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A statistical model for streambank erosion in the Northern Gulf of Mexico coastal plain

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ABSTRACT

Stream restoration practitioners often rely upon empirical models to quantify annual streambank erosion rates and identify streambank erosion hotspots. Such models are designed to be widely applicable by incorporating readily available field measurements, but they must be calibrated to each hydrophysiographic region and may not reflect the dominant streambank erosion processes in a given region. Here, we present statistical models for streambank erosion using physical and environmental data collected at 53 locations throughout the northern Gulf of Mexico coastal plain. The data include channel geometry, bank characteristics, precipitation, above-ground biomass density, and root density, the latter two surveyed using techniques introduced here. We developed a statistical model selection process using Akaike's Information Criterion (AIC) and repeated cross-validation (CV). Models derived from the literature that were applied *a priori* were only weak predictors of erosion rate, but AIC-CV model selection identified 3 strong statistical models. The best model according to AIC showed a significant correlation to lateral streambank erosion rates ($R^2 = 0.54$) and included the five strongest covariates of our dataset (bank slope, biomass density, curvature index, BEHI, and understory cover). When volumetric erosion rate (m^2/year) was predicted, the fit of this model increased ($R^2 = 0.65$). CV-based selection resulted in a more conservative model with the four strongest covariates and a lower fit ($R^2 = 0.47$). The similarity of the AIC and CV models indicates the stability of the two-tier model selection approach, and suggests it has utility for modeling phenomena with many potential variables. Our models also showcase the ability of our biomass survey to quantify root reinforcement of streambanks. Our approach incorporates measurements familiar to the stream restoration community and can be applied throughout the northern Gulf of Mexico coastal plain, a region characterized by low relief fluvial valleys, unconsolidated alluvium and meandering single thread sand bed channels. The approach, which is based on field observations and robust statistical modeling, offers an alternative for stream restoration practitioners to more traditional streambank erosion prediction methods that underperform in the region, and may have applicability elsewhere.

1. Introduction

Streambank erosion is widely recognized as a key geomorphic and ecological process that can be impacted by a variety of human influences (Gregory, 2006). The sediment delivered from eroding banks is often the dominant sediment source within a watershed (Bull, 1997; Kronvang et al., 2013; Sekely et al., 2002) and is an important source of channel and floodplain nourishment (Florsheim et al., 2008). It can also contribute to sediment pollution and eutrophication (U.S. Environmental Protection Agency, 2000). Quantifying streambank erosion rate is thus an important aspect of modeling channel planform evolution (Howard, 1992), sediment loading to stream channels (Rosgen, 2001; Van Eps et al., 2004), sediment discharge from watersheds (Bartley et al., 2008; de Vente et al., 2013), and sediment Total Maximum Daily Load (TMDL) development (Gellis and Walling, 2011; Rosgen, 2001; Smith et al., 2011). Sediment TMDL development requires information about streambank erosion rates because bank erosion is a major source of sediment loading, and the location and magnitude of sediment loading are crucial for sediment TMDL development. However, many TMDL models do not include a streambank erosion component (Borah et al., 2006), which underscores the need for robust streambank erosion prediction models such as the one presented here. These bank erosion prediction models have to be applied judiciously because they estimate gross sediment production from bank erosion and do not differentiate between the proportions of the eroded sediment that are then deposited in different environments (point bars,

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abandoned channels, floodplains, receiving water bodies). Lauer and Parker (2008) pointed out that the proportion deposited locally in point bars can be significant (80–90%). Depending on the particular application, failure to differentiate between the proportions can be a limitation of many of these models.

Many studies have investigated the physical and environmental processes responsible for streambank erosion. In meandering channels, secondary flow and topographic steering lead to scour of the stream bed near outer banks and to direct fluvial scour of bank material (Dietrich et al., 1979; Dietrich and Smith, 1983; Hooke, 1975). Although channel curvature is responsible for the development of secondary flow and increased shear stress near outer banks, the largest meander migration rates have been observed in bends with intermediate, rather than high, curvatures (Hickin and Nanson, 1984; Nanson and Hickin, 1983), i.e., erosion rate sharply decreases past a critical curvature value. Similar results have been reported elsewhere (Hooke, 2003; Nanson, 2010) and have been partially explained as a result of the relative shortness of sharp bends, which limits secondary flow development (Furbish, 1988); as a result of the spatial lag between channel curvature and velocity perturbations, which is more pronounced in sharp bends (Crosato, 2009); as a result of the saturation of turbulent energy and secondary flow in very sharp bends (Blanckaert, 2009); and as a result of the development of a protective outer-bank cell (Blanckaert, 2011; Hickin, 1978; Nanson, 2010).

Fluvial scour steepens the bank and primes it for mass failure (Thorne, 1982). Failure is resisted by bank cohesion, which depends on composition (Couper, 2003; Konsoer et al., 2016; Wynn and Mostaghimi, 2006), moisture conditions (Simon et al., 2000), and the presence of roots (Micheli and Kirchner, 2002; Pollen, 2007; Pollen-Bankhead and Simon, 2010). Sand-rich banks, in particular, are often more easily eroded than silt- or clay-rich banks (Constantine et al., 2009; Pizzuto, 1984). Forested streambanks have been observed to retreat at a much slower pace than similar non-forested banks (Allmendinger et al., 2005; Hubble et al., 2010; Micheli et al., 2004; Miller et al., 2014; Sass and Keane, 2012; Stott, 1997). Trees growing directly on streambanks exert an additional control on erosion rates by acting as natural buttresses (Pizzuto and Meckelnburg, 1989; Pizzuto et al., 2010). On the other hand, Trimble (1997) inferred that the large woody debris introduced to channels by trees can lead to increased scour and bank erosion in some cases. It is also possible for bank trees to shade out the understory layer, preventing the growth of dense grasses and shrubs (Allmendinger et al., 2005), which would otherwise reinforce the bank. Bank retreat is thus the result of many interacting processes, some of which are highly localized.

Numerous numerical models describing river meandering have been built on the so-called "excess velocity" relationship (Parker et al., 2011), which assumes that bank erosion rate is proportional to the near-bank velocity excess (measured in m/s, relative to the reach-averaged velocity) times a dimensionless erodibility coefficient (Ikeda et al., 1981). This equation has successfully reproduced the meandering behavior of natural rivers, especially when tree cover was incorporated into the erodibility coefficient (Pizzuto and Meckelnburg, 1989). In addition to excess velocity, excess near-bank depth (measured in m, relative to bankfull mean depth) due to basal scour is often an important factor when considering bank erosion rates (Odgaard, 1987, 1989). Increased depth near the bank toe effectively increases bank height and thus bank instability and erosion rate. Near-bank depth excess is related to the so-called "scour factor" of classic meander models (Blanckaert and de Vriend, 2010; Ikeda et al., 1981; Johannesson and Parker, 1989) and to the ratio of near-bank maximum depth to mean depth, a widely-used estimate of near-bank shear stress in the stream restoration community (Sass and Keane, 2012; Van Eps et al., 2004).

Applied scientists and stream restoration practitioners face the challenge of predicting annual streambank erosion rates throughout large areas such as major watersheds. In stream restoration, predicted erosion rates are needed for reach prioritization but, depending on the goal of the restoration, many other types of data such as stream classification, hydraulic geometry, ecology, and land-use plans are needed to support the decision-making process. Ideally, geomorphological, hydraulic and ecological data for a local undisturbed system should also be assessed to optimize the restoration in order to help the restored system revert to a pre-disturbance state. The Bank Assessment of Nonpoint Source Consequences of Sediment (BANCS), for example, is a major aspect of the Watershed Assessment of River Stability and Sediment Supply (WARSSS) (Rosgen, 2009) and associated Natural Channel Design (NCD) paradigms. The BANCS framework allows practitioners to estimate annual streambank erosion rates throughout a hydrophysiographic region by correlating erosion rates with easily observable bank parameters (Rosgen, 2001). BANCS has been widely adopted by the stream restoration community in the U.S. (Lave, 2009) and endorsed by the U.S. Environmental Protection Agency (2012), the U.S. Forest Service (Yochum, 2015), and the U.S. Fish and Wildlife Service (http://nctc.fws.gov/). A common application of BANCS is estimating sediment yields from streambank erosion throughout a watershed (Van Eps et al., 2004).

Despite its popularity among stream restoration practitioners, BANCS suffers a few key weaknesses, including a reliance on visual (or ocular) estimates and a largely arbitrary data indexation process. The BANCS statistical model assumes that erosion rate is a function of bank erodibility hazard index (BEHI) and near-bank shear stress (NBS). Such models have been developed for Colorado Front Range (Rosgen, 2001), Yellowstone National Park (Rosgen, 2001), NE Kansas (Sass and Keane, 2012), and the Sequoia National Forest (Kwan and Swanson, 2014), but other researchers have reported predictive models with large amounts of scatter, including negative correlations between observed erosion rates and BEHI-NBS (Coryat, 2014; Harmel et al., 1999; Markowitz and Newton, 2011; Peacher, 2011). In a previous study, we attempted to calibrate the BANCS model for the northern Gulf of Mexico coastal plain and found that BEHI and NBS were largely uncorrelated to erosion rates in the region (McMillan, 2016). Currently, no comprehensive empirical model exists to predict the erosion rate of forested coastal plain streambanks.

In this paper, we present the results of a 3-year field campaign investigating the characteristics of streambank erosion in the northern Gulf of Mexico coastal plain. Streambanks in the area are comprised of unconsolidated alluvium. The alluvium is typically very sandy (sand and loamy sand texture classes), making the banks susceptible to erosion. During this campaign, we measured streambank erosion rates and relevant physical/environmental data at 53 locations throughout the study area. The goal of this paper is to develop a statistical model for streambank erosion rates within the study area that is easily applicable, based on field data collection, and useful as a practical tool, attributes it shares with BANCS. Therefore, we collected data that can be measured at channel cross-sections or individual bends. We also performed above and below-ground biomass surveys as well as bank shear strength measurements and soil analyses. To predict bank erosion using these data, we gathered several statistical models from the geomorphology literature, and we also developed a statistical model selection process.

2. Study area

The study area is located in the northern Gulf of Mexico coastal plain (Fig. 1), a region characterized by low-relief alluvial valleys, high annual precipitation averaging 1300–1600 mm/year (30-year normals, PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed May 2016), and heterogeneous land cover including mixed forest, cropland, and pasture. During the study, annual precipitation was average in the study area except for the southwest portion which received approximately 1900 mm during the first year of the study. Short-term variability of precipitation was high (McMillan et al., 2017), which is characteristic for the region. Alluvial floodplains