Geomorphic response of the Madison River to point sediment loading at the Madison Slide, southwest Montana
by Theodore Roy Turner

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
The nature and rates of morphologic adjustments of streams to point sediment loading are poorly understood. No widely applicable method or model currently exists for predicting the magnitude and duration of effects of point sediment loading on channel morphology and longitudinal profile development, including the form, extent, and ages of terraces that may develop during stream rejuvenation following a sediment loading event.

This study presents an empirical, numerical model that quantifies the geomorphic response of the Madison River in southwest Montana to the sediment imposed on it by the Madison Slide in 1959. The basis of the model is the thirty year adjustment of the river longitudinal profile below the slide. The model provides a conceptual framework for future investigations of the morphologic impact of coarse, point-sediment loading on channel morphology.

The adjustment of the river longitudinal profile is reconstructed using 1959 and 1989 surveys of the water surface and surveys of a flight of fluvial terraces that are forming below the slide. The timing of terrace formation is established using aerial photographs, discharge data, and estimates of threshold-exceeding flows.

The river has incised approximately 20 m into the slide debris and currently lies 39 m above its former channel at the slide crest. The locus of bedload aggradation is currently 2.7 km below the outlet of Quake Lake. The model predicts that the future limit of recognizable bedload aggradation below the slide will occur approximately 5.5 km downstream of the Quake Lake outlet, or 2.8 km from where it is currently. Calculated aggradation and degradation rates using post-1959 terrace long profile data suggest that the time needed for slide debris to prograde this distance is approximately 110 years.

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Theodore Roy Turner

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The nature and rates of morphologic adjustments of streams to point sediment loading are poorly understood. No widely applicable method or model currently exists for predicting the magnitude and duration of effects of point sediment loading on channel morphology and longitudinal profile development, including the form, extent, and ages of terraces that may develop during stream rejuvenation following a sediment loading event.

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INTRODUCTION

The Problem

The nature and rates of morphologic adjustments of streams to point sediment loading are poorly understood. Much research regarding stream response to sediment loading has been in proglacial systems adjusting to changes in water and sediment discharges imposed by changes in the state of flux of a glacier (Krigstrom, 1962; Fahnestock, 1963; Price, 1971; Church and Ryder, 1972; Maizels, 1979; Thompson and Jones, 1985). Others have examined sediment transport and channel adjustments following mass movements into stream channels (Harvey, 1980; Madej, 1982; Pearce and Watson, 1986; Perkins, 1989; Miller, 1990) and increased sediment loads imposed by human activities such as mining (Gilbert, 1917; Pickup and others, 1983; Lewin and Macklin, 1987; James, 1989; Knighton, 1989). A recent example of rapid geomorphic response from sediment loading of high magnitude is terrace formation along the upper Toutle River drainage following deposition of rockslide–avalanche and pyroclastic debris from the 1980 eruption of Mount St. Helens, Washington (Paine, 1984; Meyer and Martinson, 1989).

However, no widely applicable method or model currently exists for predicting the magnitude and duration of effects of point sediment loading on channel morphology and longitudinal profile development, including the form, extent, and ages of terraces that may develop during stream rejuvenation following a period of aggradation brought on by increased sediment loads. The numerous studies initiated more than thirty years ago on the physics of fluid dynamics and particle motion may allow modeling of sediment transport and channel adjustment over very brief time periods, and the assumption of a steady–state may be appropriate for geologic time periods. Yet, the time scale in which modeling of fluvial forms and processes is least understood is on the order of years to centuries (Meade, 1982). These are precisely the time scales land managers, environmental scientists, and civil engineers must incorporate into their design and management activities. It is important therefore to define the nature of stream response to perturbations such as point sediment loading where historic data on such responses are available.

The objective of this study is to quantify and explain the geomorphic response of the Madison River, in southwest Montana, to the point addition of sediment imposed on the river by the Madison Landslide (Madison Slide), a large earthquake–induced rockslide that dammed the channel in 1959 (Figure 1). More specifically, this study develops an empirical numerical model that quantifies the evolution of the long profile and identifies the variables controlling the formation of a sequence of fluvial terraces below the slide as the Madison River regrades. The study also documents the nature of the downstream propagation of the sediment load from the slide across both time and space and suggests a methodology for generalizing to other rivers and sediment inputs.

The introduction of 3.7 x 10^7 yd^3 (2.8 x 10^7 m^3) (Hadley, 1964) of debris into the channel at the Madison Slide has created a natural laboratory in which to study and document 30 years of terrace formation and channel adjustment in a high energy environment. The site not only bears the advantages of natural scale but also many of the advantages of flume models such as a large quantity of readily available and erodible unvegetated sediment, rapid response time, and relatively well–known discharges. Emergency work and spillway construction on the slide by the United States Army Corps of Engineers (A.C.E.) in the months following the event has provided a detailed database of initial channel response, including the early adjustment of the channel long profile. Only rarely are initial and boundary conditions so well known in natural systems. No study, either cursory or comprehensive, has been directed at the responses of the Madison River to the Madison Slide following work by the A.C.E. in the fall of 1959. The Board of

Consultants, employed to oversee emergency work at the slide by the A.C.E. and others in 1959, suggested that surveys of channel response be continued at the slide for several years (A.C.E., 1960), however, these surveys were never carried out.

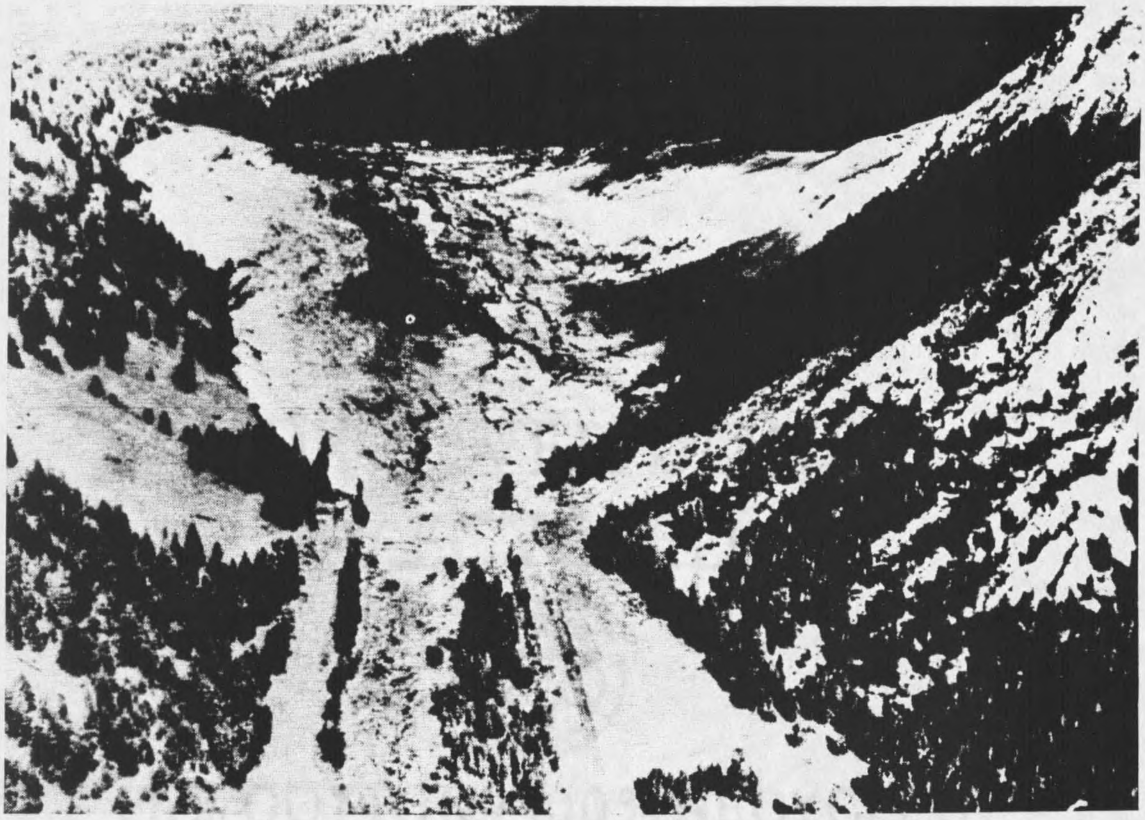

Figure 1. The Madison Slide shortly after it blocked the Madison Canyon in August of 1959 (from A.C.E, 1960).View is upstream.

The ultimate aim of studies of this type is a predictive model of stream response to sediment loading. Perhaps the most important application of such a model is the prediction of stream responses as a function of stream energy, amount and caliber of imposed load and valley morphology, including the prediction of erosional and depositional thresholds. For those who are attempting to control or manage the fluvial system, such predictions are useful. Quantitative modeling of how much variation in the controlling variables a stream system can tolerate before change occurs is also an important goal in the fields of fluvial geomorphology and hydraulic engineering.

An understanding of long profile adjustments of a stream to sediment loading will also aid the interpretation of ancient fluvial deposits and landforms such as glacial outwash terraces. Terraces are common in many basins and they provide the geomorphologist with the opportunity to observe the form of the river long profile as grade is approached from an initial disequilibrium profile. Terraces are commonly used to date events and document changes in fluvial conditions, in particular the rates of channel adjustment of which little is known. The post–1959 terrace sequence below the Madison Slide may serve as a modern analog to terraces of larger scale, assuming terrace formation is scale independent.

Questions

In light of the objectives, the research questions to be addressed in this study are:

- What is the nature of the spatial and temporal evolution of the longitudinal profile of the Madison River in response to the point addition of load from the Madison Slide?
- How far downstream from the Madison Slide point will channel morphology be affected?
- At what rate will the locus of channel aggradation and prograde down the valley and what variables control this rate?

The methodology employed to achieve the above objectives and questions involve quantifying the morphologic response across time and space. Specifically, this includes reconstructing the thirty year evolution of the long profile from surveyed water surface and terrace long profiles and determining the nature and rates of aggradation and degradation downstream of the slide and the variables that control these processes. Rates of vertical channel adjustment and chronology of the post–1959 terrace sequence below the slide are interpreted using aerial photography and discharge records. Description, genesis, and correlation of the terrace sequence are also detailed. Morphologic adjustments of streams to sediment loading may be controlled by morphologic variables other than slope. Therefore, planimetric adjustments of the river are identified using aerial photographs.

Morphologic adjustment processes of streams are dependent on the stochastic nature of water and sediment discharges, therefore, stream behavior prediction is a probabilistic problem (Heede, 1980). However, the resistance of streams to change is also a function of deterministic properties such as the particle size of channel sediments. These properties, therefore, are analyzed in the context of measured aggradation and degradation rates and the processes which controlled terrace formation below the slide. The results are then numerically modeled with the purpose of predicting the temporal and spatial limit of morphologic change that is a direct result of the point addition of sediment from the Madison slide.

Study Area

The Madison River heads in Yellowstone National Park, Wyoming, and flows northwest where it enters Hebgen Lake (Hebgen Reservoir), a Montana Power Company water storage impoundment (Figure 2). The river then flows west through the Madison Canyon and leaves the Madison Range at the canyon mouth in the vicinity of the Madison Slide where it flows through the Missouri Flats region of the southern Madison Valley — an alluvial valley 10 km wide by 20 km long. The river eventually joins the Gallatin and Jefferson rivers near Three Forks, Montana where they form the Missouri River.

In the Missouri Flats region is a sequence of well preserved terraces which lie approximately 3–15 m, 30 m, and 45 m, above the modern river [Qta and Qt sequence of Lundstrom (1986)]. These surfaces and others in the Madison Valley were first recognized by Peale (1896) and have been subsequently described by many others [see Lundstrom (1986) for a comprehensive list of authors]. The terraces are inferred to be glaciofluvial in

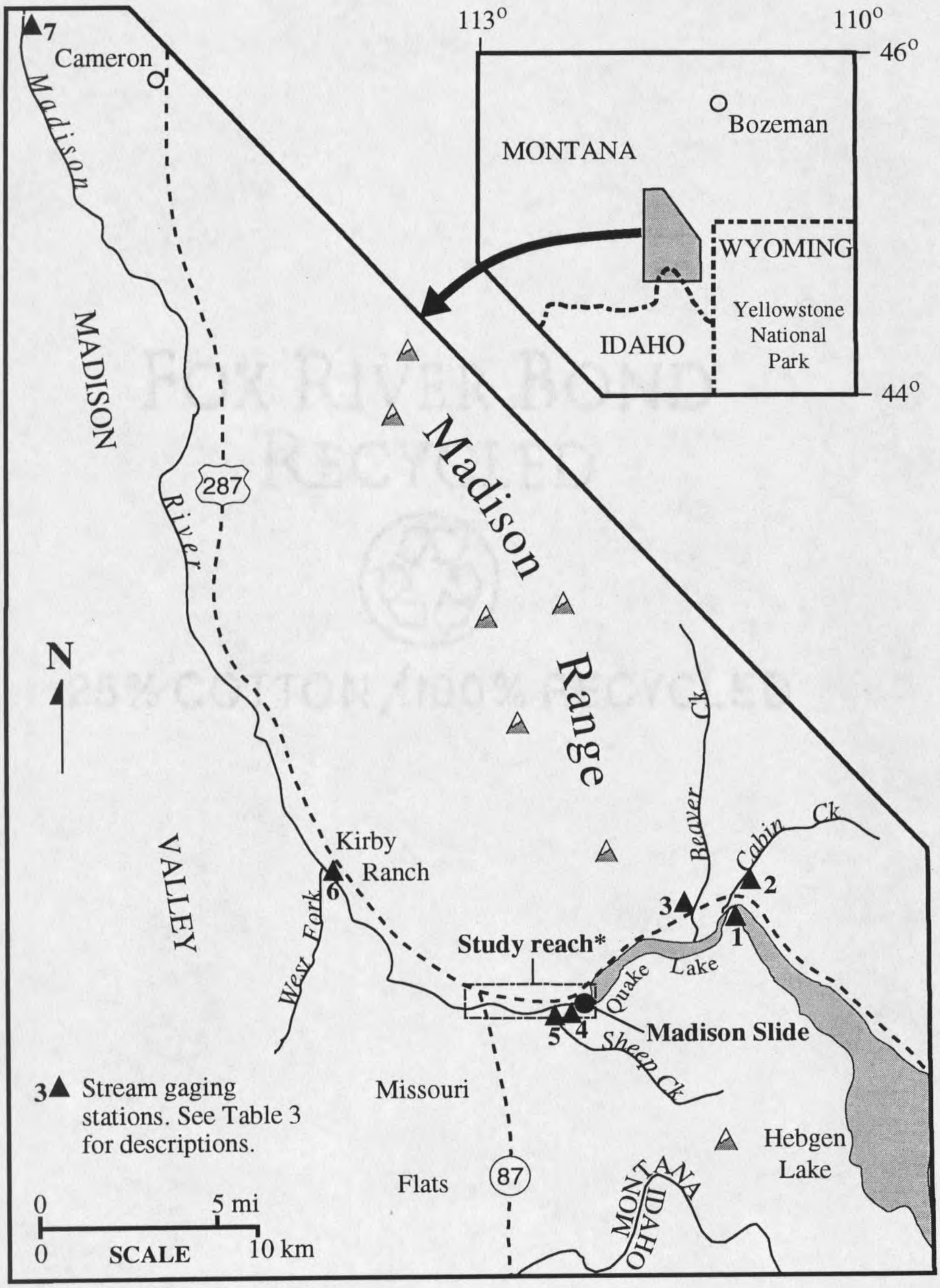

Figure 2. Study area. *See Figure 26 for detailed map of study reach.

origin (Lundstrom, 1986; Alexander and Leeder, 1990), and represent aggradational periods during stades of Pinedale and possibly Bull Lake glaciations of the Madison Range and Yellowstone Plateau (Richmond, 1964). Incision of the alluvial fill and formation of the terrace flights may have been the result of periodic high discharge events, or periods of low sediment load. Lundstrom (1986) has suggested that periodic jokulhlaups from valley glaciers tributary to the Madison may have also occurred.

Based on estimated ages of the Missouri Flats surfaces and those on the upper Madison above Hebgen Reservoir (Nash, 1984; Lundstrom, 1986; Alexander and Leeder, 1990), the youngest Missouri Flats terrace may be no older than 30 ka yet no younger than approximately 7.1 ka. This suggests that very little terrace formation along the Madison River has occurred, except for the post–1959 changes, during the Holocene.

Study Site

The reach of the Madison River examined in this study begins at the outlet of Quake Lake and ends at the Raynold's Pass bridge (Highway 87), approximately 3 km downstream (Figure 2). This reach presently is a solitary meandering channel in the upper 1 km of the study area, a broad, braided reach of 3 to 4 channels in the middle 1 km, and a gravel dominated, single channel with sparsely vegetated bars and banks in the lower 1 km.

Drainage basin area at the study site is approximately 2,590 km^2. Average annual precipitation in the upper part of the drainage basin near Yellowstone National Park is approximately 76 cm, decreasing to approximately 40 cm in the lower part of the study reach (USDA–SCS, 1980). Most of the precipitation falls as snow, which results in peak streamflows in May and June for tributaries to the Madison (e.g., Beaver and Cabin Creeks upstream of the study site and Sheep Creek below the Madison Slide) (Table 1). These streamflow peaks are out of phase with the Madison River below Hebgen Reservoir because of the controlled releases from Hebgen Dam.

Table 1. Estimated mean monthly streamflows for the Madison River below Hebgen Reservoir (MR), and for Cabin (CC) and Beaver (BC) Creeks which flow into Quake Lake (upper numbers in $ft^3 s^{-1}$; lower numbers in $m^3 s^{-1}$). Madison River values are measured (recording gage); Cabin and Beaver Creek values are estimates based on regression analysis of basin characteristics, channel width, weighted average estimates (Parrett and others, 1989), and concurrent measurement (U.S.G.S., 1989).

	J	F	M	A	M	J	J	A	S	O	N	D
MR	890	820	810	920	730	1200	1000	1100	1200	1300	1400	970
	25.2	23.2	23	26	20.7	34	28.3	31.1	34	36.8	39.6	27.5
CC	7	6	4	33	180	300	100	23	15	13	9	8
	0.2	0.2	0.1	0.9	5.1	8.5	2.8	0.7	0.4	0.4	0.3	0.2
BC	19	20	14	55	240	300	130	54	37	31	26	21
	0.5	0.6	0.4	1.6	6.8	8.5	3.7	1.5	1.0	0.9	0.7	0.6

Response in the Fluvial System

Equilibrium

The concept of equilibrium in fluvial systems is fundamental to virtually any analysis and discussion of stream adjustment. Put simply, a stream, if left undisturbed, will adjust and stabilize its morphology so that it is just capable of transporting the sediment supplied to a given reach with the prevailing discharge of water. A change in any of the controlling (independent) variables will necessitate a response of the dependent variables which will tend to offset the effects of the change (Figure 3). A stream in equilibrium is therefore self–stabilizing and negative feedbacks dominate the process/response nature of stream systems (Gessler, 1970).

Grade. The graded stream concept (Gilbert, 1879; Davis, 1902; Mackin, 1948) is commonly used to define fluvial systems in equilibrium. A graded stream, or graded stream reach, is currently defined as one in which "over a period of years, slope, velocity, depth, width, roughness, pattern, and channel morphology delicately and mutually adjust to provide the power and efficiency necessary to transport the load supplied from the drainage