Geomorphically Effective Floods

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Investigations of the hydrology and geomorphology of recent floods from the rapid failure of two small upland dams document the unusually large peak boundary shear stress and peak stream power per unit area for each flood. Downstream consequences to alluvial channels and floodplains, however, were minimal. Lack of geomorphic change is attributed to the short duration of the floods, which lasted about six and sixteen minutes each. Distribution of stream power over hydrographs of eight exceptional floods is constructed from channel geometry, discharge rating curves, and flood hydrographs; the resulting curve is defined as a stream-power graph. A stream-power graph gives a better portrayal of the potential for a flood to be geomorphically effective than simple statements of flow magnitude. From stream-power graphs, total energy expended over a flood hydrograph can be computed. Total flood energy may not be a sensitive measure of geomorphic effectiveness without consideration of channel and floodplain resistance. A conceptual model combining flow duration, peak stream power per unit area, flood energy, and alluvial and bedrock thresholds may represent the effectiveness of floods and can distinguish among such cases as (a) floods of long duration, moderate to large energy expenditure, but low peak stream power per unit area. These floods are ineffective in causing significant landform changes in alluvial or bedrock channels; (b) floods of medium to long duration, with medium to large total energy expenditure, and large peak stream power per unit area. These are believed to be the most effective geomorphic floods in any kind of channel because of the optimal combination of peak flood power, duration, and total energy expenditure; and (c) floods of very short duration, low total energy expenditure, but large peak stream power. These floods are also ineffective agents of geomorphic change in spite of record values of peak stream power per unit area because of their short duration, and resulting low energy expenditures.

1. INTRODUCTION

One fundamental underpinning of the science of geomorphology is that the form of the earth's surface is the consequence of past and present geophysical forces acting on the earth's landforms. In fluvial geomorphology, this notion led to the classic question of whether valleys and channels were primarily shaped by frequently-occurring moderate flows, and resulting small forces, or by rare and cataclysmic flows with corresponding large forces [*Wolman and Miller*, 1960].

The maximum discharge of a flood is commonly used as a measure of the potential of a flow to be an effective geomorphic agent, primarily because maximum discharge is routinely measured or computed and published for large floods. In general, the larger the discharge, sometimes indexed by drainage area or recurrence interval, the more change that is anticipated in the channel and valley. A dilemma for geomorphologists is the observation that floods of similar magnitude and frequency sometimes produce surprisingly dissimilar geomorphic results. Unfortunately, few quantitative hydraulic data on large floods have been presented to assess disparities in landform response. Recently, channel boundary shear stress and stream power per unit boundary area have been shown to be more useful concepts than discharge alone in assessing the potential of flood flows to affect landscapes [*Baker and Costa*, 1987].

The concept of "geomorphic work" is difficult to define precisely, partly because the issue is clouded by semantics.

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Geomorphic work in fluvial systems has been variously defined to be represented by the rate of sediment movement [*Wolman and Miller*, 1960], or as the mass of sediment transported through a vertical distance in unit time [*Caine*, 1976]. Depending on the interpretation of what constitutes geomorphic "work", and the relative magnitude of forces acting on the landform during the time of interest, slow and persistent processes that generate low forces may appear to predominate [*Wolman and Miller*, 1960; *Andrews*, 1994], or large and rare floods that generate large forces may be considered to be most significant [*Baker*, 1977].

The recognition that some really large, rare floods may not have long-lasting effects, or cause long-term changes in channel and valley morphology [*Costa*, 1974; *Moss and Kochel*, 1978; *Huckleberry*, 1994] led to the realization that the absolute magnitude or force of a geomorphic process is not the sole factor responsible for the resulting landforms, nor their perseverance. Other controlling factors include landsurface resistance [*Bull*, 1979; *Graf*, 1979; *Brunsden*, 1993], the frequency and ordering of effective processes [*Beven*, 1981], and the rate of recuperative processes following formative events [*Costa*, 1974]. This holistic view of what constitutes an effective event in geomorphology is well captured in the benchmark paper by *Wolman and Gerson* [1978]. There are, at present, no simple measures of flow and effect that have been used consistently in describing the interaction of floods and the landscape.

1.1 *The significance of flood-flow duration*

Our investigations of the recent floods from two small dam failures in Washington and Oregon inspired us to further consider the importance of flood-flow duration with respect to the geomorphic effectiveness of floods. Although these floods had extremely high instantaneous values of shear stress and stream power, they produced few or no geomorphic changes in downstream valleys or channels. The purpose of this paper is to document the role of flood duration as an obvious, but often ignored, critical factor. Flood duration can affect geomorphic response to large flows in several ways. Long flow duration may be necessary to saturate channel banks before they will fail, or aid in the wetting and subsequent expansion of floodplain soils, with concomitant reduction in shear strength. Some finite amount of time may be necessary to break down floodplain vegetation or erode through the cohesive, root-strengthened top strata, after which erosion of less-cohesive substrata can proceed more rapidly. Also, sediment entrained from hillslopes or channels requires time to be transported onto floodplain surfaces, especially if it travels as bedforms.

Flow duration, in addition to flow magnitude and frequency, stream power, resistance of the land surface, and the restorative and recuperative processes between effective events, determines whether a large discharge event is geomorphically effective. Flow duration can be a key to understanding how floods with lower values of peak discharge, shear stress, or stream power, can have greater geomorphic impact in some alluvial channels than floods with larger instantaneous values.

2. INSIGHT FROM FLOODS FROM THE FAILURE OF SMALL DAMS

Floods resulting from the failure of small dams in upland areas can offer a unique perspective into the influence of a high-magnitude event on steep channels and floodplains in small basins. Dam failures in upland areas involve a precisely known volume of water being introduced to a channel at a point location. Dam failures also offer a mechanism for the creation of floods far larger than possible from snowmelt or rainfall-runoff, and that may be unprecedented in the recent or past geological history of the basin [*Jarrett and Costa*, 1986]. Such small-dam failures occur frequently, and many go unreported in the literature. Recent documented examples include rainfall-induced failure of seven earthfill gravity dams in 1977 near Johnstown, Pennsylvania [*Hoxit and others*, 1982], and three earthfill gravity dams in 1989 at Fayetteville, North Carolina [*Mason and Caldwell*, 1992]. The recent failures of two small upland dams in Washington and Oregon present the opportunity to evaluate the role of stream power and flood duration on geomorphic effectiveness in downstream channels and floodplains. Both dams failed rapidly and nearly instantaneously released their stored water down small, steep, upland channels and floodplains.

2.1 *The failure of Reservoir No. 3, Centralia, Washington*

Reservoir No. 3 is a small concrete-lined water-supply reservoir for the city of Centralia, Washington (Figure 1). On Oct. 5, 1991, the bedrock hillslope under the southwest side of the reservoir suddenly failed, and instantaneously released 13,250 m^3 of water down a small steep valley that led to the eastern edge of the city of Centralia. Two houses were destroyed, four city blocks were flooded, and 400 people were evacuated (Figure 2) [*Costa*, 1994].

The reason for the failure is believed to have been a landslide in the silty sandstone bedrock beneath the reservoir, caused by some combination of (a) seepage from

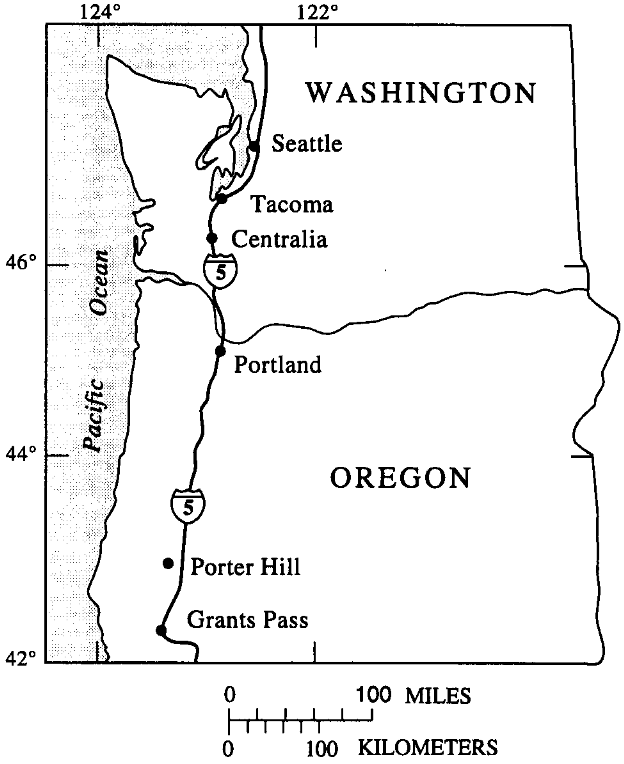

Fig. 1. Location map of Centralia, Washington, and Porter Hill, Oregon, dam failures.

cracked and deteriorated concrete panel seams into the fractured bedrock foundation; (b) stress patterns caused by the quarterly draining and refilling of the reservoir; or (c) a recent increase of 0.6 m in the water level in the reservoir. Sedimentological characteristics of deposits, high-water mark distribution, transport of unbroken beer bottles, and landforms preserved on the valley floor indicated the dam-failure flood consisted initially of a debris flow that deposited coarse gravel and boulders along the channel and floodplain. The debris flow had an estimated volume of 1,800 m^3, and was immediately followed by a water flood that achieved a stage about 0.3-0.5 m higher than the debris flow.

A four-section slope-area indirect discharge estimate was made on Oct. 10, 1991, five days after the dam failure, at a site 275 m below the emptied reservoir (Figure 3). Scour and deposition, a steep channel slope of 0.09, and uncertain roughness coefficients all contribute to some uncertainty in the final peak-discharge estimate of 71 m^3/s. An official for the city of Centralia, responsible for the operation of the reservoir, reported that the reservoir drained in three to five minutes. At a constant discharge rate of 71 m^3/s, it would take 3.1 minutes to drain the reservoir.

Several pieces of data about the dam-failure and resulting flood, such as reservoir volume, reports of drainage time, peak discharge calculations, and average velocity of the flood, allow construction of a flood hydrograph. Using the average peak-flow velocity of 4.2 m/s calculated for the slope area reach, it would take 1.1 minutes for the flood to travel 275 meters from the reservoir to the measurement site. If a triangular-shaped hydrograph is assumed, considering the 13,250 m^3 reservoir volume and the 71 m^3/s peak discharge, the duration of the flood past the slope-area site would be about 6.2 minutes. Consequently, after about 7.3 minutes from the time of the reservoir failure, the flood had passed the indirect-discharge measurement site, and moved into the city (Figure 4).

2.2 *Failure of Porter Hill dam near Roseburg, Oregon*

A private landowner constructed several small earthen dams to collect spring discharge on the flanks of Porter Hill in southwestern Oregon. The dams blocked an unnamed tributary into Olalla Creek, which flows into Lookingglass Creek and eventually into the South Umpqua River. The Porter Hill dam is the largest of these dams, and is located in the NW1/4, SE1/4, sec. 32, T28S, R7W (Tenmile Quadrangle, Oregon). Porter Hill is underlain by rhythmically bedded sandstone and siltstone that has been folded, faulted, and weathered [*Baldwin*, 1974] (Figure 1).

The Porter Hill dam was 5.8 m high, about 20 m wide, and stored an estimated 15,000 m^3 of water at the time of failure. The earthen dam was constructed of local clayey residuum. The exact date of the dam failure is unknown, but it is believed to have failed on or about February 27, 1993 (John Falk, Oregon State Dam Safety Coordinator, personal communication, April 15, 1993). The dam apparently failed during a rainstorm when a large slump on the downstream face of the dam opened a breach with a top width of about 20 m (Figure 5). The large slump led to a near instantaneous failure of the dam, and the release of about 15,000 m^3 of water down a steep upland valley.

Peak discharge from the dam failure was estimated to have been about 30 m^3/s at a location about 150 m downstream from the dam, using the slope-conveyance method (Figure 6). If a triangular-shaped hydrograph is assumed, considering the 15,000 m^3 reservoir volume and the 30 m^3/s peak discharge, the duration of the flood past the slope-conveyance site would be about 16.6 minutes. A reconstructed hydrograph for the flood is shown in Figure 4. Data for the two dams are summarized in Table 1.

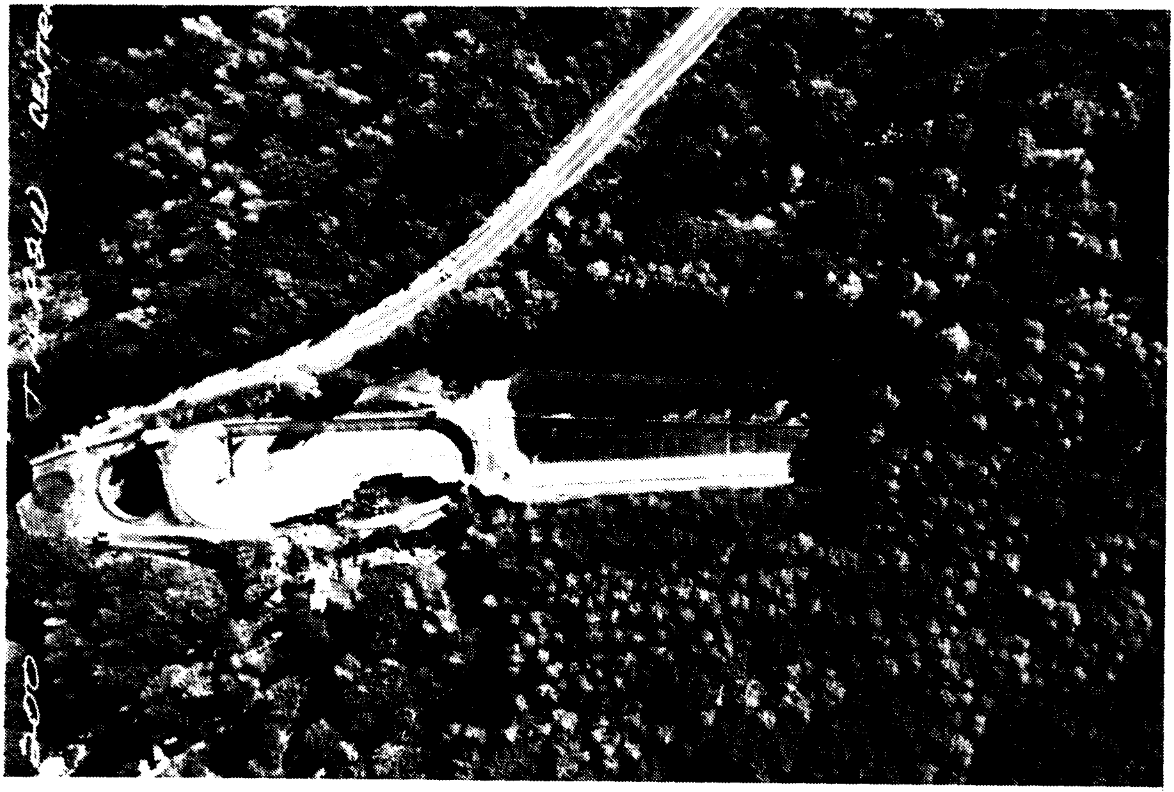

Fig. 2. Airphoto of the failure of Reservoir No. 3, Centralia, Wash. (from Costa, 1994).

3. STREAM POWER, GEOMORPHIC WORK, AND CHANNEL CHANGES

Stream power per unit boundary area (ω) expressed in watts per square meter (W/m^2), is computed from

$$\omega = \gamma QS/w$$

where γ is specific weight of the fluid (9800 N/m^3 for clear water), Q is discharge, S is energy slope, and w is water-surface width. Peak stream power per unit boundary area at the sites of indirect-discharge estimates for the Centralia flood, 3,300 W/m^2, and for the Porter Hill flood, 2,900 W/m^2, are among the largest values ever documented for historic flows [*Baker and Costa*, 1987]. The historic floods in other basins that generated similar or smaller values of peak stream power per unit boundary area all were considered geomorphically effective according to our inspections, and the authors' reports.

In contrast, in spite of the magnitudes of the peak stream power of the two dam-failure floods in Oregon and Washington, the erosional effects on downstream alluvial channels were unimpressive. Characteristics of the original channel at Centralia are not known. The floodplain is about 20 m wide and bounded by a bedrock ridge on one side, and roadfill on the other. The slope is about 0.09, and the surface is grass-covered and regular, with three or four widely-spaced large trees. Floodplain sediment consists of gravel and cobbles in a silt and clay-rich matrix. During the flood, the original channel in the small valley was enlarged, and a 1.5-m headcut formed. The 20-m-wide floodplain was entirely inundated by about one meter of water flowing at about 4.2 m/s, but neither the floodplain nor floodplain vegetation were destroyed or greatly modified (Figure 3). Most of the visible change in the floodplain is attributable to deposition of coarse sediment from the preceding debris flow, not the water flood.

At Porter Hill, the floodplain slopes at about 0.10 and consists of open forest and moss-covered stumps. The surface is covered with leaf litter, ferns, and a few fallen trees. Floodplain sediment consists of poorly-drained and unstratified gravel, silt, and clay. Following the flood at Porter Hill, moss was still intact on the upstream side of trees below high-water marks, and ferns and leaf litter were virtually undisturbed. It was nearly impossible to tell that a large flood, 10 m wide, and 1 m deep, had recently

Fig. 3. Photograph of the floodplain below Reservoir No. 3, Centralia, Wash., where there was only minimal damage from the flood.

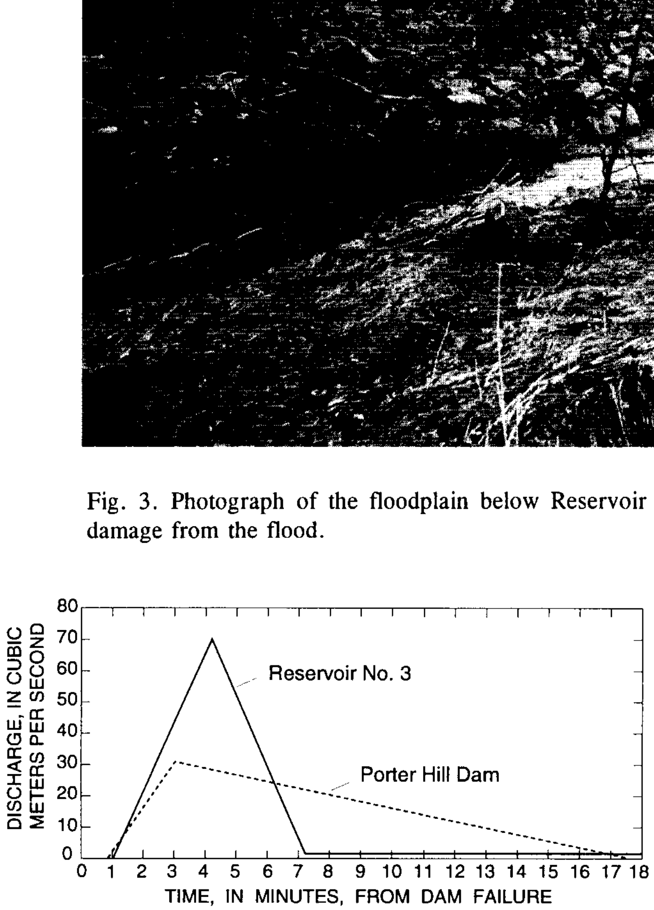

Fig. 4. Reconstructed triangular hydrographs for the Centralia and Porter Hill floods.

passed at about 3 m/s (Figure 6).

During large floods along high-energy fluvial systems, floodplains can become unraveled, severely eroded, and inundated by coarse gravel and debris [*Nanson*, 1986; *Jarrett and Costa*, 1986]. A floodplain that is not ravaged by an extreme flood is the exception, and requires explanation. Some studies that documented the lack of erosion and modifications to channels and floodplains accompanying large floods attributed the lack of land surface disruption to insufficient stream power [*Nanson and Hean*, 1985] or extraordinary stabilization of surfaces by vegetation [*Zimmerman and others*, 1967]. These explanations refer to thresholds of landscape resistance that must be overcome by the flow for it to be effective. The Centralia and Porter Hill floods generated peak stream power values that were likely capable of surpassing resistance thresholds offered by the alluvial valleys and floodplains.

We infer that the lack of disruption of the valley floor despite extraordinarily large peak stream power acting against the floodplain was chiefly a consequence of the very short duration of high stream power during the flood. In both dam-failure floods, high flows were not sustained, and the entire hydrographs passed the study areas within about 16 minutes (Figure 4). The maximum flood power, while large enough to greatly surpass landscape resistance thresholds, lasted for only a small fraction of that time and was not effective in breaking down floodplain vegetation and eroding channels and floodplains. Thus high-energy floods, of very short duration, may cause little geomorphic

Fig. 5. Photograph of breach and slump failure of the Porter Hill dam, near Roseburg, Oregon.

change. We hypothesize that other floods in the same basins with smaller peak stream power values, but longer duration, could precipitate significant and perhaps permanent changes in channels and floodplains.

3.1 *Changing stream power over a flood hydrograph*

If flow duration is believed to be an important factor in the ability of floods to alter landforms, then it is important to know the temporal and spatial distribution of stream power throughout a flood. For flooded locations not at gaging stations, indirect discharge methods are commonly used to calculate peak discharge associated with high-water marks. With data derived from these investigations, only instantaneous peak stream power for the flood can be ascertained and reported [*Costa*, 1987]. Peak stream power is useful in evaluating flood competence [*Costa*, 1983; *Williams*, 1983], but is not the sole factor in evaluating whether a flood may be geomorphically effective. Time-integrated flood power, computed over a hydrograph and combined with some quantitative measures of landscape resistance, such as shear strength of river channel banks and floodplains, may be more useful to evaluate potential for geomorphic effectiveness.

There are no widely applicable procedures to quantify landscape modification accomplished by a given flood. Valuable qualitative descriptions have been used in some studies [*Kochel*, 1988; *Miller*, 1990; *Miller and Parkinson*, 1993], but data requirements for a more rigorous quantitative analysis of landform modification preclude our use of anything but a simple two-class scheme at this time. The amount of geomorphic alteration is assigned a qualitative value of small or extreme. *Small* disruption represents sites where floodplains are inundated, but with little or no erosion of the floodplain surface. Channel scour and erosion are local, drainage patterns remain similar (e.g. a meandering stream still meanders), deposition and sedimentation are restricted to small, local areas, and the valley floor and channel have minimal changes. *Extreme* disruptions occur in areas where the entire floodplain and channel are substantially affected by erosion or deposition. New channels may be formed or the floodplain may be entirely eroded. Extensive areas of deposition may occur on uneroded floodplain or in newly eroded areas during the flood recession. Bedrock, if present, may have been eroded, and the stream channel and stream pattern may be completely realigned. We recognize that deposition of sediment from large floods can significantly alter alluvial

Fig. 6. Photograph of the channel and floodplain about 100 m downstream from the Porter Hill dam. Note the complete lack of any identifying evidence that a large flood had ever passed this location. The tape marks the maximum flood stage.

TABLE 1. Dam and flood characteristics of Reservoir No. 3, and Porter Hill Dam.

Feature	Reservoir No. 3 Centralia, Wash.	Porter Hill near Roseburg, Oreg.
Type of dam	Concrete-lined	Earthen
Date built	1914	early 1990s
Date failed	1991	1993
Height (m)	5.2	5.8
Volume (m^3)	13,250	15,000
Flood depth (m)	1.0	1.0
Slope	0.09	0.10
Discharge (m^3/s)	71	30
Peak ω (w/m^2)	3,300	2,900

forms, but our analysis focuses on the erosional thresholds of extreme floods.

For comparison to the Centralia and Porter Hill dam-failure floods, we analyzed floods from three thoroughly studied historic large-dam failures, one cloudburst-rainfall flood along a sand-bed stream in Colorado, and the flood of record along the Mississippi River (Table 2). We also include two well-known paleofloods, or series of paleofloods, the Missoula and Bonneville floods, which resulted from large natural-dam failures about 10,000 - 15,000 years ago along the Columbia and Snake Rivers.

These floods were selected because (a) we have done field work at all sites except the Mississippi River, and are familiar with the flood effects; (b) the floods were unequivocally large and capable of generating substantial hydrodynamic forces; and (c) we had the appropriate data for our analysis for each flood. All available hydraulic data, except that from the Mississippi River, are from indirect-discharge measurements. Gaging stations, where present, were destroyed during the floods. Indirect-discharge data increase the likely error, but our attempt is to present a concept and approach that can be further verified with better data.

Field investigations and descriptive reports indicate which floods were effective geomorphic floods, and which were not. Little or no change occurred to channels or floodplains associated with the floods from the two small upland dams at Centralia and Porter Hill discussed

TABLE 2. Hydraulic, energy, and geomorphic data for ten well-documented floods that demonstrate different kinds of stream-power graphs

Flood	Peak stream power (W/m^2)	Mean stream power (W/m^2)	Duration ($s \times 10^3$)	Energy expended per unit area (joules $\times 10^3$)	Geomorphic impact	Kind of power-graph	Reference
Centralia, Wash.	3300	1650	0.38	620	Small	C	Costa, 1994
Porter Hill, Oreg.	2900	1450	1.0	1500	Small	C	This report
Plum Creek, Colo.	630	110	68	3900	Extreme	B	Osterkamp and Costa, 1987
Roaring River, Colo.	4300	1200	7.2	8500	Extreme	B	Jarrett and Costa, 1986
Rubicon River, Calif.	6100	3600	22	29,000	Extreme	B	Scott and Gravlee, 1968
Teton Dam, Id.	17,200	3400	29	109,000	Extreme	B	Ray and Kjelstrom, 1978
Mississippi River, Ark.	12	6	1200	21,600	Small	A	Baker and Costa, 1987
Bonneville Flood, Burley Basin, Id.	300	150	11,200	1,700,000	Small	A	O'Connor, 1993
Bonneville Flood, Rock Creek, Id.	90,000	20,000	11,200	220,000,000	Extreme	B	O'Connor, 1993
Missoula Flood, Columbia River Gorge, Oreg. and Wash.	60,000	8100	430	3,500,000	Extreme	B	Benito and O'Connor, 1991

previously, nor to the Mississippi River floodplain or the Snake River alluvial floodplain at the Burley Basin in Idaho. The Mississippi River and Bonneville paleoflood in the Burley Basin were similar in that wide alluvial floodplains and flat channel gradients prevented peak or average stream power per unit area from exceeding erosion thresholds. The other floods all caused severe and widespread channel and floodplain erosion, channel modifications, and erosion of bedrock, where present. These floods exceeded alluvial or bedrock erosion thresholds, and were clearly effective geomorphic agents.

3.2 *Calculations of total energy expenditure using time-integrated stream power per unit area*

The average energy per unit area (Ω) that is expended over the duration of a flood can be represented by:

$$\Omega = \int \gamma QS/w \, dt$$

where γ is specific weight of the fluid (9800 N/m^3 for clear water), Q is discharge in m^3/s, S is energy slope, w is water-surface width, and t is time in seconds. We have numerically calculated Ω for seven large, well-documented historical floods, and two paleofloods (Table 2), by evaluating reported measurements of valley cross-sections, the flood hydrograph, and a stage-discharge curve. Limitation of the data sources are discussed below.

Following floods, hydrographs are constructed in a variety of ways. The ideal situation is to have a stream gage properly operating throughout the flow. In other situations hydrographs can be constructed from peak-discharge measurements, observations of duration, and assumptions about hydrograph shape [e.g. *Costa*, 1994] (Figure 7). For dam-failure floods, downstream hydrographs can be constructed from reservoir draw-down rates, or dam-break models [e.g. *Jarrett and Costa*, 1986]. Cross-sections of channels and floodplains are nearly always made during surveys following floods [*Williams and Costa*, 1988] (Figure 8). They are required for determining the hydraulic variables necessary to calculate discharge. The primary problem with cross-section accuracy results from possible scour or deposition during the flood, and the

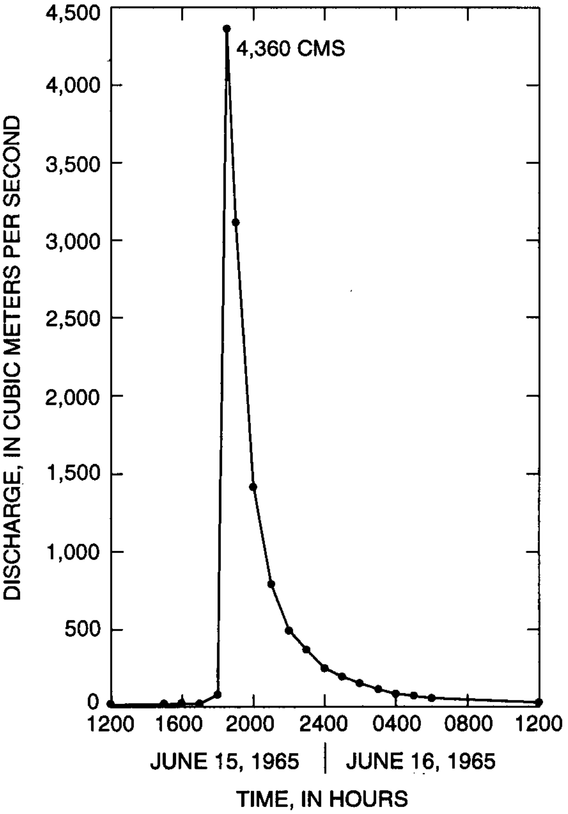

Fig. 7. Hydrograph for the Plum Creek, Colo. flood of June, 1965 (from Osterkamp and Costa, 1987).

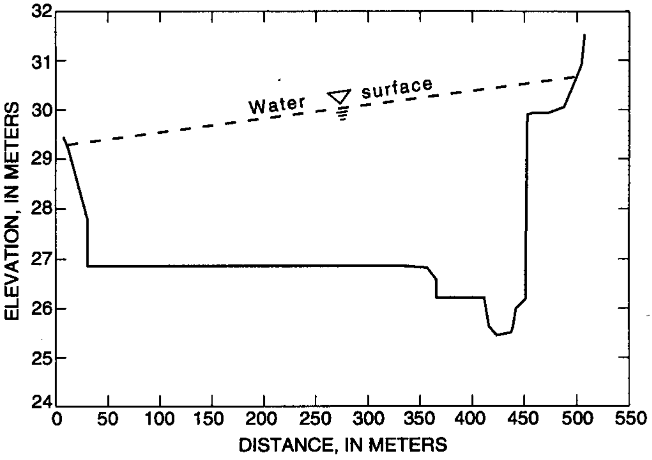

Fig. 8. Cross-section used to construct a flood rating curve for Plum Creek, Colo. flood of June, 1965.

consequent uncertainty in the exact location of alluvial boundaries during the flood peak. Judicious selection of cross-section locations can minimize possible errors. Stage-discharge curves (Figure 9) can be constructed for individual cross-sections by computing hydraulic conveyance for different elevations in the cross-section. The primary source of error in this method as we have applied it is the assumption that the flow resistance is constant at all stages. This is clearly untrue, but roughness values generally change by less than a factor of two with increasing stage once flows are overbank [*Hicks and Mason*, 1991]. Using a hydrograph, cross-sections, and a stage-discharge relation, it is possible to construct a curve of the distribution of stream power per unit area throughout the flood. We refer to these plots as "stream-power graphs" (Figure 10). From these graphs, it is possible to integrate the area under the curve to derive the total amount of energy expended by a flood per unit area, as well as an average value of stream power for the flood (Table 2). These data can then be compared to observations

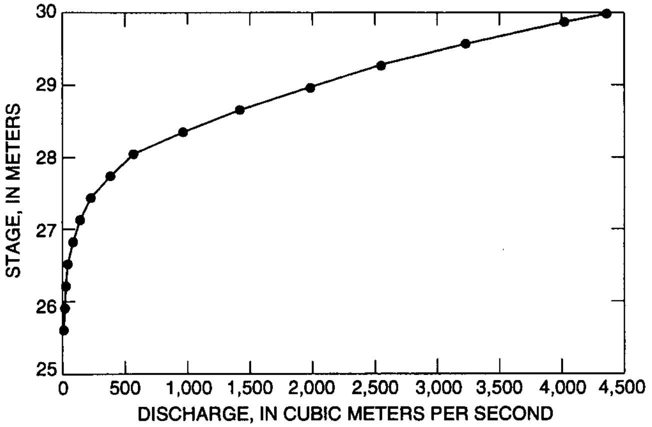

Fig. 9. Stage-discharge curve for the Plum Creek flood of June, 1965.

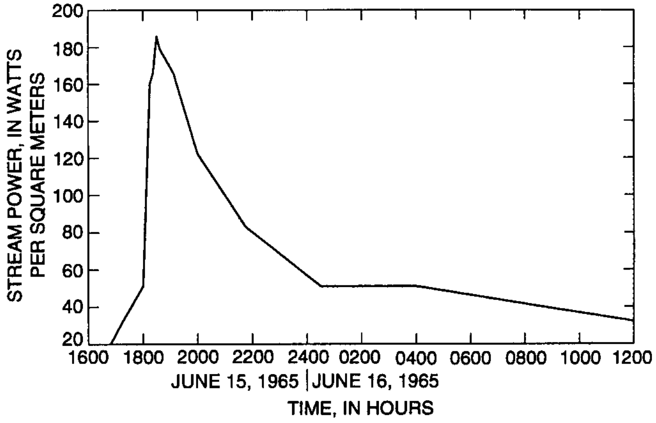

Fig. 10. Stream-power graph showing the distribution of stream power over time for the Plum Creek flood of June, 1965.

and measurements of the magnitude of channel and floodplain disruptions generated by a flood.

Data in Table 2 are not exhaustive, but the information demonstrates the kinds of data required to compute the energy expended per unit area by a flood. The absolute value of flood energy expended per unit area, or the average flood power, may provide no clear differentiation of effective and ineffective floods. Floods with a relatively low average stream power and expended energy can produce catastrophic impacts on alluvial channels and floodplains, such as during the Plum Creek, Colorado flood in 1965 [*Osterkamp and Costa*, 1987]. Other floods like the Centralia, Washington, and Porter Hill, Oregon floods, with five times the peak stream power, and over ten times the average stream power of the Plum Creek flood, can cause only minimal changes. Likewise, long-duration floods on the Mississippi River are capable of generating large values of total energy, but minimal geomorphic changes, because the peak stream power per unit area is too low to exceed resistance thresholds of its channels and floodplain. Apparently, effective floods require some optimal combination of stream power, duration, and energy expenditure. This optimal combination depends on the floodplain and channel resistance thresholds, and the hydrologic characteristics of a particular fluvial system. More data like those in Table 2 will help clarify this important problem. In the next section we propose a model to guide these investigations.

4. EFFECTIVE FLUVIAL EVENTS: A MODEL TO INCLUDE FLOW DURATION

The ability to compute the distribution of stream power per unit area of a flood throughout the hydrograph, combined with consideration of potential landsurface resistance thresholds, allows us to construct a conceptual model of geomorphically effective floods (Figure 11). Three hypothetical stream-power graphs are plotted in Figure 11. Curve A represents a flood of long duration but very low peak stream power. Total energy generated by the flood at a particular site, represented by the area under the stream-power graph, may be large. But in spite of a large total energy expenditure, and long flow duration, peak stream power never rises above the threshold required to significantly disrupt alluvial channels and floodplains. There has been some effort to identify minimum thresholds of critical stream power and boundary shear stress for alluvial systems, but far more work in a variety of environments is required [*Magilligan*, 1992; *Prosser and Slade*, 1994]. Great floods along large, low-gradient rivers such as the Mississippi River flood of 1927, which generated peak stream power per unit area of about 12 W/m², would be representative of curve A.

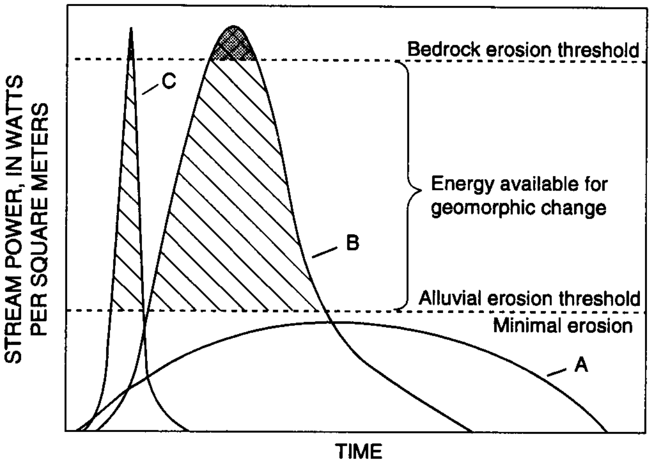

Fig. 11. Conceptual stream-power graphs used to document geomorphic effectiveness of different kinds of floods.

Curve B represents large floods that generate high values of peak stream power per unit area, and have moderate to long duration. Average flood stream power per unit area is high, and total energy expended by the flood is large. Peak stream power per unit area can be great enough to generate processes capable of eroding some bedrock boundaries, such as cavitation or macroturbulance [*Baker and Costa*, 1987; *O'Connor*, 1993]. Tremendous changes in alluvial channels are possible, even total unraveling of floodplains, because of the large energy expenditure represented by the area under the stream-power graph above the alluvial threshold. Area above the bedrock threshold represents the amount of energy available to erode and effectively modify bedrock flood-channel boundaries. Floods represented by curve B are likely to be the most geomorphically effective fluvial events in any landscape, and would include exceptional floods like the Rubicon River and Teton River dam-failure floods, and colossal paleofloods like the Missoula and Bonneville floods [*O'Connor and Baker*, 1992; *O'Connor*, 1993].

Stream-power graph C represents floods that generate high values of instantaneous peak stream power per unit area, but are short-lived. The energy represented by the area under the stream-power graph above the alluvial threshold is small, and these floods are impotent to accomplish any significant amount of geomorphic change, even though instantaneous peak stream power per unit area may be among the highest values documented and well above landscape resistance thresholds. Total energy represented by the area under the curve above the bedrock threshold is also small, and the flood engenders little or no perceptible change in alluvial or bedrock channels, even though instantaneous peak stream power per unit area may be comparable to other floods that eroded and shaped bedrock channels. These kinds of stream-power graphs are representative of flash floods in small basins that rise quickly and are gone in a matter of minutes. Such floods are generally caused by cloudburst rainstorms or the rapid failure of natural or constructed dams such as Reservoir No. 3 in Centralia, Washington, or the Porter Hill dam in Oregon.

5. CONCLUSIONS

Floods are a fascinating phenomenon that may or may not be effective agent in shaping the channels and floodplains through which they flow. We have attempted to demonstrate that it is possible to quantify approximately the amount of energy in a flood available for geomorphic work. Construction of stream-power graphs from channel geometry and flood hydrographs shows how stream power varies at a cross-section throughout a hydrograph, and allows computation of the total geomorphic energy expended by a flood. A conceptual model combining flood duration, stream power per unit area, and thresholds for alluvial and bedrock channel erosion can predict geomorphic effectiveness and distinguishes between cases where (a) some floods with long duration and large total energy expenditure along alluvial channels may not be effective channel or floodplain-disrupting events; (b) some floods with very large peak instantaneous stream power per unit area, but low total energy expenditure, may also not be effective channel or floodplain-disrupting events; and (c) floods with a combination of high peak instantaneous stream power, sufficient flood-flow duration, and large total energy expenditure are able to alter significantly the land surface, and become geomorphically effective floods.

While we believe the preceding analysis is a valuable way to conceptualize and perhaps predict channel and floodplain changes, it only addresses half of the force versus resistance equation. We suspect that quantifying landscape resistance and erosion thresholds will prove to be much more difficult than quantifying the hydraulic forces. One conclusion is sure: floods will continue to provide a bounty of questions and opportunities for generations of present and future students.

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