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Camo-maps: An efficient method to assess and project riparian vegetation colonization after a major river flood

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ABSTRACT

Major river floods provide powerful physical disturbances that create and expand gravel bars and islands. Their barren surfaces are suitable for seedling colonization by plants including poplars (cottonwoods) and willows that grow to contribute rich wildlife habitats and other ecosystem services. Conversely, in locations such as through bridges, riparian woodlands would impede future flows, elevating flood stages and increasing damage. It is consequently useful to understand where *opportunity* versus *hazard* locations occur and this encourages monitoring and predictive modeling of vegetation colonization. Colonization is related to the river inundation patterns but hydrodynamic modeling is difficult for complex channels and irregular features. Here we present an alternative empirical approach based on mapping of actual inundation patterns from a sequence of aerial photographs at different river flows. Based on field inventory of seedling distributions of different plants, we estimated inundation thresholds for six progressively lower riparian cover types: woodland, shrubland, perennial herbaceous, ruderal annuals, transition and barren. These were coordinated with the inundation patterns, enabling predictive mapping of the different vegetation classes to produce 'camo-maps'. These resemble camouflage with the irregular shapes and classification colors matching the vegetation types. The derived camo-maps were then compared with a lidar-based mapping of topography and vegetation structure. As an illustrative case study, we present the method for a large and complex gravel bar upstream from a bridge sequence and an expanded island below another bridge in Calgary Canada, where a hundred-year flood in June 2013 caused severe damage. The camo-maps reasonably represented the actual colonization patterns, although low flow years enabled some vegetation survival at lower positions than predicted. We present this as an effective and efficient empirical method to provide an alternative or complement to riparian vegetation projections based on hydrodynamic modeling.

1. Introduction

River floods provide powerful physical disturbances that erode, transport and deposit gravels, sands and other sediments, thus restructuring the bed and banks along alluvial river channels (Gordon et al., 2004; Fig. 1). The extent of fluvial geomorphic alteration relates to the flood magnitude. Rare, large floods provide extensive rearrangement of river channels and the adjacent, slightly higher floodplain zones. The scour and deposition produce extensive barren gravel bar and island surfaces that are subsequently available for seedling colonization by riparian, or streamside, vegetation (Kalischuk et al., 2001; Polzin and Rood, 2006; Scott et al., 1996). Following colonization, new plants may survive and grow, and zones with small woody plants provide new shrubland zones. Slightly higher zones allow for the recruitment of trees, creating riparian woodlands, vegetation communities that include trees, shrubs and understory plants.

The spatial patterning of vegetation colonization relates to three components: the physical, structural forms of the bar and island surfaces; the river flow and stage patterns, and the life history requirements and ecophysiological characteristics of different native and introduced plant species (Auble et al., 1994; Shafroth et al., 1998; Shoutis et al., 2010). Plant characteristics include the timing of seed production

Abbreviations: DEM, digital elevation model; HGM, hydrogeomorphic; lidar, light detection and ranging; *Q*, discharge (flow rate); UAV, unmanned aerial vehicle

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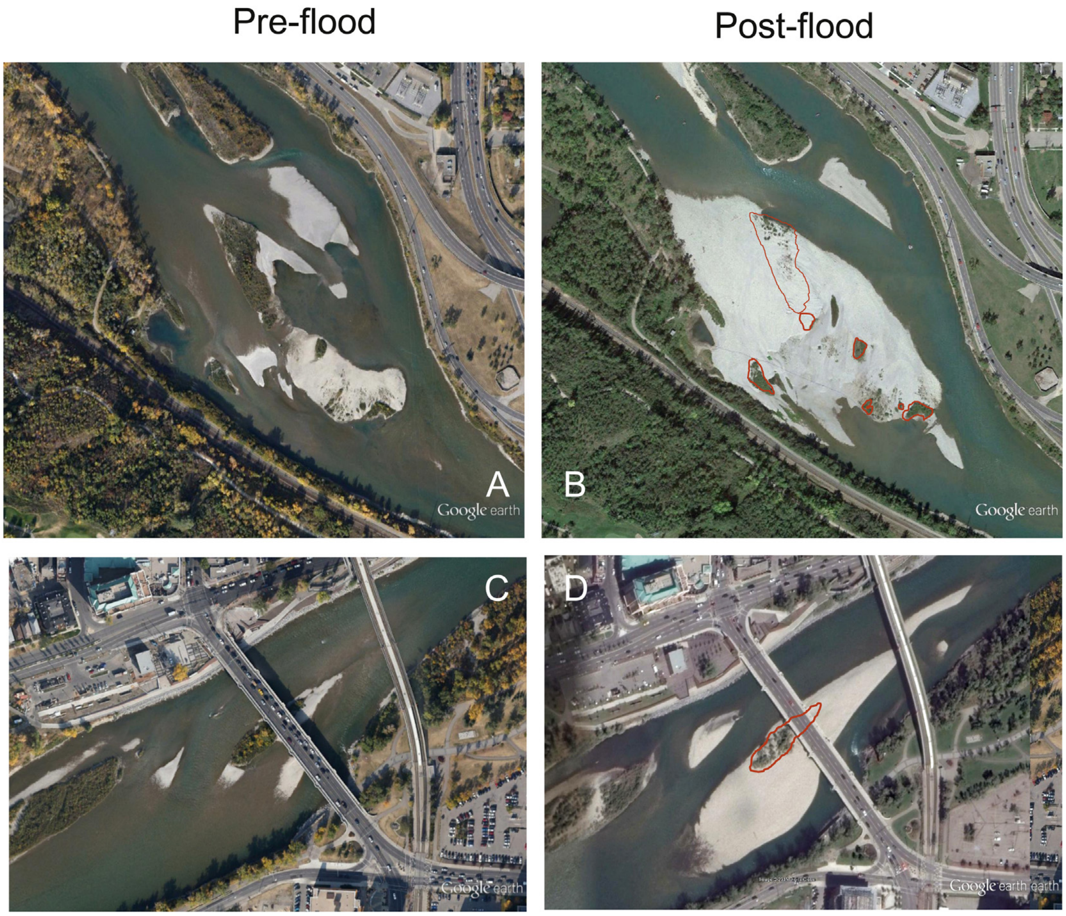

Fig. 1. Aerial photographs of the Bow River in Calgary, Alberta, before (pre-flood A and C, Sept. 22, 2012; $Q = 60\,m^3/s$) and after the exceptional June 2013 flood (post-flood B and D, Aug. 21/22, 2015; $\sim 75\,m^3/s$) for the Crowchild Bar (top, A and B), and Tenth St. Island (bottom, C and D). The pre-flood shrub or woodland patches are outlined in red the post-flood photos. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the germination requirements, and tolerances to scour, inundation and desiccation (Amlin and Rood, 2001, 2002; Dixon, 2003; Kalischuk et al., 2001). These influences commonly produce arcuate banding, with particular plants or communities in elevational bands that follow the curves of the meandering channel or the gravel bar or island shorelines. Colonization patches are also common, with groupings of one or more plant species on barren surfaces that are fairly flat and typically with common sediment and moisture conditions (Polzin and Rood, 2006; Scott et al., 1996). Different plant species and communities thus form a shifting mosaic of bands and patches that reflect the past river flows and stages that allowed colonization and growth, versus mortality through: (i) removal with scour by water or ice, (ii) inundation and root anoxia, or (iii) drought stress (Stanford et al., 2005).

With distributional structuring imposed by the hydrogeomorphic (HGM) (Egger et al., 2015; Hauer and Smith, 1998) riverine processes, the patterns of vegetation establishment and succession may be somewhat deterministic. This should enable vegetation modeling and the projection of colonization and development patterns (Egger et al., 2015; Perucca et al., 2006; Shoutis et al., 2010; Solari et al., 2016). A number of different modeling approaches have been applied and these have been reviewed by Camporeale et al. (2013), Solari et al. (2016) and especially Vesipa et al. (2017). Prior methods for projecting vegetation recruitment and mortality have particularly relied on hydraulic modeling that considers the inflowing discharge (Q, or flow rate) and the channel geometry, with consideration for the longitudinal slopes and sequential channel cross-sections (Benjankar et al., 2014; Egger et al., 2017; Garcia-Arias et al., 2013). These provide the essential inputs for hydraulic models, including the US Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS) and the Danish Hydraulic Institute (DHI) MIKE system. These estimate river shoreline positions with different discharges and are reasonably accurate for single-thread river channels. These models have been fairly successful for modeling fringe recruitment, the establishment of new arcuate bands of vegetation at particular shoreline elevations (Benjankar et al., 2014; Vesipa et al., 2017). However, hydraulic modeling becomes more complicated and less accurate as the channels become more complex, with multiple channels, islands and bars, and irregular surfaces. Consequently, the hydraulic modeling approach may be less capable of assessing and projecting vegetation colonization on complex and dynamic geomorphic surfaces that can be newly created or scoured by major floods.

Following the exceptional and very costly 2013 flood through Calgary, Canada, our task was to assess and project the colonization and development of riparian vegetation and especially riparian woodlands that could influence future flood flow patterns. The 2013 flood produced the highest flow of the century-long record for the Bow River (Pomeroy et al., 2016) and led to about $5 billion of damage (US$), providing one of the most costly natural disasters in Canadian history. The flood produced extensive sediment erosion, transport and deposition, leading to the creation or expansion of extensive, barren, gravel bars and islands (Fig. 1) that were subsequently available for seedling colonization by riparian plants.

We applied an HGM approach that emphasized the combination of water conditions and life history characteristics of the regional riparian plants. Initially, to assess river stage and inundation patterns, we anticipated a river hydraulic modeling approach. However, an extensive information resource arose with the internet posting by Google Earth of numerous georectified aerial photograph sequences that commenced prior to the flood and then provided about 40 images of the post-flood river shoreline positions over a broad range of river discharges. This provided an alternate approach for coordinating the distribution of new riparian vegetation with the river flow and inundation patterns. Thus, rather than relying on hydraulic modeling that approximates patterns of inundation with different river flows, we used an efficient empirical approach that indicated where the river shorelines actually were at different flows. This increased the spatial precision and confidence in assessing the inundation patterns that were then used to project vegetation distributions. Utilizing this resource, we introduce this new method as an alternate, inexpensive and broadly applicable complement to the hydraulic modeling approaches for the assessment and projection of riparian vegetation colonization.

2. Materials and methods

The study involved seven sequential components that provide the new empirical method. We name the method ‘camo-maps’, to recognize the resemblance of the mapped vegetation mosaic to camouflage, with irregular shapes and coloration that match vegetation and ground surface patches (Fig. 2). These components were implemented sequentially over the post-flood interval from 2013 through to 2016.

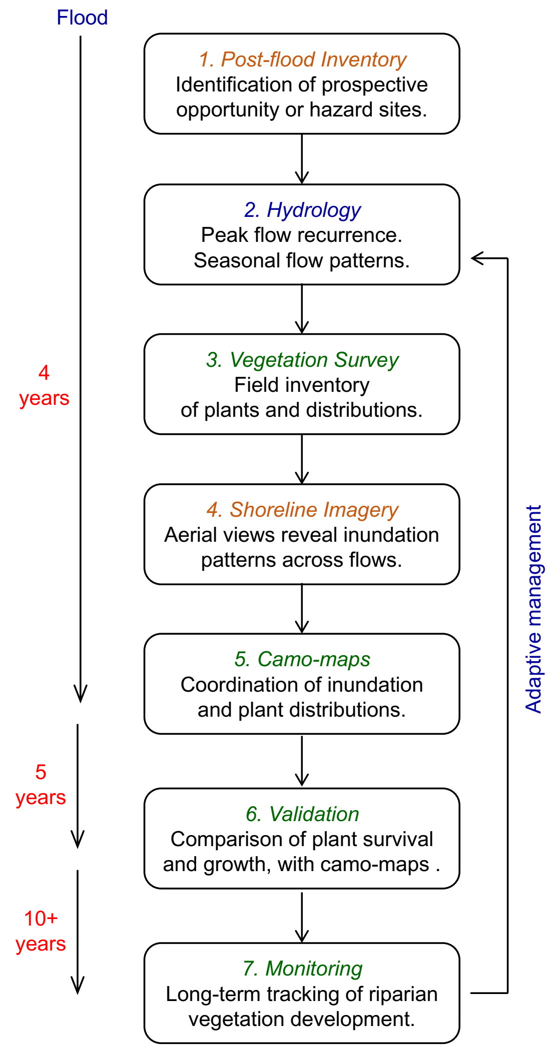

Fig. 2. Schematic for the ‘Camo-map’ methodology for projecting riparian vegetation colonization after a major river flood.

2.1. Post-flood inventory of the river channel, gravel bars and islands

The study commenced in June 2013 with observations of the Bow River valley through Calgary, Canada (Rood et al., 1999) to identify river locations that were of particular interest or concern. These included: (1) *opportunity sites*, locations with promise for the recruitment of new riparian vegetation that would contribute to wildlife habitat and other ecosystem services; and conversely, (2) *hazard locations*, where the establishment of riparian woodland could impede future river flows and thus elevate flood stages, increasing overbank flooding and infrastructure damage. Hazard locations especially occur along urban corridors and in rural areas near developments such as bridges and highways. For the present study, the emphasis was on hazard locations, and the method would be similarly applicable for opportunity sites, but with an opposing management objective, to promote rather than avoid riparian woodland development.

More systematic field inventory was undertaken in 2014 with our research team that included river engineers from the City of Calgary and consultants with expertise in river hydrology and hydraulics, fluvial geomorphology and river valley ecology. The Bow River corridor was directly observed with field visits, along with assessments of aerial photographs and other imagery, and the newly formed or substantially expanded gravel bars or islands were identified. This was undertaken for the river reach from the outflow of Bearspaw Dam downstream through the City of Calgary and some assessment continued downstream to the Carseland Weir. Prospective hazard locations were identified with a focus on the city corridor and an emphasis on river positions near or through bridges or other riverside development, and in areas that experienced extensive inundation or erosion with the 2013 flood (Rood et al., 2016).

2.2. Hydrology

The Bow River system has been extensively developed, with eleven dams upstream of Calgary, primarily for hydroelectric power generation (Rood et al., 1999; Sheer et al., 2013). To investigate the regulated river flow patterns, we accessed the historic river discharges (Q, in m^3/s = cubic meters per second) from the online database of Environment Canada's Water Survey of Canada (https://wateroffice.ec.gc.ca/). We analyzed daily mean Q for the Bow River at Calgary (#05BH004), along with the annual maximum and minimum daily Q. We also obtained from Alberta Environment and Parks (AEP) discharge values at 15 min intervals for the summer of 2015. This corresponded to the vegetation survey when there were short-term flow changes, including flow reductions to enable post-flood assessments and restoration.

Inundation patterns for gravel bars and islands are especially important for vegetation colonization and the river stage, or elevation, can be more important than the flow rate, Q. Consequently, daily mean river stages (m) were accessed along with Q for the interval from 2012 through 2016. To determine stages for the 15 min Q records for the summer of 2015 we used the daily stage versus Q values from 2015 for the Bow River gauge to derive the rating curve: stage = 0.461 x ln(Q) – 0.818 (R^2 = 0.973). We applied this to derive river stages during the different field visits. The base stage is a common reference (Polzin and Rood, 2006; Shafroth et al., 1998) and we assessed this as the stage associated with the typical minimal flow during the plant growth season of May through October. With extensive flow regulation, the minimal growth season flows have been restored after the 1954 completion of Bearspaw Dam, the newest dam that is located just upstream of Calgary (Fig. 3; Rood et al., 1999). Subsequently, we established the base stage of ‘0’ as associated with a discharge of 47 m^3/s, and a height of 1.0 m for the Bow River gauge.

Our field surveys occurred with river discharges of 70 to 80 m^3/s.

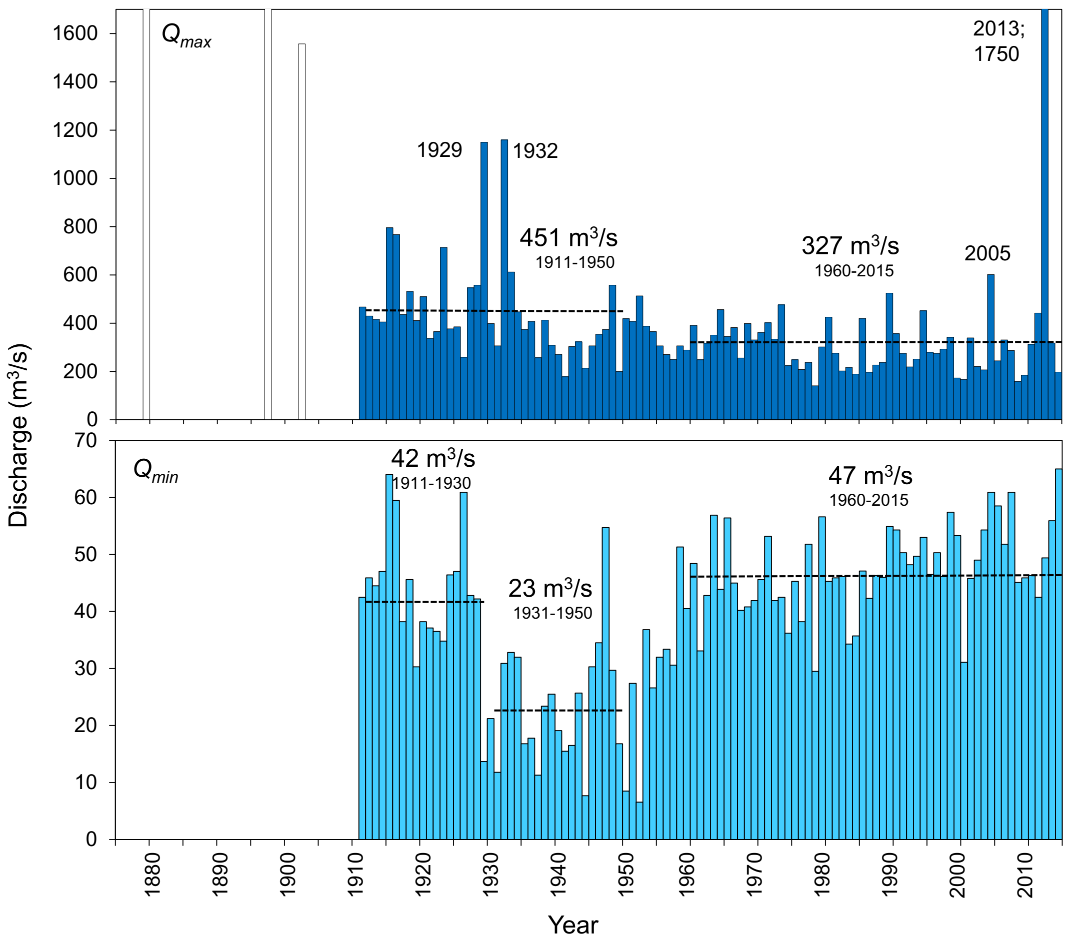

Fig. 3. Maximum (Q_{max}, top) and minimum (Q_{min}, bottom) mean daily discharges along the Bow River at Calgary (gauge 05BH004) for the period of record. Estimates for early floods are indicated with white bars but these were not gauged. Commencing in 1911, eleven upstream dams were constructed (Rood et al., 1999), with Ghost (1929) being the largest, and Bearspaw (1954) the final dam that is directly upstream from the study sites and this river gauge. Mean values are provided for different management intervals that followed these two dams.

The associated stage was about 0.2 m above the base stage and this provided the elevation offset for the inventoried vegetation plots. Our ultimate mapping was based on the actual river shoreline at various discharges, and this avoided the challenge from site-specific stage versus discharge patterns. This provides a simplification and important advantage of this empirical approach.

2.3. Survey of riparian vegetation colonization

Commencing in July 2015, we visited each prospective hazard site and observed channel, bank and vegetation conditions. We took photographs from reference positions, including views from the bridges. We undertook surveys of each bar or island with transects, additional survey placements and surveys of the vegetation quadrat positions. Along transects, we surveyed elevations (± 1 cm; Uranus Automatic Level; Tianjin, China) at ~2 m intervals for short (< 25 m) transects or at ~5 m intervals for longer transects and at transitions in surface elevation. We surveyed additional positions on the bar or island surfaces to capture the surface morphology and along the edges of the island or bar to plot the adjacent downstream-sloping river water surfaces. Due to the coarse gravels and cobbles, the surface elevations are accurate to ± 5 cm while spatial positioning is accurate to about 0.1 m, with hard tie-ins to a pump station adjacent to the Crowchild Bar and the piers of the Tenth St. Bridge.

Vegetation was assessed within quadrats that were positioned to cover the apparent range of surface elevations and vegetation occurrences. At each position a 1 × 1 m frame was dropped and all plants were identified and counted. Taxonomic treatment, names and wetland status are generally in accordance with USDA-Plants (https://plants.sc.egov.usda.gov/java/). To assess sediment textures, each frame had string grids to provide 4 × 4 intersections and the y-axis (2nd largest dimension) was measured for the sediment particle below each intersection, representing Wolman (1954) ‘pebble counts’.

Balsam poplar (Table 1) seedlings were common and these were counted by size classes that were determined with ages and years of establishment, based on stem apical bud scar counts: 2015 (0–10 cm tall), 2014 (10–30 cm), 2013 and older (> 30 cm). We uprooted some poplars to confirm their origin as seedlings rather than as suckers, adventitious shoots from shallow parental roots. For seedlings established in 2013 or 2014, the heights of the tallest three balsam poplar seedlings were measured in each quadrat.

To complement the transects and quadrats we overviewed the full bar and island and noted other plant species, other surface features and apparent flood impacts. We returned to the study sites in August 2016 to evaluate the survival and growth of poplar seedlings and other inventoried plants and to investigate other colonizing vegetation.

We selected the 2015 Google Earth terrain mosaic as a base layer for a GIS platform with ArcGIS (Esri, Redlands, CA, USA) and plotted our transects and quadrats. As a component of the camo-mapping method, Google Earth aerial photographs at different river discharges were added and while those images were orthorectified, the georeferencing was imperfect and slight adjustments based on building corners and

Table 1
Characteristics of the primary plants that colonized gravel bars along the Bow River through Calgary Alberta, after the major flood of 2013. Treatment and wetland status are generally in accordance with USDA-Plants (https://plants.sc.egov.usda.gov/java/) with progressively drier categories: FACW, facultative wetland; FAC, facultative; and FACU, facultative upland.

Common Name	Species	Plant type	Wetland status	Crowchild Bar		Tenth St. Island	
				Occurrence (% of 10 quadrats)	Density (#/m^2)	Occurrence (% of 6 quadrats)	Density (#/m^2)
Woody Plants							
Balsam poplar	*Populus balsamifera* L.	Large tree	FAC	60	4.3	83	5.2
Sandbar willow	*Salix exigua* Nutt.[a]	Shrub	FACW	20	8		
Chokecherry	*Prunus virginiana* L.	Large shrub	FAC			50	1
Gray alder	*Alnus incana* (L.) Moench	Large shrub	FACW				
Water birch	*Betula occidentalis* Hook.	Small tree	FACW				
Herbaceous Plants							
Dandelion	*Taraxacum officinale* F.H.Wigg.	Introduced perennial herb	FACU	30	1	83	1.8
Quackgrass	*Elymus repens* (L.) Gould	Introduced perennial grass	FAC	30	1.7	50	3.3
Canada thistle	*Cirsium arvense* (L.) Scop.	Noxious, introduced perennial herb	FACU			17	5
Sweetclover	*Melilotus officinalis* (L.) Lam.	Introduced annual or perennial herb	FACU	20	1	17	1
Horsetail	*Equisetum arvense* L.	Perennial herb	FAC			17	1
Reed canarygrass	*Phalaris arundinacea* L.	Perennial grass	FACW				

[a] Treated as similar to *Salix interior* Rowlee.

bridges aligned the different ArcGIS layers.

2.4. River shoreline and inundation patterns

A core component of the camo-map method is the mapping of inundation patterns at different river discharges (Fig. 2). We assessed aerial photographs that were posted on Google Earth, with the 'clock' feature to sort through ~40 post-flood aerial photographs for the Bow River through Calgary. These displayed the changes in channel, bank and bar forms, with major change in the flood year, 2013, and some subsequent change in 2014 since the major flood somewhat destabilized the channel and banks. By 2015, the new bars and islands were more static and we emphasized aerial photographs through the summer of 2015 since this provided the primary interval for the vegetation inventory.

2.5. Camo-maps

The riparian transects with elevations and the vegetation quadrats provided additional GIS layers. We subsequently considered the positions of the new seedlings relative to the inundation patterns and derived a sequence of inundation thresholds for the various riparian vegetation types.

This mapping considered the ordinary high water line (OHWL; US Army Corps of Engineers, 2015), which represents the transition from the relatively barren parafluvial zone to the zone of perennial and woody vegetation (Fig. 6). This vegetation boundary was found to be wetted with a discharge of about 350 m^3/s and approximated the Q_2, the 1-in-2 year recurrence discharge. However, many locations were less abrupt relative to the transition from wooded to barren shoreline zones and complexities involved willow shrubland zones that even occurred in lower zones that are flooded for intervals annually (Amlin and Rood, 2001).

While recognizing the complexities, we developed a sequence of typical thresholds for riparian vegetation types, commencing with the woodland threshold that matched the Q_2, and then a sequence of lower vegetation bands that were reasonably consistent with the distribution of seedlings and the established willows at the Crowchild and Tenth St. study sites.

2.6. Validation - field assessment

Our analyses relied especially on a field inventory in 2015 and we generated the map projections in late 2015. We subsequently revisited the sites in the summers of 2016 and 2017 to assess vegetation growth and survival and especially to consider the projected distributions from 2015. We emphasized the tree seedling patches that were almost entirely new balsam poplar seedlings and saplings, and we also considered the zones projected to develop into shrubland, generally dominated by willows. Photographs were re-taken from the reference positions to track seedling survival and further vegetation colonization.

2.7. Monitoring - post-flood baseline mapping

To enable further tracking of woodland and shrubland development, we surveyed the area with airborne lidar on August 8, 2016. We used a multi-spectral and bathymetric Teledyne Optech Inc. (Toronto, ON) ALTM Titan onboard a fixed-wing plane flown at 500 m above ground level with 50% overlap of scanlines. The survey included a 36° field of view and 200 kHz pulse repetition frequency per channel (532 nm, 1064 nm and 1550 nm).

We used the 1064 nm channel for the classification of ground and vegetation returns with TerraScan (TerraSolid Inc., Helsinki, Finland), following Hopkinson et al. (2016). Ground surface elevation was rasterized using a Triangular Irregular Network method (Golden Software Surfer, Inc. Colorado, USA), and vegetation canopy returns (minimum 0.1 height) were gridded based on the maximum height within a search radius of 1.5 m. The island and gravel bar terrain variations were characterized using the Topographic Position Index (TPI) of the DEM (Jenness, 2006) using an iterative circular 10 m search radius. River bed bathymetry was gridded using a Krig function in Surfer with a search radius of 3 m and the bathymetric surface was added as an additional layer to the maps.

3. Results

3.1. Initial field inventory

The preliminary overviews along the Bow River through Calgary revealed ten locations of particular interest (Klohn Crippen Berger, 2017) and to estimate vegetation thresholds we assessed all ten sites

(Rood et al., 2016). The highest concern for the City of Calgary related to bridge crossings near downtown and particularly the major expansions of gravel bars and islands upstream from the Crowchild Trail Bridge, through the Tenth St. Bridge and downstream of the Centre St. Bridge. We present the analyses and mapping for the first two bridge locations, thus illustrating the method for a large and complex gravel bar and an island.

3.2. Hydrology

3.2.1. Bow river floods

The Bow River reservoirs are relatively small but have provided some peak flow attenuation (Fig. 3). Hydrometric gauging commenced in 1911 and floods followed in 1929 and 1932. There was subsequently an eight decade interval without a major flood, until the flood of record in 2013 (Fig. 3). That flood would have a recurrence of about a century based on the gauged record but about a half-century if pre-gauge flood estimates are included (Pomeroy et al., 2016).

3.2.2. Seasonal river flow and stage patterns: 2013 to 2016

The spring peak of the Bow River generally occurs in June (Rood et al., 2016) and the 2013 flood followed heavy rains and crested June 21. This was followed with rapid initial recession and then more gradual decline (Fig. 4), providing favorable conditions for poplar seedling recruitment.

Riparian vegetation colonization also commonly continues in years following the flood, when there is less deposition and scour that can kill seedlings established in the flood year (Dixon, 2003; Polzin and Rood, 2006). Consequently, the 2014 flow pattern was also very important and this was quite favorable (Fig. 4). The moderate 2014 flows would not have scoured the higher position 2013 seedlings and rewatering of the root zones would have promoted their survival and growth. After favorable flows for seedling recruitment in 2013 and 2014, river flows were much lower with a partial drought in 2015 and relatively low in 2016 (Fig. 4).

The operations of the upstream dams probably involved rather

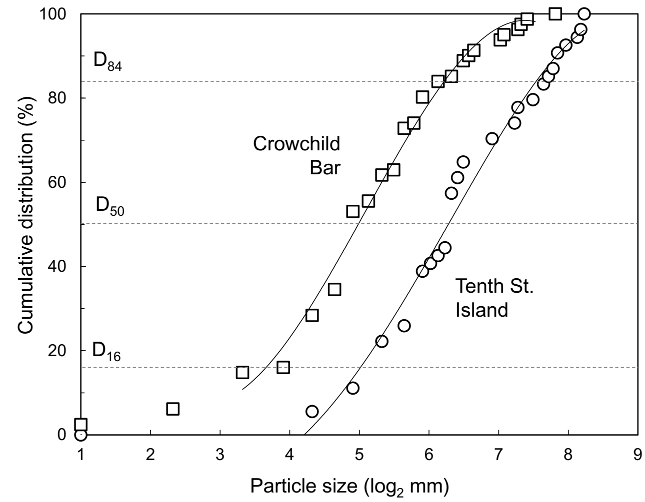

Fig. 5. Surface sediment particle sizes at the Crowchild Bar and Tenth St. Island along the Bow River, Alberta.

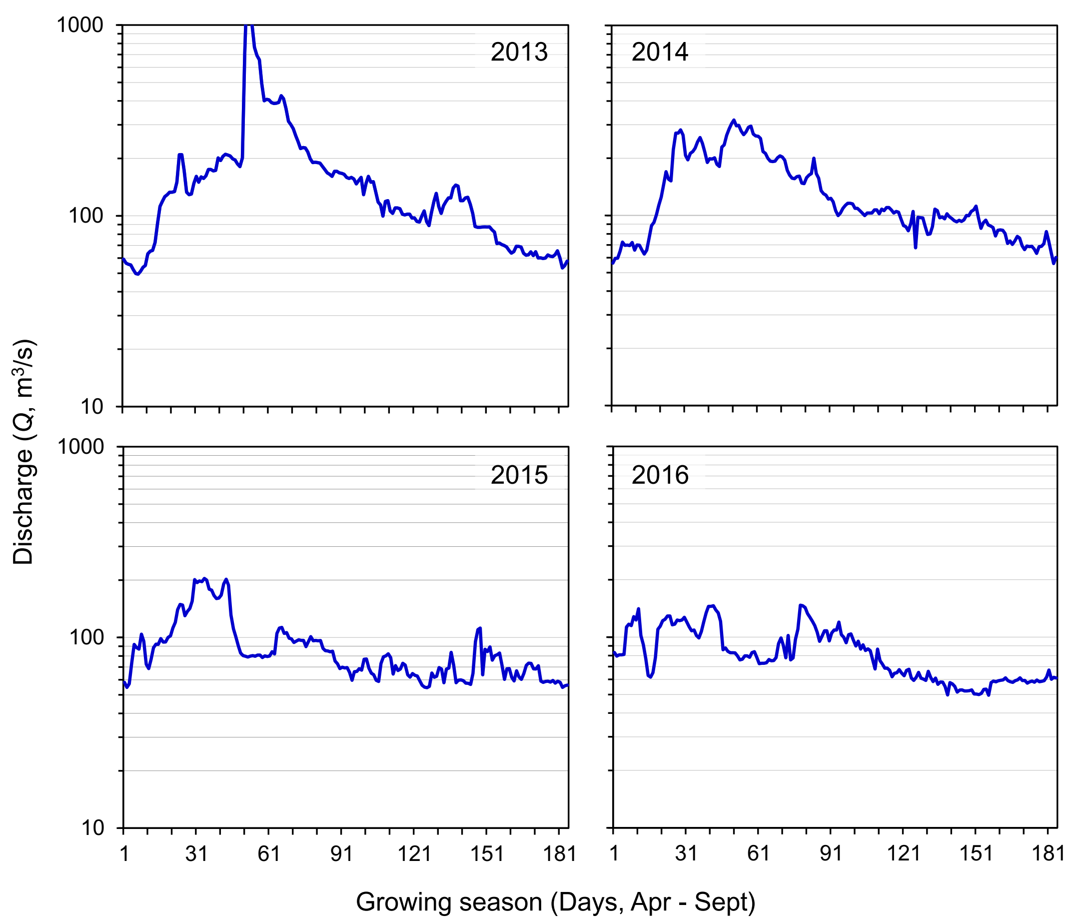

Fig. 4. Growing season hydrographs for the Bow River through Calgary for 2013, the flood year; 2014, a fairly high flow year; the drought year of 2015, and low flow year of 2016.

limited consideration for riparian recruitment (Sheer et al., 2013) but fairly natural flow patterns occurred in 2013 and 2014 since the upstream reservoirs were filled. Following the costly 2013 flood, there were changes in Ghost Dam operations commencing in 2015, to draw down this largest reservoir in the system before June, to enable additional flood flow attenuation. Subsequently in 2016, reservoir refilling after the draw-down trapped some early summer flow, contributing to the drop in flow after the relatively low spring peak (Fig. 4).

3.3. Survey of riparian characteristics and vegetation colonization

3.3.1. Surface sediments

The new and barren bar and island surfaces were covered with fairly coarse alluvial sediments (Fig. 5) that would have provided high hydraulic conductance and rapid drainage. The Crowchild Bar surface was more heterogeneous, reflecting its larger size and complexity. The sediments were primarily gravels with the mean second axis size (D_{50}) of 32 mm and commonly ranging from 12 to 76 mm (D_{16}, D_{84}). The Tenth St. Island had a coarser, flatter and more uniform surface with coarse gravels and cobbles with a mean size of 78 mm and commonly ranging from 32 to 186 mm. Observations of adjacent cut-banks revealed similar sediments but with some layers of finer interstitial sands that would slow drainage and provide a limited capillary fringe (Rood et al., 2011).

3.3.2. Colonizing riparian vegetation

The diversity of colonizing riparian plants was limited, with seedlings of only six and ten species occurring in the quadrats at the Crowchild Bar and Tenth St. Island, respectively (Table 1). These included three woody plants with one tree species, balsam poplar, and two shrubs, sandbar willow and chokecherry. Overviews of the full gravel bar and island revealed two other woody plants. A few toppled and abraded small water birch trees persisted from prior to the flood toward the upstream end of the Crowchild Bar and gray alder shrubs occurred along with balsam poplar and willows in the pre-flood woodland patch adjacent to a bridge pier at the Tenth St. Island (Fig. 1).

3.3.3. Balsam poplars

Balsam poplars are by far the predominant trees along the Bow River through Calgary and provide a prolific seed source. Subsequently, poplars were the most abundant seedlings at both sites, occurring in around two-thirds of vegetated quadrats (Table 1), with typical densities of $\sim 5/m^2$. In many quadrats and colonization patches, poplar seedlings were the only plants (Fig. 6).

The August 2015 inventory indicated that the poplar seedlings had especially established in the post-flood year, 2014 (42% and 50% for Crowchild and Tenth St.), with fewer from 2013 (35% and 15%). There were abundant, smaller seedlings from 2015 (23% and 35%) but they generally occurred at lower positions that would be prone to scour, reducing their likely survival. Reflecting the higher river stages in the flood year (Fig. 4), the 2013 seedlings were generally higher in position, often 1.0 to 1.8 m above the base stage, while the 2014 seedlings were most common from 0.6 to 1.0 m above the base. This seedling elevational range was similar to that of other cottonwoods across western North America (Mahoney and Rood, 1998), including balsam poplars and the closely related black cottonwood (*Populus trichocarpa*) along regional rivers (Kalischuk et al., 2001; Polzin and Rood, 2006).

3.3.4. Willows

Willows (*Salix* spp.) provided the second most common woody plants along the Bow River but willow seedlings, probably sandbar willows, were sparse at the two sites (Table 1). These only occurred in 20% of the vegetated quadrats on the Crowchild Bar and were absent in the quadrats on the Tenth St. Island. In addition to the scattered seedlings, there were dense patches of willows that persisted through the flood along the downstream zones of the Crowchild Bar (Fig. 1). The willows were apparently flood-tolerant and their fibrous branching and narrow leaves would have allowed them to readily bend over in the swift flood flow. In contrast, the balsam poplars and water birch in the young woodland patch at the upstream end of the Crowchild Island were toppled and uprooted.

Fig. 6. The study strategy involving the Ordinary High Water Line (OHWL, white dashed line (top)) that separates the band of perennial vegetation from the relatively barren parafluvial zone. Photographs of the colonizing plants on the island taken from a reference position on the Tenth St. Bridge. The middle photograph was taken in August 2015 and the small green plants are poplars and the green outline represents the predicted positions from the camo-map method. The bottom photograph was taken in Sept. 2016 and reveals growth of the poplars and smaller poplars to the right. The lighter plants are primarily senescent sweet clover. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.5. Other plants

The other woody plant with seedlings in the vegetated quadrats was chokecherry, with single chokecherry seedlings in a few of the vegetated quadrats on the Tenth St. Island, but none were observed on the Crowchild Bar. For wetland status, chokecherry is a classified as a facultative plant, like balsam poplar, while sandbar willow is a facultative wetland plant and thus favors lower and wetter conditions (Table 1).

There were also seedlings of herbaceous (non-woody) plants and primarily the introduced species, dandelion, quackgrass and sweet clover (Table 1). Native herbaceous plants were sparse, including aster and horsetail. The herbaceous seedlings, and especially the sweet clover and horsetail, often occurred at lower elevations than the balsam poplar seedlings. Sweet clover was prominent on the lower portions of the Tenth St. Island and along the shoreline around the Crowchild Bar. Reed canarygrass was the primary invasive plant of concern along the

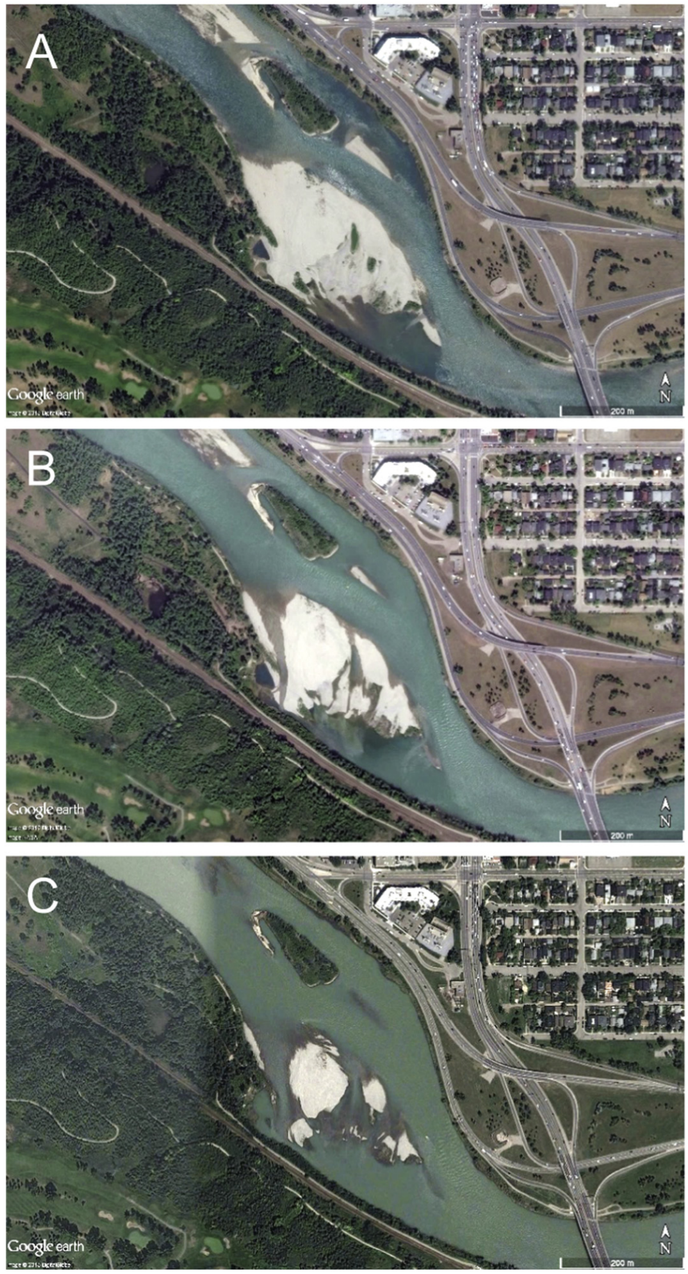

Fig. 7. Examples of post-flood aerial photographs of Crowchild Bar displaying different river discharges that were used to map inundation zones and project vegetation colonization patterns (A, July 8, 2015, 106 m^3/s; B, June 5, 2015, 200 m^3/s; C, July 9, 2013, 301 m^3/s).

Bow River, but was notably absent from the Crowchild gravel bar and Tenth St. Island (Table 1).

3.4. Inundation patterns

The Google Earth resource included about 40 georectified aerial photographs for the study sites, with the vast majority after the 2013 flood (Fig. 7). The sequential photographs displayed some changes in the island and bar shorelines and channel positions after the flood. Changes were more substantial through 2013 and 2014, and by 2015 the configuration was more stable. This indicated that as well as directly causing extensive channel change, the exceptional flood somewhat destabilized the system, allowing subsequent bank erosion.

Due to the channel changes in 2013 and 2014, we chose a 2015 aerial photograph sequence as the GIS base layer and this was the year for the initial, post-flood vegetation surveys. For the mapping of the shoreline positions at the different river flows, we accessed other photographs from 2015 but since this was a low flow year, we also used images from 2014 and even 2013, when flows were higher, to obtain the full range of inundation positions (Table 2).

3.5. Camo-maps

Through coordination of the observed vegetation positions and the inundation patterns, thresholds were selected for the different vegetation types or cover classes (Table 2). These were based on vegetation distributions at these two sites and also on the eight other gravel bars or islands along the Bow River through Calgary (Rood et al., 2016). For each site, the major colonizing plants were identified and their relative elevations were sequenced from the field inventory (section 3.3). Poplar seedlings were most abundant and consistently at the highest positions. Willow seedlings were generally slightly lower and were more

Table 2
Characteristics of the different riparian vegetation types that were assessed and projected for bars and islands along the Bow River through Calgary. Plant species are in accordance with Table 1.

Vegetation type	Description	Approximate river discharge threshold	Aerial photograph date
Woodland	Riparian woodland with trees (woody plants > 2 m tall) and primarily balsam poplars, along with various shrubs and understory plants.	350 m^3/s ~ Q_2, the peak that occurs in one-half of years	July 6, 2013
Shrubland	Abundant shrubs (woody plants 0.5 to 2 m tall), commonly including various willow (*Salix*) species, and water birch and other shrubs, along with herbaceous plants.	300 m^3/s	July 9, 2013
Perennials	Abundant perennial plants, with small shrubs (generally < 0.5 m) such as sandbar willows, along with perennial herbaceous plants such as reed canarygrass.	250 m^3/s	July 1, 2014
Annuals	Primarily ruderal annual plant species, but some perennials may occur, generally with suppressed growth due to periodic inundation. Sweetclover was especially common.	200 m^3/s	June 5, 2015
Transition	This zone may support sparsely scattered plants and primarily ruderal annuals such as sweetclover. In flow-protected locations such as backwaters, there may also be some perennial plants and inundation-suppressed sandbar willows.	150 m^3/s	June 8, 2015
Barren	This zone is generally barren of vegetation, except in some flow-protected locations.	100 m^3/s	July 8, 2015

abundant with finer substrates of surface or interstitial sands. For sites downstream of the inflowing tributaries, Nose and Fish Creeks, reed canarygrass seedlings were common and extended from the zones with poplar seedlings to below the willow seedlings. Ruderal annuals and especially sweet clover were common on sparsely vegetated zones below the perennial plants.

This descending sequence: poplars (woodland), willows (shrubland), reed canarygrass (perennials) and sweet clover (annuals) was generally consistent across the ten sites but there were more seedlings and greater overlap of the species with finer surface sediments, such as at the Centre St. gravel bar (detailed results are presented in Rood et al., 2016). Across the sites, the balsam poplar seedlings were predominant above the shoreline that was inundated when flows at the Calgary gauge were ~300 m^3/s. The zones of the gravel bars that were exposed when flows were below ~100 m^3/s were consistently barren of vegetation. The other plants were generally observed in between these upper and lower boundaries. To accommodate the four intermediate vegetation types we established common 50 m^3/s intervals for the transitions (Table 2). This provided a simplified approximation for the combined sites along the Bow River through Calgary but the transitions were shifted somewhat for individual sites. There were multiple aerial photographs at discharges near these transition thresholds and the inundation and shoreline patterns were highly consistent across the photographs with similar discharge, enabling reasonable confidence in the plotting of the camo-maps (Fig. 8).

3.6. Validation

The 2016 and 2017 field visits supported the observations from 2015 that provided the basis for the camo-map projections. The patches of balsam poplar seedlings persisted and those plants had grown into saplings reaching 1 m in height. However, some balsam poplar seedlings survived at lower positions than projected with the camo-maps, and there was also some further poplar seedling establishment at lower positions, especially along the riverside margin of the Crowchild Bar. The low flow of 2015 would have reduced inundation and scour, enabling those lower distributions.

3.7. Monitoring - post-flood reference and vegetation mapping

The lidar mapping confirmed the topographic complexity of the surfaces, especially for the Crowchild gravel bar (Fig. 9). There was also a change at the Crowchild Bar where a channel was excavated to ensure freshwater exchange for a pump intake pool (lower left).

These topographic maps will provide useful reference plots to track further changes in the shoreline positions and aggradation through sediment deposition with future flood events. Additionally, the green laser (532 nm) enabled bathymetric mapping (Fig. 9), which would be useful to analyze aquatic conditions, and could contribute to river hydraulic modeling to assess flow velocity and shear, which influence vegetation survival.

The lidar returns revealed larger plants on the features in 2016 (Fig. 9). The dark green patches indicate taller plants that persisted from the pre-flood conditions, with the expanding willow patches on the Crowchild Bar, and the woodland patch near the middle pier at the Tenth St. Island. Some post-flood poplars were apparently detected and these would have been three or four years old in 2016. Other plants were also detected, probably primarily sweet clover, the fast-growing annual that was abundant on the Tenth St. Island.

These apparent vegetation distributions from the lidar point clouds (Fig. 9) demonstrate substantial overlap with the camo-map projections (Fig. 8) but there were also some differences. An elevated oval-shaped patch to the left of center on the Crowchild Bar displayed abundant poplar seedlings in 2015 but these were not detected with lidar. We revisited this patch and the poplars persisted but had grown less rapidly than in positions that were lower and closer to the river channels. There were other differences, with a fringe of poplars along the north side of the Crowchild Bar and more extensive poplars throughout the Tenth St. Island than projected. While the low river flows and dry conditions disfavored the poplars at the higher positions, these apparently favored poplars at lower elevations. We had expected that the lower position poplars would be repressed or excluded due to inundation and scour and it will be instructive to track the fate of these lower elevation poplars with the expected return of higher, normal spring flow patterns.

4. Discussion

4.1. The camo-map method

We introduce this camo-map method as another modeling approach for the analysis and projection of riparian vegetation colonization and development. It should complement other modeling approaches (Benjankar et al., 2014; Camporeale et al., 2013; Vesipa et al., 2017) and is effective, efficient and inexpensive. The effectiveness is based on the empirical field inventory of colonizing vegetation at particular locations of interest. These are sites that are important relative to prospective hazard or environmental opportunity, with opposing objectives.

The prospective hazard could involve human developments such as bridges, river-side roadways or rail lines, or with buildings or other urban development in floodplain zones. For these, the objective would be to recognize that the development of shrub or woodland communities on geomorphic features such as bars or islands could impede flood flows and thus elevate flood stages and correspondingly increase

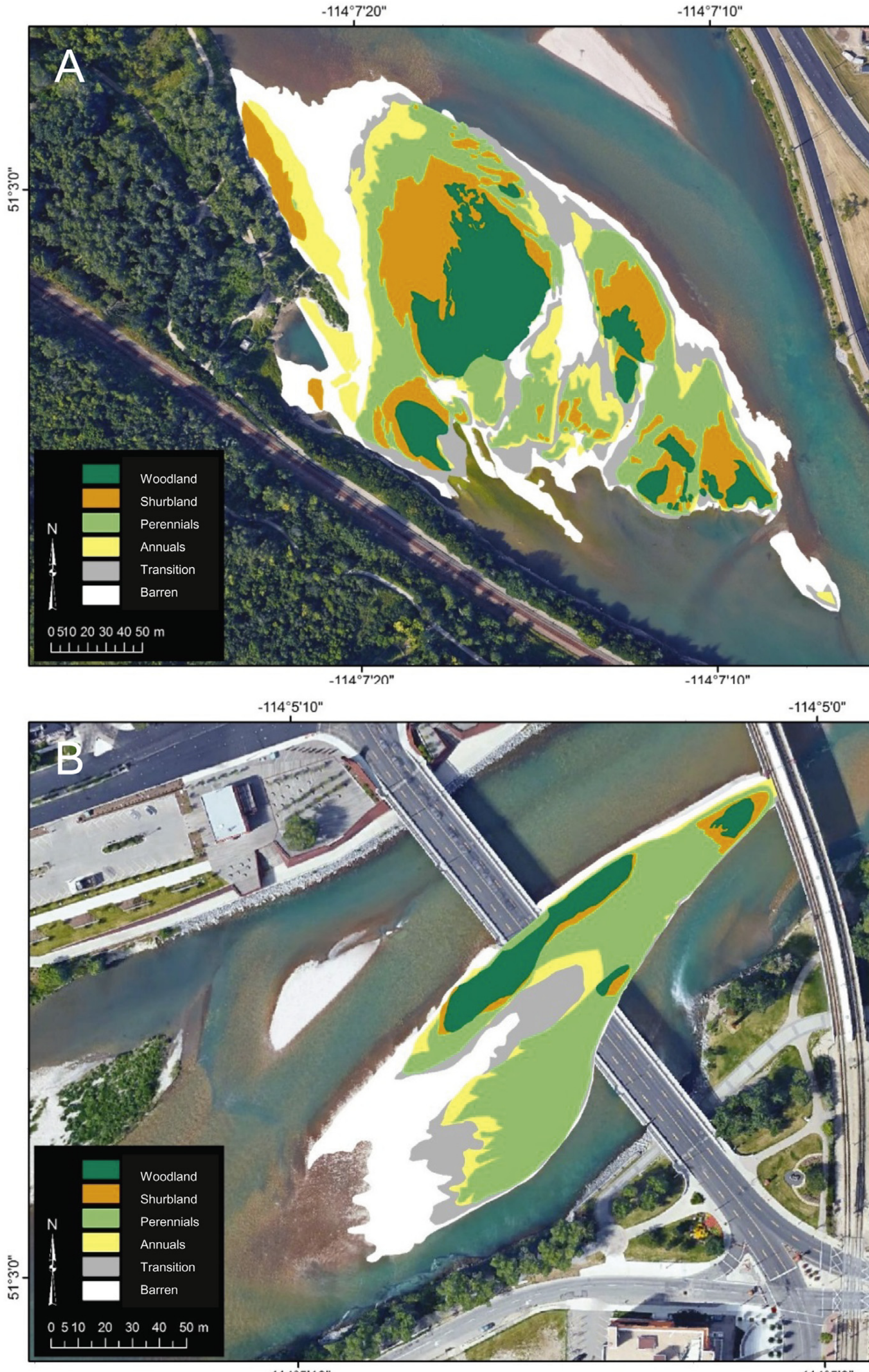

Fig. 8. A vegetation projection or 'Camo-map' (named since it resembles camouflage) for the Crowchild Bar (A) and for the Tenth St. Island (B) along the Bow River in Calgary, Alberta, with different riparian vegetation types projected.

the risk, damage and infrastructure cost. The recognition of these hazard situations could then be followed by management measures such as the excavation of the surfaces to lower the elevation below the survivable positions for trees and shrubs, or with woodland clearing.

The alternate application would be the recognition of environmental opportunities with the identification of locations where ecologically rich and diverse riparian woodlands could become naturally established after a major flood. These woodlands provide a range of valued ecosystem services including wildlife habitats, benefiting aquatic ecosystems through shading and foliar inputs to the food-web, reducing erosion and stabilizing stream banks, and contributing to water quality by intercepting and assimilating contaminants (Franks et al., 2019). For this application, the beneficial sites would be identified and management measures could be implemented including the exclusion of livestock, and limiting human uses such as recreational off highway vehicles. In an urban or park setting, there can be strategies such as quickly restoring pathways to avoid random travel and damage through the seedling colonization zones.

Related to effectiveness, we commenced our observations of the flood-altered riparian zones immediately after the June 2013 flood (Pomeroy et al., 2016). We then chose late 2015 as the major inventory interval as this would assess seedlings after up to three growth seasons,

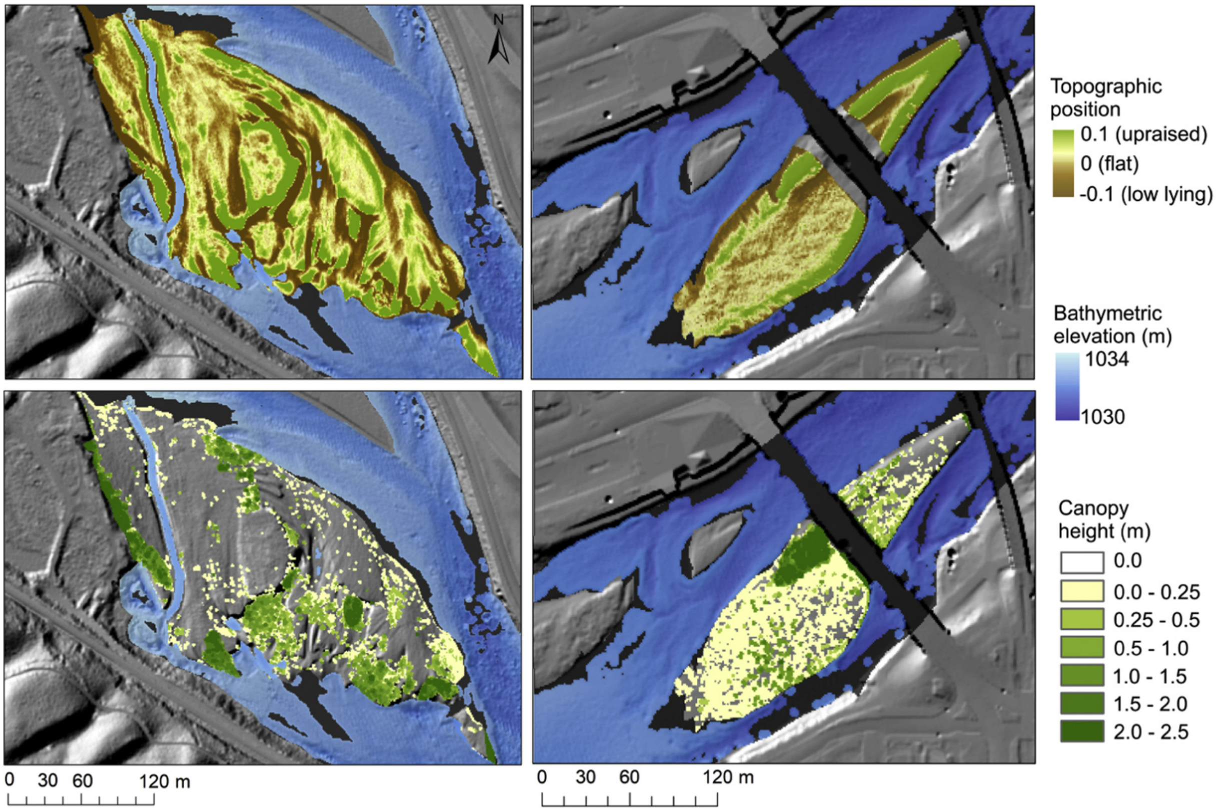

Fig. 9. Site mapping based on lidar (light detection and ranging) point clouds in August 2016 of the Crowchild Bar (left) and Tenth St. Island (right) along the Bow River in Calgary Alberta. The top images display the topographic position indices (TPI) which represent local topographic positions within 10 m radii and elevations above adjacent shorelines. The lower images display the canopy heights of riparian vegetation. For both images, the river is displayed with a bathymetric colour ramp indicating river bed elevation. Black zones indicate shallow inundation with some turbidity. The bridge over the Tenth St. Island is excluded (blackened) along with some shadow effect (gray).

when the prospect for continued poplar and willow seedling survival is reasonable (Dixon, 2003; Kalischuk et al., 2001; Polzin and Rood, 2006; Shafroth et al., 1998). Our field verification was at the end of the 2017 growth season and we recommend that future application would involve vegetation inventory in the fifth year after a major flood. While the colonization patterns were probably apparent after three years, an additional interval would provide older and larger plants, increasing the ease and confidence in the vegetation assessments.

While we would encourage the major vegetation inventory in about the fifth year after a major flood, we recommend that comparative photo points be established as soon as possible after the flood. Plants displayed in comparable photographs in years one through three should largely correspond to those inventoried in year five, and this will enable a more complete chronology, contributing to the characterization of the patterns of growth and survival and hydrogeomorphic requirements.

While the field vegetation sampling represents a fairly conventional approach (Dixon, 2003; Polzin and Rood, 2006), the more novel component of camo-mapping is provided by the efficiency of the inundation mapping. This application benefited from the extensive resource of aerial photograph sequences that have been georeferenced and openly posted on Google Earth. This enables the democratization of natural resource analysis since anyone with an internet link can toggle through the sequence to track the post-flood inundation patterns.

This air photo sequence was unusually extensive and prompted by the catastrophic 2013 Calgary flood (Pomeroy et al., 2016). Major floods through other cities might prompt similar increases in imaging and, hopefully, public posting. Equivalently extensive air photo sequences would be less likely for rural or remote areas, or for less affluent regions or nations. For those applications a practical alternative could utilize repetitive photography with an unmanned aerial vehicle (UAV, 'drone') to reveal the inundation patterns at different river flows. UAV flights could also enable DEMs through structure from motion analyses (Fonstad et al., 2013), providing an alternative or complement to elevational surveys and lidar.

4.2. A simplified system

This application with two sites along the Bow River through Calgary provided a simplified system that assisted in the development of the method. The vegetation inventory revealed a simple riparian community with seedlings of only a few plant species. The predominant seedlings, by far, were balsam poplar, *Populus balsamifera*, which provides the predominant tree in the riparian woodlands in this region. This is related to other riparian poplars, including black cottonwood, *P. trichocarpa*, plains cottonwood, *P. deltoides*, and Fremont cottonwood, *P. fremontii*, which have been extensively studied in western North America (Shafroth et al., 1998, 2017; Polzin and Rood, 2006; Braatne et al., 2007), and the black poplar, *P. nigra*, in Europe (Guilloy-Froget et al., 2002). The hydrogeomorphic requirements for cottonwood seedling colonization are reasonably well understood and have provided the basis for deliberate environmental flow regiments that have been successfully implemented for riparian conservation and restoration in southern Alberta and elsewhere (Foster et al., 2018; Glenn et al., 2017; Kalischuk et al., 2001; Shafroth et al., 1998). The camo-map method would complement the implementation of environmental flows by characterizing the site-specific inundation patterns, and contributing to the projection and monitoring of vegetation colonization.

Willows and especially the sandbar willow, were the other primary colonizing woody plants, and are related to and share ecophysiological characteristics with poplars, including requirements for seedling colonization (Amlin and Rood, 2002; Dixon, 2003). Willow seedlings were much less common than poplars on the two sites and generally occurred at slightly lower positions at the sites along the Bow River (Rood et al., 2016), partly since their seed dispersal is later, when river stages are lower. While seedling recruitment of willows may be gradual, clonal expansion is often extensive (Ottenbreit and Staniforth, 1992), and there were also some willow patches that survived through the 2013 flood.

It was notable that we did not observe seedlings of reed canarygrass at the two sites presented (Table 1). Downstream and especially below creek inflows, reed canarygrass seedlings were abundant (Rood et al., 2016). The tributary creeks have been severely invaded by reed canarygrass and would provide a source for seeds and vegetative propagules.

Another simplifying aspect results from the locations being downstream of the Bearspaw Dam. This traps alluvial sediments and consequently there was limited deposition of sands and other finer sediments. The surface sediments at both study sites were quite coarse, with gravels and cobbles. This probably reduced the seedling colonization by some plants, including some weeds that were more abundant on gravel bars downstream that had patches of finer sediments (Rood et al., 2016). More heterogeneous surface sediments would also expand the elevational distributions of some plants, and substrate sediment provides another factor that influences seedling colonization and should be considered for the camo-maps.

While the Bow River is sediment-depleted due to the upstream dams and extensive bank armoring, there is still some sediment transport; with future high flows, there will be deposition of sands and other sediments. This could increase the suitability for seedling colonization by some other plants and increase the richness, or number of species in the riparian community. Conversely, by 2017, the poplars and willows were well established and almost certain to grow and produce a mosaic of shrub and woodland patches. Additional plant species could colonize the future understory and woodland succession may follow (Egger et al., 2015).

4.3. Validation

The 2016 lidar imaging will provide a useful reference and we would recommend that this be repeated after about five and ten years, when the shrubland and woodland patterns would be well advanced. The ultimate validation of the camo-map projections will require decades for the woodlands to mature and for willows to expand to occupy the shrubland zones. It is likely that within two decades, the developing woodland would impede future flood flows thus increasing bank erosion, elevating the river stage and increasing overbank flooding. The camo-map projects that woodland development at the Tenth St. Bridge would create woodland conditions similar to those at the Fourth St. Bridge over the Elbow River in Calgary (Rood et al., 2016), where a dense woodland probably contributed to adjacent overbank flooding in 2013.

5. Conclusions

Following a costly extreme flood through a major city, we sought to develop an efficient strategy to analyze and project the locations where riparian woodlands would develop, since these would impede future flood flows. The rich resource provided by orthorectified aerial photographs publicly posted on Google Earth enabled a novel, empirical approach, and we undertook field inventories of new seedlings of riparian vegetation and coordinated these positions with the inundation positions for a complex gravel bar and island. The aerial photographs revealed the actual inundation patterns with different river discharges, and this provides an alternate or complementary approach to hydrodynamic modeling, which is less certain for multiple channels and complex surfaces. Additionally, the empirical inundation patterns would enable site-specific stage versus discharge curves, and thus contribute to river hydraulic modeling for other applications.

Based on the seedling distributions and inundation patterns, this method resulted in camo-maps that plot the likely positions of different vegetation types. These include woodlands that are favored for wildlife habitats and provide other ecosystem services in suitable locations, but are disfavored at some locations through some municipal corridors since these would elevate future flood stages. We thus recommend the camo-map method as an efficient and inexpensive strategy to characterize riparian vegetation patterns following major floods along other rivers, worldwide.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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