Impacts of Permafrost Degradation on a Stream in Taylor Valley, Antarctica

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Abstract: The McMurdo Dry Valleys (MDV) of Antarctica are an ice-free landscape that supports complex, microbially dominated ecosystems despite a severely arid, cold environment (<10 cm water equivalent/yr, -18°C mean annual air temperature). Recent observations of permafrost degradation in the coastal zones of the MDV suggest that this region is nearing a threshold of rapid landscape change. In 2012, substantial thermokarst development was observed along a large stretch of the West Branch of Crescent Stream in Taylor Valley mostly in the form of bank failures, while the adjacent East Branch was unaffected. The objective of this study was to quantify the changes to the stream banks of the West Branch of Crescent Stream, and determine the impacts on the stream bed material composition. Three annually repeated terrestrial LiDAR scans were compared to determine the rates of ground surface change due to thermokarst degradation on the stream bank. The areal extent of the thermokarst was shown to be decreasing, however the average vertical rate of retreat remained constant. Field measurements including, pebble counts, fine sediment counts, and sieve samples were collected and analyzed to determine the effects of the thermokarst activity on the stream bed material. It was determined that the West Branch and the reach downstream of the confluence (of East and West Branches) were consistently more fine than the unaffected East Branch. This suggests that the finer bed material is a result of the thermokarst development on the West Branch. The finer bed material composition of the West Branch, which was shown to increase the mobility of the of the bed material, has implications for stream morphology, endemic algal mat communities, and downstream aquatic ecosystems.

Introduction

The McMurdo Dry Valleys (MDV) are considered one of the driest, coldest deserts on Earth with a mean annual air temperature of around -18°C , and precipitation which falls as snow amounting to, 3 to 50 mm water equivalent (Doran et al., 2002; Fountain et al., 2010). In the MDV the surface energy balance has a much stronger influence on stream flow than precipitation (Gooseff et al., 2011; Hoffman et al., 2008). Much of the snow sublimates before making a significant hydrologic contribution (Conovitz et al., 1998). Despite these harsh conditions, microbial life thrives in the soils, streams, lakes, and even on the glaciers.

The streams of the MDV have been considered to be relatively morphologically stable, based on the widespread presence of armored bed material (McKnight et al., 1999). However, recent observations suggest that the MDV landscape is changing at rates greater than previously documented (Fountain et al., 2014; Levy et al., 2013). Most of these observations have been in locations where permafrost thaw has caused subsidence of the soil structure, features known as thermokarst. These features influence the topography of a landscape, and if the disturbance is adjacent to a stream, it can disturb downstream aquatic environments. The failure of stream banks can introduce sediment at rates many times greater than pre-disturbance conditions, and increase suspended sediment and solute concentrations by several orders of magnitude (Bowden et al., 2008; Kokelj et al., 2013). Abrupt changes to sediment loads and water quality considerably impact the geomorphic properties, and the biological communities of streams (Gooseff et al., 2016).

Most thermokarst research to date is Arctic related because it is a major driver of landscape change in this region. Scientists have only recently begun to assess these same processes in Antarctica. Levy et al. (2013), documented retreat rates of a significant thermokarst

feature in Garwood Valley on the Garwood River that had wasting rates on the order of ten times the estimated Holocene rates, suggesting that the rate of thermokarst degradation is increasing in the MDV. Because of anticipated climate warming in the MDV, it has become increasingly important to understand the impacts of thermokarst processes on the landscape, hydrology, and ecology of the MDV.

In January of 2012, substantial thermokarst development was discovered throughout the West Branch of Crescent Stream (Fryxell Basin, Taylor Valley, Figure 1). Substantial bank failures introduced large amounts of sediment to the active stream channel and left steep, unweathered banks (Figure 2). However, the adjacent East Branch of Crescent Stream was entirely unaffected. Site visits each year since 2012 have documented continued bank degradation on the West Branch each year, however, the subsequent degradation has been less severe than the initial impacts.

Here we illustrate the impacts of thermokarst development on Crescent Stream and investigate the response of the stream over a several year period using high-resolution terrestrial LiDAR scans (TLS) and sediment analysis. Specifically, this study addresses two main research objectives: 1) At what rate is the thermokarst development eroding the ground surface on the banks of the stream? These rates were determined by comparing repeat, annual terrestrial LiDAR scans of the impacted area to detect changes in the ground surface elevation. 2) What impacts has the thermokarst activity had on the bed material composition of the stream? This objective was addressed by conducting sediment size analysis of in-stream and near-stream sediments. Along with comparison of the bed material sediment size to the calculated critical unit stream power, which gives an estimate of stream bed material mobilization. Understanding

the response of Crescent Stream is important to inform future changes to existing polar streams in the presence of a warming climate.

Site Description

Crescent Stream, Taylor Valley, Antarctica (77°37'8.6"S, 163°11'4.1"E) is an ephemeral stream that begins to flow around mid-December, and ceases to flow around late January. However, this range is variable and dependent on the weather patterns during each flow season. The solar aspect of the glaciers is the primary control on stream flow in the MDV because the glacial runoff is the primary source of water contributing to the stream (>95%). This unique hydrologic control causes significant fluctuations in stream flow throughout the day based on the position of the sun, and topographic relief (Conovitz et al., 1998). The hydrologic variability is not only limited to diurnal cycles, these streams have also been found to have high inter-annual variation in stream flow, with some annual peak stream flows shown to vary by five times from year to year (McKnight et al., 1999).

Crescent Stream has two branches (East and West) that converge about 500m upstream of where Crescent stream discharges into Lake Fryxell (Figure 1). A stream gage (established in 1990) is located downstream of the confluence of both branches, therefore, estimating the stream flow for each branch was difficult. Field observations from the 2014/2015 season showed similar flows on each branch at the same time, thus, in assessments of flow for each branch, the gage flow was halved as an estimate of the flow in each branch.

Crescent Stream supports complex microbial mat communities composed of cyanobacteria, chemotrophic bacteria, and diatoms (McKnight et al., 1999; Stanish et al., 2013).

Throughout the MDV streams, algal abundance has been found to be greatest in stable stream reaches with stone pavements, or channel bed armoring (McKnight et al., 1999), while growth is limited in unstable, sandy, depositional reaches near the outlets of lakes (Alger et al., 1997). Therefore, it is important to understand the composition and the mobility of the stream bed material in the MDV due to the influence of these properties on endemic stream communities.

Methods

Terrestrial LiDAR Scan (TLS) Data Collection and Processing

Thermokarst activity was discovered on the West Branch of Crescent Stream in January of the 2012, the most heavily impacted area was documented with terrestrial LiDAR scanning, performed by UNAVCO using a Riegel VZ – 400. Scans were collected in 2013 and 2014 in the same location to capture the rate of ground surface change that have occurred since the initial impacts. There is no high resolution survey data available of the thermokarst impacted area before the thermokarst activity was discovered in 2012. Therefore, the most substantial changes to the ground surface likely went undocumented. Differencing between the new TLS scans and the existing 2001 2 m DEM of Taylor Valley was performed, however the 2 m resolution was too low to detect any true changes. The TLS data was processed by UNAVCO using the RiSCAN Pro software. The latitude and longitude of each point was converted into the Universal Transverse Mercator 58 South coordinate system and elevation values were computed in the World Geodetic System 1984 vertical datum.

To accurately compare the LiDAR scans, the scans were registered to each other to reduce the minor errors introduced by instrument error, GPS error, and geo-referencing errors.

The point clouds were registered to each other using a tool available in Cloud Compare (Girardeau-Montaut, 2014), an open source point cloud management software. The tool utilizes the “Iterative Closest Point” algorithm by Besl and McKay (1992). This algorithm keeps the reference cloud (2014) fixed, while the other clouds (2012, 2013) are transformed to match the reference by iteratively applying a transformation matrix and minimizing a local mean-square distance metric of randomly sampled points.

The point clouds were converted to digital elevation models (DEM) and differenced. The point to DEM conversion used natural neighbor interpolation with a 1 cm by 1 cm grid cell size resolution. The DEM differencing analysis was performed using the Geomorphic Change Detection 6.1.7 (GCD) software plugin for ArcMap (Wheaton, 2015). For original GCD algorithm details see Wheaton et al. (2009). The result is a single raster called a DEM of Difference (DoD) with raster cell values that represent the elevation difference between the two survey DEMs. This DoD is used to produce statistics such as retreat rates, volumes, and areas of disturbed landscapes. Due to inherent uncertainties in survey collection and processing, a fuzzy inference system was used to create spatially distributed error surfaces based on the point density of the surveys, and the slope of the terrain. These error surfaces were used to calculate the DoDs with a 95% confidence limit on the calculated differences.

Sediment Sampling

In January of 2015, sediment data was collected to investigate the impacts of the thermokarst development on the sediment size distribution of the west branch of Crescent Stream. Three methods were used to characterize the sediment: fine sediment counts, pebble

counts, and sediment sieving. The fine sediment counts and the pebble counts (Bunte and Abt, 2001) were performed on reaches throughout both branches of Crescent Stream (See Figure 3). Reaches were sampled over 50 m measured by tape along one side of the stream following the planform of the stream. Each reach was sub-sampled at 11 cross sections spaced 5 m apart. At each cross section a tape was laid across the channel perpendicular to the stream flow. The cross sections were sub-sampled at set intervals typically 5 or 10 cm to ensure adequate resolution. At each sample interval along the cross section, a long, narrow pin was dropped. For the fine sediment counts, if the pin hit a grain of sediment that was visually identified to be less than 2 mm, then it was classified as fine sediment, otherwise it was classified as coarse sediment. For the pebble count method, the specific grain that was struck by the pin was measured with calipers; to determine the diameter of its intermediate axis.

Samples for sieve analysis were collected at two of the sampling reaches: East 2, and West 2 (Figure 3). The reach on the West Branch was chosen because it is located in the midst of the most significant thermokarst activity and was covered by the TLS. The reach on the East Branch was chosen because it was located at a similar distance upstream with a slope similar to the reach on the West Branch. Each reach was sub-sampled at five cross sections each spaced 10 m apart. These were the same cross sections sampled in the pebble counts, however sampling was performed at every other cross section. At each cross section three characteristic areas were visually defined by looking at the surface material. Within the wetted stream channel, locations of fine material and coarse material were defined. Outside the channel, one location of the bank material was defined. This resulted in three characteristic areas per cross section fine material, coarse material, and bank material. Within each characteristic area, two sediment samples were taken. The first sample was the surface material which collected all sediment particles down to a

depth of about 2 cm, and the second sample was taken in the same exact location as the surface material and collected sediment down from about 2 cm to 8 cm. The average sample was around 80 g. The samples were baked in a lab oven at 50°C for 24 hours to ensure all water was evaporated from the samples. The sieve set was comprised of the following sizes: 0 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 3 mm, 4 mm, 6.3 mm, 12.7 mm, and 25.4 mm. This sieve setup was designed to follow the 0.5 ϕ unit spacing as close as possible, however it was largely dictated by which sieves were available for use. Before sieving, each individual sieve was weighed. The dried sediment was poured into the sieve set, and the sieve set was shaken using an automated sieve shaker for one minute. The sieves were individually removed, weighed, and recorded. The mass of the empty sieve was subtracted from the mass of the sieve plus the retained sediment, resulting in the mass of the retained sediment.

Critical Stream Power

In investigating the impacts of thermokarst development on Crescent Stream, it was of interest to consider the ability of the stream to mobilize the sediment within the channel. With the LiDAR scans there exists extremely high resolution surveys of the channel geometry in certain locations. However, because of the low flows experienced in the 2014-2015 season, very little hydraulic data was collected. The flow depth, velocity, and flow rate measurements that are necessary for verifying hydraulic models, and informing many sediment transport equations could not be collected. Stream power is a useful metric to investigate sediment mobilization capabilities using only gross channel parameters. The unit stream power (ω) is defined as

$$\omega = \rho g Q S / w \quad (1)$$

Where Q denotes the flow rate, ρ represents the density of water, g is the acceleration of gravity, S denotes the slope of the channel, and w represents the channel width. This equation represents the mean value of stream power per unit bed area.

Bed-load transport in gravel bedded rivers occurs at a very low rate until a threshold flow rate is reached. After this threshold, transport rates increase non-linearly. Knowledge of this threshold value is useful in addressing the transport capacity of gravel bedded rivers. Bagnold (1980) proposed a formula to calculate the critical unit stream power necessary to transport a bed described by a characteristic particle size, D .

$$\omega_c = c_1 D^{1.5} \log(c_2 h/D) \quad (2)$$

Where ω_c is the critical stream power, c_1 and c_2 are constants, D is the diameter of the characteristic particle size of the bed, and h is the mean flow depth. However, this equation does not distinguish between the grain size being transported and the grain size responsible for bed roughness, or account for hiding effects on the mobility of particles. This equation also requires knowledge of the flow depth. Ferguson (2005), derived a critical stream power equation that addressed these criticisms. Ferguson's full critical unit stream power equation Eq. (3) using the Manning-Strickler relation for flow resistance is used in this analysis:

$$\omega_{ci} = a \rho (\theta_{cb} R g D_b)^{\frac{3}{2}} \left(\frac{\theta_{cb} R}{S} \right)^{\frac{1}{6}} \left(\frac{D_i}{D_b} \right)^{5(1-b)/3} \quad (3)$$

(Ferguson, 2005) where a is a constant from the Manning-Strickler relation with a value of 8.2, D_b is a representative particle diameter (D_{50}) for the bed surface material responsible for the flow resistance, θ_{cb} represents the dimensionless Shields stress for entrainment of particles size D_b , R denotes the submerged specific gravity, D_i denotes the representative particle size of the bed and

b is the hiding factor with a value between 0 and 1. The representative particle size of a stream-bed, mobilized by a given stream power, can be solved for using Eq. (3). The critical stream power on the left hand side of Eq. (3) can be replaced with Eq. (1) as shown below.

$$\rho g Q S / w = a \rho (\theta_{cb} R g D_b)^{\frac{3}{2}} \left(\frac{\theta_{cb} R}{S} \right)^{\frac{1}{6}} \left(\frac{D_i}{D_b} \right)^{5(1-b)/3} \quad (4)$$

The left hand side of Eq. (4) can be calculated using known measured values of each reach. Only reaches East 2, West 2, and West 4 were used because these were the only reaches with a pebble count to inform the variable D_b in Eq. (4). The slopes of the East 2 and West 2 reaches were determined from 2015 terrestrial LiDAR scans, while the slope of West 4 was determined from a 2001 aerial 2 m resolution LiDAR scan of Taylor Valley (Schenk et al., 2004). The thalweg of the stream was extracted and a best fit line was applied to each reach, the slope of that line was taken as the average slope of the reach. The average width of each reach was calculated as the average width of the 11 cross sections within each reach.

A flow duration curve (FDC) was developed for Crescent stream (Figure 4) to inform the flow variable in Eq. 4. Crescent Stream has been gaged at 15 minute intervals since 1990 and the data were available up to 2013 at the time of this study (www.mcmlter.org). The flow record is fairly complete, however, gaps in the data are present, specifically after the gage was inundated with sediment in January 2012 coincident with the thermokarst activity. Nevertheless, there are over 41,000 fair to high quality (as noted in the dataset) recorded discharges that were used for analysis (McKnight, 2014). The only stream gage that exists on Crescent Stream measures the total flow downstream of the confluence of the two branches. Therefore, two FDCs were determined for each branch by assuming either half flow (equal flow contribution

from each branch), or total flow (an end-member scenario where all gaged flow comes from one branch).

To solve for the critical unit stream power, each percentile of flow along the FDC was used in the left hand side of Eq. (4) along with the slope of the reach of interest, and average width to create a distribution of stream powers with estimated probabilities of occurrence. The known values of the right hand side of Eq. (4) were then populated. It is assumed that $\rho = 1000 \text{ kg/m}^3$, $g = 9.81 \text{ m/s}^2$, and $R = 1.65$. The critical dimensionless shear stress, θ_{cb} , was estimated using the measured fractions of sand and Figure 1 from (Wilcock, 1998). The resulting θ_{cb} values were 0.015, 0.029, and 0.037 for West 2, West 4, and East 2 respectively. The constant $a = 8.2$ from the Manning-Strickler relation was used, and $b = 0.7$ was used for the grain hiding factor. The representative surface roughness diameter, D_b , values used were the D_{50} values calculated from the pebble counts which were 9.6 mm, 55.1 mm, and 32.5 mm for West 2, West 4, and East 2 respectively. The only unknown remaining in Eq. (4) is the D_i term, which is the diameter of the particle size that represents the bed material transported by the given stream power. This diameter was solved for using various critical unit stream powers as determined by the FDC.

Results

Rates of Ground Surface Change

The DEMs developed from the LiDAR scans were compared to determine the rate of ground surface change in the most active thermokarst area. Substantial erosion (negative change in ground surface elevation) on the order of 0.5 m was measured on the East bank of the channel for both the 2012 to 2013 and the 2013 to 2014 analyses (Figure 5). Many of the areas of major

erosion showed small amounts of deposition (positive change in ground surface elevation) on the order of 0.1 m just downslope of the impacted areas. The total calculated volume of erosion for a 40m long reach, from 2012 to 2013 was 4.7 m³, which was more than double the 1.9 m³ measured from 2013 to 2014 (Table 1), indicating that the extent of erosion is decreasing with time. The volume of deposition in this reach from 2012 to 2013 was 0.29 m³, and 0.31 m³ from 2013 to 2014. Deposition volumes were much lower than erosion volumes, indicating that eroded sediment has either been transported out of the scan area, or has been distributed as shallow deposits too small for the analysis to detect. The average depths of erosion for each time period were similar with values of 0.21 m and 0.18 m. The average deposition depths for the two years were also very similar with values of 0.1 m, and 0.07 m.

Comparison of Particle Size Distributions, Fines, and Stream Power in East and West Branches of Crescent Stream

Sediment sieving was used to compare sediment size distributions of the East and West Branches, as well as to characterize the sediment introduced by the thermokarst formation. The coarse and bank material on both branches had larger surface material when compared to the sub-surface material (Figure 6). The sediment size distribution of the sub-surface bank material from the West Branch was found to have over 60% of material less than 2mm (Figure 6), indicating that a majority of the sediment introduced to the stream channel due to thermokarst activity was fine material (< 2mm). The sieve results also show a finer distribution for the surface fine and coarse material of the West Branch compared to the East Branch.

The spatial distribution of fine material and the unit stream power were compared to determine if the thermokarst development has changed the size of the bed material on the West Branch. The plot of percent fine versus distance upstream shows the longitudinal distribution of fine sediment throughout the stream network (Figure 7A). The most upstream reaches of the East and West Branches, East 3 and West 4, had very similar average percent fine values of around 21%, and standard deviations of about 10%. Moving downstream along the West Branch, the percent fine value peaked at the West 3 location, with a value of 52% and a relatively large standard deviation of about 20%. The percentages decreased gradually downstream from 34% at West 2, and then to 31% at West 1 despite lower unit stream powers of 22 W/m², and 45 W/m² respectively. On the East Branch the percent fine values remained relatively constant despite a range of unit stream powers from 28 W/m² to 43.7 W/m². The average percent fine dipped slightly from 22% at East 3 to 17% at East 2, and then back up to 21% at East 1. The confluence value for the average percent fine value of 35% was larger than all East Branch values and similar to the lower two West Branch values.

Does Thermokarst Development Enhance Bed Material Mobilization?

The bed material mobilization analyses (Figure 8) represent the bed material particle size that would be mobilized given a certain flow, with the solid curve representing half of the observed flow (equal flow contribution from each branch), and the dashed curve representing the full observed flow (total flow is experienced by only one branch). The West 4 location had the least capacity to mobilize bed material and had the largest bed material. The location with the greatest bed material transport capacity was West 2, which also had the smallest sediment size distribution. This relationship is due to the fact that a larger fraction of sand (smaller bed

material) increases the mobility of the bed material (Wilcock, 1998). These results indicate that the West 2 reach can mobilize its bed material far more frequently than the East 2 and West 4 locations.

Discussion

Rate of Ground Surface Change Since Initiation of Thermokarst

How do the rates of change compare to nearby unaffected areas, and how does the ground surface continue to respond after the initial disturbance in January of 2012? To ensure that the measured rates of change on the east bank were substantial compared to nearby rates of change, the opposing unaffected bank (the west bank) was differenced and no change was detected. Without any high resolution survey data of the site before January of 2012, it is assumed that the most dramatic changes went undocumented. The geomorphic change that was captured, shows a substantial decrease in the volume eroded from 2012 to 2013 to the volume eroded from 2013 to 2014 (Figure 5, Table 1), suggesting the rate of erosion due to thermokarst activity is slowing. However, the average depth of erosion remained constant at about 20 cm. The decrease in the volumetric change was largely due to the fact that the areal extent of erosion decreased. The decrease in the area affected, in conjunction with the constant vertical rate of change, suggests that the extent of permafrost susceptible to thaw in the bank is likely decreasing, while the drivers of the permafrost thaw appear to be remaining constant.

Thermokarst Impacts on Stream Sediment

To assess the impacts of the thermokarst development (due to permafrost degradation) on the bed material of the West Branch of Crescent Stream, it was necessary to determine the current stream bed material, as well as attempt to infer what past bed material composition may have been. The sediment size analysis of the West Branch of Crescent Stream was designed to inform the current bed material composition – as influenced by the thermokarst formation, while the analysis of the East Branch attempted to determine what the past bed material composition of the West Branch may have been before the thermokarst impacts. The East Branch and West Branch of Crescent Stream have many similar characteristics including discharge (based on field observations), longitudinal profiles, and substrate (prior to thermokarst formation on West Branch). Due to the similarities between the East and West Branches of Crescent Stream, and the relative stability of the East Branch, the East Branch is a plausible pre-disturbance reference for West Branch providing a useful baseline condition to compare to the impacted West Branch.

In order to interpret the grain size data, we assumed the bank material sampled from the West Branch (Figure 6D) is representative of the material that eroded out during thermokarst formation. It is mostly fine material. Looking at the distribution of fine material in Figure 7A we find that the thermokarst impacted branch has more fines downstream of the thermokarst impacts than the unaffected branch. We interpret this to indicate that thermokarst erosion in Crescent Stream delivered bank sediments to the channel. Because most tills in Taylor Valley are fine grained (Wagner et al., 2006), we predict that future thermokarst erosion on streams will produce pulses of fine grained material into stable stream beds that are typically dominated by armored gravels and cobbles.

Fate of Fine Sediments Introduced to the Stream

We expected the input of fine sediment to influence the stream bed material size distribution. To explore this idea we determined how much fine material was present on the surface of the stream bed for each branch. The average percent fines composition of the West 4 location was very similar to the percent fines of all East reaches, and a similar unit stream power to that of East 3. This indicates that the West 4 branch may also serve as an example of the West Branch bed conditions before the thermokarst impacts. The location of West 4 was decided upon because it is located immediately downstream of a long, very low gradient reach. There were thermokarst impacts observed above the West 4 reach in 2012 (Gooseff et al., 2016). However, the majority of the sediment from those thermokarst impacts is assumed to have been deposited in the upstream low gradient reach, leaving the West 4 reach relatively unaffected. West 4 had the coarsest pebble count measured out of the three West branch reaches that were sampled. This result is due to the lack of sediment loading to this reach combined with a relatively high unit stream power.

Further downstream, where the thermokarst impacts are more pervasive, the West 3 reach exhibits an unusually high average percent fine value, accompanied with a large standard deviation of the percent fine values. This result is interesting because the West 3 reach has a nearly identical unit stream power as the East 2 reach. However, West 3 has a much higher percentage of fine material when compared to East 2. This suggests that some factor other than stream power is responsible for the increased number of fines on the West Branch bed, and the cause is the introduction of fine sediment due to the thermokarst activity.

The West 1 and 2 reaches exhibit a considerable reduction in the average percent fine value from the West 3 reach, despite lower stream powers. However, the West 1 and 2 locations have a higher average percent fine value than all of the east branch reaches regardless of unit

stream power. These results suggest that upstream introduction of fine sediment from thermokarst activity has caused the bed material composition of the West Branch to become more fine than the East Branch regardless of unit stream power. The confluence also had an average percent fine value larger than the entire East Branch. However, the Confluence 1 location has the lowest stream power and thus it would be expected to have a higher percentage of fines than other locations. All locations on the east branch had a nearly constant average percent fine value accompanied with relatively small standard deviations. This was a surprising result based on the wide range of stream powers observed on the East Branch. This result suggests that the effect of stream power on the percentage of fines on the bed throughout this branch is minimal.

From the pebble counts and the fine sediment counts, it is clear that the West Branch contains a greater percentage of fine surface material than the East Branch, regardless of the varying stream power and upstream conditions. The main difference between these two branches, that has the potential to cause this difference in the amount of fine sediment in each branch, is the presence of thermokarst throughout the West Branch. This result is consistent with other findings of bed material fining after fine grained sediment pulses (Venditti et al., 2010).

Comparison of GCD and Sediment Size Analysis

The results of the GCD and the sediment size analysis may appear to be contradictory. The GCD analysis shows very little aggradation in the scan area, while the increased amount of fine sediment found in the West Branch could be interpreted as aggradation of fine material on the bed surface. However, it should be noted that if aggradation of fine sediment did occur

within the stream channel, the GCD analysis would have trouble detecting small changes. The aggradation of the bed is likely a small change on the order of a couple of centimeters distributed over a large area, while the average changes the GCD can detect are around 5 cm. Another drawback of the terrestrial LiDAR technology is that it cannot penetrate water. Therefore, the point density is very low wherever water was present within the channel at the time of the scan. Therefore, the GCD analysis more accurately illustrates the changes that have occurred outside of the stream channel, whereas the sediment size analysis explains the changes that have occurred within the stream channel.

Sediment Mobilization Capacity of East and West Branches of Crescent Stream

The sediment mobilization analysis was intended to assess the extent to which the stream has the ability to transport its own bed material and the sediment introduced by the thermokarst formation. Stream power was used because it allows for the estimation of particle size mobilization using gross channel parameters that are relatively simple to measure. Calculation of the unit stream power (Eq. 1) requires three parameters: slope (S), discharge (Q), and width (w). One of the limitations of this analysis is that the width of the stream at each reach was held constant for different flow rates due to lack of data relating width and flow rate. The East 2 and West 4 locations were similar in their capacity to mobilize the bed material. However, the most severely impacted location, West 2, was able to mobilize the available bed material much more readily than the other reaches. The larger fraction of sand in the West 2 transect reduced the dimensionless critical shear stress, resulting in higher bed material mobility (Wilcock, 1998). Fine sediment pulses, similar to what the thermokarst development has produced here, have been found to greatly increase sediment transport rates in gravel bedded rivers (Venditti et al., 2010).

The results of this analysis indicate that the influx of fine sediment promotes the mobilization of the bed material, which will influence the geomorphology and the ecology of the stream, and potentially the receiving closed-basin lake (Gooseff et al., 2016).

Ecosystem Implications of Stream Bank Thermokarst Development

The biological communities of Crescent Stream and Lake Fryxell continue to experience environmental changes caused by the thermokarst activity on Crescent Stream as the stream system continues to adjust. The increased bed mobility and finer bed material size, has implications for stream and lake biota. The increased bed mobility causes more sediment to be transported downstream and deposited into Lake Fryxell, which has been shown to hinder primary production in MDV lakes (Foreman et al., 2004). The increased mobility of the bed material also limits the algae's ability to populate the stream bed (Alger et al., 1997). These potential impacts on the microbial communities of the stream and lake show that as the MDV landscape changes, we can expect to see responses in the downstream ecosystems. It would be interesting to further quantify the ecological impacts that were caused by the thermokarst bank degradation.

Conclusion

Ongoing thermokarst development and sediment erosion from the West Branch of Crescent Stream has modified bank topography and stream bed sediment distribution over the 2012-2014 observational period. The vertical rates of erosion of ~20 cm/yr are constant, however the areal extent experiencing change has decreased from 24.5 m² to 10.3 m² from 2012-

2013 to 2013-2014 respectively. The primary impacts of the thermokarst development on the West Branch of Crescent Stream are an increase in the presence of fine material on the stream bed. The addition of fine material to the West Branch of Crescent Stream has increased the mobility of the bed material compared to unaffected reaches. The increased bed mobility has the potential to alter the morphology of the stream, and limit algal growth within the stream. Considering the warming climate and the influence of polar amplification, the initiation of thermokarst features is expected to increase in this region, which will continue to challenge the resiliency of the MDV streams and their dependent biologic communities.

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Figure 1. The Lake Fryxell Basin in Eastern Taylor Valley, Antarctica. The red box highlights both East and West branches of Crescent Stream (image data courtesy of Polar Geospatial Center).

Figure 2. Images of thermokarst impacts on the West Branch of Crescent Stream taken upon discovery in January of 2012. Black dots represent locations where impacts were identified in 2012, and the highlighted dots show locations of selected example photographs that illustrate thermokarst subsidence along the banks. The red dot highlights the location of most substantial thermokarst impacts where the terrestrial LiDAR was collected. (Figure should be printed in color)

Figure 3. Map of sample types and locations. Each point represents upstream and downstream limits of sample reach.

Figure 4. Flow duration curve of Crescent Stream gage downstream of confluence. Each branch was not gaged individually, so the total gaged flow was halved to estimate what each branch might see (solid line). The actual gaged flow is also shown (dashed line) to represent a maximum end member for the potential flow each branch could see. This flow duration curve was calculated using only flows that were rated “good” or “fair” as noted in the dataset. It should be noted that this is an ephemeral stream and all zero flow measurements were thrown out.

Figure 5. DEM differencing results of a thermokarst impacted area on the West Branch of Crescent Stream. Red coloring indicates areas of measured erosion (decrease in ground surface elevation), and blue coloring indicates areas of measured deposition (increase in ground surface elevation). The location of this reach is indicated in Figure 3. (Figure should be printed in color)

496 **Table 1.** Quantitative geomorphic change detection results of a reach on the West Branch of
 497 Crescent Stream (Figure 5).

	2012 - 2013	2013 - 2014
Erosion Volume (m³)	4.68	1.90
Erosion Error Volume (m³)	1.36	0.58
Deposition Volume (m³)	0.29	0.31
Deposition Error Volume (m³)	0.16	0.41
Area of Erosion (m²)	22.5	10.5
Area of Deposition (m²)	2.81	4.51
Average Depth of Erosion (m)	0.21	0.18
Average Depth of Deposition (m)	0.1	0.07

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Figure 6. Sediment size distributions of sieve samples for East 2 and West 2 reaches of Crescent Stream, Taylor Valley, Antarctica. Samples were characterized by reach, surface or sub-surface, and by sample location type. **A:** East surface material, **B:** West surface material, **C:** East sub-surface material, **D:** West sub-surface material.

Figure 7. A: Percent fine plotted against distance upstream of gage station. **B:** Percent fine plotted against unit stream power. Points represent reach averaged percent fine of the 11 cross sections per reach. Error bars represent the standard deviations of the percent fine within each cross section. (Figure should be printed in color)

Figure 4. Bed material particle size mobilization plotted against the flow exceedance probability. Solid curve represents half of observed flow at gage, i.e. what one branch would likely experience. Dashed curve represents an end member scenario where all of the flow observed at the gage is flowing through only one of the channels. **A:** East 2, **B:** West 2, **C:** West 4. (Figure should be printed in color)

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