Investigation of 22 landslides in Upper Chase Creek, B.C.

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Abstract: The causes of 22 landslides along 2.6 km of Upper Chase Creek were investigated. Turbidity in the domestic water supplies and downstream channel aggradation had been linked to sedimentation in the upper watershed. Historic air photos were reviewed. Precipitation and streamflow records were analysed to isolate possible climatic trends. A detailed surface site investigation was carried out. 15 debris flows, 6 debris slides and a large earth slump were documented. Major aggradation on the lower floodplain and clear evidence of landslide activity throughout the study area were identified on air photos pre-dating forestry developments. The air photos also showed a gradual increase in sediment delivery to the lower channel since 1980, when logging began in the upper watershed. The climatic records showed a clear trend of higher than normal annual precipitation over this same period, with record high cumulative annual precipitation occurring in 1996/7. The site investigation findings showed that landslides had been periodically active in the study area for centuries, with widespread failure occurring in 1996/7. One instance of poor drainage control on forest roads had initiated a significant slope failure. It was concluded that both forestry developments and the increasingly wetter climate trend were responsible for increases in landslide activity over the medium and very short terms and that it was not possible to quantify the relative contribution of each of these factors. An understanding of the physical processes at work had implications for remediation and forestry development planning.

Introduction

This study addresses landslide and sediment delivery issues in a section of the Upper Chase Creek watershed, as part of the Watershed Restoration Program (WRP) for the entire Chase Creek watershed (Figure 1). The Chase Creek watershed is located about 45 km due east of Kamloops, B.C. The study area extended for about 2.6 km along Upper Chase Creek (Figure 2).

The area had been identified in the overall Chase Creek watershed restoration planning process as the second most significant sediment source to the middle Chase Creek valley. (Rossouw 1997). Landslide activity was reported to have occurred during 1996 to 1997, and conditions along a Forest Service road in the area were thought to be related to this activity.

Impacts of sediment delivered to downstream resources were reported to be channel aggradation in the lower Chase Creek valley (SRK 1997), and turbidity in Chase Creek and the South Thompson River, which is the drinking water source for the City of Kamloops. These effects had been linked to logging in the Chase Creek watershed (Bocking 1997).

A detailed landslide inventory had identified 72 slope failures along about 14 km of Upper Chase Creek (Ministry of Forests 1996). The area of this study contains 22 of those landslides, thought to be the most signivicant sediment sources in the landslide prone area.

The study objectives were to determine the forest development, geological, and hydrological cause(s) of the sediment sources in the study area, and to identify remediation strategies and priorities.

The study was commissioned by Riverside Forest Products Limited, and funded by Forest Renewal B.C. It was carried out by EBA Engineering Consultants Ltd.

Methodology

Previous studies of Chase Creek related to the hydrology (Steffen Robertson and Kirsten (SRK) 1997) and historic channel changes (Northwest Hydraulic Consultants Ltd. (NHC) 1997) were reviewed. These studies provided much useful information regarding the history of geomorphic activity in the Upper Chase Creek watershed. Most useful was a landslide inventory (MoF 1996) which contained detailed documentation of slope failures in the study area.

Air photos dating from 1951, 1959 and 1961 (pre-dating forestry development), and 1994 and 1996 (post-dating major forestry activities in the study area) were used to carry out detailed terrain mapping and identify landslides.

Analysis of historic precipitation and streamflow data was carried out to explore the possible influences of climate trends on landslide activity. Detailed site investigations concentrated on the numerous slope failures and the upslope area. The logging, geomorphic and climatic histories were compared.

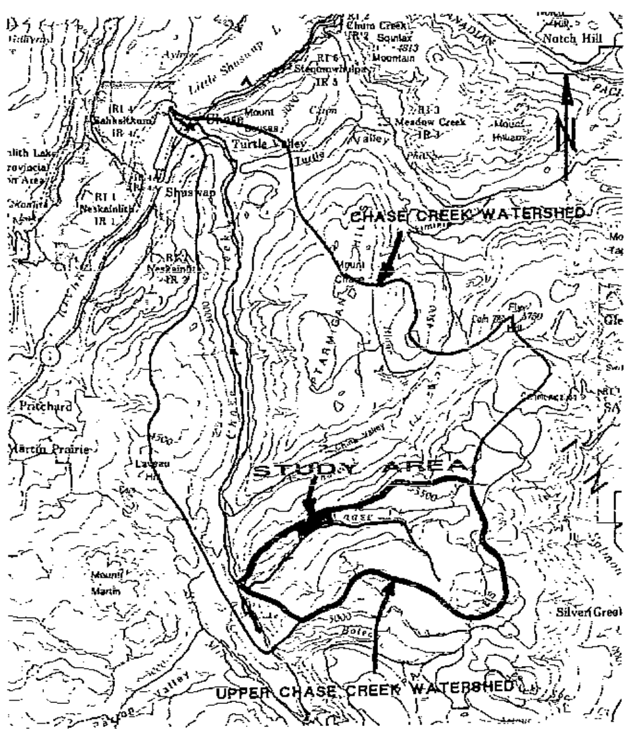
Geologic setting

The Chase Creek watershed is located in the Shuswap Highlands of the Interior Plateau physiographic region of B.C. (Holland 1976). Chase Creek is a tributary of the South Thompson River, joining it about 50 km east of Kamloops. Upper Chase Creek was defined as the westward flowing, mainly confined tributary of the Chase Creek mainstem, which flows north through a wide floodplain (Figure 1).

In the study area Upper Chase Creek was confined by moderately steep valley sidewalls, with a narrow or non-existent floodplain. The creek was incised through glacial deposits, flowing against vertical till banks up to 7m in height.

Two distinct terrain units were present in the main area of interest (Figure 2).

Fig. 1. Location map.



Scale: 1:400,000

In Unit 1, adjacent to the Chase Creek channel and/or floodplain, moderately steep slopes were encountered with slope gradients of 50 to 70 percent (H:V). Upslope in Unit 2, slope gradients were generally 30 to 40 percent.

Unit 1 consists of a thick sequence of dense tills overlain by a veneer of loose, weathered till. Generally, a very dense, grey-brown till, comprised of sand and silt with some clay and gravel, underlies a dense, tan coloured till, comprised of gravelly sand, with some silt and a trace of clay. The lower, more fine-grained till (~45 percent silt and clay) had more gravel and larger particle sizes consisting of a friable dark schist. The upper tan till (<25 percent silt and clay) had more hard granitic and gneissic coarse fragments. These two units clearly had different source areas. Drill results showed that the tills were almost 30 metres deep in places in Unit 1, thinning to 1 to 2 metres thick in Unit 2.

Compact to loose glaciofluvial sands and gravel deposits were also observed as isolated kame terraces and eskers overlying the tan till. A glaciofluvial terrace formed the western limit of the study area.

The slope break between these two main units was generally well defined, occurring over a slope distance of 2 to 5 m. All slope failures occurred within Unit 1.

No bedrock outcrop was observed on the north side of Chase Creek, in Unit 1. Very limited bedrock exposures in other areas correspond to the regional geologic mapping in the area (Fig. 2, after Okulitch 1979).

Forestry developments

In snowmelt dominated areas forest harvesting and road building can increase available water and hence landslide activity at a particular site in two ways. Clearcuts effect increased snowfall accumulations and spring snowmelt rates as well as reduced evapotranspiration, resulting in a general increase in available water. Road cuts can intercept shallow groundwater flow, increasing flow velocities by several orders of magnitude. Flow is redirected from its natural drainage path by ditches, resulting in large increases in available water at a specific location.

In the 1961 air photos the only developments visible were some narrow "pilot trails" (Fig. 3), some of which were still visible on the 1996 photos (Fig. 2). Some of these trails were investigated to determine if they were possibly intercepting and redirecting groundwater and surface flows prior to major forestry developments. It was concluded from the minor level of disturbance observed that these early trails would have had a negligible effect on runoff patterns.

Forestry developments in the study area included: the lower Chase Creek Forest Service Road (FSR) - referred to as the Old FSR in this study; the upper Chase Creek FSR - referred to as the Upper FSR, and several cutblocks (Figure 2).

Old Forest Service Road

The Old FSR was reportedly built sometime in the early 1960s to access timber and cattle grazing opportunities in the far upper reaches of Upper Chase Creek and its tributaries.

Much of road was adjacent to the creek with fill slopes, or the underlying till on which the road grade was constructed, being eroded by the creek as it flowed against the north valley wall.

Old FSR cutslopes had undercut the toe area of the earth slump and some of the debris slides which occur in the study area. It was reported that during upgrading of this road, road builders would return to the road head in the morning to find that overnight the previous days work had failed into the creek (Carson 1997).

The debris flows and some of the debris slides had initiation zones 100 to 200 m up slope of the Old FSR and the road cut was not a significant cause of landslide initiation in these cases. In fact, the road surface had in places created a low gradient bench where debris was deposited, preventing it from reaching the creek.

Generally the Old FSR grade was fairly flat, limiting the potential for significant downgrade water movement and fillslope erosion due to surface flows.

Cutblocks

The cutblocks were harvested between 1978 and 1983.

Fig. 2. Terrain and landslides in the Upper Chase Creek study area, 1996.

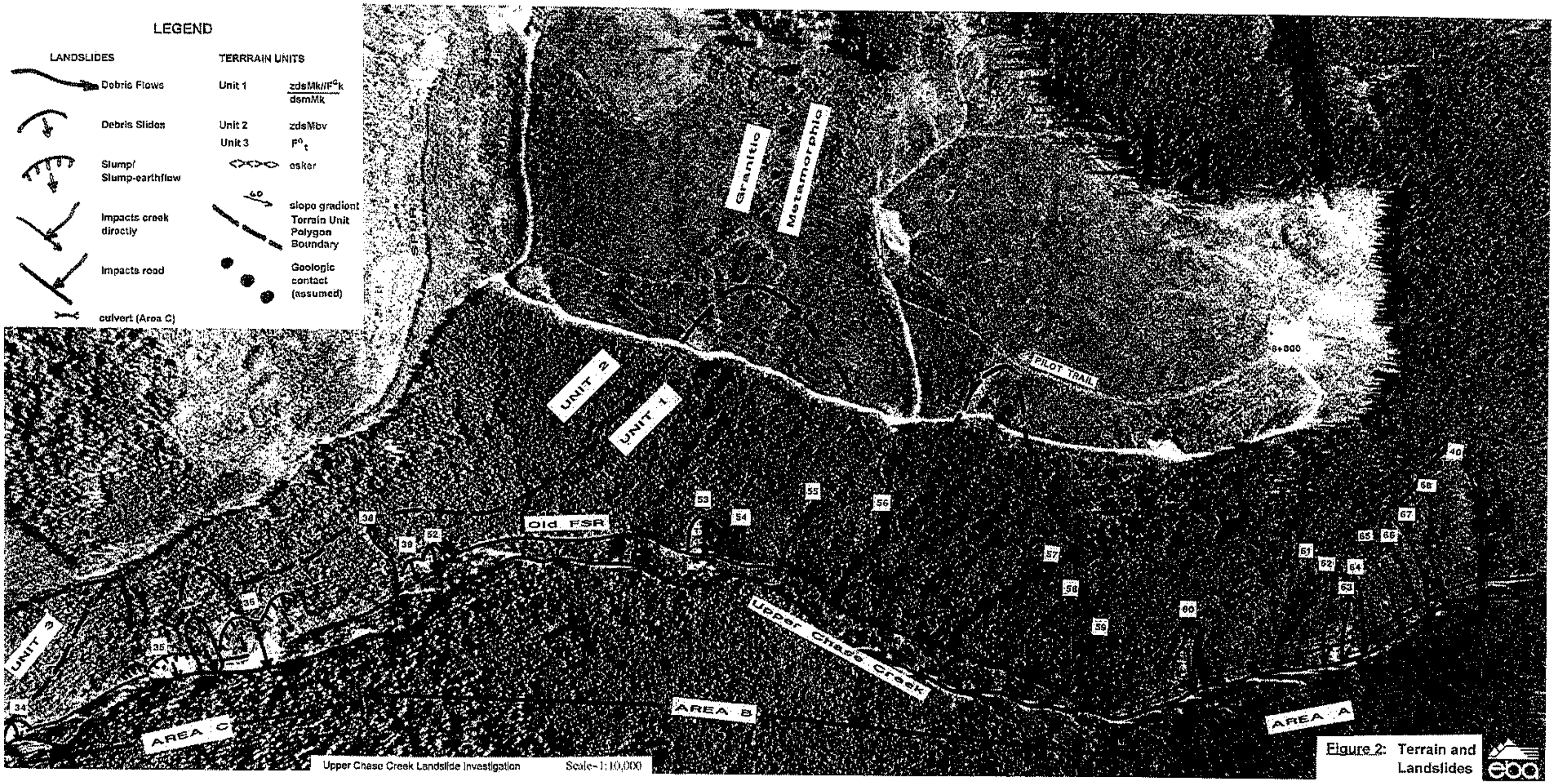
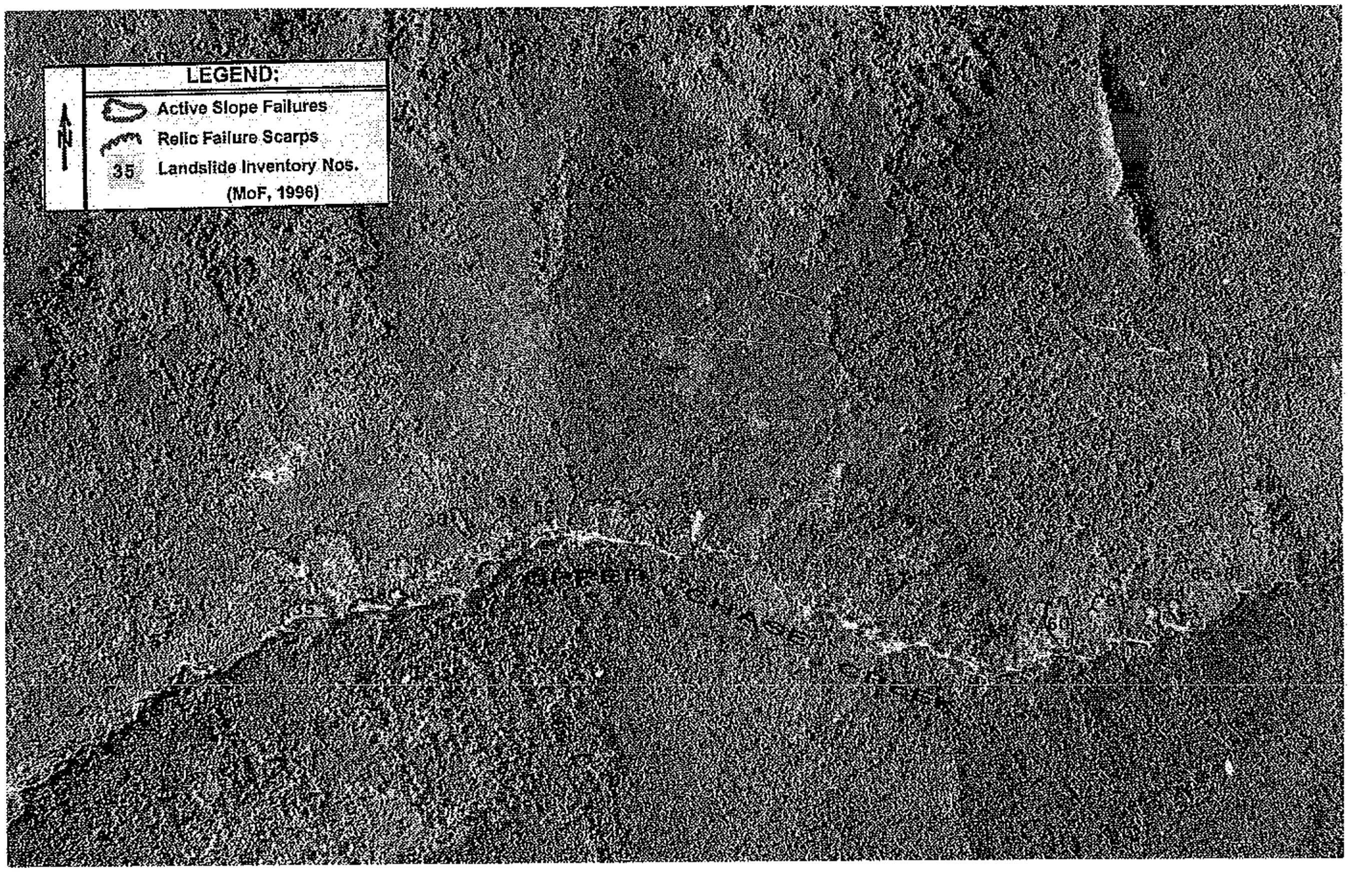


Fig. 3. Landslides in Upper Chase Creek study area, 1961.



About 45 to 60 percent of the entire up slope area contributing runoff to landslide headscarps had been clearcut harvested. Cutblock regeneration consisted of well-stocked pine stands ranging from 2 to 5m in height in most areas. Some areas had been juvenile spaced. Towards the east end of the cutblocks, areas of sparse stocking were noted.

In the Kamloops Forest Region, harvesting in excess of 20 to 25 percent of the runoff contributing area located above the H_{60} line – the elevation above which 60 percent of the watershed area is located – is considered of significant hydrological impact. The entire study area was above the H_{60} line for the Chase Creek watershed.

The rule-of-thumb is that in snowmelt dominated areas above the H_{60} line, recent clearcuts contribute on average 1.5 times more runoff than forested areas (FPC 1995). From an area which was 45 to 60 percent clearcut, this would yield a total increase in available moisture of about 23 to 30 percent for a given snowmelt or rain-on-snow event, occurring over the whole area.

Hydrological recovery is assumed to be 25 percent in sufficiently restocked areas with stand heights of 3 to 5 m (FPC 1995). Taking the stand heights observed in this study into account, the available moisture during freshet would be approximately 20 percent greater than in a totally unharvested contributing area. Therefore, the hydrological affects of clearcutting were assumed to be a potential factor in increased landslide activity in the study area.

Upper Forest Service Road

The Upper FSR was built to access upslope cutblocks in the late 1970s. It was situated predominantly on moderate gradient slopes of 30 to 40 percent in terrain Unit 2.

Few cut slope or fill slope failures, or the potential for failures, were noted along this road. The road had an average grade of about 10 percent, with 300 m long sections of over 15 percent gradients. A well constructed ditch, in places 1 m deep, and several functioning culverts and cross-ditches were noted. Cross ditches were reportedly constructed in 1995-6 (Rossouw 1997).

The depth of weathered and dense tan till overlying bedrock was 0.5 to 1.0 m. Generally the ditch line cut through the interface between the loose weathered till and underlying very dense, relatively impervious lower till or bedrock. It can be assumed that some water flowed as groundwater at this interface, and was intercepted by the ditch line. In the ditch, flow velocities could be several orders of magnitude higher than groundwater flow rates.

Detailed observations of the ditch-line, culverts and cross-ditches were made along 500 m of road above one of the most active slope failure areas (Area C, Figure 2). Water was being directed down the road surface for distances of up to 200 metres. This redirected flow was observed to exit the road at several locations, including one about 100 m directly above a recently active, large slump failure, which was the largest single sediment source to Upper Chase Creek in the study area.

Further west along the road grade, there was a culvert draining about 165 m of ditch line and road surface flow escaping over the fill slope. This flow had initiated a small debris flow about 10 m below the road which had eroded a 1 to 2 m deep gully that extended about 80m down slope. There it ran out onto moderate gradient slopes, and the water re-infiltrated. About 30 m further downslope there was a large fresh slump failure, about 35 m wide, 25 m long, with a 2 to 3 m high backscarp. The slump block was estimated to contain about 2,500 m^3 of material. This complex failure was very recent, probably having occurred in 1997. Most of the timber was still standing on the surface of the slump block in the fall of 1997. The toe of this failure was about 10 m above the old FSR, which was undisturbed.

The average gradient of the slope on which this slump occurred was 40 percent, compared with about 55 to 60 percent for the average slope of other earth slump failures in the area. Because of this lower slope gradient, it was considered unlikely this slump would have occurred without the additional water introduced from the road. As well, because of the low slope gradient of this failure, and the location of the creek some distance to the south, this slide was not expected to impact the creek or have other significant downslope impacts. It does, however, give clear evidence that at this locale, excess surface water delivered to a site can reinfiltrate and affect pore water pressures and earth slump type landslide activity.

In other areas along the Upper FSR, no such direct downslope effects such as those discussed above were observed. Nevertheless, the road surface and ditchline were redirecting flow between micro-watershed boundaries defined by ridges and swales on the hillslopes below the road.

It was concluded that concentration of groundwater and surface flows by the Upper FSR were affecting downslope landslide activity.

Landslides

There were 15 debris flows, 6 debris slides or avalanches and a large earth slump in the study area.

Debris flows

The 15 debris flows were primarily located towards the eastern end of the study area (Figure 2). They were from 150 to 250 metres long and were moderately to highly channelized. Through this region, Upper Chase Creek flowed against or close to the north valley wall, with little or no floodplain, and 7 debris flows deposited debris and sediment directly into Upper Chase Creek. The remaining 8 debris flows located to the west ran out on the Old FSR, which was further back from the creek in those locations.

The debris flows generally had initiation zones at or within 10 m below the break in slope between Unit 1 and 2. They were "transport limited" type debris flows, initiating and moving through deep erodible tills. This means that there was abundant material available to fail, and the occurrence of events was primarily controlled by the return period of climatic inputs.

In several of the smaller debris flows mud splash marks were observed on trees up to 3 m above ground level. During debris flow events then, very fluid flows several metres in depth deposited sediment directly into Upper Chase Creek.

The largest debris flow (Slide 40, Fig. 2) had occurred along the lower sidewalls and channel of a larger relic debris flow gully. It had recently failed, probably during the 1997 freshet. A slug of sediment and organic debris was observed in the channel and was being eroded by the creek, visibly increasing turbidity. This deposit was the second largest point source of sediment observed in the study area.

However, no hydrologic connection was found, or was thought to be possible, between this landslide and upslope road building or harvested area. It appeared to be an entirely natural phenomenon, both in its historical and recent activity. This was also true of four smaller, recently active debris avalanches and debris flows which occurred within 200 m to the east of Slide 40.

While the air photo evidence and the presence of vegetated relic slide scarps seen on the ground indicated that this area had been an active landslide area long before logging took place, debris flow activity appears to have increased in the last several years. This was true for both debris flows in areas potentially impacted by forestry developments - west of Slide 40 - and in areas considered to be unaffected by forestry impacts - east of and including Slide 40.

Sediment introduced to Upper Chase Creek from these debris flow channels in the future will occur as discreet events, over a very short period of time, initiated by high precipitation and/or snowmelt events. Sediment volumes of these generally small debris flows would be in the range of a few hundred cubic metres of debris, occurring at most once a year, and probably with much less frequency over the long term. It is not unlikely that several or most of these gullies would fail during the same climatic event, at basically the same time, and their impact in terms of downstream suspended sediment load could have a noticeable short-term impact. From 1500 to 2500 m^3 of debris could be introduced to Upper Chase Creek over a few hours to days if the seven debris flows that impact the creek directly failed more or less simultaneously.

Debris slides

The 6 debris slides occurred in loose glaciofluvial deposits and were spread throughout the study area.

The largest two were 100 to 150 m long by 50 m wide, with the rest being less than 50 m long. Four ran out onto the Old FSR, and two were being undercut by Upper Chase Creek and were failing into it. The slides generally displayed near vertical head scarps in loose, well-sorted sands and gravels. The air photos showed they had been very active prior to logging and road building, in response to undercutting by the creek. The Old FSR was reducing the impacts of most of these slides by providing a low gradient bench upslope of the creek. As a whole they contributed relatively minor amounts of sediment to the creek compared to bank erosion and the other landslide types.

Earth slump

A large complex failure, designated Slide 35/6, extended for about 300 m along Upper Chase Creek, and about 130 m upslope from the creek. Failing backscarps up to 4 m high were observed, as were older but still recent scarps up to 7 meters high. The backscarps could be traced on the ground as one continuous feature over 280 m. The slide exhibited slump features near backscarp areas, earthflow characteristics near the toe, and occurred in the deep till sequence described above.

This slide was very visible on the 1961 air photos (Fig. 3), as were relic lateral and backscarps delineating large areas upslope of the active area. On the ground it was observed that drainage from harvested upslope area had been intercepted and redirected down the Upper FSR, and onto slopes directly above the active area.

One portion of Slide 35/6 had failed into Upper Chase Creek in 1997, with the toe of the active slide having entered the wetted perimeter of Upper Chase Creek, redirecting streamflow from the north to the south side of the channel (Fig. 4). Freshly downed timber and slumping indicated that there was a high likelihood adjacent area would soon do the same.

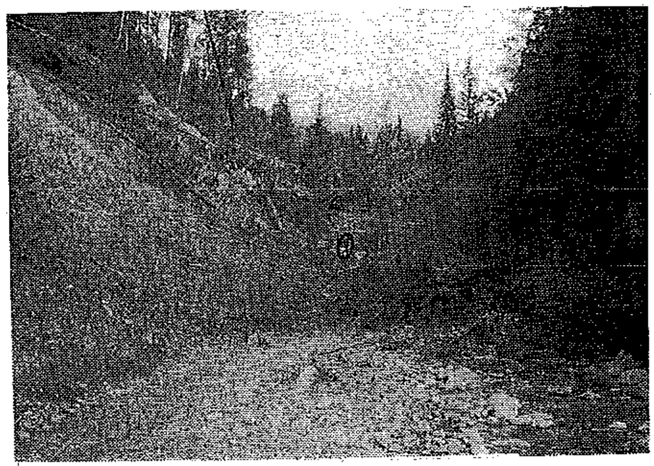
To the east very recent backscarp movement was noted, along with some 7 metre high scarps estimated to have been inactive for several years. Downslope of these backscarps the slide surface was colonized by brush species, indicating movement within the last 3 to 7 years. The Old FSR had completely failed into Upper Chase Creek through this section. To the west was the slump failure induced by redirected road drainage, as discussed above.

Grain size analyses showed that slide material was composed of 35 to 45 percent silt and clay. This material could be carried as suspended sediment for large distances during peak streamflows, affecting downstream drinking water quality

From the area of currently active and relic failure scarps in the Slide 35/6 area and cross sections with an assumed depth to the slide plane, volumes of material in various parts of the slide were estimated. Based on this model, and the assumption that ground water conditions similar to those in 1997 would re-occur in the near future, the following conclusions were drawn:

- It was estimated that about 500 m^3 of sediment was resting within the wetted perimeter of the channel, and this would likely be removed during the subsequent freshet.

Fig. 4. Toe of active portion of Slide 35/6 resting in Upper Chase Creek and redirecting creek to south side of wetted perimeter. Note circled person on slide surface for scale.



- About 2500 m^3 of saturated sediment was perched directly behind this mass, with a surface slope gradient of 70 percent. This material had a high likelihood of entering Upper Chase Creek fairly rapidly (in a few weeks to months), if and when the sediment sitting in the creek was removed during the subsequent freshet.
- Renewed activity below the most active backscarp areas would be expected given continuing high groundwater levels. It was estimated that about 18,000 m^3 of sediment would be mobilized in an area designated to be an immediate very high risk.
- It was estimated that about 90,000 m^3 of sediment had been moving within the last 1 to 7 years, below the 280 m of continuous backscarp.

Subsequent subsurface geotechnical investigations showed that there were two slide failure planes corresponding to two hydrologically unconnected piezometric surfaces, artesian water pressure near the toe of the slide, and a potential total volume of slide material of 270,000 m^3.

Landslide history

Three avenues of investigation were followed to determine the history of landslide activity in the study area: historical air photo series of the Upper Chase Creek area were interpreted; ground investigations of topography, drainage and vegetation were carried out; and the results of a detailed study of historic channel changes lower in the Chase Creek mainstem were analysed.

Landslides identified in the 1961 photos, taken prior to logging development, were compared with those identified in the 1996, post-development photos.

As discussed above, almost all landslides identified in the landslide inventory (MoF 1996) were clearly identifiable on 1961 air photos, taken prior to forestry development in the watershed (Figure 3). The earlier photos show exposed soil and/or inactive, vegetated headscarps and slide paths, for all the currently active landslides in the study area.

Most slope failures occurred in areas bounded by inactive slide scarps, indicating that landslide activity predated any of these photos.

Ground investigations confirmed the presence of old lateral scarps and back scarps vegetated with various plant species, ranging in ages from brush and emergent conifer stands to mature timber. Continuous trunk curvature of 150+ year Douglas fir 'vets' indicated that slope movement has been ongoing in this area for at least that long. Instances of very recent landslide activity, post-dating the 1996 landslide inventory were noted, particularly in the earth slump.

A detailed analysis of historic stream channel changes in the Chase Creek mainstem had been carried out by Northwest Hydraulic Consultants (1997). Selected physical characteristics of the Chase Creek channel at the confluence with Upper Chase Creek were measured by NHC, from seven different sets of airphotos taken between 1951 to 1996. Keeping in mind that channel aggradation at the mouth of Upper Chase Creek will have been a function of both sediment supply (landslides and channel erosion) and sediment transport events (floods), we used NHC's measurements as indicators of channel aggradation, and ultimately as a measure of sediment production and delivery from Upper Chase Creek. Channel area, channel width, and unvegetated bar area were plotted as a time series (Fig. 5).

NHC had concluded that, "At some time between 1930 and 1951, Upper Chase Creek became very unstable and it delivered large volumes of sediment to its fan . . " Figure 5 shows a decrease in sediment load from Upper Chase Creek for the period from 1951 to 1984. From 1984 to the present there was a less steep, but clearly definable increase in sediment delivery from Upper Chase Creek to Chase Creek. Land use changes in the upper watershed (SRK 1997) are also shown on Fig. 5.

Hydrologic and climatic history

Increased water in forested watersheds can accelerate erosion in two ways. Increased peak flows in the creeks can lead to increased rates of down cutting, bank erosion and landslide toe destabilization. Increased infiltration leads to elevated ground water levels and higher pore water pressures, one of the primary causes of landslide initiation.

Various landslide types, including debris flows, debris slides, and earth slumps were present in the study area. These different landslide types will respond differently to short-term and longer-term moisture inputs.

Deep seated rotational earth slumps in finer grained materials are driven by deeper ground water levels and pore pressures, which generally respond to climatic inputs over months to years. Total annual precipitation was considered to be an indicator of long-term inputs to these levels. The climate station at Westwold, about 23 km southeast of the study area, was the closest climate station with a long enough period of record to analyse. It had 76 years of record, and was at 610m elevation, compared to about 1200 m for the study area. The total annual precipitation time series for Westwold was analysed using a statistical filter - cumulative departure from the mean - to detect trends in the record. Results for the 1948 to 1996 period are shown in Fig. 6. A smoothed curve has been added, by eye, to highlight perceived trends.

There was a trend of greater than average precipitation from the start of the record in 1922 to about 1940 (not shown), a clear trend of lower than average precipitation from 1940 to 1980, and a clear trend of higher than average precipitation from 1980 to 1997.

As to very recent longer term water inputs, the cumulative 12 month period from October 1996 to September 1997 was the wettest 12 month period in the 100 year record over most of southern British Columbia, including Kamloops, Penticton, and other stations (Environment Canada 1997).

The saturation of soils nearer the ground surface generally affects the initiation of rapidly moving debris flow and debris slide types of failures. This occurs in response to relatively short-term extreme precipitation and snowmelt events, occurring over periods of hours to days. Because Upper Chase Creek is a snowmelt dominated watershed, the highest water inputs and infiltration rates usually result from spring snowmelt and rain-on-snow events. Like infiltration rates, peak streamflows are generated by a combination of rainfall, snowpack levels, snowmelt rates, and physical watershed characteristics. For this reason peak streamflow measurements were used as an indicator of short-term water availability in the system.

No long record of stream flows exists for Chase Creek. A close correspondence between peak flows for Chase Creek and the gauge on the Salmon River at Falkland, 15 km south of the study area (08LE020, 1948 to 1997), was noted in other studies (SRK 1997, and NHC 1997). It was assumed high peak flow events would have occurred in the same years on Upper Chase Creek and at the Salmon River gauge. We used annual maximum daily peak flows at Falkland as an indicator of the occurrences of short term maximum moisture influxes affecting debris slide and flow type landslide activity in Upper Chase Creek, and analysed for trends using cumulative departure from the mean versus time (Fig. 7).

The cumulative departure from the mean analysis shows a negative trend - consistently less than normal peak flows - from about 1956 to 1970 and from 1975 to 1981, interrupted by a small cluster of extreme events in 1971 and 1972. From 1981 on, no clear trend was detected.

It was concluded that if short-term climatic inputs were the only significant landslide initiation factor, one would expect less frequent debris flow and debris slide occurrences up to about 1980, and a normal distribution of greater or smaller events from 1980 to the present.

A frequency analysis of annual maximum daily flow at Falkland showed 1996 and 1997 were the fifth and sixth largest floods on record, with 15 and 10 year return periods

Fig 5. Channel aggradation time series, Upper Chase Creek, 1948 to 1996.

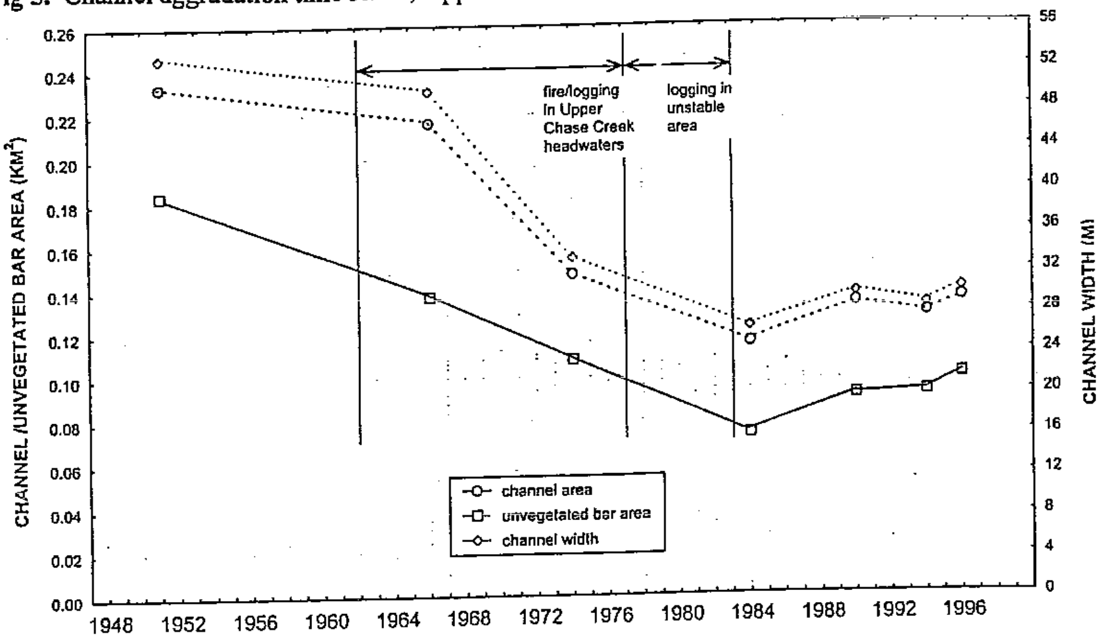


Fig 6. Cumulative departure from the mean for total annual precipitation, Westwold, B.C., 1948 to 1996.

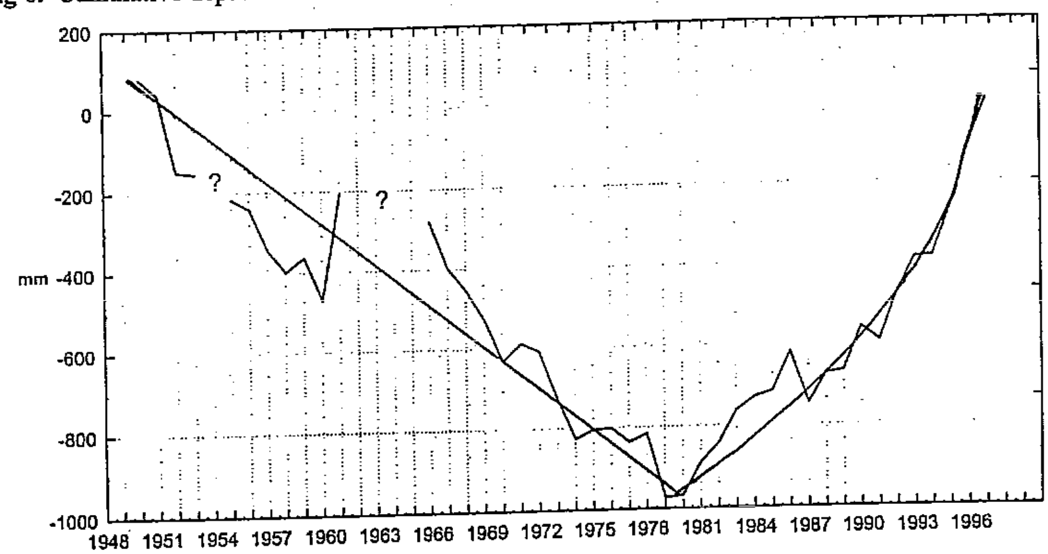
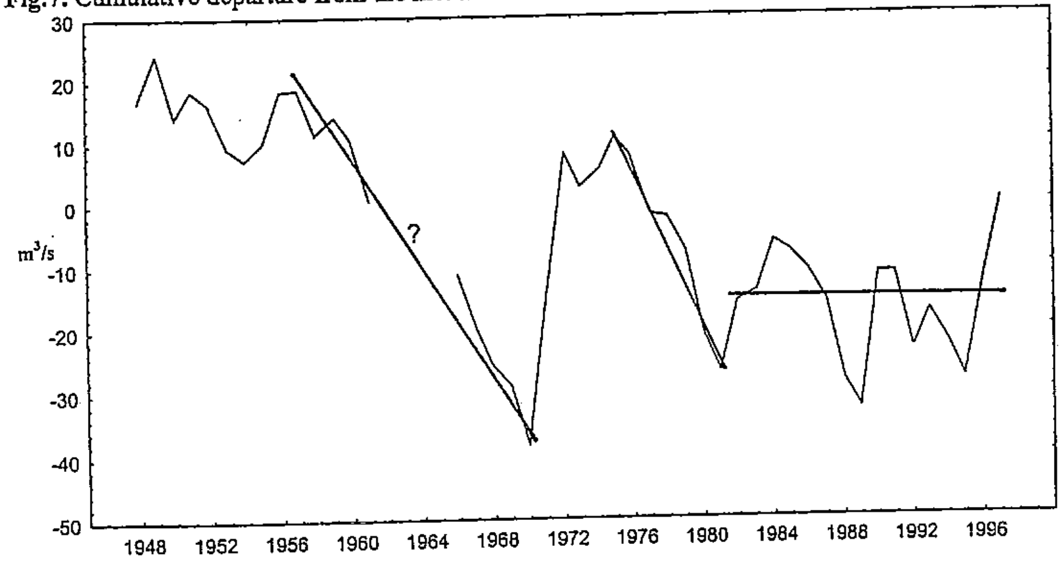


Fig.7. Cumulative departure from the mean for mean maximum daily discharge, Salmon River at Falkland, 1948 to 1996.



respectively. 1971 and 1972 were the second and third largest with 15 and 25 year return periods. 1948 was the largest flood on record, with a 50 year return period.

As to the very recent shorter term water inputs, a week of very heavy rains ending on July 11, 1997 was recorded at the Salmon Arm Climate Station, located about 25 km east of the study area. The return periods for the 4-day and 7-day totals leading up to July 11, 1997 were 50 and 80 years respectively (MELP 1998). Other notable landslides occurred in the Shuswap Highlands at the end of this period.

In summary, there has been a wetter climatic trend over the last 20 years in Upper Chase Creek.

As well, both short term (days to weeks) and longer term (annual) water inputs were very much higher than the long term average immediately preceding observed renewed landslide activity in Upper Chase Creek in 1996-7.

Discussion and conclusions

The geomorphic evidence indicated that the area of study in the Upper Chase Creek watershed had been unstable for at least several hundred, and probably for several thousand years. Upper Chase Creek continues to down cut through the thick glacial deposits, undercutting the toe of steep valley side slopes. Locally, bank erosion is the primary mechanism for delivering sediment to the creek. Further up slope landslides are the primary mechanism removing sediment from the valley walls and delivering it to the creek.

Sediment from both these sources was transported downstream, and over time contributed to the build up of the flood plain in the lower Chase Creek valley. This process continues today, as experienced in the 1996 debris flood from Upper Chase Creek onto the lower flood plain, and in the much larger pre-1951 events.

The relative activity of these processes has varied over time. Rates are controlled primarily by the amount, timing and distribution of precipitation the area receives, and by land-use changes affecting water delivery rates to slopes and creeks.

Forestry road building and clearcutting occurred primarily during the late 1970s and early 1980s, with the lower road being constructed in the early 1960s. It had been assumed that these developments had been largely responsible for landslide activity (MacDougall 1997, and Booking 1997). However, airphoto analysis clearly indicated that most existing landslides in the study area had been active prior to logging. Figure 5 shows the channel changes and the inferred landslide and sediment delivery activity at the mouth of Upper Chase Creek, plotted as a time series along with periods of major land use changes. The analyses of the short and longer-term climatic inputs over time (Figures 6 and 7) show the trends that would influence landslide activity over the same time period.

The question remained as to how much, if any, forestry activities had increased the level of landslide activity and sediment delivery to the lower Chase Creek floodplain over the last 20 years. Additionally, what had caused the observed increase in landslide activity in 1996-7? The following conclusions were drawn:

- The very large sediment load at the mouth of Upper Chase Creek prior to 1951 may have been at least partially a result of the extreme run-off event of 1948, the largest flood on record.
- There was a continuous decrease in sediment supply from Upper Chase Creek from about 1951 to 1984. The trend was not sensitive to the extreme streamflow events of 1971 and 1972, the second and third largest events on record. Both short-term (maximum daily peak flows) and long term (total annual precipitation) climatic measures showed generally drier than normal conditions, and no harvesting occurred in the study area, during this period.
- Increases in sediment production and delivery from Upper Chase Creek occurred after 1984, when logging in the study area was completed, and continued to the present. The analysis of annual precipitation and to a lesser degree annual peak flow indicated a wetter climate over this same period.
- It was concluded that much of the increase in sediment loading to the mouth of Upper Chase Creek had been caused by increased landslide activity and increased streamflows brought on by these wetter than normal climatic conditions. This was especially true for the earth slump type slide that was contributing more sediment to the creek than all the other slides combined.

Other evidence points to the effects of logging and road building:

- There was direct evidence that the slopes of terrain Unit 1 were sensitive to redirected drainage from the Upper FSR. A small debris flow and an earth slump could be directly connected to drainage from the Upper FSR and its ditchline, and it was considered unlikely that these failures would have occurred without the additional water introduced from forestry developments.

It was therefore concluded that forest harvesting and road building in the study area were also responsible to some extent for the increased activity of pre-existing landslides. Over the last 20 years this resulted in some of the increase in sediment delivery to the Upper Chase Creek channel.

It was not possible to quantify the increase in sediment loading to Chase Creek due specifically to either wetter climatic conditions or logging.

It should be noted that even with the sediment increases due to climatic inputs and logging over the past 20 years, sediment loading at the mouth of Upper Chase Creek during this period was far below the volumes delivered between 1930 and 1951. As far as bedload sediment loading to the lower Chase Creek floodplain, pre-1951 events are causing greater disruptions than post-1980 logging and landslide activity, as the pre-1951 sediment wedge works its way downstream (NHC 1997).

Landslide occurrences at the east end of the study area that were unconnected to forestry activities, the extreme annual cumulative precipitation and stream peak flows, and the extreme July 1997 cumulative 7-day rainfall event, were evidence that much of the 1997 landslide activity was due to extreme climatic inputs over the last two years. Increased landslide activity would probably have occurred in the absence of any forestry development. However, clearcutting and road building may have increased the magnitude of these recent landslides and their impacts to some degree.

Finally, whatever their causes, suspended sediment loading and downstream drinking water quality were being detrimentally affected by the increases in landslide activity in the study area. A detailed geotechnical investigation was carried out on the large earth slump. Extensive mitigation measures were carried out in 1998 by Riverside Forest Products and Forest Renewal B.C. These included installation of horizontal drains to stabilize the deep-seated failure plane, and relocation of a short section of the Upper Chase Creek channel to prevent toe erosion and further destabilization along the shallow slide plane.

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