Inclusion of Geomorphic Hazards in Floodplain Mapping and Land Use Regulation

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ABSTRACT

Floodplain maps for land use regulation are generally based on the hydraulic level and extent during a design flood event. Geomorphic channel changes during large and even moderate flood events can lead to equal or greater damages than seen from inundation alone. Geomorphic hazards, such as lateral channel migration, channel aggradation or degradation, channel widening, avulsion, sediment and debris loading, and debris damming with potential outburst floods, can result in erosion and undermining of dikes, infrastructure, and homes with complete loss of property and infrastructure.

We present how geomorphic hazards have been identified and incorporated into floodplain mapping and how this information has been used to inform regulators and public for land use regulation. An example of the approach applied during recent floodplain mapping projects in the province of British Columbia, Canada, is presented.

KEYWORDS: Floodplain mapping, geomorphic hazards, land use regulation

1 INTRODUCTION

Flood level and extent derived from local hydrology and hydraulics are the foundational information presented in the majority of floodplain maps for land use regulation. This information illustrates the inundation hazard but often neglects the geomorphic hazard. In dynamic riverine environments, geomorphic channel processes can have a sizable influence on the hydrology and hydraulics as well as impose additional hazards to property and infrastructure along the floodplain.

This paper presents an approach to evaluate geomorphic influence on flood hazards, illustrate the geomorphic information, and apply the information to land use regulation. Floodplain mapping conducted within British Columbia, Canada is used to demonstrate the methodology.

1.1 Background and Motivation

Geomorphic hazard analysis and understanding of the local river channel forms and processes are essential for floodplain mapping within a dynamic riverine environment to (1) ensure a comprehensive representation of present hydrotechnical hazards are presented in the floodplain maps and (2) to extend the useful life of the floodplain maps through evaluation and incorporation of the range of reasonably plausible future conditions. Upstream geomorphic events can affect floodplain hazards through rapidly and sizably altering the supply of sediment and debris (*e.g., sediment laden floods, debris floods, debris flows*) or the supply of streamflow (*e.g., landslide generated channel blockage and subsequent outburst*). Within a study reach flood hazards can be exacerbated by geomorphic processes such as deposition, aggradation, degradation, channel migration, erosion, scour, and avulsion. These can alter flood profiles, flood extents, or undermine, fail, or completely remove dikes, embankments, roads, rails, homes or other near-channel infrastructure. Flood profiles can also be influenced by downstream geomorphic processes that influence channel gradient, such as channel obstructions, alignment changes, or aggradation and channel encroachment. These geomorphic processes can occur during flood events less extreme than the typical design flood event yet can impose a greater hazard and loss than flood inundation on its own.

Due to the level of risk potentially imposed, geomorphic hazards are increasingly being considered during community and land use planning and subsequently incorporated into floodplain mapping. For example, geomorphic hazards are included in the soon to be released British Columbia floodplain mapping guidelines, are to be included in future publications under the Natural Resources Canada Federal Flood Mapping Guideline Series (NRCan and ECCC, 2023), and are already considered in the states of Colorado (Blazewicz et al., 2020), Washington (Rapp and Abbe, 2003), and Vermont (VT ANR, 2017).

1.2 Definitions

Geomorphology is the study of landforms and the processes that influence their development and evolution. Within this document, geomorphology is for the most part referring to fluvial geomorphology; that is, those landforms and processes related to rivers and streams.
Land use regulation refers to governmental laws and policies that control how land can be developed.
Development refers to issuance of building permits or approval of subdivision (dividing property into multiple lots).

2 ASSESSMENT METHODS

Assessment of geomorphic hazards often follows the approach of (1) delineate and characterize geomorphic study reaches; (2) identify and assess fluvial geomorphic hazards; and (3) characterize hydrologic and hydraulic implications. A generalized approach to these three steps is presented in the following paragraphs. Detailed refinement of the approach can become challenging when applied over a range of landforms, and risks producing guidance to land use regulation that lacks consistency and transparency. Focus is therefore directed towards a consistent meaning of hazard classifications instead of a rigid definition of the classification or approach.

2.1 Delineate and Characterize Geomorphic Study Reaches

This step involves segmenting the river into discrete reaches of similar form and process to establish a suitable scale for analysis. The delineation should sufficiently extend upstream and downstream to capture potential influences on flood hazard within the study reach. Characterization of the reaches should consider valley setting, channel characteristics, source and characteristics of sediment, anthropogenic influences, as well as the local geology, hydrology, and hydraulics. This step is conducted through review of maps, historic and present air photographs, field observations, regional hydrology and watershed delineation, and preliminary hydraulic modelling results (*e.g., relative elevation model*).

2.2 Identify and Assess Fluvial Geomorphic Hazards

Identify and assess the processes that may influence flood hazards through the characterized reaches from upstream to downstream. This should consider past events, present day hazards, and influence of reasonably foreseeable future conditions (*e.g., climate change, development, logging, forest fires*). Within the broader study area (*including upstream and downstream of the flood study reach*), identify locations of existing or potential obstruction (*e.g., landslide and debris flow paths, channel constrictions, steep bends, shallows, debris jams, and channel crossings)* and sources of sediment and debris that can contribute to obstructions. Evaluate their influence on hydrology (*e.g., outburst flood or bulking of flow*), flood profiles, or geomorphic hazards (*e.g., deposition, redirection of flow, or channel degradation*).

Delineate the hazard corridors for each geomorphic reach within the flood study. This often includes consideration of multiple geomorphic process corridors or hazard zones. Such as, (1) high hazard zone, where channel migration (*e.g., channel widening, erosion, or avulsion*) is reasonably plausible to reach during a single event or over 10 to 30 years if unmitigated; (2) moderate hazard zones, where most unmitigated channel migration is expected to remain over a time horizon of roughly 100 years; and (3) low hazard zones, where topographic, geologic, or ecological evidence suggests the river occupied this area under present hydroclimate conditions but the river is not expected to reach even over 100 year time horizon (*often defined as the modern valley bottom*).

In addition to the geomorphic process corridors along the study water course, adjacent geomorphic hazards may be identified and incorporated in the mapping. This can include steep banks along the river margins that extend above the mapped floodplain or geomorphic process corridors. These locations may warrant delineation if channel scour, erosion, or migration could undermine and destabilize these banks, particularly if the banks support developable land. Instead of assessing the geotechnical stability of these slopes, a geotechnical flag or warning may be used.

Alluvial fans adjacent to or intersecting the river floodplain are often delineated and where possible classified as active, non-active, or unclassified. Within steep mountain valley terrain, alluvial fans have historically been preferentially selected for development, as they often provide gently sloping ground above the surrounding floodplain. However, fans may be at risk of rapid increases in flow; deep overland flow of water, sediment, and debris; or sudden changes in flow paths. Due to this particularly extreme hazard and relatively small effort to delineate, it is often appropriate to delineate the adjacent fans.

2.3 Characterize Hydrologic and Hydraulic Implications

Hazards located upstream, downstream, or within the study reach that have the potential to influence the hydrology or hydraulics of the flood are communicated with the hydrologic and hydraulic modelling team to incorporate in model runs for the design or sensitivity simulations used to establish the hydraulic floodplain mapping extents and levels. This could include changes to flow, such as from an outburst obstruction, channel and crossing obstructions, or alternative channel geometries.

3 MAPPING OF GEOMORPHIC HAZARDS

Information from the geomorphic assessment can be used as supporting information for the development of the floodplain maps, presented as a separate set of geomorphic hazard maps, or presented within a geomorphic atlas. These three approaches are presented below followed by examples.

3.1 Floodplain Maps

Potential geomorphic events and hazards can be used as additional information to establish the typical floodplain map flood construction levels (FCL), flood extents, and setbacks. For example, flow, flow path, or channel geometry influenced by reasonably expected geomorphic conditions can be used to establish the conditions simulated to prepare the floodplain map or used in the sensitivity analysis where uncertainty is accounted for, such as with a safety factor, freeboard, or through use of probabilistic outputs.

Within the British Columbia context, a freeboard is applied to the calculated design flood profile prior to establishing the FCL and floodplain extents. The freeboard is used to account for local water level variations (*e.g., surge, superelevation, standing waves*) as well as uncertainty in the data and analysis. The freeboard may therefore take account for the uncertainty in channel geometry, streamflow, sediment supply, or obstructions within a geomorphically active environment; provided adequate study has been conducted to establish a suitable freeboard, appropriate setbacks, and understanding of residual risk. To maintain consistency the probability of incorporated geomorphic hazards should be of similar probability to the design flood event, i.e., the 200-year flood event in British Columbia. Events that are substantially less likely to occur, would typically not be included in the development of the floodplain map to guide land use regulation, at least not without careful consideration and communication of the risk and cost of using a sizably more extreme event.

3.2 Geomorphic Hazard Maps

Additional geomorphic context pertaining to the characterization, identification, and assessment of the hazards can be explicitly presented within a set of geomorphic hazard maps. These maps often present the various hazard corridors and potential sources of hazards. For example, geomorphic hazard maps can illustrate historic channel alignments, meander migration zones, avulsion routes, and other specifically identified geomorphic hazards. These maps illustrate the geomorphic hazard elements resulting from the analysis that have supported the development of the floodplain map. These maps are analogous to flood velocity and depth maps that occasionally accompany standard floodplain maps.

To maintain transparency and consistency the meaning of the hazard zones should be clear and appropriate to guide land use regulation. Continuing the with the British Columbia example;

High Hazard Zone supports the delineation of the no-build setback, indicating where most (>50%) of the unmitigated channel migration is expected in the near future (e.g. within 30 years). This hazard zone should also consider, and ideally include, the corridor required to allow for expected geomorphic processes without transferring risk to other properties.

Moderate Hazard Zone indicates areas where development may occur with the expectation that future mitigation may be required, that is areas outside the high hazard zone where most (>50%) of unmitigated channel migration is expected over the project lifetime (e.g., within 100 years).

Low Hazard Zone indicates areas where unmitigated channel migration may eventually occur but may still be suitable for development as it is outside of the high and moderate hazard zones.

3.3 Geomorphic Atlas

Further details can be provided in the form of a geomorphic atlas. Atlases provide the underlying data and analysis used to develop the geomorphic hazard maps. Atlases illustrate information such as historic air photos, delineated historic channel alignments (*i.e., banklines*), rates of channel migration, the delineated geomorphic reaches, avulsion pathways, alluvial fans, sediment sources, geologic anomalies, etc. Photographs are included to provide evidence of materials, grain size, sources of sediment and debris, active processes (*e.g., undermined banks, degradation, bar or island growth*), or past processes (*e.g., debris lobes, layered deposition, poorly sorted deposition*). Text is incorporated with the atlas to describe past events, present processes, potential future conditions (e.g., following development, forest harvesting, climate change, forest fire), and geomorphic interpretation for each geomorphic reach. Geomorphic atlases provide detailed information with a blend of text and figures well suited for storybook or other printed or digital formats. This level of detail is typically warranted in areas of high risk, complex geomorphic setting, or under substantial development pressure.

4 EXAMPLES

Following are some examples of floodplain maps prepared with consideration of geomorphic conditions. The first example (Figure 1) illustrates a typical floodplain map with the simulated design condition and freeboard applied to the resulting flood profile partially derived from the geomorphic analysis. The setback (yellow line) was added as the recommended no-build zone to limit loss and avoid notable transfer of flood risk. The setback was based on the greater of the floodway and the high geomorphic hazard corridor. For this example, the floodway was defined as the portion of floodplain that conveys the majority of flow during the design flood event, as determined using the hydraulic model. This figure also illustrates the delineated adjacent alluvial fans and geotechnical flags. The geotechnical flags were used to identify where the river potentially threatens high, steep adjacent banks.

The second example (Figure 2) illustrates a geomorphic hazard map that depicts high, medium, and low hazards zones as well as alluvial fans and geomorphic flags. The third example (**Error! Reference source not found.**) is a page from the geomorphic atlas, providing a sample of photographs, historic bankline delineation, and characterization of local sediments; elements often included in a geomorphic atlas.

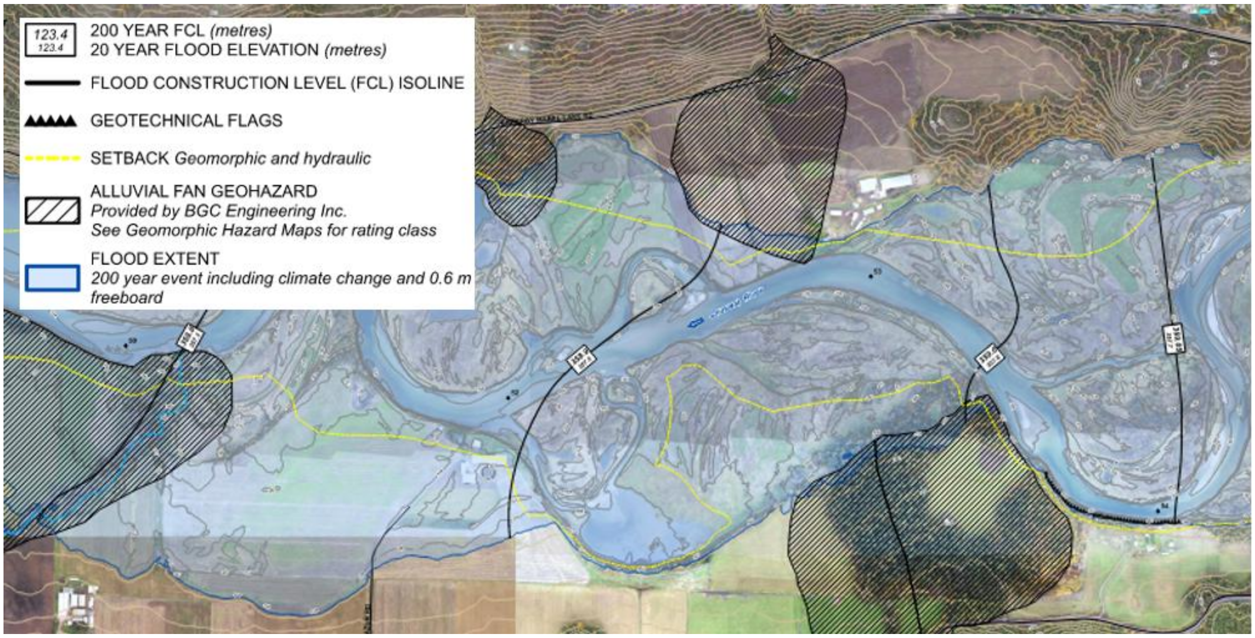

Figure 1: Sample floodplain map, Shuswap River, illustrating the flood extents (blue hatch), FCL (isolines with elevations in accompanying text box), no-build setback (yellow lines established from area of primary flow conveyance and high geomorphic hazard), and adjacent alluvial fans (diagonal hatching) (NHC, 2025)

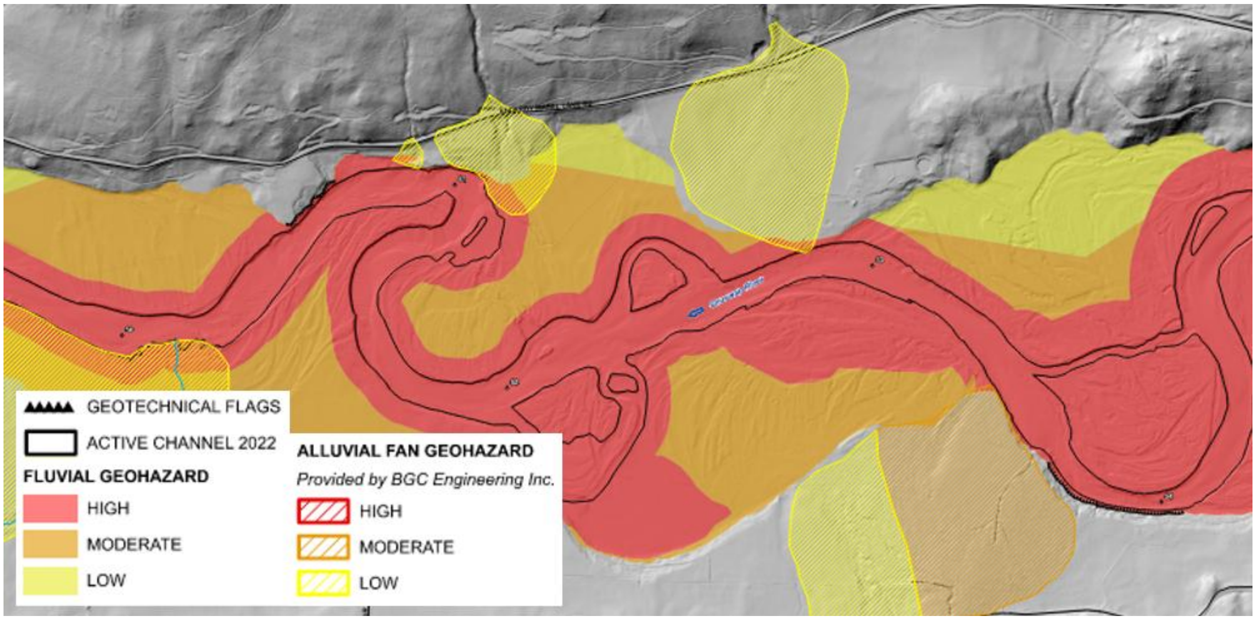

Figure 2: Sample geomorphic hazard map, Shuswap River, illustrating the classified geomorphic (colour filled) and alluvial (diagonal hatching) hazard zones for the corresponding floodplain map of Figure 1 with the high geomorphic hazard zone used in the development of the no-build setback of Figure 1, (NHC, 2025)

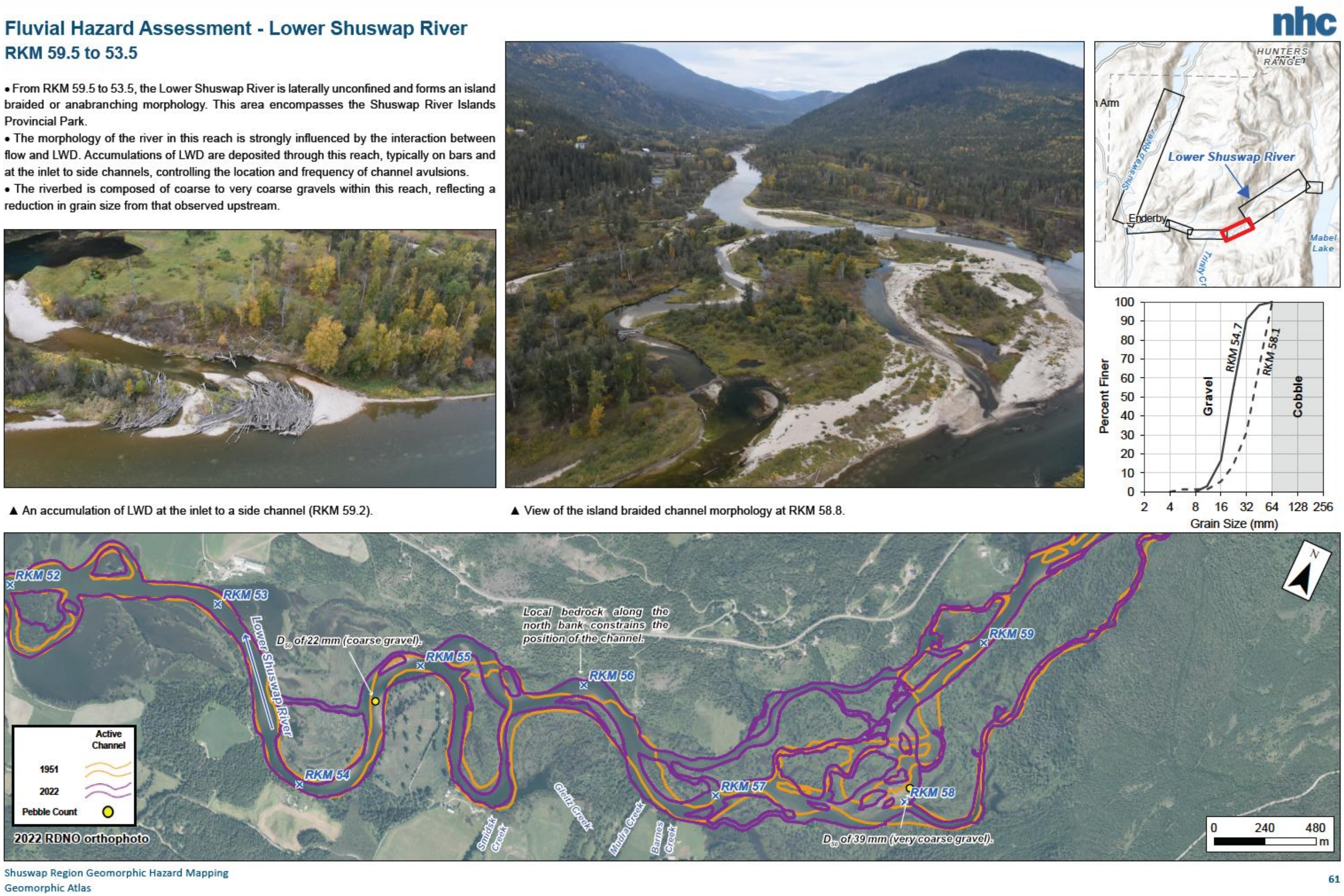

Figure 3: Sample geomorphic atlas, Shuswap River, illustrating the presentation of the underlying data and analysis used to establish the geomorphic hazard zones (NHC, 2025)

5 APPLICATION TO LAND USE REGULATION

Within a strict definition of land use regulation, maps and associated information can be used to define areas of fluvial geomorphic hazard in which future development should be constrained, controlled or avoided. In the British Columbia context, development is locally regulated by designating floodplains, establishing minimum FCL and watercourse setbacks (*no build zones*) (*e.g., using flood bylaws*), regulating the type of land use and development (*e.g., zoning*), and requiring site-specific engineering studies prior to development (*e.g., development permit areas*).

Within this context the study of geomorphic hazards must provide the delineated zones of hazard and suitable land use regulation to mitigate the hazard, such as zones of no-build, FCL, suitable type or density of industrial, commercial, institutional, or habitable development, or requirement for project specific engineering study. These zones of hazard and suitable development restrictions are typically illustrated as zoning maps, delineated development permit areas, and floodplain maps with FCL and setbacks.

Additional maps and information illustrating specific geomorphic and hydraulic hazards typically do not alter the land use regulation but can substantially improve the quality and consistency in conducting (*by developer*) and review (*by local government*) of project specific engineering studies to meet development requirements (*e.g., development permit area*) or secure an exemption (*e.g., from a flood bylaw*).

Adopting a broader definition of land use regulation, to incorporate community planning, can further benefit from additional maps and information on specific geomorphic and hydraulic hazards. Detailed information can support non-structural flood mitigation (*e.g., education, emergency planning, long-term retreat and relocations, sediment maintenance removal or nourishment*), structural flood mitigation (*e.g., justification for dikes, revetments, grade controls, sediment and debris basin*), establishment of environmental corridors (*e.g., riparian setback for present and projected future conditions*), and locating engineering works (*e.g., road and utility alignments*).

6 CONCLUSION

Geomorphic hazards can substantially alter or exacerbate flood hazards beyond that defined solely using hydrology and hydraulics. When mapping flood hazards along a dynamic river system the geomorphic setting and hazards must be considered in order to account for the range of present and future hazards. This paper presents a generalized approach to evaluate, assess, and map the geomorphic hazards in support of developing maps that are more inclusive and have a longer applicable life, and subsequently of greater value to support land use regulation.

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