# Standard deviation of streambed elevation profiles as a method to quantify channel bed roughness and its relationship to channel stability*:*

## *A case study for a small mountain creek in Southwestern British Columbia*

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ABSTRACT

Analysis of river-bed surface structure has important implications in the characterization of streambed morphology and channel morphodynamics. In particular, channel bed-surface roughness influences the size and morphology of small mountain streams by its interrelations with sediment transport, channel flow, as well as its influence on channel stability. Recognizing the appropriate conditions to describe channel stability remains a major challenge in streambed characterization, as the precise relationship between channel stability and channel roughness is unclear. The standard deviation of measured bed-surface elevations has been shown to describe the characteristic bed-surface roughness on a relative vertical scale. In particular, streambed elevation profiles can be created from multiple stream channel cross sections, from which the standard deviation can be calculated and used as a proxy for bed roughness. This project uses channel bed elevation data that was surveyed in three riffle-pool reaches of a small mountain creek in Southwestern British Columbia from 2003 – 2015. The annual standard deviation of minimum value elevations in multiple channel cross sections are used to define a characteristic roughness scale for this length of channel. Estimations of bed-surface roughness are compared over time and correlated with previous records of streamflow, but failed to correlate with sediment flux and bed elevation changes in an attempt to validate our methodology, which pointed to the importance of considering scale-dependant channel processes in analyzing channel morphodynamics. We recommend that bed roughness at the reach-scale may be better able to represent sporadic changes occurring in more localized areas, that are not evident in our roughness proxy.

# 1. INTRODUCTION

## *1.1 Brief Overview of Channel Morphodynamics*

Channel morphodynamics are subject to governing conditions that include the nature and characteristics of the channel bed [Church, 2015], which are adjusted through erosion and deposition of sediment [Church & Ferguson, 2015]. Moreover, the rate of sediment transport depends on parameters including streamflow and bed characteristics which are determined by sediment supply [Church & Ferguson, 2015]. Small mountain streams reflect a mix of hillslope and channel processes, due to the effects of channel-hillslope coupling and their proximity to sediment sources, creating high boundary / bed roughness conditions due frequent channel obstructions (i.e. woody debris and large clasts) [Hassan et al., 2005].

Montgomery and Buffington (1997) provide a framework for which channels can be differentiated based on distinct identifiable characteristics; one of them being channel-reach substrate (i.e. bedrock, colluvium and alluvium). Bedrock channels are typically confined by valley walls and lack continuous alluvial substrate, whereas colluvial channels exhibit a thin colluvial fill substrate that are characteristic of ephemeral headwater streams. Alluvial channels can display an array of different morphologies; displaying variability in confinement, roughness characteristics, slope and order in the channel network. Alluvial channels can be further dived into five distinct reach morphologies: cascade, step pool, plane bed, pool riffle, and dune ripple [Montgomery & Buffington, 1997].

Pool-riffle morphology (which is the main focus of this study) can be described as low-gradient alluvial reaches that are characteristic of small mountain streams; having a much smaller transport capacity than sediment supply, resulting in prolonged responses to changing boundary conditions (e.g. sediment supply and streamflow) [Montgomery & Buffington, 1997]. Fluvial sediment sources and bank failures provide the majority of bedform sediment, which can range in size from sand to cobbles [Klinghoffer, 2015]. The riffle sequences are flat areas made of lobate shaped, tightly packed gravel, whereas pools are topographic depressions with looser, fine sediment [Hassan et al., 2005; Clifford, 1993; Thompson, 2011].

## *1.2 Bed Roughness*

Channel bed characteristics influence channel morphodynamics and also respond to boundary conditions imposed on a stream channel [Church, 2015; Church and Ferguson, 2015]. Channel geometry, substrate material and relative grain size distributions are adjusted through erosion and deposition of sediment, and therefore reflect a balance between sediment transport capacity and sediment supply [Church & Ferguson, 2015]. For example, “coarsening or fining” of the bed surface provides a way by which channels can adjust how much sediment is transported away in response to the rate at which sediment is being supplied [Dietrich et al., 1989]. This process can be described in terms of channel gradient adjustments by aggradation and degradation (further discussed in section *4.2*).

Bed roughness is typically denoted by the relative height (e.g. elevation) differences or the "coarseness" of a channel bed surface, which will adjust to the dominant hydraulic stresses that contribute to the formation of the channel bed (i.e. bed gradient and flow conditions). Roughness will also increase - in terms of the proportion of roughness elements - as bed gradients steepen due to degradation, thereby increasing flow resistance [Schneider et al., 2015]. According to these relationships, flow resistance equations (e.g. Darcy-Weisbach or dimensionless hydraulic geometry equations) are used as a parameterization of channel flow resistance. However these relations may not be representative of steep/rough small mountain streams with channel beds that do not exhibit homogeneously sized and uniformly distributed grains [Kirchner et al., 1990], which presents a major limitation in stream-bed characterization [Schneider et al., 2015]. It is important to consider bed roughness in terms of channel morphodynamics because the variability within a bedform and grain size distribution is the primary cause of flow resistance in free-formed pool riffle channels [Montgomery & Buffington, 1997].

### *1.3 STD Roughness Proxy*

Obtaining detailed topographic information of the channel bed has allowed for measures of bed roughness using the statistical variance of bed surface topography [e.g., Heritage & Milan, 2009; Rychkov et al., 2012; Smart et al., 2002]. The standard deviation of measured bed-surface elevations has been shown to describe the characteristic bed-surface roughness on a relative vertical scale [Coleman et al., 2011; Noss & Lorke, 2016; Schneider et a., 2015]. In particular, streambed elevation profiles can be created from multiple stream channel cross sections, from which the standard deviation can be calculated and used as a proxy for bed roughness. The roughness estimate is a measure of variation between individual point elevations, indicating the irregularity of topographic features [Schneider et al., 2015].

### *1.4 Study Area*

This study is based on elevation data from East Creek, as described in Cienciala and Hassan (2013); a small mountain stream that is 4 kilometers in length and drains an area of 136 hectares in the foothills of the Coast Mountains in Southwestern British Columbia. East creek is 50 km east of Vancouver, BC (Figure 1), and consists of one plane-bed and three pool-riffle reaches [Montgomery & Buffington, 1997] referred to as "Rapid" (RAP), and "Pool-Riffle-1" (PR1) to "Pool-Riffle-3" (PR3), respectively [Hassan et al., 2005]. Our study area experiences a maritime climate with warm dry summers and mild wet winters, where the majority of annual precipitation falling as rain occurs during winter months (October – April) [Cienciala & Hassan, 2013].

*1.5 Study Objectives*

The aim of this paper is to derive a characteristic bed-surface roughness on a relative vertical scale given by the standard deviation of measured bed-surface elevations. A channel-scale roughness proxy may be used to assess changes in channel stability for the Pool-Riffle reaches (PR1:PR3) of East Creek from 2003 – 2015. As a general outline, we will discuss how this methodology is employed, the results obtained as well as how this method can be validated using ancillary data and if this proxy can tell us anything about channel stabilization over time. We will refer to the standard deviation of measured bed-surface elevations as a "roughness proxy" or "roughness estimate", and use these terms interchangeably. The roughness proxy will be discussed in terms of how well our method can be validated (i.e. correlated) using ancillary data; most of which has been presented by Klinghoffer (2015) and other research previously conducted on East Creek. Major findings in this study are therefore predominantly speculative, and serve first and foremost as a general evaluation of our methodology.

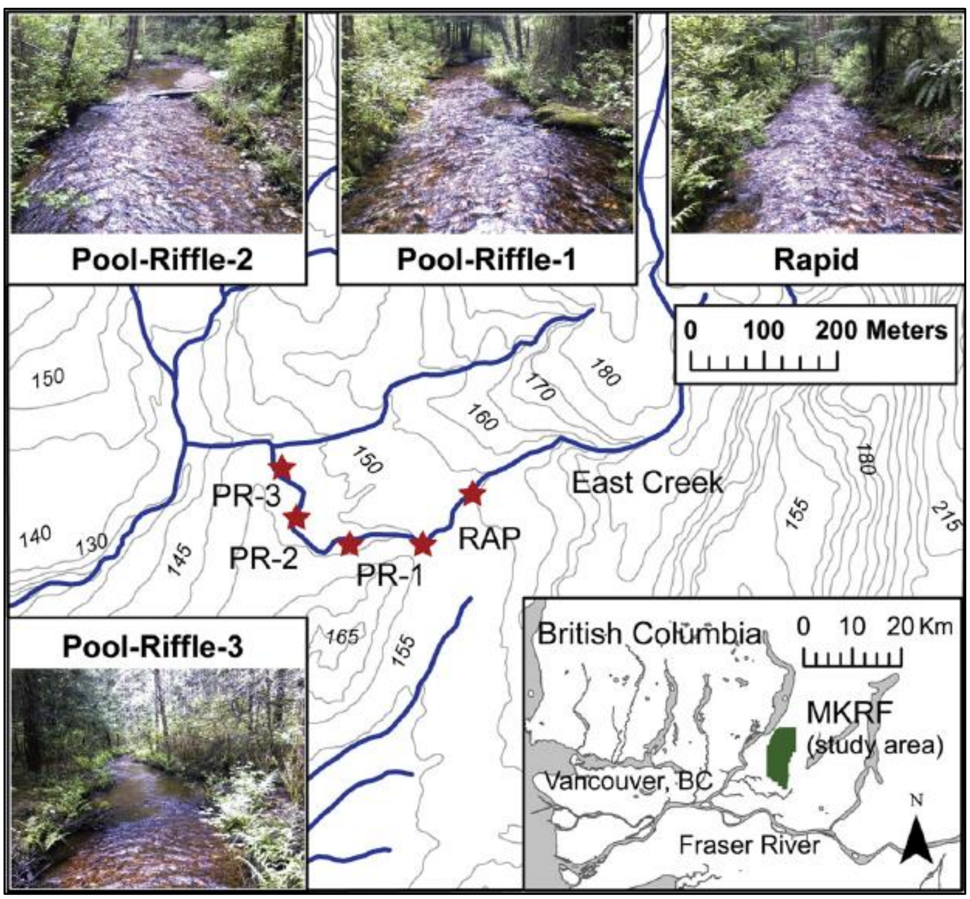


**Figure 1.** Map of the study area from Cienciala and Hassan (2013). Boundaries of the channel reaches (RAP, RP1, RP2 and RP3) indicated by red stars, inset map shows location of Malcolm Knapp Research Forest ("MKRF") in the South-west BC, numbers on main map are values of contour lines (m. a. s. l.) [Cienciala & Hassan, 2013].

# 2. METHODS

## *2.1 Bed Elevation Data*

Channel bed topography of the study reaches was surveyed annually (spring/summer) from 2003 – 2015. These surveys were performed manually using a theodolite-based total station equipped with an electronic distance meter able to take a high point density (4-9 $m^{-2}$) for detailed topographic mapping [e.g. Klinghoffer, 2015]. The resulting data was a high-resolution elevation point cloud; each point with an associated Easting, Northing, and elevation [Hassan et al., 2008].

## 2.2 *Standard Deviation of Measured Bed-Surface Elevations*

Bed elevation data was only obtained for the Pool-Riffle reaches of East Creek (PR1, PR2 and PR3), representing a ~500 meter section of the channel. Data was retrieved in XYZ format corresponding to: X = downstream distance (m), Y = cross-stream distance (m), Z = elevation (m.a.s.l). This format facilitated data representation and analysis (Figure 2). For each year in the study period, 499 channel width cross sections were taken every meter of down-stream distance, from which the minimum value in each cross section was extracted. The minimum elevation was used in order to ensure each value is characteristic of the channel bed, as opposed to the mean value, which would be considering the channel banks and outlier elevation points (i.e. woody debris / large clasts and boulders). Plotting the minimum cross section values gives an elevation profile for each year (Figure 3). The standard deviation of these minimum values was taken (i.e. STD of the elevation profile), giving roughness estimate for each year from 2003 – 2015 (Figure 4).

Given that the XYZ point cloud was not interpolated or represented as a raster surface, it was possible that some cross sections contained no XYZ points. In this case, no minimum elevation was extracted, and the cross section was not considered. The number of cross-sections taken (n = 499) was chosen to capture each meter of downstream distance [~500m] for PR1:PR3, and was reflective of the spatial resolution (i.e. point spacing) of the XYZ point cloud.

## *2.3 Elevation Profiles*

For reference, channel bed elevation profiles were taken for each year and plotted to highlight channel-scale changes occurring; such as adjustments in channel slope and bed topography (Figure 5). Bed elevation profiles were created by extracting elevation points along the channel (centerline cross-stream distance = 0).

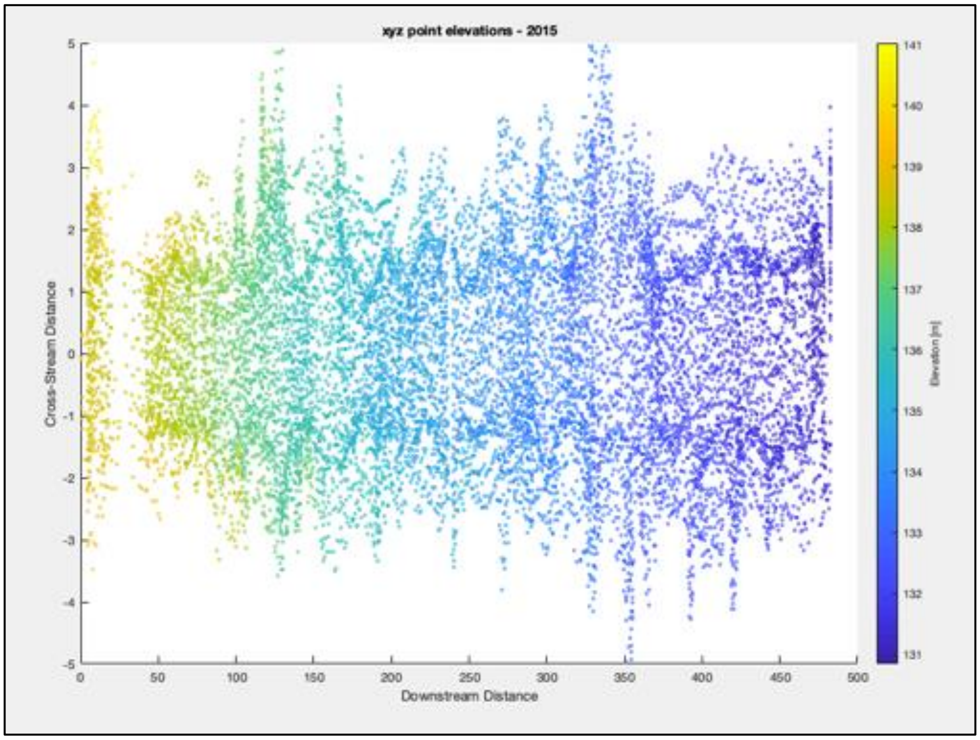


**Figure 2.** Example of XYZ point elevations (2015) plotted as downstream distance (x) and cross-stream distance (y) with an associated elevation value (z). Values are expressed in units of [meters].

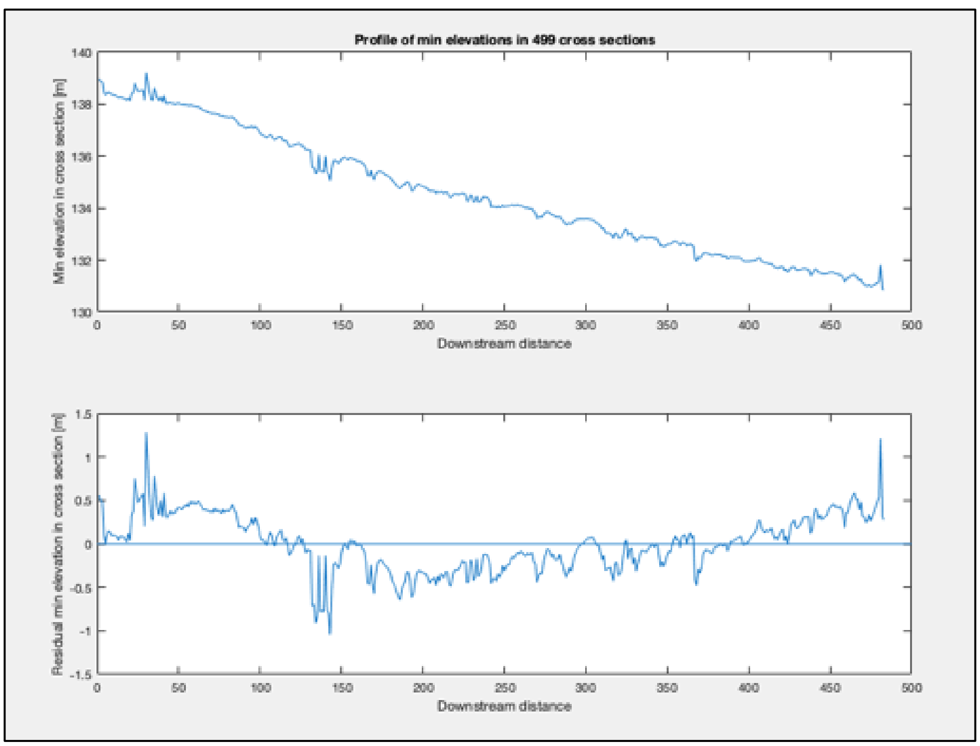


**Figure 3.** (Upper) - Example profile of minimum elevations taken from 499 channel bed cross-sections (2015). (Lower) - Least Squares Residuals plot of minimum elevations taken from 499 channel bed cross-sections (2015). Residuals shown only for reference. Values are expressed in units of [meters].

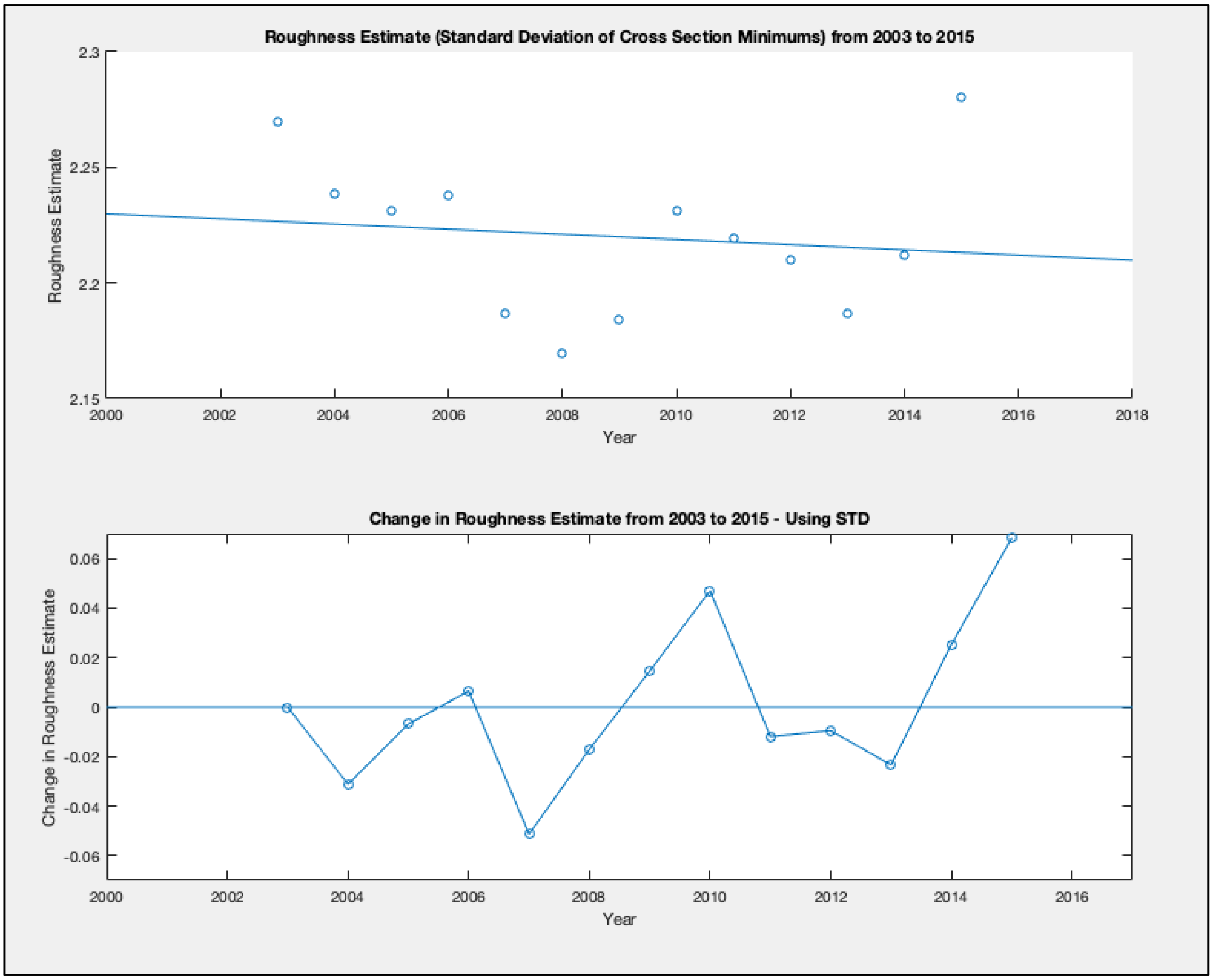


**Figure 4.** Scatter of relative bed roughness estimates for all combined reaches (RP1:RP3) of East Creek; from 2003-2015. Values are the standard deviation of minimums taken from 499 cross sections of the streambed (top), and differences between consecutive years (bottom) that are summarized in Table 1. Values that reflect the difference between consecutive years are associated the latter year.

# 3. RESULTS

## *3.1 Streambed Roughness*

Years 2003 and 2015 showed the greatest relative roughness estimates, while 2008 and 2009 showed the lowest relative roughness estimates (Table 1). The greatest changes in relative roughness estimates between consecutive years occurred between 2006-2007, 2009-2010, and 2014-2015 (Table 2). These values show a slight decrease over time based on the linear regression model, but seems relatively balanced over time if we consider how the changes between consecutive years fluctuate in the positive and negative direction over the study period (Figure 4).

### *3.2 Streambed Gradient*

Elevation profiles along the downstream centerline (cross-stream distance = 0) for each year in the study period (2003-2015) show little channel scale variation in slope, but do show reach scale topographical differences between years (Figure F). An example profile of minimum elevations taken from 499 channel bed cross-sections in 2015 highlights these reach scale topographical differences, as there is variation as great as 1.3 meters in the minimum bed elevation over a downstream distance of 500 meters (Figure B). These differences reflect the variation in bed surface texture that exists between RP1, RP2 and RP3.

**Table 1.** Relative bed roughness estimates for all combined reaches (RP1:RP3) of East Creek; from 2003-2015. Values are the standard deviation of minimums taken from 499 cross sections of the streambed.

| Year | Relative Roughness (STD) |
|---|---|
| 2003 | 2.2696 |
| 2004 | 2.2384 |
| 2005 | 2.2316 |
| 2006 | 2.2381 |
| 2007 | 2.1869 |
| 2008 | 2.1699 |
| 2009 | 2.1844 |
| 2010 | 2.2314 |
| 2011 | 2.2196 |
| 2012 | 2.2101 |
| 2013 | 2.1868 |
| 2014 | 2.2121 |
| 2015 | 2.2804 |

**Table 2.** Changes in relative bed roughness estimates for all combined reaches (RP1:RP3) of East Creek; from 2003-2015. Values are the differences between consecutive years in Table 1.

| *Δ* Year | *Δ* Relative Roughness (STD) |
|---|---|
| 2003 - 2004 | -0.0311 |
| 2004 - 2005 | -0.0068 |
| 2005 - 2006 | 0.0065 |
| 2006 - 2007 | -0.0513 |
| 2007 - 2008 | -0.017 |
| 2008 - 2009 | 0.0146 |
| 2009 - 2010 | 0.047 |
| 2010 - 2011 | -0.0118 |
| 2011 - 2012 | -0.0095 |
| 2012 - 2013 | -0.0233 |
| 2013 - 2014 | 0.0253 |
| 2014 - 2015 | 0.0683 |

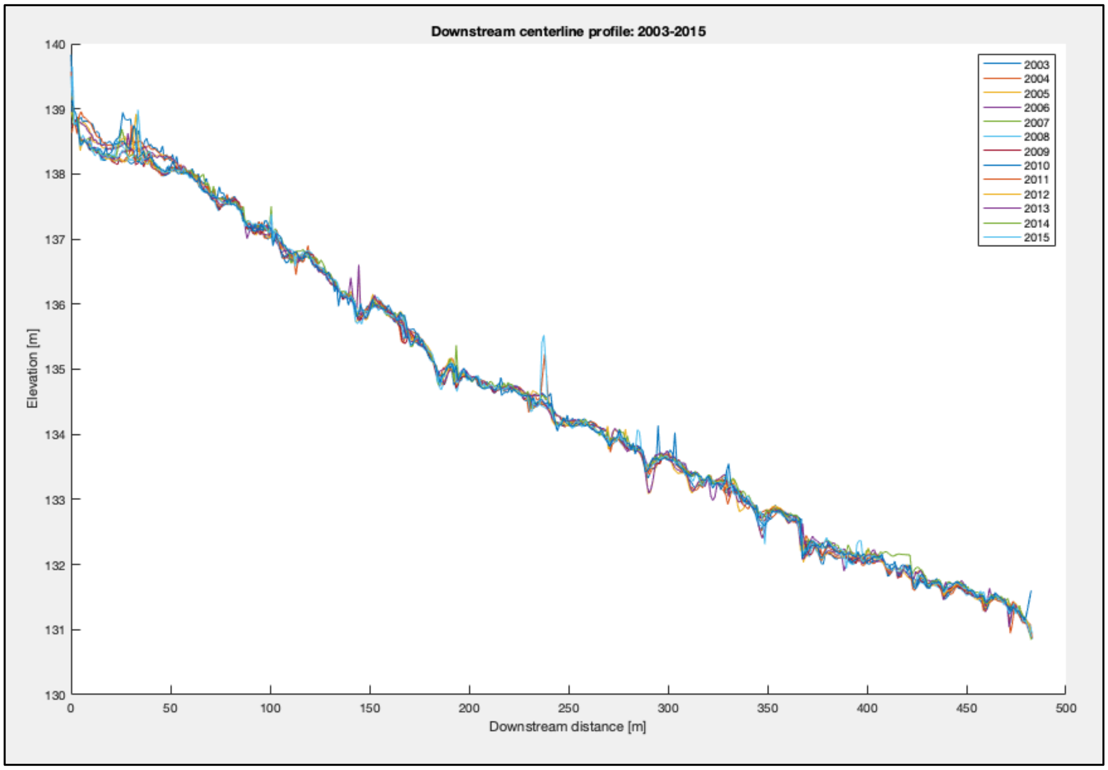


**Figure 5.** Elevation profile along the channel centerline (cross-stream distance (y) = 0) for each year in the study period. Figure does not suggest significant changes in channel slope, but does highlight more localized, reach-scale changes at downstream distances of ~140, 235 and 300 meters for certain years.

# 4. DISCUSSION

## *4.1 Stream flow*

Annual streamflow for East Creek monitored from 2004 - 2011 showed the highest peak discharges occurring in WY09 (4.5 $m^3/s$) and WY07 (4.3 $m^3/s$) and the lowest peak discharge occurred in WY06 (1.0 $m^3/s$) [Klinghoffer, 2015]. Bed roughness estimates are somewhat consistent for with high flow years, as bed roughness shows increases between 2007 and 2010, and is lowest following the 2006 water year (Figure D). As mentioned in section *1.2*, bedform and grain roughness provide the primary flow resistance in free-formed pool riffle channels [Montgomery & Buffington, 1997] and are a way by which rivers can adjust their sediment transport rates to changes in sediment supply [Church & Ferguson, 2015]. We can therefore expect bed roughness to increase in response to high flow events on the basis that the rate of sediment transport will typically exceed the sediment supply [Dietrich et al., 1989]. It is evident that the increased annual streamflow follows this relationship with the resulting roughness proxy; as our results indicate that bed roughness has increased in response to high flow years.

### *4.2 Sediment Flux*

Channel scale sediment flux (i.e. sediment transport rate) can be evaluated based on longitudinal adjustments of sediment storage in a single dimension, therefore the changes in longitudinal elevation profiles over time can provide an estimate of channel-scale sediment storage [Klinghoffer, 2015]. Channels tend towards a state of aggradation when the sediment supply is greater than its transport capacity; the channel bed increases in elevation by deposition, lowering the channel slope. Inversely, if the sediment supply is less than the channel's transport capacity, the channel bed tends to decrease in elevation by erosion; increasing the channel slope (i.e. degradation) [de Almeida & Rodriguez, 2011; Dietrich et al., 1989; Lisle 1982; Knighton, 2014; Tinney, 1962].

Between 2004 and 2006, bed elevation showed fluctuations between aggradation and degradation in more localized areas but did not show strong variation at the channel scale [Klinghoffer, 2015]. This is also evident in the longitudinal profiles along the channel centerline for each year in the study period (Figure 5); no significant changes in channel slope are seen, but more localized reach-scale changes at downstream distances of 140, 235 and 300 meters for certain years are evident from qualitative visual inspection. Klinghoffer (2015) noted that channel slope having the greatest annual changes in PR1 in 2007 (3%), PR2 in 2005 (8%), and in PR3 in 2006 (11%), however these changes are not evident in the channel-scale elevation profiles. Elevation profiles taken for PR1:PR3 separately may be able to describe these changes.

Estimates of sediment flux from differences in Digital Elevation Models (DEM) between 2006 and 2016 show that the riffle-pool reaches of East Creek have gone moderately strong degradation, with a few localized patches of aggradation in riffles and bars [Wlodarczyk, 2017]. This downstream accumulation of sediment has been associated with the re-mobilization of the sediment scoured from the upper rapids reach in 2007 [Klinghoffer, 2015; Wlodarczyk, 2017], which may explain the increase in roughness estimates during years following the 2007 scour event, and the decrease following 2010 (Figure D). However, the stochastic nature of bed mobility and scour/fill in East Creek at the reach scale [Papangelakis & Hassan, 2016] may not be evident in channel scale roughness estimates, as we are looking at the combined effects of three pool-riffle reaches. Therefore, it may not be appropriate to validate our results based on reach scale sediment flux.

### *4.3 Channel Stability*

Channels may respond to imposed change in governing boundary conditions through multiple forms of adjustment [Church, 2015; Church and Ferguson, 2015; Dietrich et al., 1989]. This means that channel stabilization should be considered the product of various system responses. [Eaton & Church, 2009]. The concept of channel stability has taken on a more significant practical importance due to increasing public awareness and the conviction to mitigate potential geomorphological hazards (i.e. flooding) Therefore, it is necessary to develop a deeper understanding of how river processes relate to the stabilization of small mountain streams [Church & Ferguson, 2015].

Cienciala and Hassan (2013) present evidence suggesting that East Creek has undergone a low sediment supply, and can be classified as a sediment-starved channel in a state of degradation from 2009 - 2011. Changes that are characteristic of degrading channels such as coarsening of the channel bed and limited bed mobility [e.g. Lisle et al., 2000; Church and Hassan, 2005] are not visible in our results. We must consider that bed mobility in East Creek bed has been shown to occur more intensely (i.e. full mobility) in localized and sporadic patches [Cienciala & Hassan, 2013; Papangelakis & Hassan, 2016]. The roughness proxy generated (Figure 4) as well as bed-elevation profiles (Figure 5) are displaying the changes in bed roughness at channel-scale and are unable to capture localized reach-scale changes.

### *4.4 Assumptions and Limitations*

It is worth noting that there were major assumptions involved in employing the methodology used in this study. The XYZ point cloud of bed elevations was not able to capture certain features observed in East Creek (i.e. individual boulders and pebble clusters) due to a mean point spacing of 0.3–0.4 meters [Hassan et al., 2008], and is therefore a generalization of channel bed topography. Since our dataset was not interpolated to a continuous surface, minimum elevation values extracted from the 499 channel-width cross sections may be excluding certain bed forms. We have assumed that the roughness proxy generated is representative of the entire channel bed, but it is possible that these minimum values are in fact more representative of pools than they are of other bed forms (i.e. riffles / bars) because they are typically lower in elevation. Our data also does not consider the effects of woody debris in the channel bed. Wood in our study site only represents a small fraction of the total bed area (~ 1%), which was assumed to have only localized influence on channel processes. However, we assume that woody debris and other large clasts are not represented in the cross section minimum elevations.

Nevertheless, these assumptions are the result of generalizations made at the channel scale. It is evident that quantifying bed roughness at large spatial scales does not consider the variability that is occurring in channel-bed processes at more localized areas (i.e. reach scale). Therefore, a large spatial scale can be considered a major limitation in this study.

### *4.5 Insights into Future Research and Investigation*

Brasington et al. (2012) highlight the importance of ‘scale’ in the context of hydraulic and morphodynamical modeling; where a significant consequence of differentiating between spatial scales is the separation of channel bed characteristics into “large-scale” topography and “small-scale” roughness. The point here is not that data chosen in this study was not suited to the application, but moreover brings foreword the question of scale-dependant channel processes in the context of channel stability assessment. We recommend that further research should therefore be considerate of channel bed roughness at the reach scale in order to validate the standard deviation method used in this study. Deriving a roughness proxy for individual channel reaches (PR1, PR2, PR3) would likely provide a more accurate depiction of channel bed processes over time, and could be compared with other reach-scale measurements (i.e. sediment flux and bed elevation changes) available from past research on East Creek.

With the introduction of spatially continuous data structures suited to smaller scale hydraulic modelling applications [Horritt & Bates, 2002; McMillan & Brasington, 2007] and their compatibility with geospatial software in the generation of spatially distributed geomorphic change detection [Brasington et al., 2000; Lane, 2005], this methodology could easily be adapted to output a roughness proxy at smaller scales, given an adequate point resolution is obtained [e.g. Brasington et al., 2012].

## 5. CONCLUSION

This study derived a characteristic bed-surface roughness proxy on a relative vertical scale given by the standard deviation of measured bed-surface elevations and was used to assess changes in channel stability for the Pool-Riffle reaches (PR1:PR3) of East Creek from 2003 – 2015. Bed roughness was correlated with peak streamflow events, but was not correlated with sediment flux or bed elevation changes. The Standard Deviation of Measured Bed-Surface Elevations method was therefore not necessarily validated against ancillary data, and points to the importance of considering scale-dependant channel processes. Bed roughness at the reach-scale may be better able to represent sporadic changes occurring in more localized areas, that are not evident in our roughness proxy. In conclusion, the adaptation of our methodology to capture reach-scale bed roughness is highly recommended.

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All figures used in this study were generated using MATLAB programming software, as well as all data analysis. For access to the MATLAB scripts used in this study, please contact me at simon.campbell@alumni.ubc.ca.

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