Geomorphology 287 (2017) 73–89

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Assessment of sediment sources throughout the proglacial area of a small Arctic catchment based on high-resolution digital elevation models

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ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 30 August 2016
Accepted 6 September 2016
Available online 10 September 2016

Keywords:
Repeat TLS surveys
DEM of Difference (DoD)
Geomorphic changes
Sediment budgeting
Proglacial gravel-bed river
Svalbard

ABSTRACT

The article presents calculations of quantitative modifications of the morphology of selected subsystems of a glacial valley through: (i) identification of the spatial distribution of important sources of sediment, (ii) assessment of the spatiotemporal variety of sediment volume and landform morphology, and (iii) assessment of the role of particular subsystems in sediment distribution. The study involved a comparison of the results of field measurements from 2010 to 2013 performed in the Scott Glacier catchment (10.1 km^2) in NW Wedel Jarlsberg Land (Spitsbergen). The assessment of the landform surface changes was performed by means of a precise Terrestrial Laser Scanning (TLS) survey. The applied field and post-processing techniques for oblique laser scanning permitted the acquisition of digital elevation data at a resolution 0.01 m and density > 500 pt m^{-2}. This allowed the development of a detailed terrain model, and balancing spatial quantitative changes in six research test areas (10,000 m^2) located within two subsystems of the catchment in a cascade arrangement. In the alluvial valley-floor subsystem, the survey covered: 1) the glacier terminus, 2) the intramarginal outwash plain, 3) the extramarginal braid-plain and 4) the alluvial fan, and in the slope subsystem: 5) the erosional-depositional slope in the gorge through terminal moraines, and 6) the solifluction slope. Three zones differing in terms of the spatiotemporal dynamics of geomorphic processes were distinguished within the two analysed valley subsystems. In the valley floor subsystem, these are: (i) the zone of basic supply (distribution throughout the melting season) and (ii) the redeposition zone (distribution particularly during floods), and in the slope subsystem: (iii) zone of periodical supply (distributed mainly in periods of increased precipitation and rapid increases in temperature in summer and during snow avalanches in winter). The glacier and the landforms of the channel and valley floor, as well as slope sediments transported as a result of mass wasting processes and activity of the active permafrost layer, constitute important sources of sediment supply over a short/3-year timescale. Evidence of major changes of the surface morphology (slopes, floodplain and channel platform) resulted in varied sediment budgets. The subtraction of consecutive DEMs of the test areas located in the alluvial valley subsystem revealed downstream spatial and volumetric differentiation, from the predominance of erosion (79% of volume; 43% of area) to the dominance of deposition (90/91%, respectively) in upper part of the valley floor to erosion predominance in the central (88/95%) and lower (87/82%) part of valley floor. The test areas located on the slope subsystem showed the opposite relationship: deposition dominance (88% of volume; 80% of area) in the upper gorge and erosion dominance (99/99%, respectively) in the lower part (solifluction slopes). The analysis of short-time repeated surveys (3-week survey) where volumes were calculated following DEM subtraction showed increased deposition (82% of volume; 79% of area) for the alluvial fan, and for solifluction slopes (70/57%, respectively).

1. Introduction

The geomorphological modification of Arctic environments stimulates an increase in the intensity of paraglacial processes (Magilligan et al., 2002; Staines et al., 2015). High rates of spatial and temporal changes are particularly important for fluvial systems (Heritage and Hetherington, 2007). Over a short time scale, this contributes to the activation of fluvial processes (e.g. bank and bed erosion, sediment mobilisation and deposition), and development of the alluvial and slope land system with the erosion and deposition subsystems (Church and Ryder, 1972; Ballantyne, 2002a,b). Within the subsystems, distribution and redistribution of sediment originating from glacial and snow cover ablation, as well as from slope processes, occur (Maizels, 1997). The rate and course of such processes are largely determined by the morphometry of the respective drainage basin (sub-)areas, and particularly by the occurrence of narrowings in the valley. These are distinguished by the higher intensity of slope-channel coupling, higher

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http://dx.doi.org/10.1016/j.geomorph.2016.09.011
0169-555X/

rates of sediment supply (Beylich and Laute, 2015), and zones of periodical or permanent sediment deposition (Church and Ryder, 1972; Ballantyne, 2002a,b), for example, moraine lakes frequently constituting specific sediment traps (Beylich and Laute, 2015; Kociuba and Janicki, 2015a). The redeposition of the supplied sediment results in high rates of variability in the valley floor surface and channel relief (Beylich and Laute, 2015; Kociuba and Janicki, 2015a,b; Kociuba et al., 2016). The identification and quantitative assessment of the temporal and spatial variability of the primary sources of sediment supply to the river in valley subsystems in cascade arrangement (Warburton, 1990) is necessary for the accurate investigation of the modern mechanisms of river sediment flux (Orwin et al., 2010). This is particularly so in a cold climate and steep mountain streams distinguished by strong interactions between slope processes and the channel network (for example Ashworth and Ferguson, 1986; Ergenzinger and Schmidt, 1994; Beylich and Warburton, 2007; Church and Zimmermann, 2007; Warburton, 2007; Orwin et al., 2010; Beylich, 2011; Comiti and Mao, 2012; Rickenmann et al., 2012; Kociuba, 2014; Laute and Beylich, 2014a,b; Beylich and Laute, 2015; Kociuba and Janicki, 2015a). However, the role of different sediment sources and patterns of delivery in an Arctic proglacial river valley, and their geomorphic coupling with specific processes, is not well understood (Kociuba et al., 2014; Beylich and Laute, 2015). In glacial catchments subject to landform surface variability, the estimation of the dynamics of modern changes of slope landforms (transformed by rock falls, snow avalanches, mass wasting processes, solifluction, landslides, and debris flow) and valley landforms (transformations by channel migration, channel bank and bed erosion, aggradation) is possible due to the application of high-resolution surveying technologies (Bitelli et al., 2004; Teza et al., 2007, 2008; Wangensteen et al., 2007; Travelletti et al., 2008; Prokop and Panholzer, 2009; Wilkinson et al., 2010). The repetition of measurements, resulting from the use of precise remote sensing tools, permits the quantitative assessment of the degree of glaciers and ice-caps changes (Bamber et al., 2005; Kääb et al., 2005; Arnold et al., 2006; Connor et al., 2009) and glacier-free relief transformation (Ødegård et al., 2003; Bremer and Sass, 2012; Kociuba et al., 2014, 2016), as well as the identification of threats of occurrence of catastrophic phenomena (Kenner et al., 2011). Accurate results are obtained by the application of Terrestrial Laser Scanning – TLS, in research on the intensity of geomorphic processes (Fischer and Huggel, 2008; Rabatel et al., 2008; Oppikofer et al., 2009; Resop and Hession, 2010; Kenner et al., 2011; O'Neal and Pizzuto, 2011; Kociuba et al., 2014). In current applications of TLS, research accuracy largely depends on the selection of not only the device, but also the strategy of field measurements (Abbelán et al., 2009; Heritage et al., 2009; Kenner et al., 2011; Bremer and Sass, 2012; Kociuba et al., 2014) and standardisation of methods of surface area and volume analysis for the improved intercomparability of results (Besl and McKay, 1992; Lichti et al., 2005; Kociuba et al., 2014).

The objective of this paper is to assess geomorphic activity with respect to sediment sources, delivery, flux, and the spatial and temporal differentiation in the analysed subsystems (alluvial valley floor and slope). The results of repeat TLS surveys permit accurate quantification of the dynamics of erosion and deposition and sediment budgets of the proglacial river valley, as well as evidencing the importance of the geomorphic coupling activity, based on high-resolution DEMs of Difference (DoD). This study provides a precise identification of a three-year period of changes of erosion and deposition, and attempts to link them with downstream spatial and volumetric differentiation. This research contributes to a better understanding of the course of geomorphic processes in deglaciating catchments.

2. Study area

The study on rates of spatial and temporal changes in the morphology of selected subsystems of a glacial catchment and their role in river bedload supply was conducted in the Scott River catchment located in the NW Wedel-Jarlsberg Land in the Bellsund region of Spitsbergen (Fig. 1A). The Scott River catchment has an area of 10.1 km^2. Approximately 40% of the catchment is covered by a valley glacier of Alpine type in the phase of recession, with a length of 3.1 km and width from 1.1 to 1.8 km (Fig. 1B). The highest parts of the glacier reached 502 m a.s.l., and the terminus was located in 2010 at an altitude of 85–89 m a.s.l. (Kociuba and Janicki, 2015a).

The catchment is drained by the Scott River with a glacial regime, dominated by proglacial waters (90%). The secondary source of supply is constituted by nival (4%), rain (4%), and permafrost waters (2%) (Bartoszewski, 1998). The glacier-free part of the catchment along a section of approximately 3.1 km is occupied by the Scott River valley (Fig. 1C). The relief of this section of the valley comprises three genetically varied and clearly distinguishable parts separated by two narrowings with a gorge character (Kociuba and Janicki, 2013; Rodzik et al., 2013; Kociuba and Janicki, 2015a): upper, covering a glacially transformed montane valley with a distributed channel system within the intramarginal outwash plain, and middle and lower (separated with the gorge section of the valley through the terminal moraine rampart). These cover the alluvial valley developed within the elevated marine terraces where the river bed occupies a relatively narrow zone in the valley floor (Fig. 2).

According to Schrott et al. (2003), a river valley can be divided into subsystems representing a typical valley landform assemblage of the sediment cascade, connected through processes and influenced by regulators (e.g., slope angle, slope length) (Chorley and Kennedy, 1971). The research was conducted in six square-shaped test areas with an area of 10,000 m^2 each, located within two valley subsystems: four – in cascade arrangement in the valley floor subsystem: 1) in glacial terminal zone, 2) on intramarginal outwash plain, 3) on extramarginal braid-plain, 4) on alluvial fan, and two – in the slope system: 5) erosional-depositional slope in the gorge through terminal moraines, 6) solifluction slope in the mouth section of the valley (Fig. 1C, 2).

2.1. Alluvial subsystem

2.1.1. Test area 1 – glacier forefield

The study area (Fig. 2) covers the SE part of the glacier terminus (2010) with the main subglacial outflow constituting the basic source of the Scott River. The marginal zone covers a group of glacigenic (terminal moraine, lateral moraine, ablation moraine, roche moutonnée) and fluvioglacial landforms (outwash fans, marginal lakes) (Fig. 3-1A, B). As a result of the fast retreat of the glacier terminus at a rate of 10–20 m yr^{-1} (Kociuba and Janicki, 2015a), this part of the catchment is distinguished by the highest dynamics of morphogenetic processes (Rodzik et al., 2013). In 2010, the W part was occupied by the glacier terminus with the main subglacial outflow (Fig. 3-1A) concentrating the drainage system of glacial waters, and directing them to NE through the distributed channel system (Fig. 3-1B). In the S part, a group of glacigenic landforms occurred: an ice-moraine rampart and lateral moraine separated by fluvioglacial landforms: outwash fan with two postglacial basins (Fig. 3-1B).

2.1.2. Test area 2 - intramarginal outwash plain

The upper part of the glacier-free catchment extends along a section of approximately 700 m between the glacial terminus and terminal moraine (Kociuba and Janicki, 2014). As a result of activity of proglacial waters, glacigenic and fluvioglacial landforms are modelled by high dynamics of geomorphic processes. Waters outflowing from the forefield are distributed through a braided system to the area of the intramarginal outwash plain. Sandurs of various ages are located at different altitudes. Older ones are flat and enriched in the channels of former proglacial streams. The youngest one, extending at the opening in the ice-moraine rampart, is developed by the braided fluvial system. Proglacial waters transport high amounts of sediments, deposited in the form of longitudinal interchannel scroll ridges (Reder and