Identification and analysis of step-pool morphometry

A study of geometric relations and spatial distributions in step-pools, following automated identification of bed morphology from a longitudinal profile.

Master's thesis in Geography

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Abstract

Global warming might increase water and sediment inputs to some river systems, and a better understanding of bed morphology and hydraulic resistance is required to adapt to future flows. The natural formation and morphometry of step-pools is valuable to understand such that river restoration projects can better replicate the necessary hydraulic resistance. Morphometry and spatial organization in the bed structure of a 1.8km long section of Vekveselva, Norway, is analysed to study characteristic dimensions and patterns of regularity in step placement. Step spacing is compared to those of random sequences, and relations between mean step properties are analysed. A custom algorithm is designed to automatically and objectively extract step-pool sequences. Results show that (1) step-locations are more clustered together than random distributions on some neighbourhood scales, and (2) the distribution of step spacings is statistically significantly different from a Poisson distribution. Large scale regularity (3) cannot be illustrated in morphometric relations between mean step properties such as step height, step spacing and local slope, indicating that local bed morphology affects step formation more than forced hydraulic deposition. No reach-scale trends in step formation can be shown.

Sammendrag

Global oppvarming er forventet å øke avrenning til noen elvesystemer, og en bedre forståelse av bunnmorfologi og hydraulisk friksjon er nødvendig for å bli bedre rustet mot fremtidige flomhendelser. Det er viktig å forstå hva som driver dannelsen av og morfometrien til step-pools slik at elverestaurerings-prosjekter kan bedre gjenskape nødvendig hydraulisk friksjon. Morfometri og romlig organisering i en 1.8km lang seksjon av Vekveselva, Oppdal, er analysert for å studere karakteristiske dimensjoner og romlig distribusjon av step-pools. Distribusjonen av steg lengder er sammenlignet med tilfeldige distribusjoner, og forholdet mellom gjennomsnittlige morfometriske variabler er analysert. En algoritme er designet for å automatisk og objektivt identifisere step-pool sekvenser og kalkulere morfometri innad. Resultatene viser at (1) lokasjonen av step-pools er mer gruppert enn en tilfeldig distribusjon ved små nabolags-skalaer, og at (2) distribusjonen av steg-lengder er statistisk ulik fra en Poisson distribusjon. (3) Regularitet i steg-dannelse kunne ikke påvises gjennom sterke korrelasjoner mellom morfometriske variabler som steg-høyde, steg-lengde og lokal gradient. Dette indikerer at lokal bunn-morfologi påvirker dannelsen av step-pools mer enn påtvungen hydraulisk avsetning. Ingen trender i steg-dannelse kunne påvises på stor skala.

Preface

This thesis is the culmination of five wonderful years at The Norwegian University of Science of Technology (NTNU). Geography is great field for anyone interested in how the world functions, and my understanding of both the physical and humanitarian world has greatly improved as a result of the effort and great enthusiasm provided by all the members of the Department of Geography.

My passion lies with the physical world, and the field of Geomorphology has further spurred this passion. I would like to thank Professor Ivar Berthling and former Associate Professor Geir Vatne for sharing their enthusiasm for Physical Geography. Their passion has inspired students for many years to question the physical world and the forces acting upon it. This thesis would not have existed if not for the valuable discussions and guidance provided by these two over the last few years, and particularly by my supervisor Ivar Berthling these past months.

I would also like to direct a note of appreciation to Joakim Tafjord for setting aside several hours of his own Master's Thesis in Chemistry to aid me in writing the algorithm, and accepting my ramblings of architecture as a challenge. The extent of my dataset made it impossible to manually extract and calculate stream bed formations in a reasonable timescale, and the algorithm is a fundamental part of how I managed to finish this thesis in time. I would simply not have been able to finish in time without this help.

This thesis has been, as it should be, the most educational experience in my five years at NTNU. This includes knowledge of the literate body of work that spans stream bed morphology, but perhaps more importantly, it has given me a vastly improved understanding of scientific method and research philosophy. The opportunity to write a Master's thesis has been a journey of self-improvement. I entered the Master's program feeling overwhelmed and rather green in terms of research capabilities. I exit the program feeling motivated to do more; finding ways to improve methodology, or simply adding more knowledge to a field of research that deserves more attention.

Trondheim, 29.04.2017
Vegard Sulebakk

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1 INTRODUCTION

1.1 JUSTIFICATION

Flash floods occur in mountainous rivers wherein the reaction time after heavy rainfall is very short and provides the river with a transport capacity that is far above its normal flows due to the lack of floodplains to dissipate excess water to (Borga, Anagnostou, Blöschl, & Creutin, 2011). Flash floods are challenging to forecast or prepare for due to their elusive and sudden nature. These events can break down bed formations, activate sediment storages and supply the flood event with massive amounts of sediment, adding to the destructive effect of the flood. Global warming is expected to cause an increase in annual mean rainfall of 5-30% towards the end of this century in Norway, and in landscapes with steep mountainous rivers, both the frequency and intensity of flash floods is expected to increase due to this (Lawrence & Hisdal, 2011). The importance of understanding the morphological structure and stability of steep mountainous river systems will only increase in relevance with global warming.

The study of stream bed morphology is in essence a study of hydraulic resistance. Abrahams, Li, and Atkinson (1995) argued that the bed morphology of steep mountain streams strive to evolve towards a condition of maximum flow resistance. This condition is crucial in steep mountain rivers as the transport capacity would be immense if not limited by hydraulic resistance. The stream bed will continuously adjust to changing flows, and can be reorganized during flood events, effectively restarting the adjustment process. The characteristic formations creating hydraulic resistance in steep mountain streams are commonly referred to as *step-pools.* The understanding of hydraulic resistance provided by step-pool formations, and the adjustment processes involved, is crucial to understanding how streams might adjust to changing water and sediment inputs. More data from a wide range of river systems is required, but perhaps more welcoming are more studies done on the same systems over a range of timescales to study the effect of time.

There is no easy way to map or identify step-pools in a stream, and data collection remains one of the main challenges in step-pool research. Until better methods for acquiring data becomes more available there is little to be done to improve this except striving to keep a high level of integrity throughout the study. Data preparation and analysis is, however, something that can be improved. New methods to automatically and objectively extract step-pool formations from longitudinal profiles have emerged these last few years (Milzow, Molnar, McArdell, & Burlando, 2006; Wooldridge & Hickin, 2002; Zimmermann, Church, & Hassan, 2008), and they have in effect reduced much of the subjectivity commonly involved in identification of step-pools. There is much subjectivity involved in step-pool research (Zimmermann et al., 2008), and any reduction of this is a welcoming effect to improve comparative studies.

This thesis aims to add a substantial amount of data to the existing library of information about Vekveselva, so that comparative studies in the future might gain more weight from which to draw conclusions. To accompany this large dataset an automatic method for identification had to be developed. An added benefit of using an algorithm for identification and calculation is the reduction of subjectivity involved. If a result is to have any value in comparative studies, it must be objective in such a way that future conclusions are not drawn upon my bias. Earlier studies of Vekveselva have not involved data collection on a scale comparative to this, and have not involved automatic identification and calculation (Mevik, 2013; Volden, 2015).

The increased attention to step-pools the last few decades can be attributed, to some degree, to increasing intensity and frequency of floods and especially flash floods (Chin & Wohl, 2005). A warmer climate will promote higher rates of evapotranspiration, which combined with a hotter atmosphere that can hold more moisture (Goudie, 2006), the future weather is expected to become both wetter and wilder. This is a change that might become especially true in Norway with many steep catchment basins in which flash floods are already a major threat to infrastructure. The relevance of understanding steep mountainous river systems lies in their methods for providing hydraulic resistance. If a reach will have to be regulated in the future to avoid damage to infrastructure, such as river restoration or erosion control, then deeper understanding of step-pools and how to reinforce or even create such formations would be very valuable to limit the effects of future floods or even re-stabilize a reach after a flood.

The relevance of this particular study is to add to a library of information about step-pools. This study has some value in studies comparing several different river systems, but its value will be highest in studies of Vekveselva or other streams of comparative morphologies. It might also inspire future students to commit to larger spatial scales of fieldwork, such that step-pool research gains more statistical weight, and that perhaps new areas of the Vekve drainage basin might be studied.

1.2 MAIN OBJECTIVES

The main objectives of this thesis can be summarized as follows:

- Produce a longitudinal profile of sufficient size to provide statistically significant data on step-pool morphology.
- Automate the process of identification of step pools and calculation of morphometry.
- Analyse the data for any geometric relations and patterns of regularity in step-pool morphometry.

This thesis presents two main hypotheses regarding geometric relations and patterns of regularity:

1. Step height does not feature a strong inverse proportional relation to step spacing, and step spacing does not feature a strong proportional relation to slope.
2. Thus, there are no apparent patterns of regularity in step-pool formations in Vekveselva.

A sizeable proportion of the work involved in this thesis has been the design of an algorithm that is simple enough to be applied as an MS Excel Macro, but advanced enough to provide detailed calculations of step-pool geometry. In many ways, this study can be classified as a methodological study, as the successful design and application of the algorithm was imperative to the success of the study.

1.3 OUTLINE

Chapter two will present the study area. Chapter three will provide a short introduction to relevant theory related to headwater streams and step-pools; their morphometry, function, formation, and challenges involved in step-pool research. Chapter four will present the methodology of the fieldwork and analyses, the algorithm that was designed for this thesis, sources of error, and finally some considerations of reliability and validity. Chapter five will present the results from both the fieldwork and the analyses. This includes distributions, statistics, analyses of correlation and variance, and finally an analysis of spatial distribution. Chapter six will discuss the results presented in chapter five and compare them with available literature. Finally, chapter seven will provide concluding remarks on this thesis, followed by suggestions for future research on Vekveselva.

2 STUDY AREA

2.1.1 Vekveselva

Vekveselva is a steep mountain stream located in the Trollheimen mountain range in Oppdal municipality, in the county of Sør-Trøndelag, Norway. The total length of the stream is 12.8km, starting at 1578m a.s.l. and draining into the main river Driva at 450m a.s.l. The drainage basin for Vekveselva spans an area of 33km^3 and annually drains about 28.4 million m^3 water (The Norwegian Water Resources and Energy Directorate, 2016). The altitude of the basin maintains the ability to store significant amounts of water as snow, and snow melt fuels much of the discharge during the melt seasons. The mean annual rainfall in the catchment for the period 1971-1990 was 670mm (The Norwegian Meteorological Institute, 2017). Average bed slope on the chosen study reach is 8.8% with ranges varying from 6-12%.

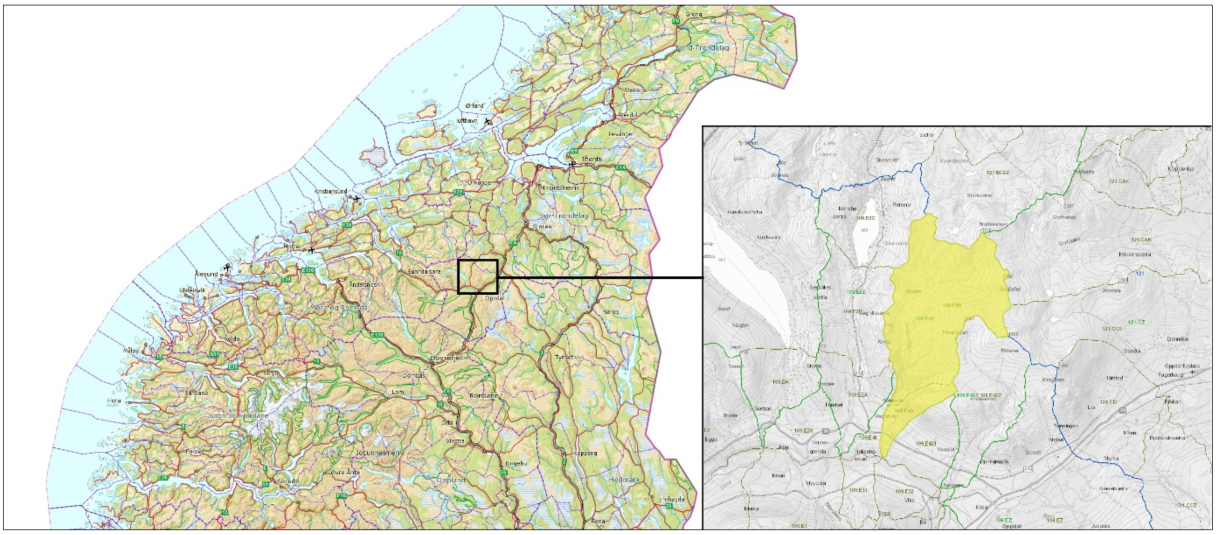


Figure 1: Vekve drainage basin in Oppdal muncipality, Norway. Basemap: Norgeskart.no. Inset map: NVE Atlas.

The starting point for the fieldwork was chosen based on local morphology and downstream distance to a sedimentation dam which would mark the end of the longitudinal profile (fig. 12). The area upstream of the starting point was deemed too coarse to provide good illustrations of step-pools, but the decision was made mostly with the temporal budget in mind. The starting point marks the convergence point of two almost equal-sized streams which separates upstream.

2.1.2 Morphology and geology

The basin is heavily affected by glacial activity during the last ice age, and materials both in the stream and in surrounding hillslopes have a high proportion of large boulders. The stream is tightly coupled to steep hillslopes with active mass wasting processes. The hillslopes consist mainly of glacial till with poorly sorted material (Geological Survey of Norway, 2016). Some areas are covered with thick layers of tills with a significant content of fines that can be added to the flow during floods and heavy rainfalls. The surrounding hillslopes bear signs of old large landslides, and both fine and coarse material is still directly coupled to the stream in many areas.

The stream features quite extreme morphologies with large step heights and pool depths, some of which are almost impossible to measure safely. Much of the material is large boulders that appear stationary due to growing lichens and proximity to old landslide sites. The largest boulders might have been deposited directly by the receding glacier some thousands of years ago or revealed by fluvial erosion, and might never have been moved by fluvial forces. Some of the downstream areas bear signs of a very old flood event of extreme dimensions, with dormant braided riverbeds stretching across almost the entire valley floor. These dry streams contain vegetated step-pool formations that are interesting paleoflood relics. The river bed provides high hydraulic resistance due to large colluvium that is not connected to fluvial formations such as step-pools.

Figure 2: Upper section of Vekveselva close to the site of an old landslide event. The figure illustrates the relatively coarse bed structure in Vekveselva.

2.1.3 Flood events

Vekveselva has been studied by the Department of Geography since 2008. In 2003, heavy rainfalls caused several large landslides. Material from this event clogged up the drainage tunnels for a local hydropower facility owned by Trønderenergi (Hoel & Sønner AS, 2016). Trønderenergi decided to build a sedimentation dam to contain the increased sediment load. The dam was finished in 2007 and recent floods have not clogged up any of the drainage tunnels. The events of 2003 left many naked hillslopes in direct vicinity to the stream. The sediment dam must be dug out twice a year to avoid overfilling (Hoel & Sønner AS, 2016).

The most recent large event was in June 2011 due to a combination of heavy rainfall and snowmelt. The event affected a large part of southern Norway, and was reported as a 100-year flood event in many areas, including the Driva drainage network which Vekveselva is a part of (Kleivane, 2011). Over 8 hours the event drained 2800m^3 of material to the sedimentation dam at Vekveselva (Mevik, 2013).

Figure 3: The sedimentation dam being emptied in October 2016.

3 THEORY

3.1 HEADWATER STREAMS

Fluvial geomorphology includes large scale modelling of fluvial erosion and landscape modelling, but the study of bed morphology and particularly step-pools in steep streams have become a popular topic for geomorphologists, and the study of steep mountain streams has blossomed these last 20 years (Chin & Wohl, 2005; Church & Zimmermann, 2007). Steep channels and their morphometric and hydraulic properties has been studied since at least 1960 (Peterson & Mohanty, 1960). Mountainous river channels are commonly known as headwater streams due to their first-order connection with drainage areas and their role in supplying lowland rivers with drainage water and sediment (Church & Zimmermann, 2007). Headwater streams amount to 60-80% of the cumulative length of river networks (Benda, Hassan, Church, & May, 2005). Steep mountain streams tend to be closely connected to steep slopes on either side, and this confined area limits the ability of the stream to meander laterally and thus the ability to dissipate excess energy of flow via erosion (Chin & Wohl, 2005). The tight connection to valley slopes also increases the coupling to sediment sources. During floods, large quantities of sediment will be supplied from the surrounding slopes via mass wasting processes or undercutting of banks or hillslopes, and a characteristic property of steep confined streams is a large concentration of colluvium mixed with alluvium (Church & Zimmermann, 2007). During normal flows, much of this material will remain stationary, but during floods this material might be activated and provide the event with massive amounts of material to be transported to lowland parts of the network (Benda et al., 2005).

3.2 STEP POOLS

The storage of relatively coarse material on the river bed provides the river with the means to counteract the steepness of the bed slope. Material will lock themselves together and create a barrier over which water will flow and develop a scour pool below. The longitudinal profiles of steep mountain streams will often feature a staircase-like shape that reflects this vertical meandering with large drops and pools. These bed formations are commonly termed *step-pools*, and function both as hydraulic resistance and sediment storage (Chin & Wohl, 2005; Molnar, Densmore, McArdell, Turowski, & Burlando, 2010). Step-pools are unique fluvial formations commonly found in narrow, steep mountain streams with a coarse gravel-boulder bed and periodic floods of sufficient capacity to move and reorganize this material (Molnar et al., 2010). Step-pools provide the means to meander vertically when lateral meandering is constricted by confining steep valley slopes, and will also provide the necessary vertical drop to transport the flow to its destination without promoting very high flow speeds. Step-pools also function as excellent sediment storages due to limited transport capacity in pools, and steps can also function as barriers, buttressing the effects of landslides immediately upstream of steps (Molnar et al., 2010). Step-pools reduce the sediment connectivity in the reach by depositing material in pools where the transport capacity drops, and will function as in-stream sediment storages that can be activated during high flows when step-pools break down (Molnar et al., 2010). Detailed characteristics of step-pools are discussed in the following sections.

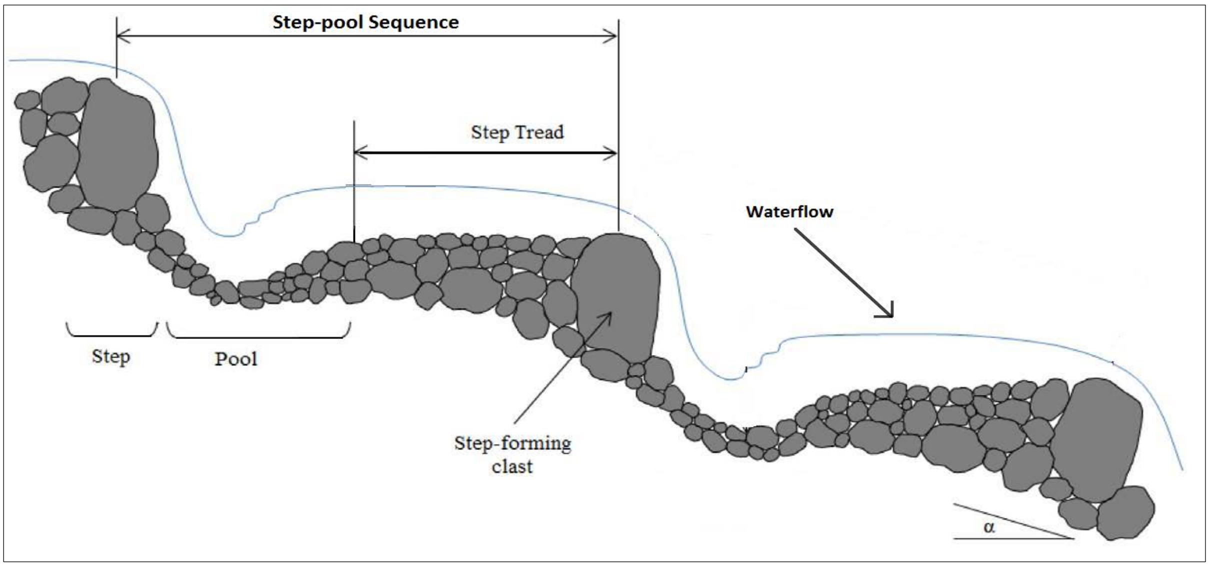


Figure 4: Simplified illustration of standard step-pool morphology. Source: Modified from Waters and Curran (2012).

3.3 MORPHOMETRY

3.3.1 Composition

A step-pool channel consists of sequences of alternating channel-spanning steps and pools over which tumbling flow oscillates between supercritical over the step and subcritical in the pool (Church & Zimmermann, 2007). The flow will erode a deep pool downstream of the step which eventually flattens out, creating a *tread* towards the next step. The steps usually consist of coarse material of mixed sizes spanning the channel width, separated downstream by areas of finer material in the pools and treads (Chin & Wohl, 2005). Steps can also be formed by fallen trees and has been shown play a significant role in stream stability (Elosegi, Díez, Flores, & Molinero, 2016; MacFarlane & Wohl, 2003). The composition of steps is usually anchored by the largest particle in the formation, commonly referred to as the *keystone*. These are usually the among the largest sediments in the stream (D_{99}) and are fundamental to step-formation when they are deposited during large floods (Church, 2002).

Step-pools have been reported on slopes as low as 4% (Grant, Swanson, & Wolman, 1990; Montgomery & Buffington, 1997; Whittaker & Jaeggi, 1982). On slopes larger than this it is supposed that some structural reinforcement in the shape of step-pools is necessary to maintain bed stability (Church & Zimmermann, 2007). Ribs and rapids are more commonly observed on slopes lower than 4%, but these do not provide the same hydraulic conditions as step-pools in which the relative roughness is higher and provides higher energy dissipation. Step-pool channels can be hard to define, and reach-scale classification might be a futile exercise in the field. Step-pools are often separated from *cascades* which appear the same, but does not span the entire stream bed (Montgomery & Buffington, 1997). These formations can occur alternating with well-developed step-pools, and the distinction can be challenging.

3.3.2 Step spacing

The morphometric variables of step-pools and their relations to each other is a fundamental part of step-pool research. Step spacing, or wavelength, is commonly defined as the horizontal distance between two successive steps. This length can be split into pool length and tread length. Step spacing has been shown in some studies to correlate with the size of the channel and varies from less than 1 to 4 channel widths (Chin & Wohl, 2005). Steeper streams will typically be narrower, and a higher relative roughness is necessary to adjust for the higher energy of flow involved in such streams. This can be adjusted by higher steps, but step spacings must also be shorter to account for the necessary vertical fall (Church & Zimmermann, 2007). Less steep streams can include treads because the overall bed slope doesn't require as dramatic reductions in elevation and high frequency of steps. Wohl and Grodek (1994) observed boulder steps up to slopes of 73% and a clear systematic reduction in step spacing up to 20%, after which no further reduction in length was observed. This might be due to lack of space to create pools rather than a clear causal effect (Church & Zimmermann, 2007). Whittaker and Jaeggi (1982) illustrated that the processes behind step-formation changed at slopes steeper than 7%, and that formation at steeper slopes is mainly controlled by jamming while several mechanisms interact on step-formation on slopes lower than this. The value of 7% is in line with Church (2002) who concluded that continuous step-pool morphology can occur on slopes steeper than 7%.

3.3.3 Step height

Step height has been shown to increase proportionally with slope, but no maximum step height has been defined (Chin & Wohl, 2005; Wohl & Grodek, 1994). Step height provides the relative roughness of the stream, and increasing slopes will require a larger roughness to account for the higher energy of the flow. Step height has also been shown to correlate strongly with the size of the keystone (Chin & Wohl, 2005; Waters & Curran, 2012), and Molnar et al. (2010) observed that the largest steps were located close to the most active hillslopes, where the supply of coarse material is usually higher. Chin (1999) and Wohl, Madsen, and MacDonald (1997) observed a mean ratio of step height and particle size at a fairly constant 1.2, and Tatsuzawa, Hayashi, and Hasegawa (1999) suggested that step heights reflects D_{84}. Step height is measured differently by different researchers, and is a source of complications when doing comparative studies. Newer studies tend to define step height as the vertical distance from the top of the step to the bottom of the downstream pool (fig. 5) (Church & Zimmermann, 2007; Waters & Curran, 2012). This provides a parameter that represents the maximum vertical drop for the streamflow, and thus the potential kinetic energy-loss. Older studies tend to define step height as the vertical distance between two successive steps, thus defining the total height drop per step sequence (Chin, 1999). Today it is common to separate these variables as respectively step height and step drop. Both provide valuable information about morphometric relations.

3.4 HYDROLOGY

3.4.1 Hydraulic function

Step-pools serve an important function in that they provide the stream with hydraulic resistance (Abrahams et al., 1995). The oscillating transitions from supercritical to subcritical flow when water flows over steps and plunges into pools dissipates much of the flow energy via turbulence (Church & Zimmermann, 2007). This provides a massive hydraulic resistance that reduces the amount of excess kinetic energy (Chin & Wohl, 2005). The oscillating flow caused by step-pools promotes tumbling flow, an energy-inefficient way to transport water. The size of the step will determine the amount of energy dissipated in the pool, as the hydraulic jump involved will drastically reduce the amount of kinetic energy of the flow (Church & Zimmermann, 2007). The hydraulic resistance provided by log-steps is very high due to this correlation between energy dissipation and step height. Log-steps will often be proportionally larger in size than its immediate neighbours, as shown by MacFarlane and Wohl (2003) where streams with a large proportion of large woody debris provided a higher flow resistance than streams without a high proportion of woody debris.

3.4.2 Sediment mobility

A particle will be deposited when its inertia becomes larger than the applied shear stress, and set in motion when the shear stress is larger (Church, 2002). This interaction is referred to as *size selectivity* wherein the movement of particles is solely controlled by the relation between inertia and shear stress (Sear, Newson, & Thorne, 2010). During larger flows, larger particles will be set in motion. Keystones are usually the largest particles in the stream, and their inertia will during normal flows cause them to remain stationary. The activation of these particles will usually only occur during very large floods (30+ years), but they have been observed to move during smaller floods (5 years) (Curran & Wilcock, 2005). These particles will also be among the first to be deposited during receding flows and act as barriers upon which smaller particles can jam and accumulate (Church & Zimmermann, 2007). The mobility of a particle that is jammed to a larger particle is controlled by the mobility of the latter, a state of mobility referred to as *equal mobility* (Sear et al., 2010). This accumulation of particles around a keystone will eventually form a step whose mobility is governed by the collective inertia of the step-forming clasts. Only large floods can destroy these formations, and can release large amounts of stored material when they do (Church & Zimmermann, 2007). The destruction of steps will cause instability due to the loss of hydraulic resistance; erosion of the bed will increase, and a stream might feature increased sediment transport and instability for many years after large floods (Lamoureux, 2002; Lenzi, 2001).

3.4.3 Flow resistance and stability

Abrahams et al. (1995) suggested that step-pools, as they break down, will reform as new step arrangements that are more adapted to the stream flow and thus provide higher hydraulic resistance. These new formations are expected to last longer due to their adaption, and Abrahams et al. (1995) went on to suggest that maximum flow resistance implies maximum stability. Shorter step spacings should produce more steps within a reach, thus creating higher resistance, and the study of Abrahams et al. (1995) concluded that flow resistance is maximised when steps are regularly spaced and the mean step steepness is slightly greater than the channel slope. The assumption that streams will evolve towards a state of equilibrium in which both stability and resistance is maximised (Abrahams et al., 1995) has inspired some of the theories presented in the next sections.

3.5 FORMATION

The step-forming mechanisms regarding accumulation at keystones are generally agreed upon in the literature, but the underlying processes that govern the location of these formations are still highly debated (Chin & Phillips, 2007; Church & Zimmermann, 2007). The literature presents mainly two different schools of thought regarding the location of steps, one of which is based upon an observed regularity in step spacing, while the other is based on the lack of any such systematic pattern. The former is commonly referred to the hydraulic theory, in which the location of steps is thought to be governed by the location of standing waves at antidunes (Curran & Wilcock, 2005; Whittaker & Jaeggi, 1982). The latter theory is based on the lack of systematic patterns, and suggests that steps are formed via random deposition and that step deposition is related to channel size (Zimmermann & Church, 2001).

3.5.1 Hydraulic theories

Several ideas for hydraulically controlled deposition has been presented, but the most cited theory suggests that steps form at standing waves under antidunes (Whittaker & Jaeggi, 1982). The deposition of a keystone will anchor the antidune and promote deposition of other stones that accumulate and lock themselves together, creating a step. The reliance on hydraulics should indicate regularity in step spacings as the stream moves towards maximum resistance (Abrahams et al., 1995; Judd, 1963), but this spatial organization is not always clear (Chin &

Wohl, 2005; Molnar et al., 2010). The theory has produced promising results in flume tests, but less so in the field (Curran & Wilcock, 2005; Egashira & Ashida, 1991). The antidune theory assumes near critical or supercritical flow over soft cohesive bed sediments that can be sorted into bedforms such as antitudes, which is an unlikely combination of variables (Chin & Wohl, 2005). Step-pool channels are formed in heterogenous gravel-boulder systems, and it is unlikely that this material is governed by relatively soft bedforms during floods of sufficient size to transport boulders.

3.5.2 Jammed state and random deposition

The apparent lack of any systematic spatial patterning spawned the theories involving random deposition of keystones. Zimmermann and Church (2001) suggested that keystones are randomly deposited by flood events or directly from hillslope processes. Their study could not observe any regularity in step spacings, step heights or pool lengths, and could not conclude that step formation was caused by some systematic mechanism. The same authors later presented their *Jammed State* hypothesis in Church and Zimmermann (2007). They suggested three main factors that affect step deposition, the first one being *the jamming ratio* (w/D) which is defined as the relation between local channel width and size of the step-forming keystone. This represents how easily large particles can jam at any location. The importance of channel width in relation to various particle sizes has been demonstrated in several studies, and it appears critical with a heterogenous distribution of materials, with a high proportion of coarse material and a relatively high D_{max} (Curran & Wilcock, 2005; Lee, 1998; Tatsuzawa et al., 1999).

The second factor suggested by Church and Zimmermann (2007) is the mobilizing force of the flow, which governs the stream’s ability to move the largest particles and reorganize the bed during large floods. Smaller floods (1.5-3 years) have been shown to control much of the adjustment of microscale step-pool morphometry, and that the larger floods (30-50 years) is responsible for large scale reorganization of the whole channel reach (Lenzi, Mao, & Comiti, 2006). The largest floods will break down step-pools and activate enormous amounts of sediment. When the flows recede, new steps will form at new locations and the hydrological regime of the stream will have been changed (Lenzi et al., 2006; Molnar et al., 2010)

The third factor is the relation between sediment supply and discharge. Studies have shown that a criterium for step development is sediment starved conditions with low transport rates

(Egashira & Ashida, 1991; Jong, 1995; Recking, Leduc, Liébault, & Church, 2012), and that higher sediment concentrations tend to fill in pools with sediment and reduce the hydraulic effect of step-pools (Ergenzinger & Schmidt, 1990; Lamoureux, 2002; Lenzi, 2001; Recking et al., 2012), thus increasing scour and causing instability (Koll, Aberle, & Dittrich, 2000; Koll & Dittrich, 2001; Recking et al., 2012).

3.6 SCALE OF STUDY

Studies of stream bed morphology will always represent a snapshot in time of that particular reach (Chin & Wohl, 2005). Floods of varying size will affect the bed in different ways, from micro-adjustments in pool-volume to total reorganizing of the stream bed (Lenzi et al., 2006). Even the smallest flows will perform adjustments to the bed, and at larger timescales it's the medium sized events that on average applies the most stress on a bed (Bunte, Abt, Swingle, & Cenderelli, 2014). A stream is adjusted at macroscale to the previous large flood event, and to understand step-morphology requires knowledge of the flood-history of a stream (Lenzi, 2001). Smaller events will still adjust the bed at meso- and microscale, but the stream as a whole will be adjusted for larger events, as larger floods will overwhelm smaller formations and reduce their effectiveness (Chin, 1999; Chin & Phillips, 2007). Understanding the scale of study is imperative, as observations of bed formations are just snapshots in time and space of a larger adjustment process. A formation might appear stable or unstable at any scale, but step effectiveness at energy dissipation will decrease with increasing scale of events (Chin & Wohl, 2005). A complete understanding of a river reach will require an understanding of the hydrological regime over a broad range of flows and time.

3.7 SUBJECTIVITY AND BIAS

The elusive nature of step-pools remains a challenge in stream research. No two studies of the same reach might provide the same results, and the same researcher might not even be able to recreate the same longitudinal profile twice. The dynamic nature of streams will always be a source of uncertainty in research. Comparative studies are made even more challenging by bias involved in data collection and subjectivity involved in identifying bed formations. Zimmermann et al. (2008) studied the effects of subjectivity in identification by presenting a longitudinal profile to several well-known geomorphologists and comparing the results of manual identification. None of the researchers identified the same formations, and any similar identifications had differing morphometry. Different researchers will identify different formations, and due to the lack of any defined set of rules when calculating morphometry, the parameters within a formation will also differ. Nickolotsky and Pavlowsky (2007) studied one reach by applying the measurement methods from three different researchers, all of whom with slightly different ideas of how to measure step spacing and step height. The study illustrated a striking difference in morphometric results that will affect the quality of comparative studies involving different researchers. Zimmermann et al. (2008) suggested a rule-based classification system that defines how parameters must be calculated in order to retain as much objectivity as possible. The study also designed an algorithm to automatically identify step-pools from a longitudinal profile, thus limiting the subjectivity involved in both identification and calculation of step-pools. The method presented in this study will attempt to do the same.

4 METHODOLOGY

Step-pools are characteristic bed formations that most fluvial geomorphologists can easily recognize in a stream, but to accurately identify large series of formations and define their morphometric proportions can be a significant challenge. Available literature is still not developed to such a degree that our understanding of step-pools is complete, and the physical measurement of these formations remains challenging due to commonly being attributed to streams in difficult terrain. Classification of the real world is a subjective experience (Trudgill, 2012), and research on such formations must be done in ways that retains the reliability of the study. Adequate planning of the fieldwork and the applied methods is essential to keep the study as objective as possible. If a result is to be used in other comparative studies it has to pass the test of reliability.

This chapter will begin by discussing the technicalities and practicalities of the fieldwork, before presenting the algorithm and analytical methods. The chapter is concluded by a discussion on sources of error and the issues of reliability and validity.

4.1 MEASURING METHOD

Bed formations can be tricky to measure and record as most remote sensing methods cannot penetrate the water surface. The most common methods in bed morphology research is the use of electronic theodolites or accurate satellite positioning. The latter was chosen as field method for this study. Differential GPS with RTK technology can calculate highly accurate horizontal and vertical positions at centimetre scale, and the method is relatively quick once the reference station is active. Speed and accuracy were two important factors in this fieldwork to accurately measure bedforms down a length of almost 2 kilometres.

4.1.1 GNSS

Global Navigation Satellite Systems (GNSS) refers to the constellation of satellites orbiting the earth providing navigational information to users on the ground. This constellation contains satellites from mainly three different space agencies; the most popular of which being the American NAVSTAR GPS. GNSS is often just referred to as GPS (*Global Positioning System*) due to this popularity. The Russian GLONASS and the European Galileo being the two lesser known satellite providers (Rød, 2015). Galileo was first made public in December 2016, but aims to be complete with 24 satellites in 2020 (The European Space Agency, 2016). NAVSTAR GPS consists of 24 satellites distributed on six orbits equally spread apart across the globe with an orbital period of 12 hours (Lechner & Baumann, 2000). The satellites transmit radio waves that are picked up by receivers on the earth that automatically calculate the distance based on the satellite's location and the transmit time. This constellation of satellites provides full coverage of 4 to 5 satellites at any point on the globe at any time of the day. To accurately estimate a three-dimensional position a minimum of 4 satellites has to be available (Longley, Goodchild, Maguire, & Rhind, 2015). The geometry of the available constellation will affect how accurate a position can be calculated. A wide constellation spread across the horizon will provide a more accurate position than if the constellation is more clustered (Rød, 2015). Receivers today can receive information simultaneously from both NAVSTAR and GLONASS.

The atmosphere, and especially the ionosphere, will affect the signals going between satellites and receivers. The amount of plasma in the ionosphere can delay the speed at which signal are being transmitted and can affect the accuracy of measurements in the field (Rød, 2015). Solar storms or just high turbulence in the ionosphere will also affect the signals in a negative way. GPS technology today has several methods to automatically adjust for any signal disturbances, but it will never be totally without fault in less-than-perfect conditions.

4.1.2 DGPS and RTK

Differential GPS is a method that involves two receivers. One of these functions as a fixed reference point that is set up on a precisely known position, and the receiver can compare the incoming satellite signals with this known position and calculate the deviation from the measured position. The difference can be applied to the data from the moving receiver commonly called a *rover*. The correction can be applied through postprocessing or in real time. Real-time Kinematics (RTK) is a technique that transfers corrected data from the reference station to the rover in real time, and positions measured by the rover are then already corrected to account for any atmospheric noise (Chivers, 2003). The use of DGPS allows for a relatively mobile rover while still being able to produce accurate positions.

4.2 EQUIPMENT

Figure 5: Top: Altus ASP-3 GNSS receiver. Bottom: Nautix x7 handheld computer.

Altus ASP-3 was chosen as both rover and reference station. This is a very accurate and precise receiver specifically designed for land surveying. With RTK enabled it can provide a vertical accuracy of 1cm + 1ppm and a horizontal accuracy of 0.6cm + 0.5ppm. The receiver supports GLONASS and GPS, and includes UHF radio and GSM networking (ALTUS, 2011).

The personal handheld computer Nautix x7 was used by an operator on land who walked alongside the operator doing the measuring in-stream. The handheld computer receives calculated UTM coordinates from the rover via Bluetooth connection.

4.3 CONDITIONS

The initial fieldwork was done 1-3 July 2016, but methodological challenges forced the data to be rejected. Fieldwork design and methodology were reformulated and more precisely defined. The final fieldwork was done over a total of five days at 19-22 September and 5 October 2016. Stream discharge was low and the cloud cover was thin; favourable conditions for both the physical and technological variables. Methodologically, we were also much more prepared in terms of proper installation of reference stations, rules of measurement, and handling of unforeseen events. Work was usually started at around 9am and finished around 5pm before the sun went down.

Vekveselva bends heavily at a few locations, with steep hillslopes closely connected to the river banks. This makes visibility to reference stations challenging, and the locations of these stations had to be pre-planned to achieve the most effective coverage. A total of three reference stations had to be set up to provide the best coverage of the entire study area. Two of these were usually active simultaneously so that one could pick up the connection if the other station lost signal. The locations of the reference stations are shown in figure 12.

Figure 6: One of the reference stations.

The receiver had on average contact with 4-6 satellites while the reference stations could have contact with up to 17. The constellation of these was usually good, except for one area in the lower parts of the stream where the surrounding hillslopes are especially constricting with thick vegetation. PDOP (Position Dilution of Precision) refers to how good the constellation of satellites is at any time, and defines the confidence level of the measured point. A lower PDOP implies a higher accuracy of measurement. PDOP values of 1-6 is considered good conditions and 7-8 as moderate conditions (Person, 2008). On a stretch of about 100 meters in the lower parts of the stream, the PDOP tolerance had to be increased to 8 to allow measurement, but was otherwise set to 6. Vertical and horizontal tolerance for accuracy was set throughout the fieldwork at 0.05m and 0.01m respectively.

Figure 7: Measuring the bed with GNSS point measuring. The operator on land would set the point when the measuring rod was securely placed.

Points were calculated at approximately every meter and at every breakpoint in the bed. Average distance between measurement points ended up at 0.8m. This provided a very detailed longitudinal profile considering the scale of the fieldwork. The operator followed the thalweg as best possible, but at locations where the stream split up and no main route was obvious a decision had to be made after discussion between the two operators. The step of a step-pool was measured on the lowest point on the step, followed by a point immediately below at the start of the pool. The deepest point in the pool was then measured, followed by a gradual measurement towards the next step. The identification of step-pools can be challenging in the field, and much discussion was necessary to understand the bed morphology. Decisions like this will affect the end result and is almost inevitable. Any decisions made during the fieldwork was attempted to be done as consistent as possible to keep the reliability of the result.

The measurements were done with one operator on the stream bank observing the operator in the stream. The operator on land would operate the personal computer to control when the receiver calculated positions. The operator in the stream controlled where measurements were made with the receiver fitted on a 1.95m long measurement rod. A bubble level was fitted to the rod to ensure accurate positioning. The advantage of using two operators is both added safety, but also because decisions can be made via discussion with two different perspectives on the stream bed.

The fieldwork was periodically challenging due to very coarse material that the operator had to climb around. Some step heights and residual depths were larger than the operator, and presented a significant risk when combined with water flow. Some areas would funnel the water flow and feature very high local discharge that could easily knock a person over even at low overall flows. Progress was slow at some areas to ensure safety, and at one location it was decided to skip roughly 30m of the stream because it was deemed impossible to measure the formation safely.

Figure 8: Illustration of bed roughness at the site of an old landslide.

The last measurement point on 22 September and the first measurement point on 05 October were set on the exact same position to ensure proper continuation of measurement. The later data processing revealed that the point from October had a height value 1.3m higher than that from September. It was decided to remove this difference from all values from October as this elevation appeared unnatural. All the points from October seemed to be elevated in relation to the earlier measurements. The cause of this is unknown, but the most obvious explanation is changed settings such as the length of the measurement rod. The consequence of this change will nevertheless not affect the morphometric relations within sequences.

4.4 PREPARATION

The raw data from the fieldwork only included North and East coordinates, and elevation above sea level. Distance between two measurement points and cumulative length was calculated via Pythagoras' theorem. Height difference between points was calculated by subtracting the elevation difference between two points. The slope value m/m between two points was then calculated as the height difference divided by the length between the two points. Average bed slope was calculated via the Slope function in MS excel, which calculates the slope of the linear regression line through a set of Y's (height) and X's (length). The dataset was then examined for obvious errors such as overlapping points from combining datasets, test points, and marker points that was set intentionally in the field.

4.5 AUTOMATIC IDENTIFICATION

Identification of steps and pools from stream longitudinal profile data can prove to be a significant challenge if the profile contains hundreds or even thousands of measurement points. There are two main challenges regarding identification and analysis of step-pools: subjectivity and time.

Stream morphology has been studied for decades (Abrahams et al., 1995; Chin, 1999; Grant et al., 1990) and the library of information on step-pool morphometry continues to evolve. The theoretical basis for these characteristic formations is, however, still somewhat loose, and to specifically define the morphometric and formational rules of step-pool systems remains a source of debate (Chin & Wohl, 2005; Church & Zimmermann, 2007; Zimmermann et al., 2008). Without a defined set of rules to follow when identifying step-pools or studying morphometric variables, researchers will often apply their own subjectivity to their work despite their effort to avoid this. Fieldwork will always be a trial of subjectivity versus objectivity, and even small decisions such as where to put the measuring rod or which settings to use will affect the end result. Until technology allows widespread automated and detailed scanning of an entire riverbed, there will always be subjectivity at play when manually measuring in the field. If the work is done consistently and the rules of measurement and decision-making are pre-planned, the effect of subjectivity can at least be kept to a minimum.

Identifying step-pools from a longitudinal profile is often done manually via visual observation either in the field or afterwards, and adds another layer of subjectivity before the morphometry are automatically calculated for these formations (Zimmermann et al., 2008). Few methods of objective automated identification and calculation have been presented and less so widely tested (Milzow et al., 2006; Wooldridge & Hickin, 2002; Zimmermann et al., 2008).

The decision to design my own method of automatically identifying step-pool segments and calculating the morphometry within was not only a pragmatic decision due to the length and detail of the longitudinal profile, but I also wanted to add my own ideas to the available literature. My method is originally based on the concept of critical slope by Milzow et al. (2006). This method identifies a step if the slope between two points is greater than a critical value of 0.45 m/m (45%). If a critical slope is identified, the upstream point is identified as the top of the step. When a new critical slope in the longitudinal profile is identified and a new top step is defined, all the points between these two features are defined as part of a step-pool segment. If two critical slopes occur successively they are treated as being part of the same segment. This method is an easy way to identify segments, but it cannot identify treads and can wrongly identify steps if the measurement density is very high. These are limitations acknowledged by both its designer Milzow et al. (2006) and Zimmermann et al. (2008).

The method presented in this thesis keeps the underlying simplicity of Milzow et al. (2006), but adds several more layers of geometric parameters. The code was written as an Excel Macro in Visual Basic for Applications (VBA), but it should be easily translatable to other languages. My parameters for geometric calculations follow the same definitions as Church and Zimmermann (2007) and Recking et al. (2012).

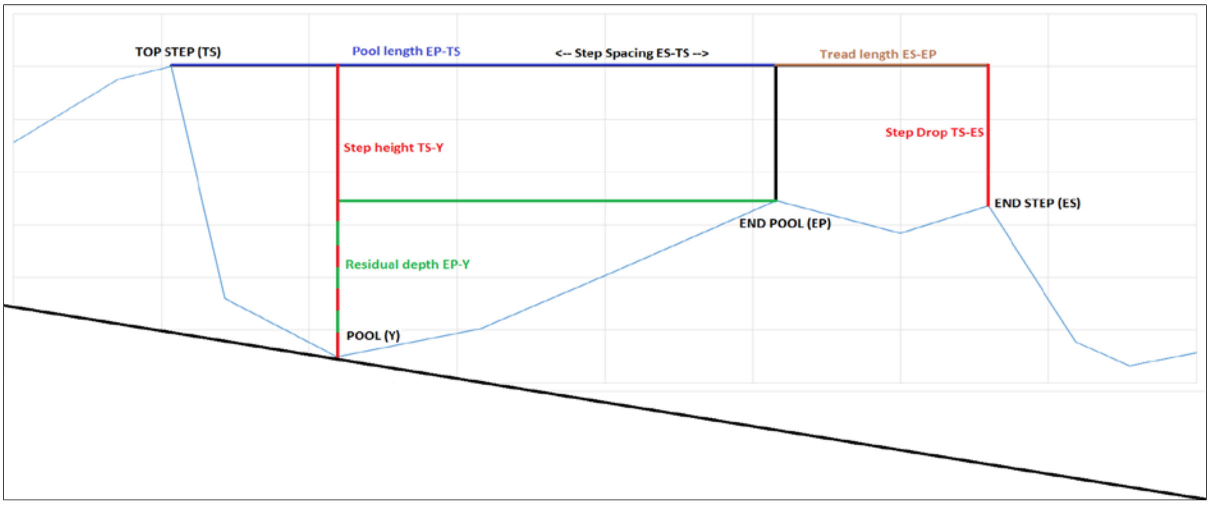


Figure 9: The parameters for calculating morphometry within a step-pool segment. The figure illustrates one sequence. The black line at the bottom represents the stream bed.

The algorithm will begin by identifying a step-pool segment and calculate the step spacing as the horizontal distance between the upstream *top step* (TS) and the *end step* (ES), which will also mark the *top step* of the next sequence. The main difference between my method and the method of Milzow et al. (2006) is the ability to identify and separate the pool within the segment. This way a tread can also be identified. The *pool* (Y) is calculated by looking for a reverse slope value after the segment has been defined. This will also be the deepest point in the pool and forms the basis for calculating step height as the vertical distance between *top step* (TS) and the depth of the *pool* (Y). If no *pool* is identified, step height is calculated as the vertical distance between *top step* (TS) and the last critical slope-value. The highest elevation-point after the *pool* (Y) will be defined as *end pool* (EP). This point might in some cases also be *end step* (ES). *Pool length* (PL) is calculated as the horizontal distance between *top step* (TS) and *end pool* (EP). *Residual depth* is calculated as the vertical distance between *pool* (Y) and *end pool* (EP). *Step drop* is calculated as the vertical distance between *top step* (TS) and *end step* (ES). *Tread length* is then calculated as the horizontal distance between *end pool* (EP) and *end step* (ES), which marks the end of the current segment. *Step steepness* is calculated as the slope m/m between *top step* (TS) and *end step* (ES), and define the deviation from the local bed slope. *Local slope* is calculated by fitting a moving window of 30m upstream and downstream of each identified step and calculating the slope value within this window.

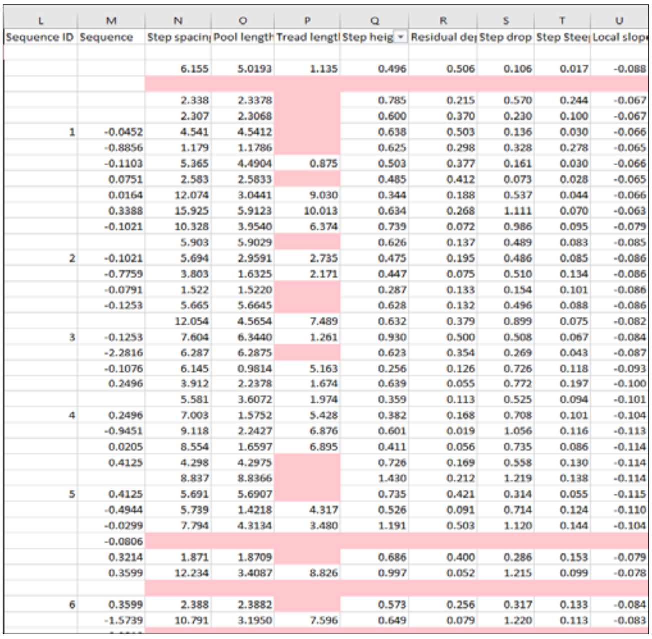
The delicate reliance on a positive slope value to identify a pool is not ignored by the author, but only 9 identified segments out of 265 did not inhabit this particular morphology. These 9 segments all contained a constant negative slope throughout the segment and neither a pool nor a tread was apparent from assessing their longitudinal profiles. These segments might be the result of misidentification or simply represent areas with low erosional impact such as bedrock or colluvial material.

The algorithm will correctly identify individual segments, but it can also misidentify. My understanding of misidentification is of course subject to my own lack of total objectivity. Figure 10 illustrates an issue wherein my subjective visual identification differs from the algorithm. The blue triangles represent what I would identify as steps while the colour coding are segments that the algorithm identified. The main strength of an automated and objective algorithm is of course the fact that it does *not* adhere to my understanding of step-pools, but the figure remains a good example of how the critical slope method can sometimes be too simple. The step marked by the first blue triangle is just barely shy of the critical slope and thus no step is identified, and the red field *is* identified as a step due to two separated critical slopes between which a very short segment is created. This may be a proper step-pool sequence, but it may also be the result of intermediate measuring on very large steps. Consideration of this should be done while collecting data in the field. Regardless of any potential misidentifications, the fact that this method will create the same results in a consistent manner each time it is applied far outweighs any deviations from the researcher's perceived reality. It's easier to compare two results created by the same algorithm than to deal with any additional bias from the researchers. More powerful algorithms might provide more accurate results, but the problem remains with the researcher's definition of an accurate classification of a step-pool channel, and how well a longitudinal profile can characterize a riverbed to begin with.

Figure 10: Illustration of different opinions of identification. Blue triangles represent what the author would identify as steps. Coloured sections represent step-pool sequences identified by the algorithm.

If the horizontal distance between two measurement points exceeds 3 meters the algorithm will restart at the downstream point. This occurs 3 times and represents areas that were too complicated to measure accurately. Additionally, a minimum step spacing was set to 1m, removing 4 sequences. The 9 sequences without pools were not included in the analyses, as these are not relevant for the study of step-pools. A maximum step spacing was set to 16m (3 times channel width) to reduce the amount of extreme lengths that I consider to not be relevant. The limit is based on average values presented in the literature (Chin & Wohl, 2005).

4.6 ANALYTICAL METHODS



L	M	N	O	P	Q	R	S	T	U
Sequence ID	Sequence	Step spacin	Pool length	Tread lengt	Step heig	Residual de	Step drop	Step Stee	Local slope
		6.155	5.0193	1.135	0.496	0.506	0.106	0.017	-0.088
		2.338	2.3378		0.785	0.215	0.570	0.244	-0.067
		2.307	2.3068		0.600	0.370	0.230	0.100	-0.067
1	-0.0452	4.541	4.5412		0.638	0.503	0.136	0.030	-0.066
	-0.8856	1.179	1.1786		0.625	0.298	0.328	0.278	-0.065
	-0.1103	5.365	4.4904	0.875	0.503	0.377	0.161	0.030	-0.066
	0.0751	2.583	2.5833		0.485	0.412	0.073	0.028	-0.065
	0.0164	12.074	3.0441	9.030	0.344	0.188	0.537	0.044	-0.066
	0.3388	15.925	5.9123	10.013	0.634	0.268	1.111	0.070	-0.063
	-0.1021	10.328	3.9540	6.374	0.739	0.072	0.986	0.095	-0.079
		5.903	5.9029		0.626	0.137	0.489	0.083	-0.085
2	-0.1021	5.694	2.9591	2.735	0.475	0.195	0.486	0.085	-0.086
	-0.7759	3.803	1.6325	2.171	0.447	0.075	0.510	0.134	-0.086
	-0.0791	1.522	1.5220		0.287	0.133	0.154	0.101	-0.086
	-0.1253	5.665	5.6645		0.628	0.132	0.496	0.088	-0.086
		12.054	4.5654	7.489	0.632	0.379	0.899	0.075	-0.082
3	-0.1253	7.604	6.3440	1.261	0.930	0.500	0.508	0.067	-0.084
	-2.2816	6.287	6.2875		0.623	0.354	0.269	0.043	-0.087
	-0.1076	6.145	0.9814	5.163	0.256	0.126	0.726	0.118	-0.093
	0.2496	3.912	2.2378	1.674	0.639	0.055	0.772	0.197	-0.100
		5.581	3.6072	1.974	0.359	0.113	0.525	0.094	-0.101
4	0.2496	7.003	1.5752	5.428	0.382	0.168	0.708	0.101	-0.104
	-0.9451	9.118	2.2427	6.876	0.601	0.019	1.056	0.116	-0.113
	0.0205	8.554	1.6597	6.895	0.411	0.056	0.735	0.086	-0.114
	0.4125	4.298	4.2975		0.726	0.169	0.558	0.130	-0.114
		8.837	8.8366		1.430	0.212	1.219	0.138	-0.114
5	0.4125	5.691	5.6907		0.735	0.421	0.314	0.055	-0.115
	-0.4944	5.739	1.4218	4.317	0.526	0.091	0.714	0.124	-0.110
	-0.0299	7.794	4.3134	3.480	1.191	0.503	1.120	0.144	-0.104
	-0.0806								
	0.3214	1.871	1.8709		0.686	0.400	0.286	0.153	-0.079
	0.3599	12.234	3.4087	8.826	0.997	0.052	1.215	0.099	-0.078
6	0.3599	2.388	2.3882		0.573	0.256	0.317	0.133	-0.084
	-1.5739	10.791	3.1950	7.596	0.649	0.079	1.220	0.113	-0.083

Figure 11: The data produced by running the algorithm in MS Excel. Sequences are separated with an ID. Each row from column N to U represents a sequence.

Most of the analytical work was done in MS Excel and IBM SPSS. The algorithm itself was written and run in VBA as an Excel macro. All identified sequences were automatically filled in with all the calculated variables for each sequence, from which descriptive statistics could be calculated. Distributions, correlation analyses and ANOVA were all performed in IBM SPSS as this is a powerful and relatively easy software in which to run several large analytical batch processes. Maps and analyses of spatial distribution were done in ESRI ArcGIS.

The Multi-Distance Spatial Cluster Analysis tool in ESRI ArcGIS was utilized to analyse the occurrence of any spatial pattern in the data. This tool is based on Ripley's K-function, and summarizes spatial dependence over any range of distances and can illustrate how the spatial distribution of a feature changes as neighbourhood size (scale of analysis) changes (Scott & Janikas, 2010). There are several tools to study spatial distributions, but Ripley's K is an efficient statistic to evaluate point features over a range of scales and can also discriminate clustered, random and dispersed patterns over the same range of scales (Kraft & Warren, 2003). This tool will produce an expected K based on the applied dataset. If the observed K at any scale is larger than the expected K this would illustrate a more clustered distribution than a random distribution. If the observed K is smaller than the expected K this would illustrate a more dispersed distribution than a random distribution. If the observed distribution is indeed fully random then the observed K would follow a straight line equal to the expected K (Haase, 1995). Upper and lower confidence intervals are generated by randomly distributing a set of points 999 times per iteration. If the observed K is higher or lower than the confidence intervals, the clustering or dispersion for that distance is statistically significant. Consult Ripley (1977) for more information about the math behind Ripley's K function.

4.7 SOURCES OF ERROR

Automatic identification has relieved a lot of the issues concerning the unavoidable bias involved in manual identification of natural formations either in the field or afterwards, but several issues still remain that can have a fundamental impact on the end result of a study.

Data can be biased or inaccurate before the collection of it even begins if the planning of a fieldwork is done improperly or field-decisions are done in haste. Poor planning might impact the consistency in which the fieldwork is done. If a rule-set is not defined for where to move, where to put the measuring rod or what to do in unexpected scenarios then the dataset might lose its reliability when erroneous decisions are made and perhaps even worse not kept consistent throughout the fieldwork. If a source of error is known and consistent it might be possible to circumvent this issue while analysing the data, but a dataset in which errors are undefined and randomly placed might end up useless for scientific study. Planning of a fieldwork also involves the correct usage of the field equipment, and technological ignorance can in some cases have a significant impact on the data produced. A good example of this is the issue presented earlier where a point measured at exactly the same spot on two different days experienced a 1.3m vertical jump. It's believed that the settings for measurement height had changed, but this was a consistent error that was easily identified and corrected post-fieldwork. Other settings such as limits for atmospheric noise, constellations or number of available satellites will also affect the accuracy of the data, but this was generally not an issue during our fieldwork and limits could be kept within acceptable values.

The fieldwork itself will always be riddled with subjectivity and bias when done manually. Proper planning will, however, aid decision-making in difficult scenarios, and I believe that the fieldwork was done as consistent as possible and that the resulting dataset represents a good version of Vekveselva. It is, however, almost certain that a different researcher would produce a different version, simply because an identical version would require a measurement that follows the exact route as this study, which is practically impossible in a system as chaotic as Vekveselva where the main thalweg is not always apparent. Streams are also highly dynamic systems in which the morphology is ever changing. This study represents a version of Vekveselva in a specific time and space and might never be perfectly reproduced. These issues of subjective measurement and limited timescale illustrate the difficulty of comparing different studies of the same streams, and accentuates the value of objective means of identification.

The analyses after automated identification by the algorithm were done with as little user-interference as possible. There are several locations in the longitudinal profile where picture-perfect morphologies of step-pools exist but does not inhabit the necessary criteria to be identified as such by the algorithm. These can be frustrating to observe, but it was important to let this study be a result of the applied algorithm. An algorithm based on numbers and custom limits will never perfectly replicate reality, but that is also not the point of an automated system. The use of algorithms to automatically identify morphology is a tool to achieve objectivity and results that are accurate and consistent enough to be used in comparative studies. Human identification of step-pools is no more accurate or correct than any other method, as nature can rarely be confined to such labels of representation. The only user-interference applied to the dataset was to adjust obvious erroneous values, remove double measurement points, overlapping points and points that were set to identify progress on a given day.

All studies should strive to achieve reliability and validity. These concepts describe the degree to which the study can be regarded as trustworthy in a scientific sense. Reliability is the degree to which a study can be replicated to produce the same results and conclusions as the original study (Yin, 2013). The concept strives to reduce the amount of errors and bias in the study such that it represents a trustworthy addition to the scientific community. This presents an issue in studies of dynamic natural processes where no two researchers will observe the same phenomena the same way. It will most likely not be possible for a researcher to produce the same results as this study due to the transient nature of mountain streams and the complex nature of field measurements. The issue of reliability spawned the necessity for automated identification, and if a researcher were to run an algorithm twice on the same dataset it would produce identical results. The means of identification in this study can be relied upon to be consistent, but the means of data collection will always be a source of error in studies where this is done manually.

Validity explains how trustworthy the study appears in terms of how valid the researcher’s decisions, analyses and conclusions are (Yin, 2013). If the researcher is transparent in his/her methodology and thought-process it provides the reader with the opportunity to understand or challenge a decision. Validity is reduced if a study is plagued with systematic errors or simply bad decisions or conclusions. The fieldwork in this study was done in a consistent manner, and if any user-driven errors were present they should at least be consistent throughout the study area. The design of the algorithm is based on available literature on common step-pool morphology, and it identifies morphologies that are logical in terms of what step-pools exist to do. The resulting analyses are a product of my own educated knowledge, but the methods to achieve these results are based on available literature. Validity is a difficult concept to critically apply to oneself, but the methodology in this study is presented in such a way that it encourages the reader to challenge my decisions.

Validity is also used to evaluate a study’s generalizability (Yin, 2013). The results in this study can have value in comparative studies, but mean values and geometry cannot be expected to follow the same pattern as other river reaches. Vekveselva, as any river system, has a unique set of attributes that affects bed morphology in a way that perhaps no other river system in the world can mirror. The value of this study is not to create generalizations, but to add to a library of step-pool information on which comparative studies can be based.

5 RESULTS

This chapter will present the initial statistics calculated by the algorithm for several parts of the river reach in addition to the total longitudinal profile, followed by correlation analyses of chosen variables, and finally concluded by an analysis of spatial distribution. The result of the fieldwork was a detailed longitudinal profile with 2025 measurement points spanning 1810m in length and a total vertical drop of 155.7m. The average bed slope is 8.8%.

Figure 12 illustrates all the measurement points with a red line following the thalweg in Vekveselva. Red triangles mark the positions of reference stations for the Differential GPS measurements. The coloured sections mark the locations for the three selected reaches. Old landslide sites are marked in transparent orange.

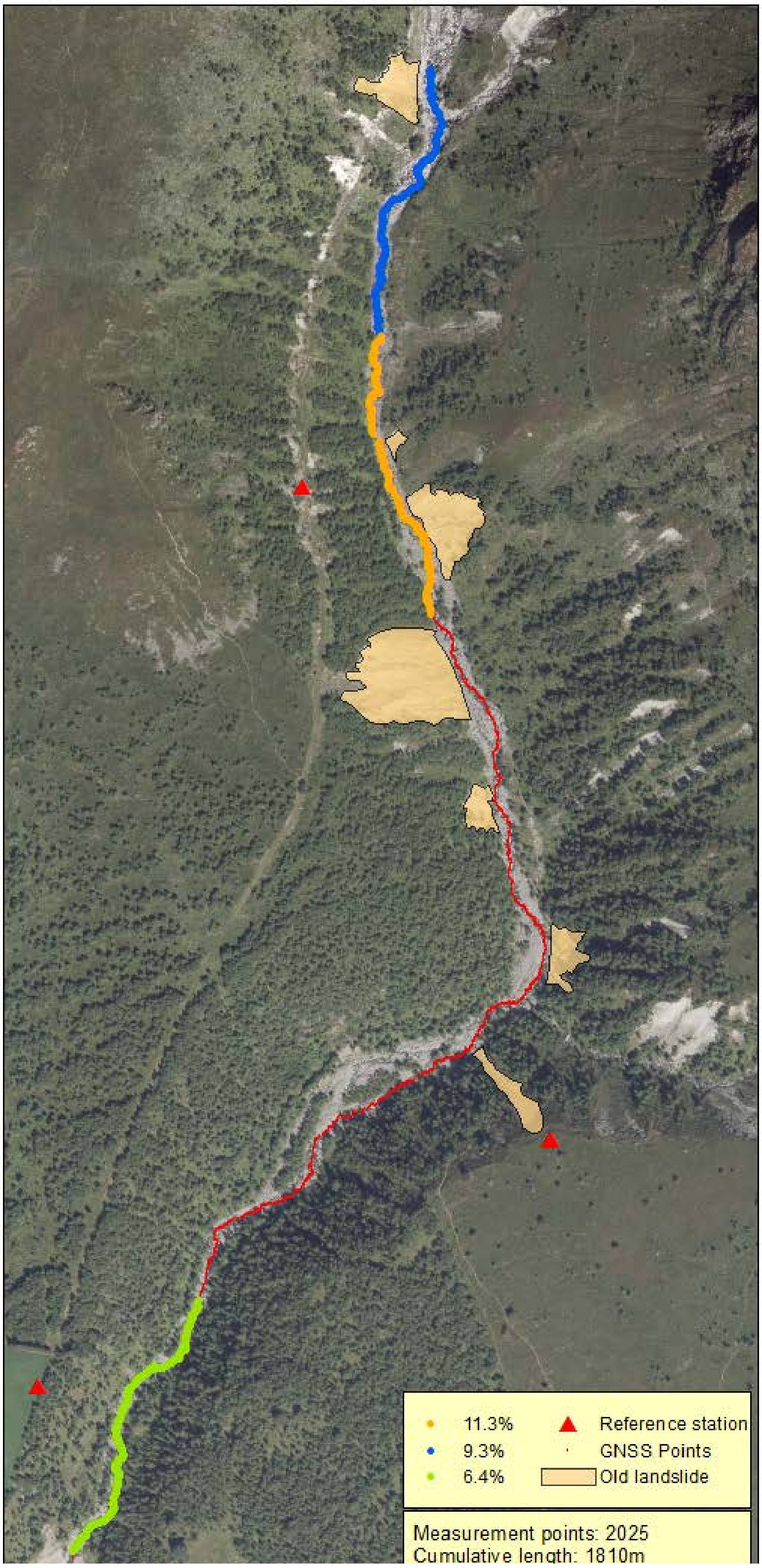


Figure 12: Orthophoto of Vekveselva overlain by the GNSS measurements, reference stations and locations of old sites of landslides.

5.1 LONGITUDINAL PROFILES

Three reaches were selected from the main long profile (fig. 12). These are all roughly 300 meters in length and will represent the bed morphology of different slope gradients varying from low, medium and high gradients. These will all be included in the following analyses to illustrate any varying statistics.

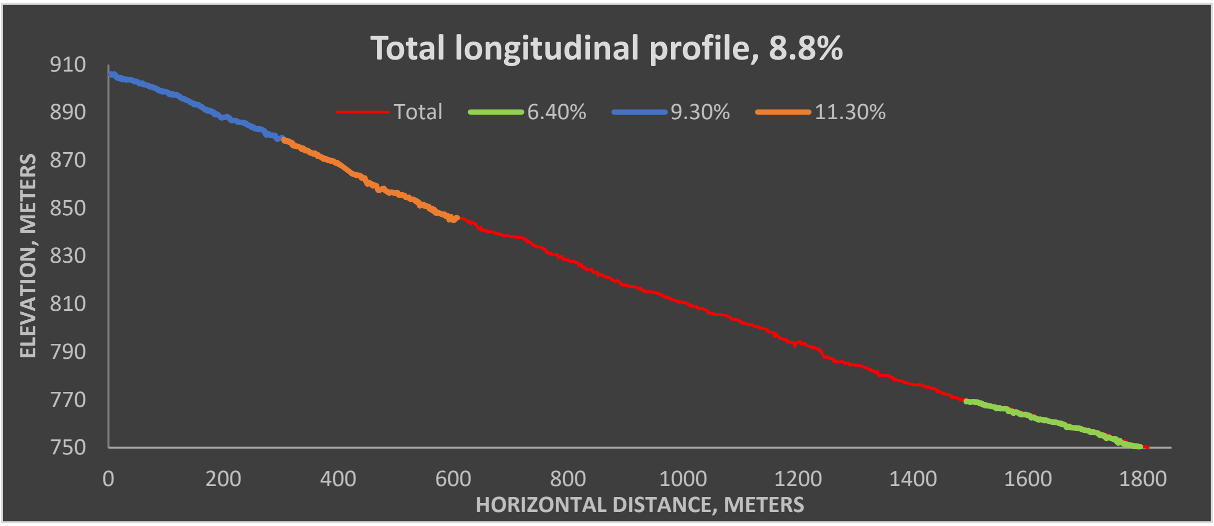


Figure 14: The total longitudinal profile has a cumulative length of 1810m and a total vertical drop of 156m. The profile is based on 2025 measurement points.

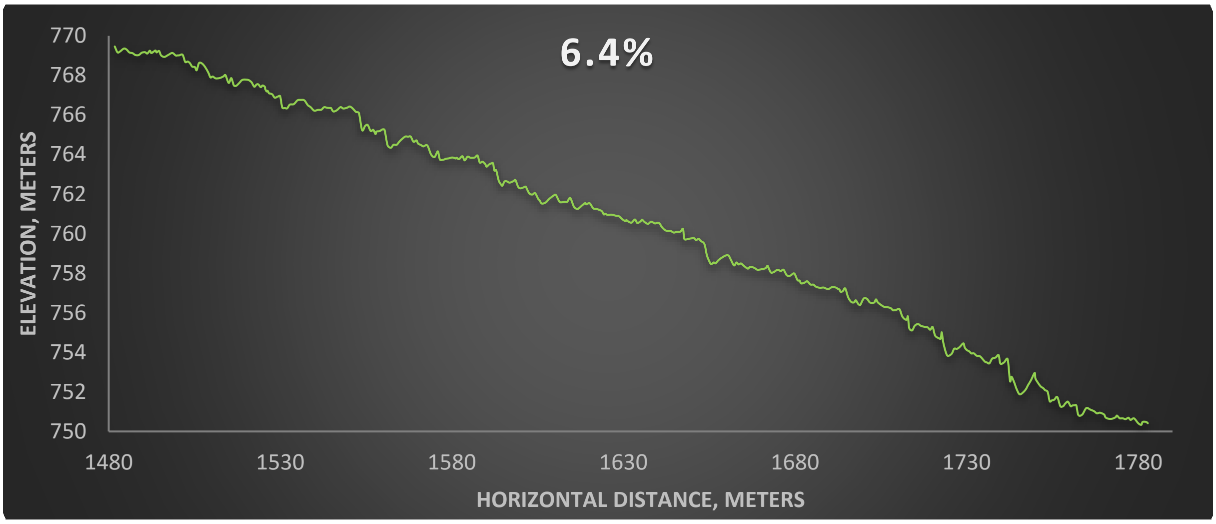


Figure 13: This profile has a cumulative length of 304m and a total vertical drop of 19m. The profile is based on 390 measurement points.

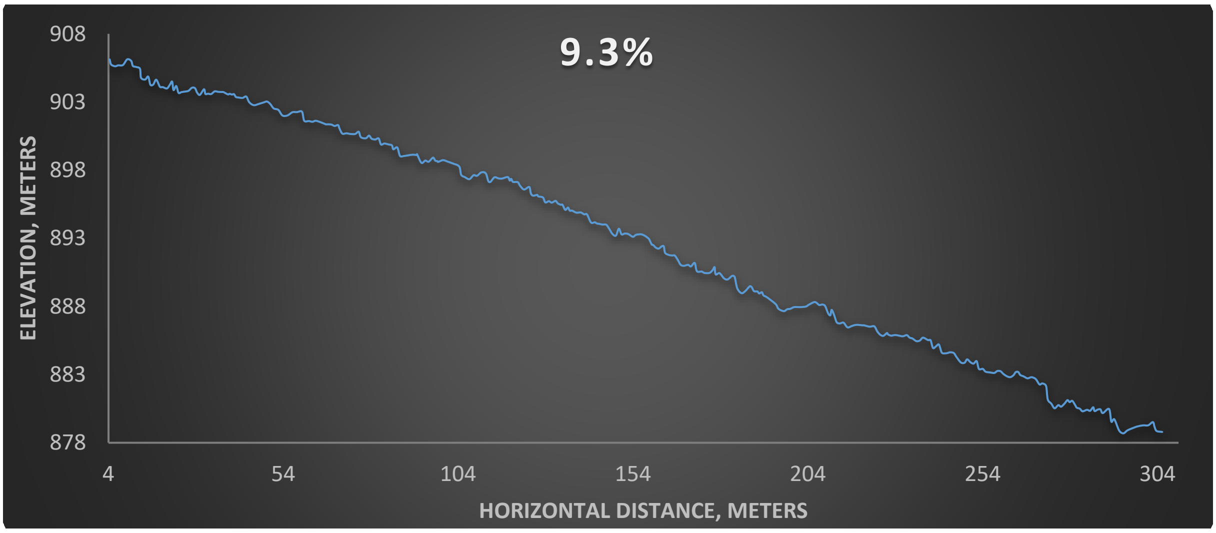


Figure 15: This profile has a cumulative length of 304m and a total vertical drop of 23.8m. The profile is based on 354 measurement points.

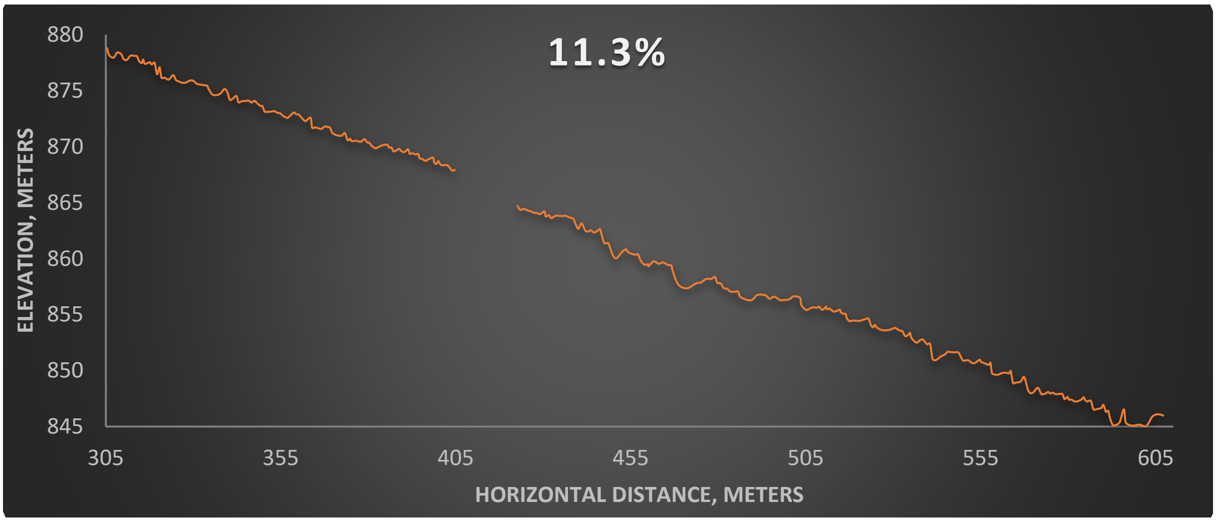


Figure 16: This profile has a cumulative length of 301.8m and a total vertical drop of 32.8m. The profile is based on 324 measurement points. The jump at 405m is a bedrock step that was not measured.

The steepest reach includes a jump of roughly 18 meters starting at around 405 meters where no measurement points were taken. This was a very large bedrock-step that was impossible to measure correctly and is not relevant to this study as a non-depositional formation. The measurement was continued some distance downstream of this location where normal bed morphology resumed. This jump has not been included in the following statistics or analyses.

5.2 MORPHOMETRIC STATISTICS

After setting the filtering rules defined in chapter 4, the algorithm identified 241 step-pool sequences and several variables were calculated for each sequence. Table 1 includes all calculated variables for the total longitudinal profile in addition to step-density for each of the selected study reaches.

Table 1: Descriptive statistics for each variable in the full longitudinal profile. All units except steepness is given in meters. Steepness is given in m/m. Multiply this value with 100 for the percentage slope value.

<table>
<tr><th></th><th>Step spacing</th><th>Pool length</th><th>Tread length</th><th>Step height</th><th>Resid. Depth</th><th>Step drop</th><th>Step steepness</th></tr>
<tr><td>Mean</td><td>5.99</td><td>3.82</td><td>4.31</td><td>0.67</td><td>0.27</td><td>0.54</td><td>0.11</td></tr>
<tr><td>Median</td><td>5.50</td><td>3.33</td><td>3.30</td><td>0.57</td><td>0.21</td><td>0.48</td><td>0.10</td></tr>
<tr><td>Std.dev.</td><td>3.54</td><td>2.32</td><td>3.21</td><td>0.35</td><td>0.26</td><td>0.35</td><td>0.09</td></tr>
<tr><td>Max</td><td>15.92</td><td>13.48</td><td>13.27</td><td>2.04</td><td>2.18</td><td>1.68</td><td>0.80</td></tr>
<tr><td>Min</td><td>1.07</td><td>0.34</td><td>0.14</td><td>0.17</td><td>0.01</td><td>-0.22</td><td>-0.05</td></tr>
<tr><td></td><td colspan="2">Total</td><td colspan="2">6.4%</td><td colspan="2">9.3%</td><td>11.3%</td></tr>
<tr><td>Step-density</td><td colspan="2">241 (0.133 m^{-1})</td><td colspan="2">39 (0.128 m^{-1})</td><td colspan="2">37 (0.123 m^{-1})</td><td>50 (0.165 m^{-1})</td></tr>
</table>

The 241 sequences cover 1445m (79.8%) of the total longitudinal profile, the rest of which can then be classified as “other”. 122 (50.6%) sequences contained a tread and the total tread length of 525m equals 29% of the cumulative length of the entire longitudinal profile. The total pool length of 920m equals 50.8% of the cumulative length. Step drop sums up to a total vertical drop of 129 meters and is responsible for 82.7% of the total vertical drop of the river. The remaining 12.7% elevation drop of the reach can be attributed to the 20.2% that is not classified as step-pools. Step height sums up to 160.6m and provides a vertical drop that is 4.5m larger than the elevation drop of the reach. Steeper reaches feature fewer step-pools and illustrate the increased necessity for a higher hydraulic resistance in steeper slopes.

Figure 17 displays the distributions of each calculated variable in histograms with fitted normality curves. None of the distributions pass the Shapiro-Wilk test for normality. The distribution of step spacing is right-skewed, and subchapter 5.6 will analyse whether this distribution can be fitted to a Poisson curve with any statistical significance. The relevance of this property will be discussed further in chapter 6.

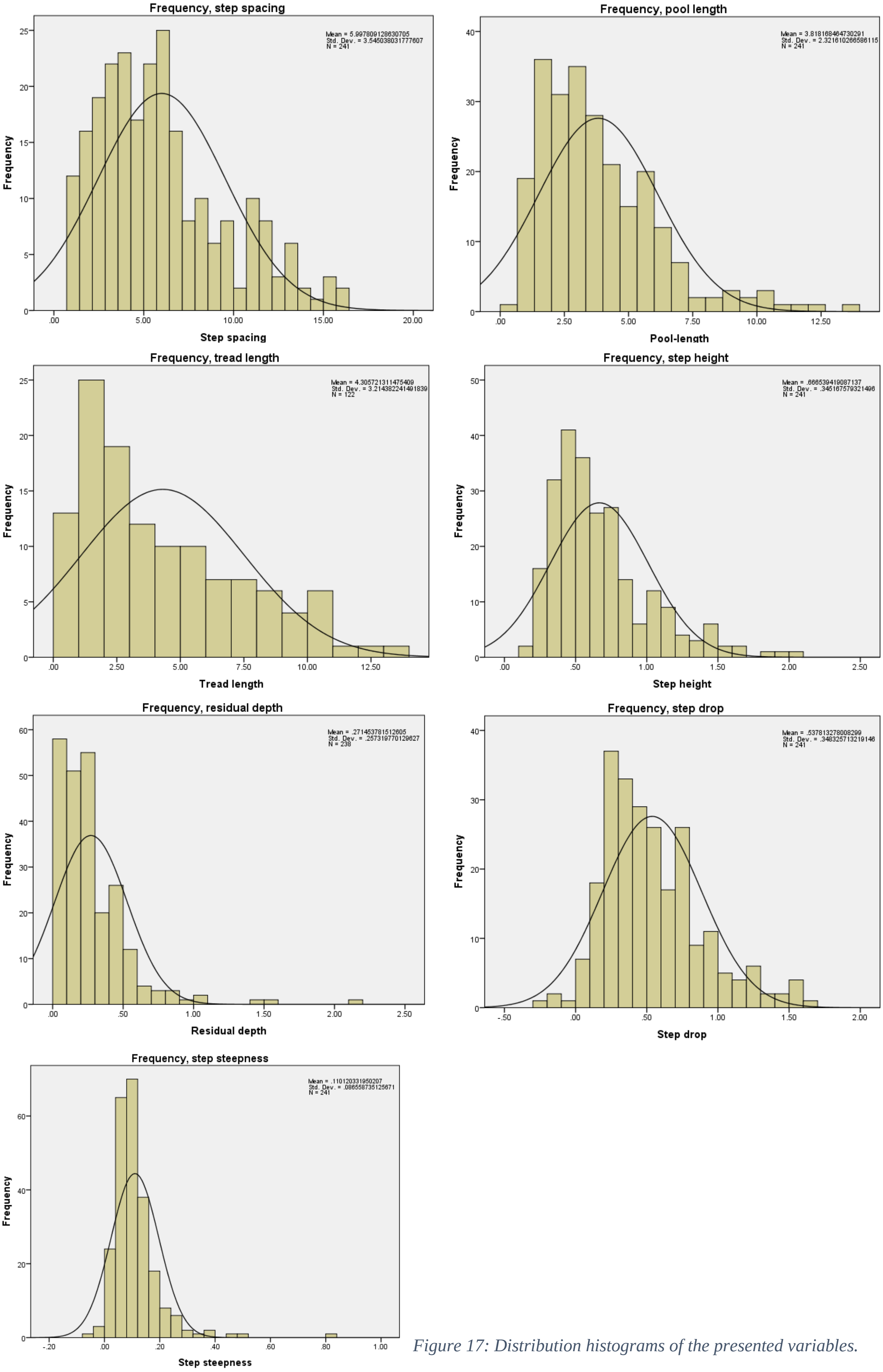


Figure 17: Distribution histograms of the presented variables.

Table 2 displays extensive descriptive statistics for each of the three selected reaches. Values in parenthesis show the percentage of that variable of the total length or height of the reach. Mean values for step spacing are smaller in the steepest reach compared to the least steep reach, suggesting that step spacing decreases with increasing slope. Mean values for step height and residual depth also increase with increasing slope, thus mirroring the hypothesis that increasing slope should feature larger steps and shorter spacings. Mean values for pool length also decrease with slope. Steeper slopes feature a larger coverage of step-pools, reflecting the density reported in table 1. The larger total step spacing values with increasing slope can be explained by having fewer identified step-pools longer than 16 meters. Statistical difference between the three reaches will be studied further via ANOVA tests in subsection 5.5.

Table 2: Descriptive statistics for each sub-reach of the total longitudinal profile. All units except steepness is given in meters. Steepness is given in m/m. Multiply this value with 100 for the percentage slope value.

Step spacing	**6.4%**	**9.3%**	**11.3%**
Mean	5.82	6.54	5.21
Median	5.60	5.74	4.57
Std.dev.	3.64	3.74	3.04
Max	15.10	15.93	13.85
Min	1.11	1.18	1.18
Total length	227m (74.7%)	241.8m (80.3%)	260.5m (86.3%)
Pool length	**6.4%**	**9.3%**	**11.3%**
Mean	3.93	3.82	3.59
Median	3.74	3.41	3.19
Std.dev.	2.36	2.23	2.26
Max	11.94	11.03	12.53
Min	0.93	0.98	0.99
Total length	153m (50.3%)	141m (46.8%)	179.4m (59.5%)
Tread length	**6.4%**	**9.3%**	**11.3%**
Mean	3.88	5.03	3.86
Median	3.16	5.30	2.99
Std.dev.	3.01	2.95	3.13
Max	9.97	10.01	10.96
Min	0.55	0.87	0.14
N	19 (48.7%)	20 (54%)	21 (42%)
Total length	73.7m (24.2%)	100.6m (33.4%)	81m (26.8%)

Step drop	6.4%	9.3%	11.3%
Mean	0.38	0.60	0.54
Median	0.35	0.52	0.52
Std.dev.	0.23	0.38	0.30
Max	0.89	1.56	1.13
Min	-0.03	0.07	-0.15
Total drop	15.5m (81%)	22m (81.5%)	26.8m (81.7%)

Step height	6.4%	9.3%	11.3%
Mean	0.53	0.66	0.73
Median	0.50	0.62	0.68
Std.dev.	0.24	0.30	0.37
Max	1.19	1.63	2.03
Min	0.20	0.25	0.18

Residual depth	6.4%	9.3%	11.3%
Mean	0.23	0.26	0.30
Median	0.21	0.19	0.23
Std.dev.	0.20	0.18	0.29
Max	1.08	0.82	1.43
Min	0.02	0.02	0.01

Step steepness	6.4%	9.3%	11.3%
Mean	0.10	0.11	0.12
Median	0.07	0.10	0.11
Std.dev.	0.13	0.09	0.07
Max	0.80	0.50	0.39
Min	-0.01	0.02	-0.03

5.3 COMPARING RESULTS

Parts of my study area overlap with studies by both Mevik (2013) and Volden (2015). Morphometric mean values were compared with the former, but not the latter study due to a limited study area. My profile contains 1154 measurement points in this area and spans about 1000m in length. The same study area in Mevik (2013) contains 466 measurement points, but is only 756m in length due to some areas that was skipped due to poor signal. My study has identified 129 step-pool sequences in this area, compared to 89 sequences in Mevik (2013). Difference in percentage is shown in parenthesis (table 3).

Table 3: Morphometric values of the overlapping study area. All units are given in meters.

	Step spacing	Pool length	Step height	Resid. Depth	Step drop
Mean	6.34	3.90	0.63	0.26	0.52
Max	15.72	13.48	1.94	2.17	1.68
Min	1.11	0.34	0.17	0.01	-0.22
Mevik 2013					
Mean	6.5 (2.5%)	4.5 (15%)	0.75 (19%)	0.27 (3.8%)	0.48 (-7.7%)
Max	17.1	13.8	2.3	1.2	1.5
Min	2.2	1.1	0.15	0.02	0.01

5.4 CORRELATION ANALYSES

Correlation analyses are a useful tool to study the relation between two continuous variables. By using Pearson Product Moment correlation coefficient (Pearson r) one can quantify the relation between two variables on a scale of -1 to +1 that illustrates the direction and strength of the linear relation (Boston University, 2013). If there is a strong positive correlation between two variables, a positive change in one variable should incur a positive change in the other. While correlation analyses can indicate a relation, they cannot prove that the correlation is caused by actual causal relations. The presented variables have been chosen carefully, and are relations that are commonly presented in other literature.

To interpret the effect of a correlation I will refer to the guidelines of Cohen (1988). R-values above 0.5 can be considered large, while values above 0.3 and 0.1 can be considered medium and small, respectively. The effect size convention of Cohen (1988) illustrates the visual impact of a correlation. Classification of strength is a source of debate, and the classifications must be considered with great care. The following subsections will present the results of the correlation analyses applied on both the entire longitudinal profile and each of the three sub-reaches of the stream. Significant correlations will be presented in scatter plots with a regression line for visualization. The regression line is fitted to the data in a manner that causes the least amount of error by a least square method. The regression analyses also produce an R^2 value that indicate the proportion of change in one variable that is caused by another. The linear relationship R^2 is presented mostly as visualization, as direction and strength of a relation is of more interest and thus the correlation coefficient r is more relevant.

5.4.1 Total profile

Table 4 contains the correlation coefficient for all selected relations. The full table of correlations is provided in the appendix. Residual depth and step height is strongly correlated, and illustrates the erosional effect of increasing vertical drop. Step height is also strongly correlated with pool length, indicating that increasing vertical fall will increase both the depth and length of the pool. Slope is not significantly correlated to step spacing, which is opposite of what hydraulically controlled and regular step spacing should inhabit. Steepness does not feature a strong correlation to slope, which again is not indicative of regularity in step formation. Slope is generally poorly correlated to any variable, and might indicate that local morphology plays a larger part in step formation than dynamic adjustments to hydraulic resistance. Figure 18 and 19 displays the scatter plots for each significant relation.

Table 4: Correlations in the total profile.
Significance: (*) α = 0.05, (**) α = 0.01

Relation	R
Resid. depth – Step height	.636**
Pool length – Step height	.533**
Step spacing – Step drop	.556**
Step spacing- Steepness	-.401**
Slope – Step drop	.246**
Slope – Step height	.276**
Steepness – Slope	.212**
Step spacing – Step height	.196**
Slope – Step spacing	No sig.

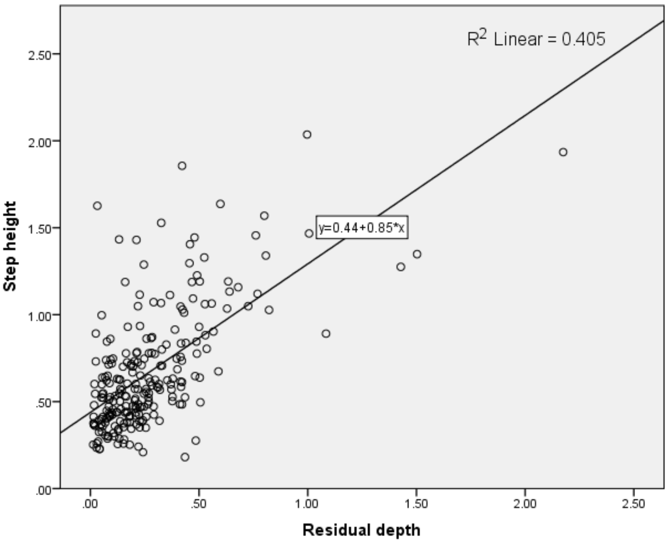


Figure 18: Regression plot for step height and residual depth. The linear relationship is medium strong.

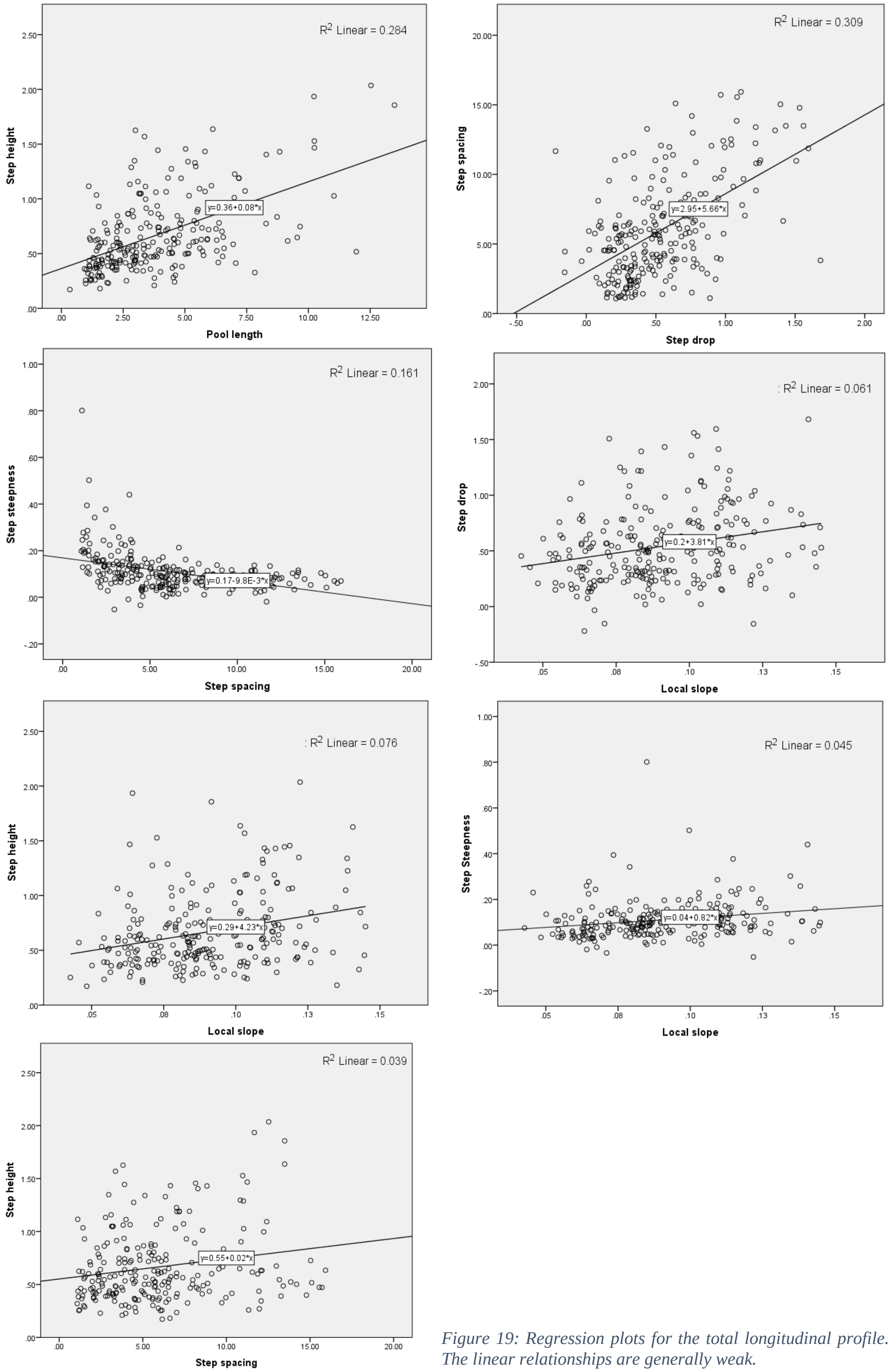


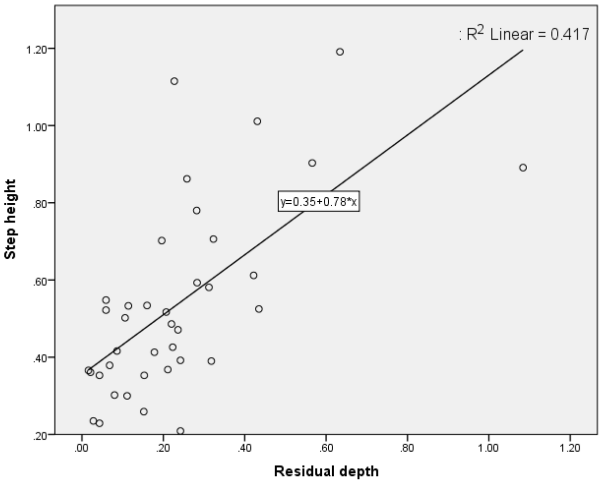
Figure 19: Regression plots for the total longitudinal profile. The linear relationships are generally weak.

5.4.2 6.4% local slope

Correlations are similar to the total profile (table 4), but local slope is only statistically significantly related to step height. A strong correlation between step height and residual depth reflects the increased erosion following higher vertical falls.

Table 5: Correlations in the 6.4% reach.
Significance: (*) α = 0.05, (**) α = 0.01.

Relation	R
Resid. depth – Step height	.646**
Step spacing – Steepness	-.411**
Step spacing – Step drop	.406*
Pool length – Step height	.401*
Slope – Step height	.399**
Slope – Step drop	No sig.
Steepness – Slope	No sig.
Step spacing – Step height	No sig.
Slope – Step spacing	No sig.



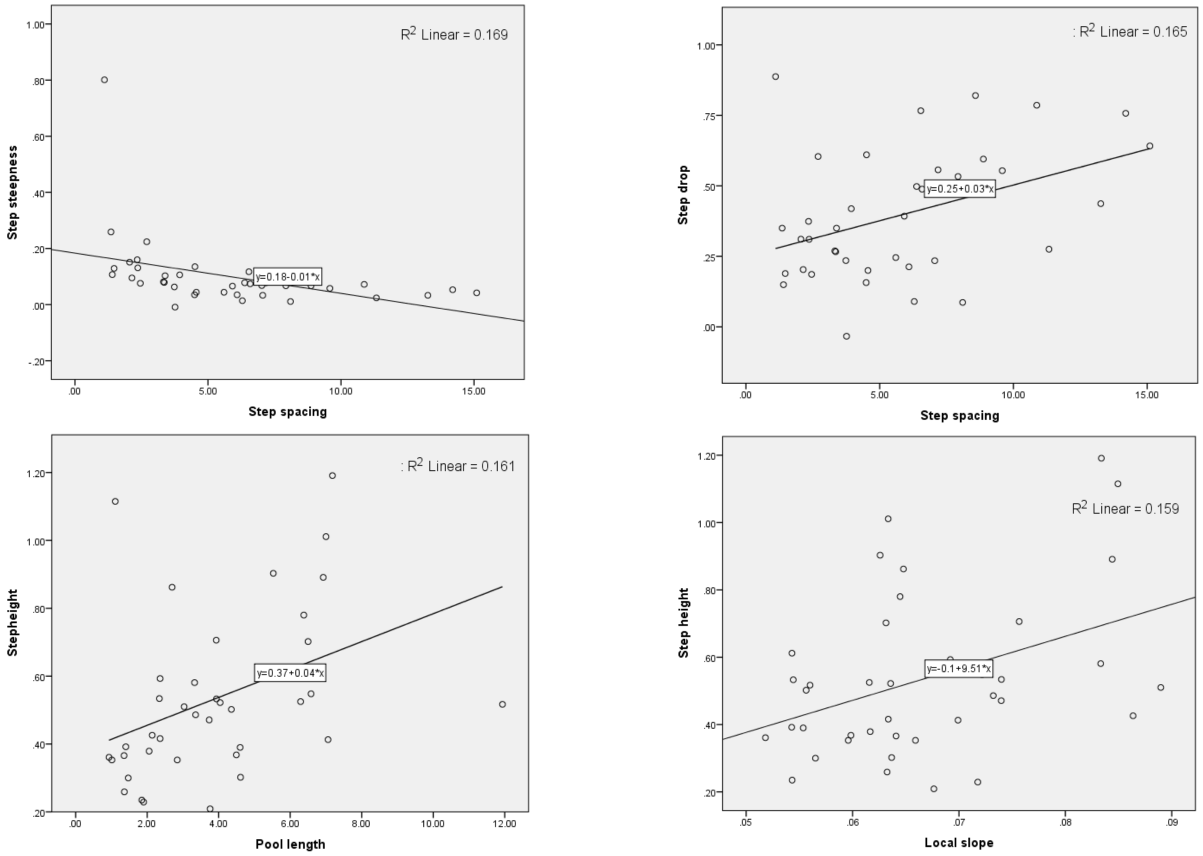


Figure 20: Scatter plots with a regression line for the 6.4% longitudinal profile. Step height – residual depth features the strongest linear relationship (R^2) in this reach.

5.4.3 9.3% local slope

Slope is not significantly related to any other variables. Step height features medium to strong correlation with pool length and residual depth, reflecting the increased erosional effect of higher vertical falls.

Table 6: Correlations in the 9.3% reach.
Significance: (*) α = 0.05, (**) α = 0.01.

Relation	R
Step spacing – Step drop	.664**
Pool length – Step height	.544**
Resid. depth – Step height	.436**
Step spacing- Steepness	-.379*
Step spacing – Step height	.347*
Slope – Step height	No sig.
Slope – Step drop	No sig.
Steepness – Slope	No sig.
Slope – Step spacing	No sig.

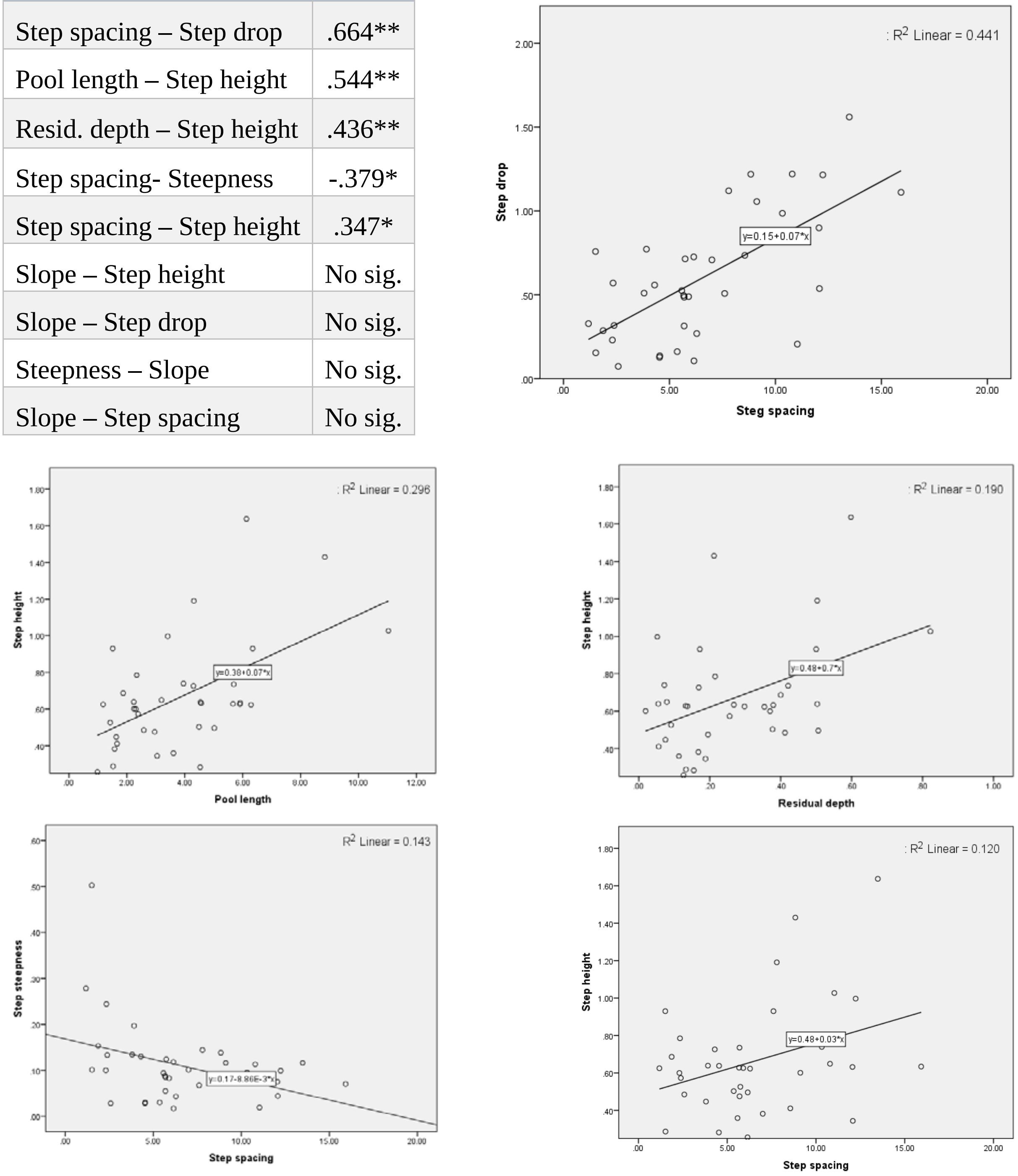


Figure 21: Scatter plots with a regression line for the 9.3% longitudinal profile. Step spacing – step drop features the strongest linear relationship (R^2) in this reach.

5.4.4 11.3% local slope

The reach features no significant relations to local slope. Step height is strongly correlated to residual depth and pool length. These correlations are stronger in this steepest reach than the two less steep reaches, perhaps reflecting an increased necessity for hydraulic resistance.

Table 7: Correlations in the 11.3% reach.
Significance: (*) α = 0.05, (**) α = 0.01.

Relation	**R**
Resid. depth – Step height	.731**
Pool length – Step height	.722**
Step spacing – Step drop	.624**
Step spacing – Steepness	-.454**
Step spacing – Step height	.318*
Slope – Step drop	No sig.
Steepness – Slope	No sig.
Slope – Step height	No sig.
Slope – Step spacing	No sig.

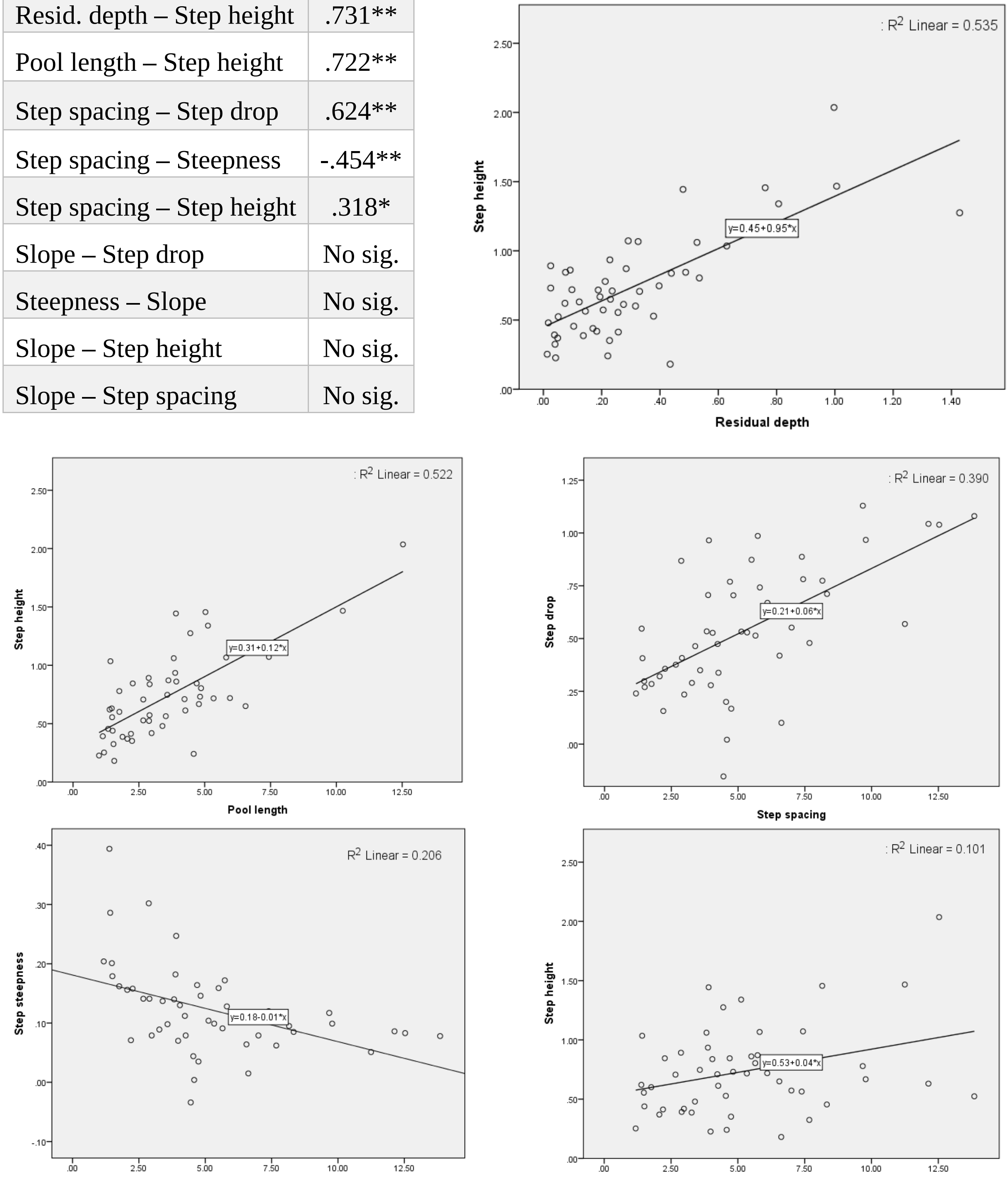


Figure 22: Scatter plots with a regression line for the 11.3% longitudinal profile. Step height – residual depth and step height – pool length feature the strongest linear relationships (R^2) in this reach.

5.4.5 Summary of correlations

Correlations between variables remain somewhat similar between the different reaches, however variance between reach slopes must be studied via ANOVA tests (See section 5.5). Table 8 provides a summary of the correlation analyses. The strongest correlations are found between step height and both residual depth and pool length on all reaches. None of the reaches featured a significant correlation between slope and step spacing. Only the total longitudinal profile featured a statistically significant correlation between slope and step steepness. A medium strong inverse correlation between slope and step height was found on the total longitudinal profile and the 6.4% section. Full tables of correlations for each sub-reach of Vekveselva are provided in the appendix.

Table 8: Summary of correlation analyses. Significance: (*) α = 0.05, (**) α = 0.01.

	TOTAL	6.4%	9.3%	11.3%
Residual depth – Step height	R = .636** R^2= 40%	R = .646** R^2= 42%	R = .436** R^2= 19%	R = .731** R^2= 53.5%
Pool length – Step height	R = .533** R^2= 28%	R = .401* R^2= 16%	R = .544** R^2= 29.6%	R = .722** R^2= 52%
Step spacing – Step drop	R = .556** R^2= 31%	R = .406* R^2= 16.5%	R = .664** R^2= 44%	R = .624** R^2= 39%
Step spacing - Steepness	R = -.401** R^2= 16%	R = -.411** R^2= 17%	R = -.379** R^2= 14%	R = -.454** R^2= 20%
Slope – Step drop	R = -.246** R^2= 6%	No sig	No sig.	No sig.
Slope – Step height	R = -.276** R^2= 7.6%	R = -.399** R^2= 16%	No sig.	No sig.
Steepness – Slope	R =.212** R^2= 4.5%	No sig.	No sig.	No sig.
Step spacing – Step height	R =.196** R^2= 3.9%	No sig.	R = .347* R^2= 12%	R = .318* R^2= 10%
Slope – Step spacing	No sig.	No sig.	No sig.	No sig.

5.5 ANALYSIS OF VARIANCE

One-way ANOVA is a statistical tool used to determine whether the means of three or more independent groups feature any statistically significant differences. ANOVA can be used to see if any morphometric values within step-pools change with any statistical significance between the three selected reaches. The reaches are set as group variables, and all variables are tested against the different groups. The results of the ANOVA tests show that only step height and step drop are statistically different between groups, but the results in table 9 cannot tell us which groups are different.

Table 9: Results of the ANOVA tests show that some groups feature a statistically significant difference in step height and step drop values.

ANOVA	Significance (α=0.05)
Step spacing	0.211
Pool length	0.773
Tread length	0.382
Step height	0.014
Residual Depth	0.388
Step drop	0.015
Step steepness	0.559

5.5.1 Post-hoc test

A post hoc test is necessary to identify the statistically different group variables. This test was run on both step height and step drop. The Bonferroni correction was applied as adjustment method. This is a relatively simple and general method, and works well for data that is not normally distributed (Taylor, 2017). Table 10 displays the results of the post-hoc test. Mean step height values are statistically significantly different between the 6.4% reach and the 11.3% reach. Mean step drop values are statistically significantly different between the 6.4% reach and the 9.3% reach. These results are discussed further in chapter 6.

Table 10: Results from post-hoc tests reveal that step height is statistically different between the 6.4% and 11.3% reaches. Step drop is statistically different between the 6.4% and 9.3% reaches. Significance: (*) α = 0.05, (**) α = 0.01.

Post-HOC (Bonferroni): Step height		
Group A	Group B	Significance
6.4%	9.3%	0.238
	11.3%	0.011**
9.3%	6.4%	0.238
	11.3%	0.905
11.3%	6.4%	0.011**
	9.3%	0.905

Post-HOC (Bonferroni): Step drop		
Group A	Group B	Significance
6.4%	9.3%	0.015**
	11.3%	0.113
9.3%	6.4%	0.015**
	11.3%	1.000
11.3%	6.4%	0.113
	9.3%	1.000

5.6 SPATIAL DISTRIBUTION

5.6.1 Statistical fit to a Poisson distribution

Curran and Wilcock (2005) fitted a modified Poisson distribution to step spacing data from several published studies and found a striking correspondence which suggests that step deposition should be equally likely along any location on the bed. This supports the jammed state hypothesis from Zimmermann and Church (2001) in which the creation of steps is governed by the random deposition of keystones whereby smaller grains will accumulate to form a step, rather than controlled and regularly deposited at preferred locations by hydraulic and geomorphic interactions. To replicate these results, a Poisson distribution was fitted to the distribution of step spacings identified by the algorithm, but the statistical fit of the distribution was not significant ($p = 0.144$ at $\alpha = 0.05$) using the Kolmogorov & Smirnov goodness of fit test (fig. 23). These results suggest that the distribution of steps is not fully random and that some spatial pattern should exist.

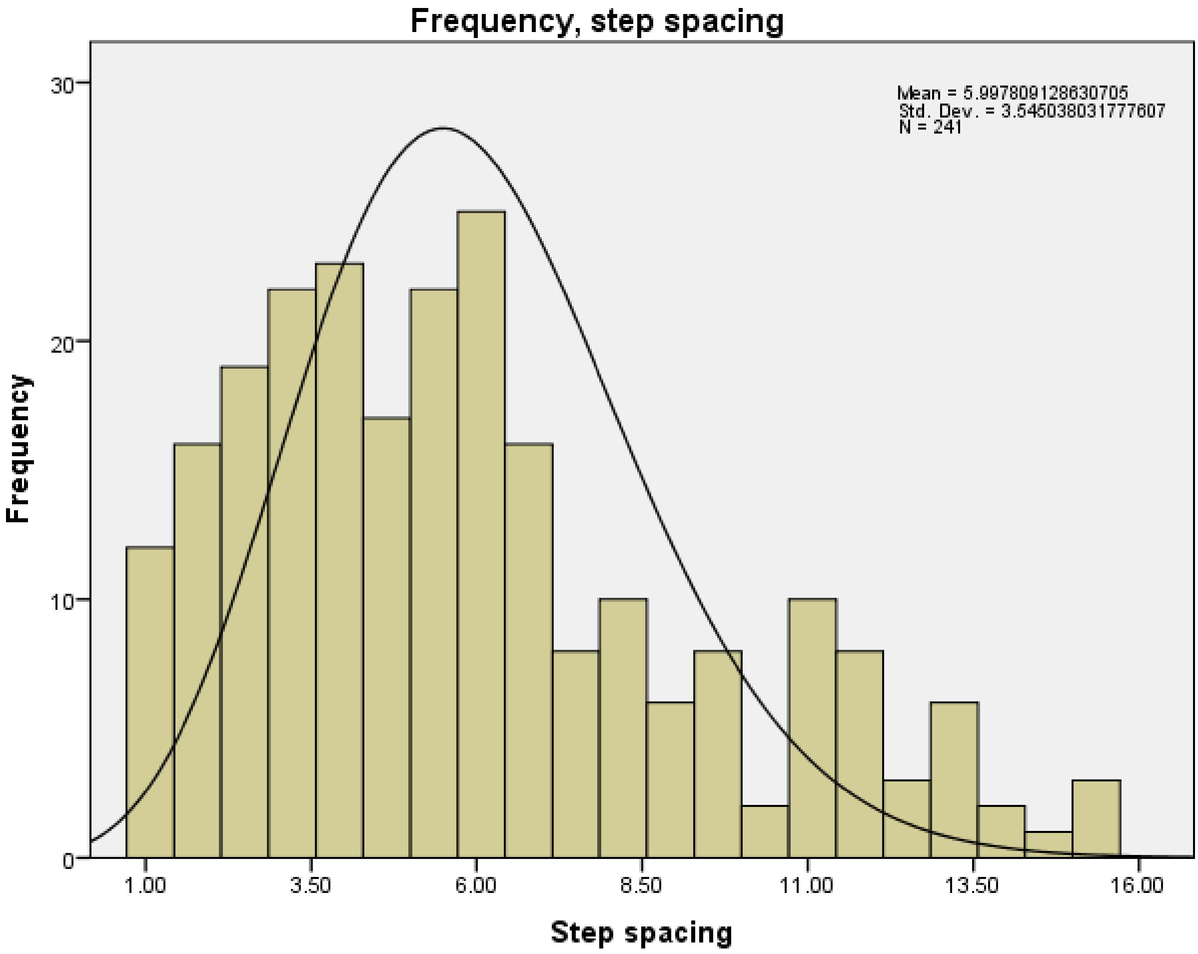


Figure 23: Frequency of step spacings with a fitted Poisson distribution. The statistical fit of the Poisson distribution is non-significant.

5.6.2 Ripley's K function

The Multi-Distance Spatial Cluster Analysis (Ripley's K) tool in ESRI ArcGIS was utilized to analyse the occurrence of any spatial pattern in the data. Figure 24 illustrates the results of this tool applied on the point locations of every step in the longitudinal profile. The results mirror the Poisson distribution in figure 23 wherein a fully random distribution cannot be proven. This distribution is heavily affected by an apparent clustered pattern at neighbourhood distances up to 230 meters after which the distribution is more dispersed than what a random distribution would entail. The clustered pattern is statistically significantly different from the expected K.

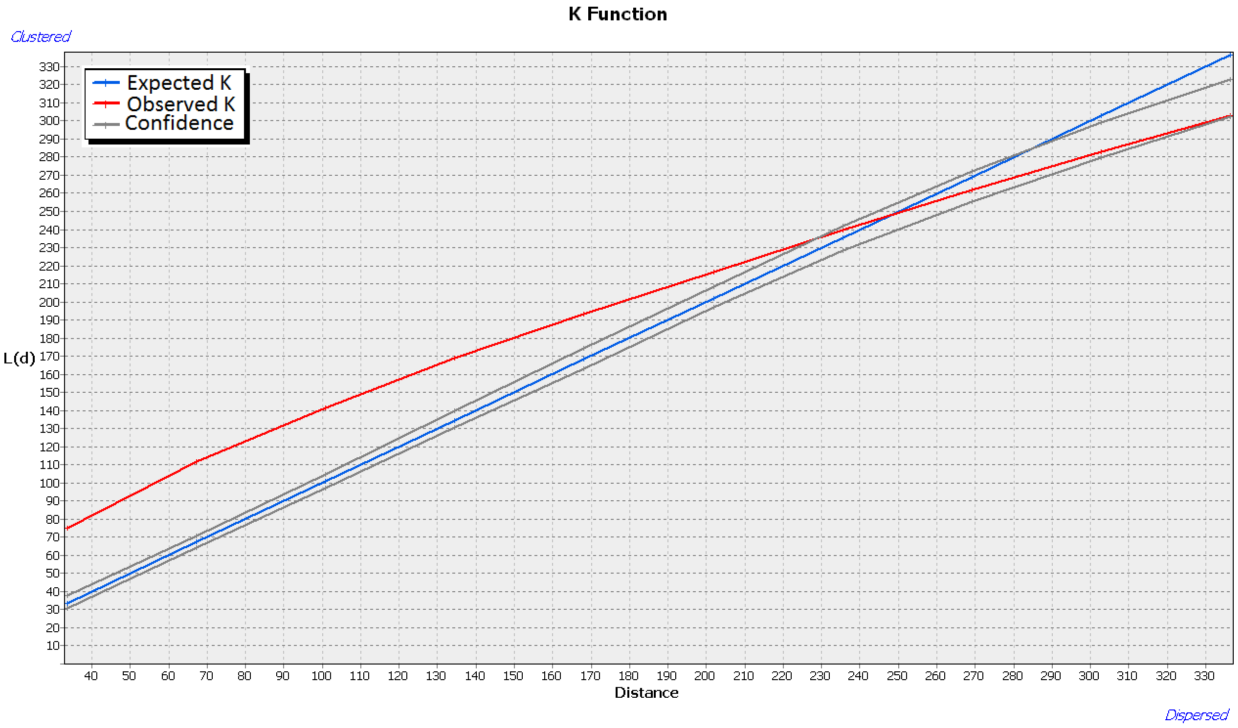


Figure 24: Results of Ripley's K function applied to the step spacing data. Deviation of the observed K from the expected K indicates a more clustered or dispersed pattern than that of a fully random distribution. Grey lines represent the upper and lower confidence envelopes, and deviation from these represent a statistically significant deviation from the expected K.

This analysis cannot show where or why a pattern emerges, but it illustrates that the distribution of steps in Vekveselva is not a result of totally random deposition. It is, however, important to note that this does not imply that the distribution is in any means regular, but it does illustrate that local conditions appear to affect the development of step-pools.

5.6.3 Downstream distribution

Figures 25 and 26 illustrate how step height and step spacing values change with downstream distance. The relations are weak, and the variables do not appear to change systematically with downstream distance.

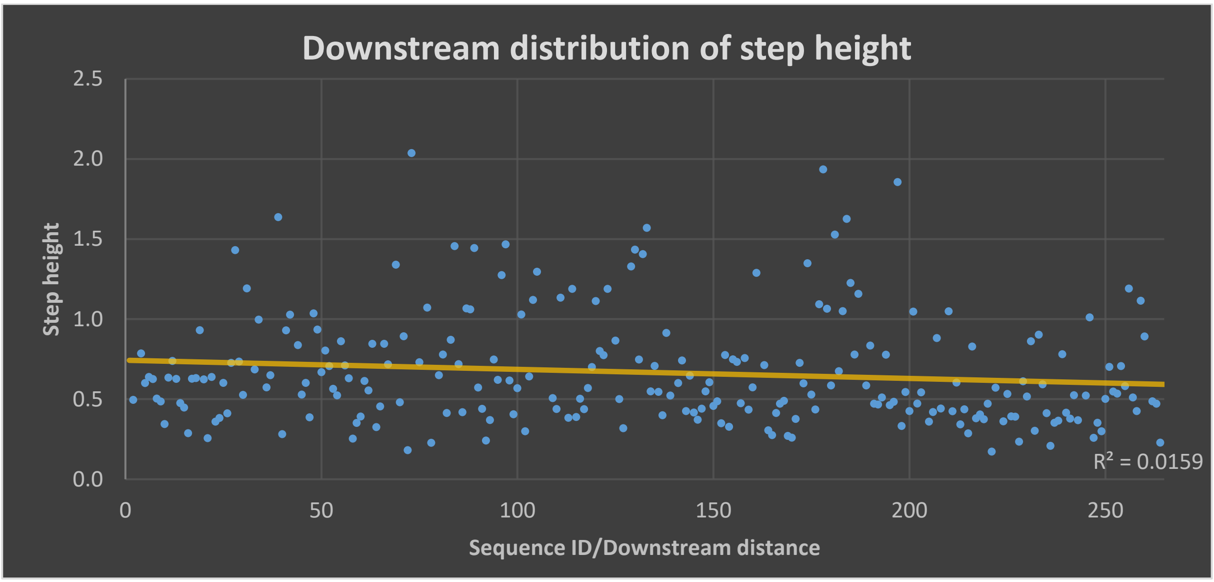


Figure 25: The distribution of step height values in downstream direction. The correlation between decreasing step height and downstream distance is weak.

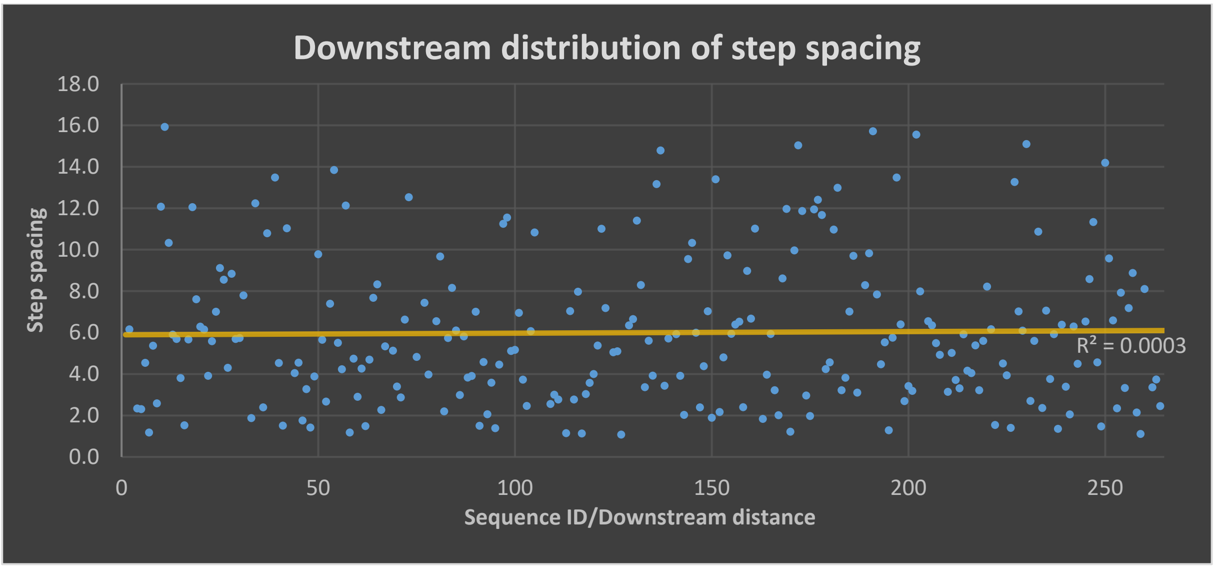


Figure 26: The distribution of step spacing values in downstream direction. The correlation between increasing step spacing and downstream distance is non-existent.

5.7 SUMMARY OF RESULTS

- The fieldwork produced a detailed longitudinal profile with 2025 measurement points over 1810 meters from which the applied algorithm identified 241 step-pool sequences and calculated several morphometric parameters. Three 300m stretches were selected based on their local slope and the same morphometric calculations and analyses were performed on them.
- Mean values compared with Mevik (2013) were found to be quite similar, with step spacing and residual depth being within 2.5% and 4% of each other, respectively. Pool length and step height was 16% and 19% higher than mine.
- Very strong correlations between residual depth and step height were found for all studied reaches except for the medium steep reach where the correlation was less strong.
- Step height was found to be strongly correlated with pool length, with increasing reach-scale slope featuring increasing strength of correlation. Pool length was also found to be medium to strongly correlated with residual depth.
- Local slope was found to be poorly correlated to step spacing, step steepness, step height and step drop on all reach scales. The exception was a medium sized correlation between step height and slope on the 6.5% reach.
- ANOVA revealed a statistically significant difference in step drop and step height values between the three selected reaches. Step height was statistically different between the 6.4% reach and the 11.3% reach. Step drop was statistically different between the 6.4% reach and the 9.3% reach.
- The distribution of step spacing data could not be fitted with statistical significance to a Poisson distribution, and step formation could then not be illustrated as being the result of a fully random Poisson process.
- A statistically significant clustered pattern is shown via Ripley’s K at a wide range of neighbourhood scales and a more dispersed pattern is shown only at the largest scales.
- There is no systematic reduction in step height or increase in step spacing with downstream distance.

The relevance of these results will be discussed in the following chapter.

6 DISCUSSION

6.1 MORPHOMETRY

This chapter will discuss two of the three main objectives of this study; (1) the successful design and application of an automated system for identification of step-pools and (2) analysis of the geomorphometric data it provided. The latter objective will be discussed first. The following comparative study has been a reflection of the issues pointed out by Nickolotsky and Pavlowsky (2007) concerning the importance of standardizing measurements in step-pool morphology. Step spacing and step height is defined differently by different researchers and comparing these studies can be a challenging prospect. The definitions in this study will remain as they are, but any comparison to other studies will involve a degree of conversion of terms. Another issue presented is the apparent discrepancy in results between studies based on visual identification and studies based on automated systems. Automated systems will identify less "perfect" formations where relations are not always easy to interpret. Presented correlations are all statistically significant unless otherwise noted.

The study of geometric relations within step-pool systems is a common way of studying which variables control the deposition and morphology of these formations. Step height and step spacing are often presented as the most valuable morphometric variables in step-pools (Church & Zimmermann, 2007; Curran & Wilcock, 2005), and Curran and Wilcock (2005) goes as far as to assign step spacing as the predominant variable to describe step-pool morphometry, as step height has been shown to correlate directly to the size of the largest step-forming grain (Abrahams et al., 1995; Chin, 1999; Grant et al., 1990). Average step spacing values in studies tend to vary and has been reported as 2.56m (Grant et al., 1990), 4.59m, 6.30m (Zimmermann & Church, 2001) and as large as 16.71 (Nickolotsky & Pavlowsky, 2007). Step spacing values in the present study averages 6m. Step spacing is commonly suggested to be related to channel width and while no correlation analysis has been applied to study this, step spacings in this study average about 1.13 channel widths (5.3m) which is within the mean values of less than one to four channel widths reported by Chin and Wohl (2005). At mean slope values varying from 6.4% to 11.3%, my step spacing values appear within limits of similar studies (Chartrand & Whiting, 2000; Nickolotsky & Pavlowsky, 2007). Mean step spacing might appear to decrease with increasing slope as the literature suggests (Grant et al., 1990; Judd, 1963; Wooldridge & Hickin, 2002), but the correlation is non-significant and weak at r = .082, a result not unlike that of Nickolotsky and Pavlowsky (2007) and Chartrand and Whiting (2000). Curran and Wilcock (2005) suggested that step spacing is proportional to step steepness. This relation is shown to be medium strong in this study with r = -.401 and suggests that increasing step steepness will feature a decrease in step spacing.

A common attribute in step-pool geometry is the ratio between step spacing and step drop. Chin (1999) reports an average 10:1 step spacing to drop ratio on slopes ranging from 4-12% which is close to my results (11.1:1). Correlation between step spacing and step drop is strong at r=.556. This relation is also known as step steepness and is given by H/L. Average step steepness in this study is shown to be 11% with varying mean values ranging from 10% to 12.2% increasing with local slope. These values are all well within mean values of 6 – 20% presented by Chin and Wohl (2005). As H/L is considered an important geometrical relationship in step-pools there should also be a strong relationship between H/L and local slope if slope is indeed an important geomorphological factor in step-pool morphometry. This is shown to be a relatively weak correlation with r =.212. Results from other studies are ambiguous in this regard and reported values appear to vary heavily with region (Nickolotsky & Pavlowsky, 2007). This weak relation might be indicative of a stronger influence of the local morphology than strict hydraulic adjustments. The bed morphology of Vekveselva is very coarse, and hydraulics may play a lesser part in shaping the bed than in less coarse streams.

Abrahams et al. (1995) and Molnar et al. (2010) calculate step steepness (H/L) using step height instead of step drop, effectively defining the slope of the bed within each sequence. Abrahams et al. (1995) argued that step-pools evolve towards a maximum flow resistance and should feature a mean H/L that is slightly larger than the local slope (8.8%). This would imply that step-sequences contain pools with reverse slopes, thus causing the total vertical fall of water due to steps to exceed the total elevation loss of the reach. This was shown to be true in this study, with step height totalling a vertical drop of 4.5m higher than the total drop of the reach. Calculating steepness as step height/step spacing yields an average step steepness value of 15.5%, and further illustrates that Vekveselva on average contains pools with reverse slopes (Molnar et al., 2010).

The relation between step spacing and step height is statistically significant but weak at r =.196, and slightly higher at 11.3% slope with r =.318. These weak relations do not correspond with the strong relations reported in Chartrand and Whiting (2000), but is similar to the comparative study of Nickolotsky and Pavlowsky (2007). Step height was found to have a weak relation with slope at r =.276, which is unlike the strong correlation reported in Nickolotsky and Pavlowsky (2007) but similar to the results of Chartrand and Whiting (2000) and Wohl and Grodek (1994). The relation appears ambiguous once again, as with step spacing and H/L, and might suggest that the relation is caused by shared causal linkages and that slope is a secondary control. The size of the step-forming particle has shown promising correlations with both step spacing (Chartrand & Whiting, 2000) and step height (Chin, 1999), and increasing slope is commonly associated with larger depositional formations and discharge, which suggests a more primary control on step spacing and step height than slope alone. Step height can be expected to decrease with downstream distance if particle size is also considered to decrease with downstream distance (Chin, 1999). Step height does inhabit such a decreasing trend, but it is very weak at $R^2 = 0.015$. Step spacing might be expected to increase with decreasing particle size and thus also increase with downstream distance (Chin & Wohl, 2005), but the relation is practically non-existent at $R^2 = 0.0003$. Particle size does not always show a clear downstream trend, and trends in step height and step spacing downstream is probably more related to the variability of particle size than slope or location along a reach (Chin, 1999).

The above-mentioned morphometric variables are the most commonly referenced variables when discussing step-pool morphometry, but it is worth discussing some of the other variables presented in this study. Residual depth features a strong correlation with step height at r = .636. This relation is perhaps not surprising considering step height affects the distance water must travel vertically, thus increasing its erosional power on the river bed. At a glance, mean values for residual depth appears to increase with local slope, but this relation is not statistically significant and ANOVA shows no significant variation between the three selected reaches. The strong correlation between residual depth and step height is similar to Chartrand and Whiting (2000), but their study showed a strong correlation with between residual depth and slope. The correlation between residual depth and slope is weak and non-significant in this study (ref. appendix).

The results also show a strong relation between pool length and step height (r =.533). Step spacing is often thought to decrease with step height as mentioned earlier, perhaps due to limited space in steep reaches featuring very large steps (Church & Zimmermann, 2007). Well-developed pools will usually feature a deep initial scour pool ending with a reverse slope that eventually flats out to a tread. The pool will feature large hydraulic turbulence, the diameter of which will dictate the extent of erosion and deposition. It is reasonable to suppose that increasing energy following a higher fall will increase the size of the erosional effect, thus extending the pool to accommodate the increased amount of energy needing to be dispersed via erosion. Specific studies on pool length is not known to me, and no definition of maximum pool length is known. Step height has been shown to relate to the local particle size, which is further supposed to relate to channel slope and discharge (Chin, 1999). Pool length should then by extension be limited by a critical slope value, which has been shown to limit the length of step-pools in very steep slopes (Wohl & Grodek, 1994).

Tread is usually not placed under much focus in studies, but it is generally accepted that less steep slopes require fewer steps to provide hydraulic resistance (Abrahams et al., 1995), and longer treads should be a natural consequence of fewer steps to connect these formations. Tread does not show a significant correlation with local slope. The only noteworthy, although weak, relation with tread is pool length (r = -.293). As tread length increases, pool length appears to decrease, and reflects the observations in the previous section in which step height is strongly correlated with pool length. This can indicate that treads are longer in areas in which pools don’t have to be very large, i.e. less steep slopes. The actual causality of this relation can only be speculated upon, but it is worth noting.

My results were compared with those of Mevik (2013) as that is the closest study to mine in terms of scale of Vekveselva. Cutting my profile to start and end at the same location as her profile, the total length of her longitudinal profile was 244m shorter than mine and contained 688 less measurement points. She excluded some parts of the reach due to signal issues, and parts of the reach were challenging to measure for this present study as well, but accuracy was judged to remain within acceptable limits. My algorithm identified 129 sequences compared to her 89, and much of this difference can probably be attributed to the missing 244 meters. Mean values presented in table 3 are quite similar, with step spacing and residual depth being within 2.5% and 4% of each other, respectively. The classification scheme used in Mevik (2013) has a higher tendency to classify the last point in the sequence as the end of the pool, while I try to separate the pool and tread. The 15% larger mean pool lengths in her study might be a result of this difference in calculation. She refers to tread as *other* and does not separate it as a formation within a sequence. Mevik (2013) found step heights to be 19% higher than mine. This might be explained by a larger limit to minimum step spacing in her study, such that very small formations are more filtered than mine. It’s also entirely possible that the presented differences are caused by reorganization of the bed, but this cannot be tested at present.

6.2 REGULARITY

Regularity is perhaps the most commonly mentioned concept in step-pool literature, and there is no agreement on whether the hydraulic causes behind it are significant or not (Chin & Phillips, 2007; Church & Zimmermann, 2007). This ambiguity is in large part caused by the inability to prove or disprove either concept. Some patterns of regularity have been shown at various scales, but rarely at channel reach scales in the field spanning more than just a handful of sequences (Chin & Phillips, 2007; Church & Zimmermann, 2007; Curran & Wilcock, 2005; Grant et al., 1990; Molnar et al., 2010). Regularity in step formation should also imply predictability in step-pool dimensions, and one of the arguments for regularity is the observation of correlation between the main step properties height (H), length (L) and slope (S) (Chin & Wohl, 2005). Height is often the geometric referred to as step drop in this study, and the relation to step spacing should remain the same with increasing slope. Shortening and heightening of steps and increasing step-pool frequency has been shown to increase with slope for many years (Chin, 1999; Grant et al., 1990), and fits with the hypothesis of Abrahams et al. (1995) that steps adjust their spacing to create the maximum resistance to flow. The concept of hydraulically controlled deposition stems from the apparent regularity of formations via antidune configurations in alluvial rivers (Chin, 1999; Whittaker & Jaeggi, 1982). This effect appears to be reduced in rivers containing colluvial material, and step spacings are rarely seen to be regular over large distances (Molnar et al., 2010; Zimmermann & Church, 2001). Neither H, L, nor H/L relates strongly with slope in this study, and thus no trends of systematic relations can be illustrated.

The H/L/S relation presented in this study was statistically significant, but weak (r =.212). It can be argued that unless this relation is particularly strong it is largely meaningless, as there should always be some relation between these variables as a stream must inhabit the necessary step drop and spacing to reach its intended outlet. My algorithm splits a sequence into pool and tread, and it would be interesting to separate the pool and study how it relates to variables such as slope. The algorithm was adjusted to set step drop as the vertical distance between the top of the step and the end of the pool, and a step steepness H/L was calculated based on these new variables. Slope still relates poorly to step drop (H) (r =.302), pool length (L) (no sig.) and H/L (r =.145).

The effect of the step-forming particle appears in other studies to have a large effect on the main morphometric variables within sequences (Chartrand & Whiting, 2000; Church & Zimmermann, 2007), and the lack of any strong correlations with slope in this study might be a consequence of the unique composition of highly colluvial and perhaps permanent particles in Vekveselva. Abrahams et al. (1995) suggested that channels which feature a strong connection to glacial till or were formerly subject to glacial processes will often feature large debris that is too large to be moved by fluvial forces, and that they simply block the channel wherever they appear instead of being part of some hydraulic adjustment. Hydraulic forces during normal floods might not be able to deposit material wherever it’s deemed necessary, and deposition is more likely to be controlled by local conditions like channel size and random boulders in the vicinity. Vekveselva features material that appears to have been stationary for at least a hundred years, and it is unlikely that hydraulic forces are able to shape the bed to customize the bed roughness to a large degree. The Jammed State Hypothesis of Church and Zimmermann (2007) might be the more relevant concept of deposition in the case of Vekveselva, wherein the local conditions play the larger role in deciding deposition than hydraulic forces. The lack of strong correlations with slope reflects this.

Curran and Wilcock (2005) studied the results of 12 published studies of step-pools and found that the step spacings recorded in these studies could all be fitted with a Poisson distribution. The study concludes with this correspondence that step-formation is unlikely to be regular and a result of forced hydraulic deposition, and that other local factors are more relevant to deposition. This conclusion is shared by Molnar et al. (2010) who could not observe serial correlations beyond a few meters, but the study did suggest that individual step formation might not be fully random at some locations where local factors such as sediment supply and unique bed morphology can determine deposition. Milzow et al. (2006) was unable to match the observed distribution of step spacings with a random distribution, and could not conclude that deposition of steps was the result of a Poisson process where steps would be equally likely to be deposited at any location along the bed. This mirrors the results in this present study wherein the data could not be fitted with statistical significance to a Poisson distribution.

A Ripley’s K function was applied to the distribution of step spacings to study any spatial patterns. The results could not provide reason to assume that step deposition is a result of a random process. The distribution was heavily affected by a statistically significant clustered pattern at neighbourhood distances up to 230 meters after which the distribution was more dispersed than what a random distribution would entail, however the dispersed pattern was not statistically significantly different from the expected K (fig. 24). The distribution in figure 23 shows a larger density of small and large steps than the random Poisson distribution, and might indicate that smaller step-pools tend to cluster together and larger step-pools are more dispersed. Milzow et al. (2006) applied a similar analysis which compared the observed distribution with a random distribution and could conclude that the observed distribution did not correlate well to the random distribution, and that steps of similar sizes tended to be clustered together. This thesis has not studied local factors such as particle size or local bankfull width, and relations with local spatial patterns cannot be studied, but these factors could provide an interesting insight into local impacts on step-pool morphology.

Testing variance between groups of varying mean bed slope provided values of significance only for step height and step drop. Step height features a statistically significant difference between the 6.4% slope reach and the 11.3% slope reach, reflecting the observed increase in mean step height values between the two reaches. Step drop is statistically different between the 6.4% reach and the 9.3% reach, again mirroring the differences in mean values. This statistic is perhaps not particularly valuable, as longer step spacings generally will involve a larger step drop due to the way step drop is measured. The 9.3% slope reach features both the highest mean step spacing and thus also the highest mean step drop. The variance of step height is in line with the established theories that step height increases with slope, and is reflected, if somewhat poorly, in the relations between height and slope presented earlier. The presented variables in this study all related poorly with local slope, but this might be an effect of small sample sizes rather than actual causal processes. Local bed slope is calculated as a 30m window centred at each step, and is perhaps a weak variable that is too affected by rough topography. Several of the variables display apparent trends in mean values when comparing the different reaches, such as residual depth, H/L and step height, and while they are not deemed statistically different by ANOVA tests, it is worth noting that the values appear to change with slope.

6.3 AUTOMATIC IDENTIFICATION

One of the main goals of this study was to develop a method for automatic extraction of step-pools from a longitudinal profile and calculation of morphometry. This goal can be considered to have been achieved as the algorithm designed as part of this thesis is successful in identifying bed formations that when visually examined inhabit the same general morphometry and hydrological logic that step-pools are commonly defined to have. It is reasonable to assume that the algorithm produces geometrics that are reliable. In this regard, the algorithm also fulfils the sub-goal of achieving objectivity in step-pool identification. Some pitfalls involving automatic identification has been mentioned in the methodology chapter. One central issue is misidentification due to noise, erroneous measurement or simply as a natural consequence of the applied algorithm.

Both Milzow et al. (2006) and Zimmermann et al. (2008) apply a set of geometric rules to their algorithm to limit any unnatural extreme values. This was done sparingly in this study as it was not deemed necessary for this particular stream. This might very well be a poor decision, but Vekveselva is a particularly chaotic system with an abundance of extreme morphologies observable in the field. It did not seem reasonable to apply a maximum limit to step height or residual depth in this study, as it would remove values that appear to be true representations of real-world morphologies. Milzow et al. (2006) applied a maximum step height of 1.2m to remove steps created by either bedrock or colluvial material, but filtering of alluvial material was not an objective in this study. Several steps in Vekveselva inhabit residual depths of well over 1.2 meters and even larger step heights, and these are reflected in the presented morphometry. Zimmermann et al. (2008) defined step spacing as 2 times average bankfull width and would in my case produce a limit of 10.6 meters. For this study, I've applied a more liberal limit of 3 times the channel width for a maximum step spacing value of 16 meters. The literature presents step spacings within 1-4 channel widths (Chin & Wohl, 2005). The value of 3 was chosen to filter out some of the extreme sequences that has been evaluated to hold little value as step-pool formations. The 9 sequences without pools were also chosen to not be included in the analyses, as I did not deem them relevant to the study of step-pools.

The critical slope value on which the algorithm is based has not been customized for this study, and the value of 0.45 m/m might be too liberal or conservative for this particular river reach. Zimmermann et al. (2008) tested the critical slope method originally designed by Milzow et al. (2006) with the value of 0.45 in slopes of varying steepness and found the results to be very close to the results of manual identification in the field. The successful results in that study does not, however, exclude the fact that the concept on which steps are identified is not properly customized for Vekveselva. Identifications might therefore not be totally accurate, but extensive visual examination of results has judged the method to work well for both identification and morphometric calculation. Refer to Milzow et al. (2006) for details on how the critical slope value is calculated.

The algorithm was designed to be more advanced than Milzow et al. (2006) but mechanically simpler than Zimmermann et al. (2008) so that the entire code could be written and applied as an MS Excel Macro by a user with limited VBA knowledge. The algorithm designed by Milzow et al. (2006) would originally only identify the top and bottom of a sequence and then calculate the length and height between these two points, providing a very simple morphological map of a river that includes the two most referenced geometric parameters H/L. Zimmermann et al. (2008) provides a far more detailed picture of the bed morphology, but is also more complicated to write. The algorithm presented in this study can identify the pool in each sequence, providing far more morphometric information and handles point density better than the original method. Residual depth, pool length and tread length are examples of added morphometry, in addition to the very valuable separation of step height and step drop.

One important weakness of the critical slope method is acknowledged by both Zimmermann et al. (2008) and Milzow et al. (2006). The method will identify the entire river reach as a chain of sequences. It assumes that the system is a continuous chain of steps and pools with few or no treads between. This is rarely the case in nature except perhaps on very steep slopes (Church & Zimmermann, 2007). Because this algorithm can identify pools it can also identify any remaining tread in the sequence, which is a valuable attribute, but the step spacings might get extremely long in areas with few significant steps. The method cannot identify a logical end to a step-pool if no critical slope is found. The maximum identified step spacing must either be accepted or filtered after identification as a non-relevant formation. This adds a subjective decision that might not be wanted. The algorithm originally identified 22 sequences longer than 16m, with the largest sequence at a length of 32m. These sequences contained little valuable information other than the apparent lack of pronounced steps in the area, and it was decided to filter these based on values presented in available literature. The ability to define a logical end to a formation and classify everything else as *other* is a valuable advantage of the method of Zimmermann et al. (2008).

Methods for automatic extraction of step-pools from a longitudinal profile will become a highly valuable tool for comparative studies if these methods become more widespread and rules of measurements can be defined. Automatic methods have been presented for over a decade (Milzow et al., 2006; Wooldridge & Hickin, 2002; Zimmermann et al., 2008), but comparative studies are still challenging due to different methods of identification and measurement by different researchers. Comparing results from automated extraction with results from visual extraction can often seem like a lesson in bias wherein the visually identified steps can appear too “standard” or “perfect” to be applicable to other results. Neither method provides a more accurate description of step-pools, but comparing the results can turn out to be more confusing than enlightening. Automated identification will include more information than a researcher in the field might choose to include, but visual identification might include less of the noise provided by an algorithm. Regardless of the discrepancy between subjective and objective methods, the main issue in step-pool research still appears to be any lack of standardized methods for measuring morphometric variables. The importance of this is presented in Nickolotsky and Pavlowsky (2007) and Zimmermann et al. (2008).

7 CONCLUSIONS

This thesis presented three main objectives, all of which are considered achieved with successful results. (1) A longitudinal profile of sufficient size to provide statistical weight to the morphometrical data was produced. (2) An algorithm was successfully designed that automatically identified bed formations and calculated morphometry within each sequence. Lastly, (3) a detailed analysis of geometric relations and patterns of regularity provided the means to draw conclusions on step-pool morphometry in Vekveselva.

The introduction further presented two main hypotheses.

1. Step height does not feature a strong inverse proportional relation to step spacing, and step spacing does not feature a strong proportional relation to slope.
2. Thus, there are no apparent patterns of regularity in step-pool formations in Vekveselva.

This study concludes that step height does not feature a strong inverse proportional relation to step spacing, and step spacing does not feature a strong proportional relation to slope. This indicates non-regularity in step formation. Some patterns in spatial distribution were observed, but spatial analyses could not prove systematic regularity in step-formation.

The main findings of this study can be summarized as follows.

- The observed distribution of step spacing values was found to be statistically different from an expected random distribution of step spacing values, indicating that step formation is not a result of a random process. Additionally, step spacing values was found to be statistically significantly different from an applied Poisson distribution.
- Non-randomness was illustrated on medium to small spatial scales where a clustered pattern of step-pools was observed. A dispersed pattern was observed on larger spatial scales. Patterns like these indicate that step-formation on some scales are controlled by systematic processes rather than a Poisson process.
- Regularity could, however, not be illustrated as a systematic trend at reach scale, as mean values of step drop (H), spacing (L) and slope (S) were not strongly correlated, and no reduction in step height or increase in step spacing could be observed with downstream distance.

- Step height was shown to be statistically different between the least and most steep 300m sections of the study area, but step spacing values were not statistically significantly different between the two reaches, thus further indicating that step spacing is not solely controlled by hydraulic forces and thus not systematically controlled.
- Weak relations with slope indicate that some step locations are likely defined by jamming at the chance location of large keystones. Coarse glacial till appears to negate any large-scale patterns of regularity.
- Residual depth and pool length is strongly correlated with step height, and pools on average contain reverse slopes, indicating high hydraulic resistance along the stream bed, which combined with a coarse bed structure further indicates strong bed stability.

I remain hopeful that the scale of this fieldwork will inspire future students to replicate or even expand upon this work, so that future studies of Vekveselva can involve both large datasets and timescales, so that the effect of time can be studied with some statistical significance. Vekveselva still has a lot of research potential that can complement the library of information on this stream. Generally, studies of a larger spatial and temporal scale should be performed.

Some suggestions of future studies of Vekveselva include:

- More longitudinal profiles should be created to study the effects of time. Fieldwork could be started earlier to produce two profiles from which the effects of a year could be studied. The effects of longer periods can be studied as more longitudinal profiles are created by different researchers.
- The size of the keystone in each step and its relation to other morphometric variables within the step should be studied on a large scale to see how relations compare to ratios presented in the literature. This is a particularly interesting relation in Vekveselva due to the large glacial deposits featured on the bed.
- Step-pool morphometry, including the size of the step-forming clasts, can be studied in relation to the distance to the nearest upstream naked hillslope to study the stationarity of material provided from old landslides.
- The Jamming Ratio of Church and Zimmermann (2007) could be tested on a large scale to study how the channel width and keystone relates.
- Local channel width can be studied in relation to local morphology and morphometry, and particularly local particle sizes.
- Local particle sizes can be analysed on a large scale to study if there is a systematic change in bed particle sizes or step forming clasts with slope or downstream distance. This can be studied along with step-pool morphometry to study the effect of downstream distance.

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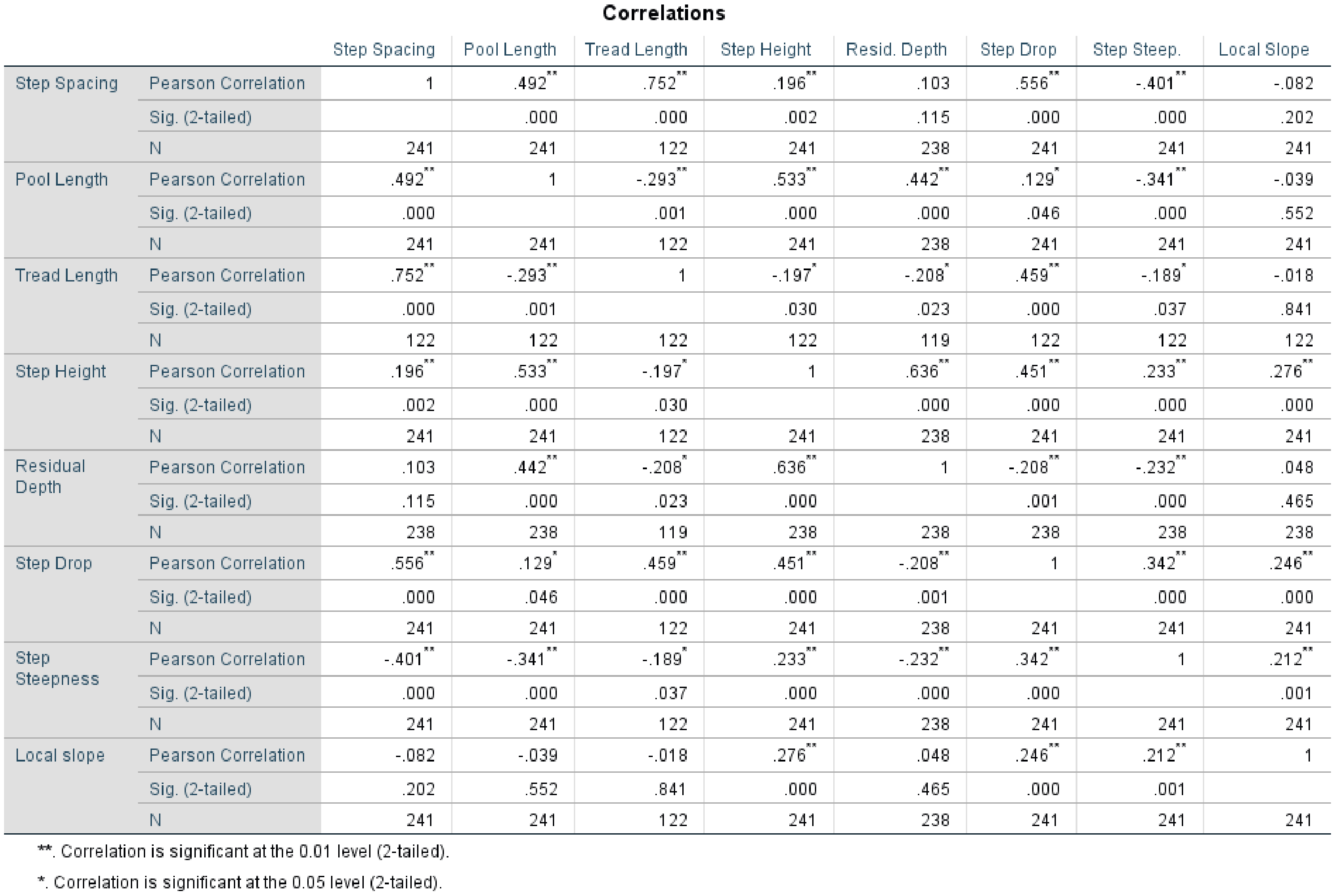
Appendix

Complete tables of correlations for the total longitudinal profile and each of the selected sub-reaches.

The complete table of correlations from the total longitudinal profile.



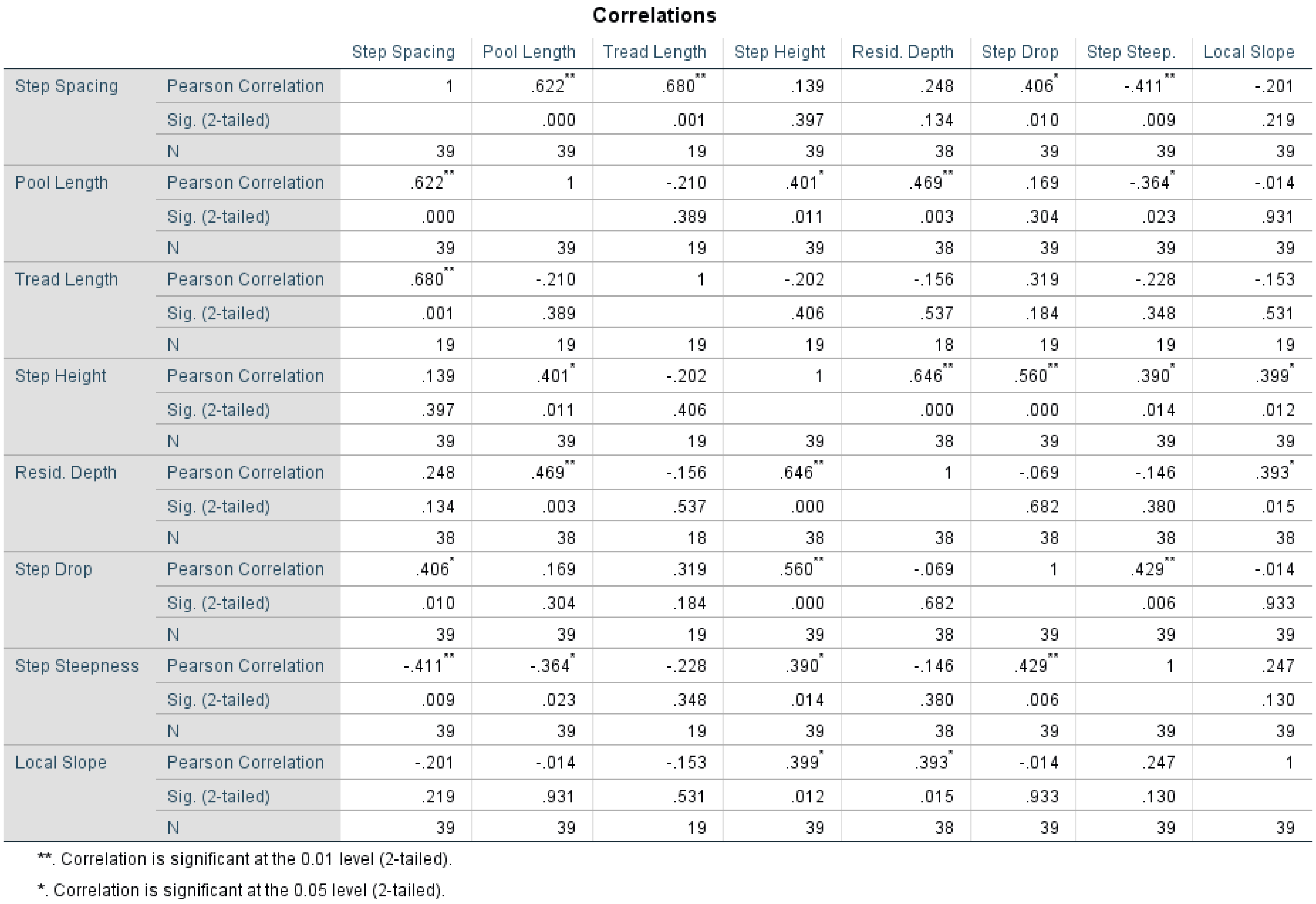
Correlations

		Step Spacing	Pool Length	Tread Length	Step Height	Resid. Depth	Step Drop	Step Steep.	Local Slope
Step Spacing	Pearson Correlation	1	.492**	.752**	.196**	.103	.556**	-.401**	-.082
	Sig. (2-tailed)		.000	.000	.002	.115	.000	.000	.202
	N	241	241	122	241	238	241	241	241
Pool Length	Pearson Correlation	.492**	1	-.293**	.533**	.442**	.129*	-.341**	-.039
	Sig. (2-tailed)	.000		.001	.000	.000	.046	.000	.552
	N	241	241	122	241	238	241	241	241
Tread Length	Pearson Correlation	.752**	-.293**	1	-.197*	-.208*	.459**	-.189*	-.018
	Sig. (2-tailed)	.000	.001		.030	.023	.000	.037	.841
	N	122	122	122	122	119	122	122	122
Step Height	Pearson Correlation	.196**	.533**	-.197*	1	.636**	.451**	.233**	.276**
	Sig. (2-tailed)	.002	.000	.030		.000	.000	.000	.000
	N	241	241	122	241	238	241	241	241
Residual Depth	Pearson Correlation	.103	.442**	-.208*	.636**	1	-.208**	-.232**	.048
	Sig. (2-tailed)	.115	.000	.023	.000		.001	.000	.465
	N	238	238	119	238	238	238	238	238
Step Drop	Pearson Correlation	.556**	.129*	.459**	.451**	-.208**	1	.342**	.246**
	Sig. (2-tailed)	.000	.046	.000	.000	.001		.000	.000
	N	241	241	122	241	238	241	241	241
Step Steepness	Pearson Correlation	-.401**	-.341**	-.189*	.233**	-.232**	.342**	1	.212**
	Sig. (2-tailed)	.000	.000	.037	.000	.000	.000		.001
	N	241	241	122	241	238	241	241	241
Local slope	Pearson Correlation	-.082	-.039	-.018	.276**	.048	.246**	.212**	1
	Sig. (2-tailed)	.202	.552	.841	.000	.465	.000	.001	
	N	241	241	122	241	238	241	241	241

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The complete table of correlations from the 6.4% reach.



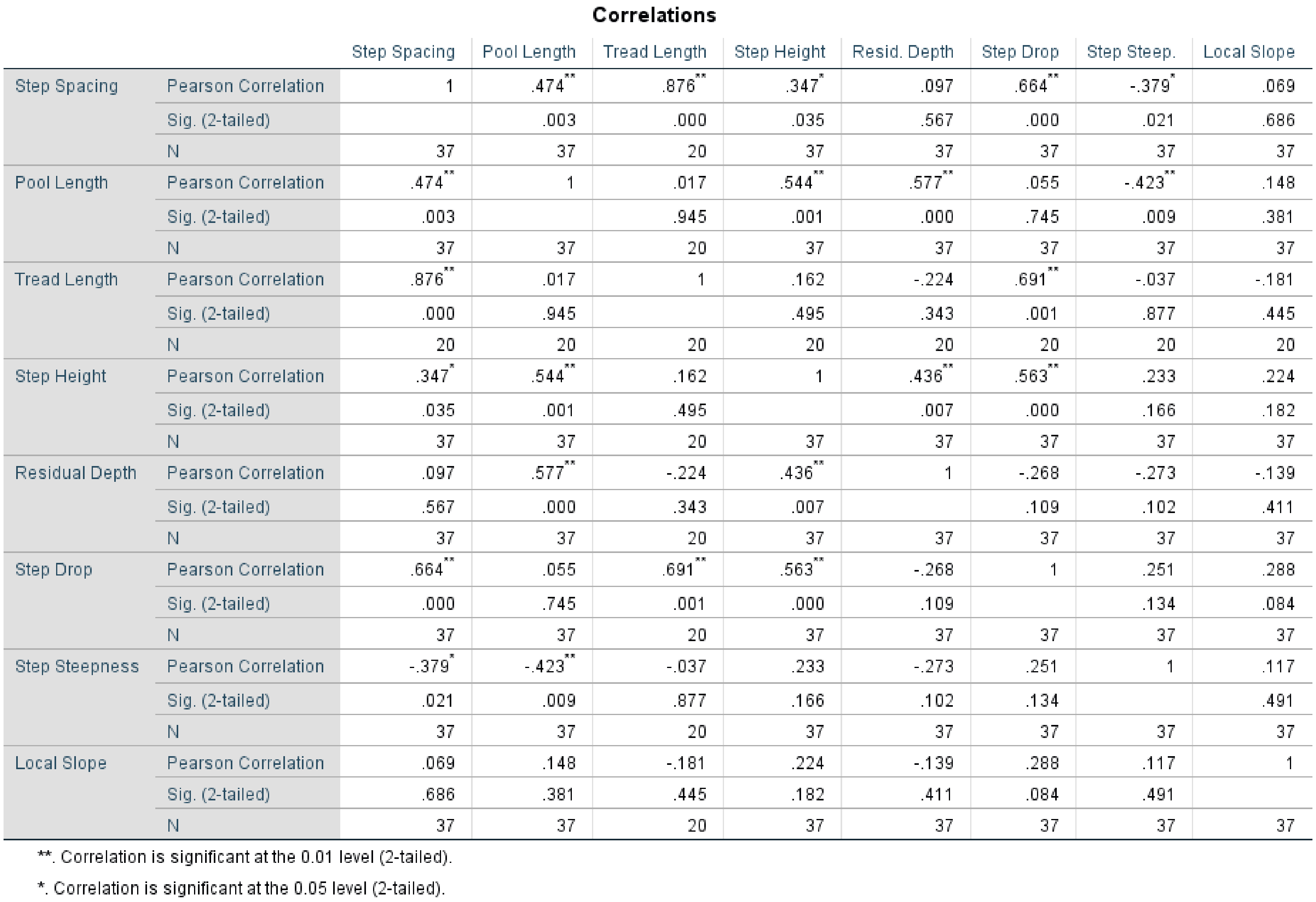
Correlations

		Step Spacing	Pool Length	Tread Length	Step Height	Resid. Depth	Step Drop	Step Steep.	Local Slope
Step Spacing	Pearson Correlation	1	.622**	.680**	.139	.248	.406*	-.411**	-.201
	Sig. (2-tailed)		.000	.001	.397	.134	.010	.009	.219
	N	39	39	19	39	38	39	39	39
Pool Length	Pearson Correlation	.622**	1	-.210	.401*	.469**	.169	-.364*	-.014
	Sig. (2-tailed)	.000		.389	.011	.003	.304	.023	.931
	N	39	39	19	39	38	39	39	39
Tread Length	Pearson Correlation	.680**	-.210	1	-.202	-.156	.319	-.228	-.153
	Sig. (2-tailed)	.001	.389		.406	.537	.184	.348	.531
	N	19	19	19	19	18	19	19	19
Step Height	Pearson Correlation	.139	.401*	-.202	1	.646**	.560**	.390*	.399*
	Sig. (2-tailed)	.397	.011	.406		.000	.000	.014	.012
	N	39	39	19	39	38	39	39	39
Resid. Depth	Pearson Correlation	.248	.469**	-.156	.646**	1	-.069	-.146	.393*
	Sig. (2-tailed)	.134	.003	.537	.000		.682	.380	.015
	N	38	38	18	38	38	38	38	38
Step Drop	Pearson Correlation	.406*	.169	.319	.560**	-.069	1	.429**	-.014
	Sig. (2-tailed)	.010	.304	.184	.000	.682		.006	.933
	N	39	39	19	39	38	39	39	39
Step Steepness	Pearson Correlation	-.411**	-.364*	-.228	.390*	-.146	.429**	1	.247
	Sig. (2-tailed)	.009	.023	.348	.014	.380	.006		.130
	N	39	39	19	39	38	39	39	39
Local Slope	Pearson Correlation	-.201	-.014	-.153	.399*	.393*	-.014	.247	1
	Sig. (2-tailed)	.219	.931	.531	.012	.015	.933	.130	
	N	39	39	19	39	38	39	39	39

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The complete table of correlations from the 9.3% reach.



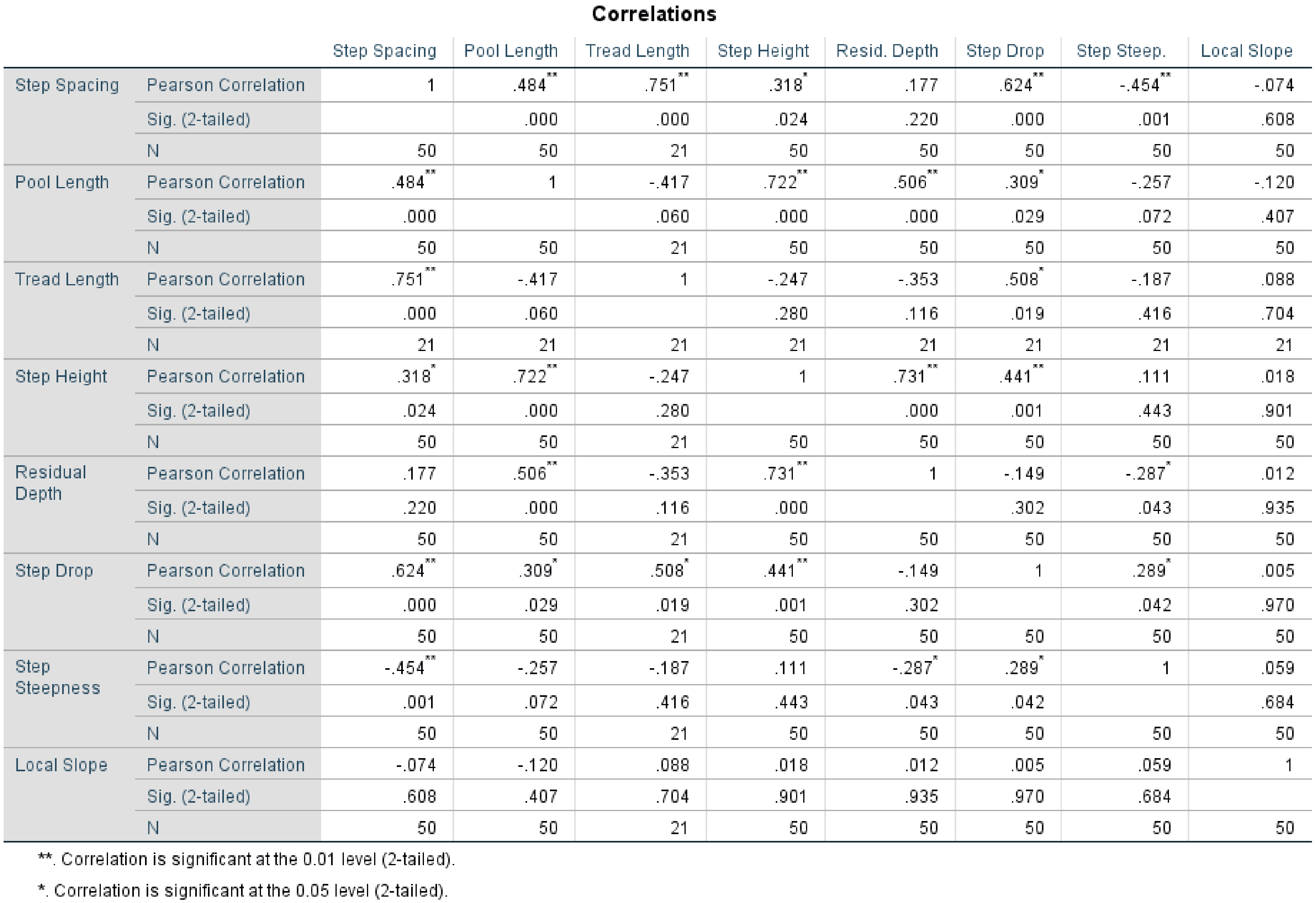
Correlations

		Step Spacing	Pool Length	Tread Length	Step Height	Resid. Depth	Step Drop	Step Steep.	Local Slope
Step Spacing	Pearson Correlation	1	.474**	.876**	.347*	.097	.664**	-.379*	.069
	Sig. (2-tailed)		.003	.000	.035	.567	.000	.021	.686
	N	37	37	20	37	37	37	37	37
Pool Length	Pearson Correlation	.474**	1	.017	.544**	.577**	.055	-.423**	.148
	Sig. (2-tailed)	.003		.945	.001	.000	.745	.009	.381
	N	37	37	20	37	37	37	37	37
Tread Length	Pearson Correlation	.876**	.017	1	.162	-.224	.691**	-.037	-.181
	Sig. (2-tailed)	.000	.945		.495	.343	.001	.877	.445
	N	20	20	20	20	20	20	20	20
Step Height	Pearson Correlation	.347*	.544**	.162	1	.436**	.563**	.233	.224
	Sig. (2-tailed)	.035	.001	.495		.007	.000	.166	.182
	N	37	37	20	37	37	37	37	37
Residual Depth	Pearson Correlation	.097	.577**	-.224	.436**	1	-.268	-.273	-.139
	Sig. (2-tailed)	.567	.000	.343	.007		.109	.102	.411
	N	37	37	20	37	37	37	37	37
Step Drop	Pearson Correlation	.664**	.055	.691**	.563**	-.268	1	.251	.288
	Sig. (2-tailed)	.000	.745	.001	.000	.109		.134	.084
	N	37	37	20	37	37	37	37	37
Step Steepness	Pearson Correlation	-.379*	-.423**	-.037	.233	-.273	.251	1	.117
	Sig. (2-tailed)	.021	.009	.877	.166	.102	.134		.491
	N	37	37	20	37	37	37	37	37
Local Slope	Pearson Correlation	.069	.148	-.181	.224	-.139	.288	.117	1
	Sig. (2-tailed)	.686	.381	.445	.182	.411	.084	.491	
	N	37	37	20	37	37	37	37	37

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The complete table of correlations from the 11.3% reach.



Correlations

		Step Spacing	Pool Length	Tread Length	Step Height	Resid. Depth	Step Drop	Step Steep.	Local Slope
Step Spacing	Pearson Correlation	1	.484**	.751**	.318*	.177	.624**	-.454**	-.074
	Sig. (2-tailed)		.000	.000	.024	.220	.000	.001	.608
	N	50	50	21	50	50	50	50	50
Pool Length	Pearson Correlation	.484**	1	-.417	.722**	.506**	.309*	-.257	-.120
	Sig. (2-tailed)	.000		.060	.000	.000	.029	.072	.407
	N	50	50	21	50	50	50	50	50
Tread Length	Pearson Correlation	.751**	-.417	1	-.247	-.353	.508*	-.187	.088
	Sig. (2-tailed)	.000	.060		.280	.116	.019	.416	.704
	N	21	21	21	21	21	21	21	21
Step Height	Pearson Correlation	.318*	.722**	-.247	1	.731**	.441**	.111	.018
	Sig. (2-tailed)	.024	.000	.280		.000	.001	.443	.901
	N	50	50	21	50	50	50	50	50
Residual Depth	Pearson Correlation	.177	.506**	-.353	.731**	1	-.149	-.287*	.012
	Sig. (2-tailed)	.220	.000	.116	.000		.302	.043	.935
	N	50	50	21	50	50	50	50	50
Step Drop	Pearson Correlation	.624**	.309*	.508*	.441**	-.149	1	.289*	.005
	Sig. (2-tailed)	.000	.029	.019	.001	.302		.042	.970
	N	50	50	21	50	50	50	50	50
Step Steepness	Pearson Correlation	-.454**	-.257	-.187	.111	-.287*	.289*	1	.059
	Sig. (2-tailed)	.001	.072	.416	.443	.043	.042		.684
	N	50	50	21	50	50	50	50	50
Local Slope	Pearson Correlation	-.074	-.120	.088	.018	.012	.005	.059	1
	Sig. (2-tailed)	.608	.407	.704	.901	.935	.970	.684	
	N	50	50	21	50	50	50	50	50

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).