INTRODUCTION: NATURAL DAMMING ON THE UPPER INDUS STREAMS

Rivers of the transHimalayan Indus basin are subject to damming by glaciers and a variety of mass movements. Among the many catastrophic outburst floods, ice dam bursts dominate the historical record, but the two largest were from failure of landslide dams in 1841 and 1858 (Hewitt, 1982, 1998a). Far more numerous are impoundments by debris flows and snow avalanches, and along glacier margins (Hughes & Nash, 1985; Kreutzmann, 1994). However, they tend to be small, the inundations or outburst floods of fairly local significance. The largest, most long-lived natural dams in the late Quaternary have been due to deep-seated rock slides and rock avalanches. The paper focuses on the latter.

ROCK AVALANCHE DAMS

In surveys between 1993 and 2001 a total of 186 rock avalanches were identified in the region (Hewitt, 2002b). Most are prehistoric events reconstructed from deposits. Of these, 161 formed cross-valley barriers impounding stream valleys (Table 1). The table identifies main impoundments on the rivers named, barriers not fully breached, and those associated with up-valley lacustrine sediments and with superimposed rock gorges. On average, one rock avalanche was found for every 14 kilometers of stream thalweg surveyed, although actual spacing is highly variable (Figure 1). They occur throughout the basin, with massive rock wall failures occurring in all elevation zones and geological terrains (Hewitt, 1998b; Searle, 1991). There are impoundments in every conceivable stage of infilling and degradation. Landforms and sedimentary features associated with the rock avalanche barriers dominate much of today’s fluvial zone. Perhaps their greatest role is evident in vast quantities of intermontane sedimentation accumulated behind the barriers. Much of this is being trenched and removed today. Yet, long after being breached and drained the barriers continue to constrain stream flow and sediment movement. Stream thalwegs and patterns of incision are affected by the sequence of rock avalanche barriers even more than by widely discussed tectonic activity (Sieber & Gornitz, 1983; Burbank et alii, 1995). Unfortunately, there is a firm date for only one prehistoric event, a 

\[ ^{14} \text{C age of 7150 years BP (uncalibrated) for Ghor} \text{o Choh I (Hewitt, 1999a). However, all indications are that the majority are late Pleistocene or Holocene events, emplaced on ice-free valley floors since the last major glaciation.} \]

IMPOUNDMENT DIMENSIONS AND MORPHOLOGICAL CLASSES OF ROCK AVALANCHE DAMS

With few exceptions, the dams had an initial effective height, i.e. the lowest part of the cross-valley barrier – greater than 10 m. More than half exceeded 25 m, about 20% exceeded 100 m, and two were over 1000 m (Table 2). Dam height is positively correlated with rock avalanche size and width (parallel to stream valley), but there is considerable variability related mainly to terrain. The highest barriers involve relatively large volumes of rock avalanche debris that formed cross-valley ramps thickened by stalling against the impact slope.
Various classifications have been developed to characterise landslide dams. Those of HEIM (1932), SWANSON et alii (1986) and COSTA & SCHUSTER (1987) emphasise barrier morphology in relation to valley topography. Costa and Schuster’s classification was adopted with several modifications to reflect specific rock avalanche and regional conditions (Tables 3 and 4). Some 30% of the dams conform to their Type II, and 31% in Type III, but Types IV and V are rare or absent. These categories are reassigned as new classes associated with complex emplacement and multiple impoundments. These comprise 34% of the inventory, and account for most of the largest impoundments, including 82% of dams that exceeded 100 m in height and all those over 250 m.
The Stability of Rock Avalanche Barriers and Breaching Histories

Extensive, multi-year lacustrine and other deposits, upstream and against the flanks of the larger dams, record relatively long-term survival. In most cases, the evidence suggests relatively gradual or phased breaching, despite the extreme geomorphic environment (Figure 2). Rock avalanche processes in rugged terrain, their composition, emplacement and morphology appear to promote stable barriers and resistance to erosion.

Where the evidence is preserved all except one barrier was overtopped prior to breaching, as in most landslide dams, but this has not necessarily or usually led to catastrophic failure. Dams may be overtopped in proximal, medial or distal parts of the cross-valley barriers, or diagonally. Most barriers are too heavily eroded or buried in later sediments to allow reconstructions of the breaching sequence. However, 20% (29 cases) preserve evidence of it, and some useful indications of controlling conditions. At first, overflow channels reflect initial dam morphology, but in the half the cases the main breach occurred along other paths (Figure 3). While 80% of the initial overflows were in proximal or medial locations, proximal and distal locations dominate the main breaching process. Moreover, these breaches tend to occur at the interface of the landslide material and bedrock valley wall. This suggests that, while overtopping is the norm, seepage and sapping along the line of the valley wall may be a significant cause of major breaching, reflecting a more vulnerable seal there and, often, intercalations of weaker or more permeable sediments plastered against the valley wall after being picked up at the front of the rock avalanche. Again, however, there are few indications of early or complete catastrophic failure, as opposed to gradual, or sudden but partial, failures.

Bedrock controlled outlets

Another important subset of these dams involves spillways superimposed upon bedrock flanks or spurs of the pre-existing valley. The size and morphology of rock avalanche dams make it unlikely the overflow channel will exactly match the buried river’s course. Where the valley has a wandering course, spillways can be let down on one or more bedrock spurs to create superimposed gorges. Some 45 of these have been identified with the rock avalanche dams (Table 1). In some cases, streams are superimposed on bedrock during the trenching of sediment fans and other bodies of sediment built up behind the barriers, for example across the distal rim of the Turi Parwak fan in the Miragam-Parwak event in Chitral. This has been the controlling base level for the trenching of the rock avalanche dam below for some centuries, although originating with the dam. In all of these cases, it is the rate of incision in bedrock that controls lake drainage, the trenching of the landslide barrier and removal of upstream sediments (Hewitt, 2002b).

Hybrid Dams

Of special interest are barriers consisting of rock avalanche and other materials. This complicates stability analyses and dam histories. Some twenty five of these hybrid dams were found and are divided into three classes in which:

<table>
<thead>
<tr>
<th>Category</th>
<th>a) Valley wall source</th>
<th>b) Tributary valley source</th>
<th>Sum</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>11</td>
<td>8</td>
<td>19</td>
<td>12</td>
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<td>24</td>
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<tr>
<td>Type V</td>
<td>8</td>
<td>10</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Type VI</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>SUM</td>
<td>103 (64%)</td>
<td>58 (36%)</td>
<td>161</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4 - Morphological classification of rock avalanches that dammed Upper Indus streams

Figure 2 - The Litak rock avalanche dam on the Huhe River, Shyok Basin, showing multi-year lacustrine deposits some 100m thick behind the now fully breached barrier (photo Hewitt, 2001)

Figure 3 - Well-preserved initial over flow channel (arrows) of the Gakutsch rock avalanche dam on the Gilgit River. Thick deposits of lacustrine sediments on the upvalley flank indicate this spillway operated for some decades. It was replaced by a rock gorge superimposed on a bedrock spur against the proximal valley wall to the right of the photograph. This is where the outflow is now, approximately 120m below the abandoned channel

i) rock avalanches over-ran glacier ice and glacial deposits (9),
ii) rock avalanches disturbed and created ‘tectonised’ and thickened areas of valley fill materials, or incorporated large masses of them (10),
iii) rock avalanches were partly transformed to debris avalanches or debris flows by uptake of moisture and sediment (6).

Each of these introduces further or different complications in
the character, stability and life cycle of the dam. Some major impoundments formerly believed to be due to glaciers prove to involve rock avalanches advancing over glacier termini or lateral and terminal moraines to actually seal the dam (Figure 4). The Malangutti, Shimshal; Batura, Hunza and Charakusa, Hushe, dams, their extensive lacustrine deposits and related features are examples.

**LONG-TERM EFFECTS OF ROCK AVALANCHE DAMS ON VALLEY DEVELOPMENT**

Formerly, many of the rock avalanche dams and related lacustrine sediments were attributed to late-glacial ice or moraine dams (BURGISSER et alii, 1983; HEWITT, 1999). Now it is apparent that the late-, and post-glacial history of these valleys involves great numbers of large landslide dams. These have played a major role in landform development throughout the fluvial zone, helping to create a naturally fragmented river system by controlling sediment movement and routing of floods from other causes (HEWITT, 2002b).

**QUESTIONS OF THE CONTINUING RISK FROM ROCK AVALANCHES AND LANDSLIDE DAMS**

The new picture of natural dams on the upper Indus poses hitherto unrecognized dangers such that questions of continuing risk assume some urgency. Nearly all the rock avalanche deposits have settlements on or near them. The main areas of habitation and agricultural land lie on river flats, former lake beds, terraces and sediment fans built up behind the landslide barriers (HEWITT, 2001). Most roads, airports, hotels and other tourist destinations are also here (JONES et alii, 1983). With more people, wealth and infrastructure at risk than ever before, the prospect of further rock avalanches, of inundations above a dam, or catastrophic outburst floods, appears unusually threatening. However, risk assessment is hampered by enormous difficulties of slope stability analysis, lack of information about what triggered the known landslides, and when they occurred. The full paper discusses how to remedy these problems and, in particular, the need to date and establish the time series properties of the catastrophic landslide dams.

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