NATIONAL CENTER FOR ENVIRONMENTAL RESEARCH
Office of Research and Development
U.S. Environmental Protection Agency

Science to Achieve Results (STAR) Program

Final Report: Formation and Propagation of Large-Scale Sediment Waves in Periodically Disturbed Mountain Watersheds

EPA Grant Number: R824779
Title: Formation and Propagation of Large-Scale Sediment Waves in Periodically Disturbed Mountain Watersheds
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Project Period: January 1, 1996–December 31, 1999
Research Category: Water and Watersheds

Executive Summary

Project Description and Objectives of Research:

Human-induced disturbances in mountain watersheds such as mining or timber harvesting, combined with hydrologic conditions appropriate for the release of large amounts of sediment, often lead to the formation and propagation of large-scale pulses of sediment in rivers. Such pulses typically enter mountain rivers as landslides or debris flow deposits. These massive inputs of excess sediment can lead to temporary or long-term deleterious effects on the morphology and ecosystem of the river. In addition, they can cause the failure of bridges and pipelines, as well as the loss of adjacent infrastructure such as roads.

Sediment pulses are natural phenomena, the frequency of which can be greatly increased by anthropogenic effects. One goal of the research was to determine how rivers "digest" this excess sediment. A commonly-advanced hypothesis is that these pulses form downstream-migrating waves that can damage river morphology and habitat far downstream of the point where the pulse initially entered the river. Another hypothesis is that the sediment pulses decay by dispersion with less massive downstream effects. The research was directed toward delineating the dominant mechanism for pulse evolution.

Another goal of the research was the development of a predictive numerical model for pulse evolution that could be applied at field scale. The predictive model was developed with the aid of theory, experiments, and field data.

A final goal was to cast the predictive model in a form so that it could be implemented by land-use managers to determine the short- and long-term effects of large sediment inputs to mountain rivers.

Summary of Findings:

The main goal of the research was achieved in the course of the project. In particular, it was demonstrated definitively that in relatively steep mountain streams covered with alluvium sediment pulses typically decay by dispersion, displaying little tendency for downstream translation. The result was confirmed by means of theory, numerical modeling, experimentation, and an analysis of field data from a landslide into the Navarro River, CA. The most important parameter governing the relative roles of translation and dispersion in pulse evolution is the flood Froude number. If this number is high (but below unity), translation tends to be minimum and dispersion dominates. At very low Froude numbers translation becomes more important. In practical terms, this implies that sediment pulses in typical high-slope mountain gravel-bed rivers tend to disperse in place, whereas in low-slope plains sand-bed streams, both dispersion and translation play an important role.

The research included theoretical, numerical, experimental, and field elements, each of which contributed to the understanding of the phenomenon of sediment pulses. Each of these elements is described below, after which a summary of specific results of the project is provided.

Theoretical Research. Theoretical analysis proved to be a useful preliminary to the main effort of the project. Linear stability analysis of erodible beds in rivers has a long pedigree in the field of fluvial morphodynamics. It was applied to the case of sediment pulses in rivers by considering wavy bed perturbations of small amplitude and specified wavelength ( ). The flow of water over the perturbed bed was described using the linearized 1-D St. Venant shallow water equations. Bed deformation was described using the linearized Exner equation of sediment continuity and an appropriate relation for sediment transport as a function of flow variables. The sediment size was assumed to be uniform. The flows in question are flood flows, which do the bulk of the work of deforming the river bed and determining stream morphology.

The analysis yields specific expressions for two dimensionless parameters: cr, which characterizes the translational wave speed of the sediment pulses, and ci, which characterizes their tendency to disperse. A ratio ci/cr << 1, for example, corresponds to a case for which the pulses translate downstream (or possibly upstream) with only minimal decay. A ratio ci/cr >> 1, on the other hand, corresponds to a case for which the pulses decay so rapidly via dispersion that they translate very little before losing coherence. The parameters cr and ci depend most strongly on two parameters—the flood Froude number

$$\mathbf{Fr}= U / \sqrt{gH}$$

where U denotes flood flow velocity, H denotes flood depth, and g denotes the acceleration of gravity; and wavenumber

$$\mathbf{k=2}\ \pi\ H/\lambda$$

where λ denotes the wavelength of the pulses.

The linear stability analysis demonstrated that small Froude numbers, which are characteristic of low-slope streams, favor pulse translation, whereas large Froude numbers (but not necessary in excess of unity) favor pulse dispersion. By the same token, small wavenumbers (long pulses) favor dispersion, whereas large wavenumbers (short pulses) favor translation. The general implication of the analysis was that long pulses in mountain streams should mostly disperse rather than translate.

Numerical Research. The linear stability analysis helped guide the numerical work, which was fully nonlinear and, thus, capable of describing real-world phenomena. The essential features of the numerical model developed in the course of the project include the following:

- The flow is described with the fully nonlinear, unsteady St. Venant equations, allowing for the routing of flood waves associated with hydrographs.
- Sediment transport was described using a field-based relation for mixtures of gravel containing a wide range of sizes. The formulation was chosen to allow a focus on high-slope gravel-bed mountain streams with heterogeneous sediment. Some studies were conducted using a relation for total load appropriate for low-slope plains sand-bed streams to allow for comparison.
- Conservation of bed sediment was described using an active-layer formulation, allowing for a mobile-bed armor and interchange of sediment between the surface layer and the substrate via bed aggradation and degradation.
- The treatment allowed for a number of rock types of differing abradability in addition to a wide range of sizes. The treatment of sediment conservation specifically allowed for abrasion of gravel to silt as well as transportation. This is important in mountain streams because sediment pulses from debris flows and landslides often contain highly abradable fresh material from hill slopes.
- A shock-capturing numerical technique was used. This allowed the model to handle cases for which the landslide dams flow behind it, which becomes Froude-supercritical as it overflows, and then forms a hydraulic jump downstream. These phenomena are frequently observed in streams that have been temporarily dammed by a landslide.
- The analysis allows for varying water and sediment input down the stream, making it possible to study multiple pulses.

Experimental Research. The numerical formulation used a gravel transport relation appropriate for field application. The relation can be expected to be less accurate in the case of the finer sediment often used in small-scale laboratory experiments. This notwithstanding, laboratory experiments played an important role in both testing the model and increasing the general level of understanding about sediment pulses.

The flume in which the experiments were performed is 45 m long, 0.5 m wide, and 0.7 m deep. It was constructed expressly for experiments on sediment pulses. The sediment fed into the flume was half sand and half pea gravel, with sizes ranging from 0.2 mm to 8 m and a median size of 2 mm. Before introducing any sediment pulses, the model river was allowed to reach a mobile-bed equilibrium at a model flood flow. This equilibrium was characterized by a flow depth of 3.25 cm, a flow velocity of 0.55 m/s, a bed slope of 0.0108, and a Froude number of 0.98. These numbers can be translated easily to field scale using undistorted Froude modeling. At a scale ratio of 1:80, the corresponding field stream would have a width of 40 m, a flood depth of 2.6 m, a median size of sediment of 160 mm, and a bed slope of 0.0108 (same as model). The model thus served as an accurate model of coarse-bedded mountain streams.

In each experiment, equilibrium was established, after which the flow was turned off and a pulse of sediment was placed over a length of the bed toward the upstream end of the flume. The length of the pulse was between 6 and 8 m, and the height varied between 2 and 3.5 cm. Pulse height was chosen to be on the order of the ambient flood flow depth to allow for a clear manifestation of flow blockage by the pulse. After placement, the model flood flow was recommenced and the deformation of the pulse was monitored.

Three kinds of pulses were considered: one with the same grain size distribution as the sediment feed, one that was noticeably coarser than the feed, and one that was much finer. In all cases, the elevation excess produced by the sediment pulse tended to disperse away, showing little tendency to translate. As expected, the time for dispersal was largest for the coarse pulse and shortest for the fine pulse. In the case of the finest pulse, however, end product of dispersion was a thin sheet of sand moving over a coarser bed. This sheet deformed into a series of migrating sand waves, each only one or two sand grains high.

When tested against the experiments, the numerical model performed reasonably well in all cases except for that of the fine-grained pulse. This was expected, as the sediment transport relation used in the numerical model applies to gravel and not sand.

At the end of the main series of experiments, two more experiments were performed to study the evolution of sediment pulses created by the removal of a dam and a debris jam. The sediment released by removal again dispersed for the most part. The experiments suggest that the "blow and go" technique of dam removal may be appropriate for dams on relatively steep mountain streams.

Field Research. The research team on this project did not specifically perform field research. Rather, they joined with an ongoing field effort based at the Pacific Southwest Research Station, U.S. Forest Service (USFS), Arcata, CA. The field effort was directed toward monitoring a landslide that blocked the Navarro River, CA, in March 1995. The slide is shown in the figure.

The Navarro slide **(Figure 1)** showed a number of interesting features. It initially blocked the river, creating a dam behind it. When the dam overflowed the slide material, a zone of supercritical flow formed on the downstream side, followed by a hydraulic jump. The backwater created by the dam resulted in the formation of a small delta about 1 km upstream. All these features were successfully reproduced by the numerical model with a minimum of calibration. In addition, a comparison between nearly uncalibrated model results and field observations over a 3-year period showed excellent agreement. Most importantly, both the model results and field observations were in agreement in describing a sediment pulse due to the slide that essentially dispersed in place with minimal translation.

Figure 1

A second field site used to develop the numerical model was Redwood Creek, California. Here, the copious field data supplied by the USFS allowed for a verification of the flow routing procedure and armoring calculation.

Project Results. The specific results of the project include:

1. It was verified that, in steep, gravel-bed mountain streams, sediment pulses are "digested" mostly by dispersion in place rather than translation. Translation of thin sand or gravel sheets with thickness of one or two grain sizes can occur once the pulse has dispersed to a very thin layer.
2. In low-slope sand-bed streams, such pulses also disperse, but they also can show a significant element of translation before decaying.
3. A numerical model designed for field application was developed to predict the deformation of sediment pulses in mountain streams. The model will be made available for general use shortly.
4. Experiments on dam and debris jam removal in steep mountain streams indicate that the resulting sediment pulse disperses rather quickly. This suggests that the "blow and go" removal technique may be appropriate in at least some cases

Acknowledgments. Thomas Lisle, Redwood Sciences Laboratory of the USFS, and James Pizzuto, University of Delaware, provided invaluable assistance in the course of the project. The help of several of their graduate students also is deeply appreciated.

Papers and Manuscripts:

Presentations:

Cui Y, Parker G. Linear and nonlinear analysis of sediment waves in rivers. Transactions Eos 1997;78(46), American Geophysical Union.

Cui Y, Parker G. Linear analysis of coupled equations for sediment transport. In: Proceedings of the XXVII Congress, International Association of Hydraulic Research, San Francisco, CA, Theme B, 1997;1256-1261.

Cui Y, Parker G, Lisle TE, Gott J, Hansler ME, Pizzuto J, Allmendinger NE, Reed JM. Sediment pulses in mountain rivers. Part 1. Experiments. Water Resources Research (submitted for publication).

Cui Y, Parker G, Pizzuto J, Lisle TE. Sediment pulses in mountain rivers. Part 2. Comparison between experiments and numerical predictions. Water Resources Research (submitted for publication).

Cui Y, Parker G. Sediment transport following dam or debris jam removal. Journal of Hydraulic Engineering, ASCE (submitted for publication).

Cui Y, Parker G. Linear and nonlinear analysis of sediment waves in rivers. Transactions Eos 1997;78(46), American Geophysical Union.

Cui Y, Parker G. Linear analysis of coupled equations for sediment transport. In: Proceedings of the XXVII Congress, International Association of Hydraulic Research, San Francisco, CA, Theme B, 1997;1256-1261.

Cui Y, Parker G, Lisle TE, Gott J, Hansler ME, Pizzuto J, Allmendinger NE, Reed JM. Sediment pulses in mountain rivers. Part 1. Experiments. Water Resources Research (submitted for publication).

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Cui Y, Parker G. Sediment transport following dam or debris jam removal. Journal of Hydraulic Engineering, ASCE (submitted for publication).

Cui Y, Parker G. Numerical model for the evolution of sediment pulses in mountain rivers. Journal of Hydraulic Engineering, American Society of Civil Engineers (in preparation).

Cui Y, Parker G. Numerical model for the evolution of sediment pulses in mountain rivers. Journal of Hydraulic Engineering, American Society of Civil Engineers (in preparation).

Supplemental Keywords: water, watersheds, land, soil, sediments, ecosystem, terrestrial, environmental assets, engineering, hydrology, geology, Pacific northwest, California, CA.

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