*Dear Associate editor:*

*Authors have responded to all comments below in full, with reviewer comments shown in bold, and responses as regular text. Notable new additions to the paper include, a simplified title and sharpening of sections at the request of the reveiwers. See below for detailed replies to all queries from the reveiwers.*

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**REVIEWER 1 COMMENTS**

**#################**
**General Comments**
**#################**

**The topic of the paper is interesting and tackles an important question related to the efficient field measurements of the river systems, which are having forest canopy. The paper is overall good, and especially the researchers from the fields of remote sensing and fluvial geomorphology will be interested in reading it. The authors have done huge work in field and with data processing. The methods are up-to-date and the paper is unique. However, before being possible to publish it, the manuscript would need clarifications in many sections, and rearrangement of the sentences / paragraphs. The terminology related to the spatial scales would be needed to define more precisely, so that readers would understand more easily what is meant with large, small etc. Overall, precision in the statements would make the paper more easily readable. The justification of the paper would be needed to write more clearly in the introduction section. The texts and figures presented in the results and discussion sections would need also re-arranmegent. Also attention should be paid to the sub-titles. Overall, clarification of the text and justification of the importance of the selected topic, methods and gained results would be needed throughout the paper. Therefore, major modifications are suggested.**

The authors are grateful for the constructive comments and thoughtful suggestions from Reviewer 1. Improvements have been made to the paper to add precision to our statements. In addition, we have incorporated more text into the introduction clarifying why we believe RPAs should be considered for surveying small forested channels and added justification for the variables included in our study. We have also sharpened several of the subtitles in the paper and reorganized some portions of the text at the request of Reviewer 1. These changes are further described in the queries below.

**#################**
**Specific comments:**
**##################**

**Title of the paper: Consider deleting words rapid and objective from the title. Introduction or aims do not include these words, and justification and need of the rapidness of the techniques does not come clearly evident from the introducing sections. Or, if wanting to keep those words, add description about the rapidness and objectivity of the approach in the introduction section. I also suggest that the close-range remote sensing approach could be good to appear in the title some way or another.**

The comment has been accepted. At the suggestion of Reviewer 1, the title has been changed to “Characterization of morphological units in a small, forested stream using close range RPA imagery”.

**Abstract: The following sentence is slightly contradictory, as you talk about both large areas and small streams. "This paper seeks to demonstrate an objective method for characterizing channel attributes over large areas, using easily extractable data from RPA imagery collected under the forest canopy in a small (width = 10 to 15 m) stream.." What do you mean with large areas? Could you clarify and modify the sentence so that it does not cause the reader to be confused between the different spatial scales under question.**

The intention was to highlight that the survey was conducted in a small forested stream, over a large section of the channel's longitudinal profile (3 km). At the suggestion of Reviewer 1, we have modified this sentence in the abstract of the revised text with the following sentence starting at L7 on page 1:

"This paper seeks to demonstrate an objective method for classifying channel morphological units in small, forested streams and to provide information on the spatial scale necessary to capture the dominant spatial morphological variability of these channels. This goal was achieved using easily extractable data from close-range RPA imagery collected under the forest canopy (flying height = 5 – 15 m above ground level) in a small (width = 10 – 15 m) stream along its 3 km of salmon-bearing channel.

**Abstract: "The results demonstrate that sub-canopy RPA surveys provide a viable alternative to traditional survey approaches for characterizing these systems, with 87% coverage of the main channel stream bed." Cold you specify already here, what are the traditional survey approaches? Does this relate to the flight altitude?**

We have adjusted this line to show that the intent was to refer to ground-based approaches (e.g. total station, automatic level) with the following text starting at L16 on page 1:

"The results demonstrate that sub-canopy RPA surveys provide a viable alternative to traditional ground-based survey approaches for mapping morphological units…"

These classification approaches are further described the introduction of the revised text, which have historically been better suited and more widely applied to streams like Carnation Creek, with the following text starting at L45 on page 2:

"Traditionally, characterization and classification of channels through field surveys has required the use of a variety of GPS-based tools and linear-survey methods involving automatic levels, theodolites, and total-stations"

**In addition, it would be actually important to also mention the flight altitudes (etc. details, which show how your method differed from the traditional approaches) in the abstract, as I would imagine that in the sub-canopy flights the height of the platform was low.**

This is correct, the flying height of the RPA was quite low. This information has been added to the abstract of the revised text with the following at L9 on page 1:

"This goal was achieved using easily extractable data from close-range RPA imagery collected under the forest canopy (flying height = 5 – 15 m above ground level) in a small (width = 10 – 15 m) stream along its 3 km of salmon-bearing channel.."

**Lines 20-22: You mention that "These characteristics can lead to a high degree of spatial variability and…". Could you clarify the sentence, especially "spatial variability" of what? Both the first and**

**second sentence of the introduction are slightly vague, and would need clarification, so that the start of the introduction would be stronger. It feels like there is repetition also in those first two sentences. Thus, make the beginning of the introduction sharper.**

We have merged these sentences together with the sentence below to clarify at L26 on page 2:

"Morphological unit classification may be particularly important in forested, gravel bed streams, where episodic and transient geomorphological processes (Pryor et al., 2011;Wohl and Brian, 2015; Hassan et al., 2019), can lead to a high degree of channel complexity even within a relatively homogeneous channel type (Madej, 1999; Nelson et al., 2010; Gartner et al., 2015).

At the suggestion of Reviewer 2, the first two paragraphs of the introduction haven been reworked for clarity and terminology as well.

**In addition, it would be good to mention already in the first paragraph in detail what are the channel characteristics, which are important for the "management", and for the study, and why those are important? Is it only gradient, as that is the only one mentioned? The justification for the variables/metrics and their wider applicability does not come clear from the introduction. Therefore, the sharper beginning of the introduction and also more clearer justification for the study (parameters, and why their detection is important) would enable the reader to understand the uniqueness and importance of the paper more clearly.**

The authors agree with this suggestion. This has been incorporated with the following lines starting at L63 on page 3:

"The primary objective of this paper is to develop and test a methodology based upon spatially continuous RPA-derived data in order to objectively classify morphological units and characterise scales of variability in small, forested rivers under dense forest canopies. The variables considered for the classification include channel slope, water depth, and grain size characteristics, all of which reflect larger basin-scale controls on channel morphology (Buffington and Woodsmith, 2003), and are easily extractable from RPA imagery. Channel slope is a key variable to consider, as it has been shown that there is a general progression of channel morphologies from pool-riffle, plane-bed, and step-pool to cascade morphologies with increasing slope (Montgomery and Buffington, 1997). Water depth metrics are important for discriminating between pool areas and other shallow water environments. Finally, grain size is a key variable as there tends to be a coarsening in bed material from glides and pools to riffles and runs (Garcia et al., 2012).

**Lines 50-54: The authors refer to Kasvi et al. (2019). That study has been done in a river system, having small channel width especially during the low flow periods. Therefore, please clarify the sentences so that the readers do not get an idea that Kasvi et al. (2019) paper has been done in larger river system. Again, please, define also in those lines 50-54, what do you mean with larger system / how do you define larger system?**

The authors appreciate this comment from Reviewer 1. Relative to Carnation Creek, the authors would consider the stream investigated by Kasvi et al., (2019) to be large. We have added the definition of channel size from Hassan et al., (2005), starting at L54 on page 2 :

“However, much of this work has been limited to larger systems. Given the importance of in-stream wood for channel structure and function (Hassan et al., 2019), we consider the classification by Hassan et al. (2005) for small to intermediate streams in the Pacific Northwest as those where the ratio between bankfull channel width to wood length is close to or greater than one and the ratio between wood piece diameter to bankfull depth is close to or greater than one (see Table 2 of the paper for more details). Streams on the intermediate side of this spectrum, where the ratio between bankfull channel width to wood length is close to one, differ from larger systems as they can be greatly influenced by wood delivered to the channel (Wohl and Scott, 2017). These channels are often overlain by dense forest canopies and are poorly suited to observation from above the forest canopy. This limitation has historically excluded a large fraction of river network length from RPA-based surveys.”

**Line 57: What is meant with “continuous RPA-derived data”? Is that spatially or temporally continuous?**

The authors had intended to be referencing the fact that data acquired from an RPA is continuous across the channel (i.e. space, rather than time). By contrast, field methods for surveying channels often involve discrete cross sections or points that must be interpolated. This has been clarified by adding “spatially continuous” to L63 on page 3 of the revised text.

**Lines 100-101: What is the altitude of the low-level flights? Please, specify already here (i.e. where you first time mention these flying specifications), and not in he later sentences.**

We have rearranged the paragraph so that the flying specifications appear when the RPA survey is first introduced in section 3.1 of the revised text (see L119 on page 5).

**Lines 100-102: You write “The RPA survey involved low-level flights conducted in tandem with placement of Ground Control Points (GCPs) that were surveyed with a Leica TPS 1100 total station.” Did you take the reference points from the sub-water areas also? Or how do you calculate the accuracy of the bathymetry cells, which you talk about in results section 4.1? Please add in the methods section clearly, how the reference points for these RMSE and ME calculations were measured, and did you measure them also from the sub-water area and how (also with a total station similarly as the dry land areas and the GCPs)? Thus, some clarification and sharpness would be needed to the methods section also.**

The authors have reworded these lines to make the survey method clearer. To reiterate, all GCPs and checkpoints were surveyed with a Leica TPS 1100 total station. The GCPs were only positioned on the dry exposed bars, whereas checkpoints include both the dry exposed bars and submerged points. This is described in the following lines of the revised text, starting at L137 on page 7:

“A minimum of ten GCPs were placed along dry exposed bars in each of the 80 channel segments to provide precise image georeferencing, with additional points positioned on the dry exposed bars and below the water surface in order to serve as independent checkpoints, to assess the accuracy of the model outputs. All GCPs and checkpoints were surveyed with a Leica TPS 1100 total station. Open survey traverses were tied into the benchmarks previously established in the study sections, and then an affine transformation applied to georeference the points in the XY-plane. The average offset between the benchmark elevations of the local open traverse and their known reference elevations were then used to georeference the points in the Z-plane. Errors were typically 2 cm in the XY-plane, and 1 cm in the Z-plane. The majority of the GCPs were distributed in a zig-zag fashion along dry exposed bars in the periphery of the channel segments, with a smaller number situated towards the centre.

**Line 114: You mention riparian vegetation here for the first time. How high is the riparian vegetation and what are the species. Was there grass and shrubs, or do you mean the "dense forest canopy composed of both coniferous and deciduous tree species", which you talk about in the study site section? In addition to mentioning the heights of the riparian vegetation (which were cleaned away from the data based of the filters), it would be good to also introduce the riparian vegetation in the study site section.**

This comment has been accepted and is addressed with the following lines in the study area section of the revised text, starting at L92 on page 4:

"The riparian vegetation includes a variety of tree species including western hemlock (Tsuga heterophylla), Amabilis fir (Abies amabilis), western redcedar (Tsuga plicata), Sitka spruce (Picea sitchensis) and red alder (Alnus rubra). The height of the riparian canopy is variable, between approximately 15 and 40 m. The riparian forest floor is composed of a variety of ferns and shrubs, such as salmonberry (Rubus spectabilis), sword fern (Polystichum munitum), trailing blackberry (Rubus ursinus) and thimbleberry (Rubus parviflorus) that may provide some cover to the channel."

**Relates to the methods and discussion section: Did the canopy effect on the pixel values of the water area? As you defined the bathymetry based on Dietrich et al. (2017) method, did the shadows and reflections of the canopy harm the water pixel colors and bathymetry calculations? What was the turbidity of the water? That information would be important to add, from the measurement times. The success of the Dietrich et al. (2017) method could depend on how turbid / clear the water was. Please, discuss about this in the discussion, and present how the turbidity was taken into account in the methods section.**

At the suggestion of Reviewer 1, we added additional text pertaining to this in the revised text, starting at L160 on page 8:

"The method requires that the water be clear such that the channel bed can be captured. The low flow conditions present at the time of the survey resulted in clear water that permitted viewing of the channel bed. Removal of overhanging vegetation using the Cloth Simulation Filter in Cloud Compare, and subsampling the DEMs to a spacing of 0.02 m using the minimum elevations in the point cloud, helped to ensure that the refraction correction was based on channel bed points and not on overhanging vegetation points that may have been incorporated in the point cloud."

As now described in the paper, Carnation Creek was very clear and turbidity was not an issue at the time of the survey. The point cloud was cleaned to remove anomalous points from overhanging vegetation that may have been incorporated into the cloud. The individual effect of factors such as shadows and reflections on the bathymetry calculations was not investigated, but rather the total errors between RPA derived submerged elevations and total station measured elevations presented in Fig. 4.

**Lines 139 -145: The authors introduce here the method for grain size estimation. However, this is the first time grain sizes are mentioned in the manuscript. Thus, there is no background literature in the introduction section, or justification why this calculation is important to conduct. You mention "a**

**metric often of interest to river managers", but it would be important to justify here, why these metrics are important for your study. Please, add in the introduction and/or in the methods section, why the grain size is needed to be defined. To some readers the necessity to define the grain sizes is not self evident.**

See our reply to your previous comment on "In addition, it would be good to mention already in the first paragraph in detail what are the channel characteristics, which are important for the "management", and for the study, and why those are important? ". We have reiterated this in the methods section where we note that grain size is a frequently described metric in classification schemes, such as Montgomery and Buffington's (1997) classification scheme (L165 on page 8).

**Line 173: I am not a native English speaker, but I think this following part of the sentence is missing one preposition "data along the… -> change it as "data along WITH the first".**

We have clarified this sentence with L220 on page 10:

"Following the PCA, the k-means clustering algorithm was run to identify groupings that may have been present in the data along its first three components."

**Many of the figures appear only within the discussion section, and the results defined in some of the figures are not analyzed in detail in the text of the results section. For example, Fig. 8 appears on page 15, but it is talked with two sentences on the page 10. Thus, rearrange the appearance of the figures so that the text and figures appear "hand-in-hand".**

The authors accept this comment. The figures have been rearranged such that the text and figures appear "hand-in-hand".

**Despite the channel morphology was one of the main topics talked in the introduction section, the channel variables and the results of the morphological detection have not been given full attention in the results section. So, please, add text in the results section related to the morphological characteristics and their spatial variation.**

The authors accept this comment. We have added text to section 4.2.1 starting at L263 on page 15 further describing differences between the identified channel types and their relative positions:

"However, plane-bed and coarse riffle morphological units are mostly located near the upstream limit of the survey extent in this region. This area represents the outlet and downstream entrance of the canyon reach, where steeper gradients and coarser sediment are found. This is highlighted in Table 2, which shows that on average these morphological units are located 3160 m upstream, with steep reach scale gradients of 0.042 m/m and coarse material with an average D50 of 8.21 cm. Similarly, the coarse riffle morphologies were located approximately 2980 m upstream on average, with relatively steep gradients and coarse material (reach scale slope = 0.024 m/m and D50 = 6.74 cm). By contrast, the average positions of the riffle, glide, run and pool morphologies were approximately 1500 m, midway along the channel's profile, indicating that these morphological units are distributed over a greater length of channel. Grain size was generally similar between these morphologies, except for the riffle unit, which was slightly coarser with a D50 of 4.10 cm. Pools were the deepest, with average water depths of 1.04 m and near zero water surface slopes, whereas riffles were the shallowest with average water depths of 0.13 m and relatively steep water surface and reach scale bed slopes. Glides and runs were intermediate between these morphologies, with glides often retaining negative local bed slopes, corresponding with the exit of pools, and runs with large positive local bed slopes, corresponding with the entry of pools."

**Discussion: Many of the sentences (such as on lines 249- 255, and 278–285) should already be presented in the results section. Therefore, rearrangement of the discussion would be needed. I am not pointing out all of the sentences in question, as there are many of them. My advice is that when you present something for the first time based on your analysis or the data sets, move those sentences under results section. Discussion is then reflection of your results (presented already previous sections) against other studies.**

The authors appreciate this perspective from the reviewer. It was the intention of the authors to have the Discussion reiterate the key findings of the study, and then introduce relevant references that help situate these findings. We have reworded lines 249-255 of the original text to make relationships between reiterated findings and references included to provide context clearer.

Regarding lines 278-285 of the original text, the table those lines discuss was included to make it easier for the reader to compare the mean values of the morphologies in our study to others in the literature. The values presented in the table for our study were extracted from Table 2 in the results. As suggested by Reviewer 2, we have also added a new Table 1 to the introduction summarizing the criteria for the classification schemes by Church (1992), Anonymous (1996) and Buffington and Woodsmith (2003). As those lines situate the results of our classification scheme in the literature, the authors feel they are still suited to the discussion and are in line with the reviewers suggestion that the "Discussion be a reflection of your results (presented already previous sections) against other studies".

**Many of the sub-titles of the results and discussion section are methodological in their nature. Go through the titles of the manuscript and modify them so that they show that it is results and discussion in question, and not an introduction to the methods. Now the titles give slightly different idea of the content than what the content actually is: such as, "5.2 Classification approach" sounds like the section would include an explanation how the classification method was used, even though it is discussed about the "success of the classification approach". Thus, the titles of the results and discussions sections are misleading.**

The authors accept this comment. As suggested by Reviewer 1, we have changed the titles for the following sections: 4.1, 4.2. 4.2.1, 4.3, 5.1, 5.2.

**REVIEWER 2 COMMENTS**

**#################**
**General Comments**
**#################**

**The paper presents a novel and useful methodology for mapping channel morphology that is well within the scope of ESurf. The methods were sound, logical and well presented. The introduction and discussion for the paper could use some adjustments, in particular clarification of the use of terminology such as channel morphology, morphological units, channel units, channel type, and morphology type. It was difficult to follow what was meant by each of these terms and if they were being used interchangeably or not. From the introduction I was expecting more of a reach scale channel type classification scheme, but I would argue that what this paper does would be better described as mapping or classification of morphological units (also called geomorphic units, channel units, habitat units, etc).**

The authors are grateful for the constructive comments from Reviewer 2. In particular, the comment on using a consistent channel morphology terminology is an important one. The authors have updated the manuscript such that we are consistent with referring to the scheme classifying "morphological units" or "channel units". Please see below for detailed responses to further queries.

**#################**
**Specific comments:**
**##################**

**Title: I recommend the title including that the method uses a RPA or remote sensing**

The comment has been accepted. At the suggestions of Reviewer 1 and Reviewer 2, the title has been changed to "Characterization of morphological units in a small, forested stream using close range RPA imagery".

**Abstract: Line 6 states "This paper seeks to demonstrate an objective method for characterizing channel attributes over large areas, using easily extractable data from RPA imagery collected under the forest canopy in a small stream, and to provide information on the spatial scale necessary to cacpture the dominant spatial morphological variability of these channels." - Rather than saying "characterizing channel attributes" it would be more precise for the author to say they are classifying or mapping channel morphological units. - provide clarification to what constitutes "large areas" - in "provide information on the spatial scale" does spatial scale mean longitudinal spatial extent?**

This comment has been accepted. At the suggestion of Reviewer 2, we have replaced "characterizing channel attributes" with "classifying channel morphological units". Furthermore, at the suggestions of Reviewers 1 and 2, we have clarified the spatial scales under investigation with the text below, starting at L7 on page 1:

"This paper seeks to demonstrate an objective method for classifying channel morphological units in small, forested streams and to provide information on the spatial scale necessary to capture the dominant spatial morphological variability of these channels. This goal was achieved using easily extractable data from close-range RPA imagery collected under the forest canopy (flying height = 5 – 15 m above ground level) in a small (width = 10 – 15 m) stream along its 3 km of salmon-bearing channel.

**Abstract: Line 14 "for characterizing these systems" it also would be better here to be more precise about mapping or classifying morphological units.**

This comment has been accepted. At the suggestion of Reviewer 2, we have replaced "for characterizing these systems" with "mapping morphological units" in L16-17 on page 1.

**Introduction: paragraphs 1 and 2 were confusing and misleading to me and could use clarification between reach scale stream classification and smaller, geomorphic/morphological/channel unit scale.**

This comment has been accepted. At the suggestion of Reviewer 1 and Reviewer 2, the first two paragraphs of the introduction on pages 1 and 2 have been reworded for clarity and to describe that the analysis is aimed at classifying morphological units:

"Channel morphological units such as pools and riffles constitute the building blocks of reach scale channel morphologies (Buffington and Montgomery, 2013), with spatial variability in these units providing critical habitat diversity. As a result, characterization of morphological units is a goal of many habitat-based classification schemes (e.g. Hawkins et al., 1993). Morphological unit classification may be particularly important in forested, gravel bed streams, where episodic and transient geomorphological processes (Pryor et al., 2011;Wohl and Brian, 2015; Hassan et al., 2019), can lead to a high degree of channel complexity even within a relatively homogeneous channel type (Madej, 1999; Nelson et al., 2010; Gartner et al., 2015). Within these streams, classification schemes can serve an important role in facilitating discussions on stream management (Buffington and Montgomery, 2013). This is evident in the array of classification schemes proposed to characterise channel types and morphological units for both geomorphologists and ecologists alike (e.g. Hawkins et al., 1993; Rosgen, 1994; Montgomery and Buffington, 1997; Brierly and Fryirs, 2005). A common challenge of these classification approaches, however, is their descriptive nature (Buffington and Montgomery, 2013; Hassan et al., 2017) and that their implementation can be subjective, differing between classifiers.

Challenges in objectively classifying morphological units are further compounded by difficulties in determining the appropriate spatial extent for capturing the primary structural variability that influences geomorphological and ecological processes at the reach or basin scale. While approaches are often taken to select 'representative sites' when the characterisation of channel variables is necessary (Harrelson et al., 1994; Bisson et al., 2006), site selection is often based on a narrow subset of metrics (e.g. gradient, see Montgomery and Buffington, 1998) and 'rules of thumb' are frequently used to define the spatial extent of the surveyed area (Bisson et al., 2006). Furthermore, traditional survey techniques often limit classification to short, accessible channel areas due to time and cost constraints, and these limitations may bias our understanding of the larger river network as a result of missing important channel areas and processes (Fausch et al., 2002; Hugue et al., 2016). Given the logistical difficulty and cost of undertaking field surveys in small, forested, gravel-bed streams, a more precise approach for site selection and objective technique for classifying morphological units is warranted."

**Methods: Line 146 says that in-stream wood was digitized, but I did not see this used or relevant later in the paper**

The authors accept this comment. Channel wood was digitized as part of the initial inventory of channel variables but was not used in the analysis. The line has been removed from the revised manuscript.

**Section 3.3: The author states that the 5 variables were chosen in part "because they reflect larger basin scale variables relevant to channel form, such as geology, climate and land use." A citation and/or examples here seem necessary**

The authors have cited Buffington and Woodsmith, 2003 here (L66, page 3). Specifically Figure 1 of their paper shows how the channel characteristics we included give rise to channel types, and are the manifestation of certain process drivers and watershed conditions. In addition, at the suggestion of Reviewer 1, we have added the following text explaining why those variables were selected, starting at L67 on page 3:

"Channel slope is a key variable to consider, as it has been shown that there is a general progression of channel morphologies from pool-riffle, plane-bed, and step-pool to cascade morphologies with increasing slope (Montgomery and Buffington, 1997). Water depth metrics are important for discriminating between pool areas and other shallow water environments. Finally, grain size is a key variable as there tends to be a coarsening in bed material from glides and pools to riffles and runs (Garcia et al., 2012)."

**Analysis: Section 3.4: line 178 describes how a morphology type is attributed to each cluster. It would be helpful to lay out prior to this what the morphology types being used are, and the criteria used for them. The author does cite 3 papers for the criteria, but it isn't clear what specific criteria from those papers were used. Also, within this paragraph it isn't clear if morphology type is synonymous with channel type or not.**

The authors accept this comment. The morphological units being classified have now been introduced prior to introducing the criteria (starting at L205 on page 10). A table (now Table 1) has also been added summarizing the criteria extracted from these papers. The terminology has also been changed to morphological unit to ensure consistency through the manuscript:

"Following clustering of the cross-sectional variables, the mean values of each channel variable for each cluster were examined and one of the following morphological units attributed to each cluster: pool, riffle, coarse riffle (riffleC), glide, run or plane-bed. The units were assigned to clusters based on obvious features (e.g. shallow water slopes and greater depth for pools, negative pool exit slopes for glides, and steeper pool entry slopes for runs) and criteria presented in Church (1992), Anonymous (1996), and Buffington and Woodsmith (2003). These criteria are described in Table 1. The resulting assignment of morphologies to clusters leads to a continuous classification of morphological units found along the study reach at 1 m intervals, and provides insight into the survey extents necessary to adequately capture the heterogeneity of the system."

**Figure 6: needs a scale bar**

This authors accept this comment. A scale bar has been added to Figure 6.

**Conclusion: The conclusion would be easier to follow if it were organized in the same order as the rest of the paper.**

The authors accept this comment. We have rearranged the paragraph so that acquisition of RPA derived rasters and ensuing PCA comes first, followed by the sentence on the exploration of the necessary spatial extent to capture the channels variability. This now follows the order of the methods.

**REVIEWER 3 COMMENTS**

**#################**
**General Comments**
**#################**

**This manuscript presents the results from an investigation to generate a high-resolution orthoimage / topographic survey of c. 3 km of channel that is beneath a forest canopy. The geospatial products are used to extract metrics to characterise channel morphology, which are subsequent used to characterise longitudinal variation in channel morphology and to assess these trends relative to those reported in wider literature. The survey effort is impressive and undoubtably novel in its ambition; I am not aware of a similar survey. However, there are aspects of the methodological description that are unclear. I also think that the authors are overselling the approach as rapid and are not sufficiently critical of how transferable the technique may be to other forested environments (e.g. where canopy densities vary, where launching the UAV from under the canopy may be more challenging, for forested rivers without unvegetated bars etc) and thus a more critical analysis of the technique could be provided. Below, I expand upon these aspects.**

The authors are grateful for the constructive comments and detailed review from Reviewer 3. The authors have included text to sharpen several aspects of the methodology. Please see below for detailed responses to further queries.

**#################**
**Specific comments:**
**##################**

**Title. Is the technique really rapid? The survey effort is still considerable from both a UAV flight and ground control perspective, and there are still some data gaps where total station survey is needed.**

Relative to a dense total station survey, the authors considered the acquisition of continuous data to be rapid. As noted in the Discussion, with the RPA we could capture, on daily average, three times more of the channel's length than that covered with a total station full channel survey. However, relative to other approaches (such as an automatic level survey of the channels longitudinal profile, or RPA surveys done at a greater height above ground level), it may not be considered rapid. As this detail cannot be discerned from a short title, the authors accept the comment and have removed "Rapid" from the title for:

"Characterization of morphological units in a small, forested stream using close-range RPA imagery".

**L9-11. More methodological detail could be provided here; reading the abstract alone I'm not able to decipher what exactly how the imagery were used (orthoimage, DEM etc). Can you give examples of the "variables".**

The authors accept this comment, and have incorporated the following text into the abstract (starting at L12 on page 1):

"From this survey data, relevant cross-sectional variables (hydraulic radius, sediment texture and channel slope) were extracted from high resolution point clouds and DEMs of the channel, and used to characterise channel unit morphology using a principal component analysis-clustering (PCA-clustering) technique."

**L101. More details are needed on the total station control network and associated errors (e.g. closure errors from traverses). How accurate are the control points?**

The total station survey was an open survey, as it was not feasible to re-survey the 3 km of channel to the close the traverse. Rather, the open traverses were tied into the benchmarks previously established in the study sections. This has been clarified with the following, starting at L140 on page 7:

"Open survey traverses were tied into the benchmarks previously established in the study sections, and then an affine transformation applied to georeference the points in the XY-plane. The average offset between the benchmark elevations of the local open traverse and their known reference elevations were then used to georeference the points in the Z-plane. Errors were typically 2 cm in the XY-plane, and 1 cm in the Z-plane."

**L104. How high was the canopy?**

At the suggestion of Reviewer 1, we have added more details on the forest characteristics surrounding the channel in the study area section (L94, page 4):

"The height of the riparian canopy is variable, between approximately 15 and 40 m."

**Were the flight plans pre-planned or was the UAV operated manually? You are arguing that this is a feasible survey approach, so some more details on the logistical / technical challenges would be useful here. If you had a pre-programmed flight, then could you obtain sufficient GNSS "lock" for navigation?**

The flights were conducted manually as due to channel obstacles, and the channel being hidden below the canopy, pre-planning the flights would have been challenging. We have added more text highlighting this with the following in section 3.1 (starting at L118 on page 5):

"The RPA survey involved low-level flights (5–15 m above ground level) conducted in tandem with placement of ground control points (GCPs) on the dry exposed bars and checkpoints on both the exposed and submerged bed. Flights were operated manually as as low-hanging vegetation and the forest canopy made pre-planned flights impractical."

**L135. Were any independent total station check points obtained to evaluate the accuracy of the bathymetric correction?**

Yes independent total station check points were obtained for the evaluating the bathymetric correction. See our response to the previous comment where we have clarified that we did have submerged checkpoints. In addition, we have added the following text, starting at L137 on page 7:

"A minimum of ten GCPs were placed along dry exposed bars in each of the 80 channel segments to provide precise image georeferencing, with additional points positioned on the dry exposed bars and below the water surface in order to serve as independent checkpoints, to assess the accuracy of the model outputs. All GCPs and checkpoints were surveyed with a Leica TPS 1100 total station."

The errors are further highlighted in Fig. 4.

**L141. Insufficient detail is given on the photo-sieving technique and how images were acquired from 2 m above ground level. If topographic roughness was calculated then were the multiple images acquired to generate a point cloud using SfM? How was the point cloud georeferenced? What was the ground sampling distance to sample 0.0025 cm roughness (smallest sample on figure 3; this seems VERY small). Are the units correct here?**

The authors accept this comment. We have clarified how the sample sites were photoseived, and how the point clouds were extracted, with the lines below (starting at L169 on page 8) :

"Each roughness sampling site was approximately 1 $m^2$ and imagery was captured for photosieving by hovering the RPA approximately 2 m above ground level. Using an in-house photo-sieving program based in Matlab (Matlab, 2017), the grain size distribution of each training site was determined. The program loads the image, prompts the user to scale the image, and then overlays a grid with 50 nodes prompting the user to measure the B-axis of grains falling below a grid node. Point clouds for each sample site were then extracted from the georeferenced point cloud that was developed for the study section that they fell within. A linear model then was then fit between each sample's D50 (Fig. 3) and their mean roughness value."

The authors thank the reviewer for noticing the error in the x-axis units for Fig 3. Initially the units were in m, but the figure has been updated so that they are in cm.

**Figure 5. It would be interesting to see elevation values for the raster. Why are bathymetry and elevation not mosaiced together (perhaps it is the legend labelling that makes this unclear)? For SA5, what explains the abrupt change in bathymetry value (shown as a vertical line) in approximately the middle of the reach?**

The intention of Fig. 5 was to show the relative coverage between the RPA survey and total station surveys. Elevations vary from around sea level at the mouth of Carnation Creek to about 140 m.a.s.l at SA9. This wide range in elevations would require each SA have its own colour bar to effectively be able to visualize patterns in elevation. Therefore, the terrain of the bed was instead shown as a hillshade layer to show patterns in bed texture without resulting in a busy figure that may take away from the Figure's purpose: to show the coverage with the RPA relative to the total station surveyed boundaries. Instead, Figure 9 was included which shows patterns in elevation along a section of the channel.

Fig. 4 in the manuscript shows that the majority of the ~ 1700 checkpoint errors were on the cm scale, indicating situations such as that observed in SA5 are outliers in the larger survey effort. Visual inspection of the point cloud reveals that this area, which is characterized as being largely submerged with dense low-lying vegetation on the fringe of a new survey section, had a lower density of points, potentially resulting in stitching issues. It should be noted that a strength of the PCA is that it highlights patterns in a dataset, and not potentially noisy areas as in SA5. In other words, although in the 3 km of channel there may be some anomalous values from poorly aligned sections, these "outliers" should not affect the general trend identified by the PCA. Text has been added to the manuscript highlighting these points in the following sections.

In the "Utility of sub-canopy RPA surveys for small, forested streams" section we have clarified our sentence on image capture difficulties with L312 on page 20:

“In addition to bank vegetation causing obstructions, submerged areas with little texture and low-hanging branches (predominantly from riparian deciduous species) occasionally led to flight difficulties that prevented sufficient collection of imagery for photo-stitching.”

In the “Assessment of classification approach” section, we added text starting at L327 on page 20:

“Another advantage of the PCA is that it highlights the trends present in a dataset, rather than focussing on specific features. For example, anomalous areas where imagery may have had stitching issues due to poor coverage (e.g. SA5 in Fig. 5) would likely appear as noise, thereby having a minimal influence on the PCA.

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# ~~Rapid and objective characterization~~ Characterization of ~~channel morphology~~ morphological units in a small, forested stream using close-range RPA imagery

Carina Helm[1], Marwan A. Hassan[1], and David Reid[1]

[1]1984 West Mall Rd. Vancouver B.C. Canada

**Correspondence:** Carina Helm (helm.carina@gmail.com)

**Abstract.**

Forested, gravel bed streams possess complex channel morphologies which are difficult to objectively characterise. The spatial scale necessary to adequately capture variability in these streams is often unclear, as channels are governed by irregularly spaced features and episodic processes. This issue is compounded by the high cost and time-consuming nature of field surveys in ~~this type of environment~~these complex fluvial environments. In larger ~~stream systems~~streams, remotely piloted aircraft (RPAs) have proven to be effective tools for characterizing channels at high resolutions over large spatial extents, but to date their use in small, forested streams with closed forest canopies has been limited. This paper seeks to demonstrate an ~~objective method for characterizing channel attributes over large areas,~~ effective method for classifying channel morphological units in small, forested streams and for providing information on the spatial scale necessary to capture the dominant spatial morphological variability of these channels. This goal was achieved using easily extractable data from close-range RPA imagery collected under the forest canopy (flying height = 5 – 15 m above ground level) in a small (width = 10 ~~to~~ – 15 m) stream ~~, and to provide information on the spatial scale necessary to capture the dominant spatial morphological variability of these channels~~along its 3 km of salmon-bearing channel. First, the accuracy and coverage of RPAs for extracting channel data ~~was~~ were investigated through a sub-canopy survey. From this survey data, relevant cross-sectional variables ~~were extracted and used to characterize~~ (hydraulic radius, sediment texture and channel slope) were extracted from high resolution point clouds and DEMs of the channel, and used to characterise channel unit morphology using a principal component analysis-clustering (PCA-clustering) technique. Finally, the length scale required to capture dominant morphological variability was investigated from an analysis of morphological diversity along ~~nearly 3 km of~~ the channel. The results demonstrate that sub-canopy RPA surveys provide a viable alternative to traditional ground-based survey approaches for ~~characterizing these systems~~mapping morphological units, with 87% coverage of the main channel stream bed achieved. The PCA-clustering analysis provided a ~~more~~ comparatively objective means of classifying channel unit morphology with a correct classification rate of 85%. ~~Analysis of morphological diversity suggests~~ An analysis of the morphological diversity along the surveyed channel indicates that reaches of at least 15 bankfull width equivalents are required to capture the channel's dominant morphological heterogeneity. Altogether, the results provide a precedent for using RPAs to ~~characterize~~ characterise the morphology and diversity of forested streams under dense canopies.

## 1 Introduction

Processes and features within Channel morphological units such as pools and riffles constitute the building blocks of reach scale channel morphologies (Buffington and Montgomery, 2013), with spatial variability in these units providing critical habitat diversity. As a result, characterization of morphological units is a goal of many habitat-based classification schemes (e.g. Hawkins et al., 199 . Morphological unit classification may be particularly important in forested, gravel bed streamsmay be transient, episodic, and possess irregular spatial patterns , where episodic and transient geomorphological processes (Pryor et al., 2011; Wohl and Brian, 2015; Hassan et al., 2019). These characteristics , can lead to a high degree of spatial variability and channel complexity , channel complexity even within a relatively homogeneous channel type (Madej, 1999; Nelson et al., 2010; Gartner et al., 2015). From a practical management perspective, there is often a need to characterize such systems to obtain metrics related to channel geometry, flow hydraulics, sediment properties, and aquatic habitat (Buffington and Montgomery, 2013) Within these streams, classification schemes can serve an important role in facilitating discussions on stream management (Buffington and Montgomery, 2013). This is evident in the array of classification schemes proposed to characterise channel types and morphological units for both geomorphologists and ecologists alike (e.g. Hawkins et al., 1993; Rosgen, 1994; Montgomery and B . A common challenge of these classification approaches, however, arises in assigning a specific morphology to complex river sections, an issue is their descriptive nature (Buffington and Montgomery, 2013; Hassan et al., 2017) and that their implementation can be subjective, differing between classifiers.

Challenges in objectively classifying morphological units are further compounded by difficulties in determining the minimum spatial extent necessary to capture appropriate spatial extent for capturing the primary structural variability present in forested gravel bed streamsthat influences geomorphological and ecological processes at the reach or basin scale. While approaches are often taken to select 'representative sites' 'representative sites' when the characterisation of channel variables is necessary (Harrelson et al., 1994; Bisson et al., 2006), site selection is often based on a narrow subset of metrics (e.g. gradient, see Montgomery and Buffington, 1998) and ''rules of thumb'' are frequently used to define the spatial extent of the surveyed area (Bisson et al., 2006). Given the logistical difficulty and cost of undertaking field surveys in small, forested gravel-bed streams, a more precise approach for site selection and resulting channel classification is warranted.

Channel classification serves to integrate the variability observed along a given length of channel into specific channel types or morphologies (Harrelson et al., 1994). In addition to describing channel types and patterns, classification schemes have served to facilitate discussions on stream management among disciplines (Buffington and Montgomery, 2013). This is evident in the array of classification schemes proposed to characterize channel morphology for both geomorphologists and ecologists alike (e.g. Hawkins et al., 1993; Rosgen, 1994; Montgomery and Buffington, 1997; Brierly and Fryirs, 2005). However, a common drawback of these classification approaches is their descriptive nature (Buffington and Montgomery, 2013; Hassan et al., 2017) and that their implementation can be subjective, differing between classifiers. Furthermore, traditional survey techniques often limit classification to short, accessible channel areas due to time and cost constraints, and these limitations may bias our understanding of the larger river network as a result of missing important channel areas and processes (Fausch et al., 2002; Hugue et al., 2016). More objective, flexible, and repeatable techniques for characterizing streamsthat can be applied at a scale relevant to the natural geomorphic and ecological processes within them are therefore desirable (see Fausch et al., 2002)Given the logistical difficulty and cost of undertaking field surveys in small, forested, gravel-bed streams, a more precise approach for site selection and objective technique for classifying morphological units is warranted.

Traditionally, characterization and classification of channels through field surveys has required the use of a variety of GPS-based tools and linear-survey methods involving automatic levels, theodolites, and total-stations (e.g. Bangen et al., 2014; Reid et al., 2019). However, advances in our understanding of connections between geomorphological, hydrological and ecological processes across the riverscape require a new approach for fluvial characterization that can capture many variables concurrently and be conducted at scales relevant to key processes and their interactions (Beechie et al., 2010). In consideration of a river network, these spatial scales are often intermediate in length (in the order of kilometers), domains over which continuous, high-resolution characterisation of channel conditions is expensive and time consuming using ground-based survey methods (Fausch et al., 2002). Over the past decade, the use of remotely-piloted aircraft (RPAs) has enabled collection of high-resolution imagery over a range of scales for evaluation of stream bed topography (e.g. Tamminga et al., 2015; Woodget and Austrums, 2017), bathymetry (e.g. Kasvi et al., 2019), and ecological parameters (e.g. Roncoroni and Lane, 2019). However, much of this work has been limited to larger systemswith relatively little obstruction from forest canopy or other overhead obstacles. Given the importance of in-stream wood for channel structure and function (Hassan et al., 2019), we consider the classification by Hassan et al. (2005) for small to intermediate streams in the Pacific Northwest as those where the ratio between bankfull channel width to wood length is close to or greater than one and the ratio between wood piece diameter to bankfull depth is close to or greater than one (see Table 2 of the paper for more details). Streams on the intermediate side of this spectrum, where the ratio between bankfull channel width to wood length is close to one, differ from larger systems as they can be greatly influenced by wood delivered to the channel (Wohl and Scott, 2017). These channels are often overlain by dense forest canopies and are poorly suited to observation from above the forest canopy. This limitation therefore excludes has historically excluded a large fraction of river network length from RPA-based surveys, particularly in densely forested environments.

The primary objective of this paper is to develop and test a methodology using based upon spatially continuous RPA-derived data for objectively classifying channel morphology and characterising in order to objectively classify morphological units and characterise scales of variability in small, forested rivers under dense forest canopies. The variables considered for the classification include channel slope, water depth, and grain size characteristics, all of which reflect larger basin-scale controls on channel morphology (Buffington and Woodsmith, 2003), and are easily extractable from RPA imagery. Channel slope is a key variable to consider, as it has been shown that there is a general progression of channel morphologies from pool-riffle, plane-bed, and step-pool to cascade morphologies with increasing slope (Montgomery and Buffington, 1997). Water depth metrics are important for discriminating between pool areas and other shallow water environments. Finally, grain size is a key variable as there tends to be a coarsening in bed material from glides and pools to riffles and runs (Garcia et al., 2012). In an effort to improve the characterization of these channels, a new framework is developed to map and classify channel attributes through the use of RPA-based data collection under forest canopies. To build this framework, this paper aims to address the following research questions:

1. What are the capabilities and limitations of a survey approach using sub-canopy RPA flights to characterise channel ~~morphology~~ attributes in small, forested streams?

2. Can spatially-continuous RPA-derived ~~continuous~~ measurements be used to objectively ~~characterize~~ characterise patterns in channel morphology?

3. What is the spatial extent of data collection necessary to capture the primary variability in geomorphic channel attributes?

To address these questions, a sub-canopy RPA survey was conducted along approximately 3.0 km of channel in Carnation Creek, B.C., a small coastal stream located on western Vancouver Island. This site serves as a valuable testing area due to the abundance of complementary channel attribute data available (Tschaplinski and Pike, 2017; Reid et al., 2019).

## 2 Study area

This research was conducted along Carnation Creek, a small gravel bed river located on the southwest coast of Vancouver Island, B.C. (Fig. 1). The watershed has been the site of a long-running fish-forestry interactions study focusing on the effect of different logging treatments on watershed response (Tschaplinski and Pike, 2017). The channel mainstem is approximately 8 km long and has a drainage area of 11.2 $km^2$ (Tschaplinski and Pike, 2017). The focus of research is along the lowermost 3 km of the channel, which possesses a low gradient (0.5–1%) and is dominated by a pool-riffle channel morphology. Upstream, the channel narrows into a canyon (Fig. 1) which contains ~~predominantly a~~ a predominantly step-pool morphology and gradient above 5% (Reid et al., 2019). The average bankfull width ($w_b$) of the lower channel is close to 15 m. The channel is located within the Coastal Western ~~Hemlock~~ Biogeoclimatic Zone, common along coastal regions of the Pacific Northwest (Hartman et al., 1982). Visual estimates suggest that over 50% of the channel is hidden below a dense forest canopy composed of both coniferous and deciduous tree species. The riparian vegetation consists of a variety of tree species including western hemlock (*Tsuga heterophylla*), Amabilis fir (*Abies amabilis*), western redcedar (*Tsuga plicata*), Sitka spruce (*Picea sitchensis*) and red alder (*Alnus rubra*). The height of the riparian canopy is variable, between approximately 15 and 40 m. The riparian forest floor is composed of a variety of ferns and shrubs, such as salmonberry (*Rubus spectabilis*), sword fern (*Polystichum munitum*), trailing blackberry (*Rubus ursinus*) and thimbleberry (*Rubus parviflorus*) that may provide some cover to the channel. The environment is typical of the Pacific Northwest: precipitation rates are high and dominated by rain (between 2,900 – 5,000 mm/year), the majority of which falls during the autumn and winter months (Tschaplinski and Pike, 2017). Streamflow ranges from 0.1 $m^3$/s to 64 $m^3$/s in fall and winter months, (Tschaplinski and Pike, 2017), and is often very low ($< 0.01$ $m^3$/s) for extended periods in the summer (Reid et al., 2020). Frequent storms in the winter months lead to multiple floods per year that are capable of mobilizing gravel in the system, with bankfull discharge between 20 and 30 $m^3$/s (Haschenburger, 2011).

The processes governing the morphological and hydraulic conditions in Carnation Creek are irregular in both time and space, creating a great deal of heterogeneity along the channel. Sediment is predominantly delivered from episodic landslides and debris flows located in the upstream half of the watershed, while large logjams intercept delivered material and lead to spatially variable sediment textures and morphological features (Reid et al., 2019). The sediment texture of the bed varies from small gravels near the stream outlet to coarser cobbles and boulders in the steeper canyon reach, but varies substantially over short distances (Reid et al., 2019). The bed surface and subsurface sediment textures are similar, representative of systems that experience comparatively high sediment supply conditions (Hassan et al., 2006).

Detailed ~~channel morphology~~ morphological data have been collected through annual topographic surveys in eight study sections (SAs 2–9), seven of which (SAs 2–8) are located downstream of a canyon (termed the ‘canyon reach’, see Fig. 1). The eighth study section (SA9) is located away from the others, upstream of the canyon. The lower study sections are 300–500 m apart and 5–10 $w_b$ (50–150 m) in length (Reid et al., 2019).

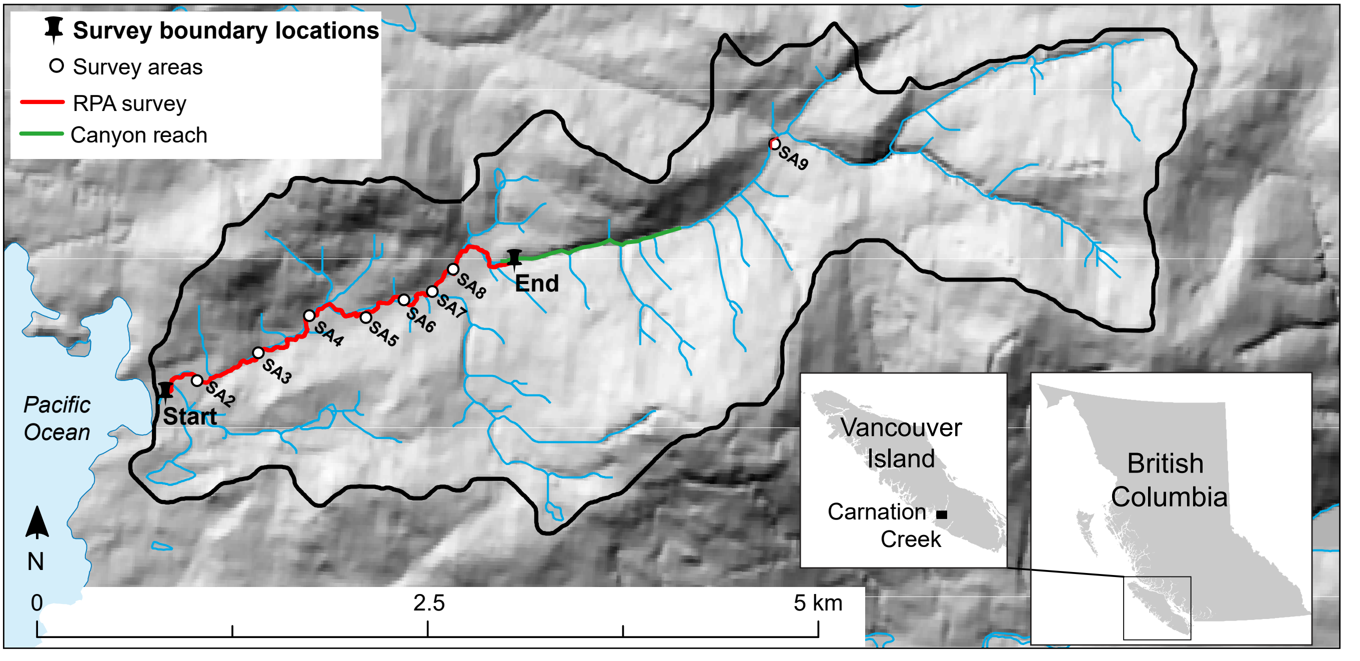


**Figure 1.** The Carnation Creek watershed, located on the south-west coast of Vancouver Island. The RPA survey extent is shown as a red line. An additional site (SA1) located in the channel estuary was active until the late 1980s, but has since been abandoned and was not included in this survey. Note that the RPA survey also included coverage of SA9, upstream of the other sites.

## 3 Methods

### 3.1 Remotely piloted aircraft survey

In July of 2018, approximately 3.0 km of channel was surveyed, with coverage extending from just upstream of the river mouth to the downstream limit of the canyon reach (Fig. 1), as well as over most of the SA9 study section. SA9 is farther upstream and possesses smaller channel dimensions, and therefore serves as a challenging test site to evaluate the coverage attainable with the RPA. Total survey time was approximately 12 full days, including flights over SA9. The RPA survey involved low-level flights (5–15 m above ground level) conducted in tandem with placement of ~~Ground Control Points~~ ground control points (GCPs) ~~that~~

were surveyed with a Leica TPS 1100 total stationon the dry exposed bars and checkpoints on both the exposed and submerged bed. Flights were operated manually as low-hanging vegetation and the forest canopy made pre-planned flights impractical. The flights were undertaken with a DJI Phantom 4 Advanced RPA, a consumer-grade RPA which contains a camera with a focal length of 8.8 mm (24 mm in 35 mm format equivalent) and a field of view of 84°. To avoid view obstruction of the channel bed, the RPA was flown manually below the canopy, with flying heights ranging from approximately 5–15 m above ground level. To obtain sufficient overlap between images, frames were acquired at two second intervals while moving at approximately 1 m/s horizontal velocity.

Due to flight obstacles (low-hanging branches, fallen trees, etc.), sightline obstructions, RPA battery life, and other practical survey challenges, the 3.0 km of channel was divided into roughly 80 segments, covered by 300–1,000 photos each. Each segment was initially flown following flight lines parallel to the channel direction, with imagery collected at 90° relative to the bed plane. While this in-flight photography strategy captured much of the channel, bank areas were often obstructed from overhead view by low-elevation shrubs, ferns, and brambles. To capture these obscured channel areas, each segment was flown with oblique and convergent imagery. 'Oblique imagery' refers to frames captured with a camera angle differing from bed-perpendicular, while 'convergent' refers to images capturing the same bed area but from different approach directions. This approach to image collection is likely advantageous in streams where riparian vegetation may prevent the RPA from flying directly over the bank, and has led to improvements in the quality of survey outcome in several studies (Wackrow and Chandler, 2011; James and Robson, 2014; Harwin et al., 2015). To collect this type of imagery, the RPA camera was tilted at a low angle (20–30° from vertical, see Figure 2 a) and a flight path parallel to the banks was taken (see Figure 2 b).

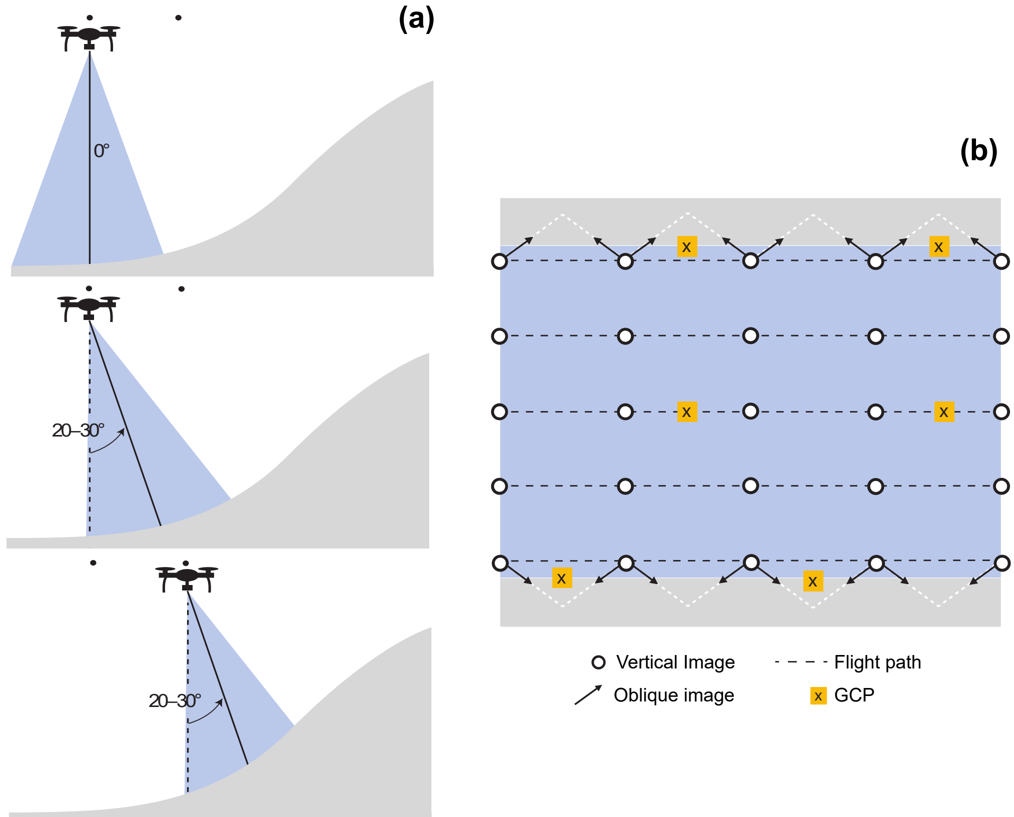


**Figure 2.** (a) Example partial channel cross-section showing the oblique angles of the RPA's camera (solid black line) for image acquisition of the banks. To ~~characterize~~ characterise the channel banks, the camera was tilted 20–30° from vertical. (b) Plan view of the flight path of the RPA with the parallel flight lines shown as dashed lines. The outlined circles show the locations of a vertical image, and the arrows show the horizontal orientation of the camera towards the channel banks for the oblique images described in (a).

~~In order to provide precise imagery georeferencing, a~~ A minimum of ten ~~ground control points (GCPs ) were placed~~ GCPs were placed along dry exposed bars in each of the 80 ~~segments~~channel segments to provide precise image georeferencing, with additional points positioned on the dry exposed bars and below the water surface in order to serve as independent checkpoints, to assess the accuracy of the model outputs. ~~The~~ All GCPs and checkpoints were surveyed with a Leica TPS 1100 total station. Open survey traverses were tied into benchmarks previously established in the study sections, and then an affine transformation applied to georeference the points in the XY-plane. The average offset between the benchmark elevations of the local open traverse and their known reference elevations were then used to georeference the points in the Z-plane. Errors were typically 2 cm in the XY-plane, and 1 cm in the Z-plane. The majority of the GCPs were distributed in a zig-zag fashion along dry exposed bars in the periphery of the channel segments, with a smaller number situated towards the centre. This configuration provided a balance between the suggested distributions of GCPs found in previously published studies (Harwin et al., 2015; Agüera-Vega et al., 2016; Tonkin and Midgley, 2016; Sanz-Ablanedo et al., 2018).

### 3.2 Basedata extraction

~~The~~ Channel elevation, bathymetry and grain size were extracted from the RPA imagery to aid in the classification of channel unit morphology. A digital elevation model was generated of the site using the software Agisoft PhotoScan Professional (AgiSoft, 2017) ~~was used~~ to generate georeferenced dense point clouds of each reach. As riparian vegetation often obstructed parts of the channel bed and introduced errors when digital elevation models are generated from point clouds (Tamminga et al., 2015), the Cloth Simulation Filter (Zhang et al., 2016) from the open source software Cloud Compare (Cloud Compare, 2017) was employed. This tool inverts the point cloud and generates an interpolated surface analagous to ‘draping’ a simulated cloth over the ground surface to approximate the terrain of an obscured area (Zhang et al., 2016). Following visual inspection of the filtered result, a cloth resolution of 0.1 m and maximum distance between 0.5 to 1.0 m was found to adequately filter the bed points.

The elevations of submerged channel bed areas are often overestimated due to the refractive effect of overlying water (Dietrich, 2017). To correct for this effect and to develop accurate bathymetry, a corrective script developed by Dietrich (2017) was employed. By determining the distance from a generated water surface mesh to the estimated bed elevations in the point cloud below, the corrected water depth for a location could be calculated as a function of the multiple viewing angles used to observe each point. ~~Prior to applying this method , the clouds were sub-sampled~~ The method requires that the water be clear such that the channel bed can be captured. The low flow conditions present at the time of the survey resulted in clear water that permitted viewing of the channel bed. Removal of overhanging vegetation using the Cloth Simulation Filter in Cloud Compare, and subsampling the DEMs to a spacing of 0.02 m ~~while retaining the minimum height in each cell to further reduce cloudnoise and ensure anomalous points from overhanging vegetation were removed in Cloud Compare~~using the minimum elevations in the point cloud, helped to ensure that the refraction correction was based on channel bed points and not on overhanging vegetation points that may have been incorporated in the point cloud.

Grain size estimates of the exposed bed were important to extract from the bed imagery, as patterns in sediment texture often follow patterns in channel morphology and are frequently discussed in classification schemes (e.g. Montgomery and Buffington, 1997) . Grain size estimates were acquired by establishing a relationship between the roughness of the point cloud for 22 training sites and their median grain size ($D_{50}$) (see method described by Woodget and Austrums, 2017), a metric often of interest to river managers. Each roughness sampling site was approximately 1 $m^2$ and ~~was photographed~~ imagery was captured for photo-sieving by hovering the RPA approximately 2 m above ground level. Using an in-house photo-sieving ~~Matlab-based GUI~~ program based in Matlab (Matlab, 2017), the grain size ~~distributions~~ distribution of each training site ~~were determinedand a~~ was determined. The program loads the image, prompts the user to scale the image, and then overlays a grid with 50 nodes prompting the user to measure the B-axis of grains falling below a grid node. Point clouds for each sample site were then extracted from the georeferenced point cloud that was developed for the study section that they fell within. A linear model then ~~fit between their~~ was then fit between each sample's $D_{50}$ (Fig. ~~3~~3) and their mean roughness value. Using a moving window analysis, grain size was then estimated across the exposed bed as described by Woodget and Austrums (2017).

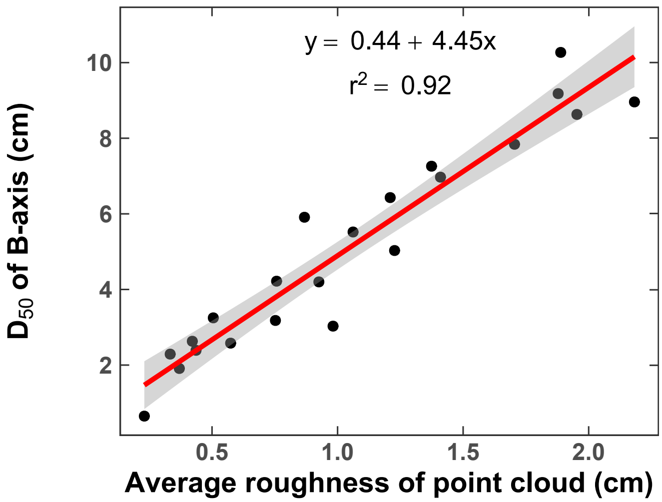


**Figure 3.** Predictive grain size relationships between the median surface sediment calibre ($D_{50}$) and the average roughness value of the training sites as determined from RPA-derived bed surfaces.

~~In-stream large wood (LW) was manually characterised and the area of each piece calculated using the DEMs and orthomosaics in ArcMap (ESRI, 2017). Pieces of wood (larger than approximately 0.1 m in diameter and 1 m in length), were digitized individually, whereas log jams were digitized as polygons as a result of difficulties in identifying individual pieces embedded within jams.~~

### 3.3 Selection of channel variables

To classify the channel along the longitudinal profile, the thalweg was first identified using the River Bathymetry Toolkit (RBT), an ArcMap add-in (McKean et al., 2009). The thalweg was used as a standardized location along which observations would be extracted at fixed intervals. To ~~characterize~~ characterise patterns in channel unit morphology, five variables were extracted: the hydraulic radius ($R_h$), median grain size ($D_{50}$), local bed ($S_l$) and water surface slope ($S_{ws}$), and the reach bed slope ($S_r$). These variables were chosen as they are straightforward to extract from the data (a key requirement for a rapid classification scheme), and because they reflect larger basin-scale variables relevant to channel form, such as geology, climate and land-use. To provide a measure of grain roughness across the channel, the average $D_{50}$ of the dry exposed bars in a 0.5 m buffer around each sampling location's cross-section was extracted. The local slopes of the bed and water surface were calculated for each sampling location by fitting a linear model through observations in a 15 m window around each sample site. This was repeated for the reach-scale bed slope using a 45 m window. Together these variables summarize the channel form ($R_h$ and $S$) and roughness of each cross-section. Cross-sections where the channel banks were not discernible (due to channel obstructions or dense low-lying vegetation) were excluded from the analysis. Exclusion of these cross-sections, along with segments of the channel the RPA could not access, comprised approximatley 25% of the channel's thalweg.

### 3.4 Analysis

Following the extraction of the five channel variables, a principal component analysis (PCA) was applied to determine which variables were important for characterizing channel unit morphology, and a k-means clustering approach was then used to classify the PCA results into ~~channel types~~morphological units. To implement the PCA and k-means clustering, the package 'stats' in R was employed (R Core Team, 2018). The general objective of a PCA is to reduce the number of dimensions in a dataset that contains interrelated variables while describing the maximum amount of variation present (Jolliffe, 2002). Because the dataset was multi-dimensional with five variables over 2,362 sampling sites, a PCA was an appropriate tool to help simplify and extract patterns in the data, a prerequisite for k-means clustering. The PCA was run using three of the five components, which together explained approximately 79.0% of the variation in the dataset, an appropriate cut-off according to Jolliffe (2002).

Following the PCA, the k-means clustering algorithm was run to identify groupings that may have been present in the data along ~~the~~ its first three components. A k-means clustering algorithm is an unsupervised classification that assigns observations from $n$ dimensions to clusters that allow the within-cluster sum of squares to be minimized (Hartigan and Wong, 1979). Following guidelines for the method described by Flynt and Dean (2016), six clusters were chosen to group the dataset, a value which is in reasonable agreement with the number of channel unit morphologies one may expect at Carnation Creek.

Following clustering of the cross-sectional variables, the mean values of each channel variable for each cluster were examined and ~~a morphology type~~ one of the following morphological units attributed to each cluster~~. Morphologies~~: pool, riffle, coarse riffle (riffle$_C$), glide, run or plane-bed. The units were assigned to clusters based on obvious features (e.g. shallow water slopes and greater depth for pools, negative pool exit slopes for glides, and steeper pool entry slopes for runs) and criteria presented in Church (1992), Anonymous (1996), and Buffington and Woodsmith (2003). These criteria are described in Table 1. The resulting assignment of morphologies to clusters leads to a continuous classification of ~~channel types~~ morphological units found along the study reach at 1 m intervals, and provides insight into the survey extents necessary to adequately capture the heterogeneity of the system.

~~To characterize~~

To characterise the diversity of ~~channel morphology~~ morphological units across the stream, a moving analysis using the Shannon diversity index (Shannon and Weaver, 1964) was conducted. This index provides a measure of the abundance and evenness of a property in an area (Lloyd and Ghelardi, 1964). While this index is often calculated with regard to species types in ecology, the approach can also be applied to ~~channel morphology types~~morphological units, similar to the work of Harris et al. (2009). To calculate index values, the proportion of each ~~channel type~~ morphological unit in an area is multiplied by the natural logarithm of the proportion. These values are then summed for all the ~~channel types~~ morphological units present in an area. In order to apply the method to the Carnation Creek data, the index values are first calculated by iteratively dividing the channel into segments based on window sizes ranging from 15–750 m in length (at 15 m intervals). For each iteration, the abundance of each ~~channel morphology~~ morphological unit in each channel segment was determined. Using the 'vegan' package in R, the Shannon's diversity index of each channel segment was then calculated.

**Table 1.** Average values for variables from morphological units found in previously published studies.

| *Morphology* | $S_{Church}$ (m/m)[a] | $S_{Hogan}$ (m/m)[b] | $S_{Buff}$ (m/m)[c] | $D/d_{Church}$ (m)[d] | $D/d_{Hogan}$ (m)[e] |
|---|---|---|---|---|---|
| ***Riffle*** | 0.02 | 0.005–0.015 | 0.001–0.02 | <1.0 | 0.1–0.3 |
| ***Riffle***$_C$ | - | 0.015–0.03 | - | - | 0.3–0.6 |
| ***Plane-bed*** | 0.02-0.04 | 0.03–0.05 | 0.01–0.04 | $\sim$1 | 0.6–1.0 |

[a] Slope values published from Church (1992)

[b] Slope values published from Anonymous (1996)

[c] Slope values published from Buffington and Woodsmith (2003)

[d] Relative roughness values published from Church (1992)

[e] Relative roughness values published from Anonymous (1996)

To determine the spatial scale required to capture the heterogeneity of the channel, the standard deviation of the diversity metrics across the channel was calculated for each iteration (using ~~the~~ an increasing window size ranging from 1–50 $w_b$ in length). For example, for the first iteration, a standard deviation value was calculated from all the diversity metrics across the channel that were based on 15 m channel segments. As sample size increases, the standard deviation of the channel segments ~~tends towards an asymptote~~would be expected to tend towards an anymptote. The length scale required to approach this asymptote can therefore be interpreted as the scale beyond which diminishing returns arise in variability captured.

## 4 Results

### 4.1 ~~Survey accuracy~~Accuracy of the RPA survey

The channel-averaged vertical survey error was estimated by calculating the root-mean-square-error (RMSE) and the mean error (ME) of differences between the elevations of check points collected with the total station survey and those estimated from the DEMs. The RMSE provides a measure of the spread of the squared residuals whereas the ME provides a measure of any potential positive or negative bias to the data, and are similar to other metrics used to evaluate RPA survey performance (e.g. Tamminga, 2016). The overall spread of this error and summary statistics are illustrated in Fig. 4. Vertical errors of the exposed bed points were found to be 0.093 m and 0.025 m for the RMSE and ME, respectively (n = 1,203), and similar values were obtained for the submerged bed points (RMSE = 0.11, ME = 0.025m, n = 521). As shown in Fig. 4, the majority of the errors for the submerged points were close to 0. However, factors such as shadows from the riparian vegetation and reflections from the canopy may have influenced the success of the refraction correction (Dietrich, 2017).

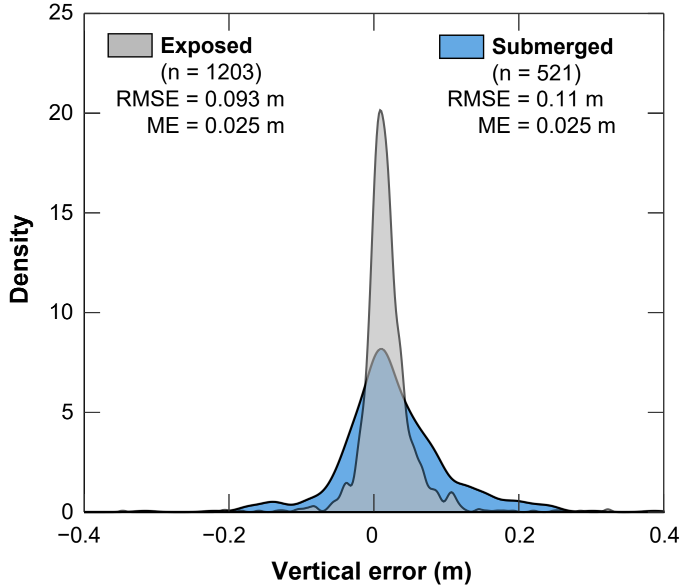


**Figure 4.** Density plot displaying the distribution of vertical errors between the modelled and field measured elevations. Summary statistics (root-mean-square-error (RMSE) and mean error (ME)) are provided for both the exposed and sumberged checkpoints.

### 4.2 ~~Survey coverage~~Coverage with the RPA survery

In order to evaluate the coverage extent obtainable with the sub-canopy RPA survey, the RPA-based results were compared to channel boundaries delineated with a total station in the eight established study sections (see example in Fig. 5). When including side channels, which were generally difficult to access with the RPA due to dense sub-canopy vegetation, it was possible to capture approximately 80% of the delineated study sections, a value which increased to 87% when side channels are excluded. When examining individual study sections that contained side channels, coverage ranged from a low of 54% in SA4, to a high of 89% in SA9. Generally, narrow (width $<$ 3 m) side channels could not be effectively surveyed, but oblique imagery was advantageous in situations where a clear flight path was present alongside an obscured channel area (Fig. 6). Similarly, bank top elevations were difficult to capture in most locations due to understory vegetation obscuring the ground surface. The inclusion of bathymetric calibration greatly increased the area over which bed topography could be estimated (~~e.g.~~ Fig. 6).

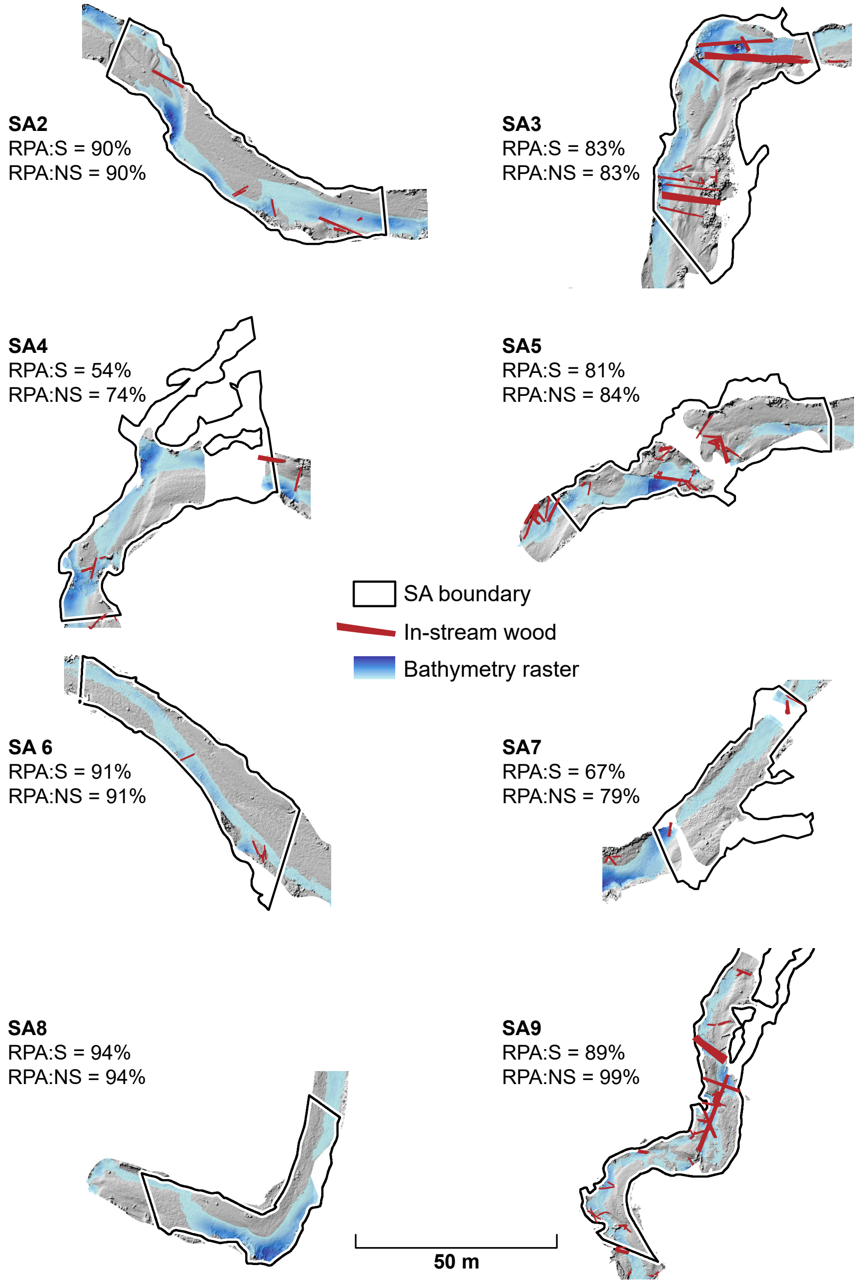


**Figure 5.** RPA coverage in comparison to the study section boundaries for SAs 2–9. Percentages of the study section covered with the RPA relative to the total station are based on whether the reference boundary included side channels (RPA:S) or just the main channel (RPA:NS).

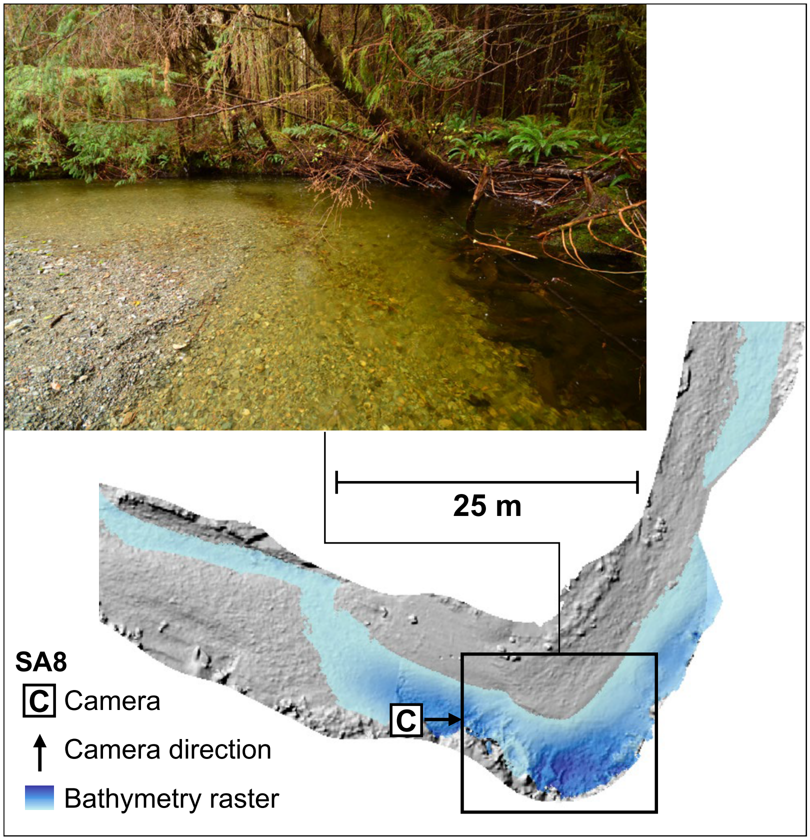


**Figure 6.** Coverage of a deep pool in SA8 under dense riparian vegetation. Note that the photo was taken in the autumn prior to the RPA survey, when the water level was higher than it was during the RPA survey. Photo courtesy of Iain Reid.

#### 4.2.1 Principal component analysis, clustering analysis, and channel classification results

The first three components from the PCA explained approximately 80% of the variation in the data, with components one, two and three reflecting 45.11%, 19.3% and 14.6% of the variation, respectively. The first component is dominated by $S_r$, $D_{50}$ and $S_{ws}$, the second by $R_h$, and the third by $S_l$ and $D_{50}$. After running the k-means clustering algorithm using six groupings on the first three components, these patterns were evident along the axis of the biplot (Fig. 7). For each cluster, the mean of each variable was calculated and the likely ~~morphology~~ morphological unit corresponding to the cluster estimated from these values (Table 2). Moving from left to right along the first dimension (Fig. 7) there is a ~~transition from~~ shift from unit morphologies with lower bed and water surface slopes and finer bed sediment ~~,~~ to those with steeper gradients and coarser material. This appears to represent a transition from pool to riffle unit morphologies along the first component. Overall, distinctions between most channel attributes arising from the clustering are clear and lead to relatively unambiguous classification of ~~morphology types~~ morphological units (Table 2). Within the riffle channel ~~type~~unit, the classification also captures a distinction between riffle unit morphologies with slightly coarser bed material, defined here as ‘~~Riffle-coarse’ (Riffle$_C$, see Anonymous, 1996)~~riffle-coarse’ (riffle$_C$, see Anonymous, 1996). When examining the second component (y axis of Fig. 7), hydraulic radius ($R_h$) decreases from top to bottom, as indicated by the transition from lower-velocity pool to higher-velocity glide unit morphologies, with remaining unit morphologies possessing intermediate $R_h$ (Fig. 7).

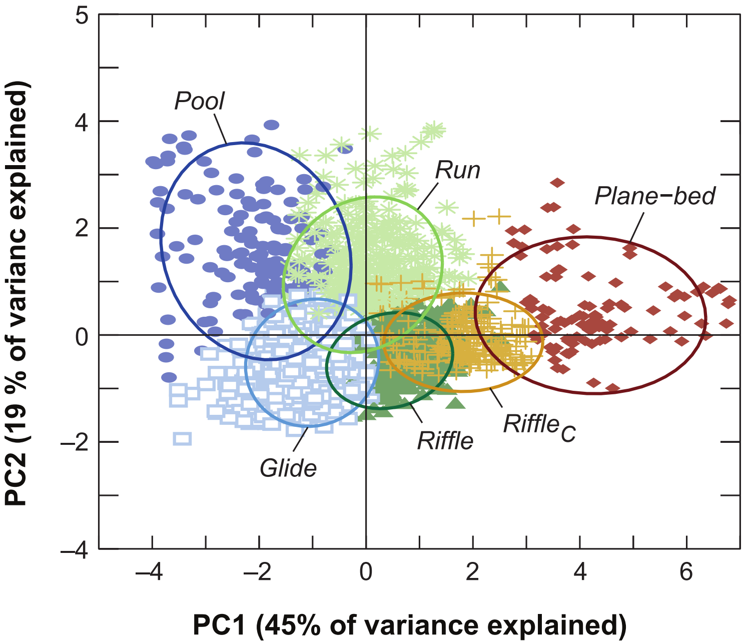


**Figure 7.** Biplot of each observation along the first two principal components PC1 and PC2. The groupings from the k-means clustering analysis are colour-coded and their centroid outlined.

Pools, riffles, glides and runs are relatively well distributed along the surveyed length of channel (Fig. 8). However, plane-bed and coarse riffle ~~morphologies~~ morphological units are mostly located near the upstream limit of the survey extent in this region. This area represents the outlet and downstream entrance of the canyon reach, where steeper gradients and coarser sediment are found. This is highlighted in Table 2, which shows that on average these morphological units are located 3160 m upstream, with steep reach scale gradients of 0.042 m/m and coarse material with an average $D_{50}$ of 8.21 cm. Similarly, the coarse riffle morphologies were located approximately 2980 m upstream on average, with relatively steep gradients and coarse material (reach scale slope = 0.024 m/m and $D_{50}$ = 6.74 cm). By contrast, the average positions of the riffle, glide, run and pool morphologies were approximately 1500 m, midway along the channel's profile, indicating that these morphological units are distributed over a greater length of channel. Grain size was generally similar between these morphologies, except for the riffle unit, which was slightly coarser with a D50 of 4.10 cm. Pools were the deepest, with average water depths of 1.04 m and near zero water surface slopes, whereas riffles were the shallowest with average water depths of 0.13 m and relatively steep water surface and reach scale bed slopes. Glides and runs were intermediate between these morphologies, with glides often retaining negative local bed slopes, corresponding with the exit of pools, and runs with large positive local bed slopes, corresponding with the entry of pools.

**Table 2.** Means of channel variables for each cluster.

| Cluster | $l$ (m)[a] | $d$ (m)[b] | $R_h$ (m/m)[c] | $S_l$ (m/m)[d] | $S_{ws}$ (m/m)[e] | $S_r$ (m/m)[f] | $D_{50}$ (cm)[g] | $W$ (m)[h] |
|---|---|---|---|---|---|---|---|---|
| ***Riffle$_C$*** | 2980 | 0.16 | 0.12 | 0.018 | 0.018 | 0.024 | 6.74 | 4.13 |
| ***Plane-bed*** | 3160 | 0.20 | 0.14 | 0.054 | 0.047 | 0.042 | 8.21 | 3.47 |
| ***Riffle*** | 1650 | 0.13 | 0.090 | 0.027 | 0.016 | 0.012 | 4.10 | 3.65 |
| ***Glide*** | 1470 | 0.28 | 0.16 | -0.020 | 0.003 | 0.003 | 3.68 | 4.99 |
| ***Run*** | 1435 | 0.61 | 0.35 | 0.044 | 0.005 | 0.016 | 3.92 | 4.94 |
| ***Pool*** | 1420 | 1.04 | 0.60 | -0.031 | -0.004 | 0.000 | 3.66 | 5.99 |

[a] The midpoint of the longitudinal span where the morphological unit occurs

[b] Thalweg depth

[c] Hydraulic radius

[d] Local slope

[e] Water surface slope

[f] Reach-average slope

[g] Median grain size

[h] Wetted channel width

~~Biplot of each observation along the first two principal components PC1 and PC2. The groupings from the k-means clustering analysis are colour-coded and their centroid outlined.~~

### 4.3 ~~Classification accuracy assessment~~Assessment of the channel classification

To assess the accuracy of the clustering algorithm, 100 locations along the surveyed length of channel were randomly selected and visually assigned to either glide, pool, run, riffle, riffle$_C$, or plane-bed ~~morphologies~~morphological units. These values were then compared to the ~~morphologies~~ morphological units predicted by the PCA. A summary of agreement between the PCA and visual classification approach is shown in Table 3. On average, 85% of sampled locations received the same ~~morphology~~ morphological unit assignment between the two approaches, with riffle areas showing the lowest agreement (72%) and plane-bed areas the highest (100%). Overall, the classification matches the typical expected progression of channel unit morphologies in a pool-riffle system, as is shown in Fig. 9 . The exit of the pool is classified as a glide, with negative bed surface gradients. As gradient increases we see shallow riffle unit morphologies that meld into a deeper run at the entry of the pool (Fig. 9). It is likely that much of the disagreement can be attributed to ‘transition’ morphologies, which most classification schemes are unable to capture or define.

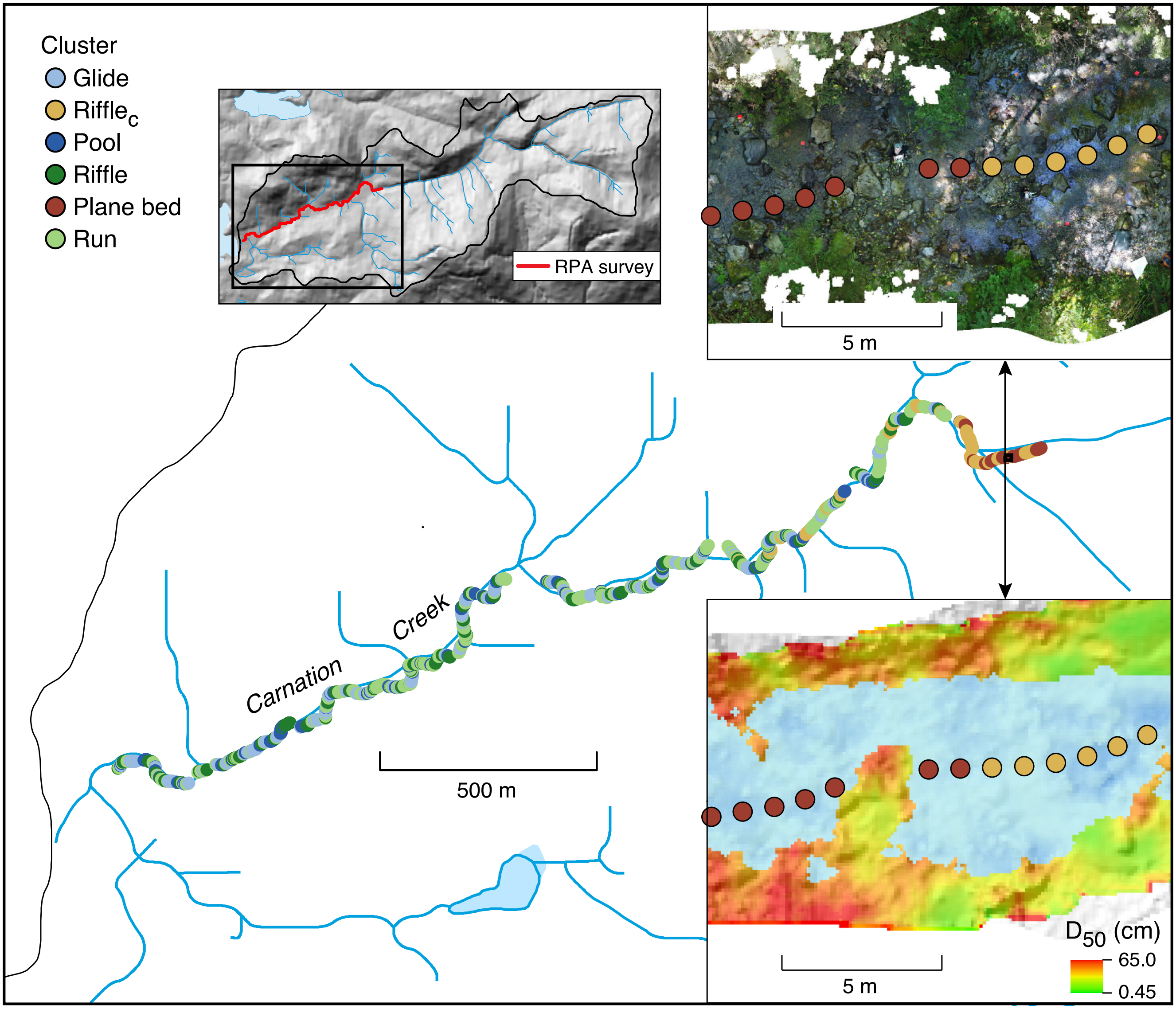


**Figure 8.** Distribution of ~~channel morphologies~~ morphological units along the surveyed reach of Carnation Creek. At approximately 2,500 m upstream, there is a marked change in channel unit morphologies from ~~the typical riffle-pool morphologies~~ pool, riffle, run and glides to much steeper and shallower channel ~~morphologies~~morphological units.

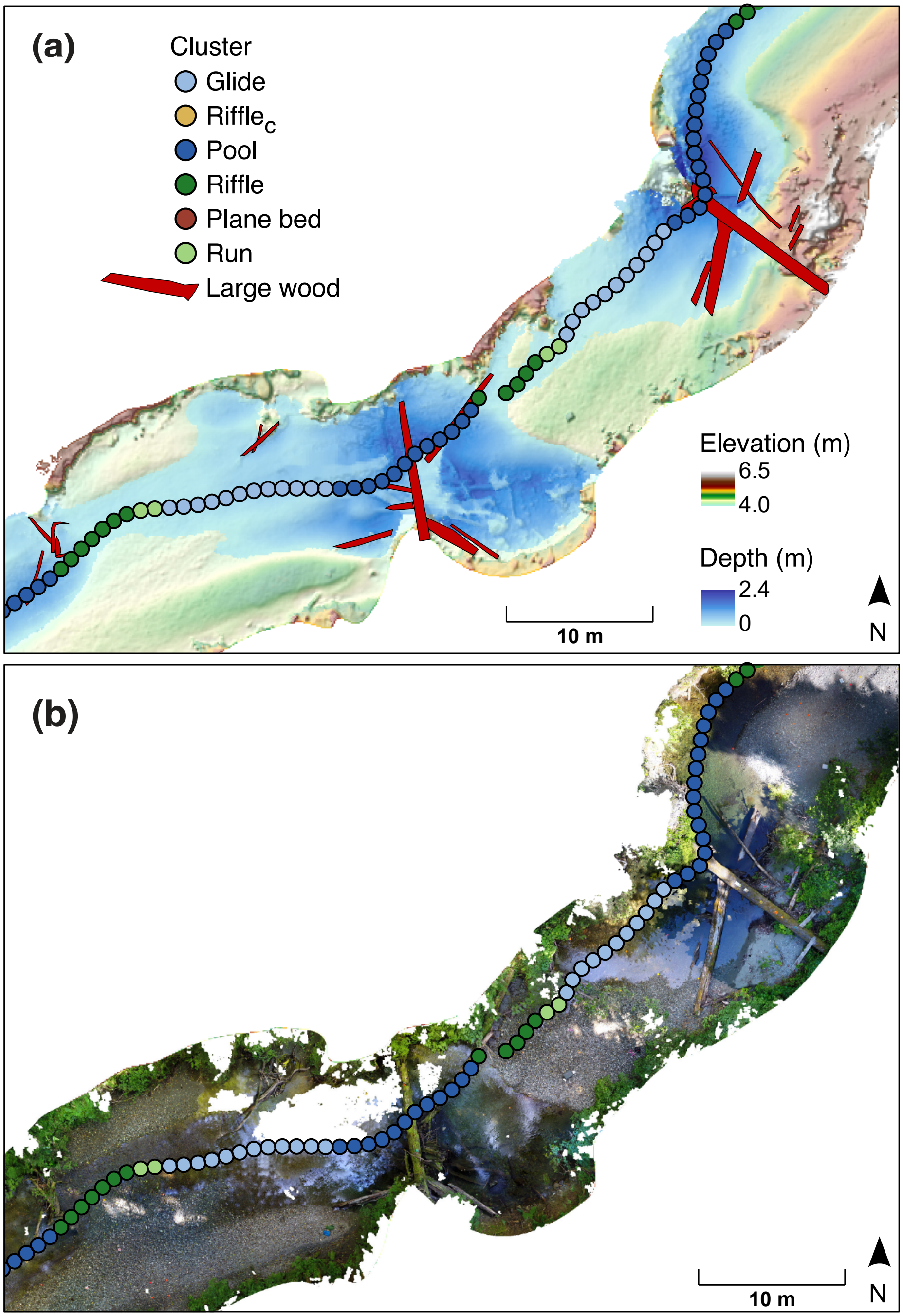


**Figure 9.** Example sequence of morphological units showing the transition from riffles to pools in a heterogeneous section of channel overlaid on (a) a DEM and (b) an orthomosaic.

**Table 3.** Accuracy assessment of morphological unit classification.

| **Morphological unit** | % Correctly classified |
|---|---|
| ***Riffle***$_C$ | 78 |
| ***Riffle*** | 72 |
| ***Plane-bed*** | 100 |
| ***Glide*** | 97 |
| ***Run*** | 85 |
| ***Pool*** | 80 |
| ***All*** | 85 |

## 5 Discussion

### 5.1 ~~Sub-canopy~~ Utility of sub-canopy RPA surveys for small, forested streams

The results of this study provide a precedent for using RPAs to ~~characterize channel morphology~~ characterise morphological units in small, forested streams below the forest canopy. This approach provides several advantages over traditional ground-based surveys. ~~Over twelve~~ We have demonstrated that over 12 field days, nearly three kilometers of ~~channel were~~ a small forested channel could be surveyed with an estimated coverage rate of 80% (including side channels) at a greater spatial resolution and extent than most traditional ground-based methods allow. ~~Total~~ For example, the traditional total station-based surveys conducted in Carnation Creek typically result in point densities of 0.5–1.5 points/m$^2$, with 500–1000 points captured in a normal field day over a 70 m length of channel. In contrast, ~~approximately~~ the average data acquisition rate with the RPA was 225 m~~of channel could be captured each~~ /day, more than three times the length coverage from the total station approach, and at a much higher resolution. The DEMs and orthophotos created from these images were of a very high resolution (0.02 m/pixel) with survey uncertainty between 0.01 m (for dry areas) and 0.1 m (for submerged bed areas). This magnitude of error is comparable to values observed in other studies (e.g. Flener et al., 2013; Tamminga et al., 2015), and is similar to error achieved using traditional ground or GPS-based point surveys in the same channel (Reid et al., 2019).

Oblique imagery appears to provide good coverage of near-bank areas traditionally difficult to capture with vertical imagery, enabling the characterisation of low-velocity, near-bank channel areas which serve as critical fish habitat (Bjornn and Reiser, 1991). This additional imagery is generally straightforward to collect, but adds to the RPA power requirements and also increases survey time as a result of the need for additional flight passes. However, should repeat surveys be undertaken, a major reduction in survey time would be achieved through the installation of permanent ground control points. New RTK-GPS systems providing centimeter-level accuracy are also becoming available for consumer-grade RPAs, though signal attenuation through dense trees may reduce survey accuracy and limit their applicability for sub-canopy surveys.

While sub-canopy RPA surveys appear promising, certain environmental conditions and aspects of the survey approach continue to present limitations. First, the techniques for extracting the bathymetry may not be suitable for streams with turbid water that prevent observation of the submerged bed. While oblique imagery aided in characterisation of some bank areas, low elevation and dense riparian vegetation still pose a challenge for capturing bank topography in some locations, information which is necessary should the resulting survey be used for hydrodynamic modeling (Cienciala and Hassan, 2013) or to quantify bank erosion (Reid et al., 2019). In addition to bank vegetation causing obstructions, submerged areas with little texture and low-hanging branches (predominantly from riparian deciduous species) occasionally led to flight difficulties that prevented sufficient collection of imagery for photo-stitching. Therefore, these techniques may be most suited to small channels in relatively mature forests that have an open understory, and flights in winter months when foliage is absent may prove beneficial. In certain circumstances, a hybrid survey with both RPA and total station data could provide complete coverage, even in locations highly obscured by dense understory foliage. In spite of these limitations, however, the sub-canopy RPA survey approach appears to offer substantial improvements over traditional survey methods.

### 5.2 ~~Classification~~ Assessment of the classification approach

The PCA-clustering classification approach appears to present a viable and less-subjective method for evaluating morphology at the ~~channel-unit~~ channel unit scale, and incorporates a larger number of key variables than traditional methods. While some subjectivity remains in the interpretation of the k-means-derived clusters, examination of the classification from the PCA-clustering analysis revealed that there was good agreement between the characteristics of the ~~morphologies~~ morphological units derived from the clustering approach and ~~morphologies~~ morphological units identified visually (Table 3), with at least some remaining disagreement attributable to transition areas between morphological units. As shown in Table 4, the mean values of the variables for each assigned ~~morphology~~ morphological unit are similar to reference values found for the slope, depth and grain size characteristics of similar channels classed in a number of other studies. Another advantage of the PCA is that it highlights the trends present in a dataset, rather than focussing on specific features. For example, anomalous areas where imagery may have had stitching issues due to poor coverage (e.g. SA5 in Fig. 5) would likely appear as noise, thereby having a minimal influence on the PCA.

Including frequently measured channel metrics in a PCA-clustering analysis, as was conducted in this study, provides a sophisticated means not only for relating physical conditions to channel form (as descriptive schemes tend to do), but for identifying which key variables impact the relationship. Such an analysis may provide a precursory understanding of key variables worthy of investigation in the development of process-based classification schemes. A challenge encountered by many classification schemes is that they often lack the generality to be applied in environments outside of those for which they were developed. For example, although Whiting and Bradley (1993) provided a strong process-based classification of channel form, it was intended for headwater channels, limiting its wider applicability (Buffington and Montgomery, 2013). Similarly, the approach to classifying channels proposed by Montgomery and Buffington (1997) has a clear process basis where the channel is partitioned into source, transport and deposition zones, but was developed for mountain drainage basins. While the classification approach proposed here is also based in a mountainous environment, the PCA-clustering technique allows for the identification of ~~morphologies~~ morphological units in any fluvial environment where sufficient variation in bed topography is present. Unlike most classification schemes, identified clusters must be interpreted after the analysis to situate them within our conceptual understanding of river systems. While this consists of an additional step, it can provide opportunities to confirm our understanding of field observations in river systems or to guide further investigation when unexpected patterns appear.

Finally, it should be noted that in order to ~~characterize~~ characterise the geometry of the channel, the PCA approach relies on wetted variables, in contrast to flow-independent features like bankfull width or depth. When considering ~~things~~ factors such as the needs of salmonids, the low flow conditions observed in late-summer may be of concern and will determine the connectivity and distribution of certain ~~channel types~~ morphological units across the riverscape. Depending on the application, however, consideration of flow-independent variables may be required, like the bankfull width or depth, which are less dependent on the particular wetted conditions observed at the time of the survey.

**Table 4.** Comparison of average values for variables of each ~~morphology~~ morphological unit to those found in previously published studies. Values from this study are indicated in bold.

| ***Morphology*** | $S_{Church}$ (m/m)[a] | $S_{Hogan}$ (m/m)[b] | $S_{Buff.}$ (m/m)[c] | $S$ (m/m) | $D/d_{Church}$ (m)[d] | $D/d_{Hogan}$ (m)[e] | $D/d$ (m) |
|---|---|---|---|---|---|---|---|
| ***Riffle*** | 0.02 | 0.005–0.015 | 0.001–0.02 | **0.012** | <1.0 | 0.1–0.3 | **0.33** |
| ***Riffle***$_C$ | - | 0.015–0.03 | - | **0.024** | - | 0.3–0.6 | **0.41** |
| ***Plane-bed*** | 0.02-0.04 | 0.03–0.05 | 0.01–0.04 | **0.042** | ∼1 | 0.6–1.0 | **0.42** |
| ***Glide*** | - | - | - | **0.003** | - | - | **0.13** |
| ***Run*** | - | - | - | **0.016** | - | - | **0.06** |

[a] Slope values published from Church (1992)

[b] Slope values published from Anonymous (1996)

[c] Slope values published from Buffington and Woodsmith (2003)

[d] Relative roughness values published from Church (1992)

[e] Relative roughness values published from Anonymous (1996)

### 5.3 Insight into scales of spatial variability

The results of calculating the standard deviation of the diversity metric for ~~channel types~~ morphological units (Fig. 10 a) suggest that a window size of approximately 13–15 $w_b$ (175–200 m in length) is necessary to capture the dominant variability along the channel. Beyond this scale, additional variability is captured, but at a decreasing rate. The 3.0 km of channel over which this analysis was conducted would likely be considered a relatively homogeneous riffle-pool reach under traditional channel classification schemes, such as that of Montgomery and Buffington (1997). The 15 $w_b$ length scale is shorter than the 30–50 $w_b$ equivalent often suggested for characterizing channel form (Bisson et al., 2006), and equivalent to 2–3 sets of pool-riffle

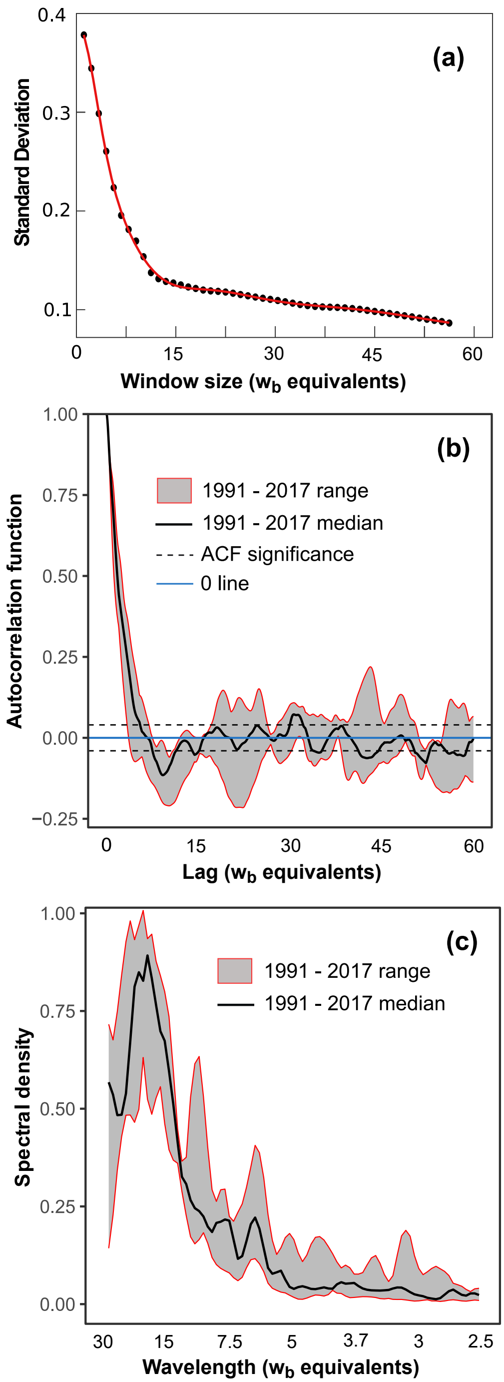


**Figure 10.** Notable length scales along the lower 3.0 km of Carnation Creek: (a) Standard deviation of channel diversity index values; (b) Autocorrelation function values extracted from channel longitudinal profile data collected four times between 1991 and 2017 (Fig. modified from Reid et al. (2019)); (c) Spectral density plot from analysis applied to longitudinal profile data in (b) (Fig. modified from Reid et al. (2019)). Note that channel width equivalents are given in relation to width determined as of 2017, equivalent to 13.4 m

units as defined by Keller and Melhorn (1978). This value fits in with the range of recommended study reach lengths that have been reported in the literature, though it is at the lower end (see Trainor and Church, 2003). For example, Montgomery and Buffington (1997) considered reaches 10–20 $w_b$ in length for their research while Woodsmith and Buffington (1996) considered reaches 20 $w_b$ in length. At the higher end, Hogan (1986) and Trainor and Church (2003) consider reaches greater than 30 $w_b$ and reaches between 50–70 $w_b$ to be conservative lengths for their research, respectively. Given that additional variability is still captured with a greater spatial survey extent, the 15 $w_b$ value should be considered a minimum.

~~Notable length scales along the lower 3.0 km of Carnation Creek: (a) Standard deviation of channel diversity index values; (b) Autocorrelation function values extracted from channel longitudinal profile data collected four times between 1991 and 2017 (Fig. modified from Reid et al. (2019)); (c) Spectral density plot from analysis applied to longitudinal profile data in (b) (Fig. modified from Reid et al. (2019)). Note that channel width equivalents are given in relation to width determined as of 2017, equivalent to 13.4 m~~

The explanation for the 15 $w_b$ domain over which a threshold in variability is reached may be related to the spacing of major sediment storage areas in the system. Previous work in Carnation Creek by Reid et al. (2019) suggests that non-random spatial patterns in sediment storage are present along the channel (see Fig. 10 b and c). Both autocorrelation and spectral analysis methods applied to four sediment storage datasets collected between 1991 and 2017 revealed a periodicity in the data in the order of 12-20 $w_b$, providing information on the spacing of major sediment storage areas. Given the similarity in length scales between Figs. 10 a-c, it is possible that these storage zones (mainly large bars) serve as end members between which the typical progression of ~~channel-unit~~ channel unit morphologies would be expected.

The bar-to-bar spacing represented by length scales shown in Fig. 10 is within the range, but close to the upper limit, of values reported for gravel bed streams in Thompson (2013). The explanation for the relatively large feature spacing may be related to the presence of major logjams along the channel, which are commonly associated with areas of major sediment storage (Abbe and Montgomery, 1996; Davidson and Eaton, 2015; Wohl and Scott, 2017). However, as of 2017 (one year prior to the RPA survey) comparatively few major jams storing large quantities of sediment remained in the channel, and average jam spacing was only between 5 and 8 $w_b$ (see Reid et al., 2019). Other factors which may explain the relatively large unit spacing in Carnation Creek ~~may~~ could be related to patterns in channel width (Chartrand et al., 2018) or flow convergence (MacVicar and Roy, 2007; Thompson and Wohl, 2009).

It is important to note that the spatial scale of measurement needed to capture variability will depend on the particular variables of interest, and also the expected morphological character of the system. Carnation Creek is a channel which experiences episodic delivery of sediment from hillslopes (Hartman and Scrivener, 1990; Reid et al., 2019). As shown by the range of values in Fig. 10 b and c, temporal variability exists in the spatial pattern of dominant channel features. The 26 year period over which the data in Fig. 10 b and c ~~was~~ were collected represents a comparatively inactive time interval in terms of colluvial sediment supply. This variability would be expected to increase during periods of episodic sediment supply, and could influence the resulting spatial scale over which dominant variance is captured. In this instance, a greater length of channel may be necessary to survey in order to increase the probability of capturing this type of localized feature. Similarly, practical survey limitations (such as site accessibility) may still factor strongly in decisions regarding site selection and survey extent. As others (e.g. Montgomery and Buffington, 1998) have suggested, examination of channel gradient or a channel profile will still provide useful preliminary information on regions of relatively homogeneous channel morphology.

## 6 Conclusions

The spatial extent needed to adequately capture variability and classify morphology of forested, gravel bed streams with closed canopies is often unclear, while the challenge of collecting comprehensive data in these environments necessitates efficient and low-cost data acquisition methods. This paper describes an approach to ~~rapidly and objectively~~ characterise and classify these channels through use of sub-canopy flights with Remotely Piloted Aircraft ~~at the channel-unit to reach-scale~~(RPA) at the channel unit to reach scale. Through the incorporation of oblique-convergent imagery, it was possible to undertake a sub-canopy channel survey along 3 km of Carnation Creek, a small forested gravel-bed stream. ~~This survey and resulting dataset allowed for the exploration of the spatial extent necessary to capture the dominant morphological variability of the channel.~~ Use of RPA-derived rasters of bed morphology, bathymetry, and grain size in combination with a PCA-clustering analysis of channel unit morphologies provided characterization of this channel at an extent and resolution that would be difficult to attain using traditional methods. This allowed for the exploration of the spatial extent necessary to capture the dominant morphological variability of the channel. After calculating a diversity index describing the heterogeneity in channel unit morphology, a spatial scale equivalent to approximately 15 channel widths was found to capture much of the variability in channel unit morphology.

Overall, the methods were successful in demonstrating the use of RPAs for collecting channel attribute data below forest canopies and in providing an objective technique for characterizing patterns in ~~channel morphology~~ morphological units of small, forested channels at a variety of spatial scales. This research helps to expand the toolkit available to geomorphologists for characterizing small channels with complex morphology residing largely below forest canopies, and presents a classification approach with fewer drawbacks from subjective morphology identification. The results of this work are presented for a single catchment; additional study is needed to evaluate the limits of RPA approaches for data collection in similar environments.

*Data availability.* Data used for the analysis can be found at doi: 10.17632/jv9rftdmst.1 (Helm, 2020).

*Author contributions.* CH led all data collection, analysis and most manuscript preparation. MH provided supervisory support and assisted with project conceptualization and manuscript preparation. DR assisted with project conceptualization, data collection, and manuscript preparation.

*Competing interests.* The authors declare that they have no conflict of interest.

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