Climatic Influences on the Ashcroft Thompson River Landslides, British Columbia, Canada

Kristen M. Tappenden
University of Alberta, Edmonton, Alberta, Canada

ABSTRACT
The Thompson River Valley, located in southern British Columbia, Canada, forms a vital artery of the national transportation network. Main lines of both the Canadian Pacific Railway and the Canadian National Railway are located in this corridor, providing a strategic connection between Canada's shipping ports on the west coast and the continent's resources and population to the east. Twelve large landslides extend along a treacherous 10 kilometer reach of the Thompson River Valley south of Ashcroft, British Columbia, and are collectively known as the Ashcroft Thompson River landslides. While the Ashcroft Thompson River Landslides today are typically slow moving, several rapid to very rapid catastrophic failures have occurred in the past 120 years. This paper focuses on the dynamic relationship between the landslides and the surrounding environment, examining the role that climate may play in triggering the slope movements. It is hoped that a better understanding of climatic influences on landslide activity will facilitate early-warning of impending landslides and empower all stakeholders to improve their level of understanding and ability to prepare for, and cope with, the potential impacts of a large landslide.

RÉSUMÉ
La vallée de la rivière Thompson, situé dans le sud de la Colombie-Britannique, au Canada, constitue une artère vitale du réseau de transport national. Grandes lignes à la fois du Chemin de fer Canadien Pacifique et le Canadien National se trouvent dans ce couloir, offrant une connexion stratégique entre les ports maritimes du Canada sur la côte ouest et les ressources et la population du continent à l'est. Douze grands glissements de terrain s'étendent le long d'une perfide 10 km la portée de la vallée de la rivière Thompson sud d'Ashcroft, Colombie-Britannique, et sont collectivement connus comme les glissements de terrain Ashcroft de la rivière Thompson. Alors que les Ashcroft rivière Thompson glissements de terrain sont aujourd'hui généralement lent, plusieurs de défaillances catastrophiques très rapides rapides ont eu lieu dans les 120 dernières années. Cet article se concentre sur la relation dynamique entre les glissements de terrain et l'environnement, en examinant le rôle que peut jouer le climat dans le déclenchement des mouvements de terrain. Il est à espérer qu'une meilleure compréhension des influences climatiques sur l'activité des glissements de terrain facilitera alerte de glissement de terrain imminents et permettre à tous les intervenants afin d'améliorer leur niveau de compréhension et la capacité de se préparer et faire face, les impacts potentiels d'un important glissement de terrain.

1 INTRODUCTION

The Thompson River Valley, located in southern British Columbia (BC), Canada, forms a vital artery of the national transportation network. Main lines of both the Canadian Pacific Railway and the Canadian National Railway are located in this corridor, providing a strategic connection between Canada's shipping ports on the west coast and the continent's resources and population to the east. Twelve large landslides extend along a treacherous 10 kilometer (km) reach of the Thompson River Valley south of Ashcroft, British Columbia, and are collectively known as the Ashcroft Thompson River landslides. These landslides have resulted in significant, recurring disruptions to the railway service, and threaten numerous other vulnerable groups located within the Thompson River Valley, including First Nations communities, residents of the villages of Ashcroft and Spences Bridge, salmonid populations within the Thompson River, and owners/operators of upland agricultural areas. While the Ashcroft Thompson River Landslides today are typically slow moving, several rapid to very rapid catastrophic failures have occurred in the past 120 years.

This paper focuses on the dynamic relationship between the landslides and the surrounding environment, examining the role that climate may play in triggering and accelerating the slope movements. Building on previous research, the effects of fluctuations in the Thompson River flow year over year and the influence of regional snow pack on the landslide movements will be investigated.

2 LANDSLIDE TYPES AND MECHANISMS

2.1 Historical Development of Slope Instabilities

Table 1 summarizes the large-scale landslide movements which have been recorded along the Thompson River Valley over a distance of approximately 10 kilometers south of Ashcroft, BC. The locations of the landslides are shown on Figure 1. The landslides are generally of two types: (1) rapid flows resulting from structural collapse of the surficial glaciolacustrine silt deposits, presumably triggered by primitive irrigation methods; and (2) translational slides in which the surface of rupture is situated in the lower-most glaciolacustrine unit overlying the bedrock formation. The translational slides typically move slowly along an existing rupture surface; however, where retrogression along a new failure surface occurs, rapid acceleration may result. A rapid translational

Table 1: Recorded movements of large landslides in the Thompson River Valley within about 10km south of Ashcroft.

Number on Figure 1	Landslide Name	Recorded Dates of Significant Movement	Predominant Type of Movement	Estimated Velocity	Approx. Volume (Mm^3)	References
1	1897	1897	Translational	Unknown	—	(a),(b)
2	CN 51	1897 (September 22)	Translational, retrogression	Probably Rapid	—	(a),(b),(d),(g)
		1972 (Fall)	Translational, reactivation	Extremely Slow	3	
		1977 (Winter)	Translational, reactivation			
		1997	Translational, reactivation			
		2000 (Fall)	Translational, reactivation			
3	Unnamed	Unknown	Unknown	Unknown	—	(a)
4	Goddard	1886 (October 19)	Flow	Very Rapid	>3	(a),(b),(d),(g)
		1974	Translational, reactivation	Very Slow	—	
		1976 (October)	Translational, reactivation		—	
		1982 (September 24)	Translational, retrogression	Rapid	2	
5	CN 53.4	Possibly 1880	Unknown	Unknown	—	(a),(f)
6	North	1880 (October 14)	Flow	Very Rapid	—	(a),(b),(d),(f),(g)
		1997	Translational, reactivation	Extremely Slow	21	
		2000 (October)	Translational, reactivation	Very Slow		
7	South	Pre-1885, Probably 1881	Flow	Probably Rapid	—	(a),(d),(f),(g)
		1977 (Winter)	Translational, reactivation	Extremely Slow	9	
		1997 (Fall)	Translational, reactivation			
		1999	Translational, reactivation			
8	Red Hill	1921 (August 13)	Flow	Rapid	—	(a),(b),(e),(h)
9	Barnard	Between 1877–1895	Flow	Probably Rapid	—	(a),(g)
10	Nepa	Between 1877–1898	Flow	Rapid	—	(a),(g)
11	Unnamed	Pre-1885	Flow	Probably Rapid	—	(g)
12	Basque	Pre-1897	Unknown	Unknown	—	(a),(c),(d)
		1977	Translational, reactivation	Extremely Slow	2	
		1997	Translational, reactivation			

References:
a. Bishop (2008)
b. Clague and Evans (2003)
c. Eshraghian (2007)
d. Eshraghian et al. (2007)
e. Evans (1984)
f. Porter et al. (2002)
g. Stanton (1898)
h. Wade (1979)

retrogression occurred in 1982 at the Goddard landslide. In examining the historical landslide events, it is important to differentiate between the flows and the translational slides. The factors which predispose and trigger the two types of landslides are very different, and the likelihood of occurrence and potential consequences of the landslides are also quite dissimilar. It should be noted, however, that many of the existing translational slides are situated within the footprint of the older flows. The flows represent first-time slope failures, while the translational slides are generally considered to be reactivations of dormant or inactive landslides. It may also be noted that smaller landslides exist along the corridor which are of importance from a railway operations perspective, but these are not addressed in this paper for the sake of brevity. The reader is referred to Macciotta et al. (2014) for a discussion of one such case (the Ripley landslide). This paper focuses primarily on the large translational landslides in the corridor, which present ongoing risks to the railways from an operational standpoint, and are of interest to a broad cross-section of stakeholders. The movements of these large translational slides are hypothesized to be the result of overall climate factors on a basin-wide scale.

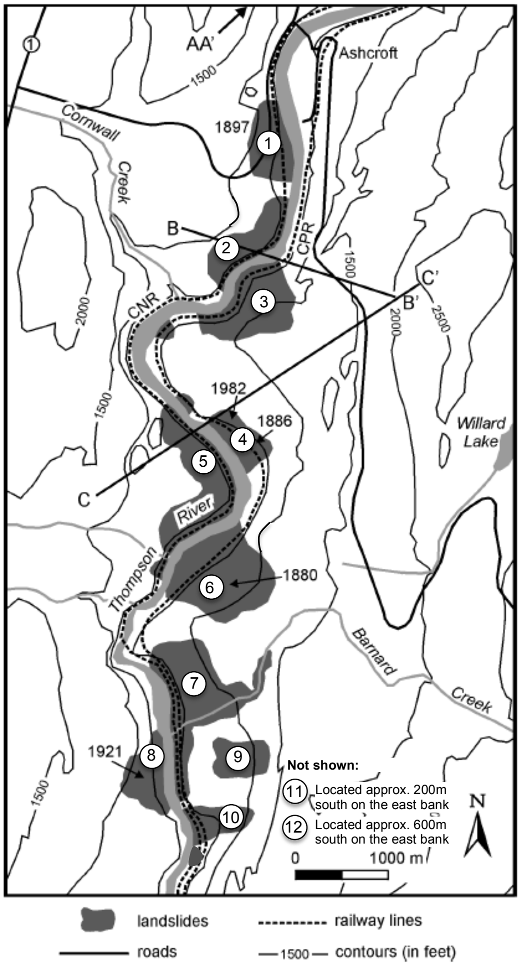

Figure 1: Landslides along the Thompson River south of Ashcroft (modified from Clague 1998).

3 GEOLOGIC SETTING

3.1 Geomorphology

The Quaternary sediment fill in the Thompson River Valley near Ashcroft is comprised of deposits from three glaciations as shown in Figure 2; the three glacial sequences are separated by unconformities produced by erosion and mass wasting during intervening interglaciations (Clague and Evans 2003). The valley fill sequence consists predominantly of permeable sediments, with the exception of a unit of rhythmically bedded silt and clay near the base of the Pleistocene sequence (unit 2 in Figure 2) (Clague and Evans 2003; Ryder 1976). Large landslides have occurred in areas where this clayey glaciolacustrine layer is present, with the failure plane located within, or along the surface of, this unit (Clague and Evans 2003). Flowing south through the study area, the Thompson River has incised to a depth of approximately 150m below the late-glaciolacustrine and outwash surfaces during post-glacial time (Porter et al. 2002; Ryder 1976). Extensive terraces were cut into the Pleistocene valley-fill sediments during this phase of degradation in the Thompson Valley (Ryder 1976). The landslides are situated on the steep walls of an inner valley that formed during the Holocene, when Quaternary sediments filling the broader Thompson River Valley were incised (Eshraghian et al. 2007).

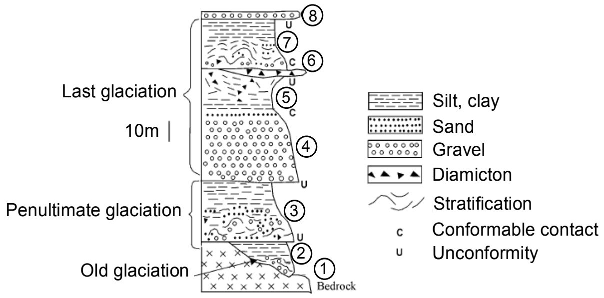

Figure 2: Generalized stratigraphy of Quaternary sediment fill in the Thompson River Valley at Ashcroft (Clague and Evans 2003).

3.2 Factors Predisposing Instability

Popescu (1994) underscores that all landslides are caused by a combination of preparatory and triggering factors. Preparatory factors make the slope increasingly susceptible to failure without actually initiating it, while triggering factors are those which initiate movement. Based on a review of the published literature, it appears that the stability of the Thompson River Valley walls south of Ashcroft are predisposed to failure as a result of two major factors: (1) the presence of a low strength, clayey glaciolacustrine unit at depth (unit 2 on Figure 2); and (2) the collapsible nature of the silt-varves which dominate the surficial glaciolacustrine deposits of the Southern Interior. These predisposing factors are described below, with a discussion of potential triggering factors provided in Section 4.

3.2.1 Geologic sequence

Clague and Evans (2003) state that the stratigraphy of the Thompson River Valley "predisposes it to failure." They identify that clayey strata are confined to a single unit—the rhythmically bedded glaciolacustrine sediment (unit 2) near the base of the Quaternary sequence, which confines and is also overlain by, non-plastic, more permeable sediments. Hodge and Freeze (1977) demonstrated that the presence of a low-conductivity unit at depth can be extremely detrimental to valley wall stability, especially where it confines a unit of higher conductivity, as is the case in the Thompson River Valley south of Ashcroft. They further noted that this contrast in hydraulic conductivity need not be more than two orders of magnitude to have a marked detrimental effect on slope stability (Hodge and Freeze 1977). The effect of this sequencing is to produce softening of the clayey glaciolacustrine unit, as well as elevated pore water pressures along the base of the layer as a result of artesian water pressures confined within the more permeable underlying units. The clay beds of unit 2 are highly plastic, with plasticity indices in the order of 15 to 55 percent, and liquid limits ranging from 45 to almost 90 percent (Porter et al. 2002). Residual friction angles estimated using the empirical correlation of Stark and Eid (1994) are in the order of 10 to 12 degrees (Eshraghian 2007). Clague and Evans (2003) note that clayey glaciolacustrine sediments older than the Fraser Glaciation play a significant role in the stability of slopes in many valleys in the Pacific Northwest, and postulate that disturbance by overriding ice or early slope movements may have created pre-sheared discontinuities predisposing these units to failure.

3.2.2 Collapsible silts

Evans (1982) notes that British Columbia glaciolacustrine sequences may be either silt-varve dominated or clay-varve dominated, indicating the dominant grain size in terms of relative thicknesses of silt or clay for a given succession (Evans 1982). The surficial glaciolacustrine deposits of the Southern Interior are dominated by silt varves, which are sensitive and collapsible under certain moisture and loading conditions (Evans 1982). Bishop et al. (2008) confirmed that within the varved formations of the Thompson River Valley near Ashcroft, the thickness ratio of the silt varves compared to the clay varves is approximately five to one. Quigley (1976) illustrated the open fabric of silts from the South Thompson and Penticton areas, and Lum (1979) established their collapse potential under certain moisture and loading conditions. He concluded that the high strength of the silts under low degrees of saturation, typical of the semi-arid environments in which they occur, is due to substantial apparent cohesion, the magnitude of which is controlled by the degree of saturation (Lum 1979). The deposits display brittle behaviour during shear and experience rapid and substantial strength loss after failure; the fact that slide blocks are not preserved in the flow debris indicates the extent to which the material is sensitive to gravitational remoulding (Evans 1982). Because the strength of the silt is dependent on the degree of saturation, it is adversely affected by water input from agricultural irrigation, especially where this additional moisture input forms a substantial percentage of the total precipitation (Evans 1982).

The only contemporary investigation of the rapid flows which occurred along the Thompson River Valley near the turn of the last century attributed the cause of the landslides to agricultural irrigation of the benchlands along the river (Stanton 1898). The case for this evaluation remains strong in light of the modern understanding of the collapsible nature of the silt-dominated surficial glaciolacustrine deposits. Water inputs of the magnitude utilized by historic ditch-and-furrow irrigation techniques are of critical importance in light of the collapsible properties of the Southern Interior silts. Stanton (1898) described the post-failure consistency of the silt as “thick pea-soup”, suggesting that complete saturation and loss of structure occurred. Moreover, these slope failures were reportedly rapid, and in the case of a flow which occurred near Spences Bridge in 1905 (not discussed in this paper), 15 people were killed by the debris and the resulting wave (Wade 1979). Stanton (1898) further reported that the flows occurred between 3 and 6 years after irrigation began above each location. In the case of the largest (North) landslide, failure was hastened by the bursting of an irrigation reservoir. Moreover, Stanton (1898) noted that aboriginal people and original settlers in the area attested to the fact that such flows had not occurred at any point along the Thompson River prior to irrigation of the benchlands. Owing to Ashcroft’s semi-arid climate, irrigation is necessary for agricultural production. Irrigation was first introduced to the area in 1868, and evolved from a crude ditch-and-furrow system to pipe-and-sprinkler techniques adopted in the mid-1960s (Clague and Evans 2003). It can be seen from Table 1 that no rapid flows have been reported since the Red Hill slide in 1921, and indeed, no flows have occurred since the introduction of modern irrigation methods, which are much more water-efficient than the techniques employed during Stanton’s (1898) time. It is therefore reasonable to conclude that primitive irrigation methods were the main cause of the rapid flows which have occurred in the corridor. The majority of these rapid flows occurred prior to completion of the Canadian Pacific Railway and the Canadian National Railway in 1895 and 1905, respectively. The ongoing translational slope movements, however, many located within the footprints of the old flows, have plagued the railways since their inception.

4 PREVIOUS WORK CONCERNING TRANSLATIONAL LANDSLIDE MOVEMENTS

While the balance of evidence suggests that the rapid flows which occurred along the Thompson River Valley were likely induced by anthropogenic factors (primitive agricultural irrigation), periodic reactivation of the slow-moving translational landslides in the corridor appears to be controlled by natural (climatic) factors, as discussed in the following sections. These may be characterized as triggering factors using the terminology of Popescu (1994).

4.1 Thompson River Flow

Based on railway maintenance records available for the 30-year period from 1970 to 2000, Eshraghian (2007) compiled a list of years in which existing large translational landslides along the Thompson corridor south of Ashcroft displayed a noticeable increase in their rate of movement. His findings are included in Table 1 above, and pertain to the Basque, CN 51, Goddard, North and South slides. Prior to 1970, reliable records of translational landslide movements were not maintained (Eshraghian et al. 2005).

Eshraghian (2007) identified the importance of the fluctuating Thompson River levels in controlling the very slow translational slide movements. In years when the Thompson River level was higher than normal, and remained high for an appreciable period of time, a noticeable increase in movement of one or more of the landslides was observed to occur upon recession of the river, typically in early fall. He plotted the cumulative river level difference from average for each calendar year (as measured upstream of the site at Kamloops), as a means of capturing both the magnitude and duration of the seasonal high water levels. He identified that reported landslide movements between 1970 and 2000 occurred in years when the maximum cumulative river level difference from average was significantly greater than zero, or in the year immediately following (Eshraghian 2007). Eshraghian (2007) postulated that the river primed the landslides for movement by creating a rapid draw-down condition. In years when the river level was high, and remained high for some time, the pore water pressure in the toe of the slide was sufficiently increased to the point of instability, and upon seasonal, comparatively rapid recession of the river, the slide would move due to the loss of the buttressing effect of the water and the elevated pore pressures remaining within the toe of the slide (Eshraghian 2007).

Porter et al. (2002) undertook stability analyses to evaluate the influence of the annual cycle of rising and falling river levels and piezometric elevations on the stability of the CN 51 landslide. They divided the translational slide into three blocks, and determined the variation in the factor of safety for each block between the high and low river level condition. The analysis showed that the river level had relatively little effect on the factor of safety of the mid-slope and upper blocks, but significantly impacted the factor of safety of the toe block by approximately 30% (Porter et al. 2002). Porter et al. (2002) argued that for retrogressive translational slides, the loss of toe stability as a result of falling river levels may have a significant impact of the mobility of the entire slide, despite what appears to be a relatively insignificant influence on the overall factor of safety.

4.2 Artesian Pore Water Pressures

Investigations at several of the translational landslides in the corridor have identified artesian pore pressures beneath the toe of the slides, contained within the fractured bedrock underlying the laminated silt and clay unit which forms the sliding plane (Porter et al. 2002). Shallow piezometers installed in the slide toes respond readily to fluctuations in the Thompson River level, while deeper-seated piezometers, also near the toes, respond to variations in river level to a much lesser degree. It is believed that artesian water pressures in the fractured bedrock control the pore pressures at the base of the silt and clay unit (unit 2 in Figure 2), while river levels exert a controlling influence on the pore pressures measured at the top of unit 2 near the toes of the landslides (Porter et al. 2002). Seasonal recharge of the bedrock aquifer on a regional scale would therefore be important in controlling the artesian water pressures below the failure surface, and could potentially trigger reactivation of the existing translational landslides.

Quinn et al. (2012) captured the importance of the fluctuating river levels and pore water pressures in presenting the vertical gradients produced below the toe of the CN 51 landslide, (Figure 3). It can be seen that the seasonally high river levels serve to substantially reduce, if not equilibrate, the upward gradient of pore water pressure measured below the slide toe, while upon recession of the river, the upward gradient rapidly increases, aggravating the instability of the marginally stable landslide.

Bishop (2008) modelled the regional hydrogeology within the Thompson River Valley south of Ashcroft, incorporating transient boundary conditions in the flow system model to simulate precipitation, irrigation, and fluctuation in the stage of the Thompson River level. His groundwater simulations confirmed that the glaciolacustrine silt and clay (unit 2) plays a critical role in controlling groundwater flow patterns, and explains the development of artesian pressures in the valley bottom (Bishop 2008). He found that the transient application of precipitation has a greater impact on the pore pressure distribution compared to modern irrigation levels or variation in the Thompson River stage, and concluded that the regional groundwater flow regime was much more sensitive to climatic changes, compared to the effects of river stage or irrigation. Bishop's work confirms that surface water that originates further upslope is channeled underneath unit 2, through the more permeable underlying units, and migrates upwards to the surface closer to river level. This regional flow regime is capable of generating elevated pore pressures in the glaciolacustrine silt and clay, fractured bedrock, and bedrock units in the lower region of the valley near Thompson River (Bishop 2008). However, Bishop's (2008) study did not consider regional water inputs due to snow melt. Quinn et al. (2012) demonstrated that the seasonal peak Thompson River flow levels correlate with the peak winter snow pack measured across the watershed. They presented a temporal comparison of the mean annual snow pack and the subsequent peak flow levels for the Thompson River measured at Spences Bridge for the years 1984 to 2009. It is postulated that melting of the snow pack on the basin-wide scale may provide considerable input to the groundwater flow regime, and play an important role in triggering translational slide movements as discussed in Section 5.2 below.

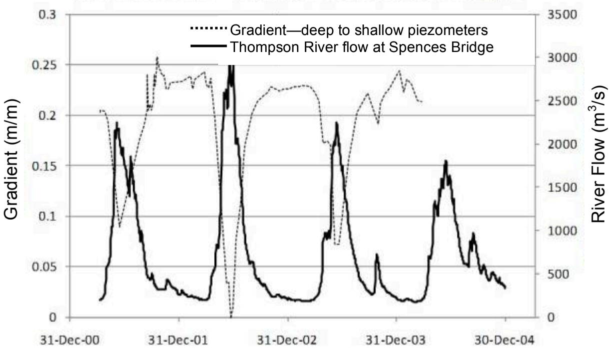

Figure 3: CN 51 landslide: vertical gradients at slide toe close to Thompson River (Quinn et al. 2012).

5 CLIMATIC INFLUENCES ON TRANSLATIONAL LANDSLIDE MOVEMENTS

5.1 Thompson River Flow

Building on the work of Eshraghian (2007), historic Thompson River discharge records were obtained for the monitoring stations near the village of Spences Bridge, approximately 40 km downstream of Aschroft (Environment Canada 2014). Based on the daily Thompson River discharge rates (m^3/s) for Spences Bridge Station 08LF051, average daily discharge values were determined for the period of record from 1952 to 2011. Assuming the daily measured discharge remains approximately uniform over the 24-hour period, the cumulative daily discharge may be calculated and compared to the average value for each day of the year. Figure 4 plots the annual cumulative river flow difference from average (in millions of cubic metres) since 1952, along with the number of large landslides showing a noticeable increase in their rate of movement between 1970 and 2000, as documented by Eshraghian (2007). It can be observed that the translational slides are most likely to show an increased movement rate in years when the cumulative river flow rises sharply compared to average conditions. The average annual river discharge at Spences Bridge is approximately 24,400 Mm^3 (Environment Canada 2014).

The powerful aspect of relating translational landslide activity to river flow levels is that there exists a much longer record of river flow data compared to landslide movement records. A second river discharge monitoring station, 08LF022, existed on the Thompson River at Spences Bridge from 1912 to 1951. Thus, nearly-complete daily river discharge measurements are available for the Thompson River near Spences Bridge for the past 100 years. These flow measurements provide

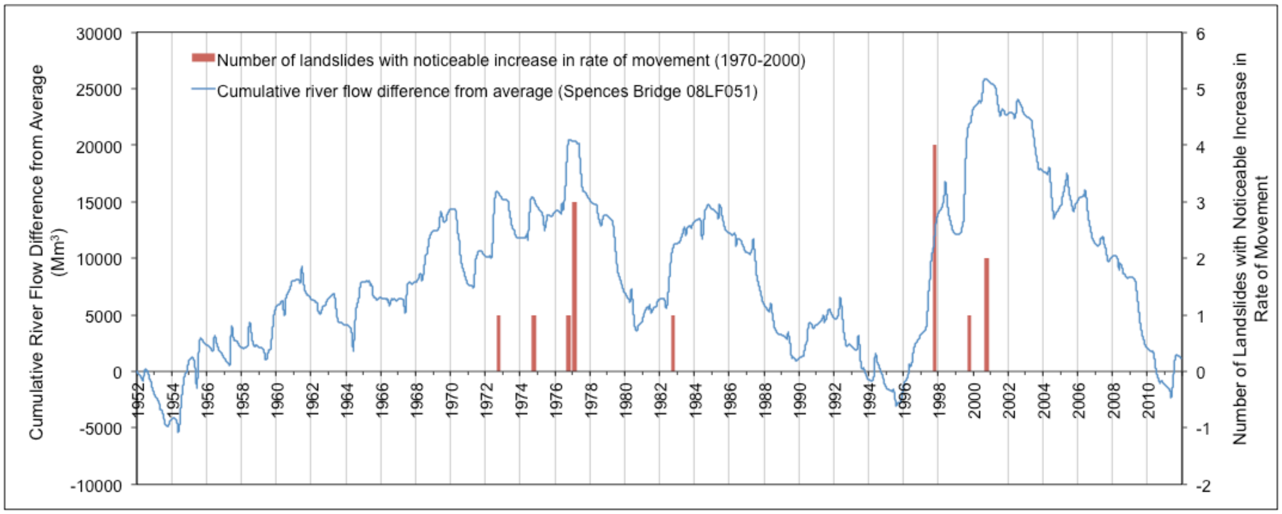

Figure 4: Thompson River cumulative flow difference from average over past 60 years at Spences Bridge.

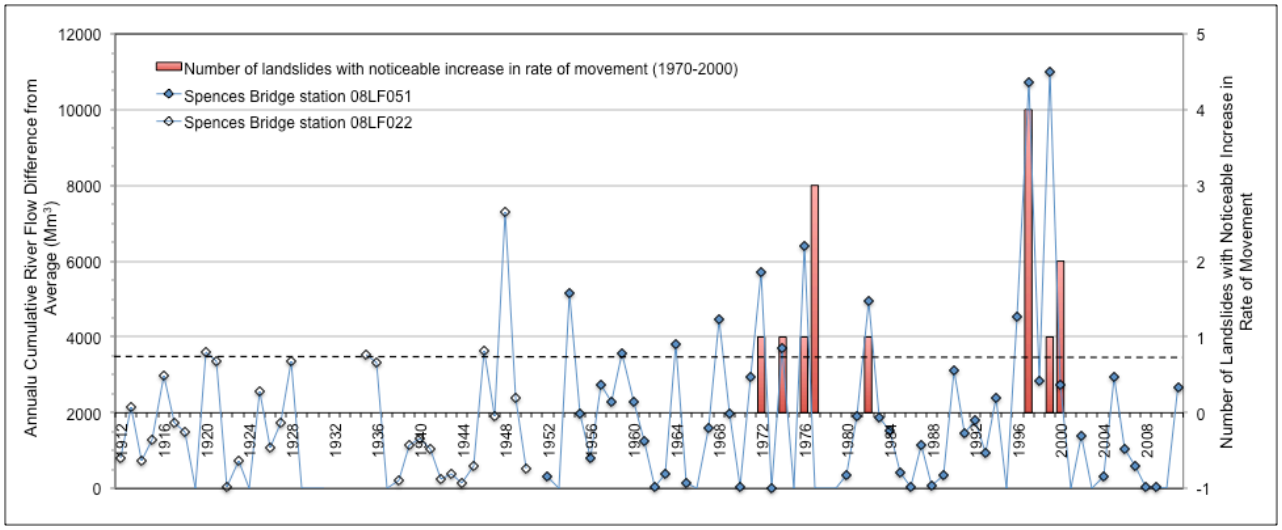

Figure 5: Annual peak cumulative Thompson River flow difference from average at Spences Bridge.

insight into a century of climate conditions, which may serve as a proxy for estimating the frequency of translational landslide movements back in time. Figure 5 shows the peak cumulative river flow difference from average for each calendar year, based on the daily Thompson River discharge measurements near Spences Bridge. The dashed line in Figure 5 represents a potential threshold value of 3,500 Mm^3, which when exceeded may portend landslide activity in the corridor. When the annual cumulative river flow difference from average exceeds 3,500 Mm^3, it appears that the large translational slides in the corridor are likely to experience a noticeable increase in their rate of movement in that year (or the year immediately following, as in 1977 and 2000). Moreover, it can be observed that the potential threshold criterion of 3,500 Mm^3 has been exceeded 15 times in the past 100 years. While further research is needed to verify the validity of this potential threshold, it demonstrates the value of utilizing the Thompson River flow records as a proxy for estimating the frequency of translational landslide activity in the corridor. The next stage of this ongoing research will be to conduct a quantitative risk assessment for the corridor using the frequency of exceedance of the river flow criterion as a proxy for the likelihood of landslide occurrence.

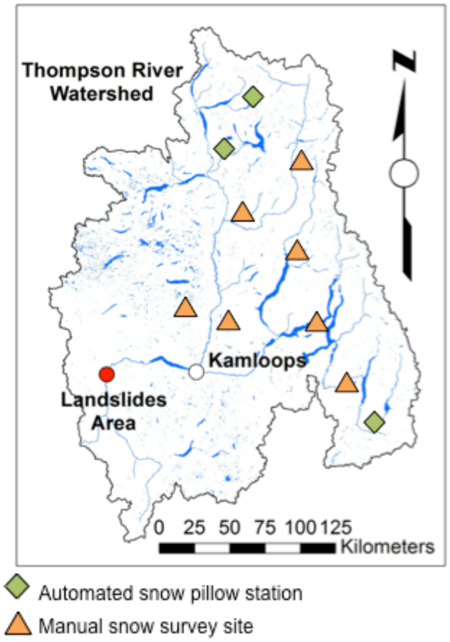

Figure 6: Snow pack monitoring stations in the Thompson Basin (modified from Quinn et al. 2012).

5.2 Melting of Regional Snow Pack

Quinn et al. (2012) demonstrated that the seasonal peak Thompson River flow levels correlate with the peak winter snow pack measured across the watershed. Their data was limited to the 16-year period of 1984 to 2009, as they considered only the automated snow pillow monitoring stations present in the Thompson River Basin (Quinn et al. 2012). However, numerous additional inactive and active manual snow survey sites also exist in the Thompson River Basin, as shown in Figure 6 (Province of British Columbia 2014). The manual snow survey sites are subject to discreet measurements of snow pack depth at intervals of approximately 2 to 4 weeks at the height of the season, as compared to the continuous measurements collected by the automated snow pillow stations. The size of the drainage basin of the Thompson River at Spences Bridge is approximately 55,000 km^2.

Snow monitoring records present the peak snow pack depth as an equivalent height of water, which can then be normalized to the average peak value over the period of record for that site. Using the basin-wide average of normalized snow pack and the daily river discharge measurements at Spences Bridge, Figure 7 presents the relationship between the average normalized peak snow pack and normalized peak Thompson River flow for the years 1956 to 2011. Only those snow stations with a minimum of 15 years of data were included in the analysis, so as to ensure a somewhat representative mean value for each station to be normalized against. Ideally, a 30 year period of record, as recommended by the World Meteorological Organization would be used, but this would limit the total number of snow pack monitoring stations to 7, as opposed to 10 (Government of Canada 2014).

Figure 7 presents a rather persuasive relationship between the normalized peak snow pack, averaged

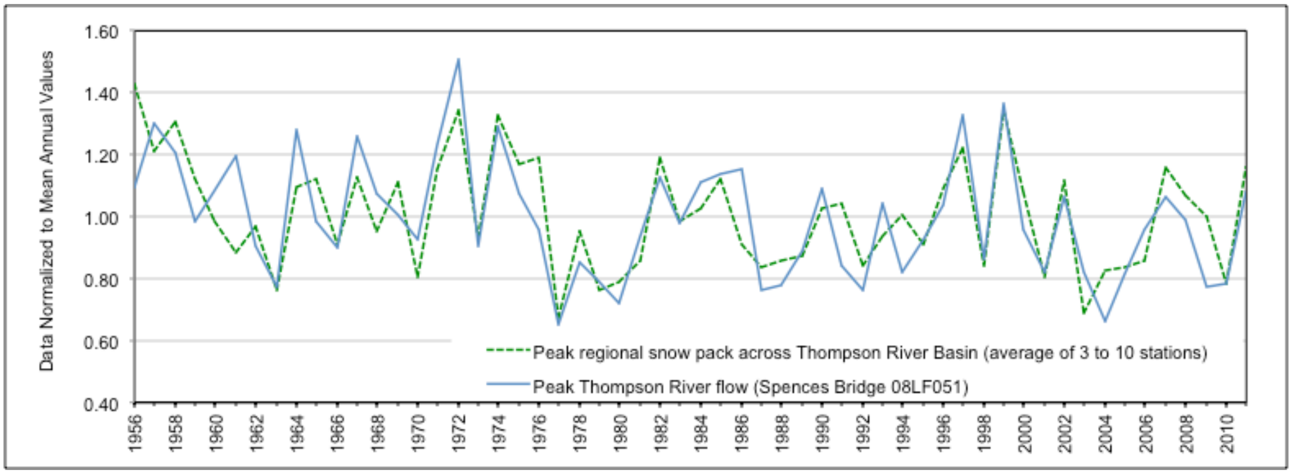

Figure 7: Relationship between average peak snow pack in the Thompson Basin and peak river flow at Spences Bridge.

between the active monitoring stations (3 to 10 stations, depending on the year), and the subsequent normalized peak Thompson River flow measured at Spences Bridge. Depending on the station elevation, the maximum snow pack typically occurs in late winter to early spring, with the peak river flow typically occurring in mid to late summer. River discharge records for Station 08LF051 near Spences Bridge indicate that the mean monthly river discharge rate varies from a low of 224 m^3/s in February, to a high of 2300 m^3/s in June, presumably driven by melting of the snow pack (Environment Canada 2014). When the average normalized peak snow pack is plotted versus the normalized peak river flow, a linear relationship is evident. A linear regression coefficient of $r^2=0.61$ is obtained for the period of 1956 to 2011, and is improved to $r^2=0.72$ for the period of 1971 to 2011, due to the increased number of active snow monitoring sites. From 1971 to 2011, there were 7 to 10 active snow monitoring stations, resulting in a more representative basin-wide average value for the peak normalized snow pack over this period of record (compared to 3 to 5 active sites during 1956 to 1970).

6 DISCUSSION

6.1 Climate Triggers

Taking an overall view of the work to date, it may be argued that the fluctuation in the Thompson River flow plays an important role in triggering movements of the slow translational landslides. It appears that the river flow affects both (1) the timing and (2) the magnitude of the landslide movements; (1) the timing, in that the majority of the translational slide movements occur in the fall, upon seasonal recession of the river and (2) the magnitude, in that the movements do not necessarily occur every year, but in years when the river flow is high and remains high for an appreciable period of time (or in the year immediately following). The above-average river flow may affect the slides in at least three ways: controlling the degree of saturation of the toe of the landslides; reflecting the overall climate conditions, especially the degree of recharge of the underlying aquifer and the extent of the artesian water pressures acting on the sliding surface; and controlling the amount of erosion occurring at the toe of the landslides.

In turn, the height of the winter snow pack measured across the Thompson River basin appears to play a significant role in controlling the subsequent peak river flow levels. The snow pack monitoring stations have not been active as far back in history as the river discharge monitoring stations, so the correlation of peak river flow to peak snow pack does not improve the frequency analysis of the landslide movements. However, the correlation does serve the important purpose of linking the peak Thompson River flows to the overall regional climate conditions, which could in turn, serve as a potential early-warning tool for predicting slope movements in the corridor, as suggested by Quinn et al. (2012). Moreover, the compelling link between the peak Thompson River discharge and the peak snow pack may serve to explain the lack of success that the author and others (Eshraghian et al. 2005; Quinn et al. 2012) have had in attempting to relate landslide movements to historic rainfall records. Given Ashcroft's semi-arid climate, receiving an annual average rainfall of only 232 mm (Bishop 2008), this apparent lack of correlation between landslide movements and rainfall records is none too surprising.

Viewed on a basin-wide scale, the Thompson River represents a formidable force of nature that is both reflective of, and in turn contributes to, the overall climate conditions. Wade (1979) confirms the powerful force of the Thompson River during spring freshet, presenting historical accounts of the building of the bridge across the river at Cook's Ferry (later known as Spences Bridge). The bridge was first completed in the spring 1864, only to be completely swept away by the spring freshet (Wade 1979). The bridge was re-built by the following year, and stood until the "extraordinary freshet of 1894, which overwhelmed and utterly destroyed every vestige of it." The bridge was ultimately rebuilt, for the third time, as a "more substantial" structure (Wade 1979). It appears that the Thompson River flow, controlled primarily by melting of the snow pack on a basin-wide scale, contributes significantly to the activity of the large translational landslides in the Ashcroft Thompson River corridor.

6.2 Risk and Resilience

In seeking to ultimately quantify the hazard posed by the Ashcroft Thompson River landslides, the preceding discussion relates the translational slide movements to regional scale climatic influences as a potential proxy for a future landslide frequency analysis. The dynamic relationship between the slide movements and the regional climate conditions underscores the complexity of the landslide phenomena. The landslide movements suit Renn's (2008) definitional of a complex system, in which "the causal relationship forms a multifaceted web where many intervening factors interact to affect the outcome."

Within the scientific community, risk is generally expressed as the product of the hazard (likelihood of an adverse event) multiplied by the consequences. Risk however, is not necessarily a static value, but rather a dynamic expression reflecting fluctuating levels of the likelihood of an adverse event and its consequences. The seasonal and long-term variability of the identified climatic influences is such that the level of the hazard posed by the Ashcroft Thompson River landslides will inevitably vary over time, both seasonally and potentially in the long-term, due to global climate change. The potential consequences of a landslide, too, will have a dynamic component, in that the impacts will last for an unspecified period of time, depending on the cross-section of stakeholders affected and their ability to cope with the outcomes. This time dimension of risk is acknowledged in the concept of resilience, which may be understood as the collective ability to anticipate, cope with, resist, and recover from the impact of a natural hazard (Hufschmidt et al. 2005).

We may, therefore, view scientific advancements in understanding of the Ashcroft Thompson River landslides as a contribution towards increased ability to anticipate potential landslide movements. However, acknowledging that not all disasters can be predicted, nor avoided, it is equally important to address the ability of the system to respond to and recover from an adverse event. The resilience paradigm emphasizes the role of individuals and communities in preparing for and responding to emergency situations (Brunner and Giroux 2009). Rooted in the work of ecologist C.S. Holling (1979), resilience acknowledges the existence of multiple dynamic states of equilibrium, wherein adaptation, learning and self-organization play important roles (Frommer 2013). For complex risk phenomena such as the Ashcroft Thompson River landslides, which impact and are in turn affected by the social and natural environments in which they occur, improved stakeholder engagement holds promise for linking scientific knowledge and anticipation with more traditional forms of learning to improve the overall resilience of the system. While scientific knowledge typically consists of synchronic, short term observations of natural phenomena such as landslides, stakeholder engagement has the potential to tap into the local, indigenous and traditional forms of knowledge and social memory which are diachronic and long term.

Opportunities exist for more effective stakeholder involvement in the context of the Ashcroft Thompson River landslides. A multi-stakeholder workshop, sponsored by Transport Canada, was held in the village of Ashcroft on April 26, 2011, to elicit public input and provide information concerning the Ashcroft Thompson River landslides. The Summary Report underscored the clear consensus among participants that more effective communication amongst stakeholders is needed, with a compelling argument that better communication would enhance trust and collaboration between parties (BGC Engineering Inc. 2012). Effective stakeholder engagement in the context of natural hazard risk governance may serve both the democratic purpose of gathering a community perspective on risk tolerance, and also encourage citizens to take more responsibility for emergency preparedness by virtue of engaging community members in the discussion of risks that affect them (Wachinger et al. 2013). That is, public involvement in this type of setting may function not only to legitimize risk tolerance decisions but also to empower those affected by them (Tappenden 2014).

7 CONCLUSIONS

The preceding discussion separated the existing large landslides in the Thompson River Valley south of Ashcroft into two types: rapid flows and (typically slow-moving) translational slides. Geologic factors predisposing the valley slopes to failure were identified, and triggering factors were presented which relate the flows to primitive irrigation methods and the translational slides to the climatic influences of regional snow pack and river discharge. Given the effects of climate change and the ever-increasing frequency of severe weather events, an understanding of the Ashcroft Thompson River landslides is more relevant today than ever before. It is recognized that the high-consequence, low-probability nature of a large landslide necessitates a flexible, resilient response by all stakeholders. It is hoped that a better understanding of climatic influences on landslide activity will facilitate early-warning of impending landslides and empower all stakeholders to improve their level of understanding and ability to prepare for, and cope with, the potential impacts of a large landslide.

ACKNOWLEDGEMENTS

Dr. D.M. Cruden and Dr. C.D. Martin are thanked for their helpful comments during the preparation of this paper. Funding for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), Alberta Innovates Technology Futures, and the University of Alberta.

REFERENCES

BGC Engineering Inc. 2012. Ashcroft Thompson River landslides evaluation of factors influencing risks of landslide hazard - Phase 1: Data gap analysis, stakeholder workshop report and Phase 2 plan.

Bishop, N.F. 2008. Geotechnics and hydrology of landslides in Thompson River Valley, near Ashcroft, British Columbia. MSc Thesis, Earth Sciences, University of Waterloo, Waterloo, ON.

Bishop, N.F., Evans, S.G., Petley, D.J. and Unger, A.J.A. 2008. The geotechnics of glaciolacustrine sediments and associated landslides near Ashcroft (British Columbia) and the Grande Coulee Dam (Washington). *In* Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management, Presse de l'Université Laval, Quebec.

Brunner, E. and Giroux, J. 2009. Examining resilience- a concept to improve societal security and technical safety.

Clague, J.J. 1998. Landslides and engineering geology of southwestern British Columbia. 8th Congress, International Association for Engineering Geology and the Environment. Vancouver, British Columbia, Canada.

Clague, J.J. and Evans, S.G. 2003. Geologic framework of large historic landslides in Thompson River Valley, British Columbia. Environmental & Engineering Geoscience, **9**(3): 201–212.

Environment Canada 2014. Archived hydrometric data- Thompson River near Spences Bridge, Stations 08LF051 and 08LF022 [online]. Available from http://www.wsc.ec.gc.ca/applications/H2O/HydromatD-eng.cfm [accessed 23 January 2014].

Eshraghian, A. 2007. Hazard analysis of reactivated earth slides in the Thompson River Valley, Ashcroft, British Columbia. PhD Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB.

Eshraghian, A., Martin, C.D. and Cruden, D.M. 2005. Landslides in the Thompson River Valley between Ashcroft and Spences Bridge, British Columbia. *In* Landslide risk management: Proceedings of the International Conference on Landslide Risk Management. *Edited by* O. Hungr, R. Fell, R. Couture, and E. Eberhardt. Taylor & Francis Group, London. pp. 437–446.

Eshraghian, A., Martin, C.D. and Cruden, D.M. 2007. Complex earth slides in the Thompson River Valley, Ashcroft, British Columbia. Environmental & Engineering Geoscience, **13**(2): 161–181.

Evans, S.G. 1982. Landslides and surficial deposits in urban areas of British Columbia: a review. Canadian Geotechnical Journal, **19**(3): 269–288.

Evans, S.G. 1984. The 1880 landslide dam on Thompson River near Ashcroft, British Columbia. *In* Current Research, Part A, Geological Survey of Canada Paper 84-1A. pp. 655–658.

Frommer, B. 2013. Climate change and the resilient society: utopia or realistic option for German regions? Natural Hazards, **67**(1): 99–115.

Government of Canada 2014. Calculation of the 1971 to 2000 climate normals for Canada [online]. Available from http://climate.weather.gc.ca/climate_normals/normals_documentation_e.html

Hodge, R.A. and Freeze, R.A. 1977. Groundwater flow systems and slope stability. Canadian Geotechnical Journal, **14**(4): 466–476.

Holling, C.S. 1979. Resilience and stability of ecological systems. Annual Review of Ecology, Evolution, and Systematics, **4**: 1–23.

Hufschmidt, G., Crozier, M. and Glade, T. 2005. Evolution of natural risk: research framework and perspectives. Natural Hazards and Earth System Science, **5**(3): 375–387.

Lum, K.K.Y. 1979. Stability of the Kamloops Silt Bluffs. MASc, University of British Columbia, Vancouver, British Columbia, Canada.

Macciotta, R., Hendry, M., Martin, C.D., Elwood, D. and Lan, H. 2014. Monitoring of the Ripley Slide, Thompson River Valley, British Columbia. *In* Kingston, Ontario, Canada.

Popescu, M.E. 1994. A suggested method for reporting landslide causes. Bulletin of the International Association of Engineering Geology-Bulletin de l’Association Internationale de Géologie de l’Ingénieur, **50**(1): 71–74.

Porter, M.J., Savigny, K.W., Keegan, T.R., Bunce, C.M. and MacKay, C. 2002. Controls on stability of the Thompson River landslides. *In* Proceedings of the 55th Canadian Geotechnical Conference: Ground and Water: Theory to Practice, Niagara Falls, Ont. pp. 20–23.

Province of British Columbia 2014. Archived manual snow survey and automated snow pillow data [online]. Available from http://bcrfc.env.gov.bc.ca/data/

Quigley, R. 1976. Mineralogy, chemistry and structure of the Penticton and South Thompson silt deposits. Faculty of Engineering Science, University of Western Ontario, London, Ontario.

Quinn, P., Hall, I., Porter, M.J. and Savigny, K.W. 2012. Ashcroft Thompson River landslides- watershed scale controls. *In* Proceedings of the 65th Canadian Geotechnical Conference, Winnipeg, Manitoba, Canada.

Renn, O. 2008. Risk Governance- Coping with Uncertainty in a Complex World. Earthscan, London.

Ryder, J.M. 1976. Terrain Inventory and Quaternary Geology, Ashcroft, British Columbia.

Stanton, R.B. 1898. Great Land-slides on the Canadian Pacific Railway in British Columbia. The Institution of Civil Engineers.

Stark, T.D. and Eid, H.T. 1994. Drained residual strength of cohesive soils. Journal of Geotechnical Engineering, **120**: 856–871.

Tappenden, K.M. 2014. The district of North Vancouver’s landslide management strategy: Role of public involvement for determining tolerable risk and increasing community resilience. Natural Hazards, In Print. http://link.springer.com/10.1007/s11069–013–1016–0.

Wachinger, G., Renn, O., Begg, C. and Kuhlicke, C. 2013. The risk perception paradox-Implications for governance and communication of natural hazards. Risk Analysis, **33**(6): 1049–1065.

Wade, M.S. 1979. The Cariboo Road. The Haunted Bookshop: Victoria, British Columbia, Canada.