Paleodischarge of the late Pleistocene Bonneville Flood, Snake River, Idaho, computed from new evidence

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ABSTRACT

The Bonneville Flood resulted from catastrophic outflow from Pleistocene Lake Bonneville about 15,000 yr ago, when the lake overtopped its rim at Red Rock Pass in southeastern Idaho and discharged a vast volume of water down the Snake River. This paper provides revised estimates of the paleodischarge, volume, and duration of the Bonneville Flood, based on new evidence of its height and on current understanding of the amount of lowering of Lake Bonneville. Evidence for the revised height of the flood is derived from the altitude of erosional features and flood deposits at the head of a constricted reach of the Snake River Canyon at the mouth of Sinker Creek and from the altitudes of flood deposits at several places about 53 km upstream.

Using the step-backwater method, we estimate that peak discharge for the Bonneville Flood through the constricted reach was from 793,000 to 1,020,000 m$^3$/s and most likely was 935,000 m$^3$/s. This discharge is 2.2 times the discharge previously reported and is the second largest flood known to have occurred in the world. At this rate of discharge, the shear stress for the flood would have been 2,500 N/m$^2$, and the unit stream power would have been 75,000 N/m$^2$/s, as compared with values of 6 to 10 N/m$^2$ and 12 N/m$^2$/s for recent floods on the Mississippi and the Amazon. Other recent studies of the history of Lake Bonneville show that the volume of water released was 4,700 km$^3$, or about 3 times greater than the volume previously inferred. Although this volume indicates a flood duration of 8 weeks at constant peak discharge, an accurate estimate of the duration would require dam-break modeling at Red Rock Pass. From a dam-break model, flood hydrographs at Red Rock Pass and the hydraulics of the flood wave along the Snake River could be computed.

INTRODUCTION

During the Pleistocene, closed basins in the Basin and Range province in the western United States contained lakes of considerable size (Williams and Bedinger, 1984). The largest of these Pleistocene lakes was Lake Bonneville (Fig. 1), estimated to have once covered 51,530 km$^2$ (Currey and Oviatt, 1985). The surviving remnant of Lake Bonneville is Great Salt Lake, which covers 4,700 km$^2$. Lake Bonneville fluctuated greatly in altitude, last reaching its highest level, the Bonneville shoreline, about 15,000 yr ago (Scott and others, 1983). At that time, the lake overtopped its rim at Red Rock Pass and catastrophically discharged a vast volume of water down the Snake River in southern Idaho (Gilbert, 1878; Hunt, 1980)—an event known as the Bonneville Flood (Malde, 1968). Red Rock Pass consequently was eroded to the level of the Provo shoreline, and the flood ended.

The path followed by the Bonneville Flood down the Snake River was greatly modified by erosion and deposition. Particularly impressive are abandoned channels, areas of scabland, and gravel bars composed of huge boulders and sand. Parts of the Snake River Canyon are now known to have been flooded to depths greater than 130 m.

The altitudes of the erosional and depositional features produced by the Bonneville Flood indicate the maximum flood height and are used to reconstruct the flood profile. When the profile is considered in the context of the dimensions of the Snake River Canyon, particularly where the canyon is constricted, a peak discharge can be calculated. Based on new evidence of the flood height in a constricted reach of the Snake River at the mouth of Sinker Creek, 540 km downstream from Red Rock Pass, this paper describes such a calculation, using the step-backwater method (Chow, 1959). The constricted reach is cut in basalt between Mile 460 and Mile 462 (Figs. 1 and 2). Given certain assumptions, the peak discharge is estimated to have been from 793,000 to 1,020,000 m$^3$/s and most likely was 935,000 m$^3$/s. This estimate is 2.2 times the discharge previously calculated (Clifford T. Jenkins, in Malde, 1968, p. 11–12), using a flood height that recent study has shown to be erroneously too low. The estimated discharge then is used to appraise the geomorphic significance of the flood and to re-evaluate its duration, based on current understanding of the amount of lowering of Lake Bonneville.

NEW OBSERVATIONS OF FLOOD HEIGHT

Geologic mapping from 1979 to 1983 downstream from Bruneau disclosed several features of the Bonneville Flood higher than any previously identified in this reach of the river. The flood features were missed during earlier reconnaissance (Malde, 1968) because of their remoteness and difficulty of access. In the following discussion, altitudes of flood features are given in feet, in accord with contours on existing topographic maps, but other dimensions are given in metres.

Erosional features on a basalt bench 133 m above the Snake River (altitude 2,750 ft) at Mile 462 (Figs. 3 and 4) resemble those produced by the Bonneville Flood on basalt uplands elsewhere along the Snake River in southern Idaho (Malde, 1968, p. 20). Basalt has been partially stripped from the bench, leaving broad remnants that have irregular, embayed outlines. The bench itself has a nearly vertical face 15 m high on the downstream side, and the erosional remnants have faces about 2 m high. The upstream faces have been smoothed and rounded, presumably by the abrasion of sediment-laden waters. The downstream faces are abruptly and without adjacent debris, and are thought to represent the effect of plucking of lava by the forceful passage of the flood. Scattered boulders of basalt on the downstream part of the bench are as much as 2 m in diameter. The largest ones are angular, but some have rounded edges. Rounded smaller
boulders and a few pebbles and cobbles also are present. The large boulders clearly are lag deposits related to erosion of the bench.

A gravel bar in the lee of the basalt bench, on its northeastern side, is thought to be a deposit of the Bonneville Flood (Figs. 3 and 4). The bar is 150 m long, 64 m wide, and about 15 m high. Angular and rounded boulders as much as 1 m in diameter are scattered on the surface. The bar shows no evidence of post-flood erosion and apparently is preserved in its original form. The position of the bar in the path of the flood shows that it was deposited where the velocity of flow decreased. Together, the eroded basalt bench and the gravel bar indicate that the altitude of the Bonneville Flood at Mile 462 was at least as high as 2,750 ft.

Upstream from Mile 462, the valley of the Snake River broadens into a wide basin that extends 53 km upstream to the mouth of the Bruneau River (Fig. 1). The Bonneville Flood was hydraulically ponded in this basin because of the constricted canyon between Mile 460 and Mile 462 (Malde, 1968, p. 39–42). Deposits of flood gravel in the basin occur only at the upstream end, mainly as deltas whose altitudes indicate the minimum height of the ponded water. At site A in Figure 1 (SE¼ sec. 5, T. 6 S., R. 5 E.), deltaic gravel at an altitude of 2,700 ft spilled into ponded water in the Bruneau Valley. At site B a short distance west (SE¼ sec. 11, T. 6 S., R. 4 E.), floodwater that washed across a ridge at an altitude of about 2,750 ft deposited deltaic gravel in ponded water at an altitude of 2,725 ft. These altitudes are consistent with the altitude of flood features at

Figure 1. Map of the area inundated at the maximum height of the Bonneville Flood between Mile 431 and Mile 519. Miles on the Snake River are measured upstream from its confluence with the Columbia River. Inset map shows the northern part of Lake Bonneville (shaded area) and the location of Red Rock Pass.
Mile 462, which marks the downstream end of the ponded water and the head of the constricted canyon.

Downstream from Mile 460, the Snake River Canyon widens abruptly and contains scattered gravel bars deposited by the Bonneville Flood. The bars are littered with well-rounded basalt boulders, many of them more than 3 m in diameter. The altitudes of these gravel bars indicate the minimum height of the Bonneville Flood at its highest stage: an altitude of 2,525 ft on the right bank at Mile 459.2; 2,550 ft on the left bank at Mile 457.4; 2,560 ft on the right bank at Mile 455.6; and 2,480 ft on the left bank at Mile 451.7. The flood also overtopped the right rim of the canyon at Mile 448 and deposited basaltic sand at an altitude of 2,545 ft.

From these altitudes, a profile for the Bonneville Flood can be constructed, and a paleodischarge can be estimated, based on the dimensions of the channel and its slope (Chow, 1959). An estimate of the paleodischarge, computed for the hydraulic conditions between Mile 460 and Mile 462, is described in the following section.

CALCULATION OF PALEODISCHARGE

At Mile 460, the Bonneville Flood was confined by a rock-walled gorge, cut in resistant, basaltic lava flows and tuff (Figs. 2 and 4). The flood eroded the bedrock walls and talus but probably did not appreciably deepen the canyon (Malde, 1968, p. 42). The altitudes of flood deposits downstream indicate that the flood was unimpeded and that a state of critical flow existed at Mile 460. Under conditions of critical flow, the peak discharge of the Bonneville Flood at Mile 460 can be calculated from the height of floodwater upstream and the dimensions of the canyon, given certain assumptions about pertinent hydraulic variables. The calculation of critical flow is one form of the step-backwater method (Barnes and Davidian, 1978), which generally is recommended and applied for developing stage-discharge relations in natural channels (Chow, 1959; Bailey and Ray, 1966; Druse, 1982; Davidian, 1984; Potter and Walker, 1987). Hence, we calculate the peak discharge of the Bonneville Flood by using
Figure 4. Map of the constricted reach of the Snake River Canyon between Mile 460 and Mile 462, showing locations of cross sections used to calculate peak discharge of the Bonneville Flood by the step-backwater method. The cross sections are numbered according to their distances in metres upstream from Mile 460. The area covered by the Bonneville Flood is shown by pattern. Embayments to the left and right of the channel, although inundated by the flood, are considered to have had no measurable effect on the maximum discharge. The diagonally ruled area on the right bank at Mile 462 represents a basalt bench at an altitude of 2,750 ft that was scoured by the flood. The stippled area is a gravel bar in the lee of the bench.
the step-backwater method and by analyzing the effects of modified hydraulic factors.

Theory

For conditions of uniform flow, discharge is computed from an equation that involves channel characteristics, water-surface elevations in the reach, and a roughness coefficient. The decrease in water level in a uniform channel represents losses caused by bed roughness. Any of the variations of the Chezy equation can be used, such as the Manning equation (Chow, 1959).

The Manning equation was developed for conditions of uniform flow in which the water-surface profile and energy gradient are parallel to the stream bed, and in which the hydraulic radius and depth are constant throughout the reach. The Manning equation further is presumed to be valid for nonuniform reaches in natural channels, if the energy gradient is modified to reflect only losses due to boundary friction and losses caused by channel contractions and expansions. To evaluate these losses, resistance coefficients and coefficients for contraction and expansion of the channel are specified. This analysis is called the "step-backwater method."

Cross sections that define the channel characteristics are obtained, and the standard-step method is used to balance the Bernoulli energy equation between them (Chow, 1959). In this way, water-surface altitudes are determined for each cross section at a specified discharge. A range of discharges is used to develop a stage-discharge relation at the cross section where the flood height is known. The estimated peak discharge then is determined from the stage-discharge relation and the altitude of the flood marks.

Data Assembly

Channel and flood-plain cross sections were measured perpendicular to the flow path of the Bonneville Flood from the U.S. Geological Survey Sinker Butte and Wild Horse Butte topographic quadrangles (scale 1:24,000). Because each cross section represents only a discrete sample of the geometry of the reach, the number of cross sections affects the accuracy of the computed discharge. Our analysis was based on the dimensions of 15 cross sections between Mile 460 and the newly discovered flood marks at Mile 462 (Fig. 4). Spacing of the cross sections was based on the anticipated water-surface profile. For example, near Mile 460, where the profile was expected to be comparatively steep, the cross sections were closely spaced. Representative cross sections are shown in Figure 5. Embayments to the left and right of the canyon were considered to have had no effect on the flood, and these areas were not used to define the dimensions of the flooded channel. Rather, cross sections were drawn as if vertical canyon walls existed at the sites of these embayments (Fig. 4). The exact locations of these vertical walls have a negligible effect on the results of the hydraulic analysis.

Barnes and Davidian (1978) suggest that the length of the reach for step-backwater analysis be at least 2½ times the mean depth of the stream. This condition is satisfied, in that features used to determine the flood height at Mile 462 are about 3 km upstream from Mile 460.

Step-Backwater Analysis of the Paleodischarge

The U.S. Geological Survey step-backwater computer program J635 (Shearman, 1976; J. O. Shearman, 1977, written commun.) was used for the hydraulic analysis. This program computes the water-surface altitudes for a specified discharge when the initial calculation is based on an assumed depth for the water surface. Cross-section dimensions, distances along the channel from Mile 460, roughness coefficients, contraction and expansion coefficients, and a range of selected discharges were entered into the computer program.

After an initial run of the computer program, the hydraulic effect of possible differences from present conditions, such as changes in channel dimensions and channel roughness, were evaluated. Initially, the cross sections were assumed to be representative of conditions during the flood, a Manning's roughness coefficient of 0.040 was used, and contraction and

![Figure 5. Selected cross sections of the Snake River Canyon between Mile 460 and Mile 462, as seen looking downstream. The computed water-surface levels (v), mean velocities (V), and widths of the water surface (B) are shown for a discharge of 935,000 m³/s.](image)
expansion coefficients of 0.0 and 0.5 were specified. A stage-discharge
relation in accord with the altitude of the flood marks at Mile 462 thus
was computed, indicating a peak discharge of 1,005,000 m$^3$/s (Run 1; see
Table 1 and Fig. 5). The hydraulic conditions used in the initial calcu-
lations were modified, using different roughness coefficients, contraction
and expansion coefficients, and changes in channel width to evaluate the
paleodischarge (Table 1).

Manning's roughness coefficient was varied between 0.030 and
0.050, on the basis of guidelines given by Chow (1959) and verified by
Barnes (1967). Equations developed by Limerinos (1970) to estimate
Manning's roughness coefficient yield a range from 0.035 to 0.040 for this
study reach.

The energy loss due to contraction or expansion of a channel between
two of its cross sections is a function of the difference in the respective
velocity heads. The loss varies with coefficients in the energy equation. The
values of the coefficients normally used are 0.0 for contracting reaches and
0.5 for expanding reaches (Shearman, 1976), as was done in Run 1,
although larger values are sometimes used. For the Snake River Canyon
between Mile 460 and Mile 462, we used upper limits of 0.3 and 0.7,
respectively, for these coefficients.

Finally, the effect of a more constricted channel that was enlarged by
flood erosion was considered. Although the canyon is cut in basaltic
bedrock, some erosion of the walls and talus almost surely occurred during
the Bonneville Flood, particularly at constrictions where flow velocities
were highest. The amount of flood erosion can be estimated by considering
the volume of flood gravel in the Snake River Canyon downstream from
Mile 460. Most of the gravel was deposited downstream from Mile 448, in
a broad expanding reach of the canyon known as the Walters basin
(Fig. 1), which formed a sediment trap. The volume of flood gravel in the
Walters basin has been estimated at about 2.1 x 10$^8$ m$^3$ (Malde, 1968, p.
42). As described above, some bouldery gravel also was deposited in the
canyon between Mile 460 and Mile 448, mostly as bars as much as 90 m
in height. The distribution of the gravel bars indicates that the volume of
gavel from Mile 460 to Mile 448 is about a tenth of the amount in the
Walters basin. Thus, the estimated volume of flood gravel downstream
from Mile 460 is about 2.3 x 10$^7$ m$^3$. The gravel must have been derived
by flood erosion of talus and bedrock downstream from Mile 462, because
ponded water upstream prevented significant erosion (Malde, 1968, p. 42).

The area of the canyon walls and the canyon floor vulnerable to flood
erosion downstream from Mile 462 is calculated to have been 25 x 10$^6$
m$^2$. Hence, the volume of gravel can be accounted for by 9 m of uniform
erosion from the walls and floor in this reach of the canyon. Because
erosion presumably was greater at constrictions where flow velocities
would have been greatest, hydraulic analyses were made by assuming that
the width at sections 0 through 305 was 15 m, 23 m, and 30 m less than
the present width at the time of peak discharge. Changes in width at wider
sections upstream have an insignificant effect on the computed discharge.

**Effect on the Paleodischarge of Modified Hydraulic Factors**

The following results compare the paleodischarge obtained under the
initial conditions (Run 1) with discharges computed by assuming different
values of the hydraulic variables. The range of paleodischarge using these
assumptions was from 793,000 m$^3$/s to 1,020,000 m$^3$/s (Runs 7 and 3;
Table 1 and Fig. 6).

Different values of Manning's roughness coefficient had the least
effect on the computed discharge, primarily because of the influence of
ponded water upstream from Mile 462. Compared to a roughness coeffi-
cient of 0.040 (Run 1), a difference of 25% (0.030 and 0.050) changed the
discharge only 1.5% (Runs 3 and 4). This finding is consistent with pre-
vious experience that the step-backwater method is fairly insensitive to
flow resistance for large depths of flow.

Assumed changes in canyon width at sections 0 through 305 had a
moderate effect on the calculated discharge. For a decrease of 30 m, which
is a reasonable upper limit of erosion, peak discharge decreased about 8%
(Run 6).

Changing the contraction and expansion coefficients had the greatest
effect on the calculated discharge, because of the variable width of the
canyon above Mile 460. When very conservative values of 0.3 and 0.7
were assumed for the contraction and expansion coefficients, the discharge
was decreased 14% (Run 2).

In light of the effects of modifying the hydraulic variables, we judge
that the most likely conditions for the Bonneville Flood are: Manning's
roughness coefficient of 0.040, contraction and expansion coefficients of
0.0 and 0.5, and a width 23 m less than the present width. The peak
discharge under these conditions was computed to be 935,000 m$^3$/s (Run 8). The computed water-surface profile for this discharge and the altitude of the observed flood deposits are shown on Figure 7. The profile shows that the water level at Mile 460 decreased about 53 m, resulting in an altitude of 2,575 ft for the water surface just downstream. Under these conditions, average flow velocities ranged from 26 m/s at Mile 460, to 9.5 m/s at midreach, and 13 m/s at Mile 462 (Fig. 5). The paleodischarge would have increased moderately with increasing depth of flow (Fig. 6). For the conditions used in Run 8, water-surface profiles higher than the flood marks at Mile 462 increase the computed discharge as follows: 1,000,000 m$^3$/s at 5 m higher; 1,076,000 m$^3$/s at 10 m; and 1,161,000 m$^3$/s at 15 m.

Clifford T. Jenkins (in Malde, 1968, p. 11–12), by assuming critical flow at Mile 460, and by using an altitude of 2,625 ft for the water surface—not the altitude of 2,750 ft described here—computed that the Bonneville Flood discharge ranged from 346,000 m$^3$/s to 462,000 m$^3$/s. He suggested that the most likely paleodischarge was 425,000 m$^3$/s. Jenkins assumed that the dimensions of the canyon at the time of peak discharge were the same as at present, and he used a Manning’s roughness coefficient of 0.040. For these conditions, the step-backwater method yields a peak discharge of 503,000 m$^3$/s (Fig. 6, Run 1). Because the hydraulic assumptions made by Jenkins are incompletely known, reasons for the differences between his results and ours are uncertain.

COMPARISON WITH OTHER FLOODS

The Bonneville Flood far exceeded the magnitude of historic floods on the Snake River and on other rivers in the world. The maximum recorded discharge on the Snake River near Mile 460 was 1,340 m$^3$/s, measured at a streamflow-gaging station 10.3 km downstream. The greatest flood in recent times in the United States was the 1927 flood on the Mississippi River, which had a peak discharge of 70,010 m$^3$/s (Dalrymple, 1964). The largest known recent flood in the world occurred on the Amazon River during 1953, when the peak discharge was 385,000 m$^3$/s (Oltman, 1968).

Although the Bonneville Flood greatly exceeded the magnitude of any historic flood, it pales when compared with floods that resulted from rapid outbursts of glacial Lake Missoula, ~14,000 yr ago. Using the slope-area method and a Manning’s roughness coefficient of 0.040, peak discharge at the breakout point for Lake Missoula is estimated to have been as large as 21,300,000 m$^3$/s (Baker, 1973), although this estimate probably is 30% too large (Baker and Bunker, 1985, p. 12). Independent paleohydrologic calculations (Clarke and others, 1984) and observations of historic floods from ice-dammed lakes (Beget, 1986) suggest that Baker’s estimate may be too large, but peak discharge from glacial Lake Missoula undoubtedly represents the largest known flood in the world. The Bonneville Flood, however, was the second largest.

GEOMORPHIC SIGNIFICANCE OF THE FLOOD

Wolman and Miller (1960) proposed that the relative geomorphic importance of extreme catastrophic events, or of more frequent smaller events, is indicated by the relative amounts of work done on the landscape. The work done by streams can be expressed in terms of shear stress and unit stream power, which indicate the potential rate of movement of sediment. Shear stress is the product of the hydraulic radius, the energy slope, and the specific weight of the water. Thus, large values for the hydraulic radius or the energy slope indicate large amounts of shear stress. Unit stream power is the product of the discharge, the energy slope, and the specific weight of the water, divided by the water-surface width.

For the Bonneville Flood at Mile 460, the hydraulic radius was 63 m, the energy slope was 0.0041, and the width was 500 m. A specific weight of 9,800 N/m$^3$ for the water is assumed. From the calculated discharge of 935,000 m$^3$/s, the computed shear stress was 2,500 N/m$^2$, and the unit stream power was 75,000 N/m/s. For comparison, the Mississippi River and the Amazon River during floods have shear stress values of 6 to 10 N/m$^2$ and unit stream powers of about 12 N/m/s (Costa, 1987). In the United States, some of the greatest known values of shear stress and unit stream power are for small basins. For example, Costa (1987) reported values of 858 N/m$^2$ and 8,160 N/m/s for the 1973 flood on a tributary of the Humboldt River, Nevada.

As streams increase in size, their slopes typically decrease. Because the slope decreases faster than does the hydraulic radius, large rivers are characterized by small values of shear stress and unit stream power. The large values of shear stress and unit stream power for the Bonneville Flood at Mile 460, despite its size, are due partly to the large depth of flow, but mostly to the steep slope of the Snake River. The Snake River is one of the steepest large rivers in the United States (Malde, 1968), and this factor would have helped to maintain voluminous flow, even at a considerable distance downstream from Red Rock Pass.
NEW EVIDENCE OF FLOOD VOLUME AND DURATION

The volume of water discharged during the Bonneville Flood equals the volume of water between the Bonneville and Provo shorelines, according to current understanding of the history of Lake Bonneville (Scott and others, 1983; Currey and Oviatt, 1985). A previous estimate of the volume was attributed to downcutting only to the Bonneville shoreline, from a supposed level about 30 m higher (Malde, 1968, p. 12). The estimated volume was therefore too small.

Currey and Oviatt (1985, p. 13) reported that erosion of Red Rock Pass during the Bonneville Flood lowered the lake 108 m, from the Bonneville shoreline (altitude 1,552 m) to the Provo shoreline (altitude 1,444 m). Because the area of Lake Bonneville was directly related to the altitude of its surface, when the altitudes are adjusted for hydro-isostatic rebound (Currey and Oviatt, 1985, p. 10), the volume released by downcutting of the outlet can be calculated as the frustum of a cone, in which the base is the area at the Provo shoreline (36,720 km²), the top is the area at the Bonneville shoreline (51,530 km²), and the height is the difference in altitude between the shorelines (108 m). The volume of the Bonneville Flood therefore was 4,700 km³. If outflow from Lake Bonneville is assumed to have been at a constant discharge of 935,000 m³/s, the minimum flood duration would have been about 8 weeks. The flood duration, however, was surely longer. Peak discharge would have been achieved only after the outlet at Red Rock Pass had become enlarged by erosion, and the discharge probably waned as the level of Lake Bonneville decreased. An accurate estimate of the duration, however, would require dam-break modeling, as discussed in the following section.

DISCUSSION

The constricted canyon between Mile 460 and Mile 462 is just one place along the path of the Bonneville Flood, and it would be of geologic and hydrologic interest to evaluate the hydraulic characteristics of the flood throughout its length. Such an analysis needs to begin at Red Rock Pass, because outflow of Lake Bonneville from this breach would have been controlled by the rate of failure and by changes in the breach as it developed (Jarrett and Costa, 1985). Some aspects of the history of Red Rock Pass are known (Sewell and Shroder, 1981), but further study of the pass is needed to obtain the chronologic and topographic data needed to model its failure (D. R. Currey, University of Utah, 1985, written commun.). From the dam-break model, the following hydraulic characteristics could be computed: the duration of flooding, the traveltime of the flood wave, and flood hydrographs at Red Rock Pass and along the Snake River (Fread, 1977; Land, 1980; Jarrett and Costa, 1985). A sensitivity analysis, for which one component would be the estimated paleodischarge between Mile 460 and Mile 462, then would provide reasonable limits for the flow characteristics along the flood path. Such an analysis could be tested by considering the nearly continuous geologic record of the Bonneville Flood throughout its length.

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