AN INNOVATIVE APPROACH TO MONITORING THE PHYSICAL STABILITY OF CONSTRUCTED FISH HABITAT USING DRONES

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ABSTRACT

In August 2014, a subsurface failure at the Mount Polley mine's tailings storage facility resulted in a debris flow that scoured Hazeltine Creek and a portion of Edney Creek. Creek rehabilitation planning, design and construction commenced immediately following the incident.

A two-phased approach was adopted to reconstruct the creek and restore habitat for fish and riparian wildlife. The first phase was to construct an erosion-resistant engineered channel to control erosion and reduce turbidity in water entering Quesnel Lake. The second phase was to re-establish physical in-stream and riparian habitat along the channel to support a return of biological habitat function.

Following the construction of habitat features in sections of Hazeltine Creek and Edney Creek, drone imagery was used to georeference the locations of the constructed habitat. The aerial imagery had sufficient resolution to geospatially document each element of stream habitat, and therefore monitor its physical stability.

This novel habitat monitoring technique couples the aerial imagery from drones with geographic information system (GIS) software to reliably determine the stability of each element of habitat and develop a database of those habitat elements. This combination of technologies enables an effective, relatively rapid and low-cost means of monitoring constructed fish habitats.

<u>Key Words:</u>

Rehabilitation, breach, UAV

INTRODUCTION

On 4 August 2014, a subsurface failure of a glaciolacustrine layer beneath the foundation of the perimeter embankment of the Mount Polley mine's tailings storage facility (TSF) resulted in a breach of a section of that embankment (Morgenstern et al. 2015). The resulting debris flow scoured Hazeltine Creek and a portion of lower Edney Creek near its confluence with Hazeltine Creek. The resulting incised and widened drainage alignment was exposed to head-cutting, gully erosion and sidewall slumping, resulting in increased turbidity through erosion and downstream movement of suspended particulate material to Quesnel Lake (Bronsro et al. 2016). Detailed geochemical evaluations demonstrated that these tailings are non-acid generating and not an environmentally significant concern for metal release (SRK 2015; Kennedy et al. 2016). A detailed Human Health Risk Assessment (Golder 2017a) and Ecological Risk Assessment (Golder 2017b) found that the tailings do not pose a risk to human or ecological receptors, and monitoring studies are in progress to address areas of typical scientific uncertainty. A detailed overview of impacts from the TSF breach is provided in Nikl et al. (2016).

Planning, design and construction of new fish habitat began immediately following the incident. A two-phased approach was used to rehabilitate the creeks and re-establish their ecological functions. The first phase addressed urgent measures. This included stopping downstream turbidity entering Quesnel Lake through the design and construction of an engineered channel foundation resistant to erosion (Bronsro et al. 2016). The second phase, which is ongoing at the time of writing, involves establishing in-stream and riparian habitat values within the channel and the floodplain, respectively. To date, approximately 2.8 km of habitat has been constructed in Hazeltine Creek and approximately 1.0 km of habitat has been constructed in Edney Creek. The phased response was a matter of necessity to control turbidity under the specific circumstances resulting from the debris flow and compliance with a government order; however, work in the first phase was carried out with the *a priori* intent of the foundational channel becoming functional fish habitat once features were constructed in the second phase, which is the focus of this paper.

In recent years, drones have become readily accessible, and a growing body of literature demonstrates the use of digital aerial imagery and photogrammetry for scientific purposes. Image acquisition from low-cost commercially available drones has been demonstrated to provide spatial resolution datasets for a range of purposes, and opportunities for additional applications have been identified in recent years within the commercial sector. Opportunities have emerged in fields such as archaeology, landslide and hazard mapping, glacial landform mapping, monitoring of crops and vegetation, geomorphological mapping, and various applications in river science and engineering (Woodget et al. 2017).

Methods that use high resolution aerial imagery to characterize habitat and hydromorphologic features have been established since as early as the 1970s (Adams 1979; Winterbottom and Gilvear 1998; Carbonneau et al. 2005; Cecere 2017). The image resolution required for many of these assessments is too fine to use satellite imagery, and typically aerial imagery taken from piloted aircrafts has been required. Many researchers and professionals have begun to recognize the opportunities drones present for more affordable imagery for river monitoring and characterization (Rivas Casado et al. 2017; Woodget et al. 2017; Langhammer and Vacková 2018).

Differing approaches have been used to analyze drone imagery. Rivas Casado et al. (2017) developed an algorithm-based approach to conduct hydromorphologic characterization using drone imagery. They reported feature identification accuracies in the range of 50% to 70%. Langhammer and Vacková (2018) used a less automated and more supervised approach to hydromorphologic classification using drone imagery and reported feature identification accuracies greater than 90%. The supervised classification approach used by Langhammer and Vacková (2018) is most comparable to the approach used for habitat monitoring at Hazeltine Creek and Edney Creek described here.

HABITAT DESIGN

The design criteria for the second phase of the habitat reconstruction was aimed at restoring the life history functions for fish, in particular salmonids, as well as other aquatic (e.g., periphyton, aquatic macro-invertebrates) and riparian organisms (e.g., piscivorous and insectivorous birds).

Creek rehabilitation objectives were focused on re-establishing habitat value within Hazeltine and Edney Creeks. Restoring these creek channels to identical pre-breach conditions was not a realistic objective because of the physical changes resulting from the breach. Rather, the objective was to return life history productivity functions for fish within stream and riparian environments affected by the debris flow.

Habitat design was a collaborative process involving input from federal and provincial regulators and direct participation by the local First Nations and their consultants. This collaboration occurred through the Habitat Remediation Working Group (HRWG), which provides a mechanism to incorporate input from agencies, First Nations and Mount Polley's design and construction team, on the remediation of fish habitat as build-out occurs. The habitat design objectives were based on physical conditions (e.g., gradient), constructability, life history requirements of the fish species and a broader ecosystem context (e.g., amount of spawning or rearing habitat available to the adjacent systems). The HRWG has provided input and external review of designs to Mount Polley Mining Corporation and its river engineering and habitat ecology consultants.

The design of pools and weirs was integrated with the sinuosity of the channel. The pools and weirs were designed to create a flow regime characterized by distinct fast and slow sections. This increased complexity in the habitat designs through the variation of the flow regime between pools (where flow is slow and less turbulent), riffles (at the face of the weirs, where flow is fast and turbulent) and glides (often at the tail-end of pools, where flow is fast and less turbulent). This variation in the flow regime is a precursor to the establishment and persistence of a variety of fish life history functions, such as spawning and rearing, to be sustained by the final channel configuration (Bronsro et al. 2016).

The addition of large woody debris (LWD), salvaged from the impact zone of the debris flow, provided structural complexity and cover in the channel, floodplain and riparian areas (Adams 2015). Woody debris use included root wads, tree tops (overstream) and logs. In-stream features provide cover and hydraulic refuge for fish, while over-stream woody debris also provides cover for fish, in particular passing and holding spawners. The provision of in-stream cover is important because of the time that it will take for the riparian zone to provide functional cover.

The HRWG also developed an agreed upon set of metric criteria used to define the quality of the designed physical form of the constructed habitat, which was based on objective-based functions, as summarized in Table 1.

Table 1: Metric Criteria for Defining Poor, Fair and Good Quality Habitat (modified from Johnston and Slaney 1996)

Habitat Parameter	**Quality Rating**		
	Poor	**Fair**	**Good**
1. Bankfull width-to-depth ratio	>25:1	16–25:1	≤15:1
2. Entrenchment ratio	<1.4	1.4–2.2	>2.2
3. Channel complexity	<2 mesohabitat units/10× bankfull widths	2–3 mesohabitat units/10× bankfull widths	≥3 mesohabitat units/10× bankfull widths
4. Percent pool (by area)	<15%	15–40%	40–60%
5. Pool frequency (mean pool spacing)	>10 channel widths/pool	>8–10 channel widths/pool	<8 channel widths/pool
6. Holding pools (adult migration)	<1 pool/km >1 m deep with good cover (30% of pool area)	1–2 pools/km >1 m deep with good cover (30% of pool area)	>2 pools/km >1 m deep with good cover (30% of pool area)
7. Large woody debris (LWD) pieces per channel length, measured as bankfull width	<1	1–2	>2
8. Percent LWD cover in pools (i.e., wood cover as a percent of pool area)	pools in reach average 0%–5% LWD cover	pools in reach average 6%–20% LWD cover	pools in reach average >20% LWD cover
9. Spawning substrate size, quality and area	size mostly <6 or >60 mm; >25% fines (<2 mm); <10% spawning gravel area within wetted area of all habitats surveyed	size 6–60 mm; 15–25% fines (<2 mm); ≤25% spawning gravel area within wetted area of all habitats surveyed	size 6–60 mm; ≤15% fines (<2 mm); >25% spawning gravel area within wetted area of all habitats surveyed

Aquatic ecosystems are linked to adjacent terrestrial ecosystems by transitional riparian zones and wetland areas (Gregory et al. 1991). Rehabilitated riparian habitat designs included “stacked” log clusters to provide microhabitat for small mammals, vertical placement of habitat “trees” for insect production and perching opportunities for avian wildlife, and vegetation planting with the goal of establishing a successional trajectory for the riparian vegetation community (Golder, 2018). Site preparation methods were used to A) mix forest floor, mineral soils and any residual tailings to increase soil porosity; B) create raised microsites that have aerated root zones; and C) create plantable microsites. Once soil conditions are amenable to seed germination and growth, the early successional species will establish and late successional species will slowly colonize through dispersion from nearby seed sources (Golder 2018).

Plant species were selected for the post-debris flow soil conditions (low organic carbon and low nutrients). Plantings within the lower floodplain are exposed to surface flows during freshet and higher flow events; however, they will not be completely inundated. Plantings within the upper floodplain will not be exposed to surface flows but they will be sub-irrigated during freshet and higher flow events throughout the year (Adams 2015).

The establishment of a riparian zone successional trajectory will, in time, provide ongoing bank stability, additional natural LWD inputs, and other riparian zone function. In the shorter term, the complexing features constructed in the creek need to provide some of those functions, and the monitoring of their physical stability during the early post-construction period is an important part of verifying the success of stream habitat remediation. Riparian vegetation and in-stream aquatic community monitoring is also part of the remediation plan (Golder 2018) but is not the focus of this paper.

In-stream LWD was designed for physical stability under design flows following guidance presented in D’Aoust and Millar (2000). LWD features are subject to a combination of hydrodynamic, frictional and gravitational forces that act on both the LWD and the anchor boulders. D’Aoust and Millar (2000) present a method to calculate the stability of pieces of LWD, based on an analysis of principal forces and an experimental program of field testing and verification. This method is based on the principal forces illustrated in Figure 1.

- F_{BL}—Net buoyancy force acting on the LWD and transferred to the anchor boulder
- F_{DL}—Horizontal drag force acting on the LWD and transferred to the anchor boulder
- F_{DB}—Horizontal drag force acting directly on the anchor boulder
- F_{LB}—Vertical lift force acting directly on the anchor boulder
- W’—Immersed weight of the anchor boulder
- F_F—Frictional force at the base of the anchor boulder that resists sliding

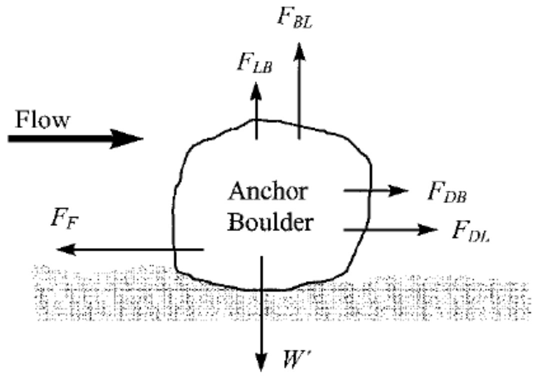

Figure 1: Principal forces acting on anchor boulders (adapted from D'Aoust and Millar, 2000).

The output from this method was a set of recommended factors of safety for installation of LWD in natural creeks and rivers in British Columbia (D'Aoust and Millar 2000). This method and recommended factors of safety were adopted during the design of LWD habitat features for this project.

Following the installation of LWD habitat features as part of the constructed habitat in Hazeltine Creek and Edney Creek, it was necessary to demonstrate that the desired physical stability of installed LWD and anchor boulders had been successfully achieved. An innovative approach to meeting this requirement is discussed in this paper.

HABITAT CONSTRUCTION

Due to active erosion along Hazeltine Creek and the urgency for action following the breach, a conventional design-apply-permit-construct approach would not have allowed for rapid compliance with government orders, and general statutory expectations to cease turbid water release, because of the time frame of such processes which could take 1 to 2 years (Tupper de Kerckhove et al. 2013). Therefore, the first phase of the habitat reconstruction used a field-fit procedure that was based on the following main steps and was agreed to by government agencies within the context of the breach event:

1. The slope of each reach was determined based on the post-breach topography.
2. The slope and design flow were used to size typical channel cross-sections for each reach.
3. Habitat use objectives were developed for each reach of creek.
4. Overall plans and profiles were created for each reach of creek.

The construction of that alignment was left to the field team to determine based on the desired channel sinuosity, the typical cross-sections for each reach, the ability to develop access within specific areas, and the overall constructability based on observed ground conditions and other factors (Bronsro et al. 2016).

The second phase of habitat construction followed a similar approach. Design concepts incorporated HRWG input, with engineering design and responsibility for performance verification being the responsibility of Mount Polley Mining Corporation and their breach remediation consulting team. The designed physical form was based on the objectives-based functions agreed to by the HRWG. Plans and typical details were developed and used in the field as a guide to field fit habitat features into the constructed channel.

Following the construction of habitat features in each section of creek, record drawings were developed using site survey information and drone imagery to georeference the as-built locations of the constructed habitat features as described in further detail below. Record drawings are an important part of the engineering design process as they document the constructed condition of the engineering works, reflecting all changes made during the construction process, and showing measured dimensions, geometry, and location of all elements of the work (EGBC 2017). Record drawings are particularly useful in this case, as they enable future changes caused by natural processes and conditions to be identified. Typically, Fisheries and Oceans Canada, the main regulatory authority for fish habitat management, requires five years of monitoring to confirm stability of constructed habitat. During the production of record drawings, it became apparent that the aerial imagery was of sufficient quality and resolution to geospatially catalogue each main item of stream habitat, and therefore assess its physical stability by tracking it over time.

MONITORING CONSTRUCTED CREEK HABITAT

The combination of available drone technology, geographic information system (GIS) software, and river engineering and habitat ecology principals was evaluated to see whether these could reliably detect both stability and instability of each main element of river habitat. Whether or not this combination of technologies would provide a system amenable to year-to-year monitoring of physical habitat stability and regulatory reporting was also evaluated. Relative to the more common method of locating each piece of habitat inventory and field surveying each item each year, this combination of technologies enables a rapid and low-cost means of monitoring constructed fish habitats and allows a considerably expanded number of survey points over what a common field survey would obtain for similar monitoring purposes.

A survey was conducted shortly after the habitat construction was finished to capture the as-built conditions, support preparation of record drawings, and provide a baseline for physical habitat stability monitoring. In the first year following construction, surveys were carried out following freshet. In years two through five, annual surveys are carried out after spring freshet and after flows have subsided to enable aerial identification and position of habitat features.

The habitat attributes captured in the GIS database are described below and illustrated in Figure 2.

- Boulder location and approximate size
- Woody debris location, orientation and length
- Weir locations and areas
- Bed load stabilizer locations and areas

Figure 2: Example of habitat information recorded in GIS database.

There are five main steps in each of the surveys:

1. A flight path is determined and flown to capture a series of consecutive high resolution images that can be stitched together into a single aerial image. For the Hazeltine and Edney Creeks, the drone was flown approximately 10 m to 15 m above the ground surface to capture the extents of the habitat and to provide safe clearance of vegetation.
2. Ground-truthing of the drone data through the collection of several control points that are used to confirm the drone imagery is correctly positioned in space.
3. Image processing and stitching, which is carried out using commercially available software (Agisoft PhotoScan™) to generate a single aerial image of the area of interest.
4. Development of a georeferenced inventory of individual habitat features, classified by habitat type, and analyzing the processed imagery using GIS software (Esri ArcMap™). The georeferencing of habitat elements was based on the centre point of the specific feature. For LWD this resulted in a detection limit of ten degrees or greater rotation, and two metres or greater displacement. This was considered suitable for purpose as some movement of LWD was tolerable and the movement that could be detected was sufficient to determine whether the physical stability of the features were functioning as intended.
5. Site verification of the GIS analysis to identify whether movements have occurred and determine their cause. The coordinates of the potential failures or areas of interest are provided to a field crew, which is then able to conduct a rapid targeted assessment of the stability failures.

The time required to collect aerial imagery of habitat features by drone typically took less than ten minutes per kilometre of creek. However, post-breach conditions required access roads to be put in to allow river construction and accessibility. As a result, launching and retrieving the drone was relatively easy and may not be comparable to field conditions encountered in other systems. Inventorying habitat features and assessing stability can be performed at a rate of approximately 100 features per hour with a trained technician. Variability in processing times may arise from factors that increase complexity in feature identification (*e.g.*, riparian vegetation, lighting conditions, water surface reflection and turbidity), particularly for deeper systems with submerged features.

RESULTS AND DISCUSSION

The initial results of early application of this method are included below. The construction of habitat in Edney and Hazeltine Creeks remains in its early stages, and Hazeltine Creek habitat construction is not complete. However, a spatial database of creek habitat features has been established and used to assess stability for two freshet periods in constructed portions of creek. A summary of the features in the database is provided in Table 2.

Table 2: Summary of constructed features in GIS database

Habitat Feature Type	Occurrences per 100 m of Stream Length		
	Hazeltine Reach 1 (500 m)	Hazeltine Reach 2 (1775 m)	Edney Creek (500 m)
Boulders	142	53	141
Large woody debris	48	26	29
Weir	3	2.5	3.5
Bed load stabilizer	0	0.5	0

Overall, the physical stability analysis showed that the engineered channel and habitat components were physically stable. Of the total of 770 spatially monitored features, 757 had not moved over the course of two years of monitoring, as of the date of this paper. The method employed was able to detect 13 features that had not remained physically stable. There were no instances of "false positives" where movement was identified when in fact it had not occurred.

As an example of movement captured, the detected LWD non-stability occurrences in Edney Creek included both shifts in alignment and complete detachment from the anchoring (Figure 3 and Figure 4). Follow up field surveys were able to determine that these failures came from a failure of the anchoring hardware, and in response, these features were replaced and re-attached to their original locations.

Figure 3: Stability failure leading to the change in orientation of a piece of large woody debris.

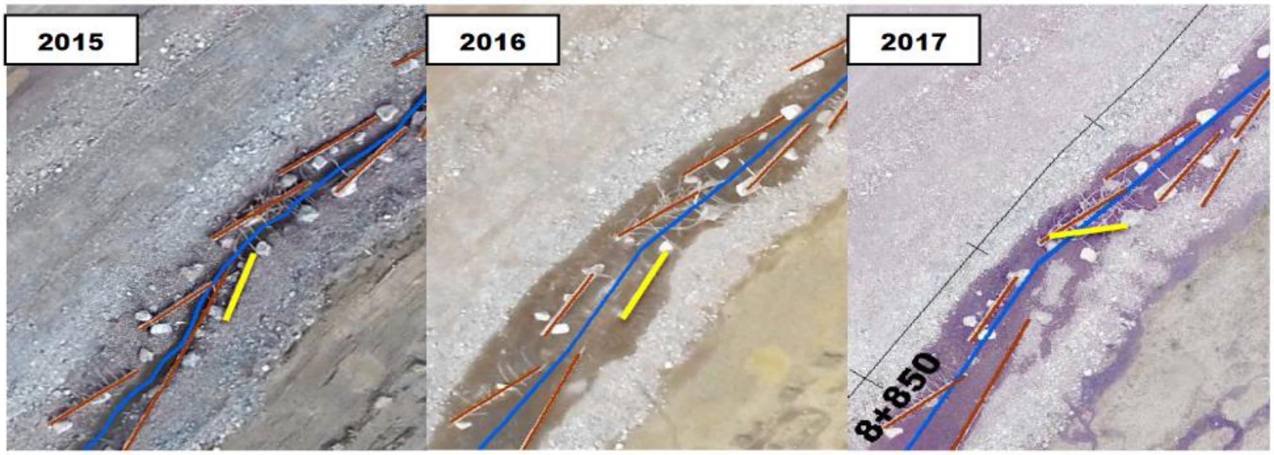

Figure 4: Stability failure leading to the complete detachment of a piece of large woody debris.

The verification of habitat performance is an important part of Canada's conservation-based approach to fish habitat management where federal law and policy allows for changes to habitat to accommodate needs for change to habitat but that comes with a series of requirements, often including the construction of habitat offsets (in-kind compensation). Effective policy implementation requires verification of the performance of the built habitats. These early findings show promise for the approach described to provide a comparatively low cost but effective technique for monitoring the physical stability of constructed riverine habitats.

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