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FLOOD HAZARD ASSESMENT APPROACHES FOR CLIMATE CHANGE

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ABSTRACT: This paper discusses three different flood hazard assessment approaches to account for climate change in Western Canada. The study areas are quite different in terms of affected community, physiographic conditions and layout, and each area will need to confront distinct flood hazards and flood management challenges. The first study evaluates flooding at small aboriginal communities in the Coastal Mountains along the Lillooet River. The Lillooet River has seen unusually large peak-flow increases over the past several decades and an adequate future degree of flood protection must be determined for these isolated communities. In this case, evaluation of future conditions relied on analysis of the historic stream flow record. The second example describes conditions at the City of Surrey on the south coast. With sea levels projected to rise by 1 m over the current century, increased flooding in this area will primarily be a function of rising seas, but increased rainfall, particularly during the winter, is also expected to strain internal drainage systems. In this case, evaluation of the effects of sea level rise on flood protection relied on continuous simulation of ocean levels and interior flood levels under current and projected future conditions. The third, and most complex case, involves flooding in the British Columbia Lower Mainland associated with potential future increases in peak flows on the Fraser River. Evaluation in this case relied on analysis of simulation results from work by the Pacific Climate Impacts Consortium in which a VIC hydrologic model of the Fraser River basin was run with driving data from multiple GCMs. The different assessment approaches and results will be compared and outstanding issues will be highlighted. The flood hazard assessment issues and approaches discussed in this paper are believed to be applicable to a number of locations.

Key Words: Flood Flow Estimates, Climate Change Impacts, Flood Management.

1. INTRODUCTION

It is widely recognized that climate change will impact flood flows, and the planning and design of both structural and non-structural flood mitigation measures need to consider potential flow increases over time. Dikes need to be engineered to withstand projected future flow and water level conditions or be designed with future upgrades in mind. Future development may need to be restricted in areas that will become more flood prone and structures flood-proofed to an appropriate extent based on their estimated lifespan.

In the province of British Columbia, in Western Canada, projections by global climate models for the end of the 21st century are for temperature increases of about 3°C and average annual precipitation increases in the range 6-17% (depending on the model) for the province as a whole (Rodenhuis et al 2009). As a result of warming, which implies a partial transition from snow to rain at elevations near the snowline, surface runoff is expected to increase in the winter. Also as a result of warming, we also expect the snowmelt freshet to occur earlier in the spring, and summers to become drier. Average annual peak flows may be reduced in large watersheds, as a result of diminished snowpack, but extreme floods could increase due to increased rainfall amounts and intensities. Smaller watersheds, dominated by rainfall events will also likely see increases in flood flows.

According to legislated guidelines (APEGBC 2012) recently introduced for British Columbia, flood hazard assessments need to account for potential increases in flood flows, although relatively little guidance is provided on how to approach this work. Broad regionalizations are to be avoided as basin topography, flow regimes, climatic zones and local conditions all may affect results. Where the scale of the hazard assessment project does not warrant detailed analysis, the guidelines suggest possible increases in the order of 10% in extreme spring flood flows by the end of the century. The guidelines further recognize that other factors such as land use change, forest fires and insect infestations may impact future flood flows.

We present three different approaches that we followed to address the specific issues of different projects where requested to evaluate future flood risk. The first study evaluates flooding at small aboriginal communities in the Coastal Mountains along the Lillooet River and relies on analysis of the historic stream flow record. The second example describes conditions at the City of Surrey on the south coast. With sea levels projected to rise by 1 m over the current century, increased flooding in this area will primarily be a function of rising seas, but increased rainfall, particularly during the winter, is also expected to strain internal drainage systems. A continuous simulation of ocean levels and interior flood levels under current and projected future conditions was performed. The third, and most complex case, involves flooding in the British Columbia Lower Mainland associated with potential future increases in peak flows on the Fraser River. Evaluation in this case relied on hydrologic and hydraulic modelling. The different assessment approaches and results are compared and outstanding issues highlighted. The flood hazard assessment issues and approaches discussed in this paper are believed to be applicable to a number of locations.

2. CASE 1. ANALYSIS OF PAST FLOW RECORDS AND EXTRAPOLATION OF THEIR LINEAR TRENDS INTO THE FUTURE

The non-stationarity of hydro-climatic time series caused by on-going climate change will mean that traditional methods of predicting extreme floods based on past flow records becomes increasingly unreliable. Historical records still provide useful information but adjusting the time series or limiting it to more recent years may improve the projection of future conditions. Short-term climatic phenomena, such as ENSO (stormy winters associated with La Niña phases) and the decade-length climate phases associated with the Pacific Decadal Oscillation, unrelated to climate change effects, may obscure or emphasize trends. Increasing peak flow magnitudes have been observed in several British Columbia river basins, yet other watersheds with long-term records do not display such trends. For the Lillooet River flood hazard assessment, a simplified approach analyzing past flow records was adopted.

The Samahquam, Skatin, and Xa'xtsa First Nations, with a combined population of a few hundred people, are located some 100 km north of Vancouver, British Columbia, and are accessible by gravel road. All three communities are experiencing population growth and existing housing has become insufficient. Flood hazard assessments were undertaken to prepare floodplain maps, evaluate appropriate flood construction levels and design improved infrastructure. In addition to flooding from the Lillooet River, the communities are also at risk from debris flows in tributary creeks.

Water Survey Canada Station 08MG005, Lillooet River near Pemberton, has been in operation near continuously from 1914. The gauge, located upstream of the three communities, has a drainage area of 2,160 km^2. The gauge record is unusual in that it shows a distinct increase in peak flows from the early 1980's onward. The reasons for this are unclear and may reflect climate change, climate cycles, land use change, logging activity or other factors. Instantaneous flow records begin in 1949. Maximum daily flows and instantaneous flows are plotted in Figure 1.

Over the past few decades, the 200-year design flow has been increased several times as ever larger floods have occurred. Of the twelve largest floods on record, all but three occurred after 1980. Statistically, a minimum of 40 years of data is generally required to estimate the 200-year flood (Watt et al 1989) and by limiting the frequency analysis to the 1970 to 2010 data, a 50% higher estimate was obtained than for the 1914 to 2010 record. Accordingly, the flood of record which occurred in 2003, previously estimated to have had a 200-year return period, would under the current flow regime have a return period in the order of 50 years.

By assuming that this increasing flow trend will continue linearly, a 200-year instantaneous design flow estimate was developed for year 2100. Flows are unlikely to increase linearly, but this approximate method is believed to provide a reasonable order of magnitude estimate of expected climate trends.

Lillooet River peak flows are a result of either: 1) rapid snowmelt plus rain in the spring/summer or 2) heavy rain storms in the late summer/fall or 3) rain-on-snow events in early winter. The highest flood flows tend to be produced by the latter type. A transitioning of the early winter from a nival regime to a mixed or rainfall-dominated regime seems like a possible explanation for the peak flow increases. For more detailed results, review of individual events and seasonal flood frequency analyses would be useful.

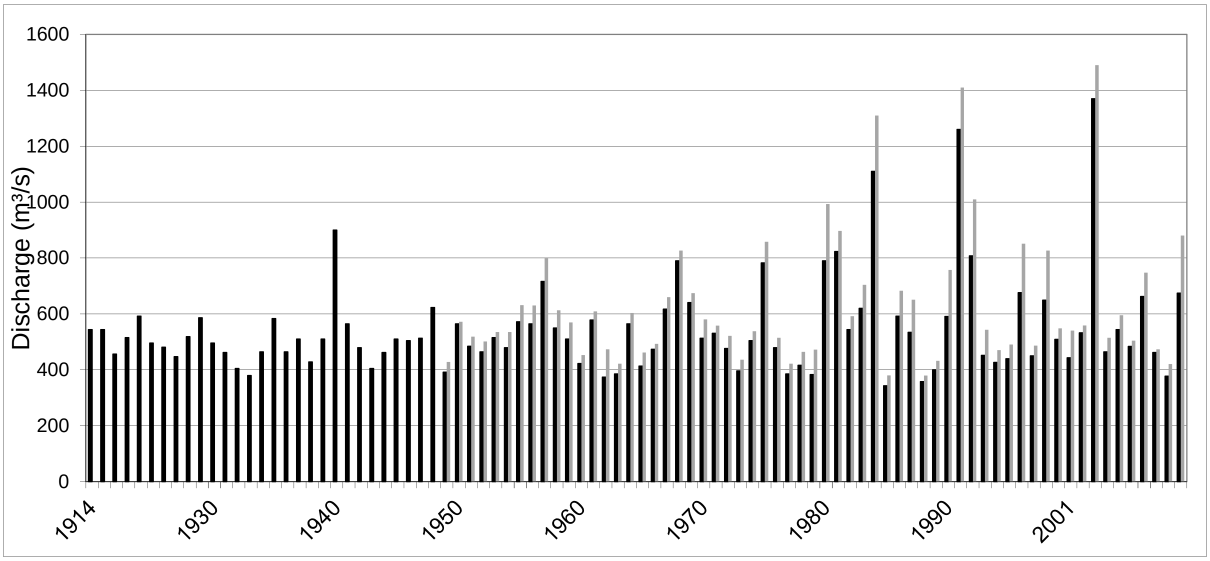

Figure 1. Lillooet River (Station 08MG005) annual maximum daily flows (black) from 1914 to 2010 and maximum instantaneous flows (grey) from 1949 to 2010.

3. CASE 2. CONTINUOUS SIMULATION APPROACH

The City of Surrey is located on the south coast of British Columbia, just south of Vancouver and north of the Canada/USA border. The greater part of the city is drained by the Serpentine and Nicomekl Rivers. These rivers, with a combined drainage area of about 300 km^2, originate in rolling uplands which have been heavily developed for residential and commercial use. The rivers then flow through flat, low-lying agricultural land to discharge into the Pacific Ocean. The lowland reaches of both rivers are extensively diked and their flood protection and drainage systems incorporate some 30 pump stations, 170 flap-gated culverts, and a complex network of flow storage areas, canals, ditches and spillways. At their outlets, the rivers drain into the ocean through flap-gated control structures ("sea dams"), with a sea dike protecting the floodplain from ocean flooding (Figure 2).

Flooding of the agricultural lowlands of the two rivers is typically the result of heavy rain or rain-on-snow events, in combination with high ocean tides and storm surge. Sea level rise and increased runoff associated with climate change are expected to have a significant impact on the Serpentine and Nicomekl basins in terms of floodplain extents and the adequacy of the existing flood protection and drainage infrastructure. Of particular concern is the increased risk of flooding at the lowland/upland interface where relatively modest increases in flood level could have a significant impact on residential and commercial properties.

Work for the City of Surrey was conducted in two phases. In the first phase, completed in 2012, analysis of the impacts of climate change focused on the effects of sea level rise on flood risk and the infrastructure improvements required to ensure a 200-year level of protection from flooding in the year 2100. The second phase of work, currently in progress, includes analysis of the impacts of both sea level rise and projected changes in rainfall regime under climate change.

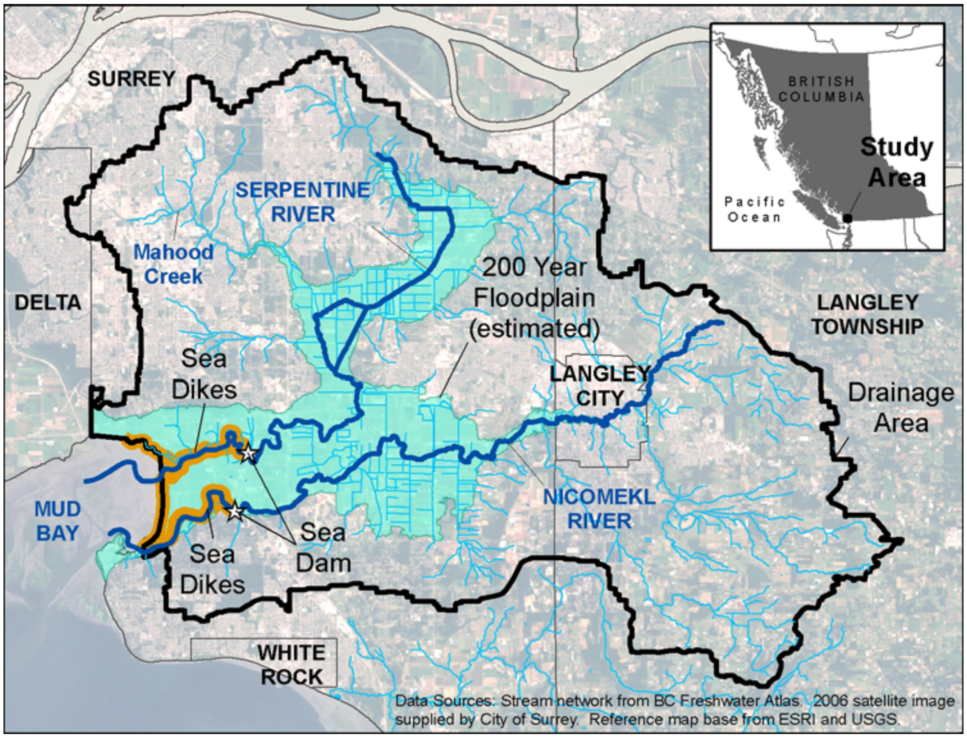

Figure 2. Serpentine and Nicomekl watersheds.

Inundation of the Serpentine/Nicomekl River floodplain is a function of:

- The volume and temporal distribution of storm rainfall and the watershed's hydrologic response to rainfall;
- The time varying sea level at the river outlets coincident with the storm event; and,
- The hydraulic response of the system (comprising floodplain storage and the various hydraulic infrastructure) to the hydrologic inputs and the sea level boundary condition.

This complex system cannot be analyzed directly by statistical means and conventional storm event analysis; i.e. it is not possible to state *a priori* what combination of sea level conditions and storm rainfall event will result in flood depths and inundation extent having an annual exceedance probability (AEP) of 0.5% (return period of 200 years). To avoid the difficulties of a direct statistical joint probability analysis, a continuous simulation approach was adopted whereby long-term (approximately 50-year) simulations were conducted of the system's hydraulic performance, and the simulated annual peak floodplain water levels were subject to conventional frequency analysis. The approach involved the following steps:

1. An approximately 50-year time series of historic hourly rainfall data was assembled and used as input to an HSPF hydrologic model to produce 50-year time series of simulated hourly runoff under current (nominally year 2010) land use conditions.

2. A hindcasting approach involving reconstruction of historic tide records and numerical modeling of historic storm surge and wind setup was used to develop hourly time series of ocean water levels for the same approximately 50-year time period.

3. The runoff and ocean level time series were then used as boundary conditions for a HEC-RAS hydraulic model of the river and floodplain system, to produce 50-year time series of simulated water levels at selected floodplain locations.

4. Annual maximum water levels at key locations were extracted from the hydraulic model results. These were analyzed by conventional frequency analysis to estimate 200-year (0.5% AEP) floodplain water levels representative of current (year 2010) conditions.

Once simulation of current (year 2010) conditions had been completed, floodplain water levels representative of the year 2100 were estimated as follows:

5. The HSPF hydrologic model was modified to reflect projected future (year 2100) land-use, and future runoff time series were developed as in Step 1). In the first phase of work, future rainfall input was assumed unchanged from the historic record. The impacts of climate change on rainfall will be considered in the second phase of work, currently in progress.

6. A relative sea level time series representative of the year 2100 was developed considering the effects of absolute sea level rise and land subsidence. Provincial guidelines (Ausenco Sandwell 2011) call for an assumed 1 m absolute sea level rise between 2000 and 2100. The observed sea level rise from 2000 to 2010 was approximately 0.03 m. We therefore assumed a further 0.97 m of absolute sea level rise from 2010 to 2100. Land subsidence was estimated from historic observations at 2.5 mm/year. The net effect of absolute sea level rise and land subsidence results in a relative sea level rise of about 1.2 m from 2010 to 2100. This adjustment was applied to the historic sea level time series from Step 2) to represent conditions in 2100.

7. Steps 3) and 4) were repeated using the runoff and ocean level time series for year 2100 to produce revised 200-year floodplain water levels with climate change (sea level rise).

The following results stem only from the projected rise in mean sea level, and changes in land use, but do not yet consider projected changes in precipitation. Compared to 2010 conditions, the 200-year flood level is expected to increase by 0.9 to 1 m on the approximately 12 km reach of the Nicomekl River upstream from the sea dam. For the approximately 14 km reach of the Serpentine River upstream from its sea dam, the 200-year flood level will increase by about 0.7 m. Further upstream, the flood level increases taper off to 0.1 m, due solely to the impacts of land-use change on peak flows. Floodplain storage cells will see 200-year water level increases ranging from 0.1 to 0.4 m. The modelling assumed that all dikes and the sea dam structures would be raised to prevent overtopping.

In response to the projected sea-level rise over time, the return period for particular flood levels will change. Water levels with a current 72-year return period will on average occur annually by the year 2100. Similarly, the existing 200-year flood level will have an estimated return period of less than 2 years.

The continuous simulation approach adopted for this work provides a number of significant advantages over traditional event analysis:

- It explicitly captures the joint occurrence of extreme sea levels and severe rainfall events;
- It explicitly accounts for varying duration and amounts of rainfall (and runoff) and the matching of the rainfall with the sea level regime;
- It captures the shift in significance of longer lower intensity rainfall events under conditions of sea level rise. (Higher sea level implies that longer duration rainfall events become more important in defining interior flood levels since the sea dams are closed for longer periods of time); and,

- It avoids arbitrary assumptions about the coincidence or lack of coincidence of individual factors which would be required if a direct statistical analysis were attempted.

Some key assumptions of the approach are that:

- The joint occurrence of extreme sea levels and severe rainfall contained in the historic record will be maintained in the future; and,

- Future sea level time series can be adequately constructed by simply increasing all water levels by a uniform amount and scaling storm surges contained in the historic record.

The information developed provides a necessary first step to understanding the system's response to climate change and the infrastructure improvement which may be necessary to manage future flood risk.

4. CASE 3. GLOBAL CLIMATE MODELS AND HYDROLOGIC MODELLING

The Fraser River, with a drainage area of 233,000 km^2, is the largest river in British Columbia and flows from the Rocky Mountains to the Pacific Ocean. At Hope, roughly 165 km from the ocean, the river enters the Fraser Valley, where the land is largely developed and protected by a system of dikes. About 0.5 million people live on the floodplain and the direct damage from a major flood would be in the multiple billions of dollars if dikes failed. Indirect economic losses from disruption of commerce would far exceed direct costs (McLean et al 2007).

Fraser River floods are snowmelt generated and typically occur in May or June. However, near the ocean, the most severe flood conditions occur in the winter from a combination of high tide levels and storm surges. The 1894 flood of record has been adopted as the design flood and is estimated to have a return period in the order of 500 years.

Recently the provincial government commissioned a study to assess climate change impacts on Fraser River extreme flows. We took advantage of pre-existing work (Shrestha et al. 2012) where the VIC distributed hydrologic model was applied and calibrated for the Fraser watershed and was then run under downscaled climate change scenarios from different global climate models (GCMs). The authors of this work (Shreshta et al. 2012) kindly made their results available to us. We took each of their simulated time series of daily streamflows (covering the period 1950-2098) for the location of interest, Fraser-Hope, extracted the annual maxima, and fit an extreme value type III distribution to each of the following sub-period series of annual maxima:

- Period 1: 1951-2000
- Period 2: 2001-2049
- Period 3: 2050-2098

The annual maximum flow quantiles estimated for Period 2 and Period 3 of each scenario were compared to the corresponding quantiles of Period 1 simulated by the same GCM run. We studied all of the scenarios available, which represented eight GCMs of the CMIP3 dataset (i.e., the simulations that served as basis to the IPCC Fourth Assessment Report), with each GCM run under 3 different scenarios of future greenhouse gas emissions (known as A2, A1B and B1). The results of the quantile comparison were tabulated, and are plotted in the form of flood frequency curves in Figure 3 for two of the climate scenarios, which were chosen as adequate representatives of a "moderate change scenario" (HadCM B1 run 1) and an "intense climate change scenario" (HadGEM A1B run 1).

For the moderate change scenario (HadCM B1 run 1), the streamflow associated with a 100-yr return period is projected to increase by 17%, and for the 10,000-yr return period the increase was 24%. For the intense change scenario (HadGEM A1B run 1), these values are: 31% for the 100-yr return period and

68% for the 10,000-yr return period. Projected changes for small return period streamflows were small and were neglected in Figure 3.

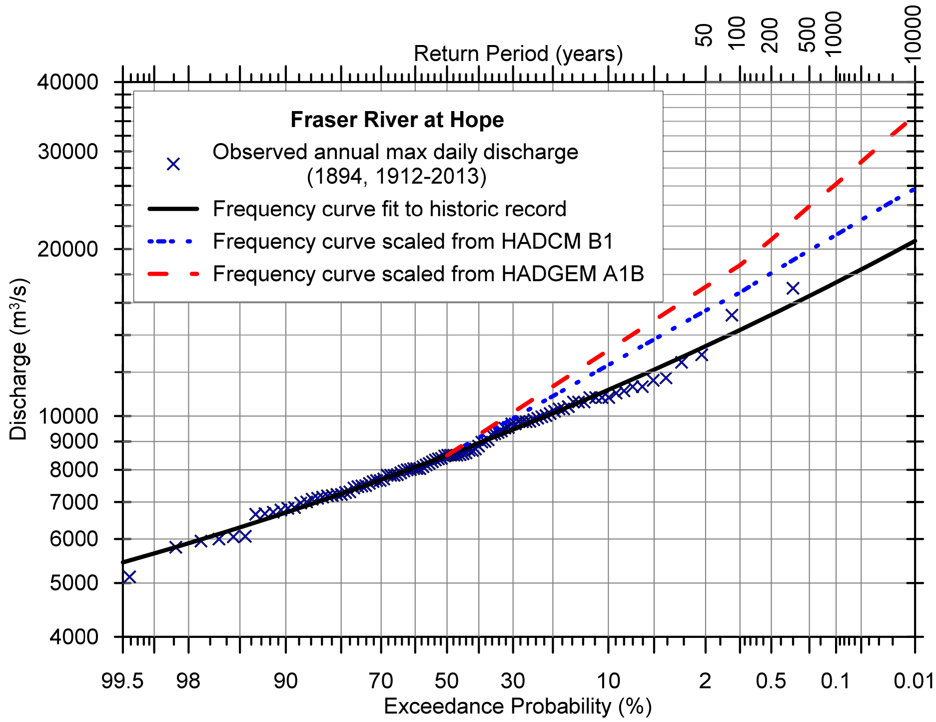

Figure 3: Historical flood frequency curve and projected curves for the latter half of the 21st century.

5. DISCUSSION

Climate change clearly has potentially serious implications for flood risk management. This paper has summarized three different approaches to quantifying the potential impacts of climate change on flooding: 1) reliance on trends in historic peak flow records; 2) continuous simulation of the effects of sea level rise on interior flooding; and, 3) hydrologic simulation using downscaled outputs from GCMs. All three approaches are subject to large and unquantifiable uncertainty. Nevertheless, the results have value in providing planners and decision makers with an initial basis for evaluating possible mitigation measures and for exploring their community's potential responses to this particular aspect of climate change.

Reliance on trends in historic peak flow data is the simplest of the three approaches explored but also the one with the weakest scientific basis in terms of projecting the impacts of climate change. There is no basis for assuming that trends in historic data will be maintained in the future and, in the Lillooet River study, the reasons for the observed trend are not known and further work would be required to establish a definitive linkage between observed trends and climate change. The approach adopted does however recognize the non-stationarity of the historic peak flow record and weights recent data more heavily in assessing flood risk.

The use of continuous simulation to investigate the impact of sea level rise on interior flooding is a conceptually straightforward application of existing techniques. The initial focus on sea level rise, one of the more certain aspects of a highly uncertain field, allowed us to separate the impact on interior flooding of sea level rise from that due to more speculative changes in extreme rainfall (the latter currently being investigated under a second phase of study). Continuous simulation provided a much improved understanding of the system's response to sea level rise, which will inform the future evaluation of coastal and interior flood protection investment decisions.

The Fraser River study which relied on hydrologic simulation using the downscaled outputs from GCMs is the most sophisticated of the three studies and in some sense the most problematic. The scenarios examined for this study indicate potential increases in the design flow on the Fraser River at Hope of up to 45%, a considerably larger increase than the nominal 10% increase in present design flows currently recommended in British Columbia to account for climate change impacts by the end of the century. The political, societal and economic implications of such large potential increases in flood risk have not yet been investigated, nor is it clear how these should be addressed given the extreme uncertainty in projections of future climate extremes.

To gain a wider perspective on issues related to uncertainty associated with extreme streamflow projections, the reader is referred to the analysis by Kundewicz et al. (2013) which is based on a vast body of literature, including the IPCC SREX report on climate extremes. The analysis by Kundewicz et al. (2013) concludes that "...presently we have only low confidence in numerical projections of changes in flood magnitude or frequency resulting from climate change". As stated at the outset, however, despite the uncertainty involved, quantification of the potential impacts of climate change on flood risk provides valuable initial information to begin an assessment of potential mitigation measures and community response.

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