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Spatial and temporal mapping of shallow groundwater tables in the riparian zone of a Swedish headwater catchment

Kartering av ytliga grundvattennivåer inom den bäcknära zonen i ett svenskt avrinningsområde

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Eva Hellstrand

ABSTRACT

Spatial and temporal mapping of shallow groundwater tables in the riparian zone of a Swedish headwater catchment

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Understanding the hydrology of the riparian zone in a catchment can be an important prerequisite for determining solute loads and concentrations in streams. The riparian zone is the transition zone between surrounding landscape and an open water stream. This study focuses on the spatial and temporal variations of shallow groundwater levels in a forested headwater catchment in the Bergslagen area of central Sweden. Three snapshot campaigns were conducted during dry, humid and wet conditions to map the spatial variability of the groundwater levels. Piezometers giving the total hydraulic head were placed in the riparian zone along a stream network consisting of three first order streams and one second order stream. To asses temporal variations five groundwater wells were installed with automatic loggers to record continuous data during the wet period. Historical streamflow records from a permanent field station were collected and related to the groundwater levels in order to assess the relationship between groundwater levels and streamflow. Additionally a landscape analysis using GIS methods was conducted in order to identify potential drivers of spatial variation of groundwater levels in the riparian zone. The results showed that the slope could partially explain the observed spatial variability of riparian groundwater levels. The results from the spatially distributed piezometers and the continuously monitored groundwater wells with loggers were contradicting. Where the piezometers showed increasing depth to the groundwater table with increasing slope the loggers indicated the opposite. However, because the piezometers outnumbered the loggers the piezometer results can be considered more representative of the spatial variation of groundwater levels. There could be no general result concluded on the catchment scale but when looking at specific subcatchments it could be found that the variations in the riparian groundwater levels could be better explained where the stream had a more distinct channel. This indicates the importance to evaluate not only slope but the profile curvature as well for groundwater predictions.

Key words: Riparian zone, recharge area, shallow groundwater tables, GIS, terrain analysis

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REFERAT

Kartering av ytliga grundvattennivåer inom den bäcknära zonen i ett svenskt avrinningsområde av första ordningen.

Eva Hellstand

Hydrologin i den bäcknära zonen kring ett vattendrag spelar stor roll för de markprocesser som påverkar vattenkvaliteten längre ner i vattendragen. Det är därför intressant att kartlägga variationer i grundvattennivåerna i den bäcknära zonen för att utreda frågor kring vattenkvalitet och ämnestransporter. I denna studie har fokus varit att karakterisera de rumsliga och tidsmässiga variationerna av ytliga grundvattennivåer inom den bäcknära zonen i ett skogsklätt avrinningsområde av första ordningen i Bergslagen i Mellansverige. En fältstudie genomfördes där grundvattendata samlades in med hjälp av piezometrar vilka anger den hydrauliska totalpotentialen i en provpunkt. Piezometrarna placerades ut parvis i den bäcknära zonen längs med bäcken i studieområdet. Grundvattendata hämtades in vid tre tillfällen då det rådde olika hydrologiska förhållanden för att fånga den tidsmässiga variationen. Förutom piezometrar installerades även grundvattenloggerar i tre olika markfuktighetsområden för att samla in kontinuerliga tidsserier under den våtare perioden av fältarbetet. Från en permanent mätstation i studieområdet hämtades tidigare uppmätta tidsserier över vattenföring och dessa relaterades till grundvattennivåer samt vattenföringen under fältstudien. En terränganalys utfördes där terrängindex beräknades och jämfördes med uppmätta grundvattennivåer. Resultatet visade att lutningen förklarar en stor del av den rumsliga och tidsmässiga variationen. Resultaten från de rumsligt fördelade piezometrarna och de tidskontinuerliga loggrarna var dock motstridiga. Resultaten från piezometrarna visade att avståndet från markyta till grundvattenyta ökade med en brantare lutning medan resultaten från loggrarna indikerade det motsatta förhållandet. Det antogs dock att resultaten från piezometrarna var mer representativa för den rumsliga variationen eftersom dessa var betydligt fler och hade större spatial utbredning. Det gick inte att dra några generella slutsatser för hela avrinningsområdet men däremot gick det att tydligt se skillnad mellan de olika delområdena. Det framgick att variationerna i grundvattennivåer gick att förklara avsevärt bättre där det fanns en tydlig bäckfåra. Det indikerar att det kan vara av vikt och intresse att vid landskapsanalyser ta hänsyn till både lutning och landskapsprofil.

Nyckelord: Bäcknära zonen, landskapsanalys, avrinningsområde, ytligt grundvatten, GIS

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PREFACE

This thesis is the final part of my degree in Master of Science in Aquatic and Environmental engineering at Uppsala University. The supervisor has been Thomas Grabs, subject reviewer Kevin Bishop and examinator Allan Rodhe.

I first of all want to thank Thomas for being such a great supervisor and constantly coming up with new ideas and explanations to everything that I could not find a logical explanation of. Then also a great thank you to my field work buddies Alexander Bergsten and Homayoun Fathollahzade for invaluable help out there fighting mosquitoes and collecting data.

Thank you also Stefan Löfgren for valuable information on the IM site and thank you Lars Lundin for helping out finding data.

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Eva Hellstrand

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POPULAR SCIENTIFIC SUMMARY

Spatial and temporal mapping of shallow groundwater tables in the riparian zone of a Swedish headwater catchment.

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Water in soils and streams does in nature what the local transit system does in your municipality, i.e. it is a transport system. Studying hydrology is thus like trying to decipher the time table. In order to understand where matter and solutes are transported and retained in our ecosystems we must understand the hydrological systems. The headwater catchments are where the transit system starts. Within the headwater catchment there is the so called riparian zone which is the strip of land surrounding the stream and connecting it to the dominating adjacent landscapes. The riparian zone is thus the last stop before groundwater discharges into the stream. As such this is a biochemical hotspot that will affect the water further downstream.

This thesis has the aim to map and characterize the variations in groundwater movements within the riparian zone in a forested headwater catchment in central Sweden in the Bergslagen area. The study area was a headwater catchment with three different first order subcatchments and one second order catchment. The topography was varying between the subcatchments with two very steep slopes, one moderately steep and one rather flat.

The method consisted of a field study where the groundwater was spatially and temporally mapped with groundwater tubes, piezometers, and wells with automatic loggers. In addition to the groundwater data, streamflow data from a permanent field station was collected and evaluated. The streamflow records were both from the field visits and two years of historical stream measurements.

A piezometer is a hard plastic tube installed in the ground so the groundwater can penetrate from the bottom and rise to the same level as the local hydrological head. The piezometers were placed in the riparian zone along streams that had varying terrain to assess the distributed variation. The groundwater levels were recorded during dry, humid and wet conditions to assess the temporal variation. The groundwater wells were bigger tubes that were perforated to allow for water intake along the vertical length of the tube. The loggers were probes that had a sensitive area for measuring capacitance and recording the water height from this. The loggers were installed and recording during the wet period.

Since fieldwork is expensive and time consuming it is of interest to develop and use models to predict groundwater levels. For this matter a terrain analysis was performed using techniques from Geographical Information Systems, GIS. In the GIS software the landscape was divided into cells, commonly called grids, and specific values indicating terrain properties can be given to each cell.

The terrain analysis consisted of calculating different terrain indices and evaluating how they could function as predictors for groundwater levels in a future model. Terrain indices are parameters calculated from the topography that quantify and illustrate relations and characteristics in the landscape. The most common and obvious example is the slope giving information on how the elevation changes in the landscape. Other indices that were calculated in this study were planar curvature, profile curvature, upslope contributing unit area, *a*, and the terrain wetness index, *TWI*. The curvature indices give information on how the slope changes in the terrain both in the downslope, planar, direction and in the perpendicular, profile, direction. The local upslope contributing area, *a*, is the upslope area draining through the focus cell divided by the contour length to give the unit area. The *TWI* is a combination of the *a* and the slope and should give an indication on how much available soil water a location has.

The evaluation of the relation between streamflow and the time series of groundwater levels showed an exponential relation between higher groundwater and increased streamflow. The historical streamflow records were analyzed in order to put the hydrological conditions during the field study in perspective. The result indicated that the encountered conditions were in the wetter range of the long-term hydrological conditions.

The results from the spatial mapping showed considerable variation in the groundwater levels between the different subcatchments. The first order streams with steeper slope had more variation both along the flowpath and temporally in the different wetness conditions. The flatter subcatchment showed less variation.

The comparison with the terrain indices showed that the slope had the strongest correlation with the groundwater levels and that a steeper slope would give a deeper groundwater table. The results also indicated that the profile curvature index can be a valuable predictor as the subcatchment with the most distinct channel profile also gave the strongest correlations between the terrain index and groundwater levels. The upslope area and *TWI* did not function well as groundwater predictors on the catchment level. There were weak indications that using an algorithm that distinguishes between left and right side of the stream could render stronger correlations between the *a* calculated for the stream cells from the separate sides compared to the groundwater levels found on the corresponding side of the stream.

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1. INTRODUCTION

The role of water as a transport agent through the ecosystem is important to understand when conducting any kind of environmental studies. Setting up environmental monitoring programs or studying nutrient fluxes through an ecosystem requires good understanding of the hydrology in the area. In order to find the right target zones for studying the effects of a remedial action or a point-source of pollution the hydrology is a key factor to include. Water acts as both a solvent in soil chemical processes and as an agent for transportation. The presence of shallow groundwater tables is intimately connected to the fluxes and presence of dissolved carbon which in turn affects many other nutrient cycles.

The Swedish government has set up 16 national environmental objectives to strive for where objective number 8 reads “Flourishing lakes and streams” and the related objective number 7 reads “No eutrophication”. These are aims set high. To meet these objectives and manage our ecosystems in a successful and sustainable way a wide range of knowledge is needed.

About 45% of the total area in Sweden is covered by boreal forest (Skogsstyrelsen, 2011) where the landscape is formed by the latest ice age, approximately 10 000 years ago, leaving shallow unsorted till soils on top of a hard, less permeable, granite bedrock. This has the effect that the groundwater table often tends to follow the surface topography and that groundwater tables are often shallow. In recharge areas, usually elevated uphill areas, the distance to the groundwater table might be defined in terms of meters while in discharge areas, downhill and closer to the valley bottom, the distance to the groundwater table can be within centimeters (Grip & Rodhe, 1994).

Water travels from precipitation through a watershed either as groundwater or overland flow. The importance of either flow depends on the transmissivity, storage capacity and infiltration capacity of the soil and groundcover in the watershed. The water will percolate and add to the groundwater as long as the soil is not saturated to the surface and the precipitation does not exceed the infiltration capacity. If the soil is saturated, or infiltration capacity is exceeded, then water will add to overland flow. In Sweden soils have a relatively high infiltration capacity and overland flow is not very common.

In glacial till soils the groundwater often contributes most water to streamflow after a precipitation event since the shallow water tables only need a small addition of infiltrating water to rise up into the superficial soil layers that have a higher hydrological conductivity during saturated conditions (Grip & Rodhe, 1994). This creates what is called the transmissivity feedback mechanism (Bishop, 1991).The hydrological conductivity is higher in the more shallow soil layers due to bioactivity and effects from freezing and thawing processes that has created less compacted and more permeable soil layers. In a saturated stage even a small elevation of groundwater levels will then rapidly increase the conductivity for the soil. This can also imply relatively quick hydrological responses of streamflow in small catchments. In small, homogenous catchments with approximately exponentially shaped transmissivity profiles in soils, the relation between discharge and groundwater levels will then show an exponential relation with exponentially increasing streamflow with increasing groundwater levels.

Riparian zones are located in the area connecting the stream bank and the dominating landcover in the surroundings. The positioning as a transit zone between a stream or a lake and the surrounding land is what makes the riparian zone hydrologically interesting since it is the last stage before connecting to a larger water body and the biogeochemical processes in the riparian zone will influence the rest of the system (Naiman & Décamps, 1997).
Since detailed field studies of groundwater levels and other environmental attributes often are time and money consuming, landscape analysis and computerized terrain analysis has become a popular way for inferring environmental conditions from remotely sensed data. However, at some stage fieldwork needs to be done to collect raw hydrological data needed for calibrating and analyzing models. Characterizing the spatial variation of groundwater levels in the riparian zone as well as relating temporal variations to stream flow would provide important information for the understanding of riparian hydrology.

The objective of this thesis was to contribute to the collected knowledge in riparian hydrology by attempting to map and characterize the variations in shallow groundwater tables in the riparian zone of a Swedish headwater catchment. The specific aims were the following:

- To map the spatial variations in shallow groundwater tables by combining field investigations with terrain analysis.
- To collect and analyze previously collected time series of groundwater levels and stream flow
- To characterize where and when in a catchment groundwater level variation is the most distinct.

2. BACKGROUND

2.1. RIPARIAN ZONES

Hydrological processes connected to water quality can be studied by looking on how a parameter, e.g. concentrations of metals, change over distance and time and from this extract information on how the water flows. Another way is by trying to estimate the water fluxes and then make inferences on the water chemistry which is connected to water quality. Water chemistry is a main driver for many ecosystem processes and thus water movements and fluxes are key issues to study. It is also important to understand the linkage within different parts of the catchment and the headwater catchment which affects conditions for downstream water quality (Takshi, et al., 2002). The riparian zone in a headwater catchment can thus be considered a hotspot for studying hydro-geochemical reactions (Grabs, 2010).

The riparian zone has been shown to be important for the variation in the chemistry of aluminum (Al). Speciation of and concentration of Al are connected to the acidity in the soil water solution. It has therefore been argued that varying sulfur deposits should have an effect on the Al chemistry. However, in a comparison in different hydrological conditions in the riparian zone along a sulfur deposit gradient it was shown that the influence from the riparian zone was greater than effects from varying sulfur deposits (Löfgren & Cory, 2010). These results illustrate the importance of riparian hydrology.

2.2. TERRAIN ANALYSIS

Terrain analysis means literally analyzing the terrain which can be done from different perspectives e.g. topographic if interested in hydrological driving processes and if looking at biological variables perhaps soil and landcover are of higher interest. In this study the perspective has been topographic with related hydrological analysis. With the use of a Digital Elevation Model, DEM, this is done by dividing the landscape into grid of cells assigning an elevation value to each cell. From this relations in elevation can be calculated and characterized. Calculating terrain indices such as slope gives information on the changes in elevation in the downslope direction and the related curvature index illustrates how the slope itself changes in the terrain. A terrain index is thus a parameter calculated, from the elevation in this case, to quantify a relation and topographic characteristic in the landscape.

Terrain indices can be divided into primary and secondary indices where primary means a variable calculated directly from the DEM and secondary is a compound of two or more primary variables. This means that slope is a primary index and curvature is a secondary index.

Combining topographic indices with flow algorithms gives the opportunity to calculate upslope contributing unit area, *a,* which is a value giving information on how many cells, upslope from the focus cell, that are contributing to the flow in the cell per contour length of the cell. The upslope unit area, *a*, combined with the slope gives the index called Terrain Wetness Index, *TWI*, introduced by Beven & Kirkby (1979).

Comparing calculated terrain indices and different field parameters is useful to evaluate if models to predict hydrometric properties can be established. The terrain indices can then be used as input for models, statistical or distributed, to predict hydrological features such as saturated areas. It has been shown that upslope area, slope and curvature, κ, (Günter, et al., 2004) are terrain indices that can be used for spatial predictions of saturated areas.

When comparing water table fluctuations in the riparian zone in different catchments, with similar methodology to this study, it has been found that in streams where the riparian terrain was flat the water table level was much more influenced by the adjacent stream or lake especially during dry summer conditions or storm events (Burt, et al., 2002). The study was focused on riparian buffers as nitrate removal zones and found that nitrate fixation had little or no effect in catchments where the riparian zone had a hillslope ending in the stream and thus the riparian hill discharge affected the groundwater levels more than the levels in the stream.

In connection to topographic terrain indices hydrological flow modeling can be done with the aim to model the flow paths in the terrain using the assumption that water flow from higher elevation to lower. The flow can be distributed between the downslope cells in different ways and there are a number of different algorithms to do so (e.g. Tarboton, 1997; Freeman, 1991; Seibert & McGlynn, 2007).

As in all digital computing the choice of algorithms can affect the result. Depending on what field parameters that are being predicted, e.g. physical such as groundwater levels or biochemical such as pH, different algorithms has different suitability. A combined index like the *TWI* can be calculated with different algorithms for the slope and the flow routing algorithm being used. A general flow algorithm has not been found so far but it has been shown that the multidirectional flow algorithm from (Tarboton, 1997) has correlated best for hydrological properties (Sörensen, et al., 2006).

A recent development of landscape analysis has also been contributed by (Grabs, et al., 2010) who has developed an algorithm to separate the left and right side of the stream and calculate the number of contributing cells draining in each stream cell form each side of the stream. This provides new opportunities in riparian hydrological modeling as it is now possible to further characterize and model the fine-grained interactions between hillslopes, riparian zones and streams. While function of the riparian zone can be a key control for soil and stream water quality, riparian zones are highly specific to the local setting and the terrain of the riparian zone has important implications for the internal processes.

2.3. STUDY AREA

The study area is called Kindlahöjden and is situated in the Bergslagen area in central Sweden in the county of Örebro (fig.1). The Kindla catchment is one out of four sites chosen for integrated monitoring, IM, of the environmental status of forest environment in Sweden. The monitoring program is on behalf of the Swedish Environmental Protection Agency (Naturvårdsverket) and jointly performed by the Swedish Geological Survey (SGU), Swedish Environmental Research Institute (IVL) and the Swedish University of Agricultural Science (SLU) (Löfgren, 2009).

Figure 1. Location of study area in Sweden

The long-term goal for the monitoring program is to survey environmental effects in natural ecosystems to see the effects from airborne and trans-boundary pollution (Löfgren, 2009) Kindlahöjden was established as an IM site in 1996 and later in 1999 the study catchment and the surrounding area, a total area of 9.33 km^2, was established as a protected park. Historically the area has been used for charcoal production supplying the traditional smeltery close by in Nyberget. There are eight remnant charcoal production pits left in the area as a trace of former activities.

The present tree stand is dated to around 100 years old and has been unmanaged since the last clear cut in the beginning of 20th century (SLU-IM, 29-09-2009). The dominant soils are shallow podsol on hillslopes and peat in valley bottoms and riparian zones. The dominant bedrock is coarse grained granite. The vegetation is dominated by Norway spruce (*Piceaabies)*. The average annual temperature is +4.2 °C and the annual precipitation is 900 mm, runoff 450 mm and evaporation 450 mm (Löfgren, 2009).

The study catchment is a small headwater catchment with an area of 0.2 km^2 (fig. 2). The catchment has considerable differences in elevation even over short distances, 70 m elevation over a distance of 350 m laterally. The catchment consists of three major plateaus with mire in the basin of the middle plateau collecting all water from above drained by a considerably larger perennial second order stream. For the study only the stream network above the mire has been used because an assumption was made that many of the processes affecting water quality take place upstream from the mire (Löfgren, 2011, pers.com.)

The studied stream network consists of two first order streams, 1A and 1B, joining into 2A, forming a second order stream, with outlet in the mire. In addition there is a first order stream, 1C, draining into the mire from the southwest part of the catchment area (fig. 2). Downstream from the mire there is a permanent field station operated by the IM-program.

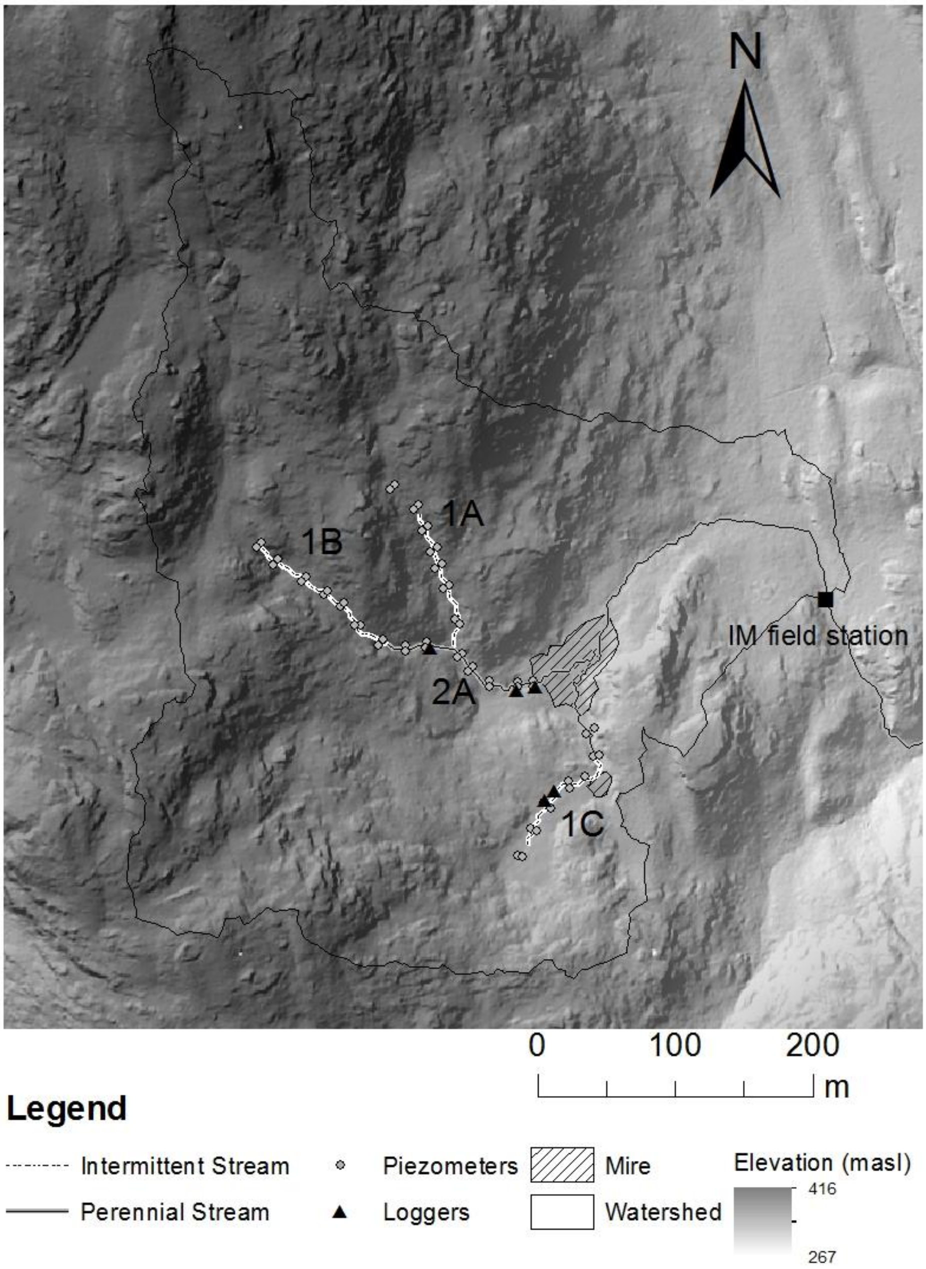

Figure 2. Overview map of the study catchment monitored from the IM field station, however it is only the upper part of the stream network that has been used for this study.

The stream network was coded starting with naming first order streams 1A,1B,1C reading from right to left, NW corner of the map (fig. 3), and then likewise for the second order stream. The coding for the streams will be used for referring to different parts of the catchment as subcatchments in the text to come.

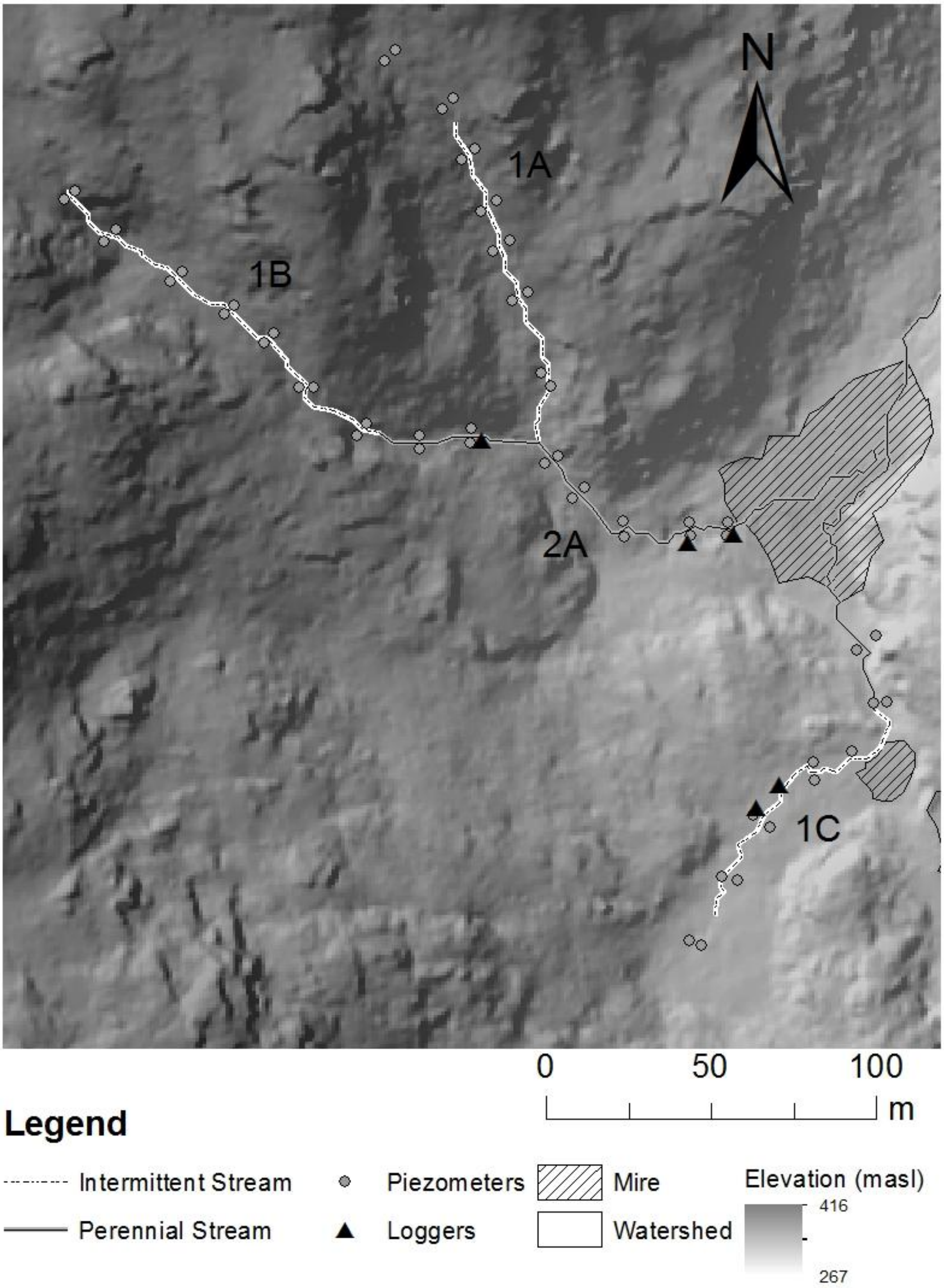

Figure 3. Close-up view of the Kindla catchment with the four stream reaches (1A, 1B, 1C, 2A) along which piezometers (circles) and groundwater loggers (triangle) were installed.

3. MATERIALS AND METHODS

3.1. STREAMFLOW RECORDS

From the permanent field station streamflow data was collected from the years 2008 – 2009. The wetness conditions that were encountered during this field study were put into a long-term hydrological perspective by evaluating the historical streamflow records.

The historical streamflow data was sorted in increasing flow and a flow duration curve could be calculated giving the probability for a specific streamflow related to the full time series. By retrieving the streamflows that were recorded during the field study these conditions could be put into perspective by comparing the probabilities to the long-term hydrograph for the catchment. Plotting the percentage and the historical streamflow and then marking the percentage found for the specific field visits illustrates the relation between the wetness conditions during this study compared to the historical records.

3.2. FIELD STUDY

The field study consisted of three field visits, June 18th – 20th, September 12th -13th and October 26th. A distributed snapshot campaign was conducted recording groundwater levels with piezometers during the different field visits. In addition during the wet period groundwater wells were installed for time continuous groundwater recording. In June the piezometers were installed and positioned and the groundwater levels were read. In September the wells with loggers were installed and the positioning measurements were improved and the piezometers were read. Finally in October the piezometers were read once more and the data was collected from the groundwater wells.

3.2.1. Snapshot campaign of riparian groundwater levels

The riparian groundwater levels were collected using piezometers made from hard plastic PET tubes that were installed at the depth of 20, 30 and 50 cm, measured from the ground surface. The piezometers were not perforated, i.e. only open in the bottom, and thus measuring the total head in the soil at that location. The assumption was made that the total head was representative for the groundwater in that location. The piezometers were placed in transects along the streams with one on each side of the stream and within the riparian zone. The average distance between transects along the stream path was 20 m (fig. 3).

The perpendicular distance from the edge of the streambed to the piezometers varied 1 – 3 m depending on the extent of the riparian zone and on the penetrability and structure of the soil. The piezometers were installed as close as possible where there was solid soil to hold the pipe and installed as deep as possible but at a maximum of 50 cm. In the text to come the groundwater levels are given in centimeters relative to the surface in negative value with the ground surface as 0 cm.

Transects were equipped with piezometers on the first day of fieldwork and then left for two days before the first reading was done to allow the groundwater table to level in the piezometers. The groundwater levels were measured by lowering a soft plastic tube into the piezometer pipe and blowing at the same time until hearing the first bubble sound when the air from the soft tube hits the water table. The length of the part of the soft plastic tube that had been descended into the pipe was measured with an mm-measuring tape. After subtracting the length of the piezometer tube above ground the measured length gives the distance related to the surface to the water table.

3.2.2. Continuous time series of riparian groundwater levels

In addition to the piezometers along the streams five groundwater height loggers were installed (fig.4). The aim of installing the loggers was to measure riparian groundwater levels continuously and relate to the streamflow recordings. The groundwater loggers (TruTrack®) consisted of a metal probe with a sensitive area where the height is measured with a capacitance sensor. The loggers were configured to measure averaged hourly groundwater levels and were installed in locations with assumed different groundwater levels to evaluate how the groundwater varies at different depths. The loggers were named L1…L5 (fig.4). The L1 and L2 loggers were placed at the outlet of the 2A stream close to the border of the major mire in a gentle slope and the organic soil layer was deep. The L3 logger was placed in a steeper slope and could not be installed at a measuring depth as deep as for the other loggers. The L4 and L5 loggers were installed in the 1C subcatchment where the terrain was almost flat and the organic soil layer was thinner, compared to the locations for L1 and L2, and with podsol layer underneath.

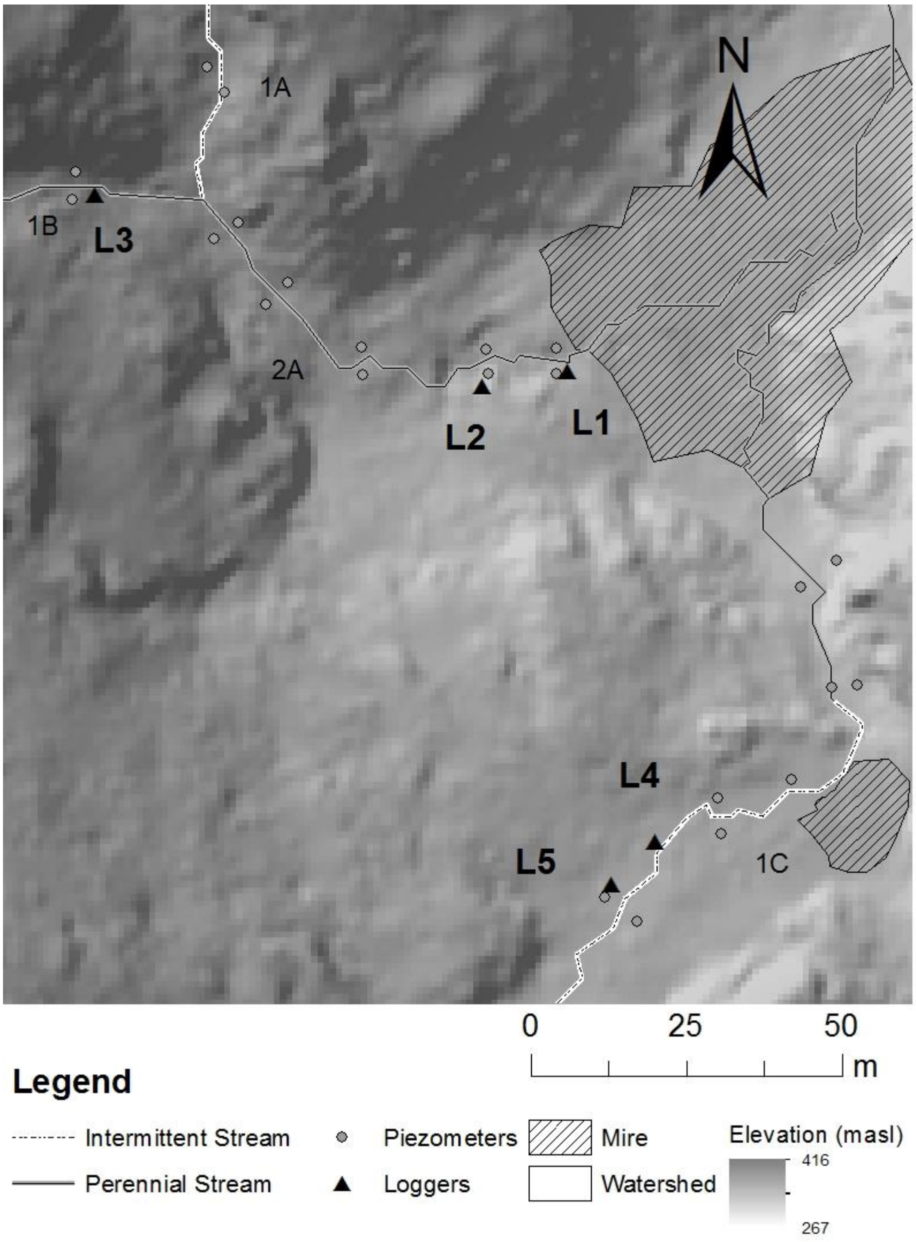

Figure 4. Locations for the loggers L1…L5.

Due to technical failure only the data from 4 loggers could be used for further analysis. The loggers were installed in September and the data was collected in October and thus capturing the wet period.

3.3. TERRAIN ANALYSIS

The terrain analysis was performed using a Digital Elevation Model, DEM, derived from a Light Detection and Ranging, LIDAR, image with a resolution of 1m. From the original DEM two new DEMs with resolution 5 m and 10 m were constructed in order to investigate any scaling issues in the calculation of terrain indices. From the DEM terrain indices were computed and compared to groundwater levels and streamflow to evaluate if there could be any relation and thus if the terrain indices could be used for prediction of spatial distribution of groundwater levels.

3.3.1. Positioning of riparian piezometers and wells

When using terrain analysis to predict groundwater tables in the riparian zone it is important to have precise positioning of the measuring points i.e. piezometers and groundwater loggers. The positioning was done with a combination of a high precision Differentiated Global Positioning System, DGPS, a handheld GPS and manual measurements. The DGPS has at its best a precision of 5 cm but this could not be applied, as there were never enough satellites to use for the position calculation. The handheld GPS had a precision in terms of 5-10 m and can thus not be used for this high precision measurement. Therefore manual measurements, using a compass and measuring tape, were made in addition to establish the angle and the distance between the mid points in the stream between the piezometers. From a few established points the positions could be back-calculated into XY-coordinates.

The final positioning was made by over layering the different position measurements (DGPS, GPS, manual) and in combination with field notes and reviewing the high resolution DEM a best estimate of the measuring point positions was made. The positioning procedure was associated with a considerable uncertainty and individual points can be expected to lie within an error distance of 5 to 10 m but still close to the stream from their estimated position.

During field visits the width of the riparian zone, from the mid-point and to the edge perpendicular to the stream flow direction, was measured with a measuring tape using 0.5 m accuracy. The riparian zone was characterized as the edge where the vegetation changed from “wet” vegetation into drier and more consistent blueberry vegetation. The elevation was also used as a boundary condition, in some places the stream had a narrow streambed with high banks clearly defining the riparian zone and in some places the stream was wide and almost a wetland. There the riparian zone had to be based on the vegetation more than the smooth elevation of the bank.

3.3.2. Terrain indices

The following terrain indices were calculated:

Slope: The slope angle from one cell to the steepest neighbor. There are different algorithms for slope calculations and they have different suitability depending on the following analysis that the output will be used in. For the hydrological processes the Maximum Triangular Slope (Tarboton, 1997) was used. When calculating the curvature indices the fitted second degree polynom (Zevenbergen & Thorne, 1987) was used. The maximum triangular slope algorithm was chosen because of its association with the flow routing algorithms used later. When calculating the curvature a bidimensional direction function, $z = f(x,y)$, is needed to evaluate the change in slope in different directions which is why a second order fitted slope function is the preferable choice (Olaya, 2004).

Profile curvature – $\kappa_{profile}$ **:** The profile curvature index gives information on the shape, convex or concave, of the slope function looking in the maximum downslope direction. It takes a value between (-1) and 1 where a negative value means a convex surface and a positive value a concave surface. A value around 0 means a planar surface.

Plan curvature – κ_{plan}**:** The plan curvature index gives the same information as the profile curvature but uses the direction perpendicular to the maximum down slope, horizontally along the hillslope that is. It is constructed the same way and takes a value between (-1) and 1 where a negative value means a convex surface and a positive a concave surface. A value around 0 means a planar surface.

Upslope accumulated unit area – a**:** The accumulated area is the sum of all upslope cells contributing to the flow in the target cell divided by the contour length. It is a measurement of how much available water there is in a cell for further downstream flow. A large sum of contributing cells divided by a short contour length means that there is a lot of water readily available and vice versa. This is a spatially distributed index and can as such be calculated for every cell in the grid. For calculation convenience the natural logarithm is used when comparing with other indices.

Upslope area Left and Right – κ_{left}, κ_{right}**:** By using an algorithm that evaluate the flow direction grid and separate it as either left or right of the stream the accumulating area contributing from left and right side can be derived. The SIDE (Grabs, et al., 2010) algorithm provides a means for this.

Topographic Wetness Index – *TWI* : The *TWI* was first introduced by Beven and Kirkby (1979) as a part of the runoff model TOPMODEL. It has since become one of the most commonly used topographic indices. It is and defined as (1):

$$TWI = \ln \frac{a}{\mathrm{Tan}\ \beta} \qquad (1)$$

Where :

a – upslope area per contour length (m)

Tan β = local slope (°)

In order for TWI calculations to be representative a few assumptions for the study area are required (Sörensen & Seibert, 2007):

- The topographic surface slope represents the groundwater table surface.
- The hydrological conductivity and precipitation is expected to be uniformly distributed over the catchment area.

Small catchments located in glacial till landscapes can be considered to fulfill these assumptions (Sörensen & Seibert, 2007). A high *TWI*-value means a large accumulating area and thus relatively more soil water available at the location and a low value means smaller accumulating area. The slope has the effect that a steep slope will create a more well-drained location and also a lower *TWI* value while a less steep slope will give a higher *TWI* value and a less drained cell.

3.3.3. Hydrological calculations

When making hydrological calculations water is assumed to flow from higher elevation to lower. It is therefore important that the DEM is continuous without any sink cells creating a "hole" in the routing algorithm. A sink cell is a cell where all the eight surrounding cells have higher elevation causing all the water from the neighboring cells to drain into the sink, which is an unlikely hydrological event. To address this issue the original DEM was preprocessed using algorithms that assigns values to all cells and detects any sink cells and fill them to the general surface shape to make sure all water flows according to the assumption of downslope water flow.

The preprocessing was made for the original 1m resolution DEM which was then resampled into the 5 m and 10 m resolution DEMs and the preprocessing steps were performed again to make sure to remove any new sinks that might have been introduced in the resampling process. The 5 m and 10 m resolution DEMs were created by increasing the grid size and using the average value of the combined cells for the new larger cell.

The main catchment and the subcatchments were delineated in several steps. First a flow direction grid was calculated from the DEM and then from a given point, the outlet, all the cells draining to that point can be delineated until hitting the water divider in the area. The main catchment had its outlet at the permanent fieldstation. The subcatchments were calculated in a later stage after the stream network had been calculated and the outlets for the subcatchments were placed at the endpoints of the flow paths (fig. 5).

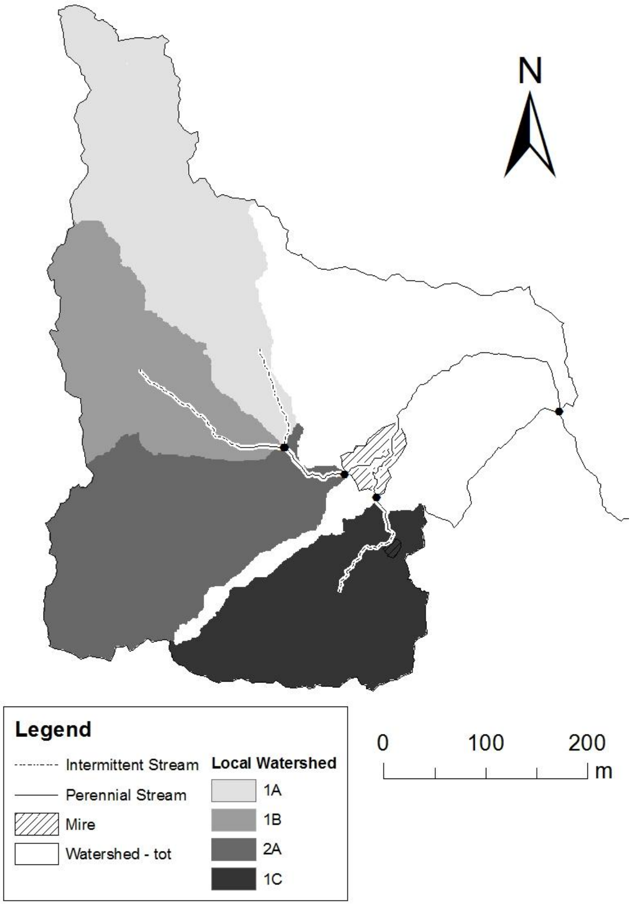

Figure 5. Delineated subcatchments for the outlets of the different streams.

After the main catchment had been delineated the stream network was calculated. The process consisted of using a single flow accumulation algorithm (D8) on the previously calculated flow direction grid. The single direction flow algorithm assumes that all water flow from the focus cell to the downstream cell with the steepest slope. The flow algorithm calculates the accumulated area of all the upslope grid cells draining into a specific cell. By putting a minimum stream initiation threshold for the accumulated cell value to be a part of a stream the network can be derived. For the analysis an upslope contributing area of 8 000 m^2 was used as an initiation threshold as this value gave the output stream network the most resemblance to the observed network in field.

As an alternative to the single directional flow algorithm a multidirectional flow algorithm can be used. The difference is that the latter algorithm does not assume that all water drains into one single neighboring cell but instead distributes the water in different directions into the adjacent cells. An attempt was made to evaluate any differences in the result when comparing groundwater levels to terrain indices using different kinds of flow algorithms. The algorithms used were Deterministic Infinity (Tarboton, 1997), Multiple Flow Direction (Freeman, 1991) and Triangular Multiple Flow Direction (Seibert & McGlynn, 2007).

3.3.4. Relation between terrain indices and groundwater levels

To evaluate the results from the GIS analysis the different indices were compared for correlation with the Spearman’s rank correlation coefficient, r_s. This is a suitable measurement since it is non-parametrical i.e. it is possible to compare parameters with different units. It is also less sensitive for outliers and can be applied to evaluate nonlinear relations. The indices with the highest assigned r_s-value were further used as in-parameters for a linear regression prediction of spatially distributed riparian groundwater levels.

The Spearman’s rank correlation coefficient is calculated by ranking all variables in descending order and calculating the difference in rank, d_i, for all data pairs (x_i,y_i). The value of r_s is then defined by (2)

$$r_s = 1 - \frac{6\mathrm{S}}{\mathrm{n}^3-\mathrm{n}} \qquad \text{n = number of data points} \qquad (2)$$

Where

$$\mathrm{S} = \sum_{\mathrm{i}=1}^{\mathrm{n}} d_i^2$$

From the definition, r_s will take on $-1 \leq r_s \leq 1$ where a value close to 1 means a strong correlation, either positive or negative. A positive value indicates that the rankings follow each other and a negative value means that the rankings are opposite each other. A value close to 0 indicates that there is no correlation between the investigated variables.

If $n \geq 30$ then r_s can be expressed with the test variable u to test for statistical significance of the correlation (Blom & Holmquist, 1998).

$$u = r_s\sqrt{n-1}$$

It is then known that u belongs approximately to a normal distribution and can be tested for significance with a standard procedure by calculating the p-value from the normal distribution.

3.4. EMPIRICAL PREDICTIONS

The output from the Spearman's rank correlation gave an indication on which variables that were more suitable to use for prediction of groundwater levels in the catchment. A linear regression model was fitted to describe the data.

A linear regression aims to describe the data using a least square fitting process. This is a standard procedure in data fitting. The algorithm minimizes the square sum of the residuals, which is the difference between an observed and the calculated value. A linear equation is then fitted to the data. Plotting the residuals gives information on how well the model fits the data.

For the empirical prediction the variables with the best correlation were put into the regression. The comparison with the terrain analysis and the groundwater levels was made for all measuring points and also for the delineated sub-catchments. After evaluation it was only the data from sub-catchment 1B that was used for regression predictions. This narrows down the generality of the conclusions that can be drawn from the empirical predictions but illustrates the importance to assess the local terrain variations.

4. RESULTS

Collected groundwater levels from the installed piezometers were checked for outliers and points with no-data values were removed. Piezometer coordinates determined from GPS etc. were used to extract terrain indices. This allowed comparison between terrain indices and the groundwater data to characterize and possibly observe patterns and correlations.

4.1. FIELD STUDY

4.1.1. Streamflow Records

The streamflow data (fig. 6) indicates that the Kindla catchment responds quickly to rainfall and snowmelt with sharply rising hydrograph and characteristic recession limbs.

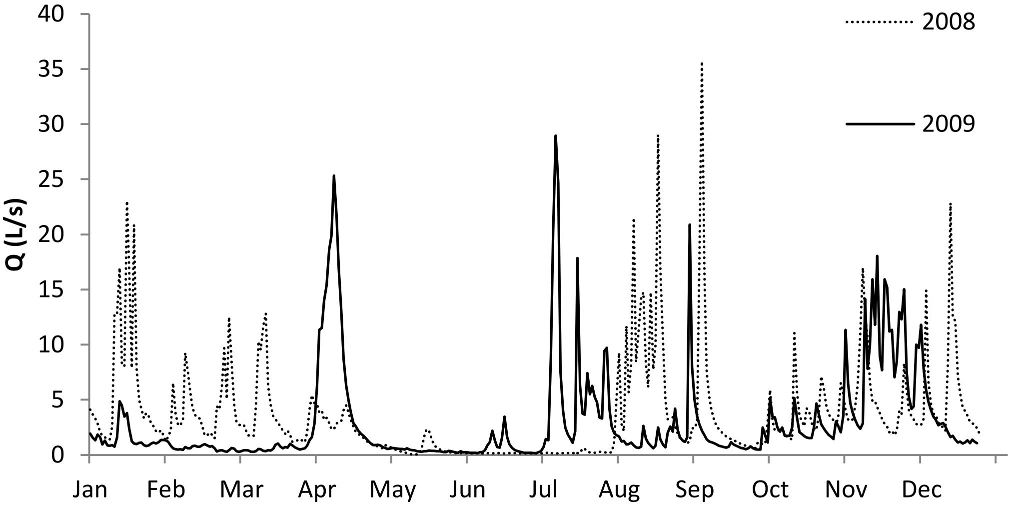

Figure 6. Streamflow data for 2008 – 2009. The values are averaged daily data.

The wetness conditions encountered during field visits were evaluated in relation to historical streamflow in a flow duration curve (fig. 7). The result indicates that the wetness conditions would be dry, humid and wet but in general they are wetter than would be expected if compared to the historical streamflow time series. During the field visits the conditions in the study area were observed as dry in June with little or no water in the streams and wet with a lot of water in September and humid in October.

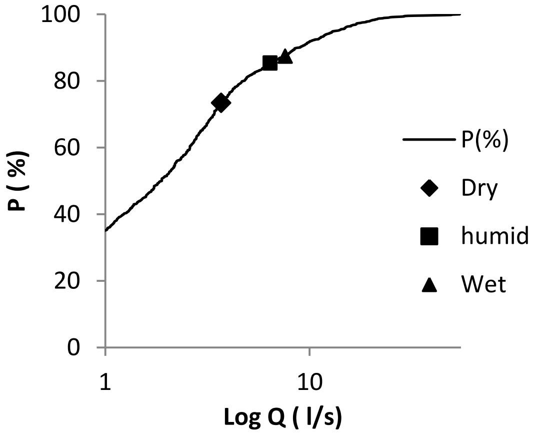

Figure 7. Stream flow during field visits in relation to the whole streamflow pattern. On the y-axis the cumulative probabilities for different stream flows to occur.

4.1.2. Snapshot campaign of riparian groundwater levels

The groundwater data from the piezometers were collected on 3 occasions, June 20th, September 13th and October 26th. The conditions were dry in June, wet in September and humid in October. The measurements of the groundwater levels from the piezometers were made with an accuracy of 0.5 cm. This was judged as a reasonable level considering the measuring error automatically introduced by the need to determine exactly where the ground surface is for the reference measurements needed for data transformation from recorded value into groundwater levels. When the groundcover is blueberry and mosses the exact edge of the surface is not always obvious.

In total 56 piezometers were installed and water was recorded in a maximum of 48 of these during wet conditions and a minimum of 29 units during dry conditions (tab. 1).

Table 1. Summary of distribution of installed piezometers and water recordings in the different streams.

Stream	Installed Piezometers	Water recordings			Tot. Record
		Dry	Humid	Wet	
1A	14	6	10	11	27
1B	18	9	14	16	39
1C	14	9	11	13	33
2A	10	5	8	8	21
Total	56	29	43	48	120

In the further presentation any value presented as *average* groundwater level is the arithmetic average from at least two measurements in the same piezometer. The piezometers with only one recorded value from the three different readings have been removed from the analysis as no data values. The piezometers recordings are in the range of (-5) – (-50) cm with an emphasis on recordings around (- 20) – (-30) cm looking at the general trend from the whole dataset (fig.8).

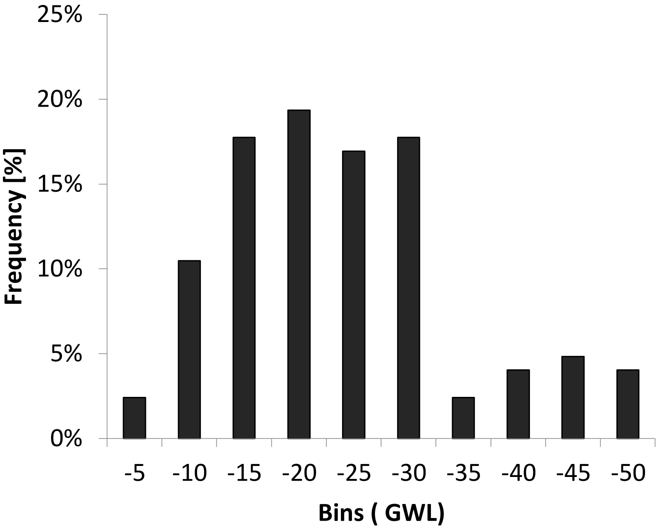

Figure 8. Frequency histogram of all recorded, n =120, groundwater levels from piezometers.

Presenting the groundwater level data in a boxplot using 25% and 75% quartiles and separating the data for each stream gives a better understanding of the internal characteristics of each stream (fig. 9). The most variation is found in stream 1B and the least in 1 C. The values presented are the averages from all of the water recordings along each stream.

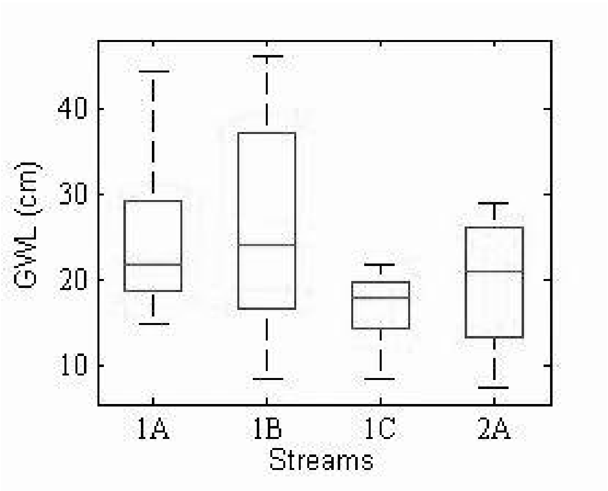

Figure 9. Boxplot of average groundwater level data for the different subcatchments.

The temporal change in average groundwater level, viewed in the different streams, characterizes the different wetness conditions in a visible way (fig. 10). The average results indicate that the 1A and 1B stream have generally deeper groundwater levels compared to stream 1C and 2A. The standard deviation bars show the plus and minus standard deviation as a reference to enhance the difference in groundwater level between the different streams.

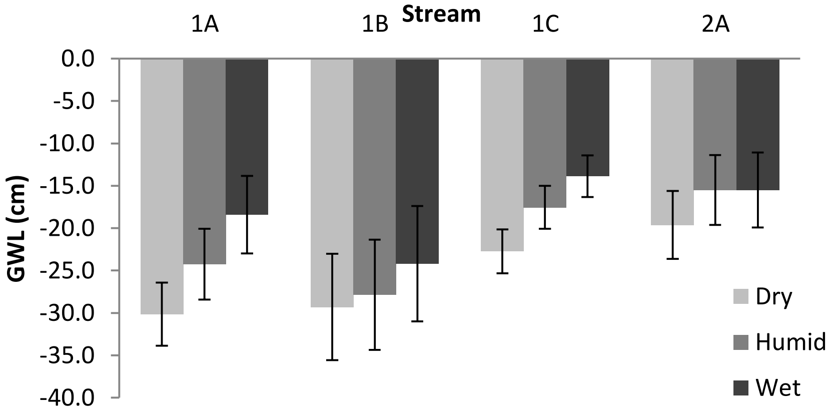

Figure 10. Average groundwater levels for all water recordings along the stream during the different wetness conditions. The bars represent the standard deviation within the streams to present the relative difference within the streams

The perpendicular distances of the riparian extent in the transects were measured and related to the corresponding groundwater levels. The relations indicate that the groundwater level is deeper as the riparian extent becomes narrower (fig.11).

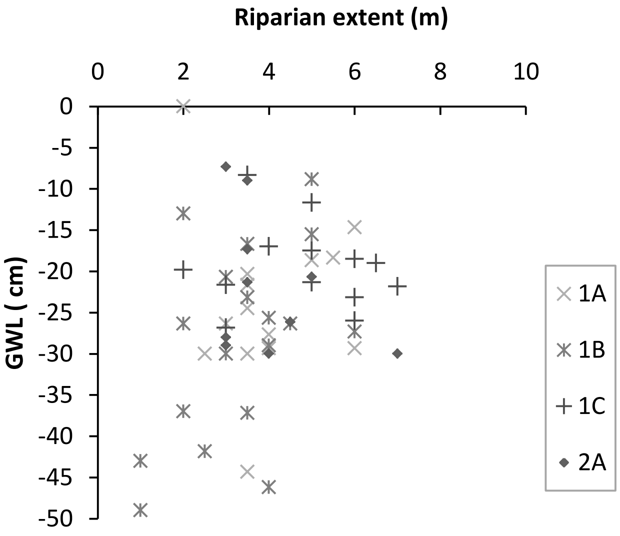

Figure 11. Riparian extent in transects where piezometers were placed. The result indicates that the groundwater level becomes deeper as the riparian zone gets narrower. It is mostly clear for the 1A and 1B subcatchments.

4.1.3. Continuous time series of riparian groundwater levels

The locations for the loggers were chosen with the aim to capture the groundwater levels variability in a dry, moderately wet and a wet location. The final locations were chosen using information from the *TWI* and the upslope area maps and also evaluating suitability when in the field. The result indicates that this aim was not achieved as the result is the opposite of what would be expected with a shallow groundwater-level in the supposedly dry site (L3) and deeper water table in the assumed wet sites (L1, L2). The loggers have recordings within the range of (-5) – (-20) cm (fig.12) which is generally shallower groundwater level than recordings from the piezometers (fig. 8)

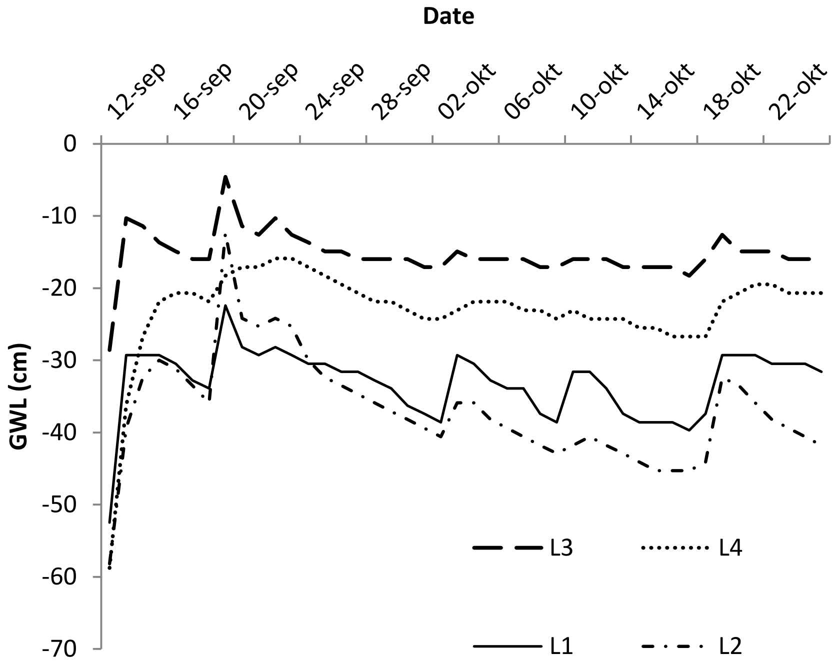

Figure 12. Continuous time series for the well loggers. The values are averaged daily levels.

A presentation of the logger time series and the corresponding streamflow for the measuring period illustrates the catchment response (fig.13). Looking at the patterns it can be noted in the comparison between the deeper groundwater tables (L1, L2) and the shallower (L3, L4) that the deeper groundwater tables has considerably more temporal variation with clear flowpeaks elevating the water table quickly and with a slower recession after the peak. The shallow sites have a more smoothened profile with the same alteration in time which is expected as the catchment is small and can be assumed to have the same response time, but with about half the amplitude.

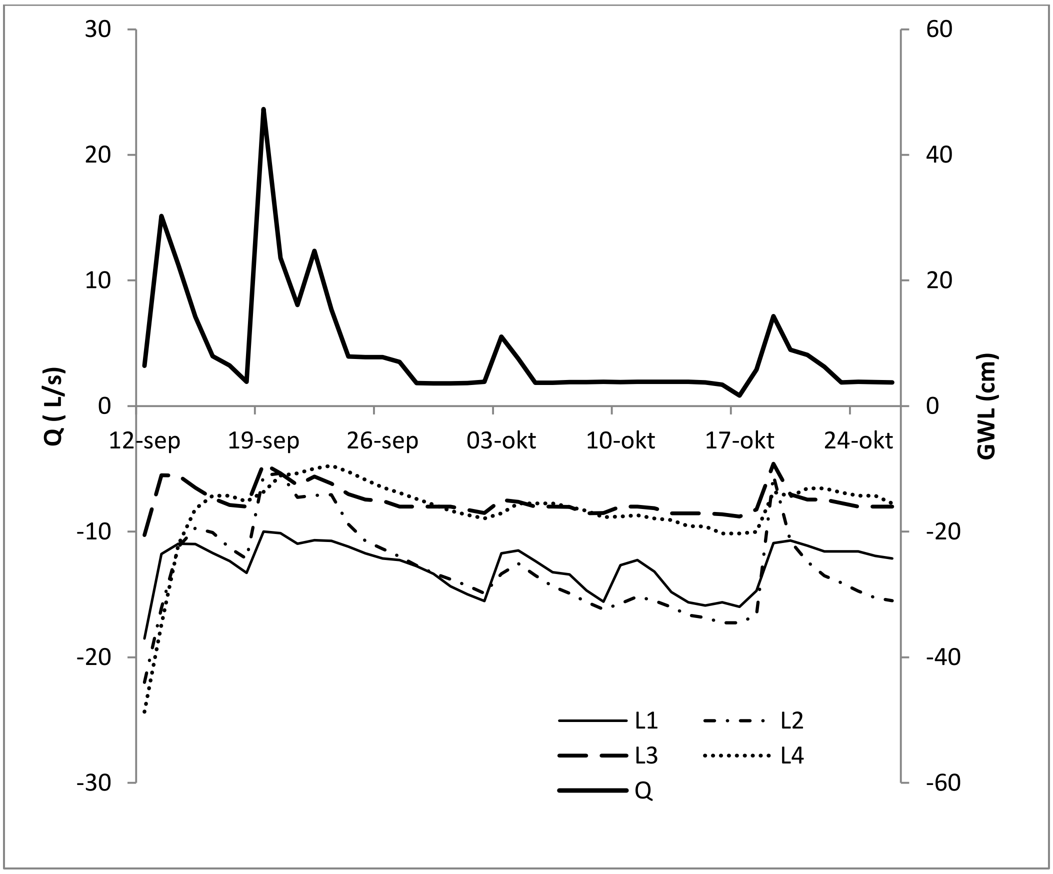

Figure 13. The GWL loggers and corresponding streamflow data from field station. The flow peaks and groundwater level peaks appear to be synchronized.

Relating the results from the loggers to the streamflow recorded at the field station during the same measuring period presents that the relation between groundwater levels and streamflow has the characteristic logarithmical increase in streamflow with increasing groundwater levels (fig.14). The outliers for the L4 logger (upper right figure) are values from the beginning of the data series for that logger that were considered unrepresentative values due to effects from the installation process.

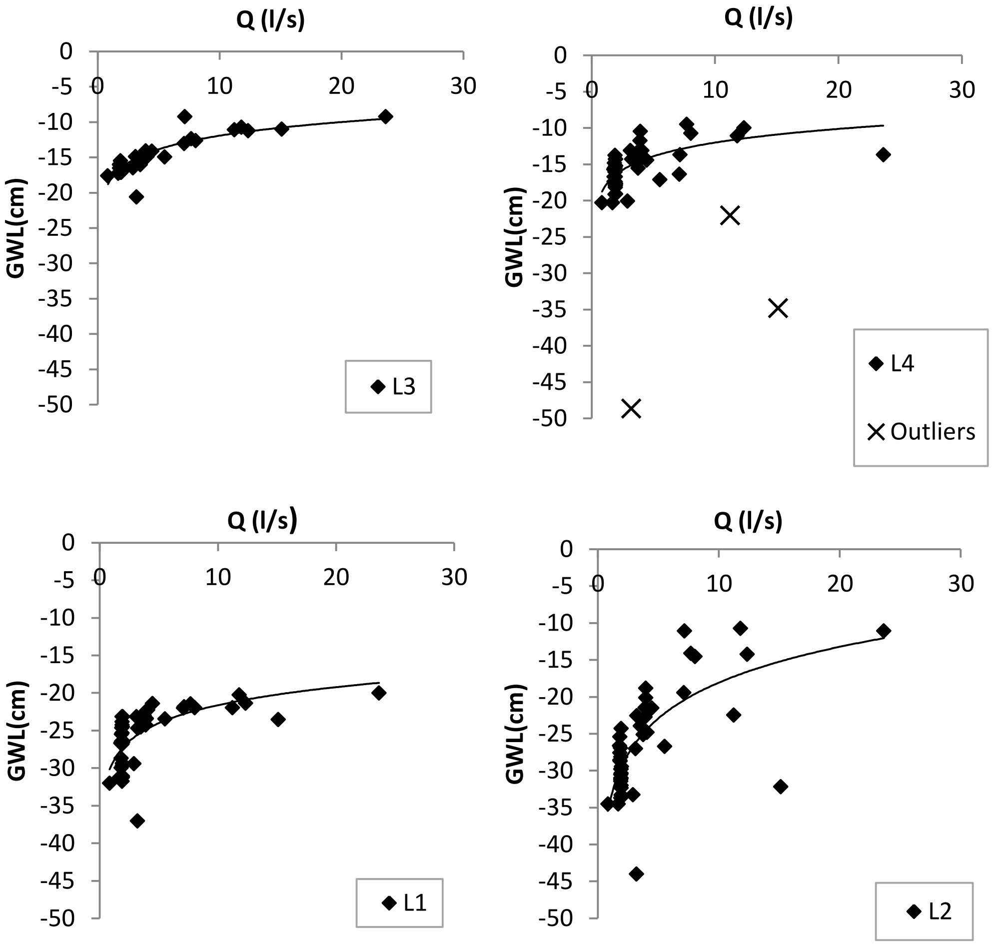

Figure 14. Groundwater level,GWL, and stream flow, Q, for the different loggers.
R^2 – L3:0.75, L4: 0.44, L1: 0.42 and L2: 0.50.

4.2. TERRAIN ANALYSIS

4.2.1. Spatial variation of groundwater levels along stream reaches

The largest change in groundwater level along the flowpath illustrates the spatial variability of the groundwater levels (fig.15). The number of data points differs between the streams and also the stream path length. The presented data is the difference between the dry (June) and the wet (September) conditions where a positive change means that the groundwater table has risen from the dry to the wet condition, and vice versa for a negative change.

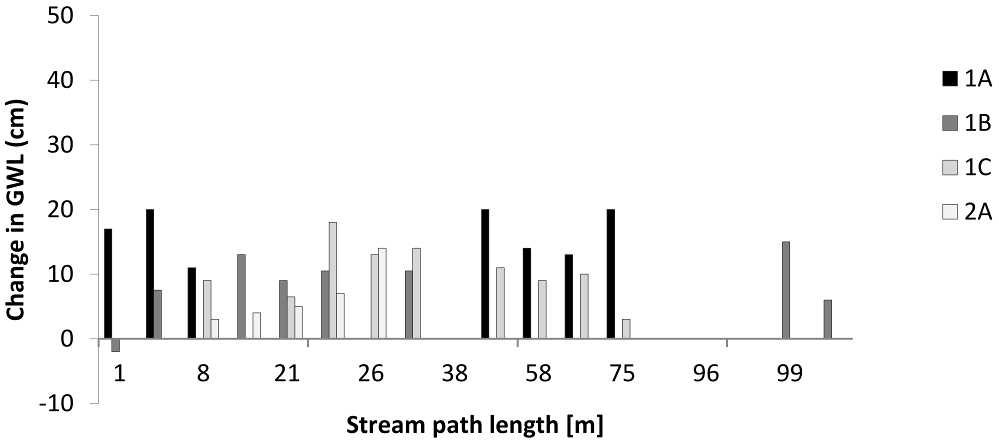

Figure 15. The change in groundwater levels in the piezometers along the streams between the dry (Jun) and the wet (Sep) conditions. The measuring points are plotted against the flowpath length.

Knowing that the topography is a major driver for groundwater movements it is interesting to review the elevation profile for the different subcatchments and note the severe difference in slope (fig.16). The 1A and 1B catchments are much steeper and on a higher hillslope about 35 m vertically above the 2A and 1C catchments.

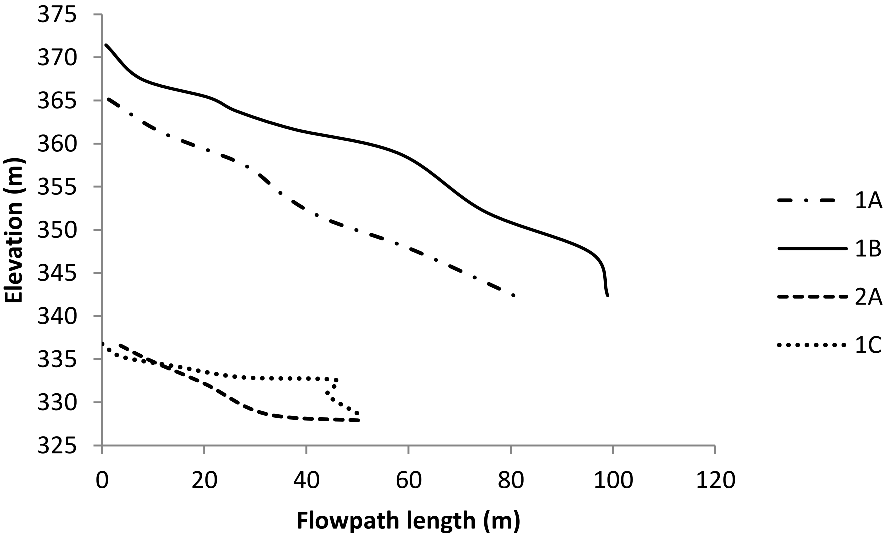

Figure 16. Elevation for the different subcatchments plotted against stream flowpath.

4.2.2. Catchment-wide relations between terrain indices and groundwater levels

The Spearman's rank correlation coefficient r_s was used to quantify the degree of correlation between groundwater levels and different terrain indices. The overview showed in general strongest correlation for the 5 m resolution for the different terrain indices (tab. 2). Tables for the 1 m and 10 m resolutions are presented in Appendix A. The correlation was calculated varying the groundwater levels used for comparison, average here means the average from all field visits and the coding *dry*, *humid*, and *wet* are the groundwater levels from the separate visits. The correlation was strongest for the slope during wet conditions and for the $\kappa_{profile}$ during dry conditions (tab. 2).

The initial evaluation of different flow algorithms, affecting the *a* and *TWI*, did not show any significant difference in correlation with groundwater levels, and was not included in the further analysis. The decision was made to proceed using only the *deterministic infinity* flow algorithm for the remaining analysis.

Table 2. Spearman's rank coefficient, r_s, for correlation between calculated terrain indices and groundwater level. The average column means the average groundwater level of all sites with at least two water registrations. n = sample size of piezometers with water registration.

5m

Terrian Indices	**Average** n = 43	**Dry** (Jun) n = 29	**Humid** (Oct) n = 43	**Very wet** (Sep) n = 48
a	0.02	0.01	0.04	0.01
Slope_(triangular)	0.46	0.30	**0.49**	**0.49**
Slope (polynomial)	0.39	0.13	0.42	0.41
$\boldsymbol{\kappa_{Profile}}$	0.15	**0.40**	0.19	0.19
κ_{Plan}	-0.16	-0.14	-0.19	-0.15
TWI	-0.12	-0.13	-0.10	-0.15

The correlation within the terrain indices was also assessed to evaluate any internal effect between the variables. The highest correlation was found between the slope and the curvature indices which were expected as the curvature indices origins from the slope calculations (tab. 3).

Table 3. Correlation between terrain indices.

	a 1m	***a*** 5m	***a*** 10m	**Slope 1m**	**Slope 5m**	**Slope 10m**	**K_{plan} 5m**	**$K_{profile}$ 5m**
***a*-1m**	1	-0.14	-0.13	0.16	0.29	0.22	0.14	-0.34
***a*-5m**		1	0.30	0.10	-0.01	0.05	-0.05	-0.29
***a*-10m**			1	-0.07	-0.25	-0.12	-0.35	0.22
Slope-1m				1	0.77	0.74	0.74	-0.28
Slope-5m					1	0.86	0.86	-0.43
Slope-10m						1	0.85	-0.20
K_{plan-} - 5m							1	-0.31
$K_{profile}$ - 5m								1.

A graphical presentation of the terrain indices show again that the slope and $\kappa_{profile}$, for the 5 m resolution gave the strongest correlation. The result indicates a deeper groundwater table with greater slope (fig. 17) and a weak correlation that a more concave profile will increase the distance to the groundwater level (fig. 18).

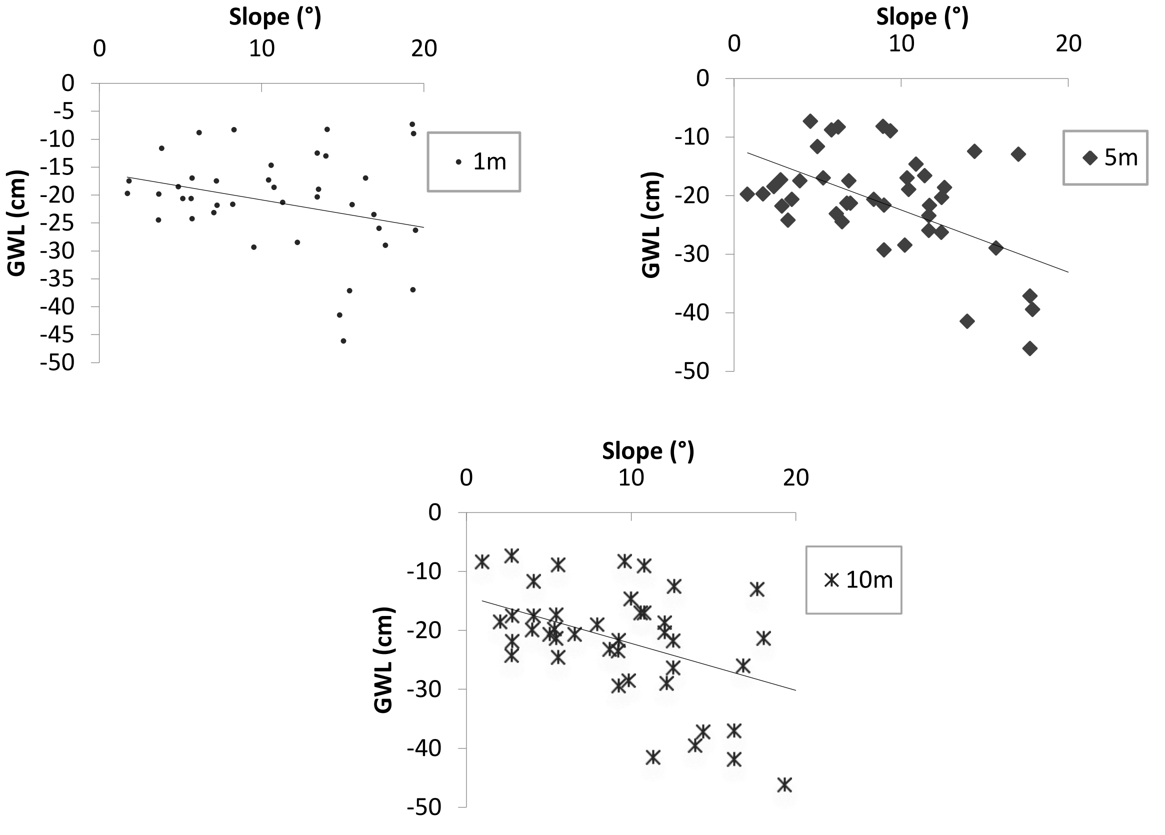

Figure 17. Average groundwater levels plotted against slope for the three different resolutions. The 5 m resolution gave the best correlation result. The r^2-values were the following: 1 m: 0.11 , 5 m: 0.34 and 10 m: 0.20

The $\kappa_{profile}$ is presented for the 5 m resolution (fig. 18) as the other did not show any distinct patterns which indicates that there is a threshold for the terrain features to be caputred in this resolution. The pattern indicates very weakly that a concave profile would generate a deeper groundwater table with the profile curvature values on the negative side of the scale.

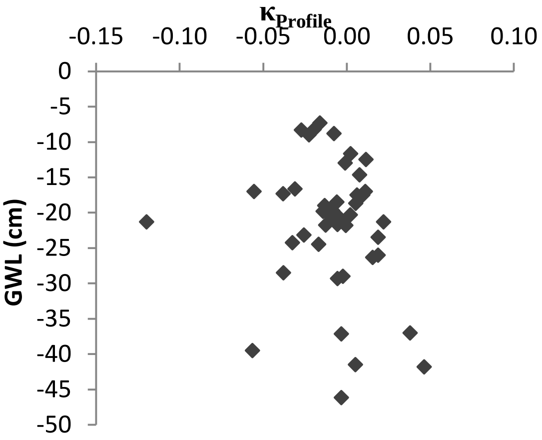

Figure 18. Profile curvature compared to average groundwater level.

The accumulated upslope area, *a*, did not give any significant correlation for the whole catchment and this is what is thought to affect the *TWI* mearsurements to not give any correlation. An increasing upslope area with coarser resolution could be detected. The values for *a* are presented as the natural logarithm of the measurements, ln *a*, in order to have easier comparable figures (fig. 19). The result from the *TWI* is presented in Appendix B.

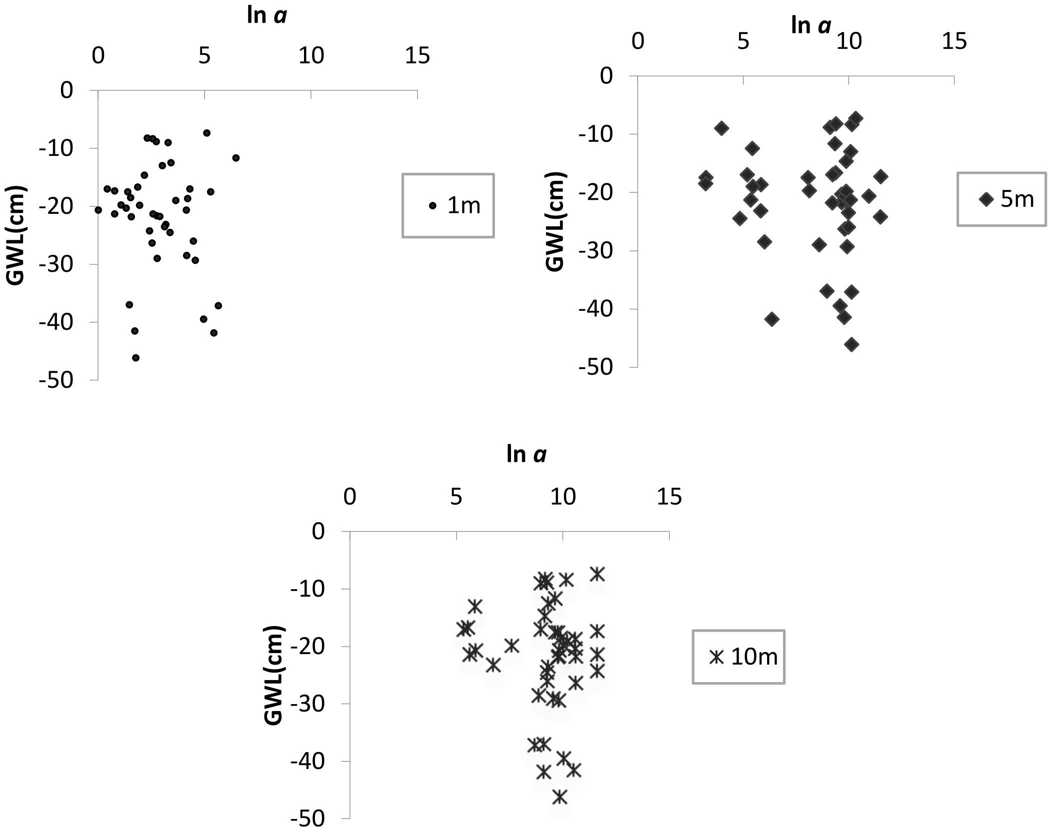

Figure 19. The natural logarithm of Uppslope area, *a*, against average groundwater levels for the three different resolutions. There cannot be seen any correlation and an increasing ln *a* with decreasing resolution. The r^2 values were the following: 1m: 0.02, 5m: 0.01, 10m: 0.01

For each stream cell the upslope contributing area *a* from the left and right side of the stream were calculated. Comparing these calculations illustrates the spatial distribution of upslope contributing areas, i.e. the lateral inflow from each side of the stream (fig. 20).

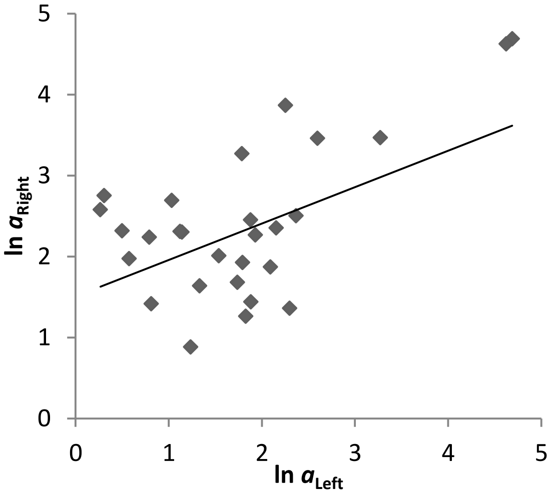

Figure 20. Evaluation of ln *a* calculations from left (x-axis) and right (y-axis) side of the stream cells. $R^2 = 0.215$

It can be seen that inflow from the left side appear to correlate weakly with inflow from the right side from the calculated lateral inflow estimations. For the graph the stream cell in the midpoints of the measuring transects has been used. When comparing with the groundwater levels on each side of the stream (fig. 21) it can be noted that the ln a_{Left} and ln a_{Right} seems to have better correlation than the ln a calculations for the main catchment.

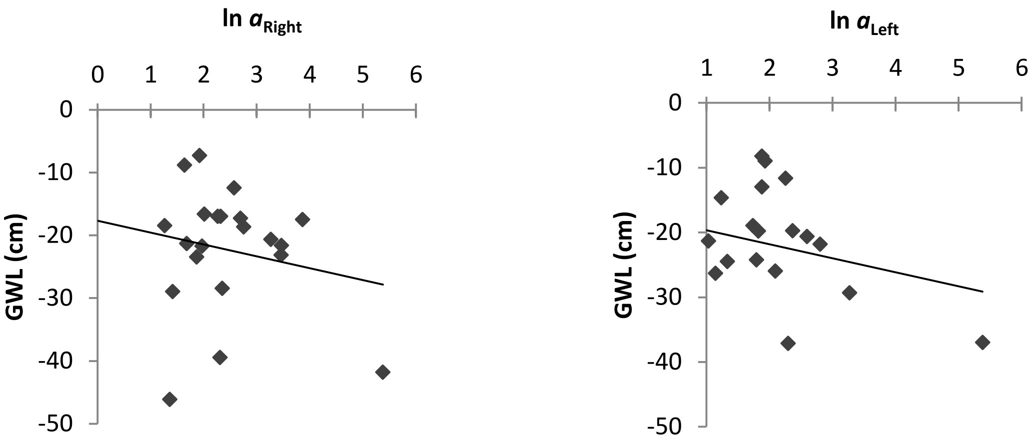

Figure 21. ln.a_{Left} and ln a_{Right} in comparison to groundwater levels. The left side had slightly stronger correlation that the right side, however not significant. R^2: Left : 0.067, Right : 0.046.

4.2.3. Subcatchment relations between terrain indices and groundwater levels

Evaluating the subcatchments gave a better illustration of the groundwater levels spatial variation in the catchment. The steeper catchments, 1A and 1B, had stronger correlation for the slope in general and the 1B had the strongest correlation with both slope and κ_{profile}.

For subcatchment 1B the slope showed a correlation to groundwater levels with $r^2 = 0.48$ (fig. 22) and the curvature a correlation of $r^2 = 0.32$ (fig. 23).The remaining subcatchment correlations did not give any significant results and are not presented.

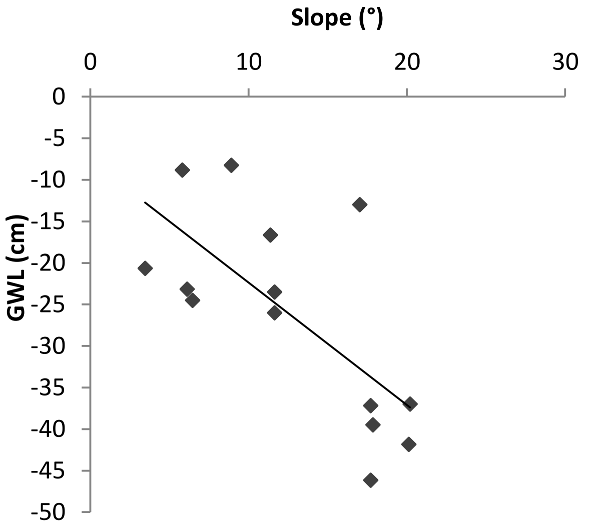

Figure 22. Slope and average groundwaterlevels for subcatchment 1B. r^2= 0.48.

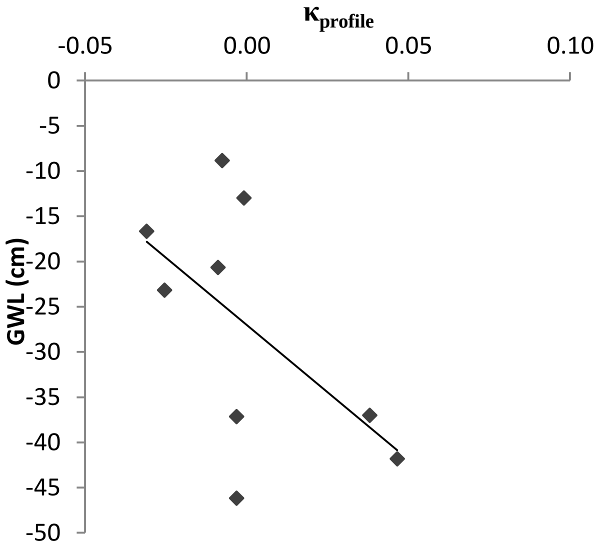

Figure 23. κ_{profile} and groundwater levels for subcatchment 1B. r^2 = 0.32

The 2A subcatchment did not show any correlation and the 1C subcatchment showed in contrast to subcatchment 1B almost a positive correlation with slope (fig. 24).

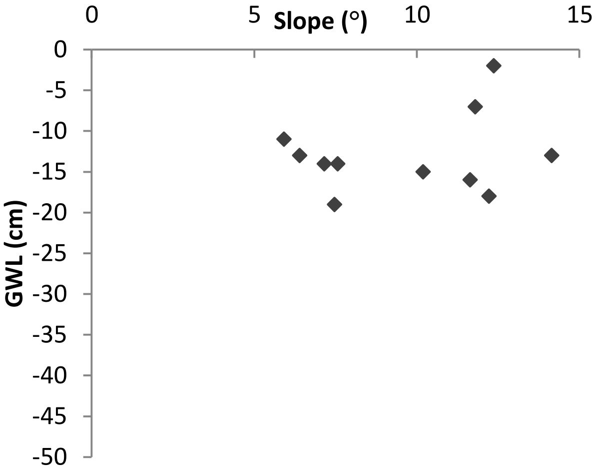

Figure 24. Relation between slope and groundwater levels in subcatchment 1C. $r^2 = 0.055$.

4.3. EMPIRICAL PREDICTIONS OF GROUNDWATER LEVELS

The result from the linear regression gives a fitted curve to the input-data for the linear regression. From the terrain analysis it was only slope that had the statistical significance to be used as an in-parameter. Plotting the residuals gives an indication that the model fits the data in a correct way (fig. 25). The resulting curve had the equation y =1.4 x – 8.7. The residual plot indicates that the data does not seem to have any internal pattern and can thus be assumed a correct linear model.

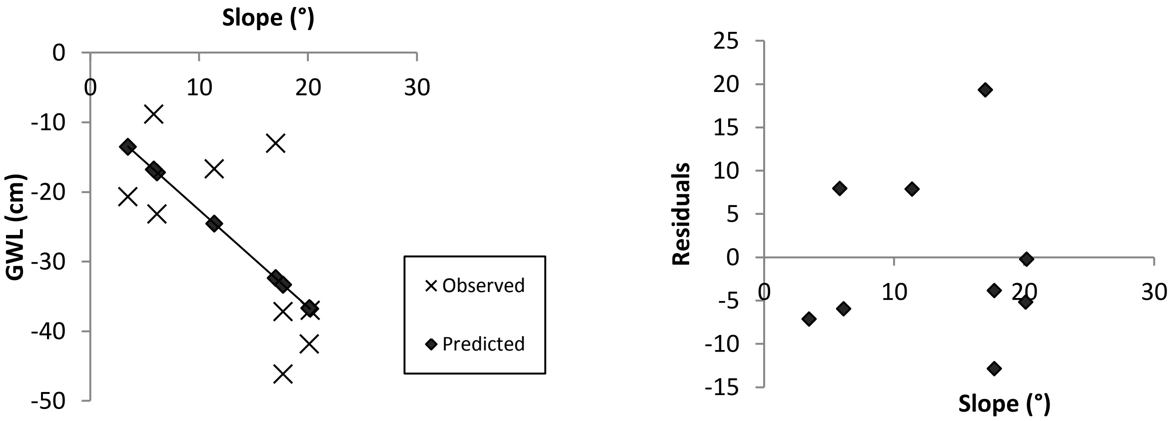

Figure 25. Result from the regression model with observed and predicted values, left, and resuduals plotted against observed slope values, right.

5. DISCUSSION

The aim for this study was to characterize and predict spatial and temporal variation of shallow riparian groundwater tables in a small, forested headwater catchment in Sweden. Some of the spatial variation found in the field study could be linked to the topography quantified by terrain slope and profile curvature indices. The other terrain indexes that were tested in the study upslope unit area, *a*, and *TWI* did not correlate with groundwater tables in any significant way.

5.1. STREAMFLOW RECORDS

The evaluation of the historical streamflow records only looking at the streamflow time series indicated that the field study should have captured dry conditions in June, wet in September and humid to wet in October. Evaluating from a percentage of the occurrence of the streamflow during the field visit however indicated that the dry conditions in June were more likely to be dry to moderately dry. The visual observations of the field conditions in the first order subcatchments in the study area during the visit in June suggested a dry label for the wetness condition. This could be an effect from a buffering function of the mire that is situated between the upper first order streams and the third order stream where the field station is located. The mire can store and drain a considerable amount of water to sustain a relatively high streamflow even if the conditions upstream of the mire are considered dry.

5.2. FIELD STUDY

The results from the spatial mapping with piezometers indicated a deeper groundwater surface with a steeper slope for the study catchment. The temporal variation could also be seen to increase with steeper slope. The study catchment has considerably varying topography in the different subcatchments. In the 1A and 1B catchments the topography is steep with boulder features and generally shallow soils. The 1C catchment is located on in its own plateau with very gentle slope and wide riparian zones and in the 2A catchment the terrain is moderately steep. The comparison between groundwater variations along the flowpath and the topographic profile for the different subcatchments also indicated more temporal variation with steeper slope. This is to be expected since a steeper slope will render more drainage and the effect is enhanced when there is a shallow soil. This can be seen from the groundwater level time series results from the automatic loggers.

The comparison of groundwater levels and riparian extent in the transects showed that the groundwater tends to be deeper in more narrow riparian zones. If the channel is more concave and narrow this will constrain the possibility for a wide riparian zone as a higher stream bank will create a physical border.

In contrast to the results from the distributed snapshot campaign the results from the logger data indicated the opposite relationship, i.e. the logger placed in a steeper slope recorded shallower groundwater tables compared to the three other loggers. The temporal variation was though consistent with the results from the piezometers. The explanation lies in part with the problems encountered during the installation of the logger. The logger site with steeper slope was chosen with the aim to find a location with a deeper groundwater table compared to the other loggers. However, during the installation it was not possible dig deep enough due to difficulties with rocks and roots and simply a shallow soil before hitting bedrock. The shallow soil then leads to a very shallow water table. It is also true that the logger recordings were collected during the wet period (September to October) which would explain generally shallower groundwater levels. It should also be noted that it is difficult to make conclusions from one local logger against the result from the piezometers that are much more well spatially representative.

5.3. TERRAIN ANALYSIS

The results of terrain analysis depend strongly on the positioning of the measuring points as the spatial distribution is a key factor in the process. If the measuring points are uncertain in the DEM it is hard to identify reliable relations between the calculated indices and the groundwater levels. It is therefore very unfortunate that the positioning part in this study did not achieve the accuracy hoped for. At the best the error estimation can be expected to be ± 5 m for the final positioning which could also be contributing to the fact that the 5 m resolution gave the best result from the terrain analysis. This would not be a problem if the goal was to capture the relations within the hillslope, with bigger features to capture, but since the focus was on the riparian zone, that had a range between 1 – 8 m. This is a problem for the study.

The issue of scale is also important here as it was found that the best scale was 5 m instead of the original 1 m resolution DEM. It could be reasoned that the results should improve with higher resolution but that is not always the case (Sörensen & Seibert, 2007). The strongest correlations were found in sub-catchment 1B, and it can be argued that it was because this area had the most distinct features in the landscape to be captured i.e. there was enough variation in the landscape captured that could explain the variations in the groundwater levels while in the other subcatchments the landscape features were not distinct enough.

Comparing 1B to the neighboring subcatchment 1A the slope profiles were similar but the same correlation with groundwater could not be seen in 1A. This is most likely because the 1A catchment did not have the same clear channel profile as in 1B. Further down the 1C catchment was too flat and the curvature too smooth to detect any correlation with the groundwater levels.

The relation between curvature measures and groundwater levels was also considered by Günter et al., (2004) who found that the curvature explained the saturated areas well for clearly defined channels but less well for wider valley bottoms with less clear channels. This is comparable to the results found in this study. It can also be seen that in general the best correlations were found during the wet period. This can usually be expected when using algorithms originating from topographic information since the more water there is, the more important will the slope be when other factors such as soil and vegetation have less impact on the flow.

The correlation results between the terrain indices and the groundwater levels were both expected and unexpected. The upslope area a had surprisingly low correlation to groundwater levels but it is interesting to see that despite no clear correlation the side distinguishing a_{Left} and a_{Right} calculations indicated better correlation from visual inspection of graphs. There was also some correlation to be found between the calculated lateral inflow from each side which is not always expected.

The poor results of the upslope area were most likely the reason to the uncorrelated results from the *TWI* calculations. The *TWI* has been used to predict saturated areas and has been known to overestimate the wetness in flat terrain, (Günter, et al., 2004). The reason could be that when calculating the flow into a single cell in a flat terrain it will receive an unlikely large upslope area combined with a low value for slope which will render an overestimation of the wetness index.

It is however surprising that the ln a and *TWI* did not predict better for the steeper terrain in this study. An explanation could be the relationship between slope and soil depth. In the upper part of a hillslope the soil is more exposed to erosion, and with a steeper slope the capacity to retain the soil is decreased. Further down where the terrain flattens out the soil layer is generally thicker. If assuming that the groundwater follows the bedrock consistently along a hillslope it could be that an observed deeper groundwater table is simply an effect from a deeper soil although it should be a shallower groundwater level when having a gentler slope. This means that a location in a flatter terrain and supposedly deeper soil will then have two counteracting processes in the same location – flat terrain gives shallower groundwater levels while at the same time deeper soil gives deeper groundwater levels. This will create problems when using the *a* and the *TWI* calculations as a predictor in a terrain that does not have a uniform soil layer.

For the Spearman´s rank correlations it was only the slope variable that proved to be statistically significant which means that the other terrain indices only explained very little of the variations in the groundwater levels. The difference in sign for the different correlations should be noted, though. The correlation for *TWI* showed a very weak correlation but was still on the negative side which would be expected since a greater value for *TWI* should indicate a shallower groundwater table and thus a smaller distance to the surface. The curvature correlations are more interesting as they are opposite to each other indicating that a profile that is convex in the down slope direction and concave in the perpendicular profile should give a deeper groundwater table. The κ_{Profile} had though stronger correlations indicating that this is a more important index for local groundwater level variations within the riparian zone.

The correlation between the different indices showed high correlations between the slope and curvature indices which were expected since the latter are calculated from the change in slope. The correlations were still considered low enough so as to keep the indices in the comparison with groundwater levels. If the correlation had been too high the secondary indices would not provide any new information. It should also be noted that the curvature indexes were only calculated for the 5-m resolution which creates the unexpected negative correlation between the curvature indices and the 1m resolution slope calculations.

For future studies it could be interesting to evaluate if there can be found a threshold value for slope where the *a* and *TWI* calculations can be used as predictors. These indices have been used in the past (Grabs, 2010) where the result indicated that the terrain indices could be used as groundwater level predictors. The result from this study illustrates the importance of evaluating different forces acting on variation in groundwater levels. It would be interesting to locate more readily available indicators to assess and weight the importance of e.g. slope compared to soil layer thickness. A further problem to solve would then be to find spatially distributed soil thickness measurements as this would require a lot more fieldwork.

6. CONCLUSIONS

These results indicate that a steeper slope in the riparian zone will give a deeper and more varying groundwater table spatially as well as temporally. It seems to be of importance to not only look at the greatest downslope angle but also to look at the curvature as a more distinct channel can have markedly different groundwater variations compared to a wider channel. Even though every catchment is unique with local variations a general assessment can still be found by combining the downhill slope and the profile of the slope. Even with correlating terrain indices the problem then remains to weigh the relevant processes against each other to be able to predict the groundwater level for a specific terrain.

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APPENDIX A

Results from the Spearman’s rank correlation for the 1m and 10 m resolutions.

1m

Terrain Indicies	**Average** **n =43**	**Dry** **(Jun)** **n=29**	**Humid** **(Oct)** **N=43**	**Wet** **(Sep)** **n=48**
Ln A	0.11	-0.12	0.13	0.09
Slope_triangular	0.26	0.08	0.24	0.35
TWI	0.00	-0.01	0.05	-0.06

10m

Terrian indices	**Average** **n = 43**	**Dry** **(Jun)** **n = 29**	**Humid** **(Oct)** **n = 43**	**Very wet** **(Sep)** **n = 48**
Ln A	0.08	0.17	0.26	0.05
Slope_triangular	0.38	0.28	0.41	0.42
TWI	-0.21	-0.22	0.10	-0.20

APPENDIX B

Graphical results from the TWI calculations.