IMPACTS OF CLIMATE CHANGE ON DEBRIS-FLOOD MAGNITUDE IN THE SOUTHERN ROCKY MOUNTAINS, CANADA: INITIAL FINDINGS

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ABSTRACT
Debris floods have led to the majority of economic loss incurred during the June 19 to 21 historic rain storm that affected much of southwestern Alberta and adjacent southeastern BC. Debris floods are characterized by unusually high volumes of bedload sediment transport, partially recruited from the watershed's channel network, and partially through bank erosion along the proximal fan reaches. As climate change raises the potential for an intensified hydrologic cycle in many regions worldwide, we attempt to quantify future changes in sediment volumes due to changes in extreme rainfall. We extracted rainfall quantiles for 10, 20, 50 and 100-year return periods for RCPs 4.5 and 8.5 using six global circulation models. Specific locations on the southwestern, southeastern and northern portion of the study area were analysed with respect to projected changes in rainfall during the key debris flood season (June to September). Our initial findings show that substantial changes are expected by mid century. Further increases of rainfall extremes emerge towards the latter part of the century though the model predictions are not unanimous. RCP 8.5 scenarios do not necessarily result in significantly higher rainfall extremes than the RCP 4.5 scenarios as moisture limitations in some areas may balance the higher theoretical moisture carrying capacity in a warmer climate. An empirical relationship that correlates extreme storms to the volume of sediment likely to be delivered to receiving fans was applied to a debris-flood prone watershed near Canmore. The analysis suggests an increase of approximately 50% in expected sediment volume transported in a 100-year return period 72-hour rainstorm could be expected by the 2080s (2071 to 2100). For comparison, this increase in sediment volume implies that the original 100-year return period debris flood would become a 20-year return period debris flood by the 2080s. This finding strongly supports integration of climate change consideration into the design of structures aimed to capture sediment, or to design flexibly to allow addition of sediment basin capacity during the later stages of the structure's design life.

RÉSUMÉ

Les inondations de débris ont entraîné la majorité des pertes économiques subies pendant la tempête de pluie historique du 19 au 21 juin qui a touché une grande partie du sud-ouest de l'Alberta et du sud-est de la Colombie-Britannique. Les débordements de débris se caractérisent par des volumes inhabituellement élevés de transport de sédiments chargés en lits, en partie recrutés dans le réseau de chenaux du bassin versant, et en partie par l'érosion des berges le long des bras proximaux de la digue. Comme le changement climatique augmente le potentiel d'intensification du cycle hydrologique dans de nombreuses régions du monde, nous tentons de quantifier les changements futurs des volumes de sédiments dus aux changements dans les précipitations extrêmes. Nous avons extrait des quantiles de précipitations pour les périodes de récurrence de 10,20,50 et 100 ans pour les RCP 4.5 et 8.5 à l'aide de six modèles de circulation globale. Des endroits précis du sud-ouest, du sud-est et du nord de la zone d'étude ont été analysés en ce qui a trait aux changements prévus des précipitations pendant la principale saison d'inondation des débris (de juin à septembre). Nos premières conclusions montrent que des changements substantiels sont attendus d'ici le milieu du siècle. D'autres augmentations des extrêmes pluviométriques émergent vers la fin du siècle, bien que les prévisions du modèle ne soient pas unanimes. Les scénarios RCP 8.5 n'entraînent pas nécessairement des extrêmes pluviométriques significativement plus élevés que les scénarios RCP 4.5, étant donné que les limitations d'humidité dans certaines régions peuvent équilibrer la capacité théorique d'absorption d'humidité plus élevée dans un climat plus chaud. Une relation empirique qui met en corrélation les tempêtes extrêmes avec le volume de sédiments susceptibles d'être livrés aux ventilateurs récepteurs a été appliquée à un bassin versant sujet aux inondations de débris près de Canmore. L'analyse suggère une augmentation d'environ 50 % du volume prévu de sédiments transportés au cours d'une période de récurrence de 100 ans, soit 72 heures de pluie d'ici les années 2080 (2071 à 2100). À titre de comparaison, cette augmentation du volume des sédiments implique que l'inondation de débris de la période de récurrence initiale de 100 ans deviendrait une inondation de débris de la période de récurrence de 20 ans d'ici les années 2080. Cette constatation appuie fortement l'intégration de la prise en compte du changement climatique dans la conception des structures visant à capter les sédiments ou à concevoir de façon souple pour permettre l'ajout de la capacité du bassin sédimentaire au cours des dernières étapes de la vie utile de l'ouvrage.

1 INTRODUCTION

The interest and legislative changes pertaining to climate change and their translation into practice are changing rapidly, spurned, in part, by the Paris accord that aims to keep global average temperature increase to less than 2 degrees Celsius below pre-industrial levels (UN Climate Change, 2014). Irrespective if this highly ambitious goal can be achieved, the effects of climate change on hydrologic processes can already be felt globally and will invariably change in coming decades (Huntington, 2006, Collins et al., 2013). This broadening realization has motivated many studies on higher order effects of global warming in the applied earth sciences in general (Davis et al. 2016) and landslide science specifically (Ho et al., 2017). However, quantitative treatments on the effects of climate change on these processes are still the exception and almost absent for debris floods that are a hybrid between landslides (debris flows) and floods (i.e. Jakob et al. 2015, Pierson, 2005). Debris floods, however, are one of the most destructive events in mountainous terrain as they can affect large fans with substantial development in any mountainous region of the world. One of the reasons for the observed under-researching is that the uncertainties in quantitative predictions of landslide response to climate change are proportional to the indirectness of the link between the two processes.

Global warming leads to temporal and spatial changes in rainfall distribution, intensity and magnitude, which in turn changes runoff behaviour and/or pore water pressures on hillslopes. Changes in runoff, in turn, change the shear stresses acting on the channel beds. More frequent intensive runoff events then imply a proportional exceedance of critical shear stresses leading to full bed mobilization, a process that appears to occur at shear stresses capable of mobilizing the D_{90} grain size. For supply-unlimited debris-flood prone systems, this implies increases in the sediment yield per unit time. Similarly, bank erosion and scour will increase proportional to the increases in runoff magnitude.

In June of 2013 a series of highly destructive debris floods occurred in the upper Bow Valley east of Banff and west of Seebee as well as in adjacent valleys of the Kananaskis. The Town of Canmore and the adjacent Municipal District of Bighorn were particularly affected due to the strong interface of urban development and associated municipal infrastructure on alluvial fans (Jakob et al., 2014). Major transportation arteries were interrupted for extended periods including the TransCanada Highway. Canmore and the MD Bighorn oversaw the production of detailed hazard and risk assessments. These local governments have since changed their policies to reflect the findings from such studies and avoid future losses while focusing on mitigation works on the highest risk creeks. Some of those works are either in construction or various phases of planning at the time of publication of this contribution. Several of the proposed structures capture sediment while allowing streamflow to continue and include some form of bank protection to reduce channel scour (Esarte, pers comm. 2018). As this paper demonstrates, the volume of debris mobilized past the fan apex and beyond depends substantially on the rainfall, and thus runoff volume, and upon exceedance of the critical bed shear stress threshold. In this paper we pose two fundamental, but related, hypotheses: First, we predict that the volume of debris floods for specific return period rainfall events will increase commensurate with increases in extreme rainfall volumes. Secondly, we argue that the frequency of debris floods will increase reflecting the projected increase in extreme rainfall and thus runoff events. Neither of these statements is new or particularly surprising. The novelty of our contribution is to quantify those changes using current downscaled climate models, empirical relationships between daily and subdaily rainfall from the region and correlations between runoff and mobilized debris volumes. We also use rainfall runoff models to estimate changes in peak discharges from those events as both peak flows and total debris volumes form input to numerical models applied in risk assessments.

This paper outlines the methods used and provide examples on how practitioners can begin to estimate the effects of climate change on changes in debris flood frequency and magnitude. Both can and should be integrated in modern hazard and risk assessments and ultimately inform the design, maintenance and operation of mitigation works that aim to capture debris or protect stream channel banks and beds. Other indirect processes and watershed changes such as beetle infestations and wild fires can occur that add layers of complexity in the effects of climate change saga to geomorphic processes in a watershed that are not included in this paper. Despite these limitations, our work provides a rational approach to assess climate change effects on debris flood activity.

3 STUDY AREA

The proposed the study area is given in **Error! Reference source not found.**. The study area is that part of the Bow River basin delineated by the Water Survey of Canada (WSC) sub-sub drainage areas (wscssda) located upstream of Canmore, AB. Specifically, this area is the amalgamation of the WSCSSDA drainage polygons 05BA (Headwaters Bow), 05BB (Upper Bow - Redearth) and 05BC (Spray), which has an area of 4773 km^2. This region is indicated as “Upper Bow” in **Error! Reference source not found.**. Also in the figure is a mesh (clipped to the extent of the Upper Bow) showing the resolution of the downscaled gridded climate data, which is 1/16-degree (roughly 30 km^2 for the latitudes of concern).

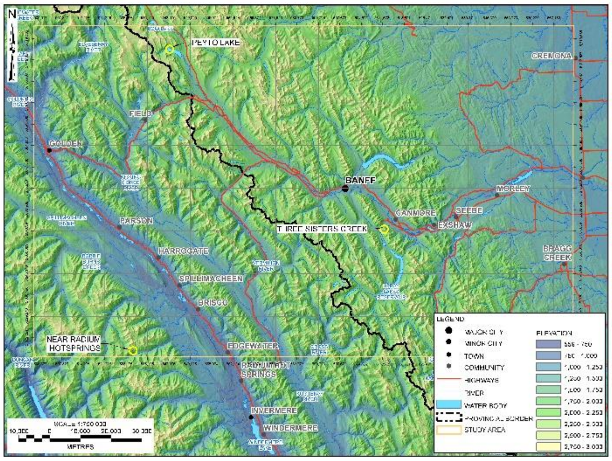

Figure 1. Study area of the upper Bow Valley

4 METHODS

During August 21-23, 2005 severe flooding occurred in a large area of northern Switzerland with significant morphological changes in stream channels (Jäggi, 2007). Similar to the June 2013 southeastern Albertan flood, this event was associated with more than 200 mm of rain within three days with corresponding return periods exceeding 100 years. Unlike the flood in southeastern Alberta, there was no snowmelt contribution in the Swiss storm. As many mountain creek hazards have been mitigated by catchment basins, the sediment volumes could be determined.

A database was subsequently created with 33 debris-flows and 39 fluvial sediment transport events, details of which are reported in Rickenmann and Koschni (2010). These authors used a variety of transport movement equations to compare modeled and predicted sediment transport volumes including those by Rickenmann (2001), Rickenmann and McArdell (2007), Hunziker and Jaeggi (1992), Recking *et al.* (2008), and D'Agostino *et al.* (1996). Rickenmann and Koschni (2010) found reasonable agreements between modelled and measured sediment volumes for channels with less than 5% gradient using the Meyer-Peter and Mueller equations. In contrast, for steeper channels, the observed sediment volumes transported by fluvial processes are over-predicted by bedload equations developed for steep channels.

Given the value of the Rickenmann and Koschni (2010) database, BGC analyzed the data further. First, BGC separated the debris-flow events from the mostly fluvial transport data. Watersheds with very large areas and correspondingly low gradients (< 1%) were also deleted from the dataset. These deletions provided a final dataset of 36 cases. Multivariate regression analysis was then applied to the log-transformed dataset to determine sediment volumes based on catchment area, rainfall volume, runoff coefficient, surface runoff and channel gradient. This analysis yielded the two following formulae:

$$logV_S = 0.753logV_R - 0.553,\ \ R^2 = 0.79 \qquad [1]$$

$$logV_S = -1.55 + 0.877logV_R + 0.019S,\ \ R^2 = 0.81 \qquad [2]$$

where V_S is the total sediment volume displaced and V_R is the total rainfall. The difference between the two formulae is the inclusion of channel slope S in Equation 2. However, since the increase in variance is very small (2%), the effect of slope appears small. Neglecting slope would not be appropriate had the entire dataset been used as that also includes debris flows. Therefore, the formula presented above is only appropriate for debris floods with channel gradients from approximately 2 to 24%.

In addition to the Swiss dataset, BGC created a dataset with 14 creeks in the Bow Valley[1] that experienced debris floods during the June 2013 storm. Sediment volumes deposited on each fan were estimated by comparing 2008 or 2009 LiDAR to 2013 LiDAR, as described in Section **Error! Reference source not found.**. Runoff volumes were calculated using the June 19-22, 2013 precipitation isohyet along with estimated snowmelt contributions for each watershed.

Both the Swiss and Bow Valley data were log transformed and a linear regression was applied to the combined data which resulted in Equation 3, which shows very little difference from the Swiss dataset regression. This combined regression was used in further analyses and yielded the following formula:

$$logV_S = 0.7375logV_R - 0.4493,\ \ R^2 = 0.78 \qquad [3]$$

where V_S is the total sediment volume displaced and V_R is the total runoff volume. The regression analysis of the combined data is shown in **Error! Reference source not found.** below.

As illustrated by **Error! Reference source not found.**, the rainfall-sediment relation observed in the Bow Valley correlates well with the Swiss dataset. This observation suggests that a relationship between runoff and sediment mobilized is location independent, as similar results were seen in the Rocky Mountains as in the Alps. While this relation appears to be location independent, it has not been verified for temporal independence. It is still unknown as to whether this relation holds for different storms of different magnitudes for individual creeks.

[1] This analysis was restricted to the general vicinity of Canmore and Exshaw.

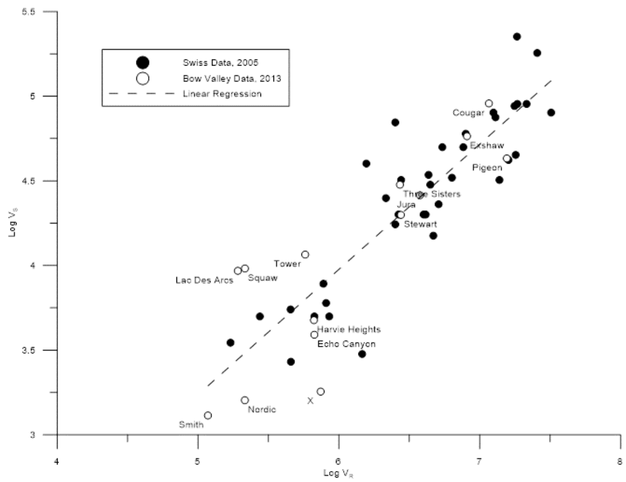

Figure 2. Log transformed sediment (V_S) and runoff (V_R) data from the Swiss and Bow Valley datasets complied by Rickenmann and Koschni (2010) and BGC, respectively.

4.1 Rainfall Data

The Rainfall analysis was based on statistically downscaled climate scenarios. These scenarios were produced for northwestern North America at a gridded resolution of 1/16-degree (or roughly 30 km^2) for the period of 1945-2100. The downscaled data are derived from Global Climate Model (GCM) projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), (Table 1) and station-based daily gridded climate data for northwestern North America produced by the Pacific Climate Impacts Consortium (PCIC). Statistical properties and spatial patterns of the downscaled scenarios are based on this gridded observational dataset.

Model	Institution
ACCESS1-0	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, AU
CanESM2	Canadian Centre for Climate Modelling and Analysis, CA
CCSM4	National Center for Atmospheric Research, US
CNRM-CM5	Centre National de Recherches Météorologiques and Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, FR
HadGEM2-ES	Met Office Hadley Centre, UK
MPI-ESM-LR	Max Planck Institute for Meteorology, DE

Table 2. List of CMIP5 global coupled climate model scenarios analyzed in the present study

Data from the GCM sources (see Table 2) was statistically downscaled to the target resolution using Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ; see Werner and Cannon 2015 for more details). Note that for the historical 1945-2005 period, which was used to calibrate the downscaling models, statistical properties of the downscaled outputs will, by design, tend to match those of the gridded observational dataset. Gridded observations may differ from climate stations and biases may be present at high elevations or in areas with low station density (Eum et al., 2014).

The downscaled climate data only contains precipitation as opposed to rainfall specifically. Hence, our analysis was restricted to the summer period (defined as June-July-August-September), during which it was assumed that all precipitation occurs as rainfall.

4.2 Rainfall Indices

Rainfall quantiles (i.e. rainfall magnitude corresponding to a specific *T*-year event, where *T* is return period) were estimated from the downscaled climate projections. Estimation was conducted by fitting the Generalized Extreme Value (GEV) distribution (using L-moments) to the sample of annual maximum 24-, 48- and 72-hour duration summer rainfall events for each grid cell. These fitted GEV functions were then used to estimate the desired rainfall quantiles for each grid cell. The results for the 72-hour duration 100-year event are shown in **Error! Reference source not found.**. For this example, the rainfall quantiles are derived using historical gridded meteorological data, which is based on station observations interpolated to a 1/16-degree grid for the period 1945 to 2012.

In a climate change context this method is used to calculate rainfall quantiles for a baseline period (1971 to 2000) and two future periods, 2041-2070 (the 2050s, or mid-century) and 2071-2100 (the 2080s, or end-century). The impact of climate change on extreme rainfall is then quantified by comparing the baseline values to those projected for the two future periods. Although we anticipate that precipitation extremes under climate warming will be non-stationary, for model fitting we assume that the climate is approximately stationary during each the 30-year analysis periods (e.g. Kharin et al., 2007).

5 RESULTS

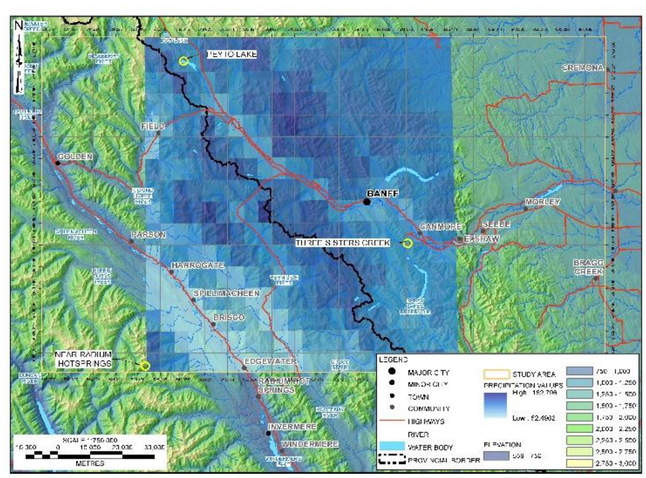

Figure 3. Magnitude of 100-yr 72-hour annual maximum rainfall based on observed data for the period 1945-2012.

Figure 4 shows a plot for baseline and projected 3-day precipitation for a 1/16th degree grid cell area boarding Three Sisters Creek. It also compares the RCP4.5 and RCP 8.5 for the 2050s and 2080s. The figure demonstrates that relatively minor changes are expected for low return period events compared to the baseline. Generally, the higher the return period, the more extreme the deviation between the baseline and projected changes. The figure also demonstrates that relatively little changes are projected between the baseline and RCP 4.5 for the 2050s. In contrast, changes will be much more pronounced for the 2080s signalling that substantial changes in rainfall extremes may occur later in the century. For example, the 100-year return period 72-hour rainfall for the baseline period is 65 mm (Table 2). For RCP 8.5 by the 2050s, this value is project to 102 mm and 91 mm, respectively. This constitutes a 56% and 40% change, respectively.

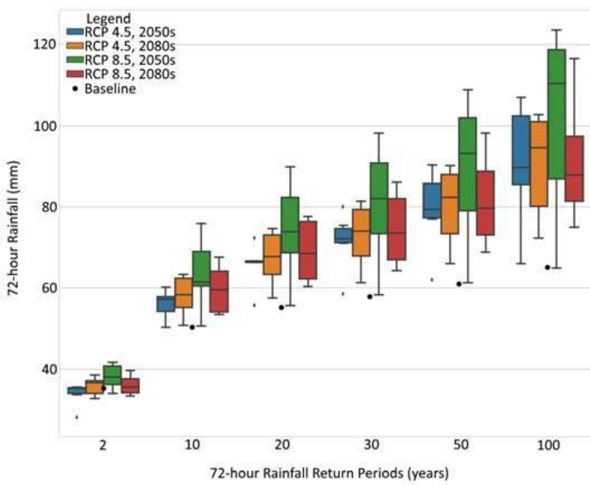

Figure 4. Projected changes in 72-hour precipitation volumes for 2050s and 2080s Canmore for various RCP scenarios and return periods.

The frequency values generated by the downscaled model ensemble do not correspond to those analysed by standard rainfall frequency analysis BGC (2014) using the closest station to Canmore with the longest records. This station (the Kananaskis station) produces much higher values for the 72-hour rainfall. Table 1 shows the frequency analysis for different return periods. This discrepancy between the downscaled rainfall data and those provided by flood frequency analysis of a nearby station may have several reasons. The most likely can be attributed to errors and bias in the downscaled data, which are inherited from the gridded observations.

Table 1. Precipitation frequency analysis for 72-hour duration at the Kananaskis weather station operational since 1939 (BGC, 2014).

Return Period (yrs)	Precipitation Volume (mm)
10	104
30	138
50	156
100	182

Arguably, the frequency analysis based on real station data is more accurate than a downscaled model ensemble. However, for this study, the percent changes are most relevant, and can be applied to the flood frequency analysis of the Kananaskis station.

Table 2. Projected rainfall volumes (in mm) and changes (in %) in 72-hour precipitation volumes for 2050s and 2080s for Canmore and other locations for various RCP scenarios and return periods. BL stands for baseline. RH is Radium Hotsprings. K FFA means Kananaskis rainfall frequency analysis.* original value from BGC's (2014) rainfall frequency analysis.

Location	**BL**	**RCP 4.5, 2050s**	**RCP 4.5, 2080s**	**RCP 8.5, 2050s**	**RCP 8.5, 2080s**
Near Canmore	65	91	90	102	91
% change		*39*	*39*	*56*	*40*
N. of Canmore	75	99	98	114	107
% change		*33*	*31*	*53*	*43*
W. of Canmore	62	83	85	94	87
% change		*33*	*36*	*51*	*40*
S. of Canmore	80	106	101	120	111
% change		*32*	*25*	*49*	*38*
% change avg.		**34**	**32**	**52**	**40**
Adjusted K RFA	182*	240	244	240	277
NW of RH	69	95	83	95	113
% change		*38*	*20*	*38*	*64*
Peyto Lake	83	95	99	102	114
% change		*12*	*16*	*20*	*34*

Intuitively, one would expect that the change from the RCP 4.5 to 8.5 should be positive due to the more pronounced radiative forcing. Equally, one might expect that the effects of climate change are more pronounced for the 2080s than for the 2050s. However, as this example shows, the projected 72-hour 100-year return period rainfall for RCP 8.5 for the 2080s has the same value as for RCP 4.5, suggesting substantial variability prevails even though the values are all consistently higher than the baseline period. For the next cell north, the percentage changes are similar and again suggesting that the most substantial changes are associated with RCP 8.5 for the 2050s.

The analysis for two other locations (one in the far west of the study area – near Radium Hotsprings) and one in the far north (near Peyto Lake) signal different trends and different percentage change. For example, near Radium Hotsprings, RCP 8.5 by the 2080s shows the strongest change from baseline conditions with 64% increases in the 72-hour 100-year return period rainfall. This is almost twice as much change than near Peyto Lake (34% change from baseline conditions). These results suggest that rather than relying on an individual cell, it may be more appropriate to analyse all four adjacent cells and then calculate the average from the adjacent cells and the centre cell. The following example illustrates how this method would be applied to a hypothetical development case at Three Sisters Creek.

6 EXAMPLE

A developer may wish to build homes, hotels and other infrastructure on the alluvial fan created by Three Sisters Creek (Figure 1). For the development to be approved and associated risk being reduced to tolerable, the developer may need to be responsible for the construction of a debris basin suitable to fully contain the sediment associated with a 100-year return period debris flood created by a 72-hour storm. The Town of Canmore may mandate that a sensitivity study be done for RCPs 8.5 and that the analysis be conducted for the 2050s. The nearby study cell-averaged percentage change from the baseline to the 2050s is 52% (Table 2). Using the Kananaskis rainfall frequency analysis, this implies that the baseline 3-day rainfall of 182 mm would change to 277 mm (Table 2). Applying Equation 3, we can calculate a sediment volume associated with a 100-year return period debris flood of (rounded) 22,000 m^3. This constitutes an increase of 36% from the original 16,000 m^3. Therefore, in absence of climate change considerations, by the end of the 21st century, and ignoring inherent uncertainties, one could expect that the basin may have been under-designed by 6000 m^3. The calculations were repeated for the spectrum of return periods considered. The changes of the frequency-sediment-volume curves are shown in Figure 5. Note that debris floods are unlikely for return periods below some 10 years.

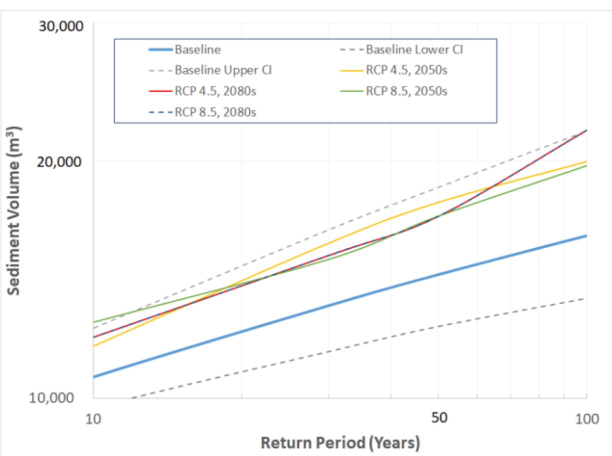

Figure 5. Frequency-sediment volume curve for Three Sisters Creek under baseline (blue) and RCP 8.5 scenarios for the 2050s (yellow) and 2080s (red). The RCP 4.5 and 8.5 for the 2080s are almost identical (blue dashed and red). The grey dashed lines show the confidence bounds for the baseline data.

Figure 5 also highlights some other aspects of interest. The difference between the RCP 4.5 and 8.5 is almost in distinguishable, but show a strong upward trend for higher return periods. It is also not guaranteed that a higher radiative forcing necessarily results in higher rainfall amounts. The upper confidence intervals for the 100-year return period event matches the 2080s projections for the RCP 4.5 and 8.5 scenarios. This implies that a prudent designer reliant on the upper confidence bound may have ended up with the same result as presented herein. This, however, is likely coincidental. It does, however, suggest that in absence of a climate-change specific analysis, design for the upper bound confidence interval may be a wise decision.

The above calculations suggest that for basins constructed now, and with an expected life time of 100 years or longer, an additional sediment allowance of 6000 m^3 should be factored into design. Given that the entire sediment frequency-magnitude curve is shifting upwards, it also infers that any structures designed to store sediment will need to be cleaned out more frequently which results in higher long-term maintenance costs.

7 DISCUSSION

This contribution, to the best knowledge of the authors, is the first of its kind that attempt to quantify changes in debris flood sediment volumes as a consequence of climate change. It is reliant on a number of key assumptions such as the validity and accuracy of the climate models used, the correctness of the statistical downscaling procedure, and the assumption that the relationship between rainfall volumes and sediment volumes holds for the return period range considered.

The analysis showed that changes in short-term extreme precipitation, and by extension changes in sediment volumes, are non-linear. Thermodynamic mechanisms which provide upper bounds on maximum credible precipitation through temperature-related moisture flux are balanced by horizontal moisture convergence and associated convective updrafts. These would change non-linearly in a warmer atmosphere (Sugiyama et al., 2010). The thermodynamic and dynamical processes likely occur in unison and their relative importance may differ by season as shown by Berg et al. (2009) in Europe.

The procedure outlined in this paper is only valid for alluvial bed supply-unlimited debris flood prone watersheds and cannot be transferred to debris flow prone watersheds that have different sediment transfer mechanisms to the fan areas. Nor does this method apply to supply-limited debris flood prone watersheds as there is not a quasi-infinite amount of erodible sediment available and Equation 3 no longer applies. For supply-limited debris flood watersheds, the method applied herein would likely result in exaggerated sediment volumes.

The design of debris flood mitigation works not only includes consideration of sediment volume but also peak discharge. Peak discharge cannot be estimated from the present methods. Projected climate change impacts on peak flows can be modeled via rainfall-runoff models that require input from high resolution forecasts in rainfall intensity. This is the subject of ongoing research. Similarly, projected increases in runoff are likely to lead to changes in bank erosion rates as well as scour, all of which can result in some damage to infrastructure that had been designed for a stationary climate.

Climate change will not only manifest itself in terms of changes in rainfall amounts. Pronounced warming will occur, for the region in question by some 2.6°C to 3.4°C by the 2050s and 3.2°C to 6°C by the 2080s, for the RCP 4.5 and 8.5 scenarios, respectively[2]. This may substantially alter the type and distribution of vegetation, as well as the frequency and severity of wildfires. Should the temperature increases be accompanied with either/or/and increase in the frequency and/or magnitude of wildfires, more sediment could be supplied via feeder channels to the main channel before vegetation has sufficiently recovered to regain similar root strength characteristics and canopy precipitation intercept. It could also imply higher runoff volumes as less moisture would be stored in the tree canopy or organic duff layer. This, in turn may lead to higher runoff coefficients and shorter times of concentration. However, the geomorphic effect of wildfires on forest fires quickly diminishes over time. The coincidence of an extreme rainstorm shortly (within years) of a stand-replacing wildfire is possible but given that those are joint probabilities of statistically independent events, their occurrence is believed to be rare.

8 CONCLUSIONS

This paper applies downscaling procedures for six GCM models to project precipitation intensities for variable time frames, durations and return periods in the south western Rocky Mountains of Alberta and southeastern mountain ranges of British Columbia.

It demonstrates that the emissions pathways and time frames strongly affect changes in precipitation and hence the potential volume of debris floods in supply unlimited basins. An example is presented that demonstrates that for the RCP 8.5 scenario and the 2080s time horizon, sediment volumes from Three Sisters Creek for a 100-year return period event could increase from 16,000 to 22,000 m^3. This implies that under this scenario, by the 2080s, the 100-year return period event will have diminished to roughly a 20-year event.

Much work remains to be explored in this field: The next research step entails determination on how climate change will affect the intensity-frequency-duration (IDF) relationship for the sites in question. The appropriate durations will then be selected to model climate change adjusted runoff coefficients and time of concentration in a rainfall-runoff model to determine how peak discharges change over time. Furthermore, the study will be expanded to all mountainous regions in British Columbia and Alberta and changes in rainfall volumes and peak flow changes contoured across those regions to obtain an understanding of the absolute differences between regions. This is important as more dramatic changes particularly in regions with a high density of developed alluvial fans (for example in the Okanagan or the Kootenay regions of BC) would then attract a focus for geohazard risk assessments.

[2] Estimated as ensemble mean change from 1971-2000 baseline period

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