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CALGARY FLOOD MITIGATION RESEARCH

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Abstract: The catastrophic 2013 Alberta flood that inundated downtown Calgary was Canada's most costly flood and second most costly natural disaster. The flood caused five deaths, required evacuation of 100,000 people, and resulted in $6B in estimated damages. Subsequently, the Province of Alberta and City of Calgary have undertaken extensive engineered mitigation works to minimize the consequences of future flood events. This paper begins with a brief overview of the flood, followed by research that has informed engineering design of proposed mitigation works; morphodynamic numerical modelling of Bow River, and physical modelling of the proposed Springbank Diversion on the Elbow River.

Morphodynamic models of Bow River were developed using the Delft3D package, including the reach from Bearspaw Dam to the Calgary Weir. Pre- and post-flood surveys of river bed bathymetry were used to calibrate morphodynamic predictions of the model. The model is being used to assess proposed flood mitigation and fish habitat enhancement works, such as manipulation of mid-channel bars.

A large scale (1:16) physical model of the river diversion structure for the proposed Springbank Off-Stream Reservoir Project was constructed at the National Research Council's (NRC) Ocean Coastal and River Engineering (OCRE) Research Centre in Ottawa. The model included structures to divert Elbow River flow from the main river channel to a constructed diversion channel, structures to regulate flow down-river, as well as realistic representation of the approach channel and floodplain. Designs of the diversion and main channel structures were studied and optimized based on model test results to ensure adequate conveyance and control during flood conditions as well as minimal blockage by sediment and woody debris. Natural woody debris was employed during model testing, which proved to be important for realistic model representation of debris jamming.

1 2013 ALBERTA FLOOD

The catastrophic 2013 flood in Alberta resulted in an estimated $6B in damage, Canada's most costly flood and second most costly natural disaster. The flood caused five deaths, required evacuation of 100,000 people, damaged more than 10,000 homes, and resulted in closure of 985 km of degraded roadway, including closure of many bridges (Government of Alberta 2014; Expert Management Panel 2014). The flood arose unexpectedly due to cyclonic orographic precipitation June 19-21 from a large storm event that stalled over the eastern slopes of the Rocky Mountains (Milrad et al. 2015; Pomeroy et al. 2016; Teufel et al. 2017; Milrad et al. 2017). Precipitation was heaviest in the foothills west of Calgary: recorded precipitation totals were 68 mm in Calgary, 200 mm in Canmore, and 345 mm in Burns Creek

(Pomeroy et al. 2016). This precipitation fell on remaining mountain snowpack at elevations above about 2000 m, which contributed to the flooding. The resulting flood zone extended from the US border to the Red Deer River valley north of Calgary (Pomeroy et al. 2016), thus high water in both Elbow River and Bow River contributed to flooding in the City of Calgary.

The Elbow River and Bow River peak discharges and associated return periods were estimated by Golder (2014). Discharge in Elbow River above Glenmore Dam peaked at 1240 m^3/s with an estimated return period 1:200 years. Elbow River flow was regulated through Glenmore Dam, thus discharge downstream of the dam peaked at 700 m^3/s with an estimated return period of 1:90 years. Bow River discharge in Calgary (below Bearspaw Dam but upstream of the confluence with the Elbow River) peaked at 1840 m^3/s. The return period of this flow has been estimated at 1:80 years. However, this return period estimate relies upon historical water marks from three ungauged larger floods in the late 19th and very early 20th centuries.

Calgary, like many other communities in Canada and around the world, has historically developed within a floodplain. As a consequence, portions of the city are inherently vulnerable to flood impacts from extreme events. The downtown core and several communities within the city built in low-lying areas were inundated in 2013 due to their vulnerability to surface flooding, high groundwater levels and/or sewer back-up. The flood zone included portions of Calgary's central business district, the Saddledome sports arena and the Calgary Stampede grounds, and several shoreline communities. The residential neighbourhoods along the Elbow River immediately upstream of the Bow River confluence were particularly affected.

A subsequent flood resiliency action plan for the City of Calgary (Expert Management Panel 2014) identified priority actions, including: assessment of review and update of official flood hazard maps, maintenance of a comprehensive flood risk database, and evaluation of social, economic, and environmental impacts of flood mitigation options. Several flood mitigation solutions are under consideration. For example, in partnership with the Province of Alberta, the off-channel storage of Elbow River flood water at the proposed Springbank Off-Stream Reservoir Project has been deemed a preferred solution to reduce flood flows. Furthermore, within the City of Calgary, critical river channel protection initiatives for the Bow and Elbow Rivers have and are being implemented to protect infrastructure, minimize flood hazards, and safeguard drinking water quality and natural habitat for fluvial species (Klohn Crippen Berger 2016). These channel works have included bank protection, bar reshaping, and channel cutting.

This paper reviews engineering research conducted in support of some of these proposed initiatives. First, three-dimensional morphodynamic numerical modelling of the Bow River is presented. Second, a large scale physical model study of the diversion structure for the proposed Springbank Off-Stream Reservoir Project is reported.

2 MORPHODYNAMIC MODELLING OF BOW RIVER

Central to flood risk mitigation is the need to understand river channel morphodynamics. The spatiotemporal distribution of sediment transfer through a reach of river determines channel morphology, which in turn, dictates flow resistance and river conveyance capacity, and thus has profound implications for flood hazard. Sediments are eroded from scour zones, where flow is converging, and are deposited in locations where flow is diverging. Erosion from the toe of a river bank can lead to bank failure, which can undermine infrastructure located in or near the river. Sediment transport and resulting channel morphology also determine the availability of riverine habitat, and thus have important consequences for water and habitat quality, fluvial biota, and species diversity.

Bed sediments in the Bow and Elbow Rivers were mobilized during the 2013 flood. Erosion was observed particularly at channel banks, and deposition resulted in new mid-channel bars (Klohn Crippen Berger 2016). Notably, deposition occurred upstream of some obstructing bridges. The City has identified increased flood hazard in some locations due to this sediment redistribution, and is currently in the process of designing flood mitigation strategies (Klohn Crippen Berger 2016). At the same time, the City recognizes that flood mitigation works may impact availability of habitat for fish and other aquatic and riparian organisms.

Morphodynamic models can be used to predict dynamic behavior and changes in river channel morphology by considering water and sediment transport, including erosion and deposition of boundary sediments. Morphodynamic models couple hydraulic models of river flow with prediction of sediment transport induced by flow, such that the flow boundary changes over time. Such a model can be used to determine morphological consequences of channel works, and thereby the optimal approaches to mitigate flood risks and enhance habitat.

Delft3D is open-source freeware, developed by Deltares, for 2D or quasi-3D morphodynamic numerical modelling. Given its accessibility, relative ease of implementation, incorporation of several bedload transport prediction equations, handling of bed material sorting in layers, and track record of successful application, Delft3D is widely used for 2D and 3D morphodynamic modelling of rivers, including meandering river bends (e.g., Parsapour-Moghaddam and Rennie 2014; Kasvi et al. 2015) and braided rivers (e.g., Williams et al. 2016; Mineault-Guitard et al. 2017; Mineault-Guitard et al. in review). Delft3D has also been used in combination with a number of fish habitat models to investigate river habitat quality for various aquatic species (e.g., Wang et al. 2012). The morphological module of Delft3D has been validated (Lesser et al. 2004), and is capable of simulating sediment fractions in multiple vertical layers, including non-cohesive and cohesive sediments (e.g. Sdqy et al. in review).

Several in-stream projects proposed by the City of Calgary for flood hazard mitigation and fluvial habitat augmentation have involved complicated 3-D flow fields and bank erosion. In order to understand these flow fields, potential bank erosion, and long-term consequences of in-stream channel works, we have been using the open-source freeware Delft3D software to analyze flooding and morphodynamic factors related to management of Bow River (Parsapour-Moghaddam and Rennie 2016a,b; Parsapour-Moghaddam et al. in review).

2.1 Study Reach and Boundary Conditions

The Bow River has a length of approximately 645 km, extending from Bow Glacier in Banff National Park to the confluence with Oldman River, defined as the start of South Saskatchewan River. The study area was a 50 km reach of Bow River as it passes through Calgary, extending from Bearspaw Dam to Policeman's Flats. The bankfull discharge for this reach is roughly 500 m^3/s, although the contribution of Elbow River flow to the middle portion of the study reach needs to be considered. Following Melethil (2015) we have been modelling the 2013 flood between June 19 and June 26 using 12 hour increments of the measured Bow River and Elbow River flows, as well as associated downstream water levels as determined by the City of Calgary's calibrated 1D HEC-RAS model.

Detailed pre-flood channel bathymetry of Bow River was surveyed by the City of Calgary in 2010. A post-flood survey was also conducted in 2013 (Golder Associates 2015). We interpolated the raw survey data to create pre-and post-flood digital elevation models (DEMs) from which Delft3D boundary meshes were generated. Furthermore, the pre- and post-flood DEMs were compared to determine a DEM of difference to ascertain the degree of morphodynamic channel change during the flood. Based on bathymetric output of 2013 flood model runs starting from the pre-flood DEM, the DEM of difference has been utilized to assess morphodynamic model predictions of channel change during the 2013 flood.

Models have been generated for several different sub-reaches. We conducted both 2D and 3D morphodynamic modelling on a short portion of the downtown core as well as the upper half of the reach between Bearspaw and the Calgary Weir just downstream of the Elbow River confluence (Parsapour-Moghaddam and Rennie 2016a,b). Most recently we have assessed 2D hydrodynamics in greater detail in the short downtown reach (Parsapour-Moghaddam et al., in review).

2.2 Sensitivity Analyses

Sensitivity analyses were performed on a large range of model parameters, including grid resolution, 2D versus 3D modelling, number of vertical layers employed in 3D modelling, eddy diffusivity, horizontal eddy viscosity, roughness, sediment transport formulation, and the influence of explicitly modelling bridge openings (Parsapour-Moghaddam and Rennie 2016a). Many of these analyses focussed on results observed in the Home Road Bend where an initial modelling attempt by Melethil (2015) displayed unrealistic scour in the inner bend and deposition in the outer bend that was not observed during the 2013 flood. The model proved to be most sensitive to roughness, horizontal eddy viscosity, and sediment transport formulation; even small changes in these parameters can impact the simulated results of sedimentation and erosion. It was found that use of spatially distributed roughness and horizontal eddy viscosity allowed for best match with observed erosion and deposition patterns. Lastly, dry points were added at bridge pier locations in the model reach, including at the three bridges in the studied bend. The resulting model suitably predicted erosion at the outer bank and deposition at the inner bank of Home Road Bend (Figure 1). Furthermore, it was found that generation of a better Delft3D model mesh can improve results (Parspapour-Moghaddam and Rennie 2016b). Specifically, grid cells should have aspect ratio close to 1.0 and the model mesh elevations should faithfully represent the surveyed bathymetry data. Finally, 2D modelling of the downtown reach confirmed the model is significantly sensitive to roughness and horizontal eddy viscosity (Parsapour-Moghaddam et al., in review). Furthermore, finer grid resolution with cells averaging 150 m^2 was found to be required to reproduce detailed hydrodynamics in the 2D model.

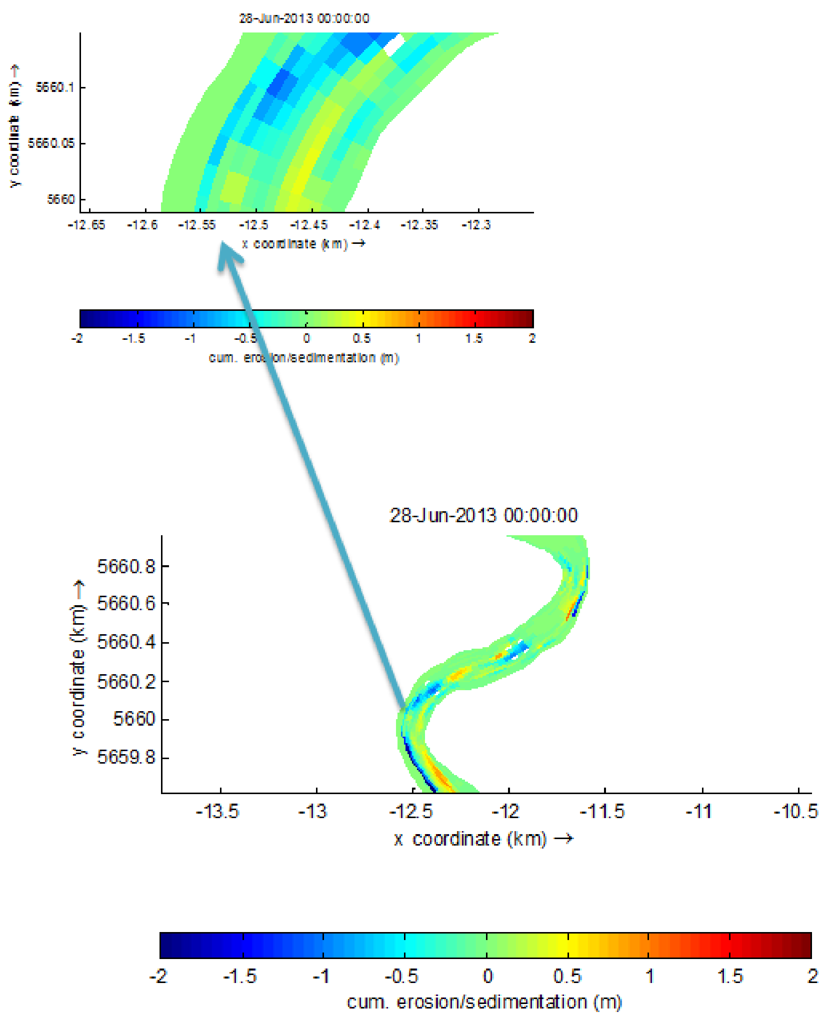

Figure 1: Predicted erosion and deposition in Home Road Bend during 2013 flood using a two-layer 3D Delft3D model of Bow River from Bearspaw Dam to the Calgary Weir with spatially distributed values of

roughness and horizontal eddy viscosity. Flow from north to south (top to bottom) (Parsapour-Moghaddam and Rennie 2016a)

2.3 Model application

The next step will be to develop Delft3D models for key reaches of Bow and Elbow Rivers where the need for management decisions has been identified. The first reach of interest will be the downtown section of the Bow River, between 14th Street and Centre Street. This particular reach has important flood and erosion management issues related to gravel-bar accumulation near bridges and flow bifurcation (Expert Management Panel 2014; Klohn Crippen Berger 2016). Key sub-reaches identified for flood mitigation works that require 3D morphodynamic modelling include the 10th Street reach (between the 14th St Bridge and just downstream of the 10th Street Bridge) and Prince's Island reach (from Peace Bridge to Centre Street Bridge). Gravel bars accumulated at and upstream of the 10th Street Bridge during the 2013 flood. These bars are currently vegetating and pose increased flood and erosion hazards. Potential interventions include gravel bar lowering to reduce flood risk and side channel cutting to improve habitat quality. Morphodynamic modelling is required to guide design of these works. In particular, the potential for long-term erosion and deposition as a result of the proposed works need to be quantified. Prince's Island reach includes a side channel, which is cut through a large meander bend. Extensive flooding occurred in this downtown location in 2013, and highly resolved modelling is required to quantify current and future the flood risks. The reach of interest on the Elbow River is centered at the Mission (4th Street) Bridge (between 26th Ave. SW and Roxborough Ave.). Extensive deposition has led to the growth of Elbow Island below the bridge, such that only one of four bridge spans is open to flow at most river discharges. Again, the proposed solution is to reduce flood risk by lowering the gravel bar and to improve habitat by cutting a channel through the bar. Again, morphodynamic modelling is required to evaluate long-term impacts.

3 SPRINGBANK OFF-STREAM RESERVOIR PROJECT

Some of the most severe flooding in 2013 occurred along the lower reaches of the Elbow River. One of the proposed solutions to reduce flooding in Calgary is to divert a portion of Elbow River flood flow before it reaches the city. The proposed $372M Springbank Off-Stream Reservoir Project is scheduled to begin construction in late 2018, following completion of an ongoing environmental assessment process (Alberta Transportation 2017). The project would be situated approximately 15 km west of Calgary at Springbank Road, and would include construction of a weir structure to divert a portion of high Elbow River flow via a new channel to an off-stream dry storage reservoir (Figure 2). The water stored in this basin would then be routed back to the river after flood recession.

3.1 Diversion Structure Physical Model

The proposed diversion structure would include both an inlet to the diversion channel and a sluice/spillway to pass remaining flow to the Elbow River. Sedimentation and/or obstruction by large woody debris (LWD) are serious concerns for design of any river diversion structure. In order to test and modify proposed designs to prevent undermining erosion or blockage by sediment and/or LWD, a large scale (1:16) physical model was constructed at the National Research Council's (NRC) Ocean Coastal and River Engineering (OCRE) Research Centre in Ottawa. NRC was commissioned to construct and test the model by Stantec for Alberta Transportation. The University of Ottawa assisted NRC with the physical modelling. The physical model has been described previously in Knox et al. (2017), Cornett et al. (2017), and Perry et al. (in review). A brief summary is provided herein.

The physical model was built within a 50 m by 30 m basin. Realistic scaled representations of structures and local topography were constructed, including the diversion inlet structure and the diversion channel, the sluice/spillway leading downstream to the Elbow River main channel, and the Elbow River approach channel (Figure 3). The approach channel included a vegetated mid-channel island. Channel bathymetry was constructed of concrete grout, and vegetation was modelled using natural tree branches inserted into the wet grout. Flow into the system was regulated using a variabl- pitch pump, and downstream water levels in each receiving channel were controlled with individual tail gates.

The diversion inlet and the sluice/spillway were fitted with gates to regulate flow into each channel. Prototype (model) flows tested within the model were 60 m^3/s (0.06 m^3/s), 120 m^3/s (0.12 m^3/s),320 m^3/s (0.31 m^3/s), 760 m^3/s (0.74 m^3/s), and 1240 m^3/s (1.21 m^3/s). Prototype discharge into the downstream Elbow River main channel was maintained at 120 m^3/s for the three lower flow conditions, and 640 m^3/s for the highest flow condition. The original design called for a diversion inlet width of 46 m (2.88 m) divided into four bays and a main channel sluice of 10 m (0.63 m) and spillway of 31 m (1.94 m) width.

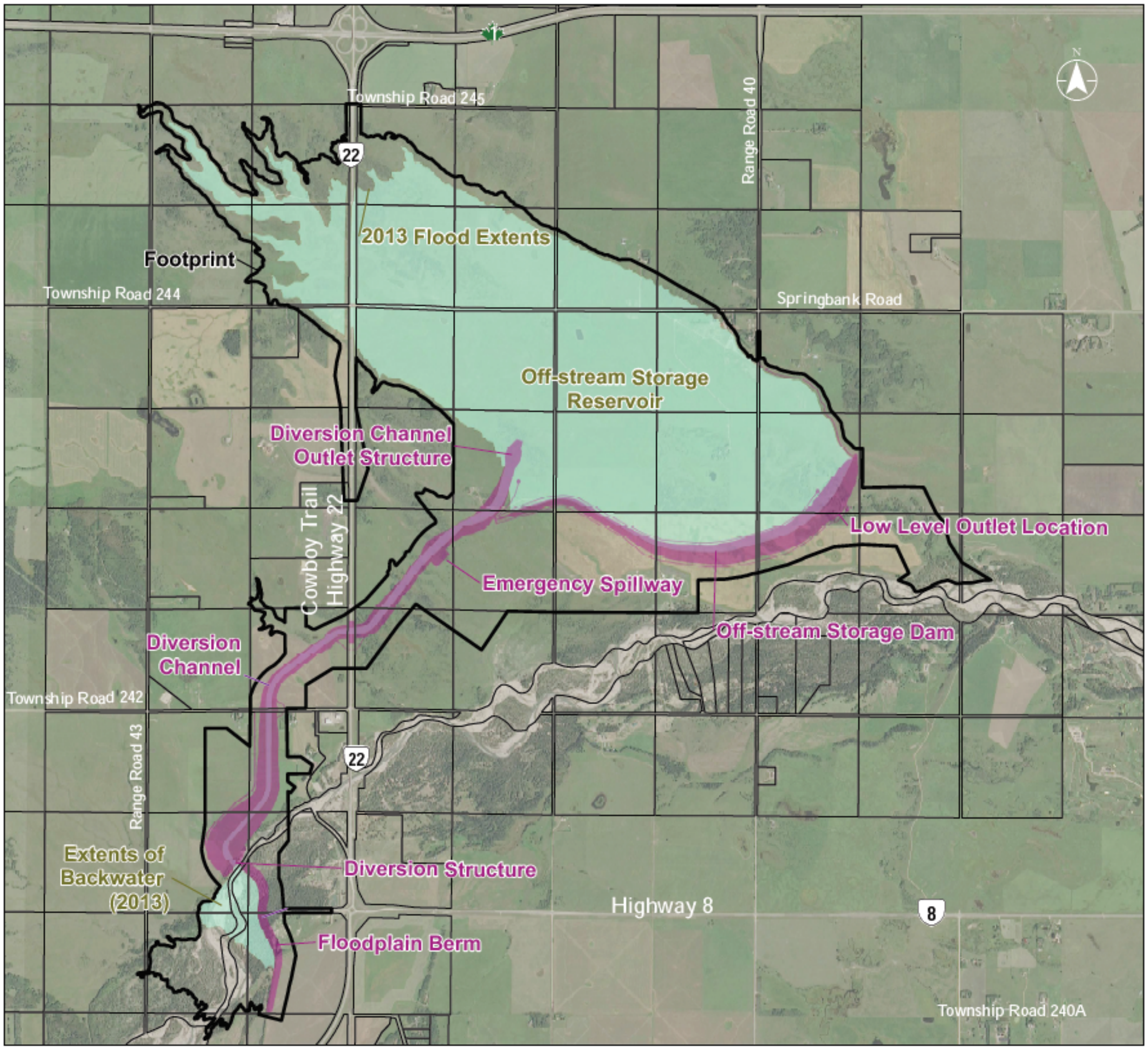

Figure 2: Proposed Springbank Off-Stream Storage Project (Government of Alberta 2017). Flow from west to east.

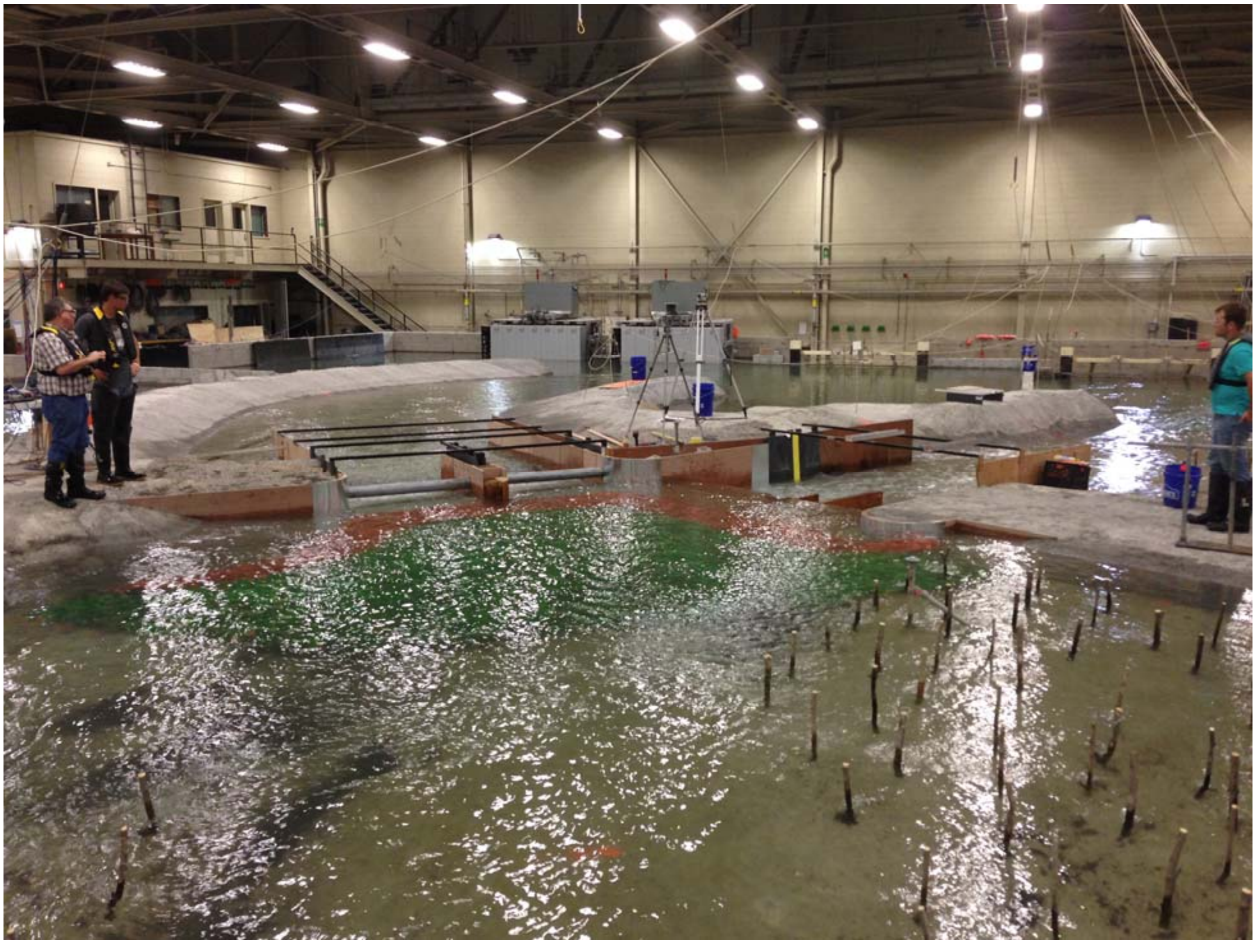

Figure 3: Undistorted Froude scale (1:16) physical model of modified diversion structure for proposed Springbank Off-Stream Reservoir Project. Facing downstream. Diversion channel to the left, and Elbow River main channel to the right.

3.2 Testing procedure

An extensive series of model tests was performed to evaluate the diversion structure for flow distribution, erosion, sedimentation, and LWD jamming. Initial testing of the four model flows focussed on replication of the desired flow distribution between the diversion channel and Elbow River downstream main channel. Once modelling of the flow distribution was deemed satisfactory, the model was used to test for erosion of riprap protection placed on the upstream edge of the diversion structure. Next, the potential for sedimentation was evaluated. The Elbow River bed sediment distribution was measured and scaled at 1:16. Small adjustments were made to the finer fractions of the model distribution to maintain Shields scaling of equivalent mobility. Regardless, due to modelling constraints, only the upper half the distribution was employed. This sediment was introduced at the upstream end of the model and resulting locations of deposition were identified. Finally, the model was tested for LWD jamming. Model debris was scaled to dimensions of LWD observed at the field site. Three types of model LWD were employed: 1) straight cylindrical dowels, 2) natural LWD cut from tree branches, and 3) natural LWD cut from tree branches augmented with model root wads consisting of thin wood strips attached in an X-pattern to the end of each branch.

3.3 Outcomes

As a result of model testing for flow distribution, erosion, sedimentation, and LWD jamming, the diversion inlet and main channel gate structures were modified. Small adjustments were made to the diversion structure layout to ensure appropriate flow distribution for each model flow. Perhaps most useful were the tests using LWD. It was determined that the initial diversion structure design was prone to debris jamming, largely because the gate widths were less than the LWD length, which allowed LWD to span a gate opening and hence become trapped. The initial trapped piece of LWD was then likely to obstruct and prevent passage of subsequent LWD pieces, leading to a debris jam. Consequently, the diversion structure gates were redesigned with fewer wider gates. It was also found that natural LWD were more prone to jamming than cylindrical dowels (Perry et al., in review), thus natural debris should be employed in physical model testing of LWD jamming.

4 CONCLUSIONS

The 2013 Alberta flood event was unprecedented in Canada. Since the flood, the Province of Alberta and the City of Calgary have proactively pursued flood mitigation measures. This paper briefly describes engineering research support provided to evaluate two such initiatives. First, numerical modelling has been employed to evaluate morphodynamic processes in Bow River. Such models will be used to evaluate in-channel modifications such as bar scalping and channel cutting for flood hazard mitigation and fish habitat enhancement in key reaches. Second, large scale physical modelling was conducted to test and modify a flow diversion structure for the Springbank Off-Stream Reservoir Project to diminish Elbow River flood flows. The physical model tests led to design modifications of the diversion structure to ensure appropriate flow distribution and to minimize potential for large woody debris jamming.

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