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Impacts of land use conversion on bankfull discharge and mass wasting

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Abstract

Mass wasting and channel incision are widespread in the Nemadji River watershed of eastern Minnesota and northwestern Wisconsin. While much of this is a natural response to glacial rebound, sediment coring and tree ring data suggest that land use has also influenced these erosional processes. We characterized land use, inventoried mass wasting, surveyed stream channels and collected discharge data along segments of five streams in the Nemadji River watershed. Due to natural relief in this region, wetlands and agricultural lands are concentrated in the flatter terrain of the uplands of the Nemadji watershed, while forestland (coniferous or deciduous) is concentrated in the deeply incised (50–200% slope) stream valleys. Bankfull discharge was higher where forests had been converted from coniferous to deciduous forests and where there were fewer wetlands. Mass wasting increased exponentially with bankfull flows. While mass wasting was not correlated with forest type conversion and agricultural land use, it was negatively dependent upon wetland extent in headwater areas. Interactions between the spatial distribution of land use and terrain obfuscate any clear cause-and-effect relationships between land use, hydrology and fluvial processes.

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Keywords: Watershed management; Forest hydrology; Mass wasting; Sedimentation

1. Introduction

The Nemadji River watershed encompasses 1110 km^2 of eastern Minnesota and northwestern Wisconsin (Fig. 1). This region, dominated by lacustrine clay deposits, glacial till, and beach sands, is naturally unstable and extremely erosive. The Nemadji River transports an average of 120,000 tons of sediment to Lake Superior annually (NRCS, 1998a). This is the largest source of sediment to Lake Superior, second only to lake bluff erosion (Stortz and Sydor 1976). Much of the Nemadji's sediment load is the result of a natural erosional response to active geologic uplifting and climate. However, sediment core analyses from the neighboring St Louis River delta in Lake Superior indicate that the rate of alluvial sediment deposition has increased in the past 150 years (Kingston et al., 1987). The onset of this increase in the mid to late 1800s coincided with intensive forest harvesting across the St Louis and Nemadji watersheds. Kemp et al. (1978), using a combination of *Ambrosia* pollen analysis and lacustrine sediment dating, determined that the sedimentation rates of western Lake Superior, near the outlet of the Nemadji River, have increased from 0.89 mm/year during the pre-historic, post-glacial period to 2.00 mm/year from 1890 to 1955. During this period, the Nemadji River watershed experienced intensive forest harvesting, two major forest fires (Hinckley Fire 1894, Moose Lake Fire 1918) and conversions to agricultural land use in the early 1900s.

Results from dendrochronological analysis of trees on floodplains, terraces and relic channels in the Nemadji watershed revealed that episodes of channel incision co-occurred with forest harvesting in the 1850s, forest fires in 1894 and 1918, and agricultural expansion in the 1930s and 1950s (Riedel et al., 2001; Verry, 2000). Fitzpatrick (1999) reported a similar pattern of fluvial response following widespread forest harvesting and agricultural land use conversion in the Fish Creek watershed, located

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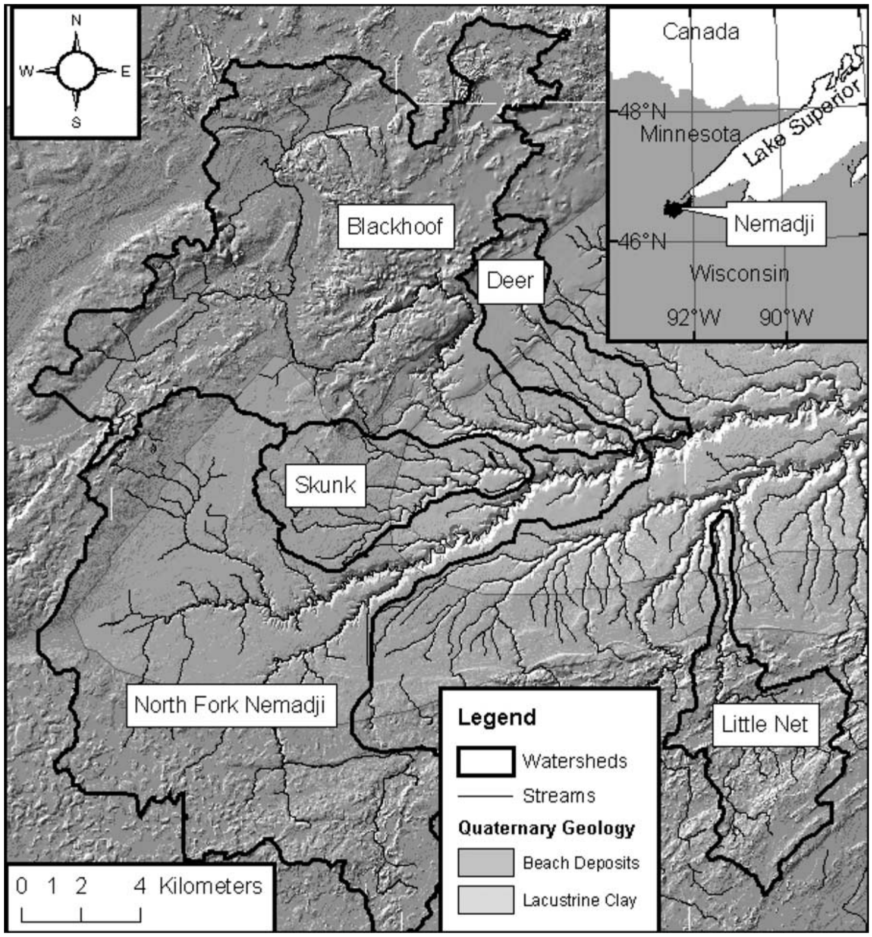

Fig. 1. Location of Nemadji River watershed, study sites and watershed boundaries. Lacustrine clay and beach deposits are from glacial lakes Duluth and Nemadji.

approximately 160 km east of the Nemadji watershed. This co-occurrence of land use change and increased sedimentation rates suggest that erosional processes in this region respond to land use change. Our objectives were to determine: first how differences in land use, through alteration of hydrologic regime, explain differences in bankfull discharge; second, to determine how differences in bankfull discharge affect mass wasting and third, determine if there is empirical evidence of a causal link between land cover and mass wasting in the Nemadji River watershed.

The conversion of a forested landscape from one forest type to another or, from forest to non-forest, changes the hydrologic regime of a watershed. Perhaps the most significant change results from differences in evapotranspiration (interception and transpiration) losses between various vegetation types, as summarized by Calder (2002), Whitehead and Robinson (1993) and Bosch and Hewlett (1982). Land management practices, such as forest harvesting and conversion to agriculture, which reduce interception capacity and vegetative transpiration typically increase water yield (Sun et al., 2004). The magnitude of water yield increase is dependent upon the scale of the forest harvesting or conversion. Clear-cutting hardwood and coniferous forests in boreal forests of the Great Lakes region increased annual stream-flow by 30–80% during wet and dry years, respectively, (Verry, 1986). The conversion of mature pine forests (*Pinus* spp.) to aspen (*Populus* spp.) increased net annual precipitation by 15% by simply reducing the canopy interception of rainfall and snowfall (adapted from Verry, 1976). Murray and Buttle (2003) reported similar results following the clear-cut of a northern hardwood forest in Ont., Canada. Snow accumulation and snow water equivalents were higher on the clear-cut sites. The larger snow packs melted faster, increasing the volume and rate of spring runoff.

Trimble and Weirich (1987) investigated water budgets in the southern United States ranging in size from 2820 to 19,450 km^2 and concluded that 10–28% increases in forest cover reduced annual water yield by 4–21% (3–10 cm). On average, this translated to a 0.3 m^3 reduction per square meter of reforestation. Land use conversions from coniferous to deciduous forests or from forested to non-forested cover types reduce interception and transpiration losses, causing soil moisture to increase and raising water table elevations (Sun et al., 2004; Whitehead and Robinson, 1993; Bosch and Hewlett, 1982). Over the past 150 years, the Nemadji watershed has been subjected to such land use conversions (Riedel et al., 2001).

Land use conversion also influences storm flow hydrographs. In northern Minnesota, the removal of aspen increased peak discharge from snowmelt by 11–143% and rainfall events as much as 250% while storm flow volumes increased up to 170% (Verry et al., 1983). The two-year peak flows from rain events were 1.5 times greater following harvesting while 10-year peaks were 2.5 times greater. Even with natural forest regeneration, doubling of annual peak stream-flows may persist for up to 15 years (Verry, 1986). Lu (1994) simulated the effects of clear-cutting aspen on the frequency of stream-flow peaks from rainfall events and found that peak-flow discharges were elevated for all events up to the 25-year recurrence interval.

Similarly, the conversion of two mixed oak and hickory watersheds to white pine stands at the Coweeta Hydrologic Laboratory, located in the southern Appalachian Mountains of western North Carolina, reduced water yield and flow duration on both watersheds (Swank and Vose, 1994). Peak flows decreased for events ranging up to approximately the 25-year event. The 1.5 year event was reduced by 50%, from 0.02 to 0.01 $m^3/s/km^2$. Using the Prosper model to explain observed results, Swift et al. (1975) simulated the hydrologic effects of pine conversion on the watershed. Interception by the white pine canopy reduced annual net precipitation by 40%. Transpiration rates were similar between the stands from May through October; however, water yield from the pine stand was 120% lower during the period of November through April due to interception losses.

Jones and Grant (1996) reported increases in water yields and peak stream flows following forest harvesting on watersheds ranging from 0.6 to 600 km^2 in the Cascade Mountains, Oregon. Peak flows on small harvested watersheds increased by 50% while those on the larger watersheds increased by 100%. Jones and Grant (1996) reported peak-flow increases associated with the 1 year event from 10 to 50%. Conversely, Thomas and Megahan (1998), debating the analytical methods and results of Jones and Grant, analyzed the same data and concluded that flows on the small watersheds increased up to 90% while those on the larger watersheds increased by no more than 40%. Beschta et al. (2000) further conducted an extensive analysis on the same data. They found that the 1- and 5-year peak flows on the small watersheds increased from 13 to 16% and from 6 to 9% post-harvest, respectively. Beschta et al., reported forest harvest on the large watersheds accounted for less than 7% of the observed variability in peak storm flow. As with Thomas and Megahan, Beschta et al., found no significant increases in flow volumes or magnitudes for the large events, contrary to the postulation of Jones and Grant.

The effects of land use change on water yield and stream-flow patterns are often considered to manifest themselves in fluvial processes and stream morphology. Jacobson et al. (2001) conducted a literature review and concluded that land use changes commonly drive responses in fluvial systems. Knox (1977) reported that basin-scale conversion of the largely deciduous Platte River watershed to agricultural land use in southern Wisconsin during the mid 1800s increased overland flow, flood magnitude and flood frequency. Soil loss increased, as did sedimentation and aggradation of downstream river reaches.

Forest harvesting and associated road building in the Cascade Mountains, Oregon, exacerbated channel scour and landslides that were associated with a large storm event in 1964 (Lloyns and Beschta, 1983). This stimulated aggradation and widening in the downstream river network. Here, the hydrologic regime was not substantially altered; the forest harvesting and road construction represented less than 20% of the total basin area and were dispersed over a 40-year period. Lisle and Napolitano (1998) and Napolitano (1998) found historic and contemporary forest harvesting activities increased stormflows and stream sedimentation in Casper Creek, northern California. Lisle and Napolitano (1998) noted the yield of bed material sediments from the system did not increase and speculated the storm flow increases were too small to transport sediment from the basin. Ryan and Grant (1991) utilized aerial photography and ground measurements to quantify riparian canopy openings caused by landslides, large floods and excessive sedimentation in the Elk River Basin of southwestern Oregon. They determined that sediment deposition and riparian canopy openings increased downstream of clear-cuts and forest roads.

We conclude forest harvesting and conversions to agricultural land use reduce evapotranspiration, and increase soil moisture, water yield and surface runoff. While this change in hydrologic regime would likely not increase large storm-flow peaks (e.g. 20+ year event), smaller storm-flow peaks on the order of 1–10 year events can increase. These frequent events, including the bankfull discharge (e.g. ~1.5 year recurrence interval), are responsible for forming and maintaining stream channels (Leopold et al., 1992; Chang, 1979) and cumulatively perform the most work in the fluvial system (Costa and O'Conner, 1995; Wolman and Miller, 1960). Robinson et al. (1995) suggested as watershed scale increases, the hydrologic response of a watershed increasingly affects the fluvial response of the drainage network, which in turn, increasingly (and non-linearly) drives the geomorphic response of catchments.

We hypothesize that broad scale forest harvesting and agricultural land use in the Nemadji River watershed, by increasing water yield, have increased bankfull discharge and the occurrence of mass wasting. Consequently, land use should explain differences in bankfull discharge and mass wasting throughout the Nemadji River watershed.

1.1. Background

For clarity, mass wasting in the Nemadji Basin occurs as planar and rotational slumping of valley walls (Fig. 2). The slumps are typically located where stream channels meander against valley walls, eroding the stream bank and undermining the base of the valley wall slopes. This destabilizes the valley walls and causes mass wasting.

Two large interagency investigations have addressed the frequent occurrence of mass wasting and sedimentation within the Nemadji River watershed. The first was a demonstration project in the mid 1970s that investigated the causes of mass wasting and implemented a number of restoration practices to reduce sedimentation from mass wasting sites. The restoration practices included the construction of a number of large sedimentation basins, stabilization of slumping roadways and the re-routing of a stream away from a failing valley wall (Andrews et al., 1978, 1980). Andrews et al. (1978) found: (1) mass wasting was largely a natural phenomenon, (2) construction practices had exacerbated mass wasting near roads, (3) slope failures occurred where streams impinged on valley walls, (4) groundwater discharge through springs and seeps in the valley walls encouraged mass wasting, (5) clay soils were inter-bedded with lenses of beach sands, creating subsurface flow paths and slippage plains that were naturally susceptible to failure, and (6) the natural shrink/swell tendencies of the montmorillonite clay soils produced deep tension cracks during dry periods allowing rapid infiltration and initiation of slope wall failure.

One of the most important findings: mass wasting occurred on completely forested slopes despite large differences in root tensile strength among species. This is contrary to findings typical for western states (Prellwitz, 1994; Ziemer, 1981; Gray and Megahan, 1981) where root strength plays an important role in stabilizing slopes. In the Nemadji, Andrews et al. (1978) found the dense clay soils caused tree roots to be concentrated near the soil surface. This limited root reinforcement of the hill slopes to shallow depths, presumably above that of the failure planes.

The second study, in the mid 1990s, concluded the vast majority of sediment leaving the Nemadji comes from mass wasting and this is degrading water quality and fish and invertebrate populations (NRCS, 1998a). They hypothesized watershed scale conversion of coniferous forests to agricultural land uses likely exacerbated mass wasting by increasing water yield, runoff, and soil moisture—the impetus for this study. They further recommended restoration practices to alleviate the degradation of land and water resources from erosion and sedimentation.

1.2. Geology

Glacial rebound and base level change in the Great Lakes region are strongly influencing geomorphic process in the Nemadji basin. More than 10,000 years before present, massive glacial lobes suppressed the land surface in this region. As the glaciers retreated, their melt-waters formed Glacial Lakes Duluth and Nemadji, submerging approximately one-half of the present day Nemadji watershed. The lacustrine clays deposited by these lakes and clay rich glacial tills of the Superior Lobe often exceed 60 m of depth (Basig, 1993; Banks and Brooks, 1991). As the glaciers melted, the ice mass was removed and the land surface

Fig. 2. A typical mass wasting site located where the Nemadji River meanders against a valley wall (Courtesy of United States Environmental Protection Agency). The river is approximately 20 m wide.

began to rise, or rebound. Using national geodetic survey data, Schumm (1977) estimated the rate of uplift in this region to be as high as 1 m per century. Glacial Lake Nemadji formed beach ridges at a present day elevation of 330 m above sea level. As the glacial lakes drained through the St Lawrence Seaway and the St Croix River, water levels fell to that of present day Lake Superior, 183 m above sea level (Olcott et al., 1978) while the uplands rose by glacial rebound. Lake Superior serves as the base level for the Nemadji River consequently, streams in the Nemadji basin were forced to incise through the beach ridges, till deposits and ultimately into the lacustrine clay to maintain their connection with the 'falling' levels of Lake Superior.

In 1902 riparian and navigation interests were balanced with water diversions for hydropower generation to maintain stable levels in Lake Superior (Lee and Southam, 1994). Lee and Southam (1994) researched historical lake level records and the lake level maintenance criteria known as the land-to-water surface area ratio. In order to maintain this ratio, lake levels in western Lake Superior have increased by 0.21 m since 1902 and will need to increase another 0.34 m by the year 2050. While this management of the water levels of Lake Superior partially offsets the effects of modern glacial rebound on tributaries to Lake Superior, the past effects of glacial rebound are already propagating through the Nemadji River and its tributaries (Riedel et al., 2001).

1.3. Hydrology

The Nemadji basin yields 42% of its annual precipitation as discharge. This is among the highest runoff-to-precipitation ratio in the state of Minnesota, approaching those of bedrock soil regions along the North Shore of Lake Superior. Streams in this watershed have some of the highest discharge frequency relationships in the state. Though largely forested, sub-watersheds of the Nemadji River have peak flow frequencies exceeding those of many similarly sized watersheds within the agricultural Minnesota River Basin (NRCS, 1998a).

The Nemadji also exhibits the highest average annual sediment loading per unit area of all the USGS gauged watersheds in Minnesota and Wisconsin (Tornes, 1986). Maximum sediment yields of tributaries in the region range from 20 to 80 metric tons/km^2 per day. Sediment budgets generated by the NRCS (1998b) revealed that mass wasting and channel incision produce more than 90% of this sediment.

1.4. Land use

In the mid 1800s, the Nemadji basin was dominated by vast stands of valuable White Pine (*Pinus strobus*) and Red Pine (*Pinus resinosa*) (Koch et al., 1977). By the late 1800s and early 1900s, forest harvesting across the Nemadji basin was extensive. To facilitate the transport of timber from the basin, the Nemadji River was subjected to channel cleaning, straightening, and splash dam operations (Rector, 1951). Channel cleaning consisted of removing woody debris, snags and obstructions that might hinder log transport through stream channels. Channel straightening was accomplished by cutting new channels across floodplains to circumvent tortuous river meanders likely to cause logjams. Splash dams were constructed using temporary structures to impound large volumes of water and dewatering the channel downstream. Caches of harvested timber were then stored in the dewatered riverbeds. The dams would be exploded with dynamite and the resultant flood surge drove the log caches down river. These practices destabilized the Nemadji River and it's tributaries (Riedel et al., 2001) along with other rivers in the region (Fitzpatrick, 1999). Following the extensive logging, deciduous forests, dominated by quaking aspen (*Populus tremuloides*—the local pioneering species), replaced the pine forests—a change that would be expected to increase water yield.

2. Methods

We chose the North Fork of the Nemadji River and four of its tributaries, Deer Creek, the Blackhoof River, Little Net Creek and Skunk Creek as study sites because they are typical of streams in this region (Fig. 1). The streams drain headwater regions dominated by outwash sands and gravel. The streams then cut through the beach ridges of glacial lakes Nemadji and Duluth. Stream gradients increase at the beach margins as they incise into the Superior Lobe till, known locally as red clay (Queen et al., 1995) and, beneath this, the cohesive, lacustrine clay deposits of the glacial lakes (Riedel, 2000).

2.1. Stream data

During the summer of 1996, we surveyed sets of three cross-sections on each of 21 study reaches across the five study streams (Harrelson et al., 1994). The most downstream study reach in each stream was located just above the confluence with each stream's trunk river; the lowest study reaches on Blackhoof, Deer and Skunk Creeks were located just upstream of their confluence with the North Fork Nemadji River, the lowest reach on Little Net Creek was located upstream of its confluence with the South Fork Nemadji River, and the lowest reach on the North Fork Nemadji River was upstream of its confluence with the South Fork Nemadji River. The most upstream reach on each stream was located in the headwater areas of the study watersheds. We interspersed the remaining study reaches within the rapidly incising valleys on each stream. While the study reaches spanned multiple channel meanders, we installed the cross-sections for each study reach along straight riffles. Bankfull stage along each reach was identified as the elevation of the alluvial floodplain.

We sampled substrate particle size distributions (using the method of Bevenger and King (1995)), surveyed water surface slope, sinuosity, bankfull width, bankfull depth, and flood prone width at each cross-section. We used the average metrics from the three cross-sections in our data analyses.

We used the stream survey data to construct regional bankfull geometry curves of channel width and depth (Fig. 3) and cross-sectional channel area (Fig. 4) for the Nemadji basin. We employed these figures to validate our identification of bankfull stage along the study reaches. For comparative purposes, regional curves for Midwestern streams (adapted from Leopold and Maddock, 1953) are included in these figures.

We measured discharge across a variety of flow conditions on a number of the study reaches, as listed in Table 1, from June, 1996 to September, 1997 to obtain representative stage, discharge and corresponding hydraulic geometry data for each reach. Historic peak flow data for three of the sites were obtained from United States Geological Survey gauging stations. We also installed a Steven's model FW-1 analog stage recorder on study reach, Skunk 3. Site selection and discharge measurements followed standard methods (Buchanan and Somers, 1969). Unfortunately, the range of measured flows was insufficient to develop rating curves that included reliable estimates of bankfull discharge for each study reach. Consequently, we used surveyed flow and slope data on each stream to solve

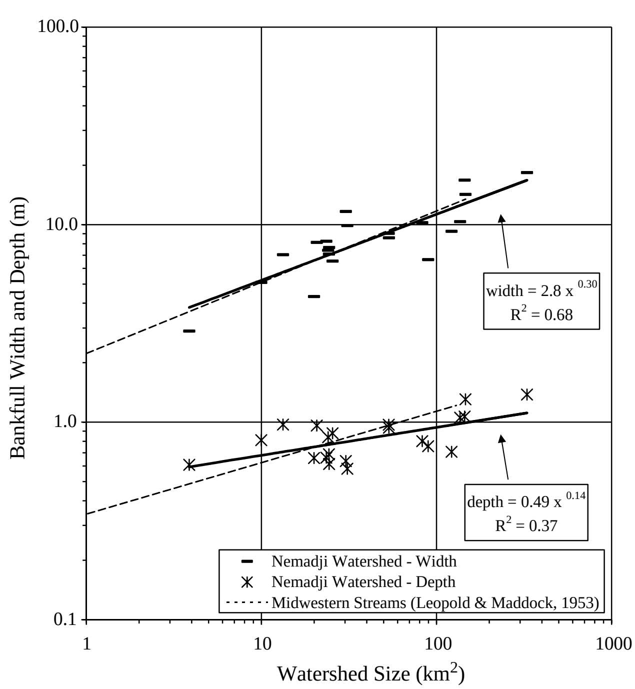

Fig. 3. Regional hydraulic geometry curves of bankfull width and depth for study streams in the Nemadji watershed, Minnesota as compared to regional curves for Midwestern streams derived by Leopold and Maddock (1953).

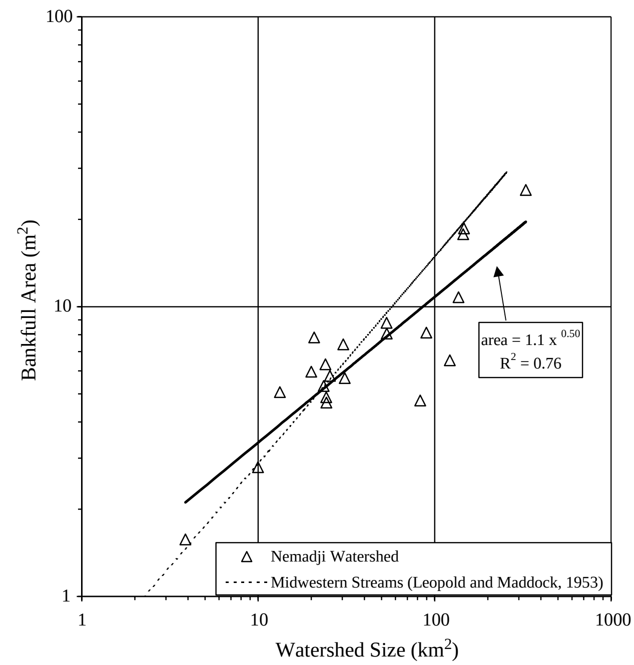

Fig. 4. Regional hydraulic geometry curve of bankfull channel area for study streams in the Nemadji watershed, Minnesota as compared to regional curves for Midwestern streams derived by Leopold and Maddock (1953).

Manning's discharge equation (below) for Manning's roughness coefficient, n across the range of measured flows.

$V = R^{2/3} \times S^{1/2}/n$
V velocity (m/s)
R hydraulic radius (m)
S water surface slope (m/m)
n Manning's roughness coefficient

The calibrated Manning's n values ranged from 0.030 at low flows to 0.028 near bankfull. These are in very good agreement with published Manning's n values for bankfull conditions in similar stream channels (Barnes, 1987). The calibrated Manning's n values and surveyed bankfull channel metrics were then used to estimate bankfull discharge for each site, (Table 1). On sites with no measured discharge data, we estimated roughness coefficients based upon those from upstream or downstream locations having similar hydraulic characteristics including substrate composition and channel morphology.

2.2. Land use

Land cover data for each study reach were obtained from 1:40,000 scale black and white aerial photographs (1992), color infrared aerial photographs (1992), and United States Fish and Wildlife Service, National Wetlands Inventory (NWI) data in digital format. Four land cover types were delineated at a minimum mapping unit of 0.8 hectare. These were coniferous forest (>50% coniferous canopy cover),

Table 1
Land use (ha), bankfull discharge (m^3/s) and mass wasting (m) within each study reach

Study reach	Conifer	Deciduous	Agriculture	Wetland	Watershed area	Discharge method	Bankfull discharge	Mass wasting
Blackhoof 1	909	1771	2897	2712	8290	Temp.	6.41	0
Blackhoof 2	1004	2114	3068	2782	8968	Est.	13.14	0
Blackhoof 3	1368	3314	4057	3443	12,181	Temp.	14.69	61
Blackhoof 4	1694	3925	4507	3522	13,648	Est.	15.76	132
Blackhoof 5	**1,882**	**4,575**	**4603**	**3594**	**14,654**	Est.	**24.47**	**2212**
Deer 1	94	437	264	202	997	Est.	6.09	0
Deer 2	141	565	382	239	1328	Est.	9.99	481
Deer 3	295	843	537	324	1999	USGS	15.27	1152
Deer 4	**319**	**867**	**563**	**325**	**2075**	Est.	**16.30**	**1777**
Little net 1	172	1437	30	766	2405	Temp.	5.65	0
Little net 2	259	1812	84	880	3035	Est.	9.66	341
Little net 3	**281**	**1835**	**98**	**880**	**3093**	Temp.	**10.68**	**388**
Nemadji 1	880	2004	851	1603	5338	Temp.	20.35	632
Nemadji 2	891	2005	851	1604	5352	Est.	20.91	632
Nemadji 3	2025	4825	2743	4908	14,501	Est.	25.11	2173
Nemadji 4	**4574**	**11,072**	**8137**	**9067**	**32,849**	USGS	**42.96**	**5135**
Skunk 1	66	111	123	87	387	Est.	6.36	0
Skunk 2	346	841	677	486	2351	Est.	7.86	330
Skunk 3	356	891	696	487	2430	Analog	8.19	352
Skunk 4	358	895	696	487	2437	Est.	8.19	475
Skunk 5	**377**	**987**	**699**	**487**	**2551**	Est.	**11.36**	**989**

Discharge method column refers to bankfull discharge estimate: Temp, temporary gauging station; USGS, USGS gauging Station; Analog, Stage recorder; and est, Manning's equation. Numbers in bold represent watershed totals at confluences.

deciduous forest (>50% deciduous canopy cover), NWI wetlands, and agricultural (predominately pasture) (Table 1). Verification of the land cover classification was performed with 1:15,840 scale, 1992 series, color infrared aerial photographs and field inspection. Land cover data were then digitized into a geographic information system (GIS) for management and spatial analysis purposes.

Due to the deep incision of streams in the Nemadji watershed, there is a strong dependence of land use on terrain. Agricultural and residential land use is confined to the relatively flat uplands, leaving the valleys predominantly forested. Consequently, as valleys get larger with increasing watershed size, forest cover also tends to increase while agricultural land and wetlands decrease (Fig. 5). Conversely, when all of the sites are grouped together, forest cover tends to decrease with watershed size while wetlands increase and agriculture land use shows no trend. Bankfull discharge and mass wasting also increase with watershed size (Figs. 6 and 7).

To account for the spatial distribution of the land cover types across the watersheds, we computed the ratio of land use types within a study stream subwatershed to that within the entire study stream watershed (e.g. hectares of coniferous forest in third subwatershed of Skunk Creek to hectares of coniferous forest in the entire Skunk Creek watershed). This metric provides a measure of the spatial distribution, or geographic concentration, of land uses within each study reach subwatershed and across the five study watersheds.

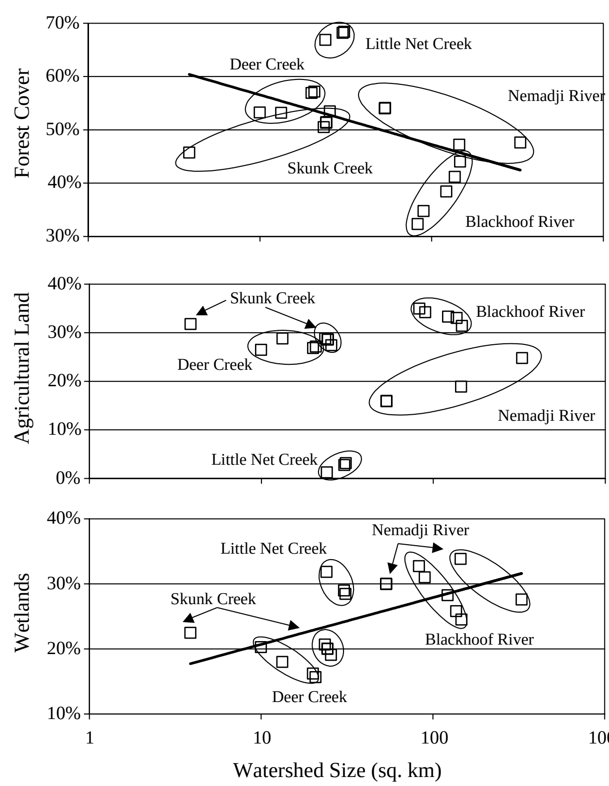

Fig. 5. Land use trends with watershed size for the study watersheds. Ovals delineate data trends for each subwatershed while solid line indicates trend for all sites ($p<0.01$).

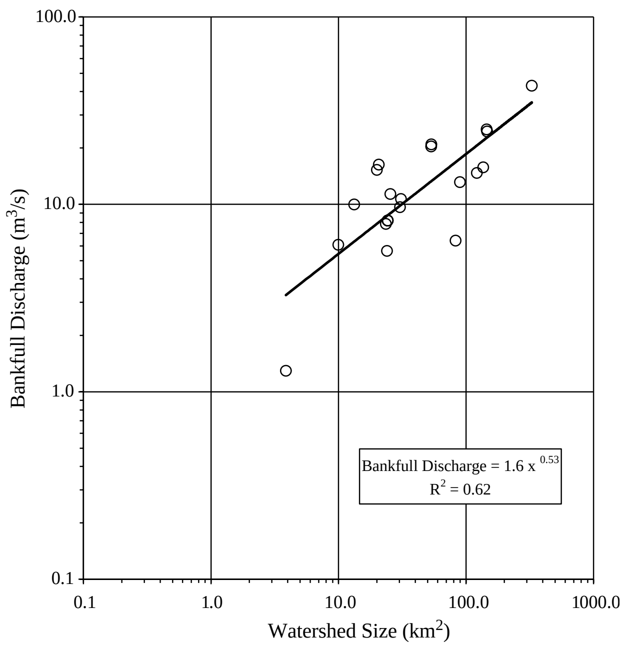

Fig. 6. Increasing magnitude of bankfull discharge with watershed size. Bankfull discharge was determined from hydraulic analyses of study streams.

2.3. Mass wasting

Given the vast size, remote nature and general inaccessibility of the Nemadji watershed, it was not feasible to conduct an exhaustive field inventory of all mass wasting sites in the study watersheds. Consequently, we used aerial photographs with field validation to inventory mass wasting sites. We could not locate smaller mass wasting sites from 1:40,000 scale black and white aerial photographs (leaf-off). However, these were readily identified using 1:15,840, color infrared (leaf-on) and 1:10,000 black and white aerial photographs (1992—leaf-off). Our minimum mapping unit was determined to be 1 mm on the 1:15,840 photos, a ground scale of 16 m. We could not reliably identify the locations of mass wasting sites that were older than approximately 10 years in age because the exposed soil scars had become overgrown by tree saplings. The dimensions of each mass-wasting site could not be accurately delineated because of the encroachment of tree canopies along their boundaries. However, the length of the interface between each mass wasting site and the adjacent stream channel could be accurately measured. Thus, for each study watershed, the cumulative length of stream channel that was being impacted by mass wasting was measured as a surrogate for mass wasting (Table 1).

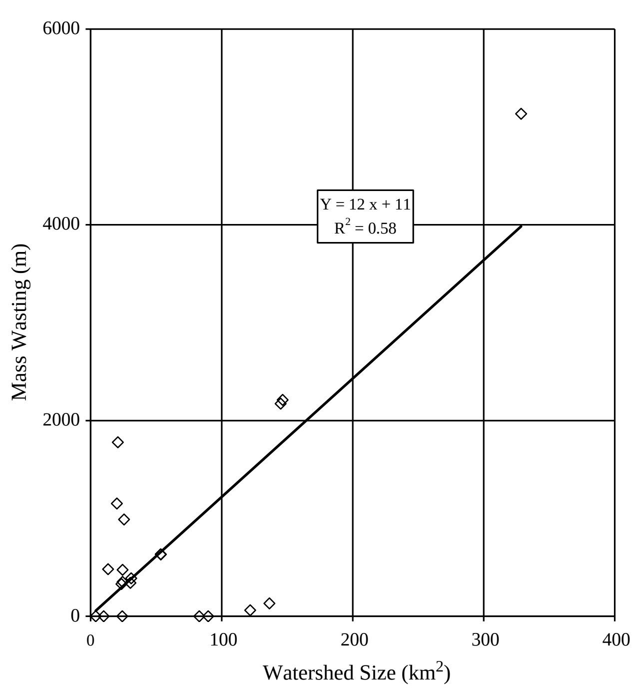

Fig. 7. Positive trend between mass wasting and watershed size.

3. Results

Seventeen of the 21 study sites are nested in an upstream/downstream manner within the five study watersheds (Table 1). Consequently, there may be some interdependency of data amongst sites within each subwatershed. We have used two approaches to address this issue. In the first we only include the five most downstream sites from each of the five study watersheds. In the second, we include all 21 sites but identify each site by subwatershed, thus illustrating trends within each sub-watershed (sub-population) as well as across all of the sites (population).

3.1. Bankfull discharge

The percentage of total wetlands in each of the large, five study watersheds was the only land use that significantly explained observed variability in bankfull discharge per unit area, Fig. 8 ($p=0.075$, 3 d*f*). Bankfull discharge ($m^3/s/km^2$) was proportionately lower in watersheds with more wetlands; decreasing four fold per percent increase in wetland area (slope of the regression line$=-4$). The relatively frequency of mass wasting at these five sites is indicated by the numerical labels.

When looking at all of the sites, wetlands and deciduous forest were significant ($r^2=0.91$, $p<0.01$, $df=17$) in explaining the variability observed in bankfull discharge.

$Q = 32.5\ D - 36.9\ H$

Q Bankfull discharge/watershed area ($m^3/s/km^2$)
D Spatial distribution of deciduous forest (percent)
H Spatial distribution of wetlands (percent)

Bankfull discharge tends to be lower in a given watershed that has more wetlands in its headwaters.

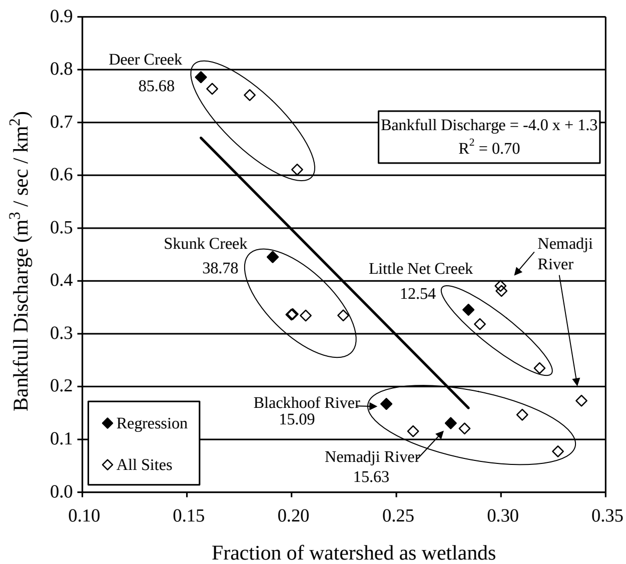

Fig. 8. Bankfull discharge regressed on wetlands for each study stream watershed. Slump occurrence for each site (meters of stream channel affected by slumps/watershed area) is indicated by the numerical value adjacent to each point.

Conversely, bankfull discharge tends to be higher when the headwaters region of a watershed has more deciduous forest cover.

3.2. Mass wasting

The length of stream channels in each basin that was impacted by mass wasting increased with bankfull discharge (Fig. 9, $r^2 = 0.79$). To remove the scale interactions previously identified, we divided the mass wasting data and bankfull discharge by watershed area. Mass wasting (m/km^2) is non-linearly related to bankfull discharge, q (m^3 s^{-1} km^{-2}) (Fig. 10). Stream reaches that exhibited no mass wasting were located in the relatively flat terrain of the headwater areas of the Nemadji watershed, and were excluded from this analysis. Bankfull discharge

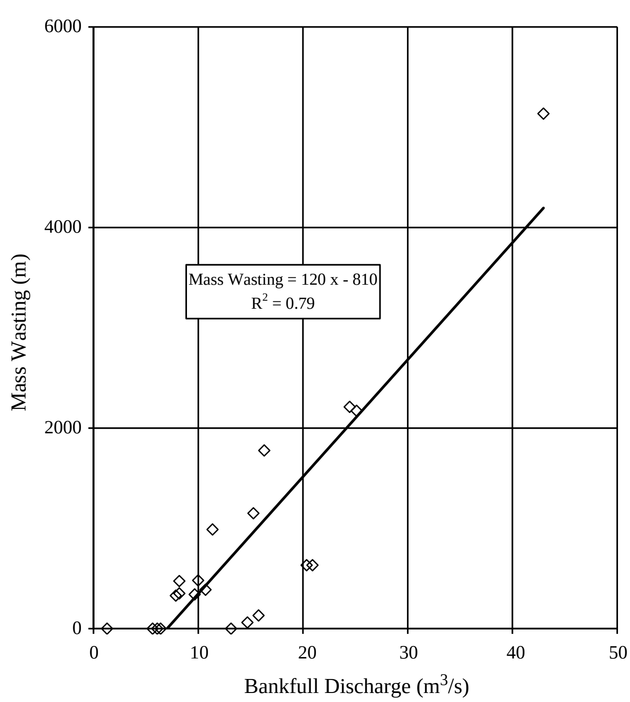

Fig. 9. Positive trend between mass wasting and bankfull discharge.

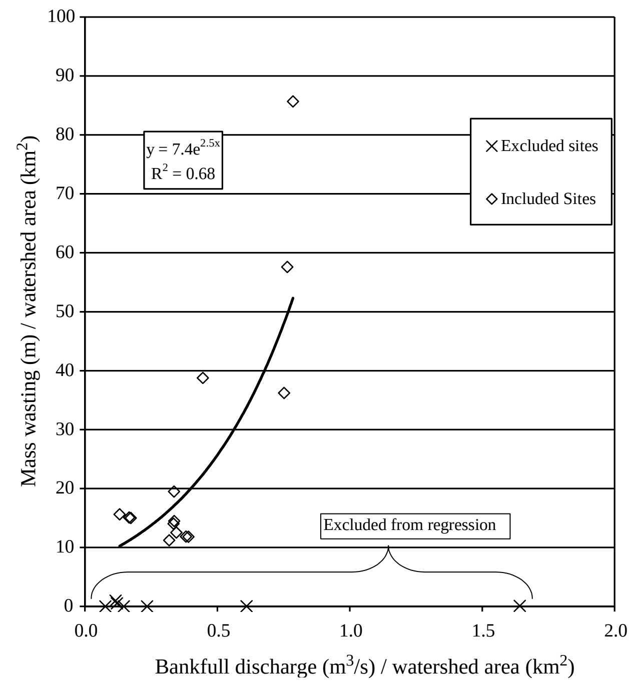

Fig. 10. Regression of mass wasting on bankfull discharge per unit area. Mass wasting and bankfull discharge are divided by watershed size to remove scale dependencies (Figs. 6–8). Sites without mass wasting have been excluded from the regression analyses.

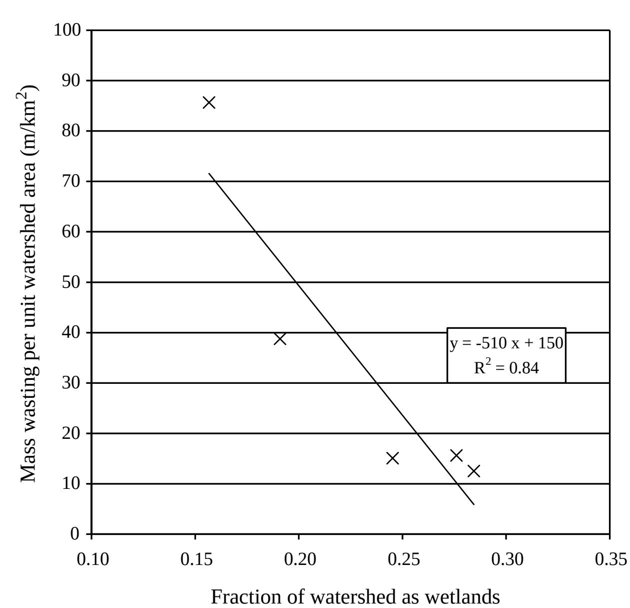

Fig. 11. Mass wasting regressed on wetlands for each study stream.

explained 68% of the variability observed in the occurrence of mass wasting along stream channels.

3.3. Land use and mass wasting

The relatively frequency and extent of mass wasting at these five sites was inversely related to wetlands (Fig. 11). The fraction of watershed land cover as wetlands explains 84% of the variability observed in mass wasting.

4. Discussion and conclusions

Bankfull discharge and mass wasting are empirically dependent upon land use in the naturally unstable Nemadji River watershed. Our results indicate the occurrence of mass wasting increases exponentially with bankfull discharge (bankfull discharge/watershed area). Further, bankfull discharge is greater where forest cover has changed from coniferous to deciduous forest and in watersheds with smaller amounts of wetland area. Finally, the occurrence of mass wasting was negatively correlated with wetland area in a watershed.

These results suggest that when land use change increases bankfull discharge, the subsequent increases in mass wasting are exponentially greater. If land use reaches a critical, or threshold, level, a disproportionate response would be observed in the occurrence of mass wasting. From Fig. 10, mass wasting begins to increase disproportionately with bankfull discharge as it approaches 0.4 $m^3\ s^{-1}\ km^{-2}$. Verry et al. (1983) found a similar threshold response in snowmelt runoff peaks following Aspen harvesting in northern Minnesota. Peak streamflow response to a harvest of one-half of the watershed area slightly decreased the snowmelt peaks because snowmelt in the harvested and forested areas was desynchronized whereas a harvest of 2/3 of the total watershed area doubled the snowmelt hydrograph. Jacobsen (1995) also reported a threshold response for fluvial processes in gravel bed streams of the Ozarks. Spatial variability of land use conversion resulted in complex channel responses including channel degradation and the propagation of sediment pulses along channel bottoms. Jacobsen concluded that a relative decrease in sediment inputs from land use contributions increased the export of sediments that had been stored within the channel system.

Our results indicate broad scale land use changes may have significantly altered stream flow and mass wasting in the Nemadji River watershed. As this is consistent with a wealth of research reporting the importance of the bankfull discharge for channel maintenance and sediment transport (Andrews and Nankervis, 1995; Leopold et al., 1992; Wolman and Miller, 1960), we feel that this result reveals a direct process driven linkage between land use and mass wasting.

We have attempted to account for the geographic distribution of land use in our analyses. Our results indicate mass wasting is significantly lower in watersheds having greater concentrations of wetlands in their headwaters. This is reasonable because, in comparison with other land use types, wetlands exhibit low volumes of annual water yield because of their high rates of evapotranspiration (Verry, 1988; Verma et al., 1993; Van Seters and Price, 2001) and they attenuate peak flow discharges associated with bankfull flows (Hey and Philippi, 1995; Miller, 1999). However, the wetlands naturally occur in the flat terrain of the headwaters within each watershed. So while our results suggest that wetlands may be limiting mass wasting, it might be that wetlands are acting as a surrogate for the geologic driving variable of slope. In contrast, conversion of forest to pasture would be expected to increase flow rates and thereby exacerbate mass wasting. With pasture and other agricultural land use occurring primarily in the flat uplands, it is conceivable that the lower slopes here counteract expected increases in runoff velocity, and hence bankfull discharge and mass wasting. This would explain why bankfull discharge and mass wasting were not correlated with agricultural land use. Despite refining our efforts to account for the spatial distributions of land use, we have not been able to clearly differentiate between the effects of the primary driving variable, terrain (slope) and those of a secondary driving variable, land use, on bankfull discharge and mass wasting. When coupled with the reported increase in sediment deposition near the outlet of the Nemadji River in Lake Superior over the past 150 years, however, our study suggests that land use patterns influence bankfull flows and mass wasting.

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