SAND TRANSPORT AND BED EVOLUTION MODELING APPLICATIONS IN THE COLORADO RIVER, GRAND CANYON

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INTRODUCTION

The closure of Glen Canyon Dam in 1963 shut off the mainstem sand supply and altered the natural flows in the Colorado River through the Grand Canyon. The effect of these alterations to the natural river has been the subject of ongoing research, including studies of the changes in sand supplies and sedimentary processes, with an emphasis on the erosion and restoration of sand bars. One component of these studies has been the development and application of unsteady flow models (Wiele and Smith, 1996; Wiele and Griffin, 1997), 1-dimensional sand transport models (Randle and Pemberton, 1987; Bennett, 1993), and multi-dimensional models of flow, sand transport, local erosion and deposition (Wiele and others, 1996; Wiele, 1997; Wiele and others, 1999; Wiele and Franseen, 1999). This paper is a brief overview of the multi-dimensional model and outlines modeling applications to date.

BACKGROUND

Prior to the closure of Glen Canyon Dam (Fig. 1), approximately 57 million metric tons of sediment, 40% sand, was delivered to the Grand Canyon in the mainstem annually (Topping and others, 2000a). Two main tributaries continue to supply sand. The Paria River, located about 24 km downstream from the dam, delivers about 3 million metric tons of sediment annually, 50% sand (Topping and others, 2000a), and the Little Colorado River, located about 120 km below the dam, supplies about 8.6 million metric tones of sediment annually, 30 to 40% sand (Topping and others, 2000a). Ungaged tributaries deliver about 0.70 million metric tons of sediment, 75% sand, between the dam and the Little Colorado River confluence (Webb and others, 2000). Peak discharges, which typically exceeded 2800 m^3/s during spring flows prior to the dam, currently rarely exceed the 900 m^3/s maximum that can used for power generation at the dam.

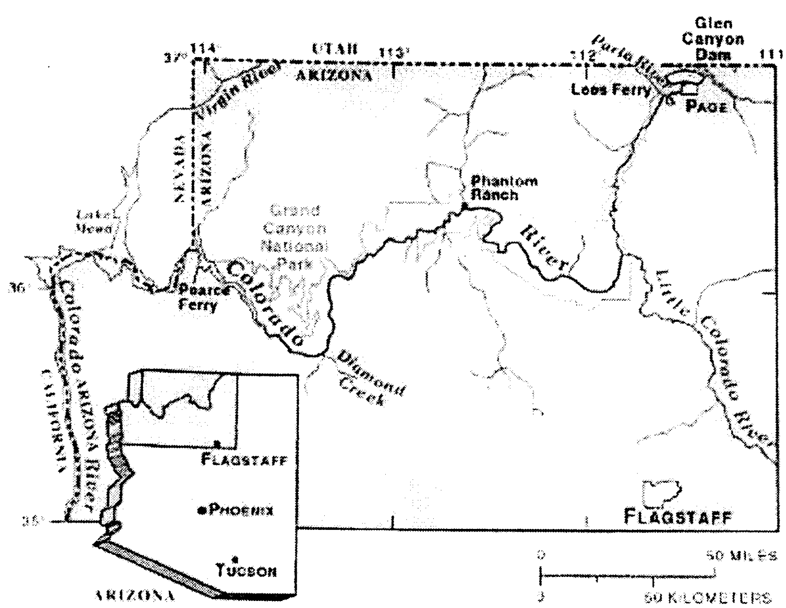

Figure 1. Map of the Colorado River below Glen Canyon Dam.

Maintenance and restoration of sand deposits has focused on distributing the sediment supplied by tributaries to near-shore sites by releasing high discharges in excess of power-plant capacity (Bureau of Reclamation, 1994). Optimum use of tributary-supplied sediment would require high flows to coincide with or shortly follow tributary activity (BOR, 1994). Timing releases with Little Colorado River flows was recommended by Lucchita and Leopold (1999). Careful analysis of suspended sediment measurements and the implications for sand transport processes by Topping and others (2000b) led to their recommendation that high releases instead be triggered by Paria River flows. They concluded that this would produce maximum deposition in the critical Marble Canyon reach, which is upstream from the confluence with the Little Colorado River and has a relatively small sand supply.

A controlled release from the dam in 1996 of 1270 m^3/s for 6 days, although not closely following major tributary activity, rejuvenated many of the near-bank sand bars, especially below the confluence with the Little Colorado River (see Schmidt, 1999, for a summary of monitoring and research results). This release demonstrated that judicious high releases from Glen Canyon Dam can be effective in mitigating some of the deleterious effects of the dam on the downstream river corridor. The model described below is designed to provide a predictive capability of the effects of sand supply and dam operation on sand deposits.

OVERVIEW OF THE MODEL

The multi-dimensional model is an extension of a model initially developed to study bank erosion and bar formation and stability in gravel-bed rivers (Wiele, 1992). For Grand Canyon applications, suspended-sand transport was added. The flow field is calculated with the vertically averaged momentum and continuity equations for open channel flow. A 3-dimensional advection-diffusion equation that governs the suspended sand field is solved using a parabolic eddy viscosity related to the local shear velocity to quantify the turbulent mixing. A sand concentration near the bed (Smith and McLean, 1977; Wiberg and Rubin, 1985) is used for the lower boundary condition. The sand fall velocity is calculated using the method of Dietrich (1982). The vertical variation in velocity is estimated using a logarithmic velocity profile consistent with the parabolic eddy viscosity. The product of the velocity and suspended sand concentration is integrated vertically to calculate the local suspended sand discharge. The sand transported as bedload is calculated using a bedload function (Meyer-Peter and Mueller, 1948) including the effect of local bed slope on transport rates (Nelson and Smith, 1989). In areas with sufficient sand thickness, local roughness and skin friction are calculated using the method of Bennett (1995) that relates bedform dimensions to flow conditions and sand size. In areas with little or no sand, local channel roughness is calculated as a function of the spatial variability in the bathymetric measurements that form the basis for the gridded channel topography. Local change in bed elevation is then calculated for a small time step with a sediment continuity equation. More detailed descriptions of the model can be found in Wiele and others (1996, 1999).

The bathymetry used to generate the gridded topography in the model was measured by the U.S. Geological Survey (USGS) and the Grand Canyon Monitoring and Research Center. Sand flux into the reaches was taken from measurements (Konieczki and others, 1997) or rating curves for specific events (G.G. Fisk, USGS, personal communication, 1994), or from a model that predicts sand flux as a function of discharge for specified sand supplies (Topping, 1997).

MODEL APPLICATIONS

The model has been used to examine processes during a tributary flood, compare the effects of natural and dam-generated high flows on sand deposits, predict the effects of variations in water discharge and sand supply on deposition rates and magnitude, and examine the effect of channel shape on locations of deposition and scour and changes in deposit volume. Applications to other disciplines include predictions of sand bar response in reaches containing archeological artifacts (Wiele and Franseen, 1999) in which preservation has been linked to the size and persistence of sand bar deposits (Hereford and others, 1993; Thompson and Potochnik, 2000). The flow component has been used to examine the effect of discharge on endangered fish habitat.

A comparison of natural and artificial events and the effect of sand concentration on sand deposition was examined by Wiele and others (1999) by comparing the results of a flood on the Little Colorado River (LCR) in 1993 and the 1996 controlled release from Glen Canyon Dam. The LCR flood transported about 4 million metric tons of sand into the main channel and increased the mainstem water discharge to a peak of about 950 m^3/s. Massive sand deposits were observed after the LCR flood receded, especially in the 20 km below the confluence. The USGS measured 3 to 5 channel cross sections in 4 reaches ranging from 1/4 to about 1 km in length before and after the LCR flows. The reaches are typically bounded upstream and downstream by riffles or rapids that are formed by debris flows that partially constrict the channel. Recirculation zones form in the lee of the debris fans and can act as effective sand traps. Sand input into the mainstem estimated from gage records (G.G. Fisk, USGS, personal communication, 1993) was used to set the upstream sand boundary-condition for the reaches.

In the reach known colloquially as the Salt reach (Fig. 2a), about 129 km below the dam, model predictions agree well with the measured cross sections (Wiele and others, 1996). Both the model and the measured cross sections show deposition in the main channel, filling a deep hole scoured into the bedrock downstream from the reach inlet, as well as extensive deposition within the recirculation zone during the LCR flood (Fig. 2b). This result contrasts sharply with the deposition pattern during the 1996 controlled release (Fig. 2c) during which sand concentrations were much lower than during the LCR flood and the water discharge was higher. During the 1996 controlled release, which had a discharge of 1270 m^3/s, the main channel was scoured. Deposition in the recirculation zone was focused at the reattachment point. Sand was carried in suspension into the recirculation zone and initially deposited rapidly. Once the initial accommodation space (defined by Hazel and others, 1999, as the underwater volume of potential deposition sites) was filled, the model shows that further deposition could proceed only at the rate at which sand was redistributed within the recirculation zone as bedload. Model predictions are compared to bathymetric measurements during the 1996 controlled release (Andrews and others, 1999). The model accurately predicts the general deposition and scour patterns recorded by the bathymetric measurements (Wiele and others, 1999). A disparity exists, however, downstream from the main channel scour zone where deposition was documented by the bathymetric measurements in a high-stress zone. This discrepancy is likely a result of the transport and deposition of coarser material than is represented in the model.

In reaches in which deposition is dominated by recirculation zones, model predictions of sand deposition as a function of water discharge and sand supply follow a consistent pattern. A reach designated the Palisades reach (Fig. 3) by Hereford and others (1991, 1993), at 134 km below the dam, was modeled with 2 discharges, 1270 and 2800 m^3/s, and with 3 different sand supplies (Topping, 1997). The sand conditions represent sand supplies during historically high measurements (high); during the 1996 controlled release, which is representative of the post-dam conditions (intermediate); and a relatively depleted state resulting from prolonged high discharges approaching 2800 m^3/s after the closure of the dam (low). At the highest flows modeled, 2800 m^3/s, with the lowest sand supply, modeled deposit volume exceeds the volume deposited predicted at lower discharges even with the highest sand supply (Fig. 4). This result demonstrates the importance of the magnitude of the accommodation space in determining deposit volume and the effect of the hydraulic isolation from the main channel on the accumulation of sand in the recirculation zones.

Recirculation zones have tended to be the focus of sediment research due to the effectiveness with which they retain sand. While reaches dominated by recirculation zone show a consistent pattern, other reaches can show considerable variability in response to discharge and sand supply. The reach designated the Above Lava-Chuar (ALC) reach (Fig. 5a), about 133 km below the dam, contains a relatively constrained recirculation zone, but also has a gradual expansion with a sand deposit just downstream from the reach inlet. At 1270 m^3/s and the intermediate sand supply, this bar is partially eroded (Fig. 5b), but at 2800 m^3/s with the intermediate sand supply, the bar is scoured out (Fig. 5c). This modeling result is consistent with the conclusions of Melis (1997) that the slope of the channel side at constrictions plays an important role in determining whether scour or deposition occur in the lee of the constrictions. Increased scour at the higher discharge for a given sand supply is opposite to the response in recirculation zones. Overall, the response of sand deposits in reaches such as the ALC reach is likely to be far outweighed by deposition in recirculation zones, but the response is of particular interest in some reaches, such as those containing archeological artifacts.

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