Landslide dams, Peace River lowlands, Alberta

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ABSTRACT
Five landslide dams in west-central Alberta are described. The landslides are comprised entirely of Quaternary sediment. The rupture surfaces extend beneath the channels, causing uplift of up to 30m. New channels form at the toes of the landslides. The landslide lakes drain over several years through stream incision into the dams and sediment infilling. Incision is slowed by coarse alluvium from the pre-landslide channels. Several decades can pass before the channels return to their pre-landslide levels.

RÉSUMÉ
Cinq barrages de glissements de terrain dans l'Alberta ouest-central sont décrits. Les glissements de terrain sont composés entièrement de sédiment quaternaire. Les surfaces de rupture s'étendent sous les canaux, causant un déplacement ascendant jusqu'à 30m. De nouveaux canaux se forment à la pointe des glissements de terrain. Les lacs de glissements de terrain sont égouttés sur plusieurs années par l'incision de ruisseaux dans les barrages et le remplissage de sédiment. L'incision est ralentie par l'alluvion grossière des canaux de pré-glissements. Plusieurs décennies peuvent passer avant que les canaux reviennent à leurs niveaux de pré-glissement.

1 INTRODUCTION

Large landslides that create dams are commonplace in the Peace River regions of Alberta and British Columbia. The dams disrupt stream flow, damage timber, and threaten infrastructure both downstream and upstream. Dams on the larger systems often last for short durations. For example, the Attachie dam on the Peace River (Evans et al. 1996, Fletcher et al. 2002) and the Halfway River dam (Bobrowsky and Smith, 1992) lasted for a few hours. Often the larger streams are not fully obstructed by landslide deposits. Large landslides on smaller streams tend to fully obstruct the valleys, creating lakes that persist for decades. Here we examine five landslide dams on small tributaries of the Peace River: the Eureka River dam (Miller and Cruden 2002, Miller 2000), the Saddle River dam (Cruden et al. 1993), the Hines Creek dam (Lu and Cruden 1998), the Montagneuse River dam (Cruden et. al. 1997), and the Spirit River dam (Miller 2000) (Table 1, Figure 1).

Each landslide is composed of Quaternary sediments, originally deposited within a pre-glacial valley. Quaternary glaciation filled the pre-glacial valleys with advance-phase glaciolacustrine sediments, overlain by till, which in turn is overlain by retreat-phase glaciolacustrine sediments. The pre-landslide streambeds are armoured with coarse alluvium (cobbles and boulders), originally eroded from the till.

The landslides characteristically had rupture surfaces that extended beneath the stream channels causing the channels to be displaced upwards and the dams to form. New channels formed around the toes of the landslides, abandoning the pre-landslide channels.

Landslide dam classification in the paper follows Costa and Schuster (1988). Landslide terminology follows Cruden and Varnes (1996).

2 LANDSLIDE DAMS

2.1 Eureka River Landslide Dam

The June 1990 Eureka River landslide was an enlarged earth slide, which moved southwards by translation. The landslide's rupture surface, in advance phase glaciolacustrine sediment, extended beneath the streambed, causing the streambed to be thrust vertically upward by some 20 to 25m, creating a Type 6 landslide dam (Costa and Schuster 1988) (Figure 2). The dam's width was 1km (river km 10.7 to 11.7, measured from the confluence with the Clear River). The dam is comprised mostly of silt and clay rhythmites, with isolated pockets of coarse alluvium from the pre-landslide channel.

The landslide caused the Eureka River to abandon its pre-landslide channel and a new channel formed around the toe of the landslide. In the new channel, between river km 10.8 to 11.5, coarse alluvium is mostly absent and as a result, stream incision has been rapid. Incision is enhanced by softening of the lacustrine sediment, when the deposit is submerged.

By August 1999 the new channel had incised by up to 20m. This rapid incision has promoted extensive instability from both banks (Figure 3). Between river km 11.0 and 11.1, and between 11.4 and 11.5, instability has caused coarse alluvium (cobbles and boulders) from the pre-landslide channel to be introduced into the new channel. However, this coarse material was not stable within the new channel and was subsequently transported downstream, leaving the channel unprotected.

At its maximum, the landslide lake exceeded 8 km in length (river km 11.5 to 19.8) (Figure 2). The lake's high stand was recorded by flood debris in the branches of trees. By 6 October 1992, the lakeshore had regressed almost 2km to river km 17.8 (Alberta aerial photographs

Table 1. Characteristics of landslides and dams. The landslides in the 1990s may signify a wetter climate.

Landslide (LS)	Year	LS Vol. (Mm^3)	Dam Height (m)	Dam Width (m)	Lake Length (Km)	Reference
Eureka River	1990	50	20 - 25	1000	8	Miller and Cruden 2002
Hines Creek	1990	-	25	120 - 150	1.5 – 1.7	Lu et al. 1998
Hines Creek	Pre-1952	48	-	1000	5	Lu et al. 1998
Montagneuse River	1939	78	30	-	4	Cruden et al. 1997
Saddle River	1990	39	24	800	5	Cruden et al. 1993
Spirit River	1995	20	9	-	2.1	Miller 2000

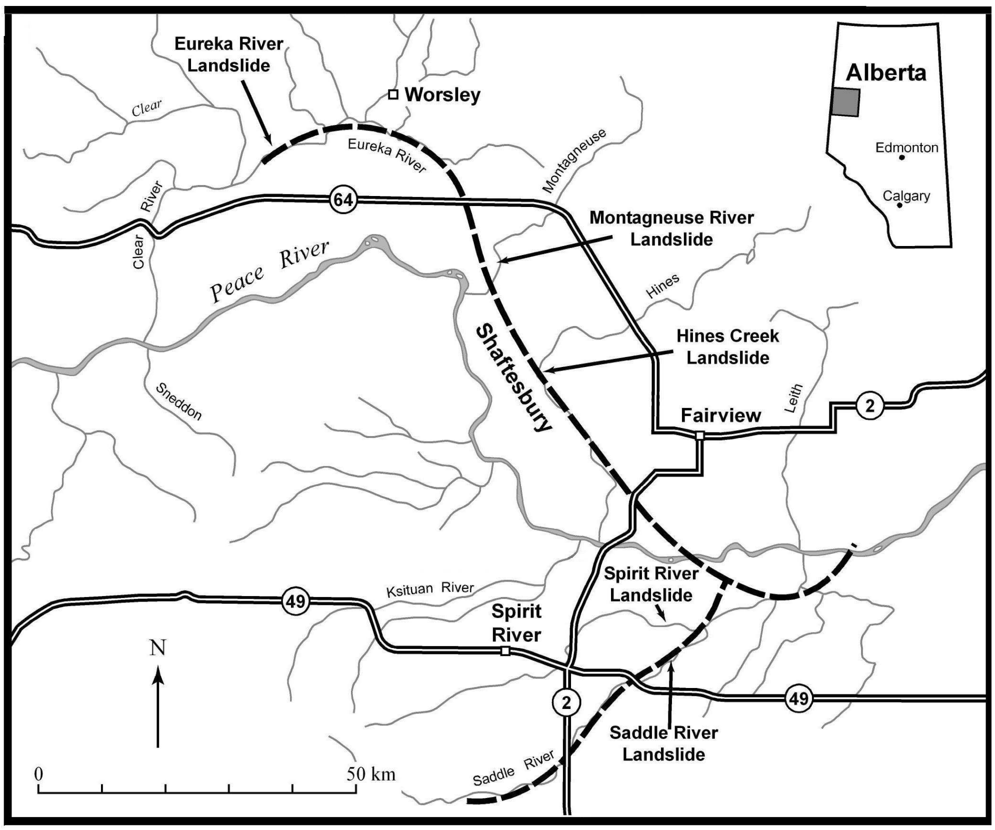

Figure 1. The Peace River Lowlands, with the locations of recent, dam-forming landslides. The bold dashed lines indicate the presumed locations of major pre-glacial valleys (Carlson and Hackbarth 1977, and Kerr 1971).

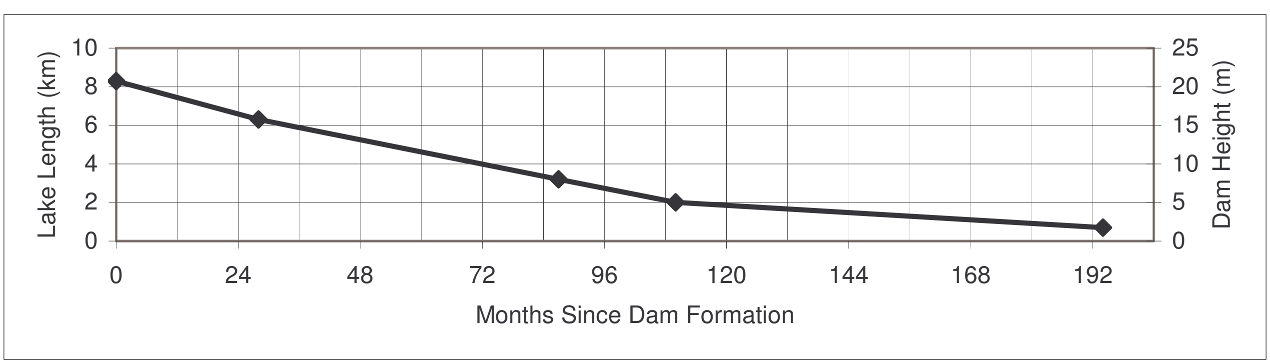

Figure 2. Change in the length of the Eureka River landslide lake since the dam formation. The dam height was determined by comparing the extent of flooding to topographic data. This value does not consider deltaic deposition at the head of the lake and therefore underestimates actual dam height.

Figure 3. Extensive instability at the toe of the Eureka River landslide has caused coarse alluvium from the pre-landslide channel to be introduced into the new channel. This coarse alluvium has subsequently been transported downstream. Photo captured on September 28, 2007 looking northwest towards the 1990 landslide.

Figure 4. Eureka River dam on September 28, 2007. Photo captured looking upstream towards the large lake (not visible). Coarse alluvium from the pre-landslide stream (centre) protects the dam from erosion.

AS4333 #176). This regression corresponds to a decrease in dam height of about 5m (derived by comparing the lake length to topographic data, and does not consider deltaic sedimentation, so underestimates the dam height).

By 1 September 1997, the lakeshore had regressed a further 3.1 km to river km 14.7 (Alberta aerial photograph AS4892, 148), which corresponds to a further decrease in dam height of about 8m. By this time, the lake had divided in two over a high spot at river km 11.7, creating a small lake between river km 11.5 and 11.6, and a large lake between river km 11.7 and 14.7.

A field survey in August 1999 found the large lake extended to km 13.5, which represents a regression of 1.2 km and a water surface lowering of about 3m. A beaver dam exaggerated flooding by about 20cm. Between the small and large lakes, the Eureka River flowed along the edge of the pre-landslide channel. The bed of the former channel was tilted towards the new channel (Figure 4). Coarse alluvium, from the pre-landslide channel, was forming armour in the bed of the new channel.

The most recent aerial photographs (Alberta AS5379B-15, August 25, 2006) show flooding to river km 12.5, which represents a further shoreline regression of 1.0 km and lake surface lowering of 3m. The length of the lake in 2006 photos was approximately 700m; the height of the dam was approximately 2.2m. The smaller lake had mostly drained by this time. A field survey of the site on September 28, 2007 found only minor further shoreline regression of the large lake. Coarse alluvium was effectively slowing erosion at the outlet.

2.2 Saddle River Landslide Dam

The June 1990 Saddle River landslide was a reactivated, retrogressive earth slide. The landslide rupture surface, in advance phase glaciolacustrine sediment, extended under the Saddle River, causing the streambed to be displaced southwards by 60m and upwards by 24m, creating a Type 6 landslide dam (Costa and Schuster 1988) (Figure 5). The dam was comprised of till, lacustrine clay, and coarse alluvium from the Saddle River (Cruden et al. 1993).

The landslide dam was first inspected on July 24, 1990 by Alberta Environment (Hanson 1994). At that time the lake level was approximately 20m above the pre-landslide river level. There was approximately 4m of freeboard (Figure 6).

The dam was again visited in the fall of 1990 (McClung 1990). There had been little inflow into the lake over the preceding summer and lake levels remained relatively constant. The volume of water retained behind the dam was approximately 4Mm^3. There was no seepage downstream of the dam.

"*Overtopping* [of the dam] *began with the runoff from the annual snowmelt in 1991. On 11 April 1991, flows of about 2m^3/s eroded a new channel where the landslide debris meets the opposite bank of the river. By the end of April, severe erosion was occurring at the downstream end of the displaced mass where a 50m long chute sloping at 18^o had developed. Displaced material was falling intermittently into the eroded channel. Upstream of the chute, a pond 40m wide and 200m long had formed and a smaller chute above it accounted for a further 5m rise to the spillway crest and the main reservoir. The upper chute is armoured with uplifted coarse granular river deposits. Overtopping of the landslide toe continued intermittently through the remainder of 1991, dropping the spillway crest elevation by 1.5m*" (Cruden et. al. 1993, p. 1009).

By April 21, 1993, upstream of the small pond, the channel had widened to 8 to 10m, bypassing accumulated rock (Hanson 1994). Downstream of the pond, the channel had cut deeply into the south valley wall and the toe of the landslide, forming a vee-groove chute measuring some 10.6m deep and 9m wide at the top. A continuous supply of sand and silt was being wasted into the chute.

Figure 5. The Saddle River landslide lake in July 1999. A logjam, at the outlet of the lake, is in the foreground.

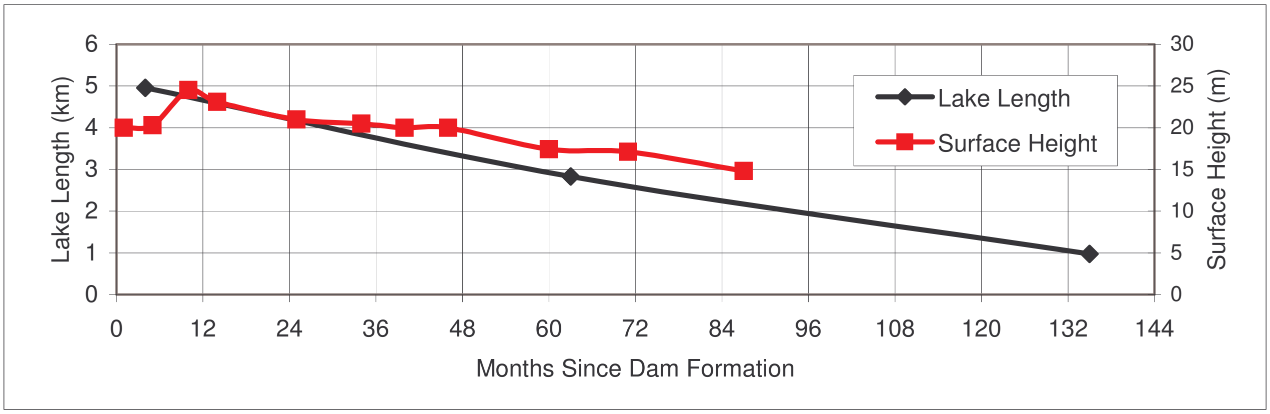

Figure 6. Change in length of the Saddle River landslide lake (from aerial photographs) and change in water surface height (Water Resources Administration 1997) since dam formation in June 1990.

By October 26, 1993, erosion over the summer had straightened and widened the outlet channel, draining the small pond in the process (Hanson 1994). The inlet of the lake had shifted downstream by 200m over the summer, due to deltaic deposition and a 0.45m drop in lake levels.

By September 19, 1995, the lake had split over a high spot near the upstream edge of the landslide, forming a smaller lake measuring some 200m long and 80m wide downstream of the larger, 2.8km lake (Alberta aerial photograph AS4680-33). By September 17, 2001, the smaller lake had divided again forming a 100m by 25m lake downstream of a 110m by 15m lake (Alberta aerial photograph AS5194B-40). By this time the larger lake was approximately 1km long.

2.3 Hines Creek Landslide Dam

The 1990 Hines Creek landslide was a reactivated, retrogressive earth slide, with a rupture surface in till. The slide caused a 25m dam and a 1.5 to 1.7km long lake (Lu et. al. 1998). The first post-slide aerial photographs (Alberta AS4314-251 (August 17, 1992)) show a 1.4km lake. By September 1, 1997 the lake had drained (Alberta AS4891-79). The lake existed for less than 87 months.

Of interest is what appears to be an extensive sedimentary deposit, immediate upriver of the Hines Creek landslide. Lu et al. (1998) attribute this deposit to a lake that formed behind a landslide from the valley wall opposite the 1990 landslide. They estimated the volume of this landslide to be 48Mm^3, approximately the size of the Eureka or Saddle River landslides. The landslide predates a 1952 aerial survey of the area. The earlier landslide was a major cause of the 1990 landslide as it directed the stream into the opposite valley wall, undercutting the slope (Lu et. al. 1998).

The 1988 aerial photographs (Alberta AS3729-88) show Hines Creek as an entrenched meandering stream upstream of the landslides, where it flows over the sedimentary deposit. Approximately 2m to 3m of incision are apparent on the active floodplain. Terraces are also present. Both upriver and downriver of this reach, the stream is irregular in form with the valley walls coming to the channel's edge.

An increase in the slope of the channel at the site of the landslides is apparent from the aerial photographs. This condition is likely due to the stream never fully reaching its pre-landslide level. The water of the former lake would have been displaced by incision into the dam and accumulations of lacustrine and deltaic sediments within the basin. When the lowering hydraulic head encountered the accumulating sediment, incision likely slowed. Incision into the dam and mobilization of the sediments is continuing. The 1997 aerial photographs (AS4891-79) show the stream has eroded about 1m beyond the level in 1988 (AS3729-88).

2.4 Montagneuse River Landslide Dam

The April 1939 Montagneuse River landslide was a reactivated, retrogressive earth slide that moved in translation. The landslide's rupture surface, in advance phase glaciolacustrine sediment, extended under the channel creating a 30m, Type 6 landslide dam (Cruden et. al. 1997). The dam stopped the flow in the river for about 2 weeks, causing a 4km lake to form.

By June 15, 1945, the lake had drained (Canada aerial photograph A8108, 23-25). Cruden et al. (1997) mapped lacustrine deposits extending some 1.5 km upstream of the landslide dam using 1952 aerial photographs. They note that by 1988, the sedimentary deposit had been eroded away.

2.5 Spirit River Landslide Dam

The July 1995 Spirit River landslide was a reactivated and retrogressive earth slide in till that moved southwards by translation. Alberta aerial photograph AS4680-32 (September 19, 1995), captured about 75 days after the landslide, shows the Spirit River obstructed in four locations (river km 9.2, 9.3, 9.4, 9.8, measured from the confluence with the Saddle River). A fifth dam, at km 8.8, was not visible in the aerial photograph due to shade, but was identified in the field.

The landslide dam at km 8.8 was estimated to be 8 to 10m high (Miller. 2000). Two rupture surfaces were seen in the vicinity of this dam; one day-lighted above the stream, and the other extended under the stream and day-lighted at the opposite valley wall, forming a pressure ridge. The dam would have been a combination of a Type 1 or 2, and a Type 6 (Costa and Schuster 1988). The dam at km 8.8 washed out in the spring of 1996.

The landslide dam at km 9.2 was due to a small flow from within the 1995 landslide colluvium, forming a Type 2 dam, about 2 to 3m in height.

The landslide dams at kms 9.3, 9.4 and 9.8 are due to pressure ridges that formed at the toe of the landslide. These dams are Type 6 dams, with heights between 8 and 12m. A July 1999 field survey found that the dams at km 9.2, 9.3, and 9.4 were no longer impounding water. These dams existed for less than 48 months.

The dam at km 9.8 still impounded water in July 1999, though the extent of flooding had decreased from 2100m in 1995 (Alberta AS 4680 #32) to 700m (100m of this reduction was from the downstream end of the lake). This corresponds to a decrease in height of the dam of approximately 6m (from 9m in 1995 to approximately 3m in 1999). A beaver dam exaggerated the extent of flooding by nearly 1m. The greater resistance to erosion of the km 9.8 dam, as opposed other dams, may be due to the new channel crossing the pre-landslide channel and encountering coarse alluvium.

The 1999 field survey found coarse alluvium was absent in much of the channel, between km 8.8 and 9.9. Isolated pockets of alluvium were seen (i.e. at kms 9.5, 9.7, and 9.8), though these are mostly not within the contemporary stream channel. Downstream of the landslide, abundant channel armour was present. The absence of coarse alluvium between kms 8.8 and 9.9 is likely due to the coarse alluvium being displaced by the landslide out of the active channel (as occurred at kms 9.5 and 9.7), or being buried beneath landslide debris (km 9.8 to 9.10), or being destabilized by the landslide and later transported by stream action. Until armour is re-established, the streambed remains susceptible to erosion.

3 DISCUSSION

The five described landslide dams provide sufficient information to develop a preliminary understanding of how landslide dams on small tributary streams in the Peace River region form and change.

Each landslide dam formed by the rupture surface of the associated landslide extending beneath the stream channel, causing the channel to be displaced upwards, and creating a Type 6 landslide dam (Costa and Schuster 1988). Type 6 dams are common in the Peace River regions of Alberta and British Columbia, but are rare elsewhere. Of the 184 landslide dams (world wide) reviewed by Costa and Schuster (1988), only 3% were Type 6. The Attachie (Evans et al. 1996, Fletcher et al. 2002) and Halfway River dams (Bobrowsky and Smith, 1992), mentioned earlier, were both Type 2 dams.

We are not aware of any flooding, either upstream or downstream (due to a dam breach), or damage associated with the five described landslide dams. Costa and Schuster (1988) note that Type 6 dams are typically less hazardous than other dams, as the streambeds are difficult to erode, bed gradients are often gentle, and volumes of impounded water are generally small. This statement is consistent with observations in the Peace River region, with the exception of the volume of impounded water. Valley topography and bed gradients are such that impounded volumes can be considerable (for example, the Saddle River dam impounded an estimated 4Mm^3). As such, these dams have the potential of being hazardous.

The tributary valleys in the study area have valley slopes that characteristically come to the channels' edges. Flood plains, where present, are narrow. The landslides fill the valleys bottoms with large volumes of material. This material is primarily fine, Quaternary sediment, originally deposited within a pre-glacial valley.

After overtopping the dams, the streams cut new channels into the fine sediment, abandoning their pre-landslide channels. This fine sediment erodes readily by stream processes. The effectiveness of fluvial erosion is enhanced by the sediment softening when submerged.

Incision is slowed where the contemporary channel encountered the coarse alluvium of the pre-landslide channel. Coarse alluvium was observed in locations within the Eureka, Saddle and Spirit River channels.

Coarse alluvium was ineffective at slowing incision where clast imbrication had been upset. At the Eureka River landslide, extensive quantities of coarse alluvium entered the new channel due to landslide activity adjacent to the channel. Despite this, very little material remained where it fell, but was subsequently washed downstream. Upstream of this location, where the contemporary stream flows along the edge of the pre-landslide channel, the coarse alluvium appears to be effective at slowing incision. At the Saddle River dam, coarse alluvium was effective at limiting downward incision, until the channel widened and bypassed the alluvium (Hanson 1994).

An upstream progressing knick point can also disturb clast imbrication. Costa and Schuster (1988) note that in most of the documented dam breach cases, the breach is associated with upstream progressing head-cutting of the channel.

The slope of the streambed across the landslide dam is a major factor affecting the incision rate and, in turn, the longevity of the dam. This slope is a combination of the pre-existing bed slope and the increase in slope caused by the landslide. The pre-landslide bed slopes of the Eureka and Saddle River channels are comparable, at 0.33% and 0.42% respectively. The slope of Hines Creek is somewhat steeper at 0.68% (Miller and Cruden 2002). The actual slope is likely steeper yet as Hines Creek has not fully recovered the slope that existed prior to the pre-1952 landslide. The slopes associated with the Eureka and Saddle River dams are also similar, at 2.0% to 2.5% (20 to 25m high over 1000m), and 2.9% (23m high over greater than 800m) respectively. The slope across the Hines Creek dam was 16.6% to 20.8% (25m high over a distance of 120 to 150m). The Eureka and Saddle River dams have existed for at least 207 and 135 months respectively. Hines Creek dam, having considerably higher slopes, existed for between 26 and 87 months.

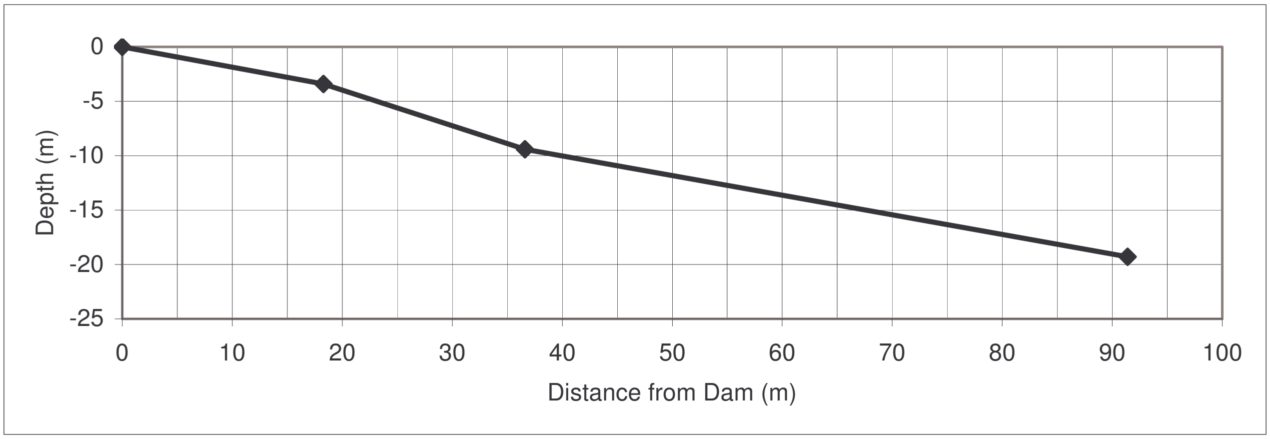

Figure 7. The submerged extent of the Saddle River landslide dam on June 30, 1991 (Hanson 1994). As the stream incises into the landslide dam, the width of the landslide dam becomes progressively larger.

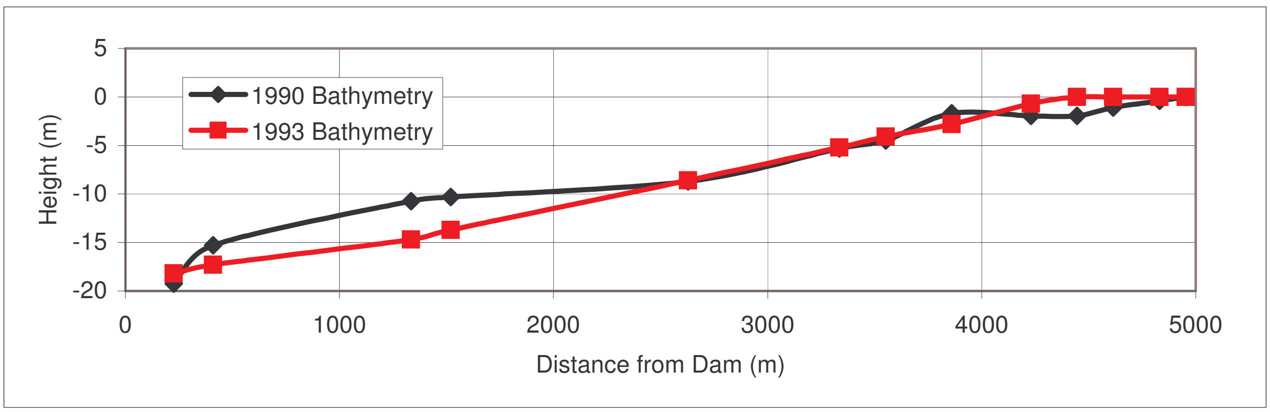

Figure 8. Depth sounding of the Saddle River landslide lake on October 3, 1990 and October 26, 1993, derived using a lead-line (Hanson 1994). Lake levels had decreased by 0.10m in 1993, from 1990 levels. Challenges with identifying the drowned thalweg explain transposed data. Noteworthy is the extensive deltaic accumulation at the head of the lake.

Deriving slope values is not straightforward, as ponding along the dam's length and the submerged extent of the landslide debris must be accounted for - as the lake level is lowered, the width of the landslide dams become progressively larger (Figure 7). The maximum dam height is also not obvious as the dams obstruct the river over a considerable distance and affect a range of bed elevations (for example, the Eureka dam is a maximum of 25m above the pre-landslide channel, but the landslide lake was 20m deep).

Beaver activity has been noted at the Eureka, Saddle and Spirit River dam sites. The habitat created by the landslide dams is not conducive to long-term occupation of the lakes by beavers, and as such, the dams are short-duration features. Beaver dams likely have little impact on landslide dams. A beaver dam will exaggerate a landslide dam's height, which may affect the prograding delta by causing a temporary shoreline regression. A beaver dam may also cause some localized increase in flow velocity.

A logjam occurred at the Saddle River dam (log jams did not occur at the Eureka or Spirit River dams; there is no information on log jams for the Hines Creek or Montagneuse River dams) (Figure 6). The logjam at Saddle River may be due to the extensive forest flooding that occurred because of the gentle topography at the foot of the valley slope. The effects of logjams on landslide dams largely depend on the nature and arrangement of the logs; logjams that are more effective at retarding flow have a greater effect. The effectiveness of logjams to retard flow may also decrease with decreased stream flow. The logjam on the Saddle River is expected to have a similar effect to a beaver dam.

The landslide lakes are eventually drained by basin infilling and incision into the dam (Figure 8). The Montagneuse River and Hines Creek (pre 1952) landslide dams provide insight into the long-lasting effects of the landslides on the tributary streams. These examples suggest that the Saddle and Eureka River watersheds could take several decades to fully recover from the landslide events.

4 CONCLUSIONS

Landslide dams on smaller streams in the Peace River regions of Alberta and British Columbia often form when a landslide's rupture surface extends under the channel, causing the channel to be displaced upwards. Subsequently, the streams find new paths around the toes of the landslides, abandoning the pre-landslide channels. Stream incision into the landslide dams can be rapid due to the fine texture of the Quaternary sediment that comprises the landslides. Stream incision is slowed when the new channel encounters the pre-landslide channel. Lakes that form behind the landslide dams are drained over a period of up to two decades by stream incision into the dams and basin infilling. Several decades can pass before the streams return to their pre-landslide profiles.

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