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A modeling framework for evaluating streambank stabilization practices for reach-scale sediment reduction

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ABSTRACT

Process-based models can predict stream response to streambank stabilization. However, a framework does not exist on how to explicitly utilize these models to evaluate stabilization measures prior to implementation. This research developed a framework to evaluate stabilization practices using hydraulic and sediment transport models, landowner preferences, construction costs, and effectiveness. This framework produces sediment reduction graphs to determine the stabilization length as well as cost graphs. The methodology was applied to Fivemile Creek in western Oklahoma. A CONCEPTS simulation was developed for a 10.25-km reach and several stabilization techniques (grade control, riprap toe, and vegetation) were simulated. Incorporating multiple stabilization practices simultaneously resulted in higher sediment loads, but also higher costs which were quantifiable using the framework. Vegetation with 2:1 bank slopes was the most cost-effective stabilization technique. With that said, the framework provided a process-based understanding of the system that also highlighted the need for grade control for long-term effectiveness.

Software and/or data availability

The framework is not specific to any one model but can be applied to any reach-scale bank erosion/stability model. The primary software used in this manuscript to form the basis of the modeling framework is the CONservational Channel Evolution and Pollutant Transport System (CONCEPTS), developed by Dr. Eddy Langendoen at the USDA-ARS National Sedimentation Laboratory in Oxford, MS (address: 598 McElroy Drive, Oxford, MS 38655, telephone: 662-232-2924, email: eddy.langendoen@ars.usda.gov). The model can be downloaded free of charge at the following website: https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/concepts/concepts-overview/. The downloadable executable file is 660 KB. The program was first developed in 1999, described and evaluated in the research report in Langendoen (2000), and evaluated in a number of stream systems since that time.

1. Introduction

Excess sediment from upland sources, channel and gully erosion, and the resuspension of bed material is a major polluter of surface waters across the United States with streambank erosion from unstable channels contributing as much as 50%–90% (Wilson et al., 2008; Fox et al., 2016). Stream restoration or stabilization can reduce sediment contributions from the streambanks and these practices have become more common in recent years with the goal of correcting anthropogenic disruptions to streams (Beechie et al., 2010). However, an increase in stream restoration has not reduced the number of degraded miles of streams since the early 1990s (Langendoen, 2011). Restoration typically involves extensive channel modification and integrates channel stabilization to lock the channel in place. Florsheim et al. (2008) highlighted several shortcomings of current streambank erosion management strategies, including failure to understand erosion processes, failure to consider bank erosion on the appropriate scale, and failure to

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understand secondary effects of bank infrastructure.

Current channel modification strategies place an emphasis on channel form rather than channel erosion processes (Kondolf, 1996) and often fail to address the cause of degradation (Beechie et al., 2010). Typically, a "cookbook" approach that relies on channel classification rather than erosion process is applied to stream restoration and stabilization projects (Kondolf, 1996; Lave, 2009). This method often relies on creating a certain channel form that is considered "good", but this channel form may not be suitable for the amount of sediment or the valley slope and will eventually fail (Beechie et al., 2010). Understanding erosion processes, such as fluvial erosion of the bed and bank and mass wasting, are vital to a successful restoration or stabilization project (Shields et al., 2003). For example, river stabilization often only addresses fluvial erosion and will fail where mass wasting is a dominant process (Florsheim et al., 2008). Streams adjust to changes within the watershed by the processes of erosion until a dynamic equilibrium is reached. Channel modification projects that do not allow for a balance of sediment supply and transport capacity often fail (Shields et al., 2008) and lead to either aggradation or degradation of the channel.

Stabilization practices often address erosion at the site scale, focusing on local scour and deposition, not considering sediment transport outside of the project site and system wide instability (Kondolf, 1996; Shields et al., 2008). A basin-wide analysis or the potential for geomorphic processes to impact the project site rarely occurs (Miller and Kochel, 2010). The limited focus of stabilization on the site and ignoring the location within the watershed is a common reason for project failure (Palmer and Allan, 2006; Langendoen, 2011). The consideration of upstream condition is vital as sediment and water discharge are influenced by land use and affect channel response up and downstream (Morris, 1995; Palmer and Allan, 2006).

While the effect of stabilization on sediment transport and downstream bank erosion is apparent, literature discussing actual sediment reduction to be expected from streambank stabilization is limited. Many bank stabilization projects do not consider the downstream impacts or include a long term monitoring plan; therefore, the amount of sediment reduction on the reach or watershed scale is not known. Stabilization or restoration projects often utilize an empirical "cookbook" approach rather than utilizing process-based models that are available to determine the effect of restoration on sediment reduction prior to implementation. In addition, the lack of guidelines for the evaluation of stabilization or restoration practices through the use of process-based models limit the applicability of these tools. Research is needed to quantify the amount of sediment reduction from bank stabilization on the reach-scale and prioritize stabilization practices prior to implementation.

Furthermore, the cost of streambank erosion practices is often quite high and a major factor for stakeholders when determining which practices to adopt. Several conservation programs funded by federal and state governments are available to assist with the cost of erosion control including the Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), and Environmental Quality Incentives Program (EQIP) (Tong et al., 2017). With a finite amount of resources for these programs, it becomes vital to understand which practices are the most cost effective for a particular stream system to achieve optimal sediment reduction. Furthermore, the costs of streambank stabilization projects are highly variable depending on the type of stabilization, materials used, amount of earthwork needed, channel dimensions, and other factors (NCHRP, 2005). For example, Bair (2000) reported costs of typical stream restoration projects ranging between $40 to $220 per linear meter of stream.

Therefore, the objectives of this research were to develop a framework for prioritizing streambank stabilization practices for sediment reduction, to evaluate the potential sediment load reduction from those practices, and to determine the cost associated with a desired amount of sediment reduction. This framework was applied using a tributary to the Fort Cobb Reservoir, Fivemile Creek, as a case study.

2. Methods and materials

2.1. Process-based framework

A graphical representation of the proposed methodology for evaluating streambank stabilization is shown in Fig. 1. Several factors contribute to a successful stabilization project and are integrated into this process including public and landowner perception, costs, and, most importantly, effectiveness. This methodology results in the development of a set of sediment reduction graphs, one for each stabilization practice, to determine the length of stream that needs to be stabilized to achieve a desired sediment reduction and a second set of graphs to determine the cost of stabilization based upon length of stream stabilized.

This framework was designed to be in line with the Shields et al. (2003) stream restoration design approach, with stabilization as the key design objective. Shields et al. (2003) specifically noted that stability checks are required within their design approach including the use of either simple qualitative indicators or more in-depth bank stability and sediment transport calculations. This research specifically calls for the move towards more in-depth approaches that make use of the most recent scientific and engineering research.

2.1.1. Determine study reach

The study reach should include an entire stream system if possible, or at least highly unstable sites within the stream system and areas immediately up and downstream of the unstable areas, to evaluate potential negative geomorphic effects (Reid and Church, 2015). Study reach lengths will vary depending on scale of erosion problems and size of the channel. A rapid geomorphic assessment (RGA) (Simon and Klimetz, 2008b) or historic aerial photos can be used to aid in the selection of the study reach.

2.1.2. Set stabilization objectives

Once the study reach is determined, specific and measurable project parameters should be set (e.g., a desired sediment reduction or cost constraint). Ultimately, both cost and sediment reduction will be considered, but one or the other may be a driving factor for the project. For example, if a certain amount of money is available for stabilization, the objective could be to determine the most effective stabilization practice for that investment. Alternatively, a certain amount of sediment reduction may be required to be in compliance with water quality standards; thus, the objective may be to find the least expensive solution to achieve the sediment reduction goal.

2.1.3. Select stream channel model

An appropriate stream channel model should incorporate sediment transport and bed adjustment, fluvial erosion and mass wasting processes of the streambank, and should be able to simulate these processes on a reach-scale. Incorporation of a reach-scale model allows for the consideration of any potential negative effects of stream stabilization upstream and downstream of the site of interest. A number of one-, two-, or three-dimensional numerical models for hydraulics and sediment transport are available. While one-dimensional models cannot simulate complex flows around in-stream structures or localized changes in morphology as