Soil and Phosphorus Losses to Streams via Stream Bank Erosion: A Review

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Abstract:

Stream bank erosion in agricultural landscapes is a major pathway for non-point source sediment and phosphorus loading of the receiving waters. The objective of this review was to provide some background information regarding stream bank erosion, its measurement methodologies and recommends suitable management practices to minimize sediment and phosphorus input to surficial waters to help improve stream water quality. Depending on the physical and hydrological characteristics of the stream channel, sediment and phosphorus contributions to streams via bank erosion can exceed 60% of the total loads. The major bank erosion processes are mass failure, fluid entrainment and subaerial preparation. The “Erosion Pin Method” is the most widely used measurement methodology for the bank erosion rates in order to quantify the amount of soil loss. In-field conservation practices are usually not sufficient to meet the requirements for significant sediment and nutrient removal from agricultural fields to streams. Riparian forest buffers and grass filters have the potential to reduce non-point source pollutants by significantly reducing stream bank erosion while at the same time slowing surface runoff, trapping sediment, and providing high soil water infiltration.

Key terms: streambank erosion, grazing pasture system, water quality, sedimentation, phosphorus

Introduction:

Increased sediment load can negatively impact local stream integrity while also increasing the downstream flux of the attached nutrients (Iowa Department of Natural Resources, 1997). Phosphorus (P) moves to surface waters predominantly attached to sediment, as particulate P (Sharpley et al., 1987). Phosphorus has been identified as the limiting nutrient for eutrophication of many lakes and streams (Correll, 1998). Increased P concentration in streams often promotes algal blooms and excess growth of other aquatic nuisance plants. Aerobic decomposition of the enhanced organic matter production may lead to hypoxic conditions and reduce stream integrity (Carpenter et al., 1998). Gullied and stream banks are major contributors of non-point source (NPS) sediment and P (Zaimes et al., 2004). Bank erosion can contribute significant amounts of sediment to fluvial systems (Laubel et al., 1999).

The quantification of sediment and P loss from agricultural landscapes is essential in order to develop practices that maintain both the sustainability of agricultural practices and the ecological integrity (Dinnes et al., 2001). Row crop cultivation and grazing are the most common agricultural practices. Both land-use practices can contribute high amounts of P and sediment to surface waters (Zaimes and Schultz, 2002). Well-managed pasture forages may limit P loading of surface waters by preventing soil erosion. Still some researchers have found that watersheds with a higher proportion of pastures than row crop cultivated areas may contribute more sediment and P to streams (Downing et al., 2000). There also are significant variations among different grazing practices. Research conducted by Zaimes et al. (2004) suggested that using rotational or intensive rotational grazing practices instead of continuous grazing could decrease the amount of sediment and P load to streams. The effectiveness of these grazing practices not only depend on the number of grazing paddocks along the stream, but also the stocking rates, weather conditions, length of grazing period and how well the grazing system guidelines are followed by landowners.

While erosion from extended lengths of pastured stream banks can provide significant sediment and P loading, critical source areas (CSAs) along the banks, such as livestock access...
points down the bank into the channel and stream-side loafing areas may provide proportionally significantly more sediment because of their intense disturbance (Zaimes et al., 2004; Tufekcioglu et al., 2013). On an area basis, CSAs account only for about 10% of the area but about 90% of available P export (Pionke et al., 1997). While Zaimes et al. (2004) found an average of 80-140 livestock access points per km in continuously grazed pastures in three different regions in Iowa, their sediment and phosphorus contribution to the streams were not evaluated. High amounts of sediment and P are contributed from source areas that have high surface runoff or bank instability. Management should focus on these areas to reduce those contributions (Sharpley et al., 2003). These areas of high sediment and P loading could be eliminated by establishing riparian buffers or fencing livestock from pasture streams (Line et al., 2000, Zaimes et al., 2004; 2006). However, these practices are not popular methods of conservation with farmers. A study conducted by Sherer et al. (1988) to determine the impact of livestock on fecal coliform levels in stream sediment found that livestock access points to the stream were potentially major contributors of bacteria to the underlying sediments. It is, therefore, important to understand the contribution of all major sources of sediment and P in the various grazing systems so that locally embraced watershed management systems can be designed to increase the sustainability of agriculture with respect to water quality while supporting the livelihood of farmers and also improving the integrity of the terrestrial and aquatic ecosystem. With this review it was aim to provide some background information on stream bank erosion measurement methods, soil loss via bank erosion, attached P input to surface water and recommends suitable management practices to minimize this input for the prospective stream quality.

Sediment and the attached P:

Stream bank erosion is a natural continuous process of healthy meandering streams that can be accelerated or decelerated by human activities (Henderson, 1986). Along with overland flow and stream bed sediment re-suspension it is one of the important pathways of NPS pollutants into surface waters (House et al., 1998; Sharpley et al., 1993; Daniel et al., 1994). Among these pathways, stream bank erosion can account for more than 50% of a catchment’s sediment export (Laubel et al., 1999; 2003). It was estimated that 227,000 km of stream banks in the United States needed stream bank protection to reduce bank erosion at the cost of $1 billion in 1981 (United States Army Corps of Engineers, 1983).

Bartley (2004) reported that gully and stream bank erosion contributed 52% of the total sediment load to an estuary. In Australia, Howard et al. (1998) reported that stream bank erosion was responsible for 42% of the suspended sediment in upper catchments and 70% in lower catchments in Gowrie Creek, near the city of Toowoomba. In the Midwest of USA, total P contribution to channels from stream bank erosion varied between 7-10% (Sekely et al., 2002) and 56% (Roseboom, 1987). Zaimes (1999) found that stream bank erosion along row-crop fields and continuously grazed pastures accounted for as much as 45-60% of the sediment load to streams in Iowa. Schilling and Wolter (2000) also reported that 50% of the annual suspended sediment movement to a stream was due to stream bank erosion in Iowa. The range of the sediment load to streams from bank erosion is large because of the large number of variables involved in the process and the unique relationships between them including over-hanging banks, bank angle, bank vegetation cover, estimated stream power (Laubel et al., 2003), channel width, depth, and slope (Odgaard, 1987).

Stream bank erosion processes:

There are three major stream bank erosion processes (Lawler, 1992a). The first is fluid entrainment, a fluvial process that is related to the action of flowing water on the stream bank. During a high discharge event there is an increase in water velocity and an increase in shear stress along the entire wetted perimeter that dislodges soil from the bank. The second process is subaerial preparation, a physical process that includes desiccation of soil materials and freeze-thaw cycles that expand...
and contract pore spaces in the soil loosening the adjacent soil particles and causing them to slough off into the stream (Lawler, 1992a). This is more of a preparatory process that later stream flows can move more easily the loosened material. Finally, mass bank failure, a geotechnical process, can also occur when large blocks of bank fall into the stream because the bank angle is too steep and the bank exceeds its critical stable height (Lawler, 1992a). Which erosion process dominates in a stream system depends on the location of the eroding bank (downstream, mid and upstream) and the amount of drainage area of the watershed above the point of failure. Mass failure processes are dominant in the downstream portion of large river systems, fluvial processes in the midstream or mid-sized drainage basins, and the subaerial preparation in the upstream or the small drainage basin (Lawler, 1995).

**Stream bank erosion measurement methods:**

Studying stream bank erosion is difficult because of its high variability along the same stream. This high variability has led to the development of a number of different techniques depending on the objectives of the study. The most significant component in these techniques is the time scale considered for bank erosion. The techniques can be divided into: long, intermediate and short time scale methods. Lawler (1993) has described the most important techniques of measuring bank erosion. Long time scale methods detect erosion changes over 10-20,000 years. The most typical methods provide sedimentological, botanical and historical evidence. All of these techniques involve graphical reconstruction of the channel in different time periods. The sedimentological method involves establishing alluvial chronologies. This is based on fluvial deposits on the stream banks that can be dated. The botanical method looks at the living vegetation on the bank or dead vegetation that exists in the soil of the banks. Finally, the historical method uses sources like early maps, aerial photographs, surveyor’s notes and diaries.

Intermediate time scale methods detect erosion for a period of 1-30 years (Lawler, 1993). The most important techniques are planimetric resurvey and repeated cross-profiling. The planimetric resurvey method simply surveys lengths and widths of the channel. This can be done with plane-tabling, baseline resurvey, tacheometric methods and electronic distance measuring. Repeated cross-profiling is similar to planimetric resurvey with the addition of permanently marked channel cross-sections.

Short time scale methods can detect erosion over a few months up to a few years, with the most important techniques being terrestrial photogrammetry, erosion pins (will be explained in more detail in the following section) and photo-electronic erosion pins (or PEEP). Terrestrial photogrammetry uses a photogrammetric camera, integrated with a theodolite and takes stereoscopic pairs of pictures of eroded banks. The PEEP (Lawler, 1992b) is a recently developed method and consists of a clear acrylic tube that contains photovoltaic cells. The tube is inserted perpendicularly into the bank. Erosion leads to exposure of cells to sunlight that is converted to voltage output and recorded by a datalogger. Short time scale methods have high resolution compared to the long and intermediate time scale methods. Finally, there are a number of miscellaneous techniques that have been used that mostly provide qualitative data. These are morphological evidence, local opinion, ‘thermal disturbance’ method, hydrographic resurvey, sediment traps, repeated photography, painted sections, erosion boxes and erosion frames (Lawler, 1993).

**Stream bank erosion pins:**

Emphasis will be given to the pin method that has been frequently used to quantify the amount of sediment loss from bank erosion. It is used because it is practical for short time-scale studies needing high accuracy for measuring small changes in bank surfaces that may be subject to deposition or erosion (Haigh, 1977; Lawler 1993). Another advantage is the relatively low cost of the method and ease of
use. With this technique, researchers are able to relate the amount of bank erosion to individual hydro-meteorological events or sets of events, and to focus on spatial variations (Lawler, 1993). Although the pin method is very practical to use, there are some disadvantages. In the winter-time, it is very difficult to find and measure the pins because they are often covered with snow. They can also be lost when bank erosion rates exceed the length of the pins and the bottom rows may be difficult to measure when the stream water level is high (Zaimas, 1999).

Pin diameter and length are very important in terms of stream bank material disruption and measurement accuracy. The diameter should be as small as possible to minimize public visibility and bank material disruption. Typical values range from 2-6 mm. Pins should be long enough to avoid being lost in major erosion events, yet the length depends upon not only the rates of erosion expected, but also the planned frequency of site visits and pin resetting. Most workers have adopted pin lengths of between 250-500 mm (Lawler, 1993) although pins up to 800 mm are commonly used (Hooke, 1979; Zaimas et al., 2004).

Severe and very severe eroding stream banks are usually selected for erosion pin network plots because they are the major source of the sediment (Zaimas et al., 2004). Bare soil with slumps, vegetative overhang and/or exposed tree roots are the indications of severe eroding banks as defined by United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) (1998). Very severe eroding banks are defined as bare with massive slumps or washouts, many exposed tree roots and severe vegetative overhang (USDA-NRCS, 1998). The number of pin rows and columns in each eroded bank area depends on the eroded length and height of the bank (Hooke, 1979; Tufekcioglu et al., 2012)

**Conservation Practices - Multi-species riparian buffer systems:**

In-field conservation practices are usually not sufficient to meet the requirements for significant sediment and nutrient removal from agricultural land to streams. Riparian forest buffers and grass filters have the potential to capture NPS pollutants by slowing surface runoff, trapping sediment, and providing high soil water infiltration (Schultz et al., 2004). Buffer strips, located along streams have the potential to sequester C from the atmosphere, immobilize N in biomass and trap sediment and nutrients before they reach the stream, thus, improving water quality not only for human needs but also for other organisms and animals that rely on them (Tufekcioglu et al., 2003). The soils of buffer strips have high water infiltration (Bharati et al., 2002) and soil organic matter content which is considered to be an important soil quality indicator in terms of soil erosion resistance (Marquez et al., 1999). Phosphorus loads from overland flow can be reduced as much as 95% by buffer strips that are 10 m wide (Lee et al., 2000). Denitrification rates have been found to be high within riparian buffers on soils with high water tables (Addy et al., 1999). With buffer strips, the residence time of the shallow ground water increases as it passes through the soil, increasing denitrification (Lowrance et al., 2000). Buffers also stabilize stream banks and improve the aquatic habitat for both invertebrates and fish (Lene et al., 1995).

Stainton et al. (2003) stated that soil hydraulic condition plays an important role in defining buffer zones and buffer effectiveness. Riparian buffers with sandy soil, dominated by subsurface drainage systems, are less likely to reduce sediment and nutrient loading to streams from the agricultural land (McKergow et al., 2003). Therefore, buffers should not be used as an initial management practice to control nutrient loading to streams without detailed knowledge of the hydro-geologic environment (Simpkins et al., 2002). In addition, trees and shrubs in the riparian zone show great potential of increasing soil water storage by plant water uptake (Bosch et al., 1994; Caubel et al., 2003) so that dewatering of the soil by buffer vegetation provides more soil water storage for runoff events.

Streambank erosion adjacent to riparian forest buffers, grass filters or riparian areas where cattle were fenced out of the stream, was significantly lower than on banks adjacent to
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agricultural practices (row crop fields, continuous, rotational and intensive rotational pastures) (Zaimes et al., 2004; 2008; Tufekcioglu et al., 2010). Specifically, in the Bear Creek study if all non-buffered sub-reaches (7.8 km) had established riparian forest buffers, soil losses from stream bank erosion would decrease by a total of 3,709 tons or an 84% reduction over a four year period (this percentage ranged from 77-97 depending on the year) (Zaimes et al., 2004). In a study in three Iowa regions, soil and P losses per unit length of the conservation practices (forest buffer, grass filters and pasture with fenced stream banks) were in the range of 2-48 times and 2-62 times less, respectively than the agricultural land-uses (Zaimes et al., 2008). However, if stream power is not reduced along with the increased bank protection, the channel will erode sediment from other non-buffered reaches to maintain the channel-equilibrium as suggested by Lane’s (1955) model.

Conclusions:

The mitigation of increased sediment and nutrients loads is a necessity in most agricultural watershed to sustain or improve the water quality. In addition to overland flow and stream bed re-suspension, stream bank erosion is one of the important pathways of the soil and its attached P loss to surface water. In many case stream bank erosion is the most important pathways of sediment movement to streams. Soil loss to stream from stream bank erosion ranges from 23 to 76% of the total loads (Tufekcioglu et al., 2012). This large range is due to higher number of variables that involve in the bank erosion process, including physical and hydrological characteristics of the channel (bank angle and vegetation cover, channel width, depth and slope, and stream power as a driving force).

The high numbers of variables have led to three major bank erosion processes including mass failure, fluid entrainment and subaerial preparation. Mass failure usually takes place downstream portion of the stream network, fluid entrainment at midstream portion, and subaerial preparation at upstream portion of the stream network or the small drainage basin. The dominant process need to be considered when management plans are developed to mitigate stream bank erosion.

The high temporal and spatial variability of stream bank erosion require the use of short time scale measurements. Erosion pin method is such a method that has been used in many bank erosion studies to quantify amount of soil loss by the mentioned erosion processes. With this method, researchers are able to measure bank erosion with high accuracy and at a relatively low cost. Another major advantage of this method is that the data can be related to set of hydro-meteorological events. These relationships can help understand the processes that cause stream bank erosion

Multispecies riparian buffer system has been recognized as a major conservation practice that reduces the stream bank erosion and overland flow erosion by reducing the water flow and increasing the infiltration rate of the surface soil and enhances the habitat for wildlife and fish species in agricultural watersheds.

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