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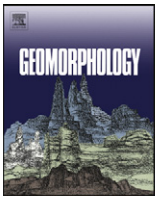

Assessment of river bank erosion in Southern Minnesota rivers post European settlement

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ABSTRACT

River bank erosion is one of the major sources of sediment for many rivers around the world. With the current emphasis on developing total maximum daily loads (TMDLs) for impaired waters in the United States, there is heightened interest in quantifying background sediment levels in rivers. In this study, we assessed variations in river bank erosion over time using a combination of 1855 Public Land Survey System plats, aerial photographs from 1938 to 2009, and light detection and ranging (lidar) data from 2005 to 2009 for sediment impaired rivers in Southern Minnesota. Results showed that bank erosion was episodic, making comparisons of erosion rates from dissimilar time intervals unreliable. For comparable time intervals, average river bank retreat rates (0.51 m yr^{-1} from 1855 to 1938 vs. 0.37 m yr^{-1} from 1938 to 2009) were statistically similar ($t = 2.13$, $p = 0.14$) suggesting that bank erosion rates have remained stable since European settlement. Comparisons over shorter time intervals of 1938–1971 and 1971–2009 also showed similar statistical trends ($t = 0.76$, $p = 0.45$) with average river bank retreat rates of 0.57 and 0.50 m yr^{-1}, respectively. However, additional 145 observations of bank retreat were found in the period 1971–2009 relative to 1938–1971, indicating that the number of actively eroding river banks may have increased over time. Contrary to assumptions made in the literature, bank erosion measurements using lidar data showed a poor relationship ($r^2 =$ 0.01 to 0.36) with river bank physical features (face area, inclined surface area, length, slope, height, and aspect), thus suggesting that extrapolating a limited number of bank erosion observations to the whole length of a river will lead to erroneous predictions. This lack of relationship was expected considering that most of these bank physical features do not fully represent bank erosion processes such as seepage, freeze–thaw, river migration, under cutting and sapping. We conclude that, in assessing conservation measures or developing TMDLs to manage river sediment loads, (1) background levels of suspended sediments from river bank erosion should be established using comparable time intervals, and (2) up scaling of discrete volume loss measurements to an entire reach should be avoided.

1. Introduction

Suspended sediments frequently contribute to surface water impairments in many parts of the world. High concentrations of suspended sediment in rivers and lakes have deleterious impacts on recreational and navigational activities, as well as on fisheries, which in some cases can be lethal to aquatic species (Newcombe and Jensen, 1996). In many areas, bank erosion is a major source of suspended sediment loads in rivers (Thoma et al., 2005; Evans et al., 2006; Wilson et al., 2007; Belmont et al., 2011; Kessler et al., 2012; Day et al., 2013a). In the U.S., once a river is identified as impaired by excess sediment, the Clean Water Act requires that the maximum amount of sediment it can receive and still meet local water quality standards be calculated. This maximum amount of sediment is referred to as the total maximum daily load (TMDL). As TMDLs are being developed for rivers impaired by excess sediment, there is often a need to establish natural background contributions of suspended sediments from river bank erosion. Identifying natural background contributions requires identifying the degree to which natural processes vis-à-vis anthropogenic activities affect river bank contributions to suspended sediment loads.

In Minnesota, river banks have been identified as a major source of sediments in the Minnesota River and its tributaries (Thoma et al., 2005; Gran et al., 2009; Belmont et al., 2011; Kessler et al., 2012; Day et al., 2013a); all of which are classified as sediment impaired. Meyer and Schellhass (2002) estimated that as much as 623,000 mg yr^{-1} of total suspended solids (TSS) were transported by the Minnesota River at Fort Snelling in the Minneapolis/St. Paul area. Kelley and Nater (2000) estimated that Minnesota River sediments comprised at least 75% of the sediment in Lake Pepin, a floodplain lake on the Mississippi River about 80 km southeast of St. Paul. Payne (1994) reported that as much as 55% of the sediment in the Minnesota River at Mankato originated from the Greater Blue Earth River Basin (GBERB; Fig. 1), a

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relatively flat basin (54% of the land with $<2\%$ slope and 93% of the land with $<6\%$ slope) with deeply incised streams that are lined with steep and unstable banks that reach heights over 50 m (Fig. 2). Using lidar, Kessler et al. (2012) showed that river banks sloughing in Blue Earth County account for 48% to 79% of the TSS measured at the mouth of the Blue Earth and the Le Sueur Rivers. However, a limitation of Kessler et al. (2012) and other bank erosion studies (Sekely et al., 2002; Thoma et al., 2005; Wilcock, 2009; Kronvang et al., 2011) is that the bank erosion rates are only for one period and do not provide information on how erosion may have varied over time. With increased rates of sediment accumulation in flood plains and lakes, such as in Lake Pepin (Engstrom et al., 2009), there is a need to identify how river bank erosion has varied over time.

Depending upon the time scale, sediment inputs from river bank erosion can be episodic. For example, Black et al. (2010) described average migration rates ranging from 0.7 to 4.7 m yr^{-1} over a 100 year period across three rivers in the North Eastern United States. The radionuclide dating technique used in that study revealed both nearly constant and episodic migration rates at decadal time scales. Using erosion pins, Zaimes et al. (2004) suggested that 60–80% of bank erosion along a creek in central Iowa occurred over a period of a few days during a two year study. In spite of the observations that bank erosion processes can be largely episodic, recent research has drawn comparisons between river bank erosion measurements made at dissimilar time intervals (Gran et al., 2009; Belmont et al., 2011; De Rose and Basher, 2011). If bank erosion exhibits episodic characteristics then comparisons made between measurements taken at short (i.e. decadal) and long ($>$100 years) time intervals could lead to erroneous interpretations and conclusions.

Worldwide, several different techniques have been used to quantify river bank erosion. In addition to airborne lidar, erosion pins, terrestrial lidar scans (TLS), traditional survey, fallout radionuclides, and numerical models have all been used to estimate river bank erosion. Erosion pins are commonly used and provide accurate measurements at the locations they are installed (Couper et al., 2002). However, the bank must be accessible in order to insert the pins; inserting the pin can cause localized erosion; and erosion in between pin measurements must be interpolated. Recently, terrestrial lidar has been shown to provide high resolution measurements of bank erosion (Day et al., 2013b). However, there is a limitation on the number of banks that can be surveyed requiring extrapolation of measurements from a few river banks to the entire length of a river channel. Currently, most extrapolation techniques are statistical and are not based on any bank erosion mechanisms. Another technique for assessing bank erosion includes numerical models. Numerical models are generally based on physical principles and require substantial inputs for simulating bank erosion from even one bank (Rinaldi and Casagli, 1999; Simon et al., 2000; Pollen and Simon, 2005; Cancienne et al., 2008; Lindow et al., 2009), not to mention a whole reach which may extend several hundred kilometers. For example, the Bank Stability and Toe Erosion Model (BSTEM) requires several measurements on physical and geometric properties of the bank including effective cohesion, length of failure planes, bank angle, bank failure plane angle, matric suction or soil pore-water pressure, and pore-air pressure (Cancienne et al., 2008).

Aerial photographs also provide a means to assess past river bank erosion rates (Leys and Werritty, 1999; Shields et al., 2000; Hughes et al., 2006; Hooke, 2007; Nicoll and Hickin, 2010; De Rose and Basher,

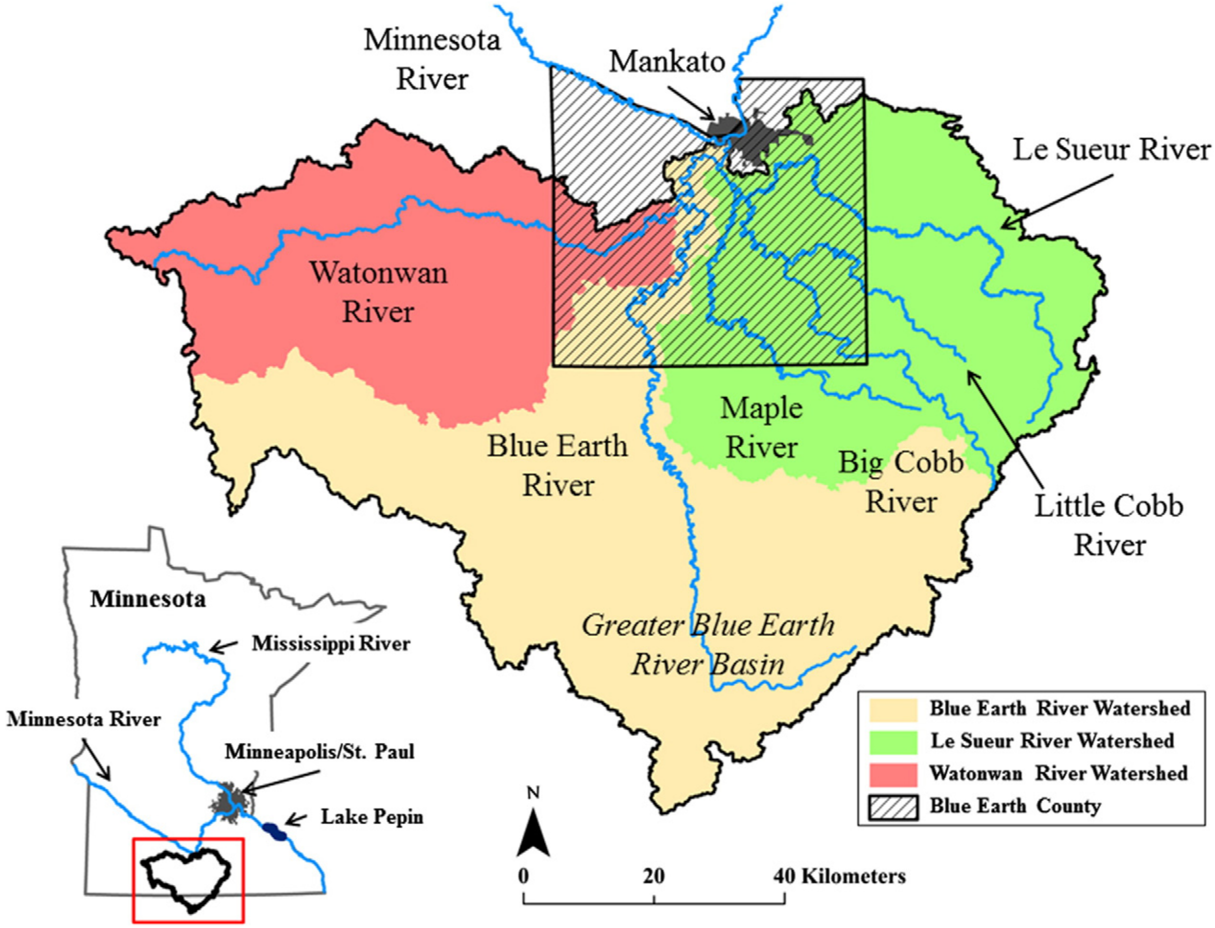

Fig. 1. Map of the Greater Blue Earth River Basin (GBERB) and surrounding areas.