STREAM BANK STABILITY ASSESSMENT IN GRAZED RIPARIAN AREAS

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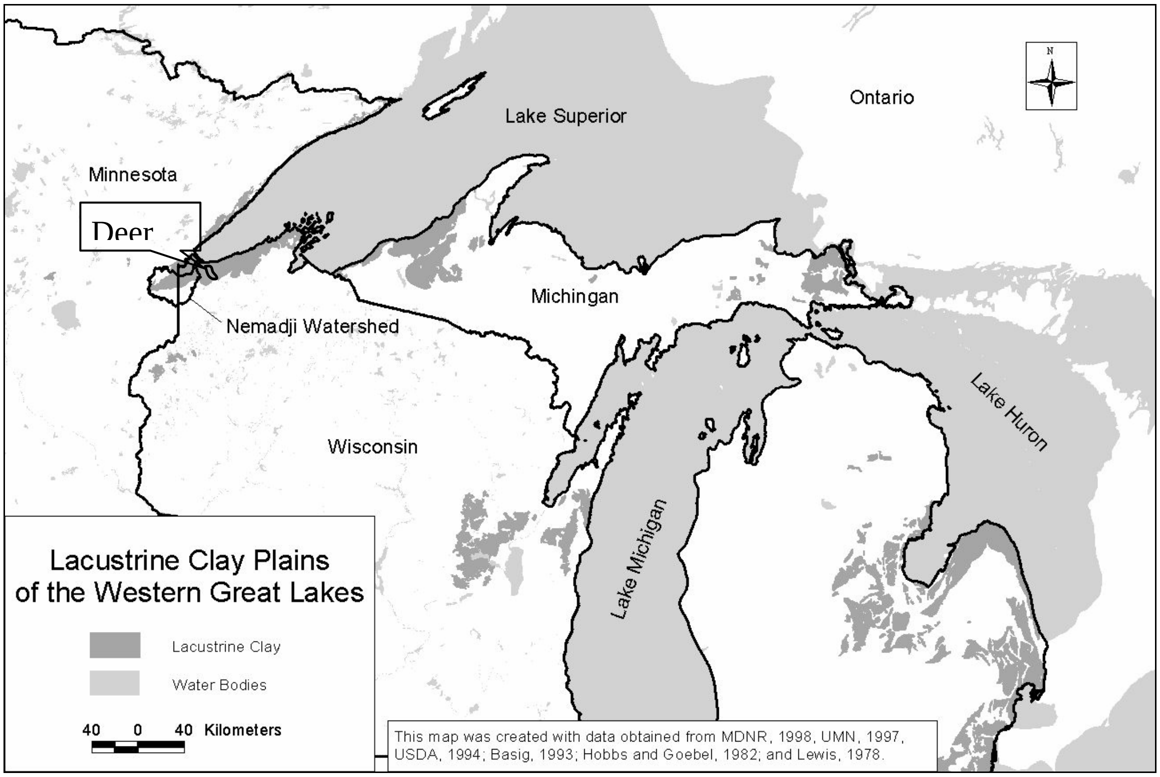
Abstract: Streams in the Nemadji River Watershed of east-central Minnesota are deeply incised in lacustrine clay and glacial till. This region is naturally erosive because of recent glacial activity (~10,000 years ago). Indeed, the Nemadji River is the largest source of fluvial sediments to Lake Superior. While natural land cover was predominantly coniferous forest, riparian areas were commonly converted to pasture by the late 1800's. We investigated stream bank stability under a variety of riparian cattle traffic scenarios to determine the impacts of cattle traffic on stream bank stability over a 3-year period. Grazing significantly reduced stream bank stability. In response, grazed streams adopted “stable” stream bank geometry. While root tensile strength of riparian species dominated resisting forces, the cohesive strength of the lacustrine clay channels was generally sufficient to maintain stable channel geometry in ungrazed streams. The “Pfankuch” method of rating stream bank stability in the field was very consistent with mechanistic estimates and measured values of stream bank stability.

INTRODUCTION

Streams in the Nemadji River Watershed of east central Minnesota and northwestern Wisconsin cut into glacially derived cohesive, lacustrine clay and clay till (Figure 1). This is important



This map was created with data obtained from MDNR, 1998, UMN, 1997, USDA, 1994; Basig, 1993; Hobbs and Goebel, 1982; and Lewis, 1978.

Figure 1 Location of Nemadji Watershed and Lacustrine Clay deposits.

because clay increases the strength and stability of streams (Schumm, 1960). Smith (1998) and Grissinger, et al (1981) found channels in flumes shifted to stable meandering forms when cohesive clays were present. Grissinger, et al observed erosion decreased 50% as clay content increased by 33%. Similarly, Dunaway, et al, (1994) reported bank erosion rates decreased as clay to silt ratios increased and noted root density limited bank erosion. Riparian land use conversion often reduces the stability of "natural" gravel and sand bed streams (Abernethy and Rutherford, 2000; Millar, 2000; Hupp, 1999; Hupp, 1992; and Charlton, et al., 1978) and causes morphologic response (Osman and Thorne, 1998 and Huang and Nanson, 1998). In-situ influences of streamside land use on stability and morphology in cohesive clay channel streams is largely undocumented. We observed morphology and stability on a cohesive clay channel stream experiencing cattle disturbance over three consecutive summers.

Site Description: Three study reaches were installed on Deer Creek (Figure 2). The upstream Reach I (50 m long, 4 cross sections, 3.47 km^2 watershed), separated a barn and adjacent 16 ha pasture. The stream experienced frequent traffic (many times/day) from 40 beef cattle and 25 sheep. Most native cover was gone and streambanks were 20% vegetated with perennial grasses and herbs. Flood plain vegetation consisted of herbaceous plants and perennial grasses, and a 30 % deciduous tree canopy dominated by quaking aspen (*Populus tremuloides*), black ash (*Fraxinus nigra*) and paper birch (*Betula papyrifera*) with diameters ranging from 20 – 50 cm at breast height (dbh).

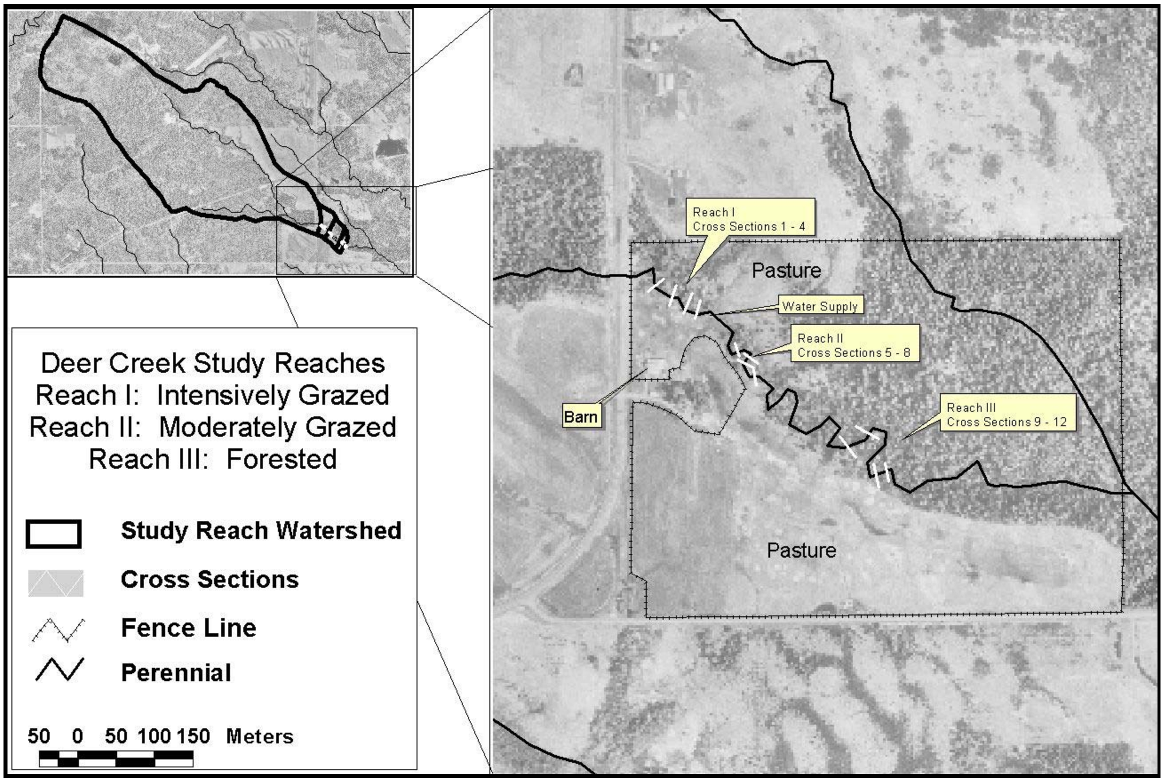


Figure 2 Location of Deer Creek study reaches.

Downstream, Reach II (75 m long, 4 cross sections, 3.52 km^2 watershed) flowed through a forested pasture. Native vegetation was largely absent, cattle access infrequent (few times/day), and ground cover well established. Stream banks were 40% covered with grasses and shrubs. Forest canopy of aspen, black ash, white pine (*Pinus strobus*), birch, jack pine (*Pinus banksiana*) and balsam fir (*Abies balsamea*) covered 80% of the floodplain (trees from30 to 70 cm dbh).

Reach III (150 m long, 4 cross sections, 3.58 km^2 watershed) was another half kilometer downstream. The flood plain and valley forest had 100% canopy closure by aspen, balsam fir, birch, black ash, white pine, and white spruce (*Picea glauca*). Herbaceous vegetation, hazel (*Alnus serrulata*), and balsam fir covered more than 60% of the stream banks. There was no cattle traffic and stream morphology was similar to natural reference streams with watersheds that were completely forested for at least 70 years (Riedel, et al, 2005 and Riedel, et al, 2002).

METHODS

We analyzed stability for stream banks and beds using two methods:
1. Pfankuch's (1975) empirically based stream bank stability index (PSI);
2. Mechanistically based estimates.

PSI Rating: The PSI for each reach was determined according to the methods of Pfankuch (1975). Stream bank characteristics include bankfull channel capacity, bank rock content, channel obstructions, channel incision, and channel aggradation. Channel substrate was rated by rock angularity, rock brightness, degree of substrate armoring, substrate grain size distribution, occurrence of localized scour and deposition, and the existence and vigor of aquatic vegetation.

Mechanistic Stream Stability Analysis: We estimated mechanistic stability by comparing shear strength (resisting) and shear stress (driving) forces as the factor of safety (FSh):

$$FSh = S / H^*(\gamma t) \qquad (1)$$

where S = Shear strength (kPa), H = bank height (m), γt = saturated weight of soil (kN/m^3).

Stream Banks: We adapted the Mohr-Coulomb equation to include soil cohesive strength (adapted from Millar and Quick 1998) and the contribution of root tensile strength;

$$S = (Ns)cu + \sigma * \tan(\phi) + Cr \qquad (2)$$

where
Ns = saturated dimensionless stability (Huang, 1983) = $3.83 + 0.052\,(90 - \theta) - 0.0001\,(90 - \theta)^2$ (Taylor, 1948);
cu = Soil cohesive strength (kPa) = 1.93 + 0.1444(PI) (lbs/ft^2, Cousins, 1984),
    PI = Plastic Index = plastic limit – liquefaction limit
σ = Bank shear strength (kPa),
ϕ = Internal friction angle = angle of repose for stable banks,
Cr = root cohesion (kPa) (Gray and Megahan, 1981) = $tr * (\cos(\theta) * \tan(\phi) + \sin(\theta))$ (Wu, 1976),
    tr = root tensile strength per unit area (kPa m^{-2}) and θ = angle of root shear distortion.

Taylor's (1948) method to estimate Ns has been tested for stream bank applications (Millar and Quick, 1998). Undrained cohesive strength was estimated from PI, plasticity and liquefaction data (Mengel and Brown, 1979 and Lewis, 1978). Estimates of soil cohesion were consistent with published values (Huang, 1983 and Bjerrum and Simons, 1960). We computed shear strength under saturated conditions, the $\phi = 0$ approach (Huang, 1983), to remove the dependence on soil moisture content and pore water pressure ($\sigma \tan(\phi) = \text{zero}$) (Spangler and Handy, 1982 and Peck and Lowe, 1960). Such conditions often preclude bank failure and occur following bankfull or larger flows (Alabyan and Chalov, 1998; Hickin, 1995; Leopold, et al., 1992; and Chang, 1979).

We estimated tr by Wu's (1976) "theoretical model of a fiber-reinforced soil" which accounts for lateral and normal force components (Hammond, et al, 1992). This approach is valid when roots shear rather than slip and is applicable in cohesive soils (Abe and Ziemer, 1991 and Megahan, et al 1978). We obtained root mass and tensile strength data from a field study of 40+ sites in the Nemadji Watershed (Kaputska and Davidson, 1979). Root distributions were limited to 0.5 m depth by the cohesive clay soils. Roots greater than 8 mm in diameter were not tested so we assigned these tensile strengths equivalent to those in the 8 mm size class.

Stream Beds: Bankfull average bed shear stress was estimated as;

$$\tau \text{ bed} = \gamma * R * S \qquad (3)$$

where
γ = Specific weight of water (kg/m^3),
R = Bankfull hydraulic radius (m) = Ax / Wp, Ax = channel area (m^2), Wp = wetted perimeter (m),
S = Bankfull water surface slope (m/m),

Estimates were consistent with those from dimensionless values (ASCE, 1998; Ritter, et al., 1995; and Schumm, 1960). Shear stress distribution between the stream bed and banks was estimated with the empirical relationship of shear stress distribution in trapezoidal channels developed by Knight, et al (1984) and Flintham and Carling (1988):

$$\text{SFbank} = 1.77 * (\text{Pbed} / \text{Pbank} + 1.5)^{\wedge(-1.4)} \qquad (4)$$

where
SFbank = Proportion of total shear stress acting on channel banks;
Pbed, Pbank = Wetted perimeter of stream bed and banks, respectively (m).

Critical shear stress for the cohesive clay was estimated by two methods: 1. by sodium adsorption ratio (SAR), pore fluid salt concentrations, and conductivity (Arulanandan, et al, 1980). These data were obtained from the red clay study of Bahnick, et al, (1979); 2. Chow's unit tractive force relationships for cohesive soils (Chow, 1959). Estimated values were 3.61 Pa, and 4.79 Pa, respectively; we used the geometric mean, 4.16 Pa. Stream bank stability with respect to fluvial erosion was estimated as the factor of safety with respect to bank shear, FSτ.

$$\text{FS}\tau = \tau \text{ crit} / \tau \text{ bed} \qquad (5)$$

where
τ crit = shield's critical shear stress for bank sediments (kPa),
τ bed = mean bed fluvial shear stress (kPa).

RESULTS

Width-depth ratios were largest and stability lowest on grazed reaches (Figure 3).

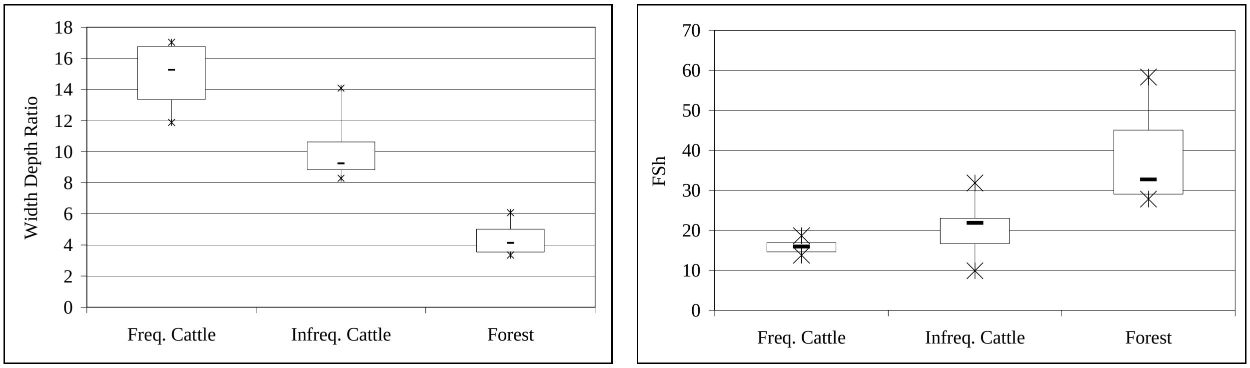


Figure 3 Stem and whisker plots of width depth ratios and mechanistic stream bank stability by reach (n=16/reach) (adapted from Riedel, et al, in review).

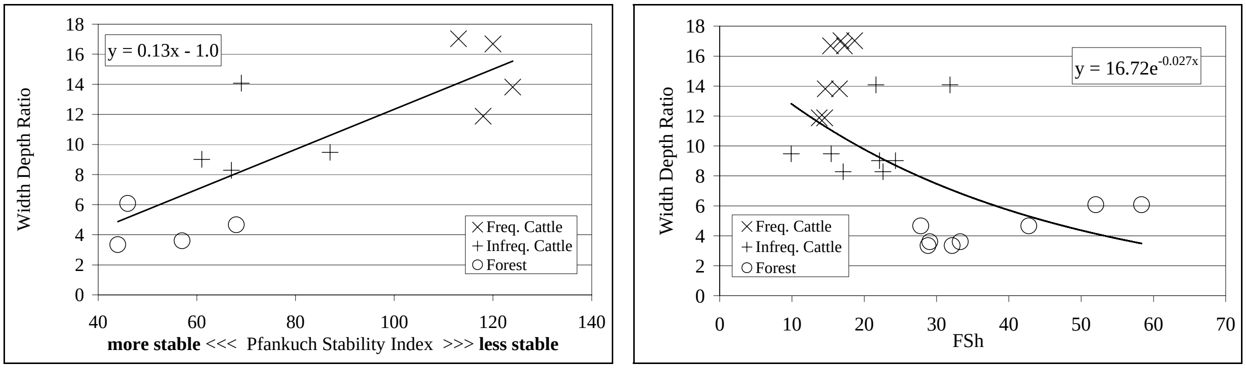


Figure 4 Scatter plots of width depth ratio by PSI and FSh. Note - PSI is inversely related to stability. Upstream / Downstream (dependence) arrangement of sites precludes regression and correlation analyses.

The width-depth ratio of streams increased with PSI (decreasing stability) in the study reaches (Figure 4). Width-depth increased as FSh decreased from forest to cattle sites (Figure 4). While stream banks were fluvially stable, stream beds were generally not stable (Figure 5). Bed stability was near the threshold at the frequent cattle site and declined slightly to the forest site.

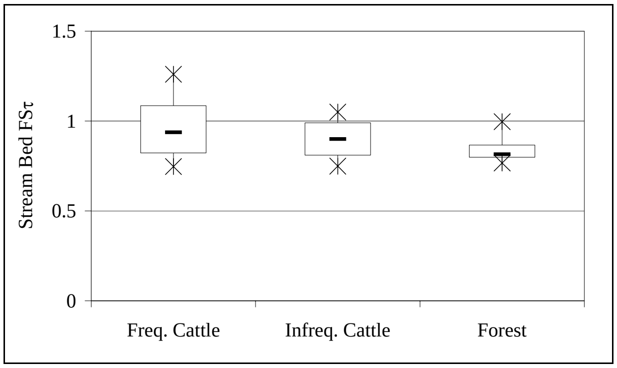


Figure 5 FSτ of stream beds for each reach (n=16/reach)

PSI was inversely correlated to FSh (Figure 6) but independent of stream bed and bank $FS\tau$.

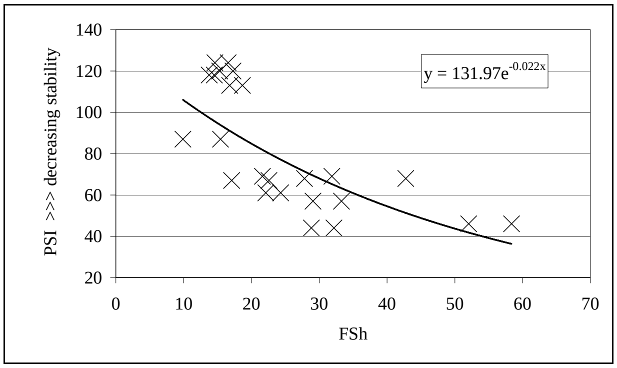


Figure 6 Pfankuch Stability Index (PSI) as related to calculated FSh There are 2 FSh values per reach. Upstream / Downstream (dependence) arrangement of sites precludes regression and correlation analyses.

DISCUSSION

Mechanisms which alter the riparian land use condition have consistently been found to reduce the stability of the stream banks and induce erosion. Platts (1981) noted that stream banks had eroded, channels widened, and mean depth decreased in response to disturbance by sheep. Hupp and Simon (1986) attributed stream widening to reduced bank stability caused by vegetation removal and channelization. Millar and Quick (1998) found that riparian vegetation increased the critical bank shear stress of natural streams and allowed them to be narrower and have steeper bank angles. Burckhardt and Todd (1998) reported riparian forests stabilized the outside bank of meandering streams - unvegetated banks eroded three times faster. Numerous authors have found that the width-depth ratio of a stream increases in response to decreased bank stability. Schumm (1960) documented the tendency of normally narrow clay channel streams to widen in response to destabilization such as changes in stream bank vegetation. On Deer Creek, the width-depth ratio increased as bank stability decreased with cattle traffic. The width-depth ratios in the grazed riparian areas is controlled by frequency of cattle traffic because the cohesive banks have sufficient strength to resist gravitational failure. Conversely, the width-depth ratios of the forested stream reaches are dependent upon the factors of safety with respect to stream bank and streambed shear.

CONCLUSIONS

Width-depth ratio of the study reaches were strongly related to both the Pfankuch (1976) and mechanistically estimated measures of streambank stability. Hoof shear from cattle traffic had the largest impact on stream bank stability because even with the loss of riparian vegetation, FSh was normally not exceeded. The $FS\tau$ indicated that the stream bank materials were generally stable from fluvial erosion. It was the factor of safety for fluvial shear, $FS\tau$, of the stream bed materials that was commonly found to be exceeded. Instability of the stream banks only occurred with the removal of riparian vegetation and subsequent bank erosion caused by cattle traffic. The fluvial erosion thresholds for the stream bank materials were exceeded once materials were introduced into the streambed. The stream morphology and subsequent erosion of stream bank and streambed materials were due to the destabilizing effects of cattle grazing and traffic on the stream banks. Consequently, stabilization of cohesive clay stream banks in this region may be accomplished by simply excluding cattle.

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