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Bedload entrainment in low-gradient paraglacial coastal rivers of Maine, U.S.A.: Implications for habitat restoration

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ABSTRACT

The rivers of coastal Maine flow through mainstem lakes and long low-gradient reaches that break the continuum of bedload transport expected in nonparaglacial landscapes. Stream erosion of glacial deposits supplies coarse sediment to these systems. The land use history includes intensive timber harvest and associated dam construction, which may have altered the frequency of substrate-mobilizing events. These watersheds are vital habitat for the last remaining wild anadromous Atlantic salmon in the United States. Future adjustments in channel morphology and habitat quality (via natural stream processes or restoration projects) depend on erosion, transport, and deposition of coarse sediment. These factors motivate our study of competence at four sites in the Sheepscot and Narraguagus watersheds. Three of the four sites behaved roughly similarly, with particle entrainment during intervals that include winter ice and spring flood conditions, and relatively minor bed mobilization during moderate floods in the summer and fall (with a recurrence interval of 2–3 years). The fourth site, on the Sheepscot River mainstem, exhibits more vigorous entrainment of marked particles and more complex three-dimensional channel morphology. This contrast is partially due to local geomorphic conditions that favor high shear stresses (particularly relatively steep gradient), but also likely to nourishment of the bedload saltation system by recruitment from an eroding glacial deposit upstream. Our results suggest that the frequency and magnitude of bedload transport are reach specific, depending on factors including local channel geometry, upstream sediment supply and transport, and formation of anchor ice. This presents a challenge for stream practitioners in this region: different reaches may require contrasting management strategies. Our results underscore the importance of understanding channel processes at a given site and assessing conditions upstream and downstream as a prerequisite for conducting habitat restoration projects.

1. Introduction

Rivers are dynamic systems that evolve in response to changes in factors including climate (e.g., Knox, 2000; Brardinoni and Hassan, 2006), tectonics (e.g., Snyder et al., 2000), and land use (e.g., Leopold et al., 2005; Walter and Merritts, 2008). The morphology (substrate type, width, flow depth, slope, etc.) of a given river reach reflects the integrated history of water and sediment transport through the reach (e.g., Lisle et al., 2000), among many other factors. Morphologic characteristics such as the size distribution and frequency of transport of bed sediment strongly influence habitat suitability for aquatic species (Kondolf and Wolman, 1993). Interactions among bedload and suspended load transport, flood frequency and magnitude, and erosion and deposition dictate how rivers evolve in response to future changes. In the coming decades, the desire to mitigate the effects of past land use practices on aquatic ecosystems will motivate numerous stream restoration projects (Bernhardt et al., 2005). At the same time, streams are on a "natural" trajectory in response to the compound history of changes in land use and climate history within watersheds (Montgomery, 2004). Therefore, a clear understanding of stream morphology and associated dynamics of bedload transport is a prerequisite for predicting future responses to land use and climate change and for designing successful restoration projects.

Numerous studies have found that substrate entrainment in gravel-bedded rivers typically begins at or near bankfull stage, which occurs on the order of every 1–2 years (e.g., Parker, 1979; Andrews, 1983). These studies have focused on self-formed (or alluvial) rivers with well-defined floodplains and no significant limitations on bedload supply. In this study, we investigate whether gravel-bedded reaches of two low-gradient coastal rivers in Maine, USA have sufficient competence to transport the coarse part of their beds during typical floods. Three factors motivate our work: (i) the non-alluvial characteristics of these rivers; (ii) a lack of prior research on bedload dynamics in the region; and (iii) a need for a more robust framework to guide habitat restoration projects.

The rivers of northern New England are not self-formed; they flow through a deglaciated landscape they did not create. Resistant bedrock

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knobs and glacial deposits adorn these watersheds, with streams essentially scattered onto this template. These "imposed-form" rivers are still actively responding to the local glacial and bedrock history (Church and Ryder, 1972; Ballantyne, 2002; Brardinoni and Hassan, 2006). This disequilibrium results in variable channel morphology, substrate and habitat distribution, unlike the more predictable self-formed rivers that have received greater attention in the classic geomorphic and restoration literature (e.g., Leopold et al., 1964; Rosgen, 1996). In systems like these, coarse sediment sources and transport and erosion of bedrock are first-order controls on morphology (Church and Ryder, 1972; Wohl, 1998; Whipple, 2004) and on aquatic habitat (Montgomery, 2004).

Unlike rivers in other parts of the world, a paucity of relevant bedload transport data exists for this region. We know of no previous published studies presenting measurements of bedload entrainment in Maine rivers. Furthermore, the rivers often show little obvious morphologic indication of active transport of coarse bedload, such as bedforms or sediment storage behind large roughness elements. A goal of this study is to evaluate how well traditional relationships between hydraulics and coarse bedload entrainment, developed in self-formed systems, apply in these paraglacial rivers.

The rivers of coastal Maine are the site of stream restoration projects focused on mitigating the effects of past land use practices and improving habitat for anadromous fish species. Maine rivers have been impacted by land use changes over the past few centuries, particularly related to timber harvest and associated log transport in rivers (Montgomery, 2003; NRC, 2004; Magilligan et al., 2007). These rivers are believed to be currently wider, shallower, and freer of large roughness elements than in pre-European-settlement times because of diminished bank stability from the harvest of trees adjacent to streams, channel clearing for log transport, and increased fine sediment delivery from clear-cutting and road building (Montgomery, 2003; NRC, 2004). Declining Atlantic salmon populations in rivers of the region may be related to loss of habitat diversity and quality caused by these changes, and this motivates restoration efforts (Thompson and Stull, 2002; Arter, 2003; NRC, 2004; SVCA, 2005). Specifically, altered channel geometry could change the frequency of coarse substrate-mobilizing events. This could lead to channel-bed armoring or embeddedness, both of which are associated with poor conditions for salmon spawning success (e.g., Kondolf and Wolman, 1993; Suttle et al., 2004). Armoring, typically from low bedload sediment supply (Dietrich et al., 1989), is problematic because adult females must move gravel (median, $D_{50}\approx15$–35 mm, Kondolf and Wolman, 1993) to build redds in which to lay their eggs. Embeddedness may occur from an overabundance in supply (often related to land clearing) or buildup of sand and silt if coarse substrate-mobilizing events are too infrequent to flush finer particles. In either case, the problems result in a reduction of flow of dissolved oxygen to incubating eggs in redds and declines in macroinvertebrate diversity (Barnard and McBain, 1994; Suttle et al., 2004). At the end of this article, we discuss how our findings on coarse bedload transport can guide future habitat restoration efforts.

2. Study area

2.1. Maine rivers

In this study, we present observations of bedload entrainment during floods using marked particles at four locations in the Narraguagus and Sheepscot River watersheds (Fig. 1). While our focus is on contemporary processes, the geologic, geomorphic, and historical land use context of these systems is important background.

The SW–NE trend of the Maine coast primarily reflects oblique deformation during the Silurian–Devonian Acadian orogeny (Osberg et al., 1989). Paleozoic metamorphic rocks underlie the upper Narraguagus watershed and Devonian granites dominate the lower part. The metasedimentary rocks underlying the Sheepscot watershed are located within the Norumbega shear zone (Osberg et al., 1985), which imparts a strong NE-trending fabric onto the drainage pattern (Fig. 1).

These rivers flow through a landscape that bears the imprint of late Pleistocene glaciation and retreat, isostatic depression and rebound, and Holocene eustatic transgression (Belknap et al., 2002). The Narraguagus watershed upstream of the Beddington Lake outlet (>120 m elevation; Fig. 1) is landward of the maximum transgressive shoreline during deglaciation (~12.5 ka) and dominated by an esker than runs along the west side of the present course of the mainstem river (Smith, 1985; Thompson and Borns, 1985). The lower part of the watershed is dominated by a coarsening-upward sequence of glaciomarine muds with overlying sand and gravel that has been incised by the river (FitzGerald and Tary, 2001). The Sheepscot watershed is seaward of the late Pleistocene shoreline (Smith, 1985), so fine-grained glaciomarine deposits dominate the river valley. Sand and gravel outcrops in zones of coarse glaciomarine and esker deposits in the western and northern parts of the watershed (Thompson and Borns, 1985).

The longitudinal profiles of lowland Maine rivers are characterized by variable gradient in the downstream direction (Fig. 2), unlike the monotonic declining trend expected in rivers in general (e.g., Mackin, 1948; Hack, 1973). These "steeps" (typically with channel gradient, $S>0.002$) and flats ($S<0.0005$) reflect the bedrock and glacial history of the watershed. The higher-gradient sections are typically pebble- or cobble-bedded and straight, with few bars or other depositional features, and occasional outcrops of bedrock. Streams in the Sheepscot watershed are steep when they cross the lithology (flow SE) and are low gradient in strike-parallel reaches (Fig. 2). Both rivers have mainstem lakes along their profiles (Figs. 1 and 2). The low-gradient reaches (some ~10-km long) are known locally as "deadwaters" and are characterized by relatively deep (>1 m), single-thread channels surrounded by wetland floodplains. In some cases this channel morphology may be partially influenced by breached dams (Walter and Merritts, 2008). However, over the long term, these low-gradient reaches likely reflect the transformation from lakes to wetlands as troughs fill with sediment scavenged from glacial deposits. Bedrock sills that the rivers have encountered as they erode through glacial sediments also control base level in many places. For the purposes of this study, the wide variation in channel gradient along the river profiles is important because the deadwaters break the continuum of bedload transport. Gravel cannot be transported through the long low-gradient reaches (particularly the mainstem lakes), so it must be sourced locally, mostly by mainstem and tributary erosion of glacial deposits. Mass-wasting processes are rare in these low-gradient watersheds. The relative lack of gravel bars or sand deposits behind channel boulders or large woody debris (LWD) (Magilligan et al., 2007) is consistent with sediment supply-limited conditions (Yarnell et al., 2006).

Superimposed on the post-glacial response, land use changes over the past few centuries affect the rivers of Maine (Montgomery, 2003; NRC, 2004; Magilligan et al., 2007). Intensive timber harvest began around the start of European settlement. Peak deforestation occurred in the late nineteenth century, and forest cover has increased since then (Montgomery, 2003; NRC, 2004; Wilson, 2005). Historically, both the Narraguagus and Sheepscot Rivers were used to transport logs, which included removing LWD and other roughness elements from channels. Splash dams, which create temporary lakes to store cut timber and then sluice the logs downstream, were used in the Narraguagus watershed and probably used in the Sheepscot as well. Currently ~60% of the Narraguagus watershed (mostly in the upper part) is managed by timber companies for harvest (Arter, 2003). Commercial blueberry fields are also common. The Sheepscot watershed is mostly privately owned by small landowners and is therefore a mixture of small woodlots, agricultural fields, and homes.