ASSESSING AGROFORESTRY OPTIONS FOR WATER QUALITY USING REGIONAL HYDRAULIC GEOMETRY CURVES

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ABSTRACT

Agroforestry practices can buffer peak streamflows and attenuate nonpoint source pollutants. However, given climatic, geologic, and landscape complexity it can be challenging to determine where and how agroforestry practices are applied within a watershed to enhance water quality. Excessive stream sediment, and associated turbidity and phosphorus, may be locally derived or transported long distances downstream because of systemic watershed and stream channel degradation. This paper presents the use of regional hydraulic geometry curves as an assessment tool for evaluating sediment contributions from channel erosion caused by increased peak streamflows resulting from land-use changes in the watershed. To illustrate the use of geomorphic tools in evaluating agroforestry options, five different hydrogeomorphic settings across Minnesota were selected for the development of regional hydraulic geometry curves. The statistical results show differences in curve slope, intercept, and $R^2$, depending on the location, geology, climate, and method used to identify the channel forming or bankfull stage. When the influence of geology was clearly defined, better fitting curves were possible by stratifying the data. If channel incision is not clearly defined with respect to channel evolution processes, stream water quality impairment will occur over time. Incised channels present challenges to properly identifying the bankfull stage, however this obstacle can be overcome by the gage station technique presented in this paper. In watersheds undergoing land-use change, agroforestry practices provide opportunities to improve water quality in both upland and riparian settings. Nevertheless, agroforestry cannot solve all hydrologically driven water quality problems, especially where natural phenomenon drive the impairment of water quality.

Keywords: Stream channel, Agroforestry, Incised channel, Hydraulic geometry curves, Water quality.

INTRODUCTION

Agroforestry practices offer land-use alternatives in riparian areas that enhance stream channel stability and improve water quality. Riparian zones provide a buffer between the terrestrial and aquatic systems and have been a focal point of water quality for several decades (Osborne and Kovacic 1993; Schultz et al. 2004). The US federal government has developed a Conservation Buffer Initiative, a public-private program with the aim of establishing 3.2 million km of conservation buffers (USDA-NRCS 2003). This effort is driven by the fact that upland best management practices (BMP) alone are insufficient in preventing impaired water quality. Over the last two decades we have learned much about the effectiveness of riparian woody buffers ability to sequester carbon (Tufekcioglu et al. 2003), nutrients (Rotkin-Ellman et al. 2004), organics contaminants (Rockwood et al. 2004), and mediate peak streamflows (Menzel 1983) in
a variety of landscapes, yet there are still knowledge gaps (Lowrance et al., 2002). One of the gaps is our lack of understanding channel evolution with respect to cumulative effects of land use and climate change (Magner and Steffen 2000). Another is where and how agroforestry practices should be applied in a watershed to prevent impairment of water quality. The combination of climate, geology, terrain, and land use produce unique hydrogeomorphic settings that require water quality planning beyond standard buffer designs. For example, in Minnesota some riparian areas contain high quality wetlands that have codified intrinsic value (Minnesota Rule Chapter 7050) apart from an adjacent stream or river. If high value riparian wetlands (e.g., calcareous fens) exist, but are not identified within the riparian corridor by a watershed assessment, then potential impairment (i.e., loss of wetland function or value) could occur over time from changes in land use. Development in areas adjacent to the riparian zone can result in direct overland runoff, sediment and chemical discharge into the wetlands. Changes in the watershed that affect the magnitude of discharge to a riparian wetland can cause systemic channel disequilibrium. Loss of riparian function may not become apparent until a significant amount of land use change has occurred over time (Wang et al. 1997).

Agricultural drainage in south-central Minnesota has resulted in hydrologic instability, streambank erosion and impaired water quality (Magner et al. 2004). In southern Minnesota more than 80% of the prairie pothole and riparian wetlands were drained during the first 80 years of the 20th century (Leach and Magner 1992). Restoring drained riparian wetlands is difficult because typically the water table has been lowered to accommodate crop growth (Menzel 1983). Yet, a lower water table means the channel bed elevation must be lower to provide for gravity flow of lateral drainage systems. A constructed deeper channel, such as a ditch, can create bank instability depending on the bank angle and soil cohesion (Christner, Jr. et al. 2004).

Higher annual water yields have resulted from agricultural drainage and the conversion of perennial vegetation to corn and soybean crops in southern Minnesota (Miller 1999). A 10 to 18% increase in land cultivated for soybeans, with slight increases in corn production is important because 71% of the total runoff from southern Minnesota cropland occurs in the months of April, May, and June (Randall et al. 2003) when annual croplands are bare. Perennial crops, on the other hand, exhibit lower runoff than annual crops (Randall et al. 1997). The cumulative effect of cropland drainage and the loss of perennials have altered the hydrologic functions of watersheds and pathways of water flow. Subsurface tile-drains and ditches redirect water from the old pathways of depressional storage, evaporation, and transpiration from perennial vegetation to channel flow. Although a row crop, such as corn will transpire large amounts of water in July and August, the corn plant has little effect on soil moisture in April, May, and June. Typically, April, May, and June are months with above-average antecedent moisture along with high rainfall; consequently, the rainfall drives high nitrate-nitrogen soil water in to drainage systems (Magner and Alexander 2001).

The loss of perennial vegetation in southern Minnesota did not happen over years but decades during the 20th century. Recently we have begun to fully appreciate the cumulative effects of those land use changes (Goolsby et al. 1999; Magner et al. 2004) upon the water resources of the Mississippi River and the Gulf of Mexico. One of the reasons water quality degraded in the upper Mississippi River basin, was our collective lack of understanding of important water quality thresholds associated with land use change; for example geomorphic signs were present,
yet we failed to read and understand their water quality meaning. Today, we are trying to apply agroforestry practices to intensively managed landscapes to understand how much buffer capacity is needed to meet water quality standards (Brooks et al. 2002). Yet, in some respects, we may be too late; once channel incision occurs, typically more streambank erosion will be required before a stream becomes stable again (Schumm et al. 1984). At the beginning of the 21st century, streams and rivers throughout southern Minnesota show evidence of channel incision (Magner and Steffen 2000) along with impaired water quality.

In addition to altered agricultural areas, urbanizing areas will typically increase the percentage of imperviousness, which will produce increases in the peak streamflows of frequent storms (Schueler and Holland 2000) and erode downstream beds and banks. Clearly, both agricultural and urban land use change are reflected in downstream water quality impairment. Land-use managers need a tool for assessing land use change with respect to potential water quality impairment. This paper highlights the value of developing regional hydraulic geometry curves at gaged sites and discusses agroforestry options across several hydrogeomorphic settings in Minnesota with the intent of illustrating where and how agroforestry practices can best influence hydrology, and protect water quality. However, before jumping into methods and results, we need to provide a working understanding of fluvial processes to appreciate the usefulness of regional hydraulic geometry curves.

THEORETICAL RATIONALE

Hydraulic geometry relationships (Singh et al. 2003) suggest that spatial variation in stream power is accomplished by an equal spatial adjustment between flow depth and width. As flow depth increases within limits, channel width must also increase assuming friction or roughness is fixed, to allow equilibrium conditions to occur in the channel. This theory is based on the concept of dynamic or quasi-dynamic equilibrium under steady state conditions which tends to maximize entropy (Jaynes 1957). Maximum entropy of a system occurs when the change in stream power is distributed among the changes in flow depth, channel width, flow velocity, slope, and friction factors or resistant materials, as determined from particle size (Langbein 1964; Yang et al. 1981). To simplify, these processes can be explained by the principle of tractive force theory expressed in Lane’s (1955) continuity equation, where sediment size and sediment load are proportionally balanced by stream discharge and channel slope. Yet, given the theory behind hydraulic geometry, the reality of hydraulic geometry for any given channel changes over time, typically because of land use changes described in the introduction.

Principles of channel evolution models (CEM) developed by Schumm et al. (1984), and Simon (1989) can be used to estimate the likely direction of channel adjustment. The CEM illustrates fluvial process which proceeds toward incision and enlargement requiring future adjustment, downcutting and/or widening. However, the CEM approach is mostly theoretical and requires some quantifiable measurements to properly define field observations with respect to CEM stage of evolution. Figure 1 illustrates similar channel form, yet one channel is incised and the other is not; knowing the difference is important from a management prospective. Rosgen’s (1994) stream classification system uses the channel forming flow or 1 to 2-year recurrence interval (RI), average = 1.5-yr RI flow as the primary point of reference. Recent analysis by Simon et al.
Figure 1. Cross-sectional schematics representing different drainage areas; the upper illustrates an incised channel that contains flows above the 1.5-yr RI, the lower is a channel form that allows out-of-bank flow above the 1.5-yr RI.

(2004) confirmed that the 1.5-yr RI is the correct streamflow associated with channel formation. To accurately identify where the 1.5-yr RI stage is located for a given stream, field observations must be made at stream gage stations (usually US Geological Survey [USGS] gage stations) for a given climatic and landscape regime. Geomorphic data from gage station sites are then used to develop regional curves for hydraulic geometry.

Watson et al. (2002) developed a quantifiable approach to estimate channel bed and bank stability for incised channels. Field measurements of channel slope and bank features allow for characterization of the evolutionary stage of channel adjustment presented by Schumm et al. (1984) and Simon (1989). Drawing from the work of Lane (1955), the core assumption of the Watson et al. (2002) model is sediment continuity; where sediment supply is balanced by the sediment transport capacity. If sediment supply becomes limited, stream energy will attempt to draw material from the bed and banks, depending on the resistance of the bed and bank materials. If sediment supply becomes excessive, stream energy will lack transport capacity and material will aggrade in the channel bed. Channel stability according to Watson et al. (2002), is a function of sediment continuity and bank characteristics. Bank characteristics are defined as the height of the bank, bank angle, bank material type (particle size), cohesiveness of bank materials, arrangement of particles (stratification), and the vegetative regime. An assessment of these channel features helps identify localized or watershed wide problems and should be accomplished before recommending a riparian agroforestry system. However, to properly interpret your field data you are required to properly identify the bankfull stage!
METHODS

The methods used in this paper apply the concepts presented in Rosgen (1994), Schumm et al. (1984), Simon (1989), and Watson et al. (2002). The first step involves defining regional relationships and the extent of their applicability. A single hydraulic geometry curve (cross-sectional area vs. drainage area) could be developed for an area as large as Minnesota; however, the $R^2$ would be so poor the curve would be of little value for selecting the bankfull stage at a specific stream channel. As illustrated in figure 1, the bank height with respect drainage area will determine if the channel is incised. However, identifying morphological features of the bankfull flow in incised channels can be very difficult without the help of a regional hydraulic geometry curve.

To evaluate stream morphology with respect to the bankfull stage, nonregulated USGS gage stations with at least 20-25 years of record were selected using sites (figure 2) identified in Lorenz et al. (1997). After selecting a range of drainage areas for each defined region throughout Minnesota, station description sheets were obtained from the USGS office in Mounds View, Minnesota. Station description sheets were examined for the type of gage, channel control features, and the datum reference. Flows associated with 1-to 2-year recurrence intervals were examined and a range of gage heights noted before collecting field data. A visit was made to each site to look for morphological evidence of the bankfull stage. The approximate field elevation of the bankfull stage at a riffle was noted and compared to the gage height to insure that field observations based on field indicators were within the 1-to 2-year recurrence interval.

The bankfull channel width and depth were measured at a riffle to determine a cross-sectional area for the gaged drainage area. Sites that were incised or lacked good field indicators were revisited under lower streamflow conditions to more closely examine morphological features. In east-central and mid-central Minnesota data was collected at 9 and 10 sites, respectively. In southeastern and western Minnesota and the Nemadji River watershed, data was collected at 19, 26, and 5 sites, respectively. In addition to the data collected at five USGS sites, data was collected at 15 nongaged sites in the Nemadji River watershed. The collected data were then plotted against drainage area on a log-log scale to form regional curves for hydraulic geometry. This step was essential for visual calibration to correctly identify bankfull indicators across changes in scale. The regional curves were constructed across similar geomorphic, land-use, and climatic regimes.

Field data at USGS gage stations was collected by the lead author; additional data was collected by students learning the Rosgen stream classification method in the Red River of the North Basin, in northwestern Minnesota. Regional hydraulic geometry curves were not used for the field data collected by the students reported in this paper. The student data was collected from 39 non-USGS gaged sites (figures 5 and 6) using only field indicators of the bankfull stage. The data are presented for the purpose of illustrating the need to calibrate field observations with measured peak streamflows for a defined region.
Figure 2. Map of study locations in Minnesota. The blue area highlights the western study area, with the Ottertail and Wild Rice rivers. The brown and red area is southeastern Minnesota, and green is east-central Minnesota. Mid-central Minnesota is white, and above the green area in dark brown is the Nemadji River.
RESULTS

The regional hydraulic geometry curves were developed for locations shown in figure 2 and are presented in figures 3 to 7. The curve for the steeper sloped, east-central Minnesota Region (Figure 3) shows a relatively strong $R^2$ (.99) in contrast to the mid-central Minnesota Region (Figure 3) with an $R^2$ of 0.95. The curve labeled “East” shows a steeper slope than the curve labeled “Mid” because of a relatively higher precipitation to runoff ratio.

Figure 4 illustrates the power of stratification by geology and the ability to obtain a stronger $R^2$ based on separating the influence of bedrock from nonbedrock channels in the Southeast Region of Minnesota. The line with the lower intercept (labeled “Karst”) shows the influence of hydrologic pathway formation in carbonate bedrock, whereas the line with the higher intercept (labeled “Till”) reflects the channel resistance factors associated with glacial based soils of southeastern Minnesota.

Figure 5 demonstrates differences in how the bankfull cross-sectional area is determined. The curve with the weak $R^2$ (labeled “Field”) was developed using in-field channel indicators of bankfull, whereas the stronger $R^2$ curve (labeled “Gage”) was developed with USGS gage data to corroborate bankfull stage. Note the data points for the second curve extend south of the Red River of the North Basin to include data from southwestern Minnesota (lower part of the Western Region in figure 2).

Figure 6 separates data from the “Field” curve in figure 5 by Rosgen stream type. Rosgen F type channels illustrate a relatively weak $R^2$ compared to C and E channel types. Identifying the channel forming or bankfull flow in incised, F type channels is very difficult; hence one of the advantages of a regional hydraulic geometry curve.

Figure 7 highlights the effectiveness of a specified regional hydraulic geometry curve. The curve labeled “USGS” represents five USGS gage stations at different scales in the Nemadji River watershed. Using this relatively steep regional hydraulic geometry curve, geomorphic data was collected from 15 nongaged sites across the upper Nemadji River watershed. One data point, labeled “Harding,” was removed from the curve labeled “Clay” because this site was located in beach ridge sand and not lacustrine clay. The “Harding” data point similar to the data in figure 4 drives home the importance of geology on channel formation.
Comparison Between USGS Gage Sites In Mid-and East-Central Minnesota

**Figure 3.** A plot of the bankfull cross-sectional area vs. drainage area at USGS gage sites for streams in mid-central Minnesota, and east-central Minnesota.

South-Eastern Minnesota Regional Hydraulic Geometry Curve At USGS Gage Sites

**Figure 4.** A plot the bankfull cross-sectional channel area vs. drainage area at USGS gage sites for streams in south-eastern Minnesota by geology.
### Comparision Between Red River Field Bankfull Indicator Vs USGS Gage Sites for Western Minnesota

- **Field**
- **Gage**
- **Power (Field)**
- **Power (Gage)**

#### Figure 5
A plot the bankfull cross-sectional channel area vs. drainage area at USGS gage sites and nongaged sites for streams in western Minnesota and the Red River basin, respectively.

#### Red River Regional Hydraulic Geometry by Rosgen Type

- **“C”**
- **“F”**
- **“E”**
- **Power (“F”)**
- **Power (“C”)**
- **Power (“E”)**

#### Figure 6
A plot the bankfull cross-sectional channel area vs. drainage area at nongaged sites for streams in the Red River basin by Rosgen stream type.
Regional Hydraulic Geometry Applied to Fifteen Sites in the Nemadji River Watershed

Figure 7. A plot the bankfull cross-sectional channel area vs. drainage area at USGS gage sites and nongaged sites in the Nemadji River watershed. A single data point (triangle) for Harding is not included in the power function and plots below the curves.

DISCUSSION

Agroforestry systems have promise as watershed management tools to improve water quality and enhance stream channel stability throughout Minnesota. However, before systems can be prescribed for riparian areas, the morphological characteristics of stream channels and their stability must be taken into account. Data presented for east-central Minnesota in figure 3 shows a strong linkage between the channel hydraulic geometry and the drainage area. Compared to other parts of the state, there has been little land use change over the past century in east-central Minnesota. Stream channels are well connected to their floodplains and riparian areas and thus attenuate flood peaks to downstream reaches. The upper St. Croix basin has forested riparian zones which provide excellent water quality protection, exhibiting some of the best water quality in Minnesota (Goldstein et al. 1999).

The mixed land use of mid-central Minnesota reflects the transition zone between the forested northland and the intensively managed cropland of southern Minnesota. Within this region some stream channels have become enlarged (plot above the curves in figure 3) as a result of increased contributing drainage area. In stagnation moraines, portions of the watershed will have no surface outlet for drainage, unless connected by drainage systems to a natural stream. Areas that have not been developed for urban or agriculture and have a contributing drainage area that is less than the total watershed area will plot below the curves in figure 3. Other features such as lakes and pothole-type wetlands will provide storage that reduces peak streamflows relative to the total drainage area. The presence of lakes and wetlands and the changes in land use make it difficult to define a uniform hydrogeomorphic region.
Agroforestry practices can essentially add hydrologic storage lost though urban and agricultural development. They represent an important alternative land use in actively urbanizing areas such as the corridor between St. Cloud and Minneapolis (figure 2). Applying buffer systems (Shultz et al. 2004) to small-order streams could preserve the existing water quality of mid-central streams. Potential alteration of hydrologic pathways must be discerned with respect to the magnitude of land use change and scale. For example, if more than half of the trees in a 1,000-ha wooded parcel are cut down for roads and homes, runoff to the adjacent stream will potentially degrade water quality compared to the same percentage of tree removal in a 10-ha wooded parcel. Agroforestry systems have the potential to provide stormwater phytoremediation and should be integrated into suburban subdevelopments (Rockwood et al. 2004).

The southeastern regional hydraulic geometry curve, shown in figure 4, illustrates the importance of geology. The lower curve developed from sites located in carbonate bedrock terrain is similar to the east-central regional curve (figure 3); high $R^2$ values are associated mostly with Rosgen E and C type channels that are well connected to the riparian flood plain and have limited channel incision. However, some specific channel reaches that are conventionally grazed showed localized signs of channel enlargement, though the effects of grazing are likely more buffered than in a sensitive geologic setting such as the Nemadji River watershed. Though grazing may be responsible for localized channel instability, upland watershed areas reflected in the upper curve (figure 4) are similar to agricultural land use effects found in south-central Minnesota. In particular, a stream reach adjacent to a managed intensively grazed (MIG) cattle operation showed counter-intuitive channel stability. A grassed MIG paddock that was only grazed twice per year had a stable bed and well-vegetated banks; whereas just downstream in a reach that was wooded on both sides, but never grazed the channel had become incised and unstable. In this instance, the apparent lack of stability under woody vegetation may be explained by watershed conditions upstream. The conversion from perennial vegetative cover to corn and soybeans over much of the watershed likely increased the magnitude of average annual peak flows downstream causing the channel to enlarge in the wooded reach. This MIG operation presented a pastoral system that resisted streambank erosion. Riparian agroforestry must account for systemic watershed disequilibrium before successful silvopastoral systems will work to protect water quality.

Not all USGS gage stations in western Minnesota are presented in the gage curve in figure 5. For example, gages in the upper Ottertail River are strongly influenced by lakes; the upper Ottertail River is largely a lacustrine flowage between wetlands and lakes. Hydraulic geometry data for this portion of the Ottertail River plots below the gage curve shown in figure 5, and contributes to the weaken $R^2$ of the field curve. We believe that the presence of lakes clustered within a watershed reflects significantly different hydrologic features and associated streamflow patterns (see also Lorenz et al. 1997). Agroforestry practices in lake regions may not offer much help for improving channel stability via hydrologic peak streamflow dampening, but still provide other water quality benefits.

In contrast to the upper Ottertail River which also lacked major land use change over the last century, the lower Wild Rice River has seen a tripling in the amount of row crops grow between 1987 and 2003 along with an annual rate increase of 0.22% in water yield (Wilson 2004). Rosgen F type incised channels have developed over time where the Wild Rice River has
enlarged in some areas. The top of an F type channel will not be the same as the bankfull elevation. By contrast, usually the top of a Rosgen C or E type channel corresponds to the bankfull elevation, which makes it easier to field identify the bankfull stage. The Wild Rice River has been altered by drainage, and is currently in fluvial disequilibrium. The loss of perennial vegetation has decreased the amount of transpiration that could occur in April, May, and June. Riparian agroforestry practices alone may not provide the desired improvements of water quality and stream channel stability. Upland agroforestry with other perennial crops and wetland restoration may be needed to significantly improve and protect water quality in the Wild Rice River. Channel restoration to connect the bankfull stage to the floodplain may also be required in some reaches.

Given the current percentage of forest in northeastern Minnesota, maintaining forested buffers along streams is a desired management strategy. Riparian agroforestry in this region is limited to managed silvopastoral practices. In the case of the Nemadji River watershed, losses of white pine forests in the early 1900s and the replacement with aspen forests and hay fields have accentuated runoff response in a watershed that inherently had a relatively high percent of runoff (figure 7). The type of perennial land use influences channel size; the Nemadji River basin is predominantly forested, however, channel cross-sectional area became larger in tributaries with a young forest and/or the influences of agriculture, (Riedel et al. 2001). The Nemadji River is listed on the Clean Water Act 303(d) list for turbid water; not because of cropland erosion, but streambank and bluff erosion. The lacustrine geology in the Nemadji River is particularly sensitive to even subtle land use changes (Riedel et al. 2001). The development of a regional curve for hydraulic geometry helped identify the scale at which lacustrine clay channels were found to be stable. Because of the cohesive nature of these soils the channels have evolved slowly. The land use practices at the turn of the 20th century set in motion watershed wide channel disequilibrium and the system has not yet recovered from this disturbance. No amount of vegetative management alone will decrease the amount of red clay and silt entering western Lake Superior. Geotechnical issues presented above by Watson et al. (2002) must also be addressed, mostly via channel widening before the Nemadji River becomes stable.

REFERENCES


