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Unsteady 1D and 2D hydraulic models with ice dam break for Quaternary megaflood, Altai Mountains, southern Siberia

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ABSTRACT

One of the largest known floods occurred during the Late Quaternary, emanating from an ice-dammed lake in Asia. Glacial lake Kuray–Chuja was formed by a 600-m-high ice dam converging in the Chuja River valley of the Altai Mountains in southern Siberia. The dam impounded up to 594 km^3 of water in the Kuray and Chuja basins.

At least three floods from lake Kuray–Chuja occurred, but only the largest, or the most recent, is modelled herein. The discharge, through an ice dam breach by tunnelling or over-topping, is analysed using dam breach equations including one specifically developed for ice dam failures. From these calculations it is concluded that the ice dam need not have failed when the water was at a maximum depth (i.e. 600 m deep) but, in consideration with flood routing models, it is probable that the lake emptied by over-topping under conditions of maximum water level. Although an over-topping model is favoured, a collapse of the ice dam due to initial tunnel development in the ice body cannot be precluded.

The resultant flood wave ran down the Chuja River valley to the confluence with the Katun River and beyond. One-dimensional and two-dimensional unsteady and non-uniform flow modelling of the flood wave routed down the river valleys is presented that includes modelling a channel bifurcation at the confluence and backwater effects. The depth of the flood model is constrained by the altitudes of the tops of giant bars deposited by the palaeoflood, which indicate maximum flood stage.

The results of the ice dam failure calculations and the flow modelling are independent of each other and are consistent, indicating in each case a flood of the order of 10 M m^3 s^{-1}, with best-fit solutions providing estimated peak flood discharges of 9 to 11 M m^3 s^{-1}. A breach, 1 km wide and 250 m deep, developed in the ice dam in as little as 11.6 h whereas the flood duration required to evacuate the total lake volume was around 1 day.

1. Introduction

The exploration and analysis of the land-forming capacity of ancient floods can use a variety of techniques. Recently attention has focused on the use of numerical, hydrodynamic models. Whilst these models cannot be relied on entirely, they can give guidance that enhances understanding of the phenomena. To date, mainly one-dimensional (1D) steady-flow models have been widely used to recreate the magnitudes of palaeofloods and the maximum water levels reached in the landscapes that they traversed. Chiefly, this approach has required a geometric representation of the floodway achieved through the provision of discrete simplified surveyed cross-sections of the floodway and evidence from the landscape of maximum flooding levels (Pardee, 1942; Baker, 1973; Dorava and Meyer, 1994; Tómasson, 1996). The progression of the peak flood level down the system is not considered in these models but the flood is assumed to peak instantaneously and simultaneously at all sections. The steady state, 1D assumption also assumes a regular distribution of velocity across a cross-section and neglects the modelling of transitions in the flows, both of which are relevant when modelling palaeofloods. Overcoming these drawbacks has become possible through a number of developments such as the availability of Digital Elevation Models (DEMs) obtained from satellite imagery, advances in hydrodynamic modelling and a reduction in processing time. In

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particular, mathematical methods can now be applied that model transitions correctly and 2D and 3D models can be implemented in order to capture velocity variations along the cross-sections. Consequently, 1D, 2D and 3D unsteady-flow models can now be applied to these geomorphological problems (O'Connor and Webb, 1988; Eskilsson et al., 2002; Alho et al., 2005).

The latest models can have a degree of sophistication that allows different flow scenarios to be explored that are physically plausible and which provide additional insight into the dynamic nature of past flow, erosion and sedimentation processes. These latter models might include the physics of ice dam failure where the flood emanated from a glacier-impounded lake, as well as a consideration of transcritical flows in space and time as the hydrograph waxes and wanes.

Recent models include a consideration of bed erosion and deposition along the floodway (Cao and Carling, 2002a,b; Cao et al., 2004). Such models can be calibrated simply using evidence of maximum water levels but also with reference to the 3D DEM representation of the floodway (which might include expansions and contractions and backwaters). Thus geomorphological evidence in the form of, for example, expansion bars and 'slackwater' deposits takes on additional relevance as these landforms can be used to constrain the loci of modelled flow transitions and backwater effects. Where relict bedforms such as dune and antidunes occur, constrains on the Froude number can be introduced. To illustrate some of these principles, this paper presents a detailed reconstruction of one of the largest known floods caused by ice dam failure. The flood — which emanated from an ice-dammed lake in southern Siberia — has been modelled previously (Baker et al., 1993; Herget, 2005), but recent advances in numerical modelling and additional geomorphological evidence now available allow a more refined modelling approach to be considered. The key objectives of this paper are to reconstruct the magnitude and the duration of a megaflood event, and to compare 1D and 2D model simulations of the flood.

2. Regional context

A Late Quaternary catastrophic flooding event in the Altai Mountains of south-central Siberia (Fig. 1) has been studied in detail (Carling et al., 2002; Herget, 2005) in order to assess the geomorphological evidence and the potential consequences of climate changes and extreme flooding events during mountain deglaciation. Giant gravel bars deposited along the flanks of the Chuja River and Katun River valleys are the result of catastrophic flooding episodes that occurred owing to the sudden emptying of the ice-impounded glacial Lake Kuray–Chuja during the Late Pleistocene (40 ka to 13 ka). These floods were of a scale similar to those recorded for glacial Lake Missoula in North America (Baker, 2002). At least three large floods occurred but until the sediments are better dated it is assumed for flood modelling that the clear evidence in the landscape of high elevation flood marks is for the most recent and/or the largest of these floods. Thus, only one flood elevation is modelled. The flood described herein ran down the steep Chuja River valley until the confluence with the lower gradient Katun River valley (Fig. 1). At the confluence, the main flood went down the Katun valley but because of the great depth of flow and a flow constriction in the Katun valley near the confluence with the Big Ilgumen River (Fig. 2), some of the floodwater coursed up the Katun valley before 'ponding' in the entrance to the Uimon Basin and then flowing back down the Katun on the falling flood hydrograph. Thus, the flow modelling problem includes a distinct gradient change from the Chuja valley to the Katun valley, a

Fig. 1. Location map of the study area in southern Siberia. The Kuray (K) and Chuja (C) basins are shown in the headwaters of the River Chuja.