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Measuring bank retreat in fluvial environments with Terrestrial Laser Scanning (TLS)

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Abstract

In the last years methods for measuring bank erosion and sedimentation have been used to understand the process of river migration to get a better understanding of river migration. For this purpose a river bank in a medium low land river has been chosen. The river bank has been measured with a terrestrial laser scanner with a high resolution over the last three years. The yielded point clouds have been filtered and digital elevation models (DEM) have been created. These DEMs have been used to compare the mass balance and slope gradient changes between the scans. To achieve this goal, the slope gradient has been averaged horizontally and vertically. In addition, statistical analyses have been used to verify the significance of changes between the scans. The results show that erosion and sedimentation processes occur simultaneous. Further is the slope gradient a valuable tool to investigate different sections within a point cloud from terrestrial laser scanner.

1 Introduction

The understanding of river migration has been investigated for many years. The quantification of sediment erosion and accumulation is an important part for the understanding of the behaviour of natural fluvial systems. The importance is not only a deeper understanding of nature, but also an understanding of erosion, sediment transport and sediment deposition, which has high value for water reservoirs and planning of infrastructure. In the last decade measurement methods have been developed to estimate the sediment balance (Thomas, 2004). Most of them are devices which measure and log sediment change. The disadvantage, however, is, that they are intrusive, such as erosion pins (Lawler, 2001; Erlingsson, 1991), and give a low spatial resolution. Though the resolution is depending on the measurement net which can be built in the field, it is not more than one measurement point per square meter, taking into account that a higher density of the measurement points do increase the impact by the devices it-

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self. Others such as Light Detection And Ranging (LiDAR) has its main use in airborne survey over large areas (Milan et al., 2010) and has its limits by surveying vertical or near-vertical structures. The use of Terrestrial Laser Scanning (TLS) avoids the impact of the measurement device and collects a high mount of measurement points. The horizontal setup direction of the laser beam makes it perfect for river bank survey with a slope gradient higher than 45°. The TLS collects data points over the entire river bank. This makes it possible to get a much higher resolution (Resop and Hession, 2010) and hence a more detailed insight in stream morphology. The investigated patches are small patches with a very high point cloud density with a resolution beyond photogrammetry (Brasington et al., 2012). In addition shall the analyses of the laser scan time series give insight in the processes of river migration that occur at a riverbank (Jaboyedoff et al., 2009). The limitation of TLS, however, is the lack of on-going monitoring.

The aim of this paper is the analysis of bank retreat and stream morphology on a yearly and short term basis with the help of TLS.

2 Study site

The surveyed river, Breivikelva, is a lowland river in the northern part of Norway (Fig. 1). The catchment covers an area of 163.7 km^2 with an altitude from 0 to 1400 m a.s.l. (NVE, 2012) and is sensitive to changes in the water input. Like it can be seen in Fig. 2, the small spikes of water level changes are most properly the result of snow melting process due to daylight. The reach is about 1100 m long and has a slope of 0.4 %. The river has a W/D ratio between 15 and 20 and a sinuosity of 3. The river can therefore be classified after Rosgen (1994) as an F-type river. The measured discharge varied between 24.3 $m^3 s^{-1}$ to 8.7 $m^3 s^{-1}$ in spring and in autumn, respectively.

The riverbanks have heights of 1–20 m above water level and consist of post glacial sediments (Corner, 2006; Corner and Fjalstad, 1993). These are fine undulated layers of sand and silt along the river bank. A soil layer on top of the bank is thin and con-

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tributes little to stabilize the river bank. The river bed in the beginning of the reach is partly covered with cobbles. The vegetation on the riverbanks consists mainly of trees and vegetation patches which felt and slid down the river bank.

3 Methods and materials

3.1 Acquisition of data

The water level has been measured at the beginning and at the end of the reach. The water level during 2011 and 2012 has alternated between 1.1 and 1.8 m a.s.l. downstream and 1.5 and 2.2 m a.s.l. upstream. During these two years no heavy rain fall with a flood character has been measured. The water level decreases during the summer with the retreat of the snow. This results in that the maximum water level after rain events later in the year also decrease. In spring season 2013 the water level logger recorded one high water event (2.3 m a.s.l.) after some days rainfall from 23 June till 27 June and a flood event in the night from 3 July to 4 July (Fig. 2) at 2.55 m a.s.l. after heavy rain. The latter one shows a rise of the water level of about 60 cm within 4 h.

The riverbank has been scanned at 6 places along the erosion bank. Over the first 4 field campaigns in 2011 and 2012 the riverbank has been measured one time after snowmelt and one time in summer (2011) and one time in autumn (2012). In 2011 have been 6 rain events with an increase in water level between the scans. In 2012 have been 8 rain events between the scans. During the last field campaign in 2013 the banks have been scanned 3 times in short time intervals with 1 distinct water level rise in between the scans (Fig. 2).

The laser scanner used was a Leica TLS1000 with ScanMaster©software. Each outer bank has been scanned from three different scan positions in order to make sure that these parts that lie in the shadow of one scan angle are covered by the other scan angles from the other scan positions. The three scan positions have been combined by overlaying of at least four geo-referenced tie points. This target-based

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registration is the standard procedure (Schürch et al., 2011). The mean error calculated by the ScanMaster©software has been between 0.002 and 0.009 m, showing the high precision of the measurement method (Schürch et al., 2011).

3.2 Post processing of point clouds

This study focuses on three different positions along the first and second bend. These positions (patches 1–3) are shown in Fig. 1. The first patch is located at the end of the first river bend and the second and third patch are from the second river bend between inflow and apex. The patches have been chosen, because their heights of the riverbank have been the same. Additionally have they been largely without vegetation over the last three years. To avoid problems with the cover vegetation and to focus on the influence of the river instead of mass movements in the upper part of the river bank the TLS data have been cut. The dimensions of the point clouds have been defined by a vertical cut at 2.8 m a.s.l. as the upper limit. The lower limit is the water line at the moment the scan has been taken. Further noise and single spikes created by the laser scanner have been removed by a density filter provided by Point Cloud Library (PCL, 2013). The filter process checked each point against the others whether the point corresponds to the criteria. If not it was defined as outliner and has been deleted. Thereby a sphere with radiuses from 0.01 to 0.15 m in steps by 0.015 m has been projected around each point. This point has been tested for how many other points are within this distance. The point quantities have been defined from 5 to 25 points in steps by 5. Did a point have less than the tested amount of points, than the point has been deleted. In this way for each point cloud 50 filtered point clouds have been created. These point clouds have been plotted and visually inspected whether enough outliners have been removed and whether the point cloud was still coherent (Table 1). The result was very different and no special pattern concerning the settings was visible. It was not possible to create a filter to remove wood, which was in front of the scanned riverbank. Therefore was it necessary to remove some point patches which have been visible in the 2-D view of ArcGIS© manually.

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For each patch a mesh has been created with a cell size of 0.005 m. On this mesh the point clouds have been projected and a digital elevation model (DEM) has been created. From this DEM the slope gradient in degree has been calculated and plotted (Fig. 4). The slope gradient ∇F is defined by

$$\nabla F = \frac{\partial F}{\partial x}\hat{i} + \frac{\partial F}{\partial y}\hat{j} \tag{1}$$

Thus, the gradient in degree (G_{deg}) has been calculated with

$$G_{\text{deg}} = \text{atan}\left(\sqrt{(\nabla F x)^2 + (\nabla F y)^2}\right) \cdot \frac{180}{\pi} \tag{2}$$

3.3 Statistical methods

For the analyses of the DEM, patch 2 and patch 3 have been virtually rotated, that the orientation is the same as patch 1: north–south. In this way each row from the DEM displays the vertical extension and each column the horizontal extension. The vertical mean slope gradient and horizontal mean gradient has been calculated by calculating the mean for each row of the grid and the mean for each column of the grid respectively. In order to investigate the significance of slope change within a measurement period the data have been statistically verified. The slope gradient for each patch within a measurement period has been compared with the aim to verify that the gradient between the scans are significantly different. To decide which statistical method is appropriate the data needed to be tested for normal distribution. Therefore the slope gradient for each patch has been tested for normality with the Kolmogorov–Smirnov test. Since the slope gradient data have not been normal distributed the Kruskal–Wallis test has been used to verify the significant difference between the slope gradients (Table 2).

3.4 Bank retreat

Finally the bank retreat and the mass balance of the river bank have been calculated. The bank retreat has been defined as horizontal difference between successive scans.

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For this purpose a DEM with a grid size of 0.1 m has been created for each scan (Fig. 3). The grid cells at the same height have been compared to each other between two successive scans and the smallest value has been used to define the distance between the two scans. To avoid wrong data at positions where gaps in the point cloud exists, the maximum distance has been defined by 0.5 m. These grid cells which have no corresponding grid cells within this distance in the second cell have been discarded. Finally the total mass balance has been calculated and the volume change is given in cubic meter per square meter.

4 Results

4.1 Bank retreat

In Fig. 3 shows the horizontal retreat over time for patch 2. The other patches have been analysed in the same way and have been round up in Table 2. On the x and y axis show the geographical position before the retreat. The red colour indicate bank erosion, and therefore bank relocation towards the outside of the river bend, or accumulation (blue), and therefore bank relocation towards the inside of the river bend. The bank retreat has been compared between all successive scans within the three patches. This includes the successive scans within a season and the scans for and after winter season. The clearest changes have been during winter and spring snowmelt events (Table 2). Patch 1 and patch 2 show sedimentation over winter 2011/12 and after that erosion until 2013. The mass balance shows, however, an overall erosion rate over the measurement campaign. Patch 3 shows sedimentation over both winter seasons and has overall sedimentation. The local distribution of the mass balance is visualized in Fig. 3. Figure 3a–f shows the evolution of patch 2. The first change (Fig. 3a) from May to July 2011 shows a clear flattening of the riverbank, with a small sedimentation rate (−0.01). The riverbank becomes slightly steeper, men with more accumulation towards the river during winter 2011/2012 (Fig. 3b). During the summer (Fig. 3c), the

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river bank flattens and accumulates again. The winter 2012/2013 triggers an erosion and a distinct replacement of the edge (Fig. 3d). The Fig. 3e and f shows the data during the short term monitoring in 2013 before and after the water level peaks. These show almost no changes in river bank displacement.

4.2 Slope analyses

The bank retreat and the mass balance alone do contribute only little to an understanding of the erosion processes. Therefore the change in the slope has been analysed.

Figure 4 shows the digital elevation model (DEM) and spatial distributed slope gradient for each raster point. Figure 4a refers to patch 1 and Fig. 4b refers to patch 2. The scans are from May 2011 and July 2011. A comparison between the two scans from 2011 in patch 1 and 2 (Fig. 4) shows that the July scan has a wider slope in horizontal direction than the previous scan. The reason is, that the water level during the July scan is 0.2 m lower than during the May scan. Patch 1 shows a similar distribution of the slope gradient in the May and July scan. The upper layer with a thickness of about 15 to 20 cm are nearly vertical (red) and below that the slope flattens (blue and yellow). The calculated average slope gradient is 31.3° and 32.7°, respectively. The maximum water level has been at 2.7 m a.s.l. and minimum 1.65 m a.s.l. In between the scan have been five rain events and therefore five peaks in the water level registered. However, this had hardly any effect on the average slope gradient.

In Fig. 4b patch 2 in the second river bend is presented for the same time span as patch 1 before. Similar to patch 1 is the upper layer (15–20 cm) staying nearly vertical in this patch. The DEM from May 2011 shows a rougher surface than the DEM in July. The plot of the slope gradient shows first steep values (red, orange) and lower angles in the July plot (blue and yellow). The red part at the left side is an artefact due to vegetation. The impact of the alternating water level is much clearer in this patch, where the flattening of the riverbank can be seen. Patch 3 is located only 15 m further downstream from patch 2. In patch 3 (no figure) the development of the slope, with a stable vertical upper layer is similar to patch 2.

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For a better understanding of the processes, the slope gradient has been averaged in the vertical and in the horizontal. The mean slope gradient in the vertical and the horizontal direction is plotted for each season and patch (Fig. 5). The mean vertical slope gradient (MVSG) shows that the edges of the scans (upstream and downstream) have the same slope gradient over the measurement period.

Patch 1 shows a steepening of the slope in the middle part from May 2011 to July 2011. This process stopped in the following year. In 2012 the June and October scans show similar MVSG along the patch. The statistical validation with the Kruskal–Wallis-Test confirms that there is no significant difference between the slope gradients from June and October 2012. The slope gradient has therefore been stable even though the time span has been longer between the scans and the hydraulic conditions, such as water level changed more often. The analyses of the short term scanning in 2013 show an increase of the MVSG from the first to the second scan. The change from the second scan before the flood event to the third scan after the flood event show an increase of the slope angle downstream and a decrease upstream.

The MVSG at patch 2 shows, in contrary to patch 1 a flattening between May and July 2011. The change of the slope gradient is not equally over the length of the patch. In some small sections, less than 1 m, no change of the MVSG occurred at all and in other sections the change was more than 20°. The following year the slope change occurred more equal over the length of the patch. However, the change of the MVSG has been much smaller with maximums around 10°. The short term monitoring of the patch in 2013 shows from the first scan an unregularly flattening. The MVSG, which has been calculated after the flood event, shows however a clear steepening of patch 2, which reaches in few sections similar values as they have been in 2011.

Patch 3 had a higher MVSG on the downstream and the middle part. At about one third of the length upstream, the slope gradient becomes smaller. The flatting which is on-going between May and July 2011 occurs over the whole length; in the steeper sections more and in the flatter sections less so that the patch became more even in July. In June 2012, after winter season, the steepness from May 2011 has been restored and the river bank flattened between June and October 2012 in a similar way as in 2011. The changes in 2013 have been less. Between the first and second scan 2013 patch 3 flattened in the downstream and middle sections, while it got steeper upstream. The change from the second scan to the third scan after the flood event shows steeper sections up- and downstream, however hardly changes in the middle part.

Statistical analyses have been performed to verify the change in the slope gradient. The statistical analyses (Table 1) confirms that the single scans are significant different ($^{*}p < 0.05$ significant, $^{**}P < 0.01$ highly significant and $^{***}P < 0.001$ highly significant). The only exception is patch 1 scan 6 and 7 from 2013. For these two scans the analyses show that the slope gradient before and after the flood event (Fig. 2) is the same.

The MHSG and MVSG show no significant difference in the slope angle. The same with the MVSG from patch 1 scan 3 and 4 from 2012. This implies that the flattening of the slope in patch 2 and 3 from the beginning of the year (after snow melt) to later in the year is taking place. The opposite trend in patch 1 is less distinct and for the short time step from scan 6 and 7 not proven at all.

5 Discussion

The post processing of point clouds is the most time consuming part. The reason for that is that the automatic filtering is very complex and needs to be adapted for each point cloud. From this it follows that each step is subject to manual, and therefore subjective, selection of filter parameters. Never the less many combinations of filter parameters have been compared and the point clouds with the seemingly most effective filter settings have been chosen. This has been a simple method to remove single outliners and artefacts from the laser scanner. In addition some parts of scattered vegetation like grass or small branches have been removed by the filter. Manual removals of other objects like dead wood on the riverbank could not have been done equally in the clouds. It is not possible to remove trunks and scrubs from the different point clouds

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within the same patch in exactly the same way. This would have made the analyses difficult because the DEM would have been created differently, based on subjective cleaning. Therefore the manual cleaning was limited to remove non-coherent patches in ArcGIS© from the bird's eye view. As a result some single peaks are visible in the DEM, but the influence of can be neglected, regarding the amount of good data.

The Kruskal–Wallis test showed that most of the slope gradients are highly significant different from the respectively two successive scans. The slope angle should not be affected by the geo-referencing error, since these results only in a dislocation between successive scans. The analyses of the change in the slope gradient shows for the first river bend a slight steepening during the season in 2011. Hardly any changes happened in 2012. This indicates a rather stable situation at this position. The small amount of mass movement, with 0.017 m^3, 0.031 m^3, and 0.043 m^3 during the summer season points to the same assumption.

The causes for changes in slope gradient and bank retreat between which happened during winter 2011/12 and winter 2012/12 are speculative. The research area lies in cold environments and has therefore much snow during the long winter. It is not unusual that the river freezes over from October until April/May. An analysis which compares over winter time has to be carefully, since it involves freezing and thawing processes and the influence of snow, which has not been estimated in this study. However, the data in the MVSG In addition is it possible to distinguish in two different observation intervals. The first one is within a season with changing water levels several times. The other one is what happened in 2013 that each TLS snapshot happened before and after a flood event. This gives insight in peak processes and long term alternating water levels.

The accuracy of the Laser scan itself is mainly given by the footprint and is according to TopCon at a maximum at 6 mm within the measurement distance during this survey. The very low error at during the overlay of the different scan angles confirms this assumption. Schürch et al. (2011) showed his study, where he mapped over longer distances, and therefore had to deal with bigger footprints, that this has hardly negative

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impact on the accuracy. Therefore, the data within one scan of a patch are highly reliable. However, on the other hand the GPS accuracy is between 0.008 m and 0.013 m in the horizontal and between 0.012 m and 0.017 m in the vertical direction. The experience showed that the GPS data are very constant within a dataset. That means that the offset for one set of measured target points is the same as long the GPS system had the reception from the satellites without longer interruptions. This again has been confirmed by the low mean error, calculated during the scan overlay. The GPS error might be avoided, if it is possible to leave the targets at the same position. This was not possible, due to a limited amount of targets which were available. Another drawback is that the TLS scans were taken during different water levels (Table 1).

The accuracy of the calculation of the horizontal retreat and the erosion balance is dependent on the accuracy of the laser scan (Schürch et al., 2011), the accuracy of the target points used for geo referencing, the vegetation included in the scans and the post processing and cleaning of the point clouds. The change in mass and bank retreat lies close to the error of the geo referencing tool. Other studies such as Picco (2013) deal with huge areas, where a verifying of the GPS data is possible and a small error does not have such an huge impact as it has on small scale studies. This means that the volume change should be regarded as a qualitative and only limited quantitative method in this study. A replacement towards the outer side of the upper edge has measured at all three patches. However, the erosion balance shows an overall sedimentation at patch 3 (Table 2). In addition the edge is replaced towards the outer side. This contradiction can be explained by the downfall of the sediment from the upper part, without further transportation in the river. This explains also the flattening of the slope angle.

During the last campaign in 2013 the change in horizontal retreat are insignificant. Though, the water level had its highest level within the last three years. These data raise the question whether a high peak over a short time has much influence in erosion and sediment transport. Patch 1 shows on the one hand an erosion of about 0.04 m^3. On the other hand, the slope gradient was stable. Regarding the described error with

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the RTK-GPS data, the calculated erosion is within this tolerance and the assumption would be that patch 1 did not experience any significant impact from the flood event.

6 Conclusions

In this study the river bank of a lowland medium sized river has been scanned with a Terrestrial Laser Scanner. The yielded point clouds have been post processed by filtering for outliers, both automatically and manually. On basis of this filtered data the bank retreat and the slope gradient have been calculated. The results showed that the bank retreat is not similar in different location under the same hydraulic conditions.

The analysis of the slope gradient and the erosion balance showed higher and highly significant changes over longer periods during the summer season. The single flood event at 3 July 2013, which was the highest flood recorded during the three field seasons had hardly impact on the slope angle or on the erosion balance.

The calculation of mass balances with help of laser scanning is difficult. On the one hand has the vegetation taken into account, on the other hand is the error from the georeferencing bigger than the retreat. The latter one especially if it is used for short term measurements. However, it can be a valuable tool when for a qualitative estimations. In addition give laser scan data with high resolution information about spatial changes. This can be valuable for future verification of numerical models.

The data show that the erosion process along a meandering river shows both erosion and sedimentation. Patch 1 and patch 2 have an overall erosion (positive mass balance: $-0.30\,\mathrm{m}^3\,\mathrm{m}^{-2}$ and 0.04), while patch 3 has an overall sedimentation (negative mass balance: $-0.63\,\mathrm{m}^3\,\mathrm{m}^{-2}$). In addition show the data from the slope gradient in patch 2 that a flattening over a long period prevails and only the flood event triggers a steeping of the river bank at patch 2. At the same time the flood event has hardly any impact at patch 3 and patch 1. This leads to the hypothesis that in front of the riverbank a certain amount of non-cohesive material accumulates before it will be transported further. This means, that all material sediments in the beginning below its source. This leads to an

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accumulation of loose sediment and flattening of the riverbank. This loose sediment will be eroded later. However, when the erosion process is started all accumulated sediment will be transported within a short time. This study did not reveal whether a certain threshold exists.

Looking on the erosion rates during at different time intervals it becomes clear that the highest amount of sediment erosion occurs during or after winter season. This study was, however, focused on the effect and processes of hydrological impact on erosion and therefore has this process not been further regarded.

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Table 1. Point cloud data and water level.

	Scan	Date of Scan	Points before Filtering	Points after Filtering	Points after Manual Cleaning	Water Level m a.s.l.		
						Min	Max	Scan
Patch 1	1	May 2011	79 735	60 252	59 151	1.67	2.38	1.84
	2	Jul 2011	52 678	36 305	35 618			1.64
	3	Jun 2012	124 040	113 854	113 415	1.35	2.16	1.58
	4	Oct 2012	180 588	168 735	1 164 403			1.26
	5	19 Jun 2013	286 670	270 056	269 707			2.01
	6	28 Jun 2013	379 610	351 198	339 921	1.72	2.25	1.81
	7	6 Jul 2013	566 067	549 132	523 337	1.72	2.55	1.71
Patch 2	1	May 2011	94 658	91 164	91 145	1.67	2.38	1.76
	2	Jul 2011	26 579	23 992	23 949			1.72
	3	Jun 2012	588 731	496 815	494 000	1.35	2.16	1.65
	4	Oct 2012	121 261	108 654	107 977			1.40
	5	19 Jun 2013	886 871	824 974	818 160			1.60
	6	28 Jun 2013	147 365	130 180	129 223	1.72	2.25	1.77
	7	6 Jul 2013	445 743	430 526	425 447	1.72	2.55	1.76
Patch 3	1	May 2011	41 569	26 706	26 665	1.67	2.38	2.03
	2	Jul 2011	27 570	20 741	20 741			1.73
	3	Jun 2012	621 165	609 966	607 381	1.35	2.16	1.67
	4	Oct 2012	164 582	124 335	124 335			1.25
	5	19 Jun 2013	907 733	887 744	887 409			1.60
	6	28 Jun 2013	109 946	99 567	98 975	1.72	2.25	1.80
	7	6 Jul 2013	297 441	242 797	239 662	1.72	2.55	7.76

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Table 2. Statistical analyses, slope gradient and volume change.

	Scan	Mean Slope	Volume Change total	Volume Change m^2	Kruskal–Wallis-Test p, Significance MHSG		Kruskal–Wallis-Test p, Significance MVSG	
Patch 1	1	31.3°			***		***	
	2	32.7°	0.268	0.017				
	3	32.5°	−6.294	−0.262	*P = 0.017		P = 0.098	
	4	34.2°	0.660	0.031				
	5	39.9°	8.857	0.423	***		***	
	6	38.5°	0.950	0.043		P = 0.755		P = 0.446
	7	39.3°	1.260	0.042				
Patch 2	1	52.0°			***		***	
	2	40.0°	−0.056	−0.014				
	3	43.9°	−1.194	−0.226	***		***	
	4	38.2°	−0.734	−0.119				
	5	51.5°	1.426	0.265	***		***	
	6	47.9°	0.920	0.092		***		***
	7	49.2°	0.414	0.042				
Patch 3	1	56.4°			***		***	
	2	44.6°	−0.283	−0.044				
	3	47.4°	−1.244	−0.257	***		***	
	4	42.8°	0.099	0.013				
	5	50.4°	−1.072	−0.169	***		***	
	6	47.3°	0.765	0.098		**P = 0.009		***
	7	48.2°	−0.025	−0.003				

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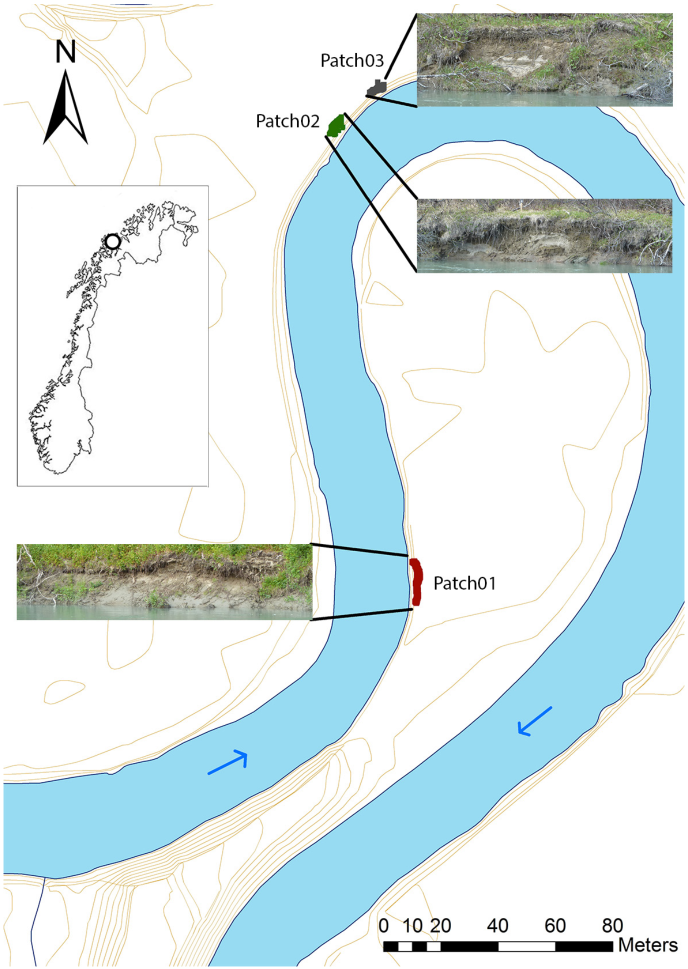

Fig. 1. Research area and location of the patches along the river Breivikelva.

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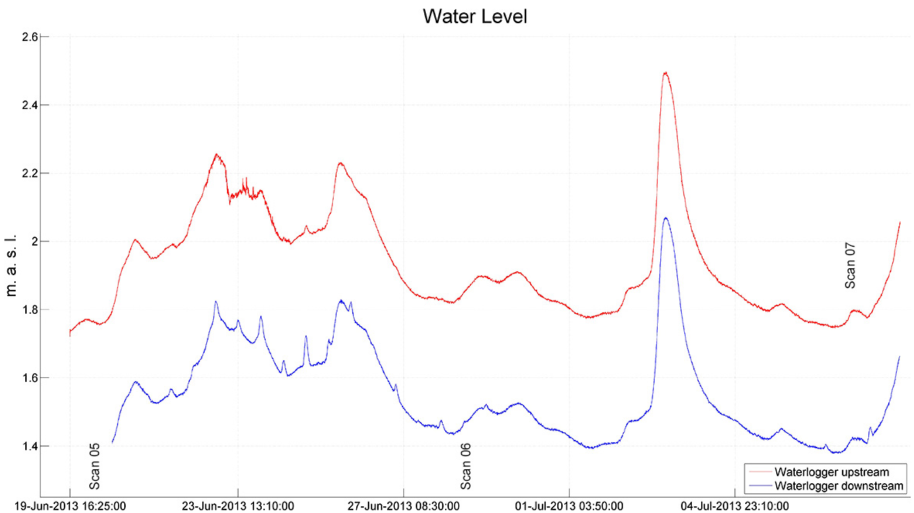

Fig. 2. Change of water level. Measured by the water logger upstream (red) and downstream (blue).

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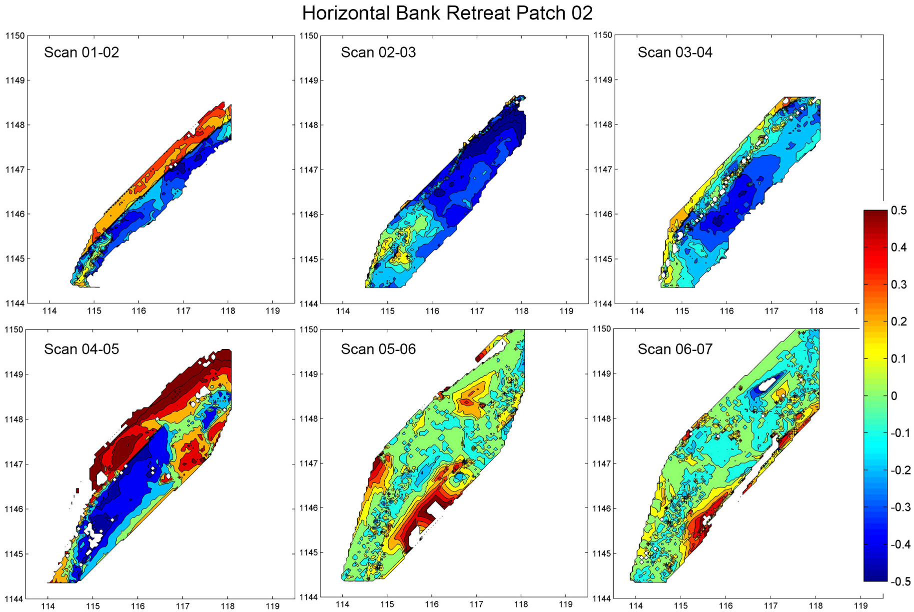

Fig. 3. Horizontal bank retreat for patch 2. Water flow is from SW to NE.

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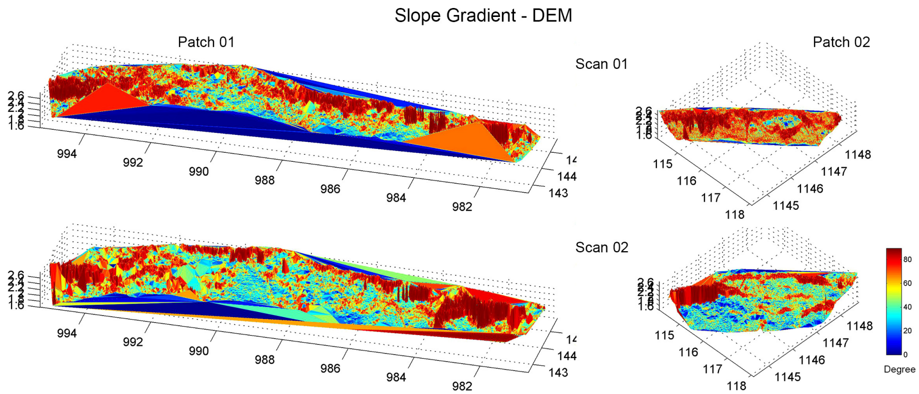

Fig. 4. Digital elevation model with slope gradient.

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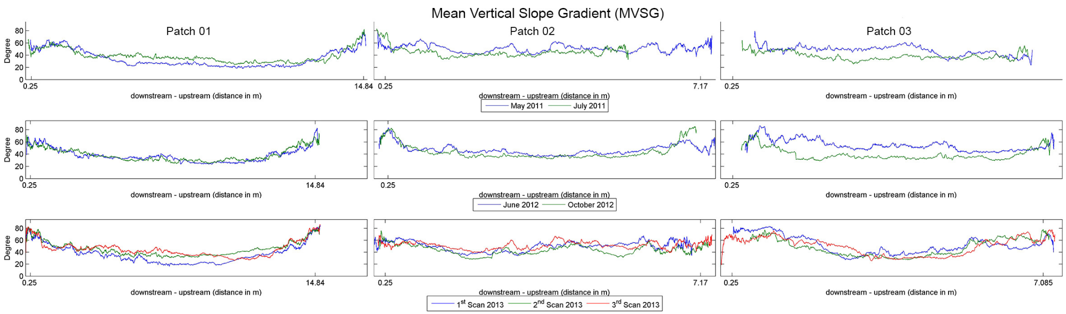

Fig. 5. Mean vertical slope gradient for patch 1 (left), patch 2 (middle), and patch 3 (right).

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