UNDERSTANDING DRIVERS OF SEDIMENT LOADS IN A MORPHOLOGICALLY ACTIVE WATERSHED: A MULTIDISCIPLINARY APPROACH TO WATERSHED MANAGEMENT

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Abstract: The Knife River is a tributary to Lake Superior in northern Minnesota draining 56,000 acres of mostly forested and wetland areas with minimal development. The river is home to the North Shore's only wild Steelhead population and is the only tributary with no barriers to upstream migration. Although development is minimal, the morphologically active and flashy nature of the watershed results in large sediment loads which impact the harbor downstream, aquatic invertebrate habitat, the trout fishery, and contribute large quantities of sediment to Lake Superior. Because of the morphologically active nature of the watershed, the river is sensitive to engineering modifications and large structural solutions may be ineffective. This places an emphasis for watershed management on understanding the sensitive hydrologic nature of the system and careful land use decisions. Our study took a multi-disciplinary approach focused on gaining an understanding of the watershed system by looking at causes, linkages, and relative contributions of different channel modifications and landuse changes within the watershed on sediment and hydrologic dynamics. We used a combination of desktop analyses, geomorphic assessments, modeling (river hydraulics, watershed modeling, and snowpack ripening), regional analyses, and sensitivity scenarios to understand relative importance of different drivers of the hydrologic system. As part of a sensitivity assessment, we examined the impacts of different forestry practices, beaver dam management, and conversion of wetlands. Our study identified areas within the watershed that that may be sensitive to land use conversion or logging. In addition, we provided a summary of how beaver dam activity and management might impact hydrology and aquatic habitats, how changes in landuse might change snowmelt characteristics, and how changes in climate patterns (snowpack dynamics and rainfall intensity) might change sediment loading patterns. With this multi-disciplinary approach, we were able to provide an overview framework for proactive watershed management in a complex and morphologically active system by understanding relative importance of many facets of the watershed hydrology.

INTRODUCTION

Watershed management for reduction of sediment loads often focuses on sediment loading from soil erosion; however, in watersheds with numerous natural and anthropogenic forces driving sediment loads, this approach may be inadequate. In systems that are geologically young and morphologically active, rivers are especially sensitive to engineering modifications and hard engineering solutions may fail. This places an emphasis for watershed management on a big-picture understanding of the sensitivity of morphologic drivers and relative contribution to

sediment load and erosion in order to make effective management and engineering decisions at the watershed scale.

The Knife River (Figure 1), a tributary to Lake Superior in northern Minnesota, is a prime example of a watershed with a very large sediment load causing impairments to aquatic life, yet land use change and development are minimal within the watershed. The watershed drains 56,000 acres of mostly forested and wetland areas (Figure 2). The river is home to the North Shore's only wild Steelhead (*Oncorhynchus mykiss*) population, and it is the only tributary with no barriers to upstream migration. Post-glacial rebound results in morphologically-active valleys in this region, and the naturally flashy nature of the watersheds creates large sediment loads which impact harbors and estuaries downstream, degrade aquatic invertebrate habitat and the trout fishery, and which contribute large quantities of sediment to Lake Superior (Riedel, et al, 2005).

Figure 1 Knife River under high flow conditions carrying large sediment load

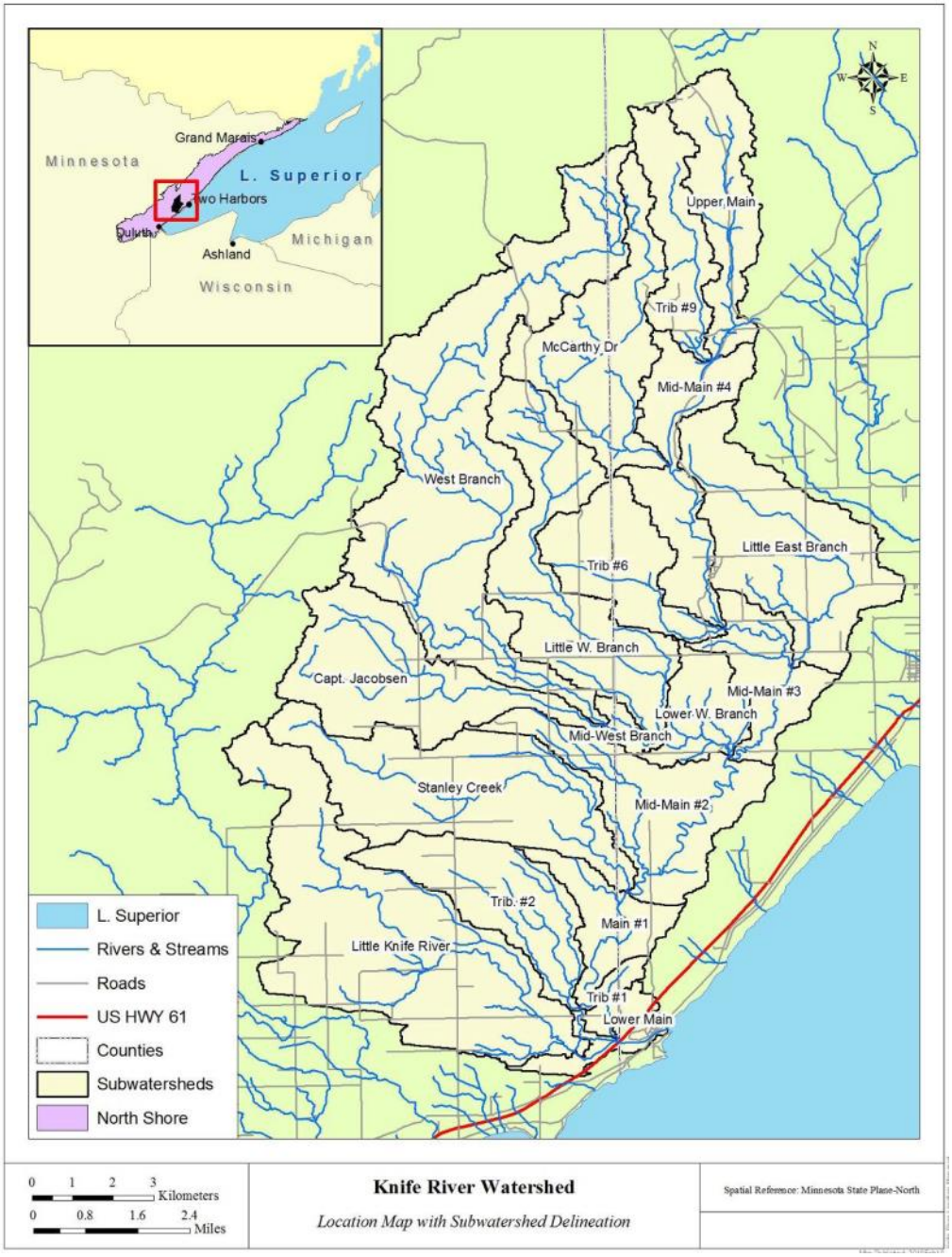

Figure 2 Knife River watershed location

While lacustrine clay and clay-dominated tills in the area under natural land cover are generally resistant to erosion (NRCS, 1998), activities within the watershed that expose soils or disturb banks can increase runoff resulting in fluvial erosion and destabilized channels (Riedel et al., 2005; Riedel et al., 2002). Our study took a multi-disciplinary approach focused on gaining an understanding of the Knife River watershed system by examining causes, linkages, and relative contributions of different channel modifications and land use changes within the watershed to hydrology and sediment loads. The knowledge gained from this multi-disciplinary approach can be used to support effective decision-making for watershed managers.

METHODOLOGY

We used a combination of desktop analyses, modeling, and sensitivity scenarios to determine the relative importance of different drivers of hydrology and sediment loading in the Knife River watershed. Four major factors driving sediment load in the watershed were examined by this study:

- Watershed physiography (climate, geology, soils, terrain, river network characteristics)
- Beaver *(Castor canadensis*) activity
- Watershed land use and disturbance
- Sediment loading relationship to hydrology

Literature and Data Review: The first step in the approach was to review available studies and data. This review included existing reports and studies as well as interviews with local and state resource managers. Data gathered for the study area included historic flow and sediment data as well as geospatial data to support desktop analyses and modeling (MPCA, 2009). Spatial data to support the study included elevation, landcover, soil, geology, canopy, and detailed wetland coverage. In addition, a comprehensive review of literature on beaver activity was conducted to understand how land use changes have resulted in dramatic changes in beaver habitat and resultant populations, density, and behavior (USDA, 2002).

Desktop analyses: The datasets collected during the literature and data review were used to complete desktop analyses to give further insight into the hydrology and morphology of the watershed. Elevation datasets were used to calculate fluvial power and pinpoint areas that may be susceptible to higher levels of erosion and mass wasting. These datasets were also used to develop longitudinal profiles of all streams within the watershed to identify potential areas of head-cut migration or river valley evolution associated with natural or anthropogenic causes.

Historic flow and sediment records from the USGS gage near the mouth of the river were reviewed to examine flow frequency, flashiness, seasonality, and historical changes in flow. Understanding the magnitude and frequency of both flood and low-flow events in the watershed from a historic perspective and existing conditions is key to understanding sediment loading patterns and the relative impact of land use changes on hydrology.

Modeling: A suite of hydrologic, hydraulic, and snowpack models were developed to understand existing conditions in the watershed and to support scenario analyses for different land management decisions. The modeling builds upon the analyses done in the literature and data review both for providing input data and context for what scenarios to assess for sensitivity analysis and management scenarios.

Beaver activity in the watershed has increased dramatically since pre-settlement conditions due to reductions in trapping (Butler and Malanson, 2005). Dam-building activity creates a step-pool structure in tributaries which disconnects riverine habitat for fish and changes thermal regime (Pollock et al., 2003), and may cause floods from cascading failures (Butler and Malanson, 2005). A 1-D HEC-RAS model of a representative reach in the watershed was developed to simulate the impacts of a variety of beaver-dam densities on the river. Pre-settlement dam density in this area was 3.0 dams/mile (Winchell and Upham, 1884), while current conditions are

much higher at 10.6 dams/mile (Verry, 2005). Results showed step-pool structures caused by high-density beaver activity with cascading dam failures under flood conditions (Figure 3).

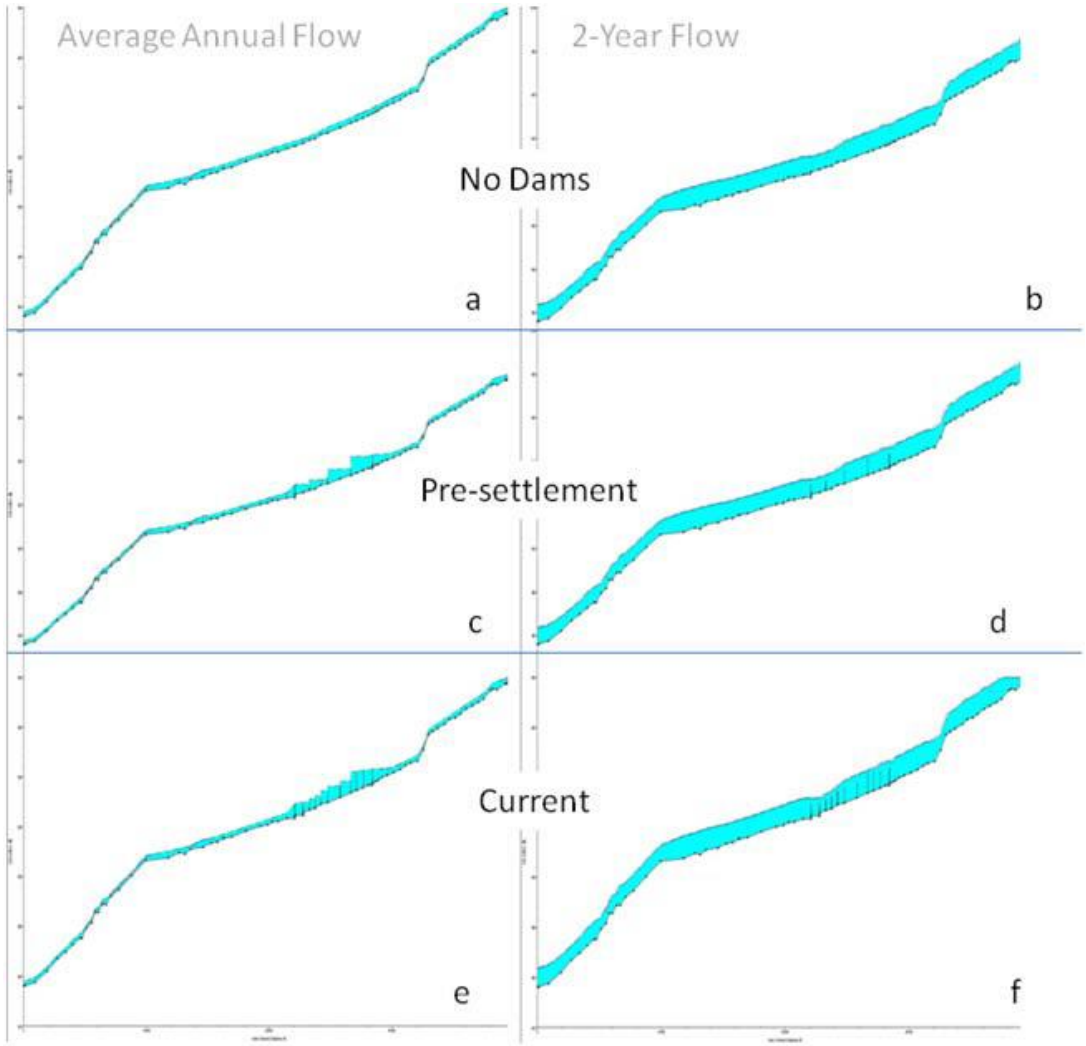

Figure 3 Beaver dam hydraulic modeling results. Beaver dams were represented under each scenario for typical spacing and density as reported in literature.

A watershed hydrology model was developed using HSPF (Hydrological Simulation Program – Fortran) to model existing conditions and simulate the hydrologic impact of potential land use changes. Several scenarios were simulated including pre-settlement conditions, various timber harvesting practices, forest restoration, and wetlands conversion. Results showed the watershed hydrology was most sensitive to conversion of wetlands relative to other land management scenarios. Wetlands play a key role in hydrologic response in the watershed, especially given the naturally low infiltration capacity of the clay soils in the watershed. Results of the existing conditions hydrology mode,l as well as the scenario applications, supported identification of areas susceptible to erosion under existing conditions as well as subwatersheds that may be sensitive to various land use changes in the future. An example of the sensitivity ranking results is shown in Figure 4.

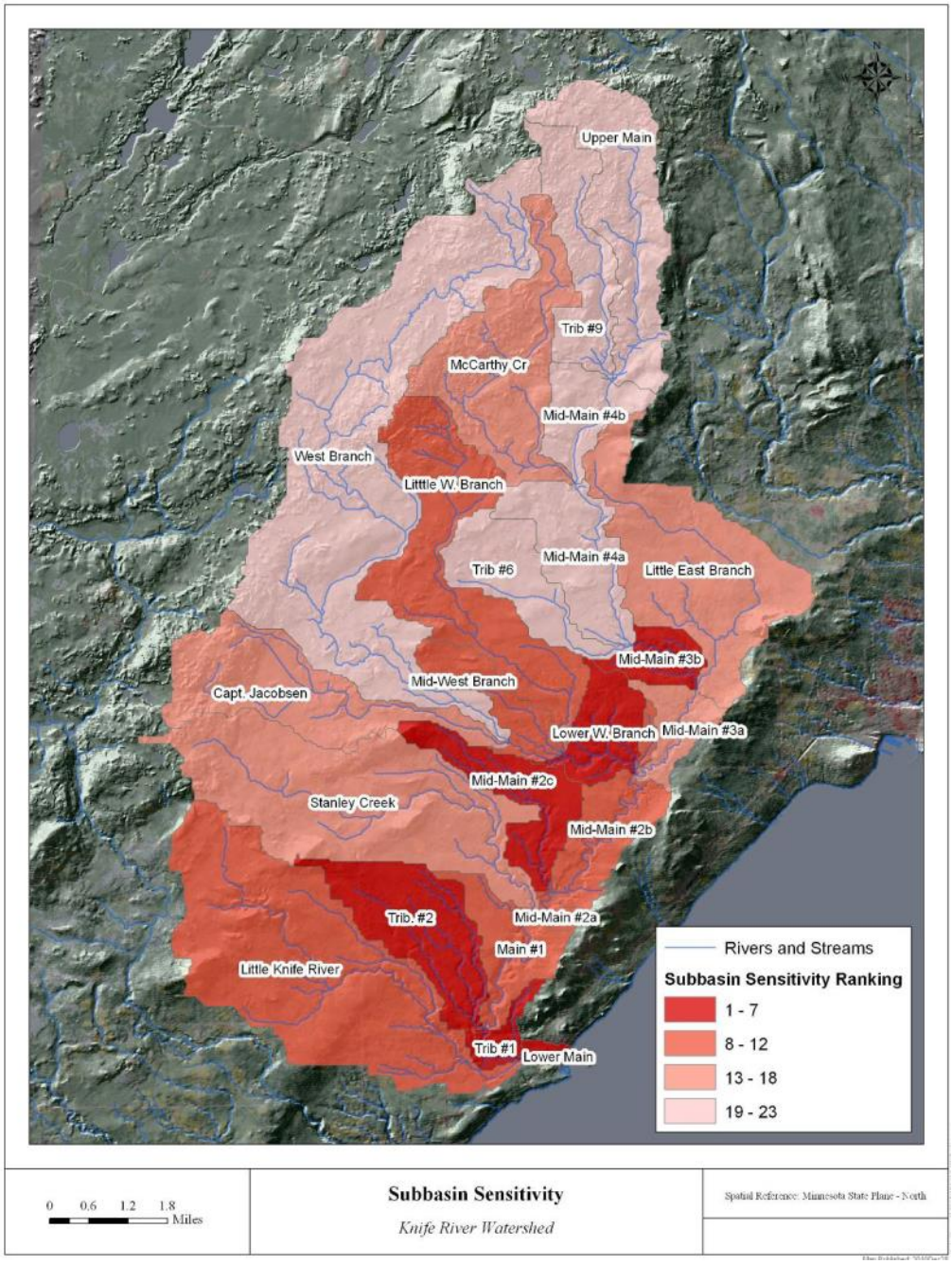

Figure 4 Example subbasin sensitive ranking

The snowmelt period plays a very important role in the hydrology of the watershed as 50 % of the runoff near the mouth occurs from mid-March through the end of May. Logging in the Midwest has been shown to have a potentially large impact on water yield and peak runoff during spring melt (Verry et al., 1983; Verry, 1986). Because of the relative importance of the melt runoff, a mechanistic snowpack model was developed to simulate the potential impacts of various land management practices on snowpack development and the corresponding melt. The HSPF model was also examined in detail during this period under several scenarios to compare results to the snowpack model.

Sediment budget analysis: Finally, a sediment budget analysis was conducted to develop a range of estimates for sediment yield for the watershed (Riedel et al., 2008). This included a variety of regional studies as well as detailed review of sediment data collected at the USGS gage. Estimates of sediment loads using a simple relationship between discharge and suspended sediment concentration fell within the expected range for yields for this region (Figure 5). The analyses indicated a strong positive relationship between discharge and sediment concentration. This observation is key in interpreting hydrologic and hydraulic analyses in relation to sediment load in the basin. Despite being predominantly forested and having extensive wetlands in its headwaters, the Knife River exhibited sediment yield results similar to watersheds with extensive agricultural land use conversion. This is because the geologic setting in this region is much more vulnerable to land disturbance and changes in climate compared to more geologically mature and evolved watersheds (Riedel et al., 2002).

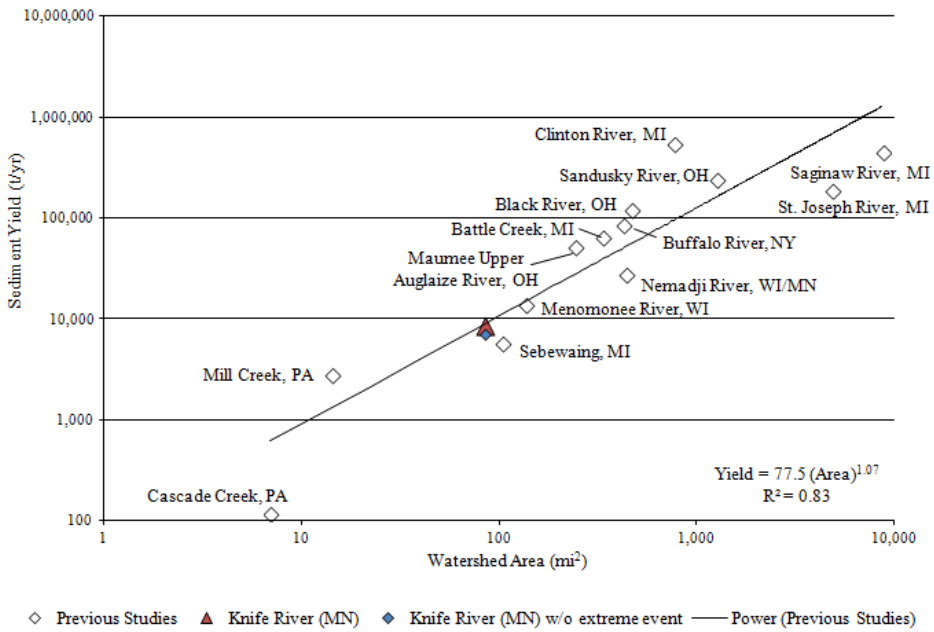

Figure 5 Regional sediment yields based on watershed area from other Great Lakes studies

Review of literature indicated that bank erosion and valley wall failure play a significant role in sediment loading in the watershed (Nieber et al., 2008). Using sediment data collected by the USGS in conjunction with local metrological data, multiple linear regression analysis was used to identify potential key weather drivers for large sediment loads. Results indicated that an interaction between rainfall intensity and cumulative rainfall (resulting in saturated soils) plays a significant role in watershed loading as well. Changes in rainfall patterns for the region may result in changes in sediment loads based on this analysis.

CONCLUSIONS

In a watershed where anthropogenic forces may not be the principal driver of sediment loads, understanding the existing conditions and sensitivity of the basin to different management practices is critical for watershed managers. Because of the morphologically active nature of the watershed and the river valleys due to post-glacial rebound, the sediment load is more sensitive

to changes in land use and changes in climate patterns than more mature watersheds. By taking a multi-disciplinary approach in the Knife River watershed, we were able to identify potentially sensitive regions within the watershed, assess the potential impact of various land management practices, provide a summary of the general impact of beaver dam activity and management, and examine how potential changes in climate patterns (snowpack and rainfall) might change sediment loading patterns. With this approach, we provide a framework for proactive watershed management in a complex and morphologically active system by understanding relative importance of many facets of the watershed hydrology.

ACKNOWLEDGEMENTS

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REFERENCES

Butler, D.R., and Malanson, G.P. (2005). "The Geomorphic Influences of Beaver Dams and Failures of Beaver Dams." Geomorphology, 71(1-2), 48-60.

MPCA, Minnesota Pollution Control Agency, (2009). “Total Maximum Daily Load Study of the Turbidity on the Knife River Watershed.”

Nieber, J.L., Wilson, B.N., Ulrich, J.S., Hansen, B.J., and Canelon, D.J. (2008). “Assessment of Streambank and Bluff Erosion in the Knife River Watershed.” Report to the Minnesota Pollution Control Agency.

NRCS. (1998). Nemadji River Basin Project Report. USDA Natural Resources Conservation Service, St. Paul, MN.

Pollock, M.M., Heim, M., and Werner, D. (2003). "Hydrologic and Geomorphic Effects of Beaver Dams and Their Influence on Fishes." American Fisheries Society Symposium 37.

Riedel, M.S., Brooks, K.N., and Verry, E.S. (2005). “Impacts of Land Use Conversion on Bankfull Discharge and Mass Wasting”. Journal of Environmental Management, 76(2005)326–337.

Riedel, M.S., Verry, ES and Brooks, K.N. (2002). “Land use Impacts on Fluvial Processes in the Nemadji Watershed.” Hydrological Science and Technology, 18 (1-4): 197-205.

Riedel, M.S., Dahl, T.A., and Selegean, J.P. (2008). “Sediment Budget Development for the Great Lakes Region.” Great Lakes Tributary Monitoring Program 516(e). July 2008.

USDA. (2002). ″Reducing Beaver Damage Through and Integrated Wildlife Damage Management Program in the State of Minnesota.″ Final Environmental Assessment. U.S. Dept. of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, January. 59.

Verry, E.S. (1986). “Forest Harvesting and Water: The Lakes States Experience.” Water Resources Bulletin, 22(6), 1039-1047.

Verry, E. S. (2005). The Dark River opportunities for restoration. Ellen River Partners. Grand Rapids, MN. 49p.

Verry, E.S., Lewis, J.R., and Brooks, K.N. (1983). "Aspen Clearcutting increases snowmelt and storm flow peaks in north central Minnesota." Journal of the American Water Resources Association, 19(1), 59-67.

Winchell, N. H. and W. Upham. (1884). The geological and natural history survey of Minnesota 1872-1882. Vol. I of the final report. p5.