**Cause analysis for a new type of devastating flash flood**

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**ABSTRACT**

This work introduces an unprecedented flash flood that resulted in nine casualties in Shimen Valley, China, 2015. Through field survey and numerical simulation the causes of the disaster are systematically analyzed, finding that the intense storm, terrain features, and the large woody debris (LWD) played important roles. The intense storm induced fast runoff and, in turn, high discharges as a result of the steep catchment surfaces and channels. The flood flushed LWD and boulders downstream until blockage occurred in a contraction section, forming a debris lake. When the debris dam broke, a dam break wave rapidly propagated to the valley mouth, washing people away. After considering the disaster-inducing factors, measures for preventing similar floods are proposed. The analysis presented herein should help others manage flash floods in mountain areas.

**Key words** | dam break, debris dam, flash flood, flood management, large woody debris

**INTRODUCTION**

Floods in mountain areas are a devastating natural disaster, becoming one of the most important restrictive factors for sustainable development of the economy and society in mountain catchments (Weingartner et al. 2003; Tezuka et al. 2014; Thaler et al. 2016). Development of risk management and disaster control measures has been attracting the attention of governments, academe, and industries (Delalay et al. 2018; Huang et al. 2018). Mountain floods are also destructive and exhibit extremes of peak capacity due to limited river conveyance and storage capacity.

Although the fact of growing flood events, such as dam break floods and floods in rivers is widely known, research on mountain rivers and floods have been rarely reported in detail in the past. However, awareness has increased during the past 20 years (Wohl 2010). Allamano et al. (2009) observed that intense floods in mountain catchments are becoming more frequent and are likely to become more frequent with global warming. Ozturk et al. (2018) discovered that the main cause of the flash flood and debris flow in Braunsbach was a series of heavy rainstorms dumping up to 140 mm in 2 h in May 2016. Bout et al. (2018) studied a flash flood event with landslides and debris flow and detected the cause was the convective storm hitting the north-eastern part of Sicily, Italy, on October 1, 2009.
Apart from storms, the dam break of some barrier lakes caused by earthquakes and landslides are also likely to induce severe floods. Zhou et al. (2022) investigated disaster drivers of the barrier lakes after the Wenchuan earthquake on May 12, 2008, and suggested some risk mitigation measures. Fan et al. (2018) studied the reactivated landslides in Tangjiawan on September 5, 2016. Some survey and satellite images from 2005, 2008, 2010, and 2015 were used to analyze the evolution of the landslide, investigating some reasons for formation of the barrier. However, dam break floods were not fully taken into account. Vermuyten et al. (2018) presented two extensions of a combination of model prediction control and a reduced genetic algorithm (RGA-MPC) technique to improve the effort of the real-time flood control.

All the mountain flood events mentioned above were caused by heavy rainstorm and/or dam break flows of the debris (primarily earthquake) in lakes. This work presents a new type of flash flood caused by the chain effects of intense rainfall, barrier dam formed by flushed large woody debris (LWD) and boulders, as well as the dam break wave propagation in Shimen Valley, Qinling Mountain, China, in order to depict the characteristics of the flood process, analyze the main disaster drivers, and accordingly, propose effective mitigating measures.

**THE SHIMEN FLOOD EVENT**

On August 3, 2015, a flash flood occurred in the mouth of the Shimen Valley, a tributary of Xiaoyu River, Chang’an district, Xi’an City, China, as a result of a very intense storm. As shown in Figure 1, the catchment of Shimen Valley has an area of 2.1 km², a channel length of about 1.7 km with an average slope around 20°.

The flood flow from Shimen Valley, a tributary of the Xiaoyu River, washed nine people into the Xiaoyu River, seven of whom were killed with the remaining two missing. The rainfall was 145.7 mm, reaching the highest value of a flood event in the 30-year monitored period. Some snapshots after the disaster are shown in Figure 2; these snapshots illustrate that large amounts of debris carried by the flood destroyed the road crossing the flow path.

The field survey discovered that a barrier lake was formed at a narrow section of the valley by debris transported by the flash flood. More and more water was stored in the reservoir until it was full. When the water level was high enough to overtop the embankment, a dam break occurred and the wave began to propagate downstream the channel, causing severe flash flooding. Figure 3 shows an aerial view of the study area. It should be noted that the scene of the accident site is different in Figures 2 and 3, as a concrete channel was built after the flood event to raise the capacity of the flow conveyance channel.

According to the field investigation on March 15, 2018, the flash flood was relevant to the extreme rainfall, the terrain features, and the vegetation conditions of the catchment, so these three main reasons leading to the new flood are analyzed in detail.

**Heavy storm**

A flash flood is normally caused by heavy rainfall in a short time, usually less than 6 hours (National Oceanic and Atmospheric Administration, NOAA, version 2.60). The catchment is located on the north slope of the Qinling Mountains, an important geographical border between the north and south of China, i.e., the transitional zone between subtropical and temperate zones. This area is reported by He et al. (2012) to be a region with high-frequency heavy rain.

In order to understand the precipitation process of the event, the hydrography of the study area is required. As there is no rain gauge in the valley, the closest rain gauge, referred to as Yinzhen, was selected to represent the storm at the Shimen Valley (9.5 km from the valley, as plotted in Figure 4). The hyetograph at Yinzhen rain gauge is illustrated in Figure 5, indicating the rainfall increased sharply from 17:00 to 18:00, on August 3, 2015. The total rainfall was 144.8 mm in 5 hours and reached 126.6 mm in the first 2 hours. According to the IDF curves of Xi’an City in the form of a Chicago storm type, this rainfall is in a return period of around 1,000 years. Such intense rainfall would be expected to produce large runoff and, in turn, lead to severe flooding.

**Terrain features**

The terrain features also play a significant role in generating a severe flood. In this work, a high-resolution digital
Figure 1 | Study area in the catchment of Xiaoyu River.
elevation model (DEM) downstream of Shimen Valley was generated from raw data collected using LiDAR from an unmanned aerial vehicle (Figure 6). According to the terrain features, two contractions existing in the channel are likely to form debris dams. Once the dam breaks, the dam break wave will accelerate down the steep channel and cause damage.

Figures 6 and 7 shows the contraction where the debris dam was created. The width of the contraction is about 15 m and is much narrower than other parts of the valley. The debris, consisting of boulders and trees carried by the flash flood, blocked the valley at the contraction. A debris dam was formed and the water began to be stored in the upstream reservoir. The water level increases until the
dam cannot hold the pressure, at which time, the debris dam breaks and a dam break wave propagates downstream.

Although no direct evidence is available, a witness living in the valley mouth reported that there was no water in the channel after about half an hour; the discharge suddenly increased once the storm started. The period with low discharge indicated there was a high likelihood that a dam had formed in the upstream reaches and that this dam blocked the main flow.

As plotted in Figures 6 and 7, the side slopes of the catchment are considerably steep. In some cross sections, the slope could reach 60° and is prone to induce fast hydrological responses; that is, the surface runoff moves quickly to the channels. The channel slope in the catchment is also very abrupt, as shown in Figure 8, with an average value of 1.5 (horizontal to vertical). The rapidly collected water in the channel will be transported efficiently to the catchment outlet and, therefore, is likely to lead to flash floods. This high-velocity flow will sweep the channel and flush boulders and trees downstream.

The dam break flow would also be expedited in the steep channel and the water move to the mouth of
the valley. Another contraction in the mouth could concentrate the flow energy like a spout. The flood will spray in the spout area to the river and flush people in the river away.

**Thick vegetation and boulders**

In this disaster, the debris consisted mainly of boulders, rock fragments, logs, sticks, branches, and other wood that fell...
into the channel (see Figure 9). Figure 10 illustrates the thick vegetation cover in the Shimen Valley, even in the river channel. Apart from the shrub on the side slope, some trees in the channel were planted by the local residents. Theoretically, the trees can increase surface roughness and reduce flood peaks. However, the logs, sticks, and branches were distributed in the slopes and river channel, and most of them were not cleaned up in time. Once a heavy storm occurs, the fast runoff will carry the LWD downstream and debris may destroy the living big trees. Some trees growing in the contraction part of the channel would block the LWD and thus form a debris dam together with the boulders.

The boulders, as shown in Figure 9, are another kind of debris source. Once the flood velocity is adequate to carry the big stones, they will move downstream, mixed with the LWDs. When they arrive at the contraction section, the debris gathered and a barrier lake was formed with the carrying action of the water. The water will be stored until the dam cannot host the water. In this area, the thick trees play an important role for building the dam, since the trees worked as pillars to trap the coming debris.

In summary, the heavy storm, the terrain features, and the debris material of LWD and boulders each made a contribution to the flash flood. The extreme storm triggered the flash flood in the river channel. The fast flood flow carries the debris material in the form of boulders and the LWDs to the lower reaches. A debris dam was created in the contraction area and then breached, leading to an aggravated flood disaster.

**REPRODUCTION OF THE FLOOD EVENT USING A HYDRODYNAMIC MODEL**

**Numerical hydrodynamic model**

In this work, a numerical hydrodynamic model proposed in Hou et al. (2015) is utilized to compute the process of the dam break flood propagation. The hydrodynamic model was developed by solving the 2D shallow water equations (SWEs) numerically, within a framework of a well-balanced cell-center Godunov-type finite volume method. The governing equations are as follows:

\[
\frac{\partial q}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} = S
\]

\[
q = \begin{bmatrix} h \\ q_x \\ q_y \end{bmatrix}
\]

\[
f = \begin{bmatrix} uh \\ u^2h + gh^2/2 \\ uwh \end{bmatrix}
\]

\[
g = \begin{bmatrix} vh \\ uvh \\ v^2h + gh^2/2 \end{bmatrix}
\]

\[
S = \begin{bmatrix} -gh\partial z_b/\partial x - c_i u \sqrt{u^2 + v^2} \\ -gh\partial z_b/\partial y - c_i v \sqrt{u^2 + v^2} \end{bmatrix}
\]

where \( t \) is time, \( x \) and \( y \) are the Cartesian coordinates; \( q \) is the vector of conserved flow variables containing \( h, q_x \) and \( q_y \), which are the water depth and the unit-width discharges in the \( x \)- and \( y \)-directions, respectively; \( q_x = uh \) and \( q_y = vh \); \( u \) and \( v \) are the depth-averaged velocities in the \( x \)- and \( y \)-directions, respectively; \( z_b \) is the bed elevation; \( f \) and \( g \) are the flux vectors in the \( x \)- and \( y \)-directions, respectively; \( S \) is the source vector; \( i \) is the source or sink of mass caused by rainfall and infiltration; and \( c_i \) is the bed
roughness coefficient, determined herein as \( gn^2 / h^{1/3} \), with \( n \) being the Manning coefficient.

The model solves the SWEs within the framework of a Godunov-type cell-centered finite volume scheme based on the structured grids. The fluxes of mass and momentum are computed by the HLLC (Harten–Lax–van Leer contact) approximate Riemann solver. The slope source terms are evaluated by the slope flux method as proposed in Hou et al. (2013). The friction source terms are evaluated by the improved explicit method. The two-stage explicit Runge–Kutta approach is applied to update the values of the flow variables to a new time level. The code is programmed by using C++ and CUDA, which can use the GPUs (graphic processing unit) to accelerate the computation.

**Model validation**

In order to validate the proposed numerical hydrodynamic model, the Malpasset dam break and an experiment flash flood accomplished by Testa et al. (2007) are chosen as two case studies in this section.

**Simulation for Malpasset dam break**

The Malpasset dam was located in the Reyran river valley in southern France, and collapsed in 1959 after extremely heavy rain. Figure 11 shows the DEM of the Malpasset and its floodplain. The locations of dam and survey points P are also plotted in the same figure. When simulating the
dam break event, the real arch dam is approximately a straight line between two points of the coordinates (4,701.18 m, 4,143.41 m) and (4,655.50 m, 4,392.10 m), and the remnants of the dam after failure are not taken into account as suggested by Goutal (1999). The maximum water level at 17 points along the two banks were surveyed by the local police after this accident.

In the simulation, a constant water level of 100 m above sea level is assumed, and the floodplain is considered as dry cell. The Manning coefficient is considered as $0.033 \text{ s m}^{-1/3}$ in all the computational domains, as in Alessandro et al. (2002) and Hou et al. (2013). The total computational domain consists of 1,581,714 structured cells. The computed water level and the measured ones at 17 survey points are compared in Figure 12. The simulated maximum water levels are in good agreement with the measured data, indicating the applied numerical model performs well for dam break simulation.
Simulation for an experimental flash flood

An experiment of flash flood presented by Testa et al. (2007) is also taken as a case study to validate the model. The physical model is to reflect flash flood propagating over a simplified urban district. Figure 13(a) shows the setup of the experiment where the urban area involves 16 buildings and two dikes. The black crossed circles represent the ten measuring gauges for water levels. The numerical model proposed by Hou et al. (2015) is utilized to simulate the flood propagation process. The boundary conditions of inflow and free outflow are imposed on the left and right boundaries, respectively. Figure 13(b) plots the inflow hydrograph. High-resolution DEM data with a resolution of 0.05 m by 0.05 m is applied to generate the computational grid. As proposed in Testa et al. (2007), a constant Manning coefficient of 0.025 is used in the numerical model.

In this work, the computed water depth at gauges 3 and 8 are selected to compare with the measured data in Figure 14. This illustrates that the simulation results are in good agreement with the measured ones. From the hydrograph, the water depths are captured accurately in terms of peak discharge and the recession process. To quantitatively analyze the model performance, the Nash–Sutcliffe efficiency coefficient (NSE) is introduced as:

\[
E_{\text{ns}} = 1 - \frac{\sum_{t=1}^{n} (Q'_t - Q_m)^2}{\sum_{t=1}^{n} (Q'_t - Q_o)^2}
\]

where \(Q'_t\) is the measured data at the time \(t\); \(Q_m\) is the simulated results at the time \(t\); \(Q_o\) denotes the average of the measured data.

The NSE at gauges 3 and 8 are 0.950 and 0.955, respectively, indicating that the model performs well in simulating flash flood.

Dam break flood simulation

The proposed hydrodynamic model is used to model the process of the dam break flood. According to the field investigation, a barrier lake with a water depth of around 7 m was formed in the upstream reach about 200 m from the accident site. As the real dam break process is unknown, a sudden breach of the dam, in order to reflect the most dangerous scenario, was assumed to produce the dam break waves. The initial conditions of the water and bed elevation are shown in Figure 15. To account for
topographic features, a DEM with a resolution of 0.2 m was applied in the simulation. A constant Manning coefficient of $0.02 \, \text{s} \cdot \text{m}^{-1/3}$ was adopted to consider the local roughness. The model was run for a simulation period of 10 min to predict the dam break flood wave propagation.

According to the field investigation, photos and videos from witnesses, the flood in the mouth of the valley reached very high levels; the flood mark on the wall of house 2 in Figure 3 is about 2 m high. In order to check the plausibility of the hydrodynamic model, a comparison point was set near the wall. The computed depth hydrograph in Figure 16 shows that the highest predicted depth is nearly 1.8 m. Thus, the simulation result is close to the measured water level. Figure 17 also shows the velocity of the flood in the valley mouth at 42 s when the flood reached the highest value. At that time, the velocity around the house is about 9 m/s. As Cox et al. (2010) reported that the limited velocity for adults and children in good conditions is 3 m/s, indeed, the kinematic energy is sufficient to cause the accident.

Figure 18 reveals the computed time series of the flood propagation. When the debris dam broke, the flood rushed downstream in a short time. After less than 30 s, the dam break wavefront arrived at the houses in the valley mouth. The enlarged pictures in Figure 18 show the dam break wavefront hit two houses. The phenomenon is compared against the flood marks and the eyewitness reports. The main stream flowed through the gap between the two houses, causing an energy concentration that resulted in people being flushed into the river.

The detailed hydraulic features of the flood event are illustrated in Figures 19 and 20 where the computed flow discharge and the maximum water depth at the two cross sections under consideration are plotted. The peak discharges of about 118 to 65 m$^3$/s are very rare in this
valley. The computed maximum water depth is close to 1.9 m, appearing in Figure 20 (Section 2). Such a high-water depth might be caused by the contraction effect of the houses at the valley mouth.

In addition, the computed discharges at Section 2 under the Manning coefficients of 0.015, 0.02, and 0.03 are plotted in Figure 21. The results seem a little sensitive to the roughness. However, they do not show significant change when the Manning coefficient varies between 0.02 and 0.03.

LESSONS LEARNED FROM THE EVENT

The flood event considered herein is a type of rare event causing a catastrophic result (nine people lost their lives). To avoid similar disasters, analysis of the precipitation, terrain, land cover effects, and human behavior can be used for development of mitigation plans:

- Apart from the heavy storm, the terrain characteristics are one of the main reasons for formation of the debris
Figure 18 | Computed flood propagation process after the dam break.
The contraction existing in the channel provides a point for trapping of LWD and boulders. Hence, additional flood risk analyses considering the potential for dam breaks arising from debris dams is suggested for catchments where contractions in the river channel occur.

- Logs, sticks, and branches are scattered over the channel and make an enormous contribution to the LWD forming the debris dam. The timely cleansing of the woody debris in the catchment, especially in the channel, is required as a priority. For example, an annual patrol can be arranged by the local authority and some big logs could be cut into pieces to avoid the river clogging before the rainy season.

- Since there are two houses at the valley mouth, a contraction occurs at this point in the river, and the flow will be concentrated through the gap between the houses. A nozzle effect takes place, and the velocity will be increased; the intensified kinetic energy and shear stress will flush objects away. Therefore, buildings should not be planned at the valley mouth or enough space should be left for flood routing.

- A road along the river is located next to the valley mouth/outlet. A flood will cross this road into the river. However, there are no protecting measures by the riverside; people, therefore, will be prone to being swept into the river. If protecting measures are implemented, the victims will be intercepted and thus prevented from being drowned. The protecting measures, e.g., guard rails (Figure 22), should be designed to convey the water but intercept people, and also host the force arising from debris.

CONCLUSION

In this paper, an unprecedented flash flood leading to nine casualties in Shimen Valley is presented. The causes of the
event are analyzed through using field survey and numerical simulation. Measures of how to mitigate the flood risk are proposed. The following conclusions are drawn:

- The flood happened so suddenly and nine people were washed into the main river channel from the riverside and drowned. It was unprecedented and may raise alarm bells for preventing this kind of flash flood in mountain areas.
- Regarding the causes of the flood, the heavy storm, special terrain features, and the LWD play important roles. The heavy storm induced quick runoff and high discharge in the valley channel, due to the steep slope of the valley and channel. The flood carried the LWD and the boulders to the downstream reach until the debris was blocked in the contraction section. A debris lake was formed and the water began to be stored. Then, the debris dam broke and the dam break wave started to propagate to the valley mouth, washing people away.
- According to the disaster-inducing factors, some measures preventing such floods are proposed. For steep catchments with contraction in the channel, where there is a great deal of LWD and boulders, apart from regularly removing the LWD and boulders, setting or firming guard rails along the river bank at the valley mouth, additional risk assessment should be made to take into account the potential debris dam and dam break process.

Since it is an ungauged catchment, detailed hydrological and hydraulic data are not available. To systematically and quantitatively analyze similar flood events, future work is planned to install rain-gauge and discharge meters in the catchment and the long-term data collected can help investigate the mechanism in detail.

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