and the drag force are directly related to the velocity squared. It is easy to see that small changes in the velocity could result in large changes in these forces. The permissible velocity is defined as the maximum mean velocity of the channel that will not cause erosion of the channel boundary. It is often called the critical velocity because it refers to the condition for the initiation of motion. Early works in canal design and in evaluating the stability of waterways relied upon this method. Considerable empirical data exist relating maximum velocities to various soil and vegetation conditions.

However, a simple method for design does not consider the channel shape or flow depth. At the same mean velocity, channels of different shapes or depths may have quite different forces acting on the boundaries. In other words, the critical velocity is depth dependent, and a correction factor for depth must be applied in application. Despite these limitations, maximum permissible velocity can be a useful tool in evaluating the stability of various waterways. It is most frequently applied as a cursory analysis when screening alternatives. Table 2, presented later in the text, provides values for maximum permissible velocity for various types of channel linings.

Critical Shear Stress

The forces shown in figure 1 can also be expressed in terms of the shear stress. The shear stresses the force per unit area in the flow direction. Its distribution in steady, uniform, two-dimensional flow in the channel can be reasonably described. An estimate of the average boundary shear stress (τ_o) exerted by the fluid on the bed is:

$$\tau_o = \gamma Rs \qquad (1)$$

where γ is the specific weight of water, R is hydraulic radius and s is slope. Derived from a consideration of the conservation of linear momentum, this quantity is a spatial average and does not necessarily provide a good estimate of bed shear at a point.

The critical shear stress (τ_{cr}) can be defined by equating the applied forces to the resisting forces. Shields (1936) determine the threshold condition by measuring sediment transport for values of shear at least twice the critical value and then extrapolating to the point vanishing sediment transport. His laboratory experiments have since served as a basis for defining critical shear stress. For soil grains of diameter d and angle of repose ϕ on a flat bed, the following relations can approximate the critical shear for various sizes of sediment:

$$t_{cr} = 0.5(l_s - l_w)d\ Tan f \quad \text{For clays} \qquad (2)$$

$$t_{cr} = 0.25 d_*^{-0.6}(l_s - l_w)d\ Tan f \quad \text{For silts and sands} \qquad (3)$$

$$t_{cr} = 0.06(l_s - l_w)d\ Tan f \quad \text{For gravels and cobbles} \qquad (4)$$

Where

$$d_* = d\left[\frac{(G-1)g}{n^2}\right]^{1/3} \qquad (5)$$

γ_s = the unit weight of the sediment
γ_w = the unit weight of the water/sediment mixture
G = the specific gravity of the sediment
G = gravitational acceleration
ν = the kinematic viscosity of the water/sediment mixture

The angle of repose, ϕ, for non-cohesive sediments is presented in Table 1, as are values for critical shear stress. The critical condition can be defined in terms of shear velocity rather than shear stress (note that shear velocity and channel velocity are different). Table 1 also provides limiting shear velocity as a function of sediment size. The V_{*c} term is the critical shear velocity, and is equal to:

$$V_{*c} = \sqrt{gR_hS_f} \qquad (6)$$

Table 1 provides limits that are best applied when evaluating idealized conditions, or the stability of sediments in the bed. Mixtures of sediments tended behave differently than do uniform sediments. Within a mixture, coarse sediments are generally entrained at lower shear stress values than presented in table 1. Conversely, larger shear stresses than those presented in the table are required to entrain finer sediments within a mixture. Cohesive soils, vegetation, and other armor materials can likewise be evaluated to determine empirical shear stress thresholds.

Cohesive soils are usually eroded by the detachment and entrainment of aggregates or crumbs of soil. Motivating forces are the same as those for non-cohesive banks, but the resisting forces are primarily the result of cohesive bonds between particles and aggregates. The bonding strength, and hence the soil erosion resistance, depends on the physio-chemical properties of the soil and the chemistry of the fluids.

Field and laboratory experiments show that intact, undisturbed cohesive soils are much less susceptible to flow erosion than are non-cohesive soils.

Table 1. Limiting shear stress and velocity for uniform non-cohesive sediments.

Class name	d_s (in)	f (deg)	t_{*c}	t_{cr} (lb/sf)	V_{*c} (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	4.36
Large	>40	42	0.054	18.7	3.08
Medium	>20	42	0.054	9.3	2.20
Small	>10	42	0.054	4.7	1.54
Cobble					
Large	>5	42	0.054	2.3	1.08
Small	>2.5	41	0.052	1.1	0.75
Gravel					
Very coarse	>1.3	40	0.050	0.54	0.52
Coarse	>0.6	38	0.047	0.25	0.36
Medium	>0.3	36	0.044	0.12	0.24
Fine	>0.16	35	0.042	0.06	0.17
Very fine	>0.08	33	0.039	0.03	0.12
Sands					
Very coarse	>0.04	32	0.029	0.01	0.070
Coarse	>0.02	31	0.033	0.006	0.055
Medium	>0.01	30	0.048	0.004	0.045
Fine	>0.005	30	0.072	0.003	0.040
Very fine	>0.003	30	0.109	0.002	0.035
Silts					
Coarse	>0.002	30	0.165	0.001	0.030
Medium	>0.001	30	0.25	0.001	0.025

Vegetation has a profound effect on the stability of both cohesive and noncohesive soils. Vegetation serves as an effective buffer between the water and the underlying soil. Vegetation increases the effective roughness height of the boundary, increasing flow resistance and displacing the velocity upwards away from the soil. This has the effect of reducing the forces of drag and lift acting on the soil surface. As the boundary shear stress is proportional to the square of the near bank velocity, a reduction in this velocity produces a much greater reduction in the forces responsible for erosion.

Vegetation not only protects the soil surface directly, but the roots and rhizomes of plants bind the soil and introduce extra cohesion over and above any intrinsic cohesion that the bank material may have. The presence of vegetation does not render underlying soils immune from erosion, but the critical condition for erosion of a vegetated bank is the threshold of failure of the plant stands by snapping, stem scour, or uprooting, rather than out for detachment and entrainment of the soils themselves. Vegetation failure usually occurs at much higher levels of flow intensity than for soil erosion.

Both rigid inflexible armor systems can be used in waterways to protect the channel bed from erosion and to stabilize side slopes. A wide array of differing armor materials are available to accomplish this. Most manufactured products are evaluated to determine their failure threshold. Product selection is usually made on the basis of design graphs that present the flow depth on one axis and the slope of the channel on the other axis. Thus, the design is based on the depth/slope product or, in other words, the shear stress.

Table 2 presents limiting values for shear stress and velocity for a number of different channel lining materials. Included are soils, various types of vegetation, and number of different commonly applied stabilization techniques. Information presented in the table was derived from a number of different sources. Ranges of values presented in the table reflect various measures presented within the literature. In the case of manufactured products, the designer should consult the manufacturers guidelines to determine thresholds for a specific product.

Table 2. Permissible shear or tractive stresses for selected lining materials[1] (adapted from references listed at the end of the paper)

Boundary Category	***Boundary Type***	***Permissible Shear Stress (lbs/sq.ft)***	***Permissible Velocity (ft/s)***
Soils	Fine colloidal sand	.02 - .03	1.5
	Sandy loam (noncolloidal)	.03 - .04	1.75
	Alluvial silt (noncolloidal)	.045 - .05	2
	Silt loam (noncolloidal)	.045 - .05	1.75 – 2.25
	Firm loam	.075	2.5
	Fine gravels	.075	2.5
	Stiff clay	.26	3 – 4.5
	Alluvial silt (colloidal)	.26	3.75
	Graded loam to cobbles	.38	3.75
	Graded silts to cobbles	.43	4
	Shales and hardpan	.67	6
Gravel/Cobble	1-inch	0.33	2.5 – 5
	2-inch	0.67	3 – 6
	6-inch	2.0	4 – 7.5
	12-inch	4.0	5.5 – 12
Vegetation	Class A Turf	3.7	6 – 8
	Class B Turf	2.1	4 - 7
	Class C Turf	1.0	3.5
	Long Native Grasses	1.2 – 1.7	4 – 6
	Short Natives & Bunch Grass	0.7 - .95	3 – 4
	Reed Plantings	0.1-0.6	N/A
	Hardwood Tree Plantings	0.41-2.5	N/A
Temporary Degradable RECP's	Jute Net	0.45	1 – 2.5
	Straw with Net	1.5 – 1.65	1 – 3
	Coconut Fiber with Net	2.25	3 – 4
	Fiber Glass Roving	2.00	2.5 – 7
Non-Degradable RECP's	Unvegetated	3.00	5 – 7
	Partial Establish	4.0-6.0	7.5 – 15
	Fully Vegetated	8.00	8 – 21
Riprap	6 – inch d_{50}	2.5	5 – 10
	9 – inch d_{50}	3.8	7 – 11
	12 – inch d_{50}	5.1	10 – 13
	18 – inch d_{50}	7.6	12 – 16
	24 – inch d_{50}	10.1	14 – 18
Soil Bioengineering	Reed fascine	0.6-1.25	5
	Coir Roll	3 - 5	8
	Vegetated Coir Mat	4 - 7	9.5
	Live Brush Mattress (initial)	0.4	4
	Live Brush Mattress (grown)	3.90-4.60	12
	Brush Layering (initial/grown)	1.1-6.25	12
	Live Fascine	1.25-3.10	6 – 8
	Live Willow Stakes	2.10-3.10	3 – 6
Hard Surfacing	Gabions	10	14 – 19
	Concrete	12.5	>18

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[1] Ranges of values generally reflect multiple sources of data or different testing conditions.

Uncertainty and Variability

The values presented in Table 2 generally relate to average values of shear stress or velocity. But velocity and shear stress are neither uniform nor steady in natural channels. Short-term pulses in the flow can give rise to instantaneous velocities or stresses of 2 – 3 times the average, so that erosion may occur at stresses much lower than predicted. Because limits presented in Table 2 were developed empirically, they implicitly include some of his variability. But natural channels typically exhibit much more variability than the flumes these data were developed from.

Sediment load can also profoundly affect the ability of flow to erode underlying soils. Sediments in suspension have the effect of damping turbulence within the flow. Turbulence is an important factor in entraining materials from the channel boundaries. As a consequence, velocity and shear stress thresholds are 1.5 – 3 times that presented in the table for flows carrying high sediment loads.

In addition to variability of flow conditions, variation in the channel lining characteristics can influence erosion predictions. Natural bed material is neither spherical nor of uniform size. Larger particles may shield smaller ones from direct impact so that the latter fail to move until higher stresses are attained. For a given grain size, the true threshold criterion may vary by nearly an order of magnitude depending on the bed gradation. Variation in the installation of erosion control measures can reduce the threshold necessary to cause erosion. Changes in the density or vigor of vegetation can either increase or decrease erosion threshold. Even differences between the growing and dormant seasons can lead to one- to two-fold changes in erosion thresholds.

To addresses uncertainty and variability, is recommended that the designer adjust the predicted velocity or shear stress by applying a factor of safety or by computing local and instantaneous values for these parameters. Guidance for making these adjustments is presented in the section titled “Application” below.

Erosion Magnitude

The preceding discussion dealt with the presence or absence of erosion. It does not address the extent to which erosion might occur for a given flow. If the thresholds presented in Table 2 are exceeded, erosion should be expected to occur. In reality, even when those thresholds are not exceeded, some minor erosion in a few select locations may occur. The extent to which this minor erosion could become a significant concern depends in large measure on the duration of the flow, and upon the ability of the stream to transport those eroded sediments.

Flow Duration

The significance of the duration of flow should not be overlooked when evaluating the stability of a waterway. Although not stated, limits regarding erosion potential published by manufacturers for various products are typically developed from studies using short durations. They do not reflect the potential for severe erosion damage that can result from moderate flow events over several hours. Studies have shown the duration of flow reduces erosion resistance of many types of erosion control products, as shown in Figure 2. In cases were flow duration exceeds a couple hours, a factor of safety should be applied in the design to account for this phenomena.

Correlations between flow volume and amount of erosion tend to be poor. Multi-peaked flows may be more effective than single flows of comparable or greater magnitude because of the increased incidence of wetting. Flows with long durations often have a more significant affect on erosion than short-lived flows of higher magnitude. Sediment transport analysis can be used to gauge the magnitude of erosion potential in the channel design, but predictive capability is limited.

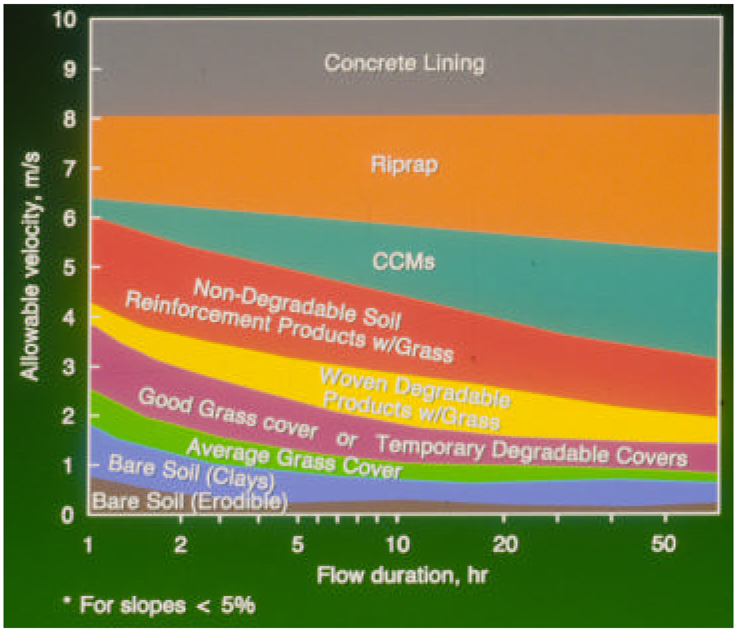

Figure 2. Erosion limits as a function of flow duration (From Fischenich and Allen, 2000).

Sediment Transport

A number of flow measures can be used to assess the ability of a stream to transport sediment. The unit stream power (P_m) is one common approach, and is related to the earlier discussion in that stream power includes both velocity and shear stress as components. Sediment transported in suspension (Q_s) increases when the unit stream power (P_m) increases. Unit stream power in turn is controlled by both the tractive stress and flow velocity:

$$P_m = v \cdot t = v \cdot \gamma_w \cdot D \cdot S \qquad (7)$$

The total power (P_t) is the product of the unit power times the channel width (W):

$$P_t = P_m \cdot W = v \cdot W \cdot D \cdot \gamma_w \cdot S = v \cdot A \cdot \gamma_w \cdot S = Q_w \cdot \gamma_w \cdot S \qquad (8)$$

Stream power assessments can be useful in evaluating sediment discharge within a stream channel and the deposition or erosion of sediments from the streambed. However, their utility for evaluating the stability of measures applied to prevent erosion is limited because of the lack of empirical data relating stream power to stability. The analysis of general erosion is not a simple extension of the non-cohesive bed case with a downslope gravity component added. Further complication is provided by other influencing variables, such as vegetation, whose root system can reinforce bank material and increase erosion resistance. Factors influencing bank erosion are summarized in Table 3.

Table 3. Factors influencing erosion.

Factor	***Relevant characteristics***
Flow properties	Magnitude, frequency and variability of stream discharge; Magnitude and distribution of velocity and shear stress; Degree of turbulence
Sediment composition	Size, gradation, cohesion and stratification of sediments
Climate	Amount, intensity and duration of rainfall; Frequency and duration of freezing
Subsurface conditions	Seepage forces; Piping; Soil moisture levels
Channel geometry	Width and depth of channel; Height and angle of bank; Bend curvature
Biology	Type, density and root system of vegetation; Animal burrows
Anthropogenic factors	Urbanization, land drainage, reservoir development and boating

Application

The stability of a waterway or the suitability of various channel linings can be determined by calculating both the mean velocity and tractive stress (by the previous equations) and comparing these with allowable velocity and tractive stress for a particular ground cover or lining system under consideration, e.g., existing vegetation cover, an erosion control blanket (ECB), or bioengineering treatment. Allowable tractive stresses for various types of soil, linings, groundcovers, and stabilization measures including soil bioengineering treatments, are listed in Table 2. Allowable tractive stress or velocity for various types of erosion control products can also be obtained from the manufacturer's product literature.

Flow of water in a channel is governed by the discharge, hydraulic gradient, channel geometry, and roughness coefficient. This functional relationship is most frequently evaluated using normal depth or backwater computations that take into account principles of conservation of linear momentum. An iterative procedure may be required when evaluating channel stability because various linings will affect the resistance coefficient, which in turn may change the estimated flow conditions. A general procedure for the application of information presented in this paper is outlined in the following paragraphs.

Step One-Estimate Mean Hydraulic Conditions.
An XP-SWMM model of the ravine (the main channel and the west ravine) was developed to determine average velocities and flow profiles. A total of 65 cross-sections were modeled for the main channel and 13 cross-sections were modeled for the west ravine. Channel cross-sections, slopes and Manning's Coefficients were determined based upon surveyed data and early spring vegetation cover. Output from the model should be used to compute main channel velocity and shear stress at each cross section.

Step Two- Estimate Local/Instantaneous Flow Conditions.
The computed values for velocity and shear stress may be adjusted to account for local variability and instantaneous values higher than mean. A number of procedures exist to do this - most commonly applied are empirical methods based upon channel form and irregularity. Several references at the end of this paper present procedures to make these adjustments. Chang (1988) is a good example.

Step Three- Determine Existing Stability.
Existing stability should be assessed by comparing estimates of local and instantaneous shear and velocity to values presented in Table 2. Both the underlying soil and the soil/vegetation condition should be assessed. If the existing conditions are deemed to be stable and are in consonance with other project objectives, then no further action is required. Otherwise, proceed to step four.

Step Four- Select Channel Lining Material.
If existing conditions are unstable, or if a different material is needed along the channel perimeter to meet project objectives, a lining material or stabilization measure should be selected from Table 2, using the threshold values as a guideline in the selection. Only a material with a threshold exceeding the predicted value should be selected. The other project objectives can also be used at this point to help select from among the available alternatives. The appendices include excerpts from Fischenich and Allen (2000) that characterize attributes of various protection measures to help in the selection. Table 4 presents velocity limits for various channel boundaries given depths anticipated for the ravine, and also can be used.

Step Five- Recompute Flow Values.
Resistance values in the SWMM model should be adjusted to reflect the select channel lining, and hydraulic condition should be recalculated for the channel. At this point, reach- or section-averaged hydraulic conditions should be adjusted to account for local and instantaneous extremes. For straight channels, the local maximum shear stress can be assumed from the following simple equation:

$$t_{\max} = 1.5t \qquad (9)$$

for sinuous channels, the maximum shear stress should be determined as a function of the planform characteristics using Equation 10:

$$t_{\max} = 2.65\, t \left(\frac{R_c}{W}\right)^{-0.5} \qquad (10)$$

where R_c is the radius of curvature and W is the top width of the channel. Equations 9 and 10 adjust for the spatial distribution of shear stress, but temporal maximums in turbulent flows can be 10 – 20 percent higher, so an adjustment to account for instantaneous maximums should be added as well. A factor of 1.15 is usually applied.

Step Six– Confirm Lining Stability.
The stability of the proposed lining should be assessed by comparing the threshold values in Table 2 to the newly computed hydraulic conditions. These values can be adjusted to account for flow duration using Figure 2 as a guide. If computed values exceed thresholds, step four should be repeated. If the threshold is not exceeded, a factor of safety for the project should be determined from the following equations:

$$FS = \frac{t_{\max}}{t_{est}} \quad or \quad FS = \frac{V_{\max}}{V_{est}} \qquad (11)$$

In general, factors of safety in excess of 1.2 or 1.3 should be acceptable. The preceding five steps should be conducted for every cross section used in the analysis for the project. In the event that computed hydraulic values exceed thresholds for any desirable lining or stabilization technique, measures must be undertaken to reduce the energy within the flow. Such measures might include the installation of low head drop structures or other energy dissipating devices along the channel. Alternatively, measures implemented within the watershed to reduce total discharge could be employed.

Table 4. Stability of channel linings for given velocity ranges.

Lining	0 – 2 fps	2 – 4 fps	4 – 6 fps	6 – 8 fps	> 8 fps
Sandy soils	🟨	🟥	🟥	🟥	🟥
Firm loam	🟨	🟨	🟥	🟥	🟥
Mixed Gravel and Cobbles	🟩	🟨	🟨	🟥	🟥
Average Turf	🟩	🟨	🟨	🟥	🟥
Degradable RECPs	🟩	🟨	🟨	🟨	🟥
Stabilizing Bioengineering	🟩	🟨	🟨	🟨	🟥
Good Turf	🟩	🟩	🟨	🟨	🟨
Permanent RECPs	🟩	🟩	🟩	🟩	🟨
Armoring Bioengineering	🟩	🟩	🟩	🟩	🟨
CCMs & Gabions	🟩	🟩	🟩	🟩	🟨
Riprap	🟩	🟩	🟩	🟩	🟩
Concrete	🟩	🟩	🟩	🟩	🟩

Key:

🟩	Appropriate
🟨	Use Caution
🟥	Not Appropriate

Recommendations

The Environmental Assessment provides several recommendations for mitigating erosion potential in the ravine. These include the following:

1. Construct a protected, aesthetically pleasing channel to carry low to moderate flows in the ravine, minimizing the duration and frequency of flow in the larger ravine.

2. Control flow velocities in critical channel areas and prevent erosion by measures such as rock protected drop pools and/or protecting the channel with rock or bioengineering.
3. In reaches with higher flow velocities protect hillsides by diverting flow away from the toe of steep slopes.
4. Maintain natural vegetation on hill slopes adjacent to flow areas to ensure long-term stability.
5. Manage invasive species to re-establish native grass/forb/shrub layers in the wooded areas. Invasive exotics such as buckthorn shade out other native species and provide poor soil holding functions.
6. Avoid placement of trails and other infrastructure on steep slopes to avoid slope stability problems.
7. Utilize depressions and wetland restorations along the flow path to capture and filter sediments.
8. See Natural Communities Mitigation Strategies for diverting flows to avoid erosion and sedimentation of the fen (and potentially the lake).

We concur with these recommendations and further suggest that the following actions be undertaken:

1. Assess hydraulic conditions throughout the project reach for the various watershed management alternatives contemplated for the project.
2. Develop a list of stabilization measures for which the stability threshold is not exceeded.
3. Select appropriate stabilization approaches from among this list, using other project criteria and objectives including cost, environmental impact, aesthetic appeal, etc.
4. If computed hydraulic conditions exceed thresholds for a desirable technique, consider employing grade control, additional storage, or other measures to reduce shear stress in the channel.

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Appendix 1
Stabilization Measures

(Excerpted from Fischenich and Allen, 2000)

Distinctions among various bank stabilization measures can be made on the basis of 1) how they work, 2) the materials used, 3) their geometry and position in the landscape, and (in some cases) 4) the character of stream system to which they are applied. Stabilization measures can be generally grouped into four broad categories based upon how they work or function:

1) Structures whose primary function is to prevent erosion by armoring the eroding bank
2) Structures that prevent erosion by deflecting the current away from the bank
3) Methods that reduce the erosive capability within the channel
4) Geotechnical methods of slope stabilization

Virtually every imaginable material has been used for bank stabilization. The most common materials include stone, vegetation, and concrete (typically formed into blocks or broken into graded riprap). A distinction among stabilization measures is often made on the basis of material use. Measures that rely upon inert materials (such as riprap) alone are often referred to as "conventional" treatments. Techniques that employ the use of vegetation independently or in combination with other natural materials, but as an integral component of the stabilization measure, are generally referred to as "soil bioengineering". A contingent of analysts regard conventional treatments as "bad" and soil bioengineering measures as "good", but the true impacts depend upon the other factors described in this report and upon the specific materials used within each of these categories.

The geometry and position of a structure can influence its function and impact. For this reason, otherwise similar structures are often given different names depending upon their size, shape, and orientation relative to the stream. For example, a low sill that extends across a channel and creates backwater can be called a weir, regardless of its size or material (riprap, concrete, sheet pile, boulder, log, etc.,). If the structure is designed to prevent the upstream migration of a nick point or headcut, it is also a grade control structure. If constructed to the floodplain elevation, it functions as, and is called a channel block. It can be oriented other than perpendicular to the flow to initiate a variety of affects in the velocity field and scour pattern, and will take on a name associated with its geometry (vortex weir, Reichmuth weir, W-weir, etc.,). Analogies can be made for virtually any other type of structure (armoring, deflecting, slope stabilizing), and the important point is that the impacts from a measure depend upon its specific geometry and landscape position.

The nature and extent of impact depends also upon the character of the stream and riparian system. Clear distinctions can be made on the basis of the stream type (meandering/braided, clay/silt/sand/gravel/cobble bed, riffle-pool/step-pool, etc.,) and dominant processes (snowmelt/ rainfall, bedload/suspended load, aggrading/degrading/stable, etc.,). Each of these systems behaves differently and, thus, affect and are affected by stabilization measures in different ways. Structures that merely deflect flows in a bedload-dominated cobble bed stream might function to trap sediments and build bars in a sand bed stream with a high suspended sediment load.

The following paragraphs provide a brief overview of common stabilization measures. They are arranged on the basis of function, because most measures are selected on this basis so as to address a particular problem on a stream. An infinite number of techniques could be identified in each category by altering the materials, dimensions, or considering their influence on different stream types, so this list of measures is not exhaustive. In most cases, bank stabilization projects will use combinations of the techniques described below in an integrated approach. Toe protection often will require the use of armoring techniques using stone, large logs, or other inert materials. Stone blankets may be placed on the bank face, perhaps supplemented with interstitial plantings, but most upper bank areas can usually be stabilized using vegetation alone, or any one of dozens of soil bioengineering techniques, particularly if slope stabilization is warranted. Deflection structures can eliminate the need for some armor structures, or can allow the use of different armor materials. Grade control or other energy reduction may be required to supplement a stabilization measure on a stream with systemic instabilities.

Armoring techniques

The armoring technique is the placement of a protective covering, usually consisting of stone, over part or all of the stream bank. Armoring techniques function by preventing the boundary shear induced by flowing water from contacting erodible bank material. These techniques affect the bank sediment input, roughness, and local shear. Material type and channel alignment determines the extent of the impacts. In general, armor structures cause a scour hole to develop at the toe of the structure and extend riverward for a limited distance. The depth of scour varies with alignment and material type. Velocity may increase in the scour region, but there is little or no change in the velocity at points further riverward. If the structure does not encroach appreciably on the channel, there should be no measurable change in river stage for a given discharge. Bed sediment movement may be affected. Properly constructed armor structures, particularly if they incorporate a vegetation component, provide a locally diverse aquatic environment without significant effect on the hydraulic conditions of the adjacent river reaches. Riparian disruption is generally the greatest environmental concern, and measures should be taken to minimize impacts.

Stone-Fill Revetments - Stone-fill revetments are perhaps the most common of all streambank protection structures. Included within this group are several variations of the general theme of placing quarried stone, broken concrete, cobble, or soil cement parallel to the eroding bankline. The stone may be placed in a toe section with or without upper bank protection. A thin blanket may be used to armor the entire bank. The revetment may be windrowed, and allowed to launch as erosion undermines the structure. Revetments are often used in conjunction with other bank protection devices. A stone toe section with revegetation of the upper bank is one of the most cost-effective solutions to most erosion problems. Revetments are very successful in stopping erosion on streams where the major problem is bank undercutting from toe erosion or general erosion of the bank by shear velocities of the river. They provide only a limited amount of protection against erosion on streams subject to headcuts or general bed degradation. Revetments must be properly designed and constructed with suitable material to be effective.

Tree Revetments and Rootwads - Tree revetments are made from whole tree trunks laid parallel to the bank, and cabled to piles or deadman anchors. Eastern red-cedar (Juniperus virginiana) and other coniferous trees are used on small streams, where their springy branches provide interference to flow and sediment trapping. The principal objection to these systems is the use of large amounts of cable and the potential for trees to be dislodged and cause downstream damage. Some projects have successfully used large trees in conjunction with stone to provide bank protection as well as improved aquatic habitat. Tree revetments perform best on streams with a high suspended sediment load, trapping sediments within the voids of the branches. These sediments are ultimately colonized by pioneer vegetation species that stabilize the banks after the trees have rotted.

Rootwads consist of large logs with intact root wads are placed in trenches cut into the bank, such that the root wads extend beyond the bank face at the toe. The logs are overlapped and/or braced with stone to assure stability, and the protruding rootwads effectively reduce flow velocities at the toe and over a range of flow elevations. This approach replicates one of the natural roles of large woody debris in streams by creating a dynamic near-bank environment that traps organic material and provides colonization substrates for invertebrates and refuge habitats for fish. The logs eventually rot, resulting in a more natural bank. The revetment is intended to stabilize the bank until woody vegetation has matured, at which time the channel can return to a more natural pattern. In truth, rootwads function more as a habitat feature than as a stabilization device. They generate considerable local turbulence and scour, and are inherently unstable unless combined with other materials.

Soil-Covered Riprap - In urban areas or highly visible locations where it is advisable to keep banks mowed for aesthetic or safety purposes, riprap may be covered with soil and seeded to accelerate vegetation growth. This may also be done in areas where mowing is desired. Benefits of covering riprap with soil and seeding grass are largely aesthetic. Although access to the stream is improved, few aquatic or riparian habitat values are derived. Edaphic and climatic conditions are the major constraints to covering riprap with soil and seeding with vegetation, particularly grass. Covering riprap with soil and seeding is feasible only if climatic conditions are conducive to the growth of the plants or supplemental irrigation is practical. The practice has largely been confined to urban areas where aesthetics is a consideration, and where machine mowing can replace more expensive hand-mowing maintenance methods. Soil covered riprap seeded with grass performs well in situations where flow velocities in the vicinity of the bank do not exceed 4 to 6 ft/s. Critical velocities vary with the variety of grass used and soil conditions.

Geotextile fabrics - On small streams, a good vegetative cover of grass or shrubs may be sufficient to protect streambanks from scour. But if the soils consist of easily erodible material such as sand or gravel, it is often necessary to provide temporary cover until the vegetation has become established. Various natural and synthetic fibers have been developed for use in erosion prevention. Many different applications may employ specific fabrics that are available. In most cases involving flowing water, fabrics used alone do not provide sufficient protection due to their buoyancy and their tendency to be moved by currents. Fabric used in conjunction with vegetation is often an effective solution. Fabrics are also used frequently as a bedding for revetments to prevent leaching of fine bank materials. Geotextiles used with vegetation produce the same environmental benefits as vegetation used alone. The major benefit is aesthetic, but when woody vegetation is used, riparian benefits can be significant, and there may be some aquatic benefits from shade and organic debris falling into the stream. The benefit of using fabrics with riprap is entirely structural. Fabrics have been used on streams in many locations. In areas without sufficient rainfall to support dense plant cover, supplemental irrigation is usually required if vegetation is used. Geotextiles work well in providing temporary protection until vegetation can become established at sites where they are not exposed to swift currents for prolonged periods of time. Natural geotextiles tend to function better than synthetics due to their ability to breakdown, to absorb moisture, and to create favorable growing environments.

LUNKERS – These are devices designed to provide overhanging shade and protection for fish while serving to stabilize the toe of a streambank. They are generally made from treated lumber, untreated oak, or materials made from a combination of plastic and wood and are constructed by nailing planks to the top and bottom of 15- to 20-cm spacer logs. These planks form stringers, which tie into the streambank at right angles. Planks are nailed to the top and bottom stringer boards and run parallel to the streambank. The entire structure forms a crib, which can be constructed onshore and moved by a loader or backhoe to the installation site.

Once in the stream, the LUNKERS are placed in position and anchored by driving 1.5-m lengths of steel-reinforcing rod through predrilled holes in the structures and then into the streambed. These structures are set in a line that simulates the outside bend of a meander. After the structures are in place, the area behind them is filled with riprap, which also is used to cover the structure, and then the entire area is covered with soil. Often, the soil is planted with various kinds of vegetation, either woody or herbaceous. Care must be taken to tie the ends into the bank with a transition of rock or into a hardpoint to prevent flanking.

Brushmattress - A brushmattress, sometimes called brush matting or a brush barrier, is a combination of a thick layer (mattress) of interlaced live willow switches or branches and wattling. Both are held in place by wire and stakes. The branches in the mattress are usually about 2 to 3 years old, sometimes older, and 1.5 to 3 m long. Basal ends are usually not more than about 3.5 cm in diameter. They are placed perpendicular to the bank with their basal ends inserted into a trench at the bottom of the slope in the splash zone, just above any toe protection, such as a rock toe. The branches are cut from live willow plants and kept moist until planting. The willow branches will sprout after planting, but care should be taken to obtain and plant them in the dormant period, either in the late fall after bud set or in the early spring before bud break. A compacted layer of branches 10 to 15 cm thick is used and is held in place by either woven wire or tie-wire. Wedge-shaped construction stakes (2 X 4 X 24 " to 2 X 4 X 36", diagonal cut) are used to hold the wire in place. A guage and type suitable for tie-wire is No. 9 or 10 galvanized annealed. It is run perpendicular to the branches and also diagonally from stake to stake and usually tied by use of a clove-hitch. If woven wire is used, it should be a strong welded wire (2- by 4-in mesh). The wedged-shape stakes are driven firmly through the wire as it is stretched over the mattress to hold it in place. The wedge of the stake actually compresses the wire to hold the brush down. All but the edges of the brushmattress should be covered immediately with soil and tamped.

Willow Wattling - Wattling is a cigar-shaped bundle of live, shrubby material made from species that root very quickly from the stem, such as willow and some species of dogwood and alder. These bundles are laid over the basal ends of the brushmattress material that was placed in the ditch and staked. The procedure of making wattling bundles and installing them over the brushmattress material is presented in more detail below. Wattling bundles may vary in length, depending on materials available. Bundles taper at the ends and this is achieved by alternately (randomly) placing each stem so that about one-half of the basal ends are at each end of the bundle. When compressed firmly and tied, each bundle is about 15 to 20-cm in diameter in the middle. Bundles should be tied with either hemp binder twine or can be fastened and compressed by wrapping "pigtails" around the bundle. Pigtails are commonly used to fasten rebar together. If tied with binder twine, a minimum of two wraps should be used in combination with a non-slipping knot, such as a square knot. Tying of bundles should be done on about 38-cm centers. Wattling bundles should be staked firmly in place with vertical stakes on the downhill side of the wattling not more than 90 cm on center and with the wedge of the stake pointing upslope. Also, stakes should be installed through the bundles at about the same distance, but slightly off-set and turned around so their wedge points downslope. In this way, the wedged stakes, in tandem, compress the wattling very firmly. Where bundles overlap, an additional pair of stakes should be used at the midpoint of the overlap. The overlap should be staked with one pair of stakes through the ends of both bundles while on the inside of the end tie of each bundle. Figures 25 a-b show a schematic of a brushmattress and wattling. Figures 26 a-c show a sequence of installing a brushmattress with wattling at a workshop. It should be noted that because of the workshop setting at a mild time of the year, non-dormant vegetative material is being used. Normally, one would preferably use dormant material. Soil should be worked into wattling by by both tamping and walking on it. About 75 percent of the wattling should be covered, leaving some of each exposed to facilitate sprouting of stems rather than roots.

Brush layering - Brush layering, also called branch layering, or branch packing, is used only in association with a hardened toe, such as a riprap toe section. This is a treatment where live brush that quickly sprout, such as willow or dogwood species, are used in trenches. Trenches are dug 2-6 feet into the slope, on contour, sloping downward from the face of the bank 10 to 20 degrees below horizontal. Live branches are placed in the trench with their basal ends pointed inward and no more than 6 inches or more than 18 inches of the tips extending beyond the fill face. Branches should be arranged in a criss-cross fashion. Brush layers should be at least 4 inches thick and should be covered with soil immediately following placement and the soil compacted firmly.

Vegetative Geogrid - This is a system that can be used in the splash zone and actually extend further up the bank into the bank and possibly terrace zones. The system is sometimes also referred to as "fabric encapsulated soil." It consists of successive walls of several lifts of fabric reinforcement. In between the lifts are placed 5- to 10-ft long live willow whips. The design is based on a dual fabric system modeled after synthetic fabric retaining walls used by engineers for road embankments and bridge abutments. Two layers of coconut fiber-based fabric provide both structural strength and resistance to piping of fine material. The inner layer is a loose coconut fiber blanket held together by synthetic mesh netting and is used to trap finds and prevent piping. The outer layer is a strong, woven coir fabric to provide structural support. Sometimes, the latter fabric is substituted by even stronger, more durable synthetic materials, that are formed by a matrix of geosynthetic bands. The disadvantage of the latter materials, however, is that they are not very biodegradable. Of course, vegetation would mask the materials so they are not visible.

Miller (1992) describes building the lifts of fabric-reinforcement as follows:

> "To build the streambanks, we would first lay down a layer of each fabric in the appropriate location. We'd place fill material, compact it, and wrap the exposed fabric over the face of the fill. The fabric would be keyed back under the next layer with wooden stakes. We'd progress upwards from layer to layer, whether the slopes were vertical or at a 3:1 slope."

Care must be taken to provide rock or some other hard material at each upstream and downstream end to prevent flanking of the treatment. For instance, one may either tie into existing vegetation, such as trees, or create hard ends by placing rock. Also, it is important to prevent scour at the bottom lift and to provide a good footing by creating a ditch and filling it with cobble or rock. The first lift is placed on top of the cobble ditch.

Dormant Post Method - This treatment consists of placing in the splash zone and perhaps the lower part of the bank zone dormant, but living stems of woody species that sprout stems and roots from the stem, such as willow or cottonwood. Willows are normally used and are cut into 10-14 ft posts when the leaves have fallen and the tree is dormant. The dormant posts store root hormones and food reserves (carbohydrates) that promote sprouting of stems and roots during the growing season. Dense stands of 4-6 year old willows make the best harvesting areas. Posts that are 4-6 inches in diameter at the base work best if material of that size is available. The bank can be shaped to a 1:1 slope with the spoil placed in a 6-inch deep layer along the top of the bank. In major erosion sites, post holes are formed in the bed and bank so that the end of the post is 2 ft below maximum streambed scour (that portion of the streambed that is subject to movement. The cutting (post) should extend 2-3 ft above ground so as it leafs out, it can provide immediate bank erosion protection. Willow posts should be long enough and placed deep enough to reach wet soil during dry summers, and should be no less than 3-5 feet into the ground to prevent streamflows from eroding soil around the cutting and failing the post. Posts should be about three to four feet apart up the streambank, and posts in one row are offset from the posts in adjacent rows. Plantings can occur at the water line, up the bank, and on top of bank in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table.

An excavator that is either fitted with a long, steel ram (often called a stinger) or an auger is typically required for installation. A steel ram on an excavator boom is more efficient at depths of 6 feet in clay soils, and is required when placing posts through riprap. In contrast, an auger on an excavator boom forms deeper and longer lasting holes in stoney or sandy streambeds. The ram on the excavator is for creating a pilot hole in which to place the willow post. The willow post is fitted with a cap that goes over the post and then the heel of the bucket on the excavator is used to push the post down into the hole. Care must be taken to ensure that the post comes in contact with the soil so that no air pockets exist. In the case of the auger, this can be done by backfilling the sides of the hole in lifts and then tamping. In the case of the ram, the ram can be placed out a few inches from the post and run along the side of it into the soil so as to close the hole containing the post, especially toward the bottom of the hole.

Dormant Cuttings - Dormant cuttings, sometimes called "Live Stakes," involves the insertion and tamping of live, rootable cuttings into the ground or as live stakes in the brushmattress and wattling as opposed to or in combination with the wedge-shaped construction stakes previously mentioned. They can also be used in the matrix openings of the root wad logs along with root pads of other vegetative materials. If cuttings are used alone, the toe should be very stable and velocities should be less than 5 fps. Also, the soil in which they are placed should be fairly cohesive. Dormant cuttings can vary in size, but are usually a minimum of 1/2 inch in diameter at the basal end. Cuttings can be used that are up to 2 to 3 inches in diameter and have been noted to have the highest survival rates. Cutting length is largely determined by the depth to the mid-summer water table and erosive force of the stream at the planting site. Plantings can occur at the water line, up the bank, and into the terrace zone in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table. Cuttings should have their side branches cleanly removed and the bark intact so that the cutting is one single stem. Care should be taken to make clean cuts at the top and the bottom so that the bark is not separated from the underlying woody tissue. Also, be sure they are cut so that a terminal bud scar is within 1 to 4 inches of the top because cuttings put out their greatest concentration of shoots and their strongest ones just below an annual ring (formed from a terminal bud scar). At least two buds and/or bud scars should be above the ground after planting. Tops are normally cut off square so they can be tamped or pushed easily into the substrate. The basal ends are often angled for easy insertion into the soil. When selecting material from a natural stand, care should be taken to see that the harvest material is free from insect damage, disease, and splitting.

Spruce Revetments – These are revetments constructed of cabled spruce trees placed along the toe of an eroding streambank to provide temporary erosion control. The spruce forms a dense brush mat that effectively armors the streambank and, under proper circumstances, induces sediment deposition in and among the juniper branches. Though the trees will deteriorate over time, the deposited sediments provide substrate for the colonization of riparian species that provide long-term stabilization benefits. The revetments are constructed by harvesting trees, placing them along the toe of an eroding bank, and anchoring the trees with deadmen and steel cable.

Flow deflection techniques

Flow deflection techniques are based upon the principle that by redirecting higher velocity flows away from the bank, erosion can be reduced or eliminated in areas between structures. This procedure usually results in a lower cost than continuous armoring of the bank. Deflective structures are constructed approximately perpendicular to the flow, and therefore reduce the effective width of the river. Locally, a scour pocket develops off the end of the structure and continues downstream in a teardrop pattern. There is usually an increase in the velocity adjacent to the structure. Average cross-channel velocity may increase, decrease, or be unaffected. Generally, there is an increase in stage and/or depth for a given flow in the channel adjacent to the structure, particularly if the structure length exceeds 1/6 of the channel width. Material type, length, height, location, and orientation of the structure will affect the degree of impact. These structures are usually constructed with less disruption to the riparian community than other erosion control techniques. Effects on wildlife species are usually insignificant. Sediment accretion behind the structures may provide additional access to the river for some species, and provides good substrate for benthic organisms. Recreational benefits increase if access is provided to the structures. The primary environmental benefit of deflective structures is the creation of additional habitat for fish species. The cross sectional changes provide diversity and, by using proper materials, suitable cover and substrate increase.

Hardpoints and Jetties - The terms hardpoint and jetty are generally regarded as being synonymous. However, for this manual, the terms are used to differentiate between differing degrees of the same basic structures. Both structures consist of a stone or soil spur that extends riverward of and perpendicular to the bank, and a stone root to prevent flanking of the structure. Hardpoints are low stubby structures that are frequently overtopped and extend riverward less than 15 or 20 feet. Jetties are generally constructed to the height of the high bank, and extend riverward more than 20 feet. Hardpoints deflect the current away from the eroding bank for only a short distance, with no attempt to change the general alignment of the river. By contrast, jetties deflect current for a considerable distance, and are often intended to alter the main flow of the river. Hardpoints and jetties are best suited to long straight reaches of river, or on the convex bankline of meanders. Structures placed on the concave bank can fail from excessive scour between structures. The main advantage of hardpoints and jetties is the low quantity of material needed to protect a given bank relative to other structural alternatives. The environmental benefits of this structure type are primarily related to fisheries and recreation. Hardpoints and jetties create habitat diversity not found with most other structure types. Scour off the end of the structure creates deep pools and high velocity flows. Scallop areas of shallow, relatively slow-moving water provide additional habitat diversity downstream of the structures.

Energy reduction methods

Energy reduction methods function by reducing the ability of the river to erode bed and bank material. In the case of vanes and fence revetments, this is accomplished by reducing boundary shear and secondary helical currents. Selective clearing and snagging and chute closures both function by reducing the most severe flows along eroding banks. Vanes and fences have little effect upon the morphology of the river. Sediment transport may be slightly reduced in the immediate vicinity of the structures, but this is of little consequence. They are intended to have minimal impact upon the channel geometry. On the other hand, clearing and snagging and chute closures can both have a dramatic effect upon the morphology of the river. Clearing and snagging reduces stages, changes the velocity distribution at a section, and can increase sediment transport through the reach. Selective clearing of bars and islands can cause realignment of the main channel of the river. Chute closures or channel blocks increase the flow in the main channel and reduce or deplete flows in the chute. The stage of the river will increase upstream of the structure, particularly during high flows. Both velocity and sediment movement may increase slightly in the channel. If flow is eliminated in the chute, sediment deposition will eventually fill it. Vegetation encroachment will occur in the chute, further reducing the flood capacity of the section. Most of these methods cause sediment accretion, which improves substrate for boring macroinvertibrates. The sediment may cover other more-desirable habitat such as cobbles. The associated hydraulic changes may adversely affect other aquatic species due to a loss of higher velocity habitat and the potential for elevated water temperature. These methods generally have very little impact upon riparian habitat. They may positively or adversely affect recreation and aesthetics.

Vanes - Vanes are structures placed within the channel at an angle to the normal flow so that they reduce the secondary currents and thus reduce the erosive capacity of the river. The most common types of vanes are Iowa Vanes, baffle vanes, and stone vanes. Iowa vanes are small flow-training structures (foils), designed to modify the near-bed flow pattern and redistribute flow and sediment transport within the channel cross-section. The structures are typically installed at an angle of 15 - 20^{o} to the flow, with a height of 0.2 - 0.4 times local water depth at designed stage. The vanes function by generating secondary circulation in the flow. The circulation alters magnitude and direction of the bed shear stresses and causes a change in the distributions of velocity, depth, and sediment transport in the area affected by the vanes. As a result, the river bed topography may be altered by selective layout of the structures. Baffle-type vanes are structures consisting of boards attached to piles that are placed in series in the stream to disrupt the secondary currents that cause erosion on the outside of meander bends. The number, locations, spacing, orientation, size, and height of the vanes are critical to success and must be determined from careful analysis. Stone vanes are low stone structures angled upstream with an acute angle of 25 - 40^{o} from the bank. They are overtopped by all but the lowest flows. There are a number of variants of this structure depending on the slope, length, relative height, and materials. Bendway weirs are an example of this type of structure.

Because vanes stop erosion by modifying secondary circulation, no bank sloping or treatment is necessary. Aquatic benefits are not destroyed, and once vegetation becomes re-established on the eroding bank, riparian habitat and aesthetic benefits are improved. During low water, the vanes are not very appealing visually, and there may be some hazard to navigation and to recreationists using the stream. Vanes have not been used extensively. Prototype vane systems have been installed in a couple of midwestern streams, including the East Nishnabotna River in Iowa. It is too soon to evaluate the success of the prototype demonstration at this site, but sedimentation was induced between the structures and the bank in model studies. The sediment deposition may reduce the effectiveness of the structures, and could induce additional erosion along the bank due to the reduction in channel capacity. Vanes have been used successfully to ameliorate shoaling problems at water intakes and bridge crossings.

Clearing and Snagging – For flood control on small streams, conventional clearing and snagging has been used to remove all obstructions from the channel and to clear all significant vegetation within a specific width on both sides of the channel. Key aspects of selective clearing and snagging involve selective removal of vegetation based on size, condition, species, or location; removal of only those snags that are major flow obstructions; use of hand labor and small equipment when feasible, and rigid access controls when heavy equipment must be used; protection of existing vegetation of disturbed areas; and greater reliance on multidisciplinary teams in all phases of project planning and management. Disturbed areas should be restored to natural contours, and preserved trees should be spaced at irregular intervals. Natural sloughs, drains, and flood-plain depressions should be left in their original condition. Because of the limited improvement in flow hydraulics (upper flow capacity limit roughly equivalent to bankfull discharge), selective clearing and snagging is most often used to provide relief from high frequency nuisance flooding, for drainage improvement in agricultural areas, and recreational benefits. Increased hydraulic conveyance results from changes in the resistance to flow values in uniform flow equations. Vegetation, channel irregularity, obstruction to flow, and design flow conditions should be considered in estimating improvements in resistance coefficients.

Grade Control Structures and Low-Head Weirs- These are structures designed to reduce channel grade in natural or constructed watercourses to prevent erosion of a channel that results from excessive grade in the channel bed or artificially increased channel flows. This practice is used to stop headcut erosion or stabilize gully erosion. Grade stabilization structures may be vertical drop structures, concrete or riprap chutes, gabions, or pipe drop structures. Permanent ponds or lakes may be part of a grade stabilization system. Concrete chutes are often used as outlets for large water impoundments where flows exceed 100 cfs and the drop is greater than 10 ft. Where flows exceed 100 cfs but the drop is less than 10 ft., a vertical drop weir constructed of reinforced concrete or sheet piling with concrete aprons is generally recommended. Small flows allow the use of prefabricated metal drop spillways or pipe overfall structures. Designs can be complex and usually require detailed site investigations. Design of large structures (100 cfs) requires a qualified engineer. The National Engineering Handbook (Drop Spillways, Section 11, and Chute Spillways, Section 14) prepared by the USDA Natural Resources Conservation Service gives detailed information useful in the design of grade stabilization structures.

Low-head weirs are essentially the same type of construction as grade control structures, but the head loss over the structures is usually 2 feet or less. Built from rocks, logs, or other material, low-head weirs are usually intended for use in lower order perennial streams for water quality improvement and habitat enhancement. They can be designed to arrest bed degradation, and can be configured in a variety of ways to modify the flow field to achieve changes in channel geometry. Weirs are most successful in smaller streams with relatively coarse substrates.

Grade control and weir structures have a wide array of impacts. They create backwater in upstream reaches – increasing depth and reducing velocity. These upstream impacts reduce sediment transport capacity and stream reaches immediately upstream of these structures often have deposited sediments on the bed that are finer than those found in adjacent reaches. The extent of the upstream impacts depend upon the height of the structure and the streambed slope. Downstream of the structure, a scour pool is generally formed with a bed material composition more coarse than adjacent reaches. The size of the pool is dependant on the relative height of the structure and its geometric configuration. Grade control structures can become barriers to fish migration, but can be designed to accommodate this concern by employing a low-flow channel or chute. If they pool a significant amount of water, grade control devices may contribute to elevated stream temperatures. Benefits cited for these devices include formation of pool habitat, collection and holding of spawning gravels, promotion of gravel bar/riffle formation, trapping suspended sediments, reoxygenating water, allowing organic debris deposition, and promotion of invertebrate production.

Slope stabilization methods

If failure is due mainly to geotechnical factors like drawdown or seepage, protection against hydraulic erosion may not be the best treatment. On the other hand, geotechnical failure may represent a delayed response to continuing scour at the bank toe, in which case toe protection against hydraulic erosion is essential. When geotechnical factors alone are involved, this usually results in mass failure of the embankment material. Several different types of mass failure can occur in banks. These include sliding along a deep failure surface, shallow slips, and lock failures. Many factors affect mass failures. They include soil type, bank slope geometry, surface and ground water flow regime, infiltration, surcharge loading, tension cracking, and vegetation. Each factor's contribution to the failure must be identified before an appropriate solution can be selected. Slope stabilization techniques typically involve large-scale modification to the bank. This can seriously disrupt the riparian environment, and may affect aesthetics and recreation. Impacts to the aquatic community are generally slight, but reductions in sediment supply and the value of existing bank cover should be addressed.

Grading – The best structural solution to most geotechnical failures is to regrade the bank to a lower angle and to protect the toe and lower bank from further erosion that might otherwise over-steepen the slope. If weakening of the bank is also a factor, steps must be taken to prevent damage by limiting access or modifying the activities responsible. Shallow slips and dry granular flows are generally addressed with minor bank modifications. Deep-seated rotational slips are a severe form of bank instability and, because the failure surface is located deep inside the bank, surficial or shallow treatments are inadequate to deal with this type of failure. Major regrading of the bank coupled with toe protection and improved drainage may be needed to achieve stability. If space limitations preclude complete regrading, a structural retaining wall must be incorporated into the design. In the field, a geotechnical site survey must be performed to identify and quantify all the relevant factors and bank parameters before any firm conclusions can be drawn regarding the cause of failure and detailed design for stabilization. Impacts from grading are primarily related to the destruction of existing riparian habitat. There are also cases where relatively steep eroding banks provide habitat for burrowing or nesting fauna and this habitat is directly impacted from regrading activities. Some short-term impacts associated with sediment yield from a regraded site can be a concern for very large projects. Benefits include a reduction in sediment yield and any improvements associated with the relative values of the existing and replaced vegetation.

Appendix 2

Impacts from Stabilization Measures

(Excerpted from Fischenich and Allen, 2000)

The practice of stabilizing streambanks affects many of the structural characteristics and functions of a stream. In point of fact, the basic purpose of any stabilization project is to interrupt erosion processes where they are deemed to conflict with social needs. In so doing, they interrupt or affect other processes and alter the physical environment. Because of the strong interrelation among the structural components and functions of a stream/riparian system, a number of secondary and tertiary impacts are associated with bank stabilization measures.

This is not to say that bank stabilization is "bad". Knowledge of the direct and ancillary impacts of stabilization can be used, for example, to select a measure and develop a design that restores or enhances the structure or function of a degraded ecosystem. Furthermore, few alterations to the structure or function of the environment are universally adverse or universally beneficial. Most benefit some components of the ecosystem at the expense of others.

For the purpose of this project, the term "impact" is used to denote a measurable change, without regard for the significance or value of the change. These changes or impacts are, by nature, very site-dependent, so the generalizations provided herein will inevitably run contrary to observations in some cases. With the above cautions in mind, the following sections present an overview of likely impacts from common bank stabilization practices in terms of:

- Impacts on water surface elevations.
- Impacts on velocities, including secondary velocities.
- Impacts on erosion/scour and deposition.
- Impacts on sediment transport through the design reach.
- Length of the river that is impacted by the specific structure type.

Impacts on water surface elevations

Stabilization practices can alter water surface elevations in one of two ways: 1) by changing the resistance characteristics (either form or friction) of the reach, or 2) by altering the channel geometry (slope or cross section). These changes can be direct (such as the addition of a weir that changes the channel slope), or indirect (structures may cause a sorting of bed materials, resulting in a coarser surface fraction with higher resistance). In addition to the type of stabilization measure, the materials used and the geometry and location of the measures are the primary determinants of the extent of impacts. The impact, or change, must be related to some baseline condition. In this case, it is assumed to be the immediate pre-project condition, not some former "stable" condition. Impacts to water surface elevations are seldom static. Channels tend to adjust their bed elevations to compensate for changes in water surface, and the resistance characteristics of most stabilization measures change as they mature (vegetation growth is the primary factor).

Table 3. Impacts on Water Surface Elevations

Category	*Impacts*
General	No generalization can be made regarding the impacts of bank stabilization on water surface elevations.
Armor Techniques	Armoring techniques in general have no local or cumulative effect upon water surface elevations beyond the influence of the change in resistance. Exceptions occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area. Impacts from resistance or cross section changes can be readily quantified through the application of the de Saint Venant Equations and resistance compositing techniques. Expansions and contractions of less than 10 percent generally result in negligible impacts. Impacts from changes to resistance are greatest for streams with a low width/depth ratio and depend upon the magnitude and length of the change. Measures with potential to increase water surface elevation: - Any bioengineering technique or other method that employs dense woody vegetation Measures with potential to decrease water surface elevation: - Bulkheads, gabions, and other vertical architecture structures - Any structure that uses concrete or other smooth finishes
Deflection Techniques	Deflectors create form roughness and reduce the cross sectional area of the channel, so they have the potential to increase water surface elevations and frequently do so. They also commonly generate scour and deepen the unprotected portion of the channel, which has the effect of offsetting the cross sectional reductions. Unfortunately, techniques to quantify these impacts are generally lacking. Furthermore, the impacts are highly dependent upon the flow condition, character of the channel, and geometry of the deflector, so empiricism is of limited use in evaluating impacts. Impacts depend also on flow magnitude, and diminish with increasing depth of flow over the top of the structure. Measures with potential to increase water surface elevation: - Any deflector that extends more that 15 percent across the channel or occupies more than 10 percent of the cross section area. Measures with potential to decrease water surface elevation: - Closely-spaced, low-profile structures that induce scour
Slope Stabilization Techniques	Slope stabilization techniques in general have no local or cumulative effect upon water surface elevations beyond the influence of the change in resistance. Exceptions occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area. Impacts from resistance or cross section changes can be readily quantified through the application of the de Saint Venant Equations and resistance compositing techniques. Expansions and contractions of less than 10 percent generally result in negligible impacts. Impacts from changes to resistance are greatest for streams with a low width/depth ratio and depend upon the magnitude and length of the change. Measures with potential to increase water surface elevation: - Any bioengineering technique or other method that employs dense woody vegetation Measures with potential to decrease water surface elevation: - Bins, crib walls, and other vertical architecture structures
Energy Reduction Techniques	Energy reduction techniques are measures that reduce kinetic energy. In general, this kinetic energy is converted to potential energy in the form of increased water surface elevation. Grade control structures also modify the slope of the channel, further raising water levels. Methods to quantify impacts to water surface elevations are straight-forward, and generally consist of backwater analyses. An exception is the impact of vanes, which have not been adequately studied for this impact. Measures with potential to increase water surface elevation: - Grade control and (to a lesser extent) vanes

Impacts on velocities, including secondary velocities

Bank stabilization measures can have a number of impacts upon velocities, and the impacts from a single structure can vary spatially. For example, a structure that causes a constriction in the channel cross section will generally increase local velocities, but the backwater effects will cause upstream velocities to decrease. Within a given cross section, a structure can have no effect on the average cross-sectional velocity, but will cause a redistribution of the velocities (higher in the zone adjacent the structure and lower elsewhere in the section, for example). In addition to the stream-wise velocity, stabilization measures can increase or decrease turbulent velocities and secondary current velocities. Variables that influence the impact of stabilization measures on velocity include 1) the materials (which affect resistance and turbulence), 2) structure geometry and location (which affect the slope, degree of expansion or contraction, flow convergence or separation, and influence upon secondary currents), and 3) structure type. Impacts to velocity tend to be localized, and only extend far beyond the project reach when the stabilization measure induces backwater conditions.

Table 4. Impacts on Velocities

Category	***Impacts***
General	No generalization can be made regarding the impacts of bank stabilization on velocities.
Armor Techniques	Armoring techniques in general have no local or cumulative effect upon velocities beyond the influence of the change in resistance. Exceptions occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area (contractions cause an increase in velocity, expansions a decrease). Impacts from resistance or cross section changes can be quantified with one-dimensional backwater models (for average velocity), or two-dimensional hydraulic models (for velocity variation across a section). Impacts to the vertical velocity profile can also be quantified by assuming a logarithmic velocity profile, a resistance coefficient, and using a known water surface elevation and mean velocity. Average channel velocities tend to be insensitive to armoring of the banks. Local velocity (within a few feet) tends to increase for smooth surfaces and decrease for rough surfaces (such as vegetation). Armor materials frequently increase local turbulence, but have little impact upon secondary currents. Measures with potential to increase velocity: - Any structure that uses “smooth” materials or constricts the channel Measures with potential to decrease velocity: - Any bioengineering technique or other method that employs dense woody vegetation
Deflection Techniques	Deflectors reduce the cross sectional area of the channel, causing a constriction, so they tend to both mean cross-section and local velocities. They also commonly disrupt secondary currents, generate eddies, and increase turbulence. Unfortunately, techniques to quantify these impacts are generally lacking. Furthermore, the impacts are highly dependent upon the flow condition, character of the channel, and geometry of the deflector, so empiricism is of limited use in evaluating impacts. Impacts depend also on flow magnitude, and vary with varying depth of flow over the top of the structure. Impacts to velocity from deflectors tend to be localized, but these structures create the most dynamic and diverse velocity fields of any stabilization technique.
Slope Stabilization Techniques	Slope stabilization techniques affect velocities only slightly, due to changes in resistance or alteration to the channel cross-section area (contractions cause an increase in velocity, expansions a decrease). Impacts can be quantified with the same means characterized for armor techniques. Average channel velocities tend to be insensitive to slope stabilization, but local velocity (within a few feet) tends to increase for smooth surfaces and decrease for rough surfaces (such as vegetation). Slope stabilization can increase local turbulence, but has little impact upon secondary currents. Measures with potential to increase velocity: - Any structure that uses “smooth” materials or constricts the channel Measures with potential to decrease velocity:

	- Any bioengineering technique or other method that employs dense woody vegetation
Energy Reduction Techniques	Energy reduction techniques are measures that reduce kinetic energy (which is proportional to the velocity squared), so reductions in velocity are the intent of these measures. Grade control structures reduce velocity for as far upstream as the backwater conditions persist, and completely disrupt secondary currents except when overtopped by more that three - five times the height of the structure. Vanes are intended to reduce secondary velocities, which has the effect of increasing the local cross-section average velocity. Methods to quantify impacts to velocity from grade control measures are straight-forward, and generally consist of backwater analyses. Quantification of the impacts to velocity from vanes have not been adequately studied for this impact. Measures with potential to increase velocity: - Vanes (though these reduce secondary velocities) Measures with potential to decrease velocity: - Grade control

Impacts on erosion, scour, and deposition

All stabilization structures and measures impact sedimentation processes. At a minimum, they reduce or eliminate sediment yield to a system from the bank they are intended to stabilize. They also tend to generate local scour, usually at the toe of the stabilized bank or immediately downstream of the stabilization measure. Measures that reduce local transport capacity tend to induce sediment deposition in those areas. Rates of sediment sorting, both from the streambed and from the water column tend to increase in stabilized areas. The primary variables that influence sedimentation processes are sediment yield, sediment characteristics, and the impacts of the stabilization measure upon flow parameters, particularly velocity, stream power, and shear stress. Algorithms exist for the computation of erosion, deposition, and scour, but these are often inaccurate and of limited value in assessing the true impacts and localized nature of these processes associated with bank stabilization.

Table 5. Impacts on Erosion and Deposition

Category	***Impacts***
General	All bank stabilization measures at least temporarily change sediment yield characteristics of a channel. Most cause local scour and many induce sediment deposition. These impacts tend to be temporary, though their results may persist for long periods of time, particularly in streams with armored beds and few tributaries.
Armor Techniques	Armoring techniques generally reduce local bank erosion, but induce local scour. Scour generally occurs at the toe of the armor structure, and extends riverward about two – three times the scour depth. Algorithms to compute scour depths are notoriously poor, but provide some means of estimating the magnitude of the scour depth. Armor techniques that utilize materials with high resistance values can also induce local sediment deposition – usually on and within the armor material.
Deflection Techniques	Flow deflection structures alter the channel geometry, create flow blockages, and generate form roughness. Consequently, they tend to significantly alter the flow field. This, in turn, generates zones where both scour and deposition occur within relatively small areas and in close proximity to each other. Scour holes nearly always form off the ends of the structures, but may also occur on the face of the structure if it is oriented perpendicular to the flow or angled downstream. Deflection structures usually establish an eddy on their downstream side and, if strong enough, may create some scour in concentrated areas. More often, however, the zone immediately downstream of a deflection structure is subject to sediment deposition as the flow velocity and shear stress decrease in these zones. The overall impact on scour, deposition, and sediment movement varies greatly with the channel type, planform, bed material characteristics, nature of transported sediments and the location, geometry, and orientation of the deflectors. Scour and deposition increase with structure length, height, and angle from the upstream bank and with increasing values of the ratio of the stream width to the radius of curvature of the bend, though there are limits to each of these values beyond which impacts tend to diminish.

Slope Stabilization Techniques	Slope stabilization techniques generally reduce local bank erosion, but may also increase local scour. Scour generally occurs at the toe of the structure, and extends riverward about two – three times the scour depth. Algorithms to compute scour depths are notoriously poor, but provide some means of estimating the magnitude of the scour depth. Techniques that utilize materials with high resistance values can also induce local sediment deposition – usually on the slope itself. Regrading an eroding bank can modify the strength of secondary currents in a bendway – affecting the growth and development of point bars, modifying thalweg depths, and altering secondary transport of sediments.
Energy Reduction Techniques	The techniques used to reduce energy within a stream have a significant impact on sediment transport, scour and deposition. Grade control measures create backwater in upstream reaches – increasing depth and reducing velocity. These upstream impacts reduce sediment transport capacity and stream reaches immediately upstream of these structures often have deposited sediments on the bed that are finer than those found in adjacent reaches. The extent of the upstream impacts depend upon the height of the structure and the streambed slope. Downstream of the structure, a scour pool is generally formed with a bed material composition more coarse than adjacent reaches. The size of the pool is dependant on the relative height of the structure and its geometric configuration. Vanes have similar effects to those described above for deflection structures, but the magnitude of scour and deposition is diminished compared to conventional deflection structures.

Impacts on sediment transport through the design reach

Many stabilization measures temporarily affect sediment transport through a design reach. Some are intended to promote deposition or scour, and all are intended to reduce sediment yield from an eroding bank. So virtually all stabilization measures affect sediment transport capacity, but they may or may not affect actual transport, which is determined also by upstream sediment yield in areas beyond the influence of the stabilization measures. Streams generally adjust to the changes imparted by stabilization and reestablish sediment continuity through a design reach in time. A number of analytical tools exist with which estimates of sediment transport capacity can be made. Determination of actual transport requires either direct measurement, or capacity analyses coupled with knowledge of sediment yield characteristics.

Table 6. Impacts on Sediment Transport

Category	***Impacts***
General	No generalization can be made regarding the impacts of bank stabilization on sediment transport through a project reach except to note that, given sufficient time, streams generally reestablish sediment continuity through a reach modified by stabilization measures.
Armor Techniques	Armoring techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance and the reduction of sediment yield from the eroding bank. Any impacts tend to be short-term, and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Deflection Techniques	Deflection techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance, alterations to secondary currents and turbulence, and the reduction of sediment yield from the eroding bank. Like armoring techniques, impacts tend to be short-term (especially in braided systems), and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Slope Stabilization Techniques	Slope stabilization techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance and the reduction of sediment yield from the eroding bank. Any impacts tend to be short-term, and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Energy Reduction Techniques	Energy reduction techniques generally reduce velocity, shear stress and stream power - three surrogate measures for sediment transport. Grade control structures reduce sediment transport

	through a reach and induce local sediment deposition. In time, continuity may be reestablished, but this depends upon the sediment yield and the characteristics of the stream and structure. Vanes are intended to reduce secondary velocities, which has the effect of reducing secondary sediment transport, but this is generally a minor transport component and is usually offset by an increase in longitudinal transport. Measures that don't affect or increase sediment transport: - Vanes Measures with potential to decrease sediment transport capacity: - Grade control and channel block structures

Length of the river that is impacted by the specific structure type

Slope of the channel is the primary determinant in defining the length of river that is impacted by stabilization measures. Techniques that realign the channel or adjust the planform tend also to have impacts that extend further up- or downstream than techniques that are employed within the existing channel geometry. Streams with highly erodible beds and banks are most sensitive to change, and impacts on these systems are more widely distributed than for relatively erosion-resistant streams. The extent of impacts can be limited by geologic or anthropogenic controls. In general, however, impacts from stabilization measures tend to be localized unless they modify the energy gradient or significantly alter the cross section.

Table 7. Length of River Impacted

Category	*Impacts*
General	No generalization can be made regarding the lengths of river that bank stabilization impacts except to note that the length is very closely related to the channel slope and bed material composition. Impact lengths are greatest over low-gradient streams and streams with sand beds. Impact lengths are least on steep gradient streams, streams with erosion-resistant bed materials, and streams with controls.
Armor Techniques	Armoring techniques seldom affect the channel more than a few feet up- or downstream of the project extents. Erosion may persist downstream of an improperly terminated armor structure, and the local scour and increased local velocities can accelerate and exacerbate this erosion. But it would be very uncommon to identify an armor structure that impacts areas of the channel further than ½ a meander wavelength up- or downstream (for a meandering stream) or more than two channel widths up- or downstream (for a braided stream). Sediment transport models could be applied to evaluate up- and downstream extents of impacts as they relate to hydraulic or sediment transport variables. No models exist for the prediction or quantification of impacts to up- or downstream bank erosion. Measures with potential to affect areas outside the zones defined above: - Armor devices that constrict the channel to the extent that contraction scour occurs completely across the section. This could induce a nick point that travels further upstream. - Any armor that protects a bank that was a significant sediment source for the channel could result in increased or accelerated bed or bank erosion downstream.
Deflection Techniques	Deflectors create a greater number of and more substantial local impacts than do armoring techniques. And the potential for cumulative impacts and impacts of greater spatial extent is higher from some of these measures than for armoring techniques. Impacts from deflectors that significantly alter flow fields generally persist for one bendway (½ a meander wavelength) up- or downstream for a meandering stream) or about four channel widths downstream and one or two widths upstream for a braided stream. Though hydraulic and sediment transport modeling could be applied to assess the sensitivity of a system to up- and downstream perturbations from deflectors, actual quantification of the impacts would be highly suspect in terms of accuracy. In general, the greater the impact to the flow field, the further up- and downstream impacts can be expected.

Slope Stabilization Techniques	Slope stabilization techniques seldom affect the channel more than a few feet up- or downstream of the project extents. Erosion may persist downstream of an improperly terminated structure, and the local scour and increased local velocities can accelerate and exacerbate this erosion. But it would be very uncommon to identify a structure that impacts areas of the channel further than ½ a meander wavelength up- or downstream (for a meandering stream) or more than two channel widths up- or downstream (for a braided stream). Measures with potential to affect areas outside the zones defined above: - Measures that constrict the channel to the extent that contraction scour occurs completely across the section. This could induce a nick point that travels further upstream. - Any stabilization of a bank that was a significant sediment source for the channel could result in increased or accelerated bed or bank erosion downstream.
Energy Reduction Techniques	Energy reduction techniques tend to have the greatest spatial extent of all stabilization measures. Grade control structures modify the slope of the channel, raising water levels and decreasing velocity and sediment transport upstream. They can also trap sediments and induce downstream degradation. Impacts from vanes are comparable to those described above for deflector structures. Methods to quantify impacts to water surface elevations, velocities and sediment transport in up- and downstream reaches are straight forward for energy reduction measures, and generally consist of backwater and sediment transport analyses. An exception is the impact of vanes, which have not been adequately studied for this impact.

Appendix B

Shear Stress Calculation

Shear Stress Calculation

Erosion potential was determined from results of the XP-SWMM model of the ravine's main channel. The model was run for local flows of 90, 120, 150, and 180 cfs, and no local flow was included in the model. Appendix 2 of the Environmental Assessment Phase I Report contains additional information regarding the XP-SWMM model.

The shear stress calculation was based on the following equation:

$$\tau = \gamma R S_f$$

where

τ = average shear stress (lb/ ft^2)
γ = specific weight of water = 62.4 lb/ft^3
R = hydraulic radius (ft)
S_f = Energy Grade Line (EGL) slope

The hydraulic radius for each ravine section was calculated by the XP-SWMM model. Due to variation in the cross-sectional areas, non-uniform flow was assumed in the ravine and the Energy Grade Line (EGL) slope, S_f, was used in the shear stress calculation for each channel section, instead of the channel slope. The EGL slope was calculated from the water surface levels (i.e. Hydraulic Grade Line) and maximum velocity from the XP-SWMM results, using the following equation (Chang, 1988):

$$S_f = \frac{\{[WS + (2 / g) \times V^2]_{upstream} - [WS + (2 / g) \times V^2]_{downstream}\}}{L}$$

where

S_f = Energy Grade Line (EGL) slope
WS = water surface level (ft)
g = 32.2 ft/s^2
V = maximum velocity (ft/s)
L = section length (ft)

The maximum velocity represents the average cross-sectional velocities at maximum flow and is applied to the entire selection. To obtain upstream and downstream velocities, maximum velocities were averaged between sections.

To account for variations in local and instantaneous velocities, the following equation was used to determine the maximum shear stress (Chang, 1988):

$$\tau_{max} = 1.5\tau$$

where

τ_{max} = maximum shear stress (lb/ ft^2)
τ = average shear stress (lb/ ft^2)

The safety factor for each ravine section was calculated by the following equation:

$$FS = \tau_{perm} / \tau_{max}$$

where

FS = factor of safety
τ_{perm} = permissible shear stress threshold (lb/ft^2)

Appendix C

Summary of Meeting with Washington County Park Personnel

Summary of Meeting with Washington County Park Personnel

Input regarding the proposed stabilization measures was obtained from Washington County Park personnel during a meeting on January 11, 2002. Preliminary impressions on the proposed stabilization measures appeared favorable to park personnel, with provisions for addressing the following issues:

- Plans for erosion control in the Cottage Grove Ravine Regional Park need to be discussed with appropriate personnel at the Minnesota Department of Natural Resources.

- Ski trails are currently located in the ravine and would need to be accommodated or relocated with the stabilization measures proposed.

- Park personnel would like erosion concerns on the east side of the park to be addressed.

- Park personnel would like to see more information on potential changes to the lake outlet to reduce the amount of bounce that might occur with increased flow through the ravine.