Simulations of cataclysmic outburst floods from Pleistocene Glacial Lake Missoula

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ABSTRACT

Using a flow domain that we constructed from 30 m digital-elevation model data of western United States and Canada and a two-dimensional numerical model for shallow-water flow over rugged terrain, we simulated outburst floods from Pleistocene Glacial Lake Missoula. We modeled a large, but not the largest, flood, using initial lake elevation at 1250 m instead of 1285 m. Rupture of the ice dam, centered on modern Lake Pend Oreille, catastrophically floods eastern Washington and rapidly fills the broad Pasco, Yakima, and Umatilla Basins. Maximum flood stage is reached in Pasco and Yakima Basins 38 h after the dam break, whereas maximum flood stage in Umatilla Basin occurs 17 h later. Drainage of these basins through narrow Columbia gorge takes an additional 445 h. For this modeled flood, peak discharges in eastern Washington range from 10 to 20 × 10⁶ m³/s. However, constrictions in Columbia gorge limit peak discharges to <6 × 10⁶ m³/s and greatly extend the duration of flooding.

We compare these model results with field observations of scabland distribution and high-water indicators. Our model predictions of the locations of maximum scour (product of bed shear stress and average flow velocity) match the distribution of existing scablands. We compare model peak stages to high-water indicators from the Rathdrum-Spokane valley, Walulla Gap, and along Columbia gorge. Though peak stages from this less-than-maximal flood model attain or exceed peak-stage indicators along Rathdrum-Spokane valley and along Columbia gorge, simulated peak stages near Walulla Gap are 10–40 m below observed peak-stage indicators. Despite this discrepancy, our match to field observations in most of the region indicates that additional sources of water other than Glacial Lake Missoula are not required to explain the Missoula floods.

INTRODUCTION

The Purcell Trench lobe of the Cordilleran ice sheet impounded Glacial Lake Missoula in late Wisconsin time and caused numerous glacial outburst floods over eastern Washington (Fig. 1). Bretz (1923, 1925, 1928a) recognized widespread evidence of such flooding, especially spectacular in the Channeled Scablands, and this evidence was later quantified by Baker (1973). Waitt (1980, 1984) found evidence for scores of huge late Wisconsin Missoula floods, a theme later confirmed and expanded by Atwater (1987) and Waitt (1985, 1994). Geomorphic features made by these great floods, broadly visible in satellite images, provide field constraints for modeling these ancient flows.

Scars left by these floods, visible on satellite images, resulted from high erosive power per unit area during flooding that stripped soil and eroded basalt bedrock to form scablands (Benito, 1997). The eroded Missoula sediments accumulated where currents slackened or ponded behind obstructions (Benito, 1997; O'Connor and Baker, 1992). The nature, distribution, and structure of slack-water flood deposits have been used to estimate sediment sources and the local flow regime during deposition (Baker, 1973; Benito, 1997). A regional rhythmic succession of graded beds records the deposition of fine slack-water sediments where successive floods repeatedly ponded (Waitt, 1985). The timing of repeated flooding is

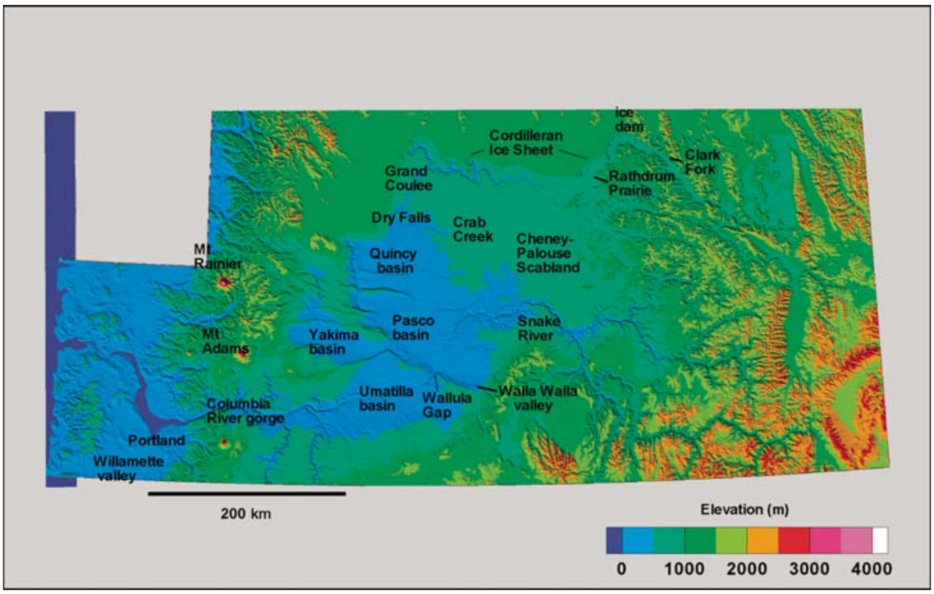

Figure 1. Location of the flood domain in the Pacific Northwest United States, showing the geographic limits and elevations. We constructed the domain from digital elevation model data using a NAD83 reference frame, forming regular meshes with spacings of 450 m, 320 m, and 250 m.

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constrained by radiocarbon dates (Atwater, 1986, 1987; Benito and O'Connor, 2003; Waitt, 1985), by tephra from volcanic eruptions (Mullineaux et al., 1978; Waitt, 1980), by secular variation in the magnetic stratigraphy of the sediments (Clague et al., 2003), and by varves between flood beds (Atwater, 1986, 1987; Waitt, 1994).

Geomorphic and sedimentologic expressions of these floods are distributed across hundreds of kilometers east to west and more than 800 m in elevation. However, some questions remain unanswered: How long did it take to drain Lake Missoula? Where did the water flow, and how was it distributed through the system over time? Was the discharge from Glacial Lake Missoula sufficient to fill all scabland channels? Was discharge from the breached dam sufficient to fill Pasco, Yakima, and Umatilla Basins to levels suggested by field data before it drained away? Or was a substantial base flow from the Cordilleran ice sheet required? Shaw et al. (1999) proposed that besides Glacial Lake Missoula, immense sources of subglacial water farther north are needed to explain the channeled scablands. Though largely refuted (Atwater et al., 2000), this idea was supported by modeling (Komatsu et al., 2000). Without such additional sources, some researchers argue that small discharge floods would not reach the Cheney-Palouse tract but would flow only down Grand Coulee (Miyamoto et al., 2006; Miyamoto et al., 2007). The one-dimensional (1-D) flow models of O'Connor and Baker (1992) and Benito and O'Connor (2003) addressed maximum flood discharge from the ice dam through Walulla Gap and through Columbia gorge. However, sophisticated models, both multi-dimensional and dynamically conserving mass and momentum for unsteady flow, have not been applied to the stage and timing of Lake Missoula flooding, nor to the entire system from ice dam to the sea. Here, we apply a nonhydrostatic, two-dimensional (2-D), shallow-water model to a typical large outburst flood caused by catastrophic drainage of Glacial Lake Missoula, starting with a high lake level of 1250 m. Testing multiple initial conditions, we describe a situation that maximizes the rate of filling of Pasco Basin. We show that this condition produces a great flood consistent with most field evidence of peak stage for the Missoula floods.

OBSERVATIONS

The distribution of scablands and field indicators of peak stage are targets to compare with our flood models. Rapid overland flow eroded linear tracts in eastern Washington to form the Channeled Scablands (Bretz, 1925, 1928a, 1959; Bretz et al., 1956). The distribution of this erosion, which on basalt flows produced knobs and depressions decimeters to tens of meters in relief, can be seen as intricate dark tracts in satellite images. Sustained erosion by the catastrophic floods enlarged stream valleys into wide coulees that are now streamless or nearly so; spectacular examples include Grand Coulee and Dry Falls (Bretz, 1959). High-water indicators distributed along Rathdrum-Spokane valley (O'Connor and Baker, 1992), along the Columbia River north of Pasco Basin (Waitt, 1994), through Walulla Gap (O'Connor and Baker, 1992), and along the length of Columbia River gorge (Benito, 1997; Benito and O'Connor, 2003) provide quantitative limits against which we test our model simulations for Lake Missoula glacial-outburst floods.

DESCRIPTION OF METHOD AND MODEL INPUT CONDITIONS

We simulated dam-break flows from Glacial Lake Missoula using the model of Denlinger and O'Connell (2008). This finite-volume model uses methods described by Leveque (2002) to solve for shallow-water flow over rugged three-dimensional terrain partitioned into a patchwork of equidimensional cells. In the center of each cell, the x, y, and z coordinates derived from a digital-elevation model (described in the following) are collocated with depth (h) and velocity components u, v, and w in the x, y, and z directions, respectively. Gravity is vertical and associated with coordinate z. Tests of the model made in dry, steep (31°) concrete flumes and comparisons made with the 1959 Malpasset dam-break disaster in France (Valiani and Caleffi, 2004) show that for dam-break flows, the model accurately simulates flow-front propagation and velocity and accurately simulates inundation over uneven terrain. Comparison of 1-D and 2-D models show that 1-D models match stage observations along rivers but overestimate discharge by a factor of 2 when channels are crooked (Denlinger and O'Connell, 2008; Goutal, 1999; Soares Frazao and Zech, 1999). Peak discharges obtained from 2-D and 1-D models are not comparable unless the channel is straight.

Boundary Conditions

Boundary conditions were determined primarily by topography and the position of the inferred continental ice-sheet margin and secondarily by surface conditions. We built model topography from a grid in the NAD83 reference for the Pacific Northwest using a series of 30 m digital elevation models (DEM). The region (Fig. 1) extends from Canada south to the 45th parallel and from the Pacific Ocean east through part of Montana. In this grid, we removed topography created by manmade dams along the Columbia River and included what bathymetry was available for each reservoir. We then subsampled topography to form grids with 450 m, 325 m, and 250 m resolutions. The coarse 450 m grid was used to test the ramifications of various configurations of Cordilleran ice-sheet margins on routing of Lake Missoula dam-break flows. These tests determined the optimum ice-margin configuration that minimized time to fill Pasco Basin (Table 1). Despite the huge scale of these flows, refinements of 325 m and 250 m grids were required to faithfully capture flows through the crooked Columbia River gorge and along small channels in the Channeled Scablands. For flow through Columbia gorge, we found that 250 m and 325 m grids gave similar flow results that substantially differed from those obtained with coarser grids.

Surface roughness conditions have a secondary influence on the regional slope of the water surface and the propagation speed of a dam-break front. We estimate that an average bed roughness for the entire flow domain is approximated by a value of 0.17 m for fully turbulent flow (Rahman and Webster, 2005). An average roughness height of 0.17 m produces a bed drag given by a Mannings "n" of 0.031 (Henderson, 1966), as shown in Table 2. Although larger values of bed roughness are appropriate for scabland topography, a single value of a few tens of centimeters is a reasonable compromise for all surfaces encountered by the Missoula floods. Tests we have made show that variations up to a meter from the value we used will not have a significant effect on the routing or the timing of these huge dam-break floods over rugged topography.

Similarly, flood routing or timing in our model is much less affected by low or variable values of friction or dry beds than by rugged terrain (Denlinger and O'Connell, 2008). Once the initial lake, surface roughness, and base-flow conditions are set, the primary control on flow is from topography. Sediment entrained in the flow could increase peak stages in basins where water accumulates. We neglect sediment erosion, transport, and deposition: the equations describe clear-water flow. This in effect achieves a lower bound on peak stages for the flow scenarios considered, and the field evidence for higher peak stages at sites like Walulla Gap may in fact reflect the volume of sediment entrained in the flows.

INITIAL CONDITIONS

We created a model of Glacial Lake Missoula by damming the Clark Fork of the Columbia River to an elevation of 1250 m,

TABLE 1. RESULTS OF DIFFERENT INITIAL AND BOUNDARY CONDITION SCENARIOS

	Initial conditions						
Scenario name	Southern ice-sheet margin	Lake Missoula surface elevation (m)	Base-flow conditions	Great bend of Columbia (northwest reach)	Grid spacings (m)	Objectives	Outcomes
Initial ice position	20 km north of upper Columbia channel (Grand Coulee to Spokane)	1200	Dry	Open	450	Floodwater travel times through Columbia and Scablands	Columbia flooding lags overland flow; Pasco takes 50 h or more to fill. Columbia path flow times are too long to create maximum stage.
Initial ice position	10 km north of upper Columbia channel	1200	Discharge of ~1000 m^3/s throughout Columbia channels	Closed west of Grand Coulee	450	Grand Coulee and Scablands travel times; influence of ice limit north of the upper Columbia	Grand Coulee flooding matches overland flow travel times over Cheney Palouse. Pasco basin fills in about 40 h.
Columbia gorge conveyance testing	N/A	N/A	Sustained 300 m water-surface elevation at Wallula Gap	N/A	450 320 250	Determine grid spacing needed for full conveyance in Columbia gorge	Conveyance increased when node spacing was decreased from 450 m to 320 m; decrease of node spacing from 320 m to 250 m produced negligible increase.
Final	5–10 km north of upper Columbia channel	1250	Max of 10,000 m^3/s throughout Columbia channels	Closed west of Grand Coulee	250	Determine peak stages from ice dam to Crown Point, maximum stream power, travel times, and time to drain Pasco basin	Fit all contemporaneous peak-stage indicators from Wallula Gap to Crown Point; 3 wk required to drain to the ocean; and peak stream power is consistent with distribution of channel landforms.

somewhat less than the 1265 m maximum lake elevation described by Clarke et al. (1984) or the 1296 m maximum suggested by field data (Pardee, 1942). We experimented with variations in the degree to which the ice sheet blocked the northern Columbia River drainage between the Okanogan valley and Lake Pend Oreille and valleys north of the Columbia's channel, as discussed in the following discussion and shown in Table 1. Blocking the westernmost channel of the Columbia River with the Okanogan lobe produced the fastest filling of Pasco Basin and therefore the highest stage, duplicating the results of Miyamoto et al. (2007). However, we made this determination with a coarse 450 m grid. High-water indicators documented by Waitt (1994) show that other conditions not addressed by these models can produce higher stages in Pasco Basin and require more detailed study.

We approximate ice-dam rupture by instantaneous removal of the ice dam. This crudely approximates exponential growth of tunnels through the ice dam (Waitt, 1985), which is the likely mechanism for failure of the ice dam by analogy with numerical studies of the historic outbursts from Grímsvötn in Iceland (Björnsson, 1974; Nye, 1976). Our model assumes that the ice dam breaks up rapidly enough (tens of minutes) relative to the time required to drain the lake (~200 h) that removal of the ice dam is "instantaneous." For the initiation of the ice-dam failure flow simulations, the initial flow velocities everywhere were set to zero, and the flow was allowed to evolve.

The final configuration we chose for the ice-sheet margin blocked the northwest reach of the Columbia River, damming Glacial Lake Columbia (Fig. 2) and diverting flow into Grand Coulee. This was the configuration during all but the earliest Missoula floods (Atwater, 1987) and was also the configuration with our lake level (1250 m) that minimized the time to fill Pasco Basin. For simplicity in moving the ice margin to create different scenarios, the ice

TABLE 2. RELATION BETWEEN AVERAGE HEIGHT OF SURFACE ROUGHNESS AND MANNINGS 'N' OVER RANGE USED IN TESTS, FROM HENDERSON (1966)

Average height of random surface roughness (m)	Corresponding value of Mannings 'n' used in other reports
0.17 (value used in this report)	**0.031 (value used in this report)**
0.81	0.04

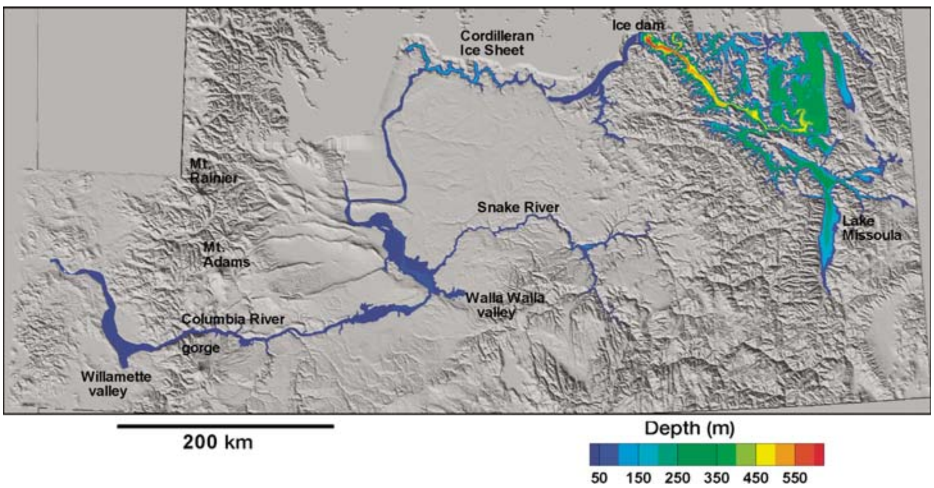


Figure 2. Initial conditions for our Missoula flood simulation. A model of Glacial Lake Missoula was formed by damming the Clark Fork of the Columbia River at the location labeled "ice dam." We experimented with various terminus positions for the continental ice sheet during Fraser glaciations ca. 14,000 radiocarbon yr B.P. to simulate various configurations that blocked and confined the Columbia River channel (Table 1). A constant terminus latitude north of Lake Missoula caused a small additional arm of Lake Missoula in the northeast, but this did not affect routing of flows. We used a base flow in the Columbia River system at the time of dam rupture ranging from dry to a maximum of 10,000 m^3/s (350,000 ft^3/s), or one-third of the flow that was measured in the gorge during the flood of 1894.

margin was approximated by an arbitrary latitude, with some modification for the great bend. West of the Grand Coulee dam and north of Glacial Lake Columbia, we filled all elevations below 1300 m (Fig. 2). East of the ice dam, the northeast corner of Lake Missoula (upper right of Fig. 2) probably was glacier rather than water, but this distant, small volume little affected the dynamics of flow routing. Other ice-margin configurations that achieve a higher flood stage in Pasco Basin with our lake level may be possible (Pardee, 1942; Waitt, 1994; Waitt and Thorson, 1983), but we did not discover it in our scenario testing (Table 1). Our preliminary tests show that opening the Columbia's great bend west of Coulee Dam delayed the maximum flood stage in Pasco Basin by 2–3 h. This resulted in a lower peak stage at Walulla Gap as flow became more developed downstream through Umatilla Basin and the Columbia gorge.

We set initial conditions for the base flow by arbitrarily filling Columbia and Snake River channels with water, obtaining discharges ranging from 1000 to 10,000 m^3/s (0.35 million ft^3/s) distributed throughout the drainage system. We chose a sea level 100 m lower than today for the Pacific Ocean.

OUTPUT

On our 250 m grid, the model calculates depth and velocity on 5.4 million cells hundreds of times per second (time step is variable and depends upon flow conditions). Consequently, on our computers, it takes 12 h of CPU time to simulate 1 h of flow time, or 250 full days for one complete model run. We present each snapshot of the dam-break flow as flood depth and flood power per unit area (kW/m^2), which is the product of bed shear stress and depth-averaged flow velocity tangential to the bed surface. Model outputs of bed shear stress and flow velocity accurately reflect measurements of stress and velocity (and hence power) in steep concrete flumes (Denlinger and O'Connell, 2008), lending confidence to our power estimates for the Missoula floods.

MODEL RESULTS

Inundation

Figure 3 illustrates detailed inundation sequences for the ice-sheet margin configuration that maximizes flux into Pasco Basin. For this ice margin (Fig. 2), rupture of the ice dam holding Lake Missoula causes rapid inundation of eastern Washington. The flood fills the Spokane and upper Columbia reaches within 8 h, while water spills south through the Cheney-Palouse

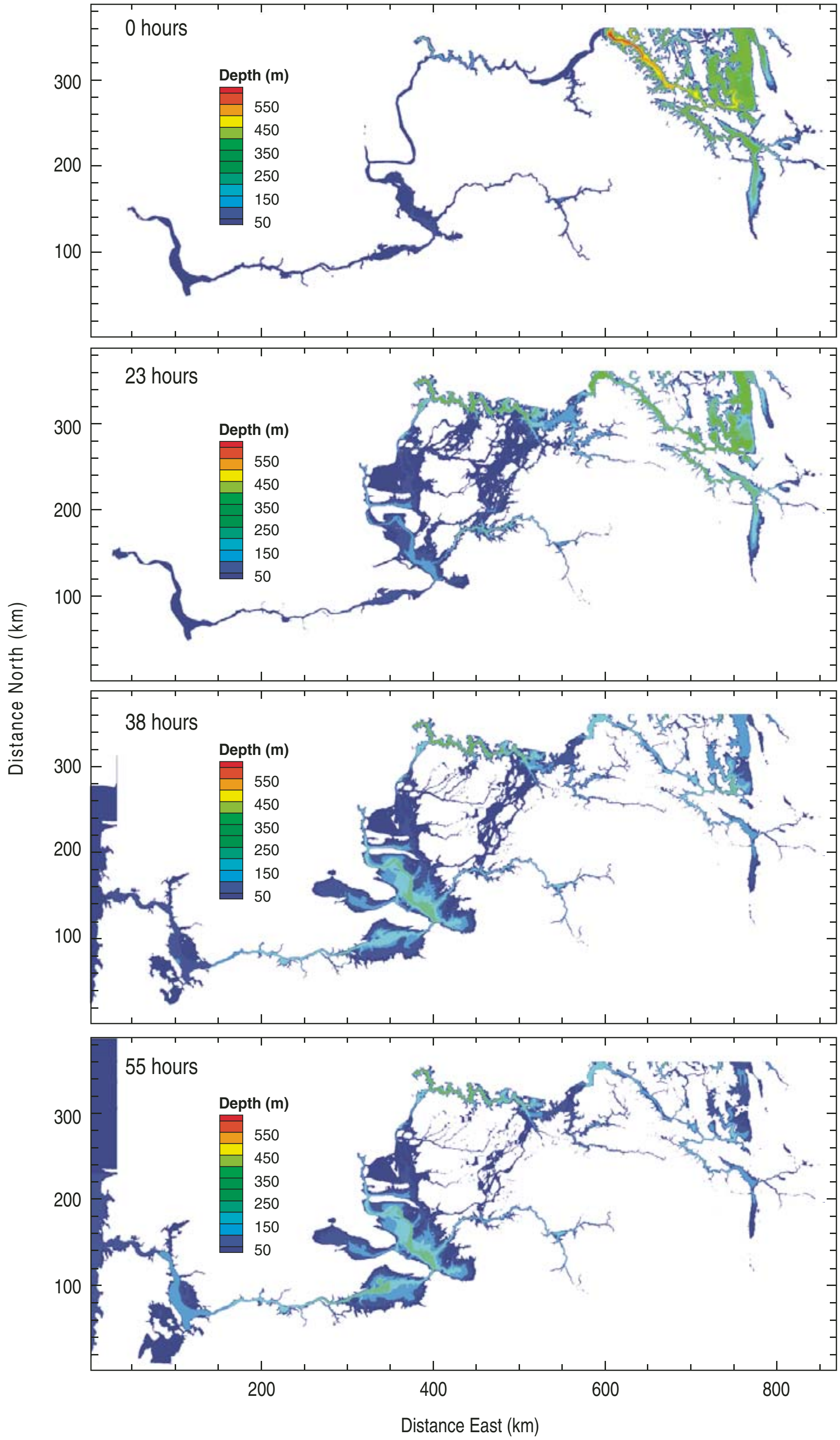


Figure 3. Flooding of eastern Washington from catastrophic rupture of the ice damming Glacial Lake Missoula was rapid and severe. Maximum inundation of the Channeled Scablands occurs 23 h after dam rupture, and this overland flow begins filling Pasco Basin a full day before flow is developed throughout the remainder of the Columbia River drainage system. Pasco Basin achieves maximum stage 38 h after dam break occurs, and maximum stage in Umatilla Basin and Walulla Gap (see Fig. 1) follows 17 h later.

and Grand Coulee scabland tracts. Floodwaters reach Pasco Basin from the Cheney-Palouse scablands first, and then from the upper Columbia channels, jointly filling Pasco Basin and Yakima Basin to their peak level within 38 h. Umatilla Basin does not reach its peak stage until 17 h later, more than 55 h after ice-dam failure. We chose the times in Figure 3 to reflect these inundation limits: 23 h corresponds to maximum discharge through the Cheney-Palouse scablands, 38 h is the time of peak stage in Pasco Basin, and 55 h is the time of maximum stage through Walulla Gap and Umatilla Basin downstream.

Drainage from these huge basins (Pasco, Yakima, and Umatilla) is restricted by the crooked channel of Columbia gorge. Pasco, Yakima, and Umatilla Basins begin to drain only 55 h after initial failure of the ice dam but require 325 h to drain to preflood levels. In the figures, we present only 260 h, since flow smoothly declines to initial conditions upstream of Crown Point from 260 h to 325 h.

The time intervals in Figures 3–6 are chosen to mark changes. Pasco Basin fills before Umatilla; both are full 55 h after dam break. By 100 h, both basins are slowly draining, and significant flood power is left in the system (Fig. 6). This power wanes by 140 h, and by 180 h after dam break, the Cheney-Palouse is completely drained. Thus, the pattern of flooding breaks naturally into two stages: (1) rapid catastrophic flooding of eastern Washington and filling of Pasco, Yakima, and Umatilla Basins (0–55 h), and (2) slow drainage of these great basins through Columbia gorge to the sea (55–325 h).

Stage 1: 0–23 h

Sudden failure of the ice dam energetically and rapidly floods Rathdrum valley downstream of the dam; the enormous discharge is driven by the slope of a surface depression that migrates southeastward into Lake Missoula. A rapid increase in water velocity down the lower Clark Fork (Fig. 3) increases power per unit area (Fig. 4). For rapid and total ice-dam rupture, the energetic flow through the Rathdrum-Spokane valley produces model flood stages and discharge (Figs. 7A and 7B) that compare well with field evidence on upper limits of flood stage in Table 3 (O'Connor and Baker, 1992). Flow velocities exceed 15 m/s near Spokane in water a few hundred meters deep. Blocked from flowing north by mountains and the ice sheet, this water rapidly deepens in Spokane valley to overflow the low drainage divide to the south, flooding the Cheney-Palouse scabland. The Cheney-Palouse overland flow into Snake River floods Pasco Basin for a full day

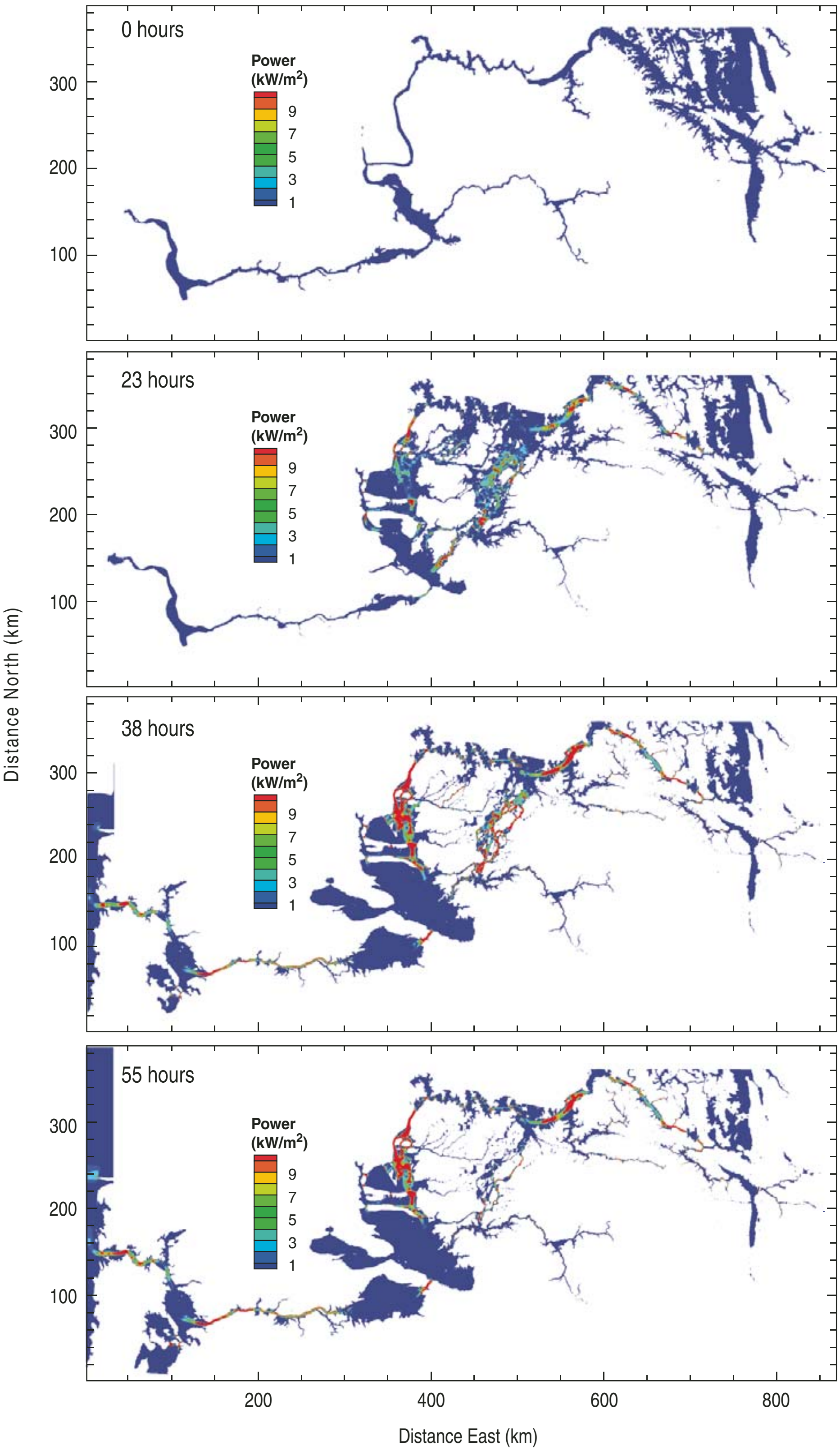


Figure 4. Distribution of power per unit area exerted by the flow on its bed during early stages of catastrophic flooding corresponding to Figure 3.

while flow develops through the upper Columbia and Grand Coulee channel (Fig. 3). Peak overland flow into the Telford–Crab Creek and Cheney-Palouse scablands from the upper Columbia channel occurs 23 h after the dam ruptured (Fig. 3), leaving scars visible from space (Fig. 8A). Model output of flood power ranges up to 5–15 kW/m^2 (Fig. 8B) and compares well with this distribution of flood erosion.

Stage 1: 24–55 h

Umatilla Basin fills 38–55 h after ice-dam rupture as discharge increases through Columbia gorge. Critical flow (Henderson, 1966) is achieved through the narrows at Crown Point on the west end of the gorge, while overland flow in the Cheney-Palouse and Telford–Crab Creek scablands wanes. Flood flow becomes established throughout the Columbia River drainage system (Fig. 3). The broad basins of Pasco, Yakima, and Umatilla continue to fill to their maximum levels. Flood stage in Pasco Basin peaks 38 h after ice-dam rupture at elevation 336 m; Umatilla Basin achieves peak stage 55 h after dam break at elevation 284 m. Critical flow through Walulla Gap is briefly established for several hours as Pasco Basin achieves its maximum stage, and then flow declines but remains close to critical for several days afterward. As broad Pasco Basin fills to its maximum level, adjacent slack-water basins such as Walla Walla and Yakima valleys (Fig. 1) also fill with water and receive suspended-load sediment eroded from points upstream. Mainstem Columbia River flow out of Umatilla Basin increases flood stage throughout Columbia gorge. In Figures 9 and 10, a snapshot of flood stage at 55 h (Fig. 8) is compared with field observations from O'Connor and Baker (1992) around Walulla Gap (Fig. 9; Table 4) and from Benito and O'Connor (2003) west of Umatilla Basin (Fig. 10; Table 5). From Umatilla Basin, floodwaters overflow southwest at two locations: long Alkali canyon (point N on Table 5) and Philippi canyon (point J), both spilling into John Day valley. Downstream, as Willamette Valley fills, flow past Crown Point becomes subcritical and remains so for the duration of flooding.

Stage 2: 55–180 h

Glacial Lake Missoula finishes draining in stage 2 of the simulation (Fig. 5). Ponded water slowly drains from stranded channels and bays within Lake Missoula and Rathdrum-Spokane valley, and discharge into the Columbia River system is negligible. Flow through Grand Coulee wanes. Throughout most of the flooded area, most of the power exerted by the flow on its bed

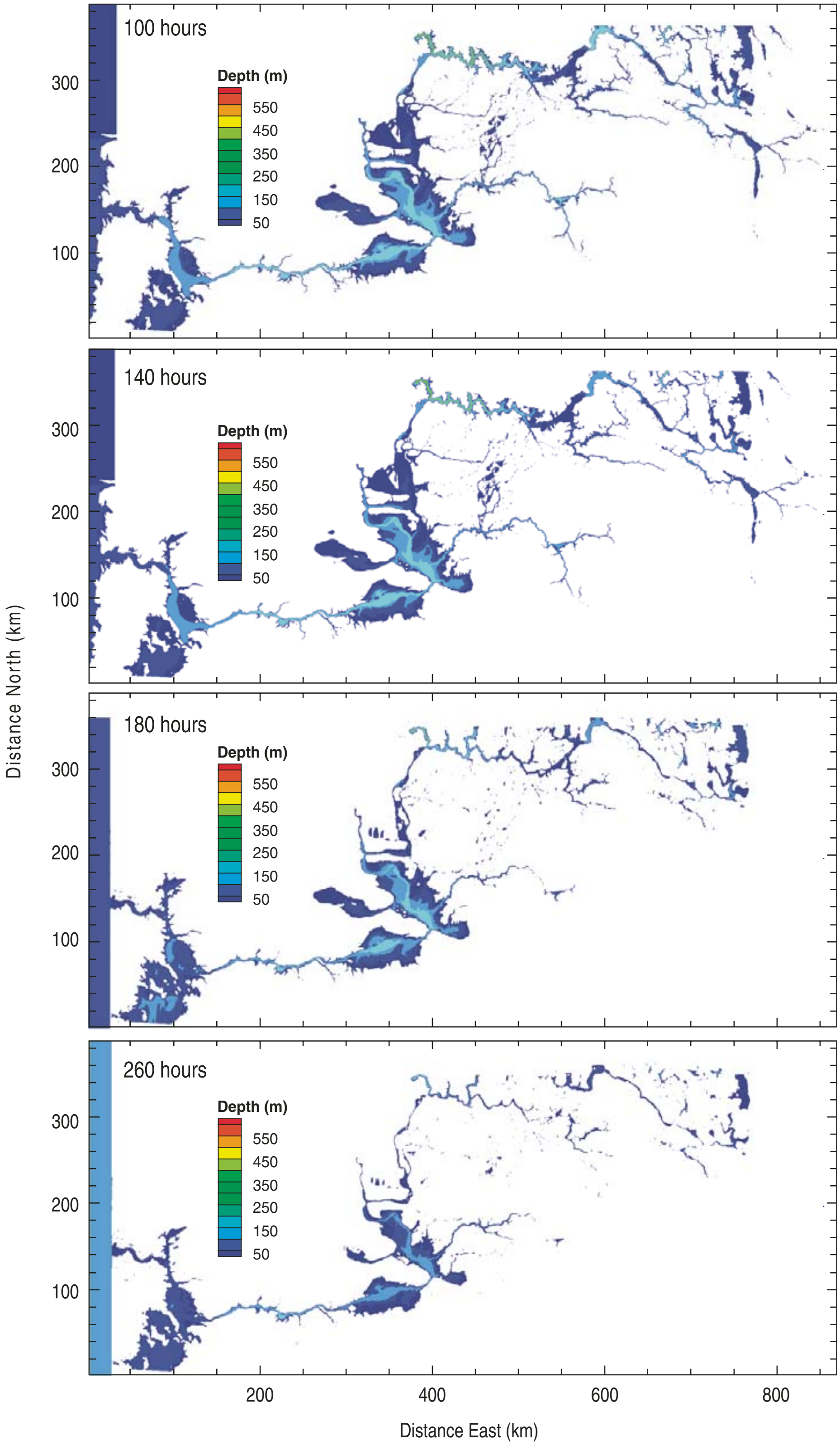


Figure 5. Drainage of Glacial Lake Missoula and the upper Columbia River system during a large Missoula flood. The broad basins of Pasco, Yakima, and Umatilla drain through Columbia gorge, extending the duration of flooding to 325 h. This long duration is primarily caused by the discharge limitation of the gorge, and secondarily by low gradients from the Willamette Valley to the Pacific Ocean in the final stages of flow.

is spent during the first 100 h. Slack-water areas like Walla Walla valley remain inundated much longer, but power per unit area remains low.

Pasco, Yakima, and Umatilla Basins drain slowly through Columbia gorge. Earlier flow through the gorge had balanced flow south into Pasco Basin, but all three basins now drain as inflow to Pasco Basin gradually decreases relative to outflow. Portland-Vancouver Basin fills as flow through the gorge increases. The earlier sharp drop in stage at the west end of the gorge at Crown Point (Benito and O'Connor, 2003) lessens as this drop in surface level spreads upstream. Maximum flood stages (Fig. 10; Table 5) along Columbia gorge (Benito and O'Connor, 2003) occur early in this period. Back-flooding of Willamette Valley increases flood stage and decreases discharge past Crown Point. Flow into the Pacific Ocean through the lower Columbia River valley begins to drain Willamette Valley as this outflow exceeds inflow at Crown Point (Figs. 3 and 5).

Stage 2: 180–500 h

During this period, Pasco, Yakima, and Umatilla Basins drain completely through Columbia gorge. Walla Walla valley remains flooded nearly as long as Pasco Basin and long after most of Yakima Basin has drained. Most of the volume of these basins drains from 55 to 260 h after dam break (Figs. 3 and 5). Despite this, the lower Columbia River system, including Willamette Valley, requires an additional 240 h to completely drain floodwaters to the sea.

Flood Power Associated with Stages 1 and 2

Flood power is the product of bed shear stress and mean flow velocity and may be used to estimate locations where erosion and deposition may occur. Previous estimates of erosion and deposition based on flood power have been made for the Missoula floods (Benito, 1997) and for the Bonneville floods (O'Connor, 1993). Benito (1997) used an empirical equation in which stream power was assumed to vary as the square of velocity; O'Connor (1993) used the same method we use here, where stream power varies as the cube of velocity.

For conditions similar to those producing the scablands tracts (Fig. 8), O'Connor (1993) obtained values for stream power in accordance with what we obtain here: depositional areas are less than 5 kW/m^2, and erosional areas are in excess of 10 kW/m^2 and often exceed 100 kW/m^2. In Figures 4 and 6, we emphasize the lower rather than the higher end of this range to show localized distribution of high erosion potential throughout the entire flow domain.

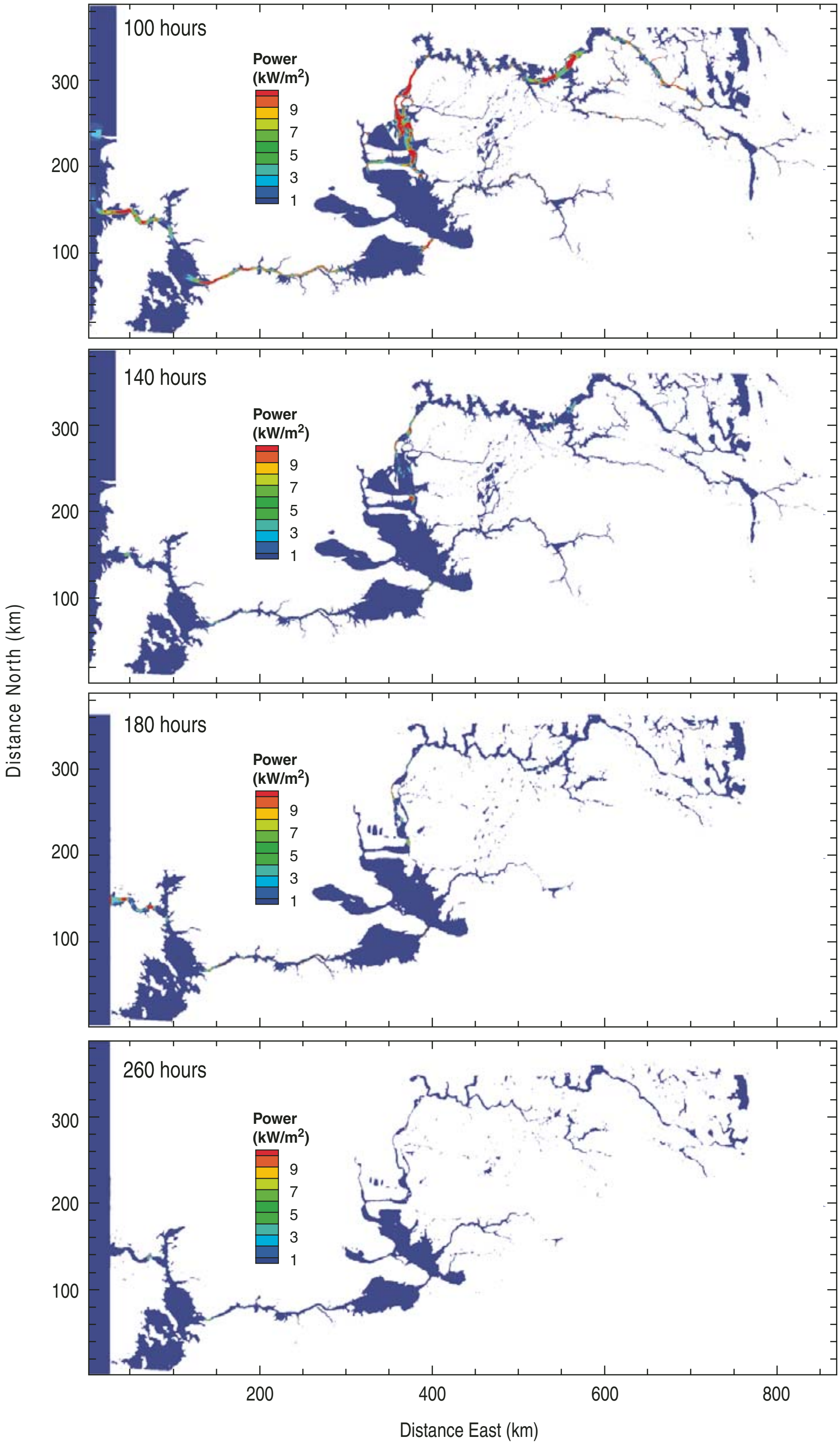


Figure 6. Power per unit area corresponding to floodwater drainage shown in Figure 5.

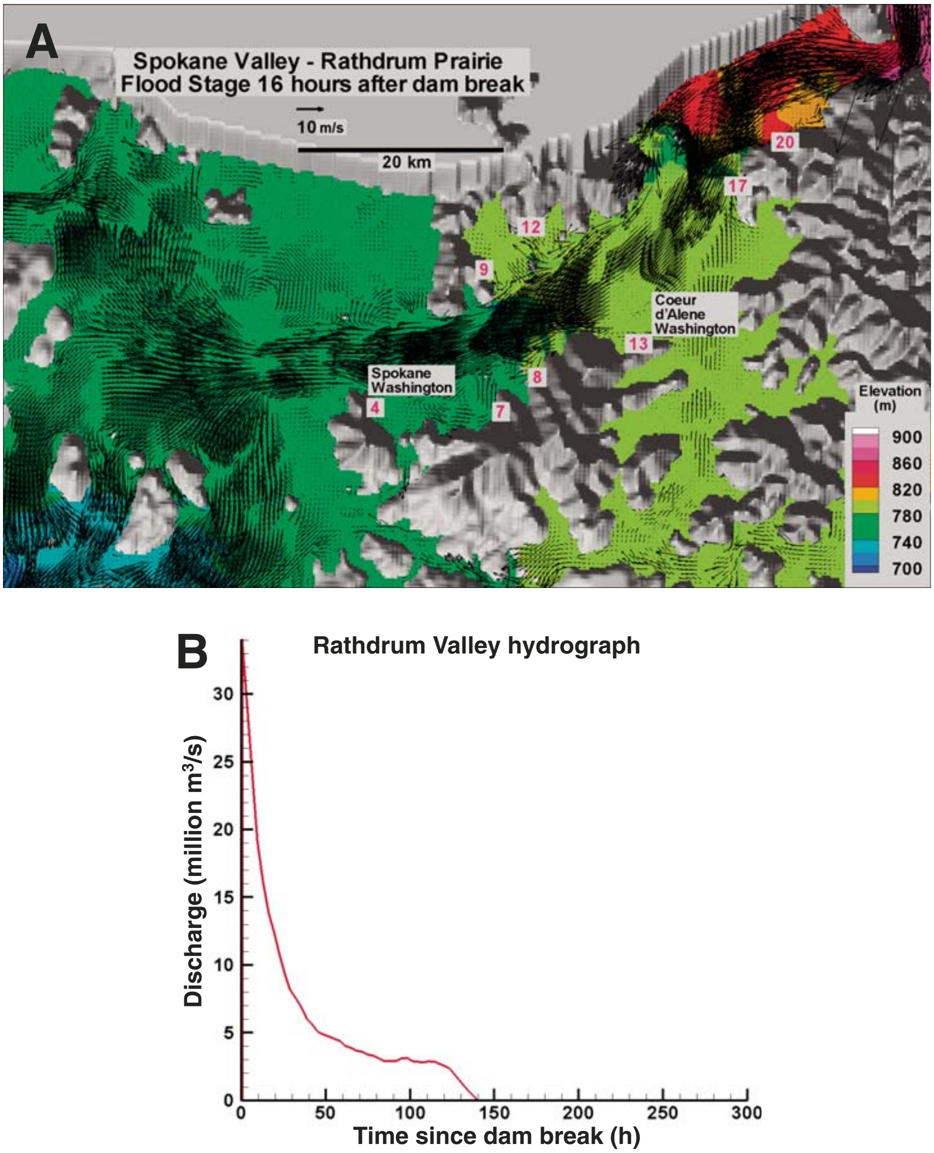


Figure 7. (A) Maximum stage of flooding of the Rathdrum-Spokane valley supplying maximum discharge into the Cheney-Palouse scablands 16 h after dam break. Flow stages are shown by color; velocity vectors are in black. Numbers correspond to field locations reported in O'Connor and Baker (1992) and compared with model results in Table 3. (B) Discharge versus time in hours entering the head of Rathdrum valley 549 km to the east.

TABLE 3. RATHDRUM-SPOKANE VALLEY COMPARISONS

Rathdrum-Spokane valley sites (O'Connor and Baker, 1992)	Elevation of flood indicator (O'Connor and Baker, 1992) (m)	Model value (this paper) (m)
4	756	763
7	762–775	761
8	781	785
9	762	782
12	799	783
13	778	796

The distribution of areas of high erosion and of areas of deposition varies substantially with time as flooding proceeds.

The first day after dam break, erosion is concentrated at Rathdrum-Spokane valley, Grand Coulee, Palouse Falls, and Walulla Gap (Fig. 4). By the end of the second day, erosion has increased over Dry Falls, between Quincy and Pasco Basins, at Walulla Gap, and overland throughout the Cheney-Palouse scablands. By the middle of the third day, little erosion occurs in Cheney-Palouse scablands, while high-energy flow continues to carve away at Grand Coulee, Dry Falls, and Walulla Gap. The second and third days also show high power values near Hood River and Crown Point in Columbia gorge, but these subside by the fourth day and thereafter. These sites of high power in the gorge match average values obtained by Benito (1997), though his peak values were much higher than ours.

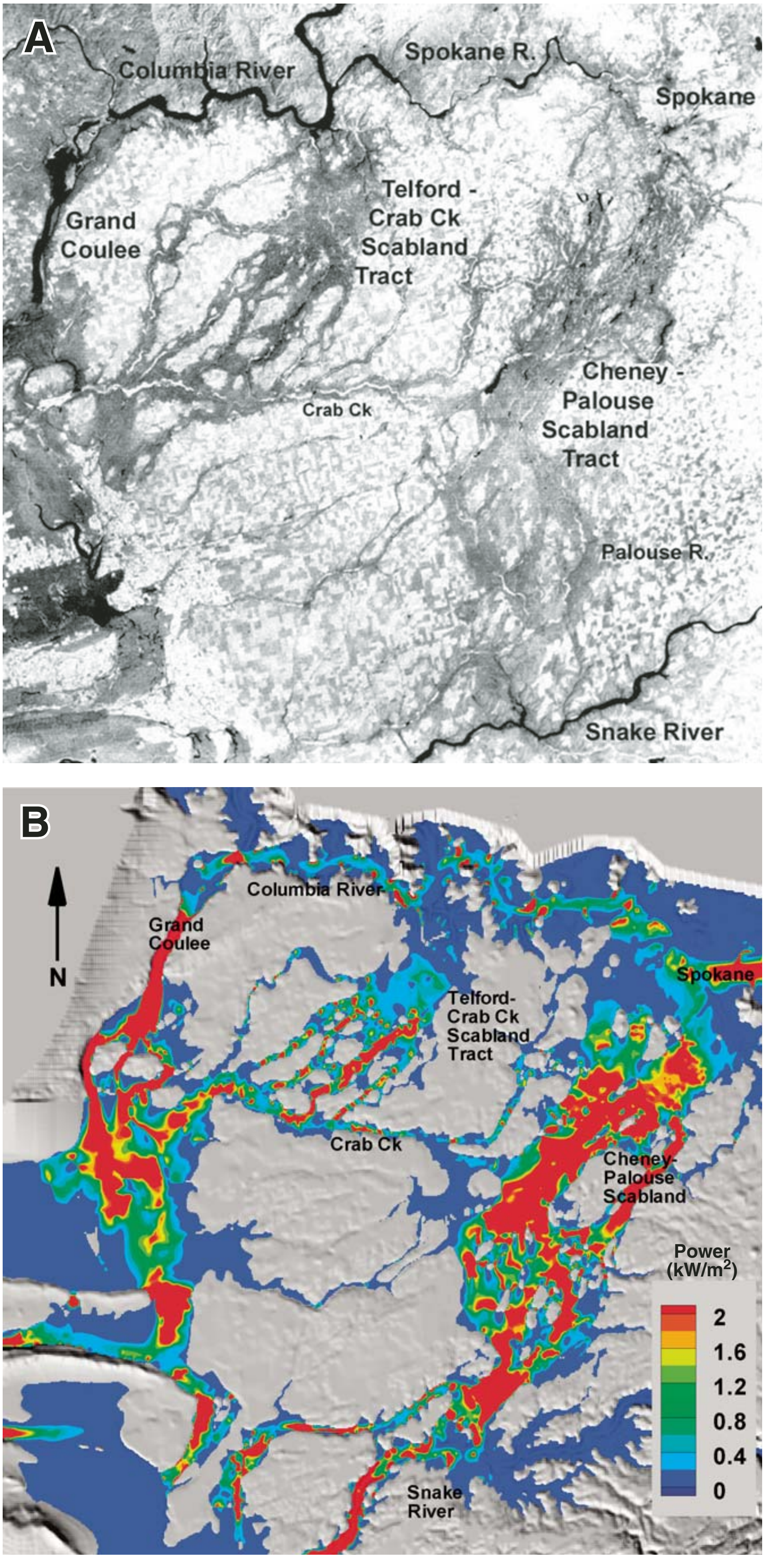
One-hundred hours after dam break (stage 2; Fig. 6), the only high values of flood power remaining are along Rathdrum-Spokane valley and Grand Coulee, and all flows north and east of Pasco Basin are waning. At 140 h after dam break, only low power values remain, and consequently sediment transport is reduced east and north of Pasco Basin.

DISCUSSION

For the ice-margin configuration chosen (Table 1), catastrophic dam rupture led to rapid filling of the broad southern basins in the first few days of flooding and overland flow. The Telford–Crab Creek and Cheney-Palouse scabland tracts coincide with the paths of maximum power that we calculated for these overland flows (Fig. 8). Laboratory (Moss et al., 1980), flume (Denlinger and O'Connell, 2008), and theoretical studies (Moore and Burch, 1986) all show that these power levels are more than sufficient to strip loose soil, and they may be large enough to erode rock as well. The estimated power distribution matches closely the distribution of scablands in eastern Washington. The scabland tracts in Figure 8A correspond to the highest power levels in Figure 8B. Debris eroded from scabland tracts supplied local sites of deposition (Bretz, 1928a, 1928b; Smith, 1993), the coarse gravel in delta bars in northern Quincy and Pasco Basins, and the finer sediment in quiet, low power per unit areas of southern Quincy Basin, southern Pasco Basin, Yakima valley, and Walla Walla valley.

In the latter part of the first stage of flow (23–55 h), floodwaters initially filled Quincy Basin, then Pasco Basin and its tributary (Yakima and Walla Walla) basins, and finally Umatilla Basin (Fig. 3). The maximum stage we obtained in Pasco Basin (336 m) from this filling does not match the maximum peak-stage field indicator of 366 m in southern Pasco Basin and at Walulla Gap (Waitt, 1980, 1985). Our peak flood stages in Pasco Basin and through Walulla Gap range from 336 m to 284 m and descend downstream to the west, as do field high-water indicators (O'Connor and Baker, 1992), yet our modeled peak stages here are consistently 10 m to 40 m too low. Model peak stages do match field observations west of Umatilla Basin near Philippi canyon (Benito and O'Connor, 2003), where our

Figure 8. (A) Satellite image of eastern Washington showing the Columbia and Snake Rivers, and the distribution of scablands across the arid prairie. Landsat MSS image (www.mines.edu/academic/geology/faculty/klee/missoula.doc). The scablands show up as dark-gray scars on the landscape, as the soil has been stripped and the bedrock (basalt) eroded into characteristic channels of scabland morphology. (B) Flood power (truncated at 2 kW/m²) during maximum simulated inundation of the Channeled Scablands 23 h after dam break. Distribution of modeled power per unit area (product of mean velocity and bed shear stress) approximates the pattern of flood scars in A.



modeled flow laps onto a ridge on the Columbia's south side. The simulated flow crosses one saddle but not another into the John Day valley, in agreement with field observations. We did not test whether an additional 15 m of stage for the initial level of Glacial Lake Missoula will achieve an additional 40 m of stage in Pasco Basin (possibly a result of increased volume from entrained sediment), nor how an additional 40 m of stage in Pasco Basin would alter model output downstream.

Drainage of maximum stages of the Pasco, Yakima, and Umatilla Basins establishes the maximum flood stages through the gorge, Portland Basin back-flooding of Willamette Valley, and drainage to the sea. Simulation of the drainage of these basins produces peak stages (Fig. 10) consistent with the high-water indicators in the gorge (Table 5) of Benito and O'Connor (2003). The capacity and conveyance of Willamette Valley combined with the large conveyance down lower Columbia valley to the sea (Fig. 1) greatly exceed conveyance through the gorge, and this results in a large drop in stage below Crown Point through the west end of the gorge. For these flood conditions, the maximum discharge of 6 million m^3/s through the gorge governs the duration of the long, waning flow of Missoula floods to the Pacific Ocean. Our two-dimensional shallow-water model halves the peak conveyance through the gorge obtained with calibrated one-dimensional models (Benito, 1997; Benito and O'Connor, 2003). This is consistent with other comparisons between 1-D and 2-D models for actual dam-break flows through crooked channels (Denlinger and O'Connell, 2008; Goutal, 1999). In other areas where the channel is relatively straight, as in

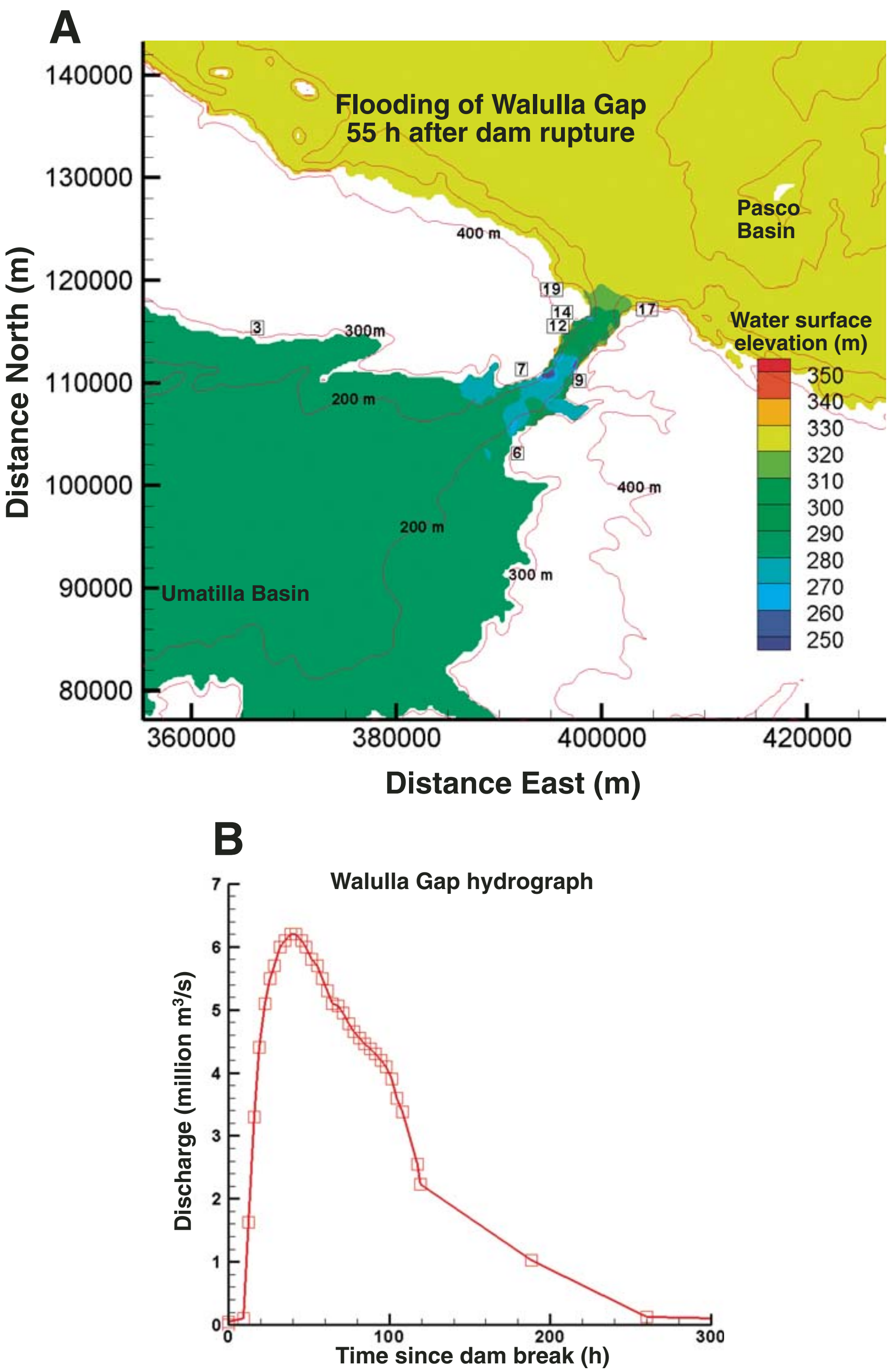


Figure 9. (A) Flood stage at Walulla Gap produced by the model 55 h after dam break, when flood stage of Umatilla Basin is at peak. Numbers correspond to field locations in O'Connor and Baker (1992) that are compared to model output in Table 4. (B) Discharge through Walulla Gap, 395 km to east, produced by this model. The peak discharge leads the peak stage in time, since discharge through the gap decreases as Umatilla Basin fills.

Rathdrum, peak discharge and stage are close to 1-D model estimates from previous studies (Fig. 7; Table 3).

Figure 11 (horizontal axis is the same as Figs. 3 and 5) illustrates how the dynamic response of flooding in eastern Washington becomes constrained by flow resistance through the gorge. (For comparison, individual hydrographs for the Rathdrum-Spokane valley and for Walulla Gap are shown on Figs. 7 and 9, respectively.) Total westward discharge at each distance east is obtained by summing westward discharge (depth times westward velocity times cell length) along each corresponding north-south column of finite volume cells (a vertical line on Fig. 2). This is done for every 250 m increment along the west-to-east horizontal axis in Figures 3–6. Maximum discharge at the head of Rathdrum valley occurs a few hours after dam break, 500 km east of the left (west) edge of the grid. However, peak flooding (stage) in Spokane valley occurs 8 h later (16 h after dam break) because of backfilling of Lake Coer d'Alene. Twenty-three hours after the ice dam ruptures, flood discharge peaks in dozens of scabland channels in eastern Washington. It is not until a day after dam break (cf. Figs. 11 and 3) that flood discharge begins to penetrate Columbia gorge. As Umatilla Basin achieves its peak stage 55 h after dam rupture, the discharge throughout the drainage area is restrained to a level dictated by conveyance through the gorge (see hydrograph for Walulla Gap on Fig. 9). For a large Missoula flood, it takes about ten times longer to drain the broad basins of Pasco, Yakima, and Umatilla than it does to fill them.

Early basin-filling stages of catastrophic flooding are sensitive to blockages and confinements under different positions of the ice-sheet terminus in different initial geographic scenarios. These cause different filling rates for the broad southern basins emptying into Columbia gorge (Table 1). If the northwestern reach of Columbia valley is not blocked by ice, most of the flood flow would continue around Columbia's great bend. In our scenario testing, we found that Pasco Basin fills fastest when ice blocks the great bend (Table 1), and energetic flow down the Cheney-Palouse scablands is combined with the maximum flow through Grand Coulee. For the alternative configurations we tested, flow down an unblocked Columbia River that exploits both Grand Coulee and Columbia valley fills Pasco Basin a few hours later than flow down only Grand Coulee and the Cheney-Palouse. However, we have not investigated all ice-sheet reconstructions that may reduce the time required to fill Pasco, Yakima, and Umatilla Basins and maximize the observed stage in Pasco Basin.

Overall, the strongest constraint on flood timing and stage is the delay imposed by the crooked channel of Columbia gorge. Our flow simulations show that it takes ~325 h to drain Pasco, Yakima, and Umatilla Basins through Columbia gorge, though only a few days were required to fill them. With this slow drainage, a different ice-sheet configuration may achieve the maximum stage at Walulla Gap that field evidence demands with the same initial lake level we used. However, a stage 30 m higher in these broad basins (increasing depth by 10%) will not significantly reduce the time required to drain them through Columbia gorge.

FUTURE WORK

We expect that the basic scenario, rapid filling and slow draining of Pasco, Yakima, and Umatilla Basins, will not change much with alternative ice-margin scenarios. Nonetheless, the full range of possible outcomes has not been tested. A more detailed ice margin, other levels of Glacial Lake Missoula and a more detailed blockage by the Okanogan lobe of ice may match all high-water indicators, including Walulla Gap. These additional tests, at a resolution high enough to be realistic, will require substantial computer resources.

CONCLUSIONS

Catastrophic rupture of the ice dam impounding Glacial Lake Missoula produced both overland flow through the Cheney-Palouse scablands and flooding of mainstem Colum-

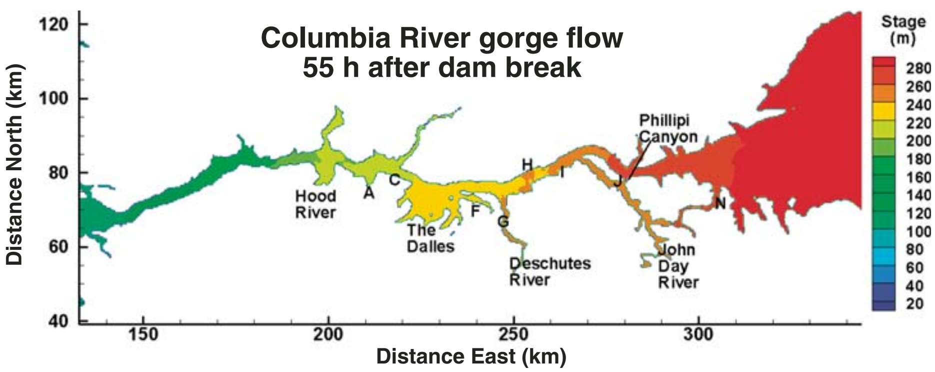


Figure 10. Flood stage west of Umatilla Basin 55 h after dam break when the flood stage of Umatilla Basin is at peak. Letters correspond to field locations in Benito and O'Connor (2003) that are compared to model output in Table 5.

TABLE 4. WALULLA GAP COMPARISONS

Walulla Gap sites (O'Connor and Baker, 1992)	Elevation of flood indicator (O'Connor and Baker, 1992) (m)	Model value (this paper) (m)
19	348	336
14	360	329
17	355	336
12	343	335
7	315	296
3	305	284
6	323	284

TABLE 5. COLUMBIA RIVER GORGE COMPARISONS

Columbia gorge sites (Benito and O'Connor, 2003)	Elevation of flood indicator (Benito and O'Connor, 2003) (m)	Model value (this paper) (m)
A	185	210
C	219	214
F	229	229
G	240	241
H	241	242
I	249	248
J	267	256
N	280	281

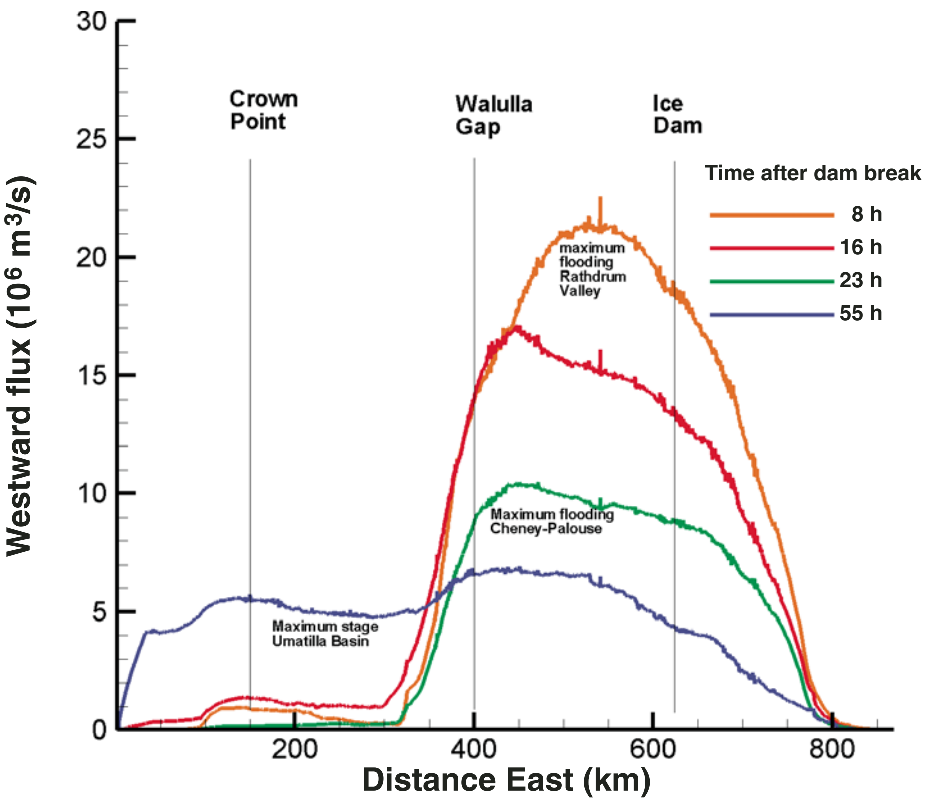


Figure 11. Total westward flux (discharge) corresponding to Figures 3 and 5. North-south component of discharge is absent here. Floodwaters accumulate in Pasco, Yakima, and Umatilla Basins because their drainage downstream is constricted. Whereas flood input to these basins ranges from 10 to 20 million m³/s, their output is limited to less than 6 million m³/s by the impedance of crooked Columbia gorge. The limited conveyance of the Columbia gorge extends the duration of flooding by an order of magnitude. The saddle for the 55 h flux between 250 and 400 km east is produced by superposition of eastward flow out of backwatered Yakima Basin with westward flow through Umatilla Basin.

bia valley. In modeling a typical large but not maximal outburst flood, we find that most of the flooding of eastern Washington occurs over the first 3 d as the broad basins of Pasco, Yakima, and Umatilla fill. An additional 19 d is required for these basins to completely drain through Columbia gorge. Despite starting with an initial level of Glacial Lake Missoula 45 m below the highest level suggested by field mapping, we achieve modeled peak flood stages that meet or exceed peak-stage indicators determined from field mapping of the Rathdrum-Spokane valley, along the main scabland tracts, and along Columbia gorge. However, our modeled peak flood stages at Walulla Gap are 10 m to 40 m lower than peak-stage indicators in the field. The high water evidence in Pasco Basin may result from flooding under conditions different from the ones we modeled, or it may reflect the additional volume of sediment eroded from points upstream. This discrepancy at Walulla Gap aside, our shallow-water model approximates peak-stage field evidence in most of the flooded region, and thus Glacial Lake Missoula is the only source of water required to produce the scabland floods. There is no need for vastly larger sources of water as proposed by Shaw et al. (1999).

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