

Using LiDAR to model rating curves

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LICENTIATAVHANDLING I
NATURGEOGRAFI

2012

Abstract

Fresh water is an essential, highly limited, and vulnerable resource that is increasingly under pressure. Most of the fresh water is held below ground or in glaciers and polar caps and is therefore difficult to access for monitoring. Strategies to assess threats due to for instance social processes and climate change, involve monitoring of streams and rivers. In remote locations, it is difficult to obtain streamflow information because of the difficulty making sufficient discharge measurements. This thesis investigates the feasibility to constrain a fluid mechanics-based flow model for defining rating curves with remotely sensed topographic data from airborne LiDAR scanning. A near infrared LiDAR scan was carried out for an 8-m wide channel in northern Sweden. The topographic information from this LiDAR scan along the 90-m surveyed reach was used to define channel geometry above the water surface. To fill in the channel bed topography below the water surface we used a detailed ground survey to create a hybrid model for comparison to a simple assumption of a flat bottom channel. Based on the boundaries of confidence intervals calculated from the direct measurements, we show that for the channel considered the simple flat bottom assumption performs just as well as the hybrid model with regards to estimating direct discharge measurements. The mismatch between the two models was greatest at low flows and may be associated with unresolved submerged bed topography. This deficiency, while rather small, could potentially be remedied by scanning during periods of low flow, or use other techniques such as multi-frequency bathymetric LiDAR or passive optical remote sensing that offer alternative ways for generating the necessary topographic information. The cost of monitoring is expensive, leading to reduced effort while the need for monitoring is increasing. The use of LiDAR-based techniques for modeling rating curves may offer alternative ways for monitoring streamflow, which can open possibilities to overcome this problem.

List of papers

This thesis consists of one paper and a summary, which includes some additional background and discussion:

Nathanson, M., Kean, J. W., Grabs, T. J., Seibert, J., Laudon, H., Lyon, S. W.: Modeling rating curves using remotely sensed LiDAR data. *Accepted January 2012.*

Related paper not included in the thesis

Lyon, S. W., **Nathanson, M.**, Spans, A., Grabs, T., Laudon, H., Temnerud, J., Bishop, H. K. and Seibert, J.: Spatiotemporal specific variability in a boreal landscape. *Submitted WRR.*

I made all fieldwork including planning, preparation of equipment, and preparation of collected raw data for the modeling of rating curves. I did the modeling of rating curves under supervision of Dr. J W Kean and my main supervisor Dr. Lyon. Statistics were calculated in collaboration with Jan-Olov Persson at Statistiska forskningsgruppen, Matematisk statistik, Stockholm University. I authored the main part of the manuscript of the first paper, under guidance of all co-authors.

Introduction

Monitoring stream water

Fresh water is an essential resource. In today's society, this limited resource is subjected to many stresses (e.g., population growth, industrialization, urbanization, and climate change). As such, there is clearly a need for strategies to assess the environmental and societal threats to fresh water (e.g., Hossain et al., 2011) that capture the key factors that influence water quality and quantity. A first step to such strategies is often monitoring of fresh water resources to gain insight to availability.

This can be problematic, however, as most fresh water is held below ground in aquifers and difficult to monitor. The fresh water held in glaciers and polar ice caps (the majority of the global surface fresh water) is also difficult to monitor due to limitations in accessibility. Therefore, a large part of our current fresh water resource monitoring effort is put towards measuring flows in streams and rivers since these flowing waters are visible and accessible to monitor.

As streams and rivers transfer water from the landscape back to the oceans (Mosley and McKerchar, 1992), they integrate water from across the landscape. Streamflow (or discharge) therefore has relevance across many disciplines and processes including, for example, the terrestrial export of compounds (Dawson et al., 2008; Destouni, et al., 2008; Schlacher et al., 2009), water chemistry (Lohse et al., 2009), carbon fluxes (Agren et al., 2007; Lohse et al., 2009), and the riverine export of nutrients to the sea (Laznik et al., 1999; Reigstad et al., 1999; Schlacher et al., 2009). Monitoring discharge and its variability across the landscape is key to our understanding and estimation of, not only biogeochemical export (Temnerud et al., 2007; Lyon et al., 2010), but also of aquatic ecosystem health (Laudon and Buffam, 2008), flood amounts and frequency

(Wilson et al., 2010), and water resource management (Koutsouris et al., 2010). So, even though streams and rivers represent a small part of the total global fresh water supply (0.7% (Shiklomanov, 1993)) streamflow itself can be considered a strong candidate for the most important observation in hydrology and plays a key part in developing strategies to aid in the assessment of environmental and societal threats to fresh waters.

At a global scale, however, many streams and rivers are currently not monitored (Bishop et al., 2008). In particular, little is known about stream headwaters and scaling-up the role of small catchments (Temnerud and Bishop, 2005). This makes it difficult to estimate current discharge let alone future changes from these smaller systems (Baggaley et al., 2009). While the unawareness about the status (environmental and chemical) in most running waters and the effects of human activities and climate change calls for extended monitoring of smaller catchments, the current trend in streamflow monitoring worldwide is for decreased observations and fewer locations of direct monitoring of streamflow (e.g., Bring and Destouni, 2009; Brown, 2002; Fekete and Vörösmarty, 2002). To counteract this trend, there is clearly a need for more cost-effective methods for monitoring of stream discharge that involve fewer direct observations.

How can we monitor stream discharge?

Discharge is typically calculated from flow measurements. Flow in open channels correlates with water surface elevation (or the 'stage') in the stream. A common approach for monitoring streamflow is to transform measured stage heights into streamflow using a rating curve (e.g. Herschy, 1993a). The rating curve describes the relationship between measured stage and discharge. Rating curves can be developed for

open channels with controlled cross-sections or for open channels with natural cross-sections.

For open channels with constructed hydraulic structures (e.g. V-notch weirs or flumes) that control the cross-section, rating curves are quite simple to develop and model as these structures restrict flow conditions and impose stable stream cross-sections allowing for definable physical relationships between stage and discharge. Since constructing hydraulic structures is often quite an investment, rating curves in smaller streams are more commonly developed for natural cross-sections. Rating curves in open channels with natural cross-sections are often estimated using field-based observations of discharge. One common technique to measure discharge in the field is the velocity-area method (e.g. Herschy, 1993b) where water velocity is measured using a current meter over a stream's cross-sectional area. Repeating this measurement over different flow rates and, thus, different stages allows for construction of a rating curve. Tracer injection methods like the commonly applied salt slug injection method (e.g. Moore, 2005) offer alternatives to the velocity-area method for measuring discharge in the field.

Regardless of how discharge is measured, the traditional procedures for developing a rating curve in natural cross-section channels remain the same. The field-based measurements of flow are correlated with stage allowing for empirical modeling of rating curves. Traditional approaches for establishing and maintaining such empirical rating curves, however, are often time consuming because flow has to be measured over a range of stages. During flooding and periods of high flow, in particular, measurements of flow in open channels are nearly impossible to carry out and can often be hazardous.

What about modeling rating curves?

As opposed to above outlined empirical methods, rating curves in natural channels can also be modeled from theoretical calculations with flow resistance equations that allow the discharge or the flow velocity to be related to hydraulic geometry. One well-known and common example of such a theoretical approach is the Manning equation (Manning, 1891) and its related expressions such as the Chezy or Darcy-Weisbach equations. These equations have been used for more than a century for modeling flow in open channels. A common theme (and limitation) in these flow resistance equations is their reliance on empirical roughness coefficients (e.g. Manning's coefficient of roughness) for estimation of discharge. In practice, these empirical roughness coefficients suffer from a high degree of uncertainty and are fairly subjective in nature. So, defining them is problematic and even when experts carry out the estimation, the resulting roughness coefficient can vary considerably (Burnham and Davis, 1990). The uncertainty that arises from estimating empirical roughness coefficients is one of the most important sources of error in the application of traditional flow resistance equations in natural channels (Lopez et al., 2007).

More recently, techniques have been developed that allow for the modeling of rating curves in natural channels without reliance on such empirical roughness coefficients. Kean and Smith (2005, 2010) put forward a theoretical physically-based method for modeling rating curves. Rather than assigning an empirical roughness coefficient, the method relies on geometric data of the stream obtained using a ground survey to estimate channel roughness. Although the Kean and Smith (2005, 2010) flow model offers a great alternative to other methods like Manning's, theoretical modeling of rating curves requires knowledge of channel geometry and roughness that can often be time intensive or logistically difficult to obtain, especially in remote areas. This highlights the

need for new methods for establishing or estimating channel characterizations such that they can be useful for developing rating curves capable of being used in stream and river monitoring efforts.

A conceptual study for pathways forward

This thesis seeks to explore one such method. The thesis considers the possibility to constrain the Kean and Smith (2010) rating-curve modeling method with remotely sensed, airborne Light Detection And Ranging (LiDAR) data. Combining LiDAR into the procedure of Kean and Smith (2010) has the potential to create a useful application for estimation of rating curves and may allow for an easier and more cost effective approach for monitoring remote streams. This thesis, thus, serves as a proof of concept for using LiDAR to model rating curves. For this, the thesis is structured as follows. First, a brief overview of two concepts, the Kean and Smith (2010) rating curve method and airborne LiDAR, are given to present the theoretical background. Then a proof of concept case study combining the two concepts is presented for the Krycklan catchment located near Umeå, Sweden. Finally, the thesis concludes by presenting potential pathways forward to test and strengthen this proof of concept.

Theoretical Background

The Kean and Smith theoretical rating curve method

The method of Kean and Smith (2010) is a two-step physically-based approach developed for modeling discharge as a function of stage (i.e., this model creates a rating curve) in relatively straight streams. The model calculates velocity profiles for every

submerged grid point on a two-dimensional curvilinear grid that follows the centerline of the channel, and is applicable for channels with (1) bed roughness elements that are small compared to the depth of flow, (2) may contain rigid bank or floodplain vegetation, and (3) have width to depth ratios of 10 or greater. It should be noted that all of these conditions are satisfied at the Krycklan River outlet that will be considered later in this thesis. Some requirements need to be solved in order to use the Kean and Smith (2010) method. First, factors that contribute to hydraulic resistance such as channel geometry and physical roughness must be quantified from field measurements. These measurements are used to calculate total channel roughness (i.e. the drag on the small-scale topographic features on the boundary, drag on the vegetation, and friction on the bed, banks, and floodplain). Secondly, a one-dimensional flow model for calculation of the stage-discharge relation over the full range of stages is constrained with the quantified channel roughness features.

The Kean and Smith (2010) channel flow model differs from standard one-dimensional flow models, for instance the Hydrologic Engineering Centers River Analysis System (HEC-RAS), in that: (1) although it yields a three-dimensional representation of the velocity fields, spatial flow accelerations are only resolved in the streamwise direction, and (2) it uses a fixed roughness based on the geometry of the roughness elements rather than using a bulk roughness coefficient (e.g. Manning's coefficient of roughness), which, because of the lumped effects of all roughness sources in the channel, can vary with stage (Limerinos, 1970).

Vegetation roughness

Drag on stems and branches in the vegetated portion of the channel can contribute substantially to total flow resistance, especially at high flow, thereby reducing the velocity. In the Kean and Smith (2010) method, the drag force is calculated using the method of Smith (2001, 2007). The drag force on the vegetated portions is specified from field measurements in terms of the mean diameter and spacing of stems assuming they are randomly distributed. However, the objective of the work in this current thesis did not include overbank flow or any vegetated parts of the studied stream and, therefore modeling of vegetation was not considered.

Channel geometry and physical roughness

In its original implementation, the method of Kean and Smith (2010) is constrained with geometric information obtained from detailed cross-sectional ground survey using a total station. From the field measurements, information about the shape of the channel, the water surface slope, and the geometric properties of the roughness elements on the bed, banks, and floodplains of the channel are obtained. Boundary roughness is specified in terms of a roughness height, z_o , for every point on a two-dimensional, curvilinear grid, which conforms to the centerline of the channel. The channel bed-roughness height for gravel channels (z_o) is related to the distribution of the particle size by $z_o = 0.1D_{84}$, where D_{84} is the 84th percentile of the grain size distribution for the protruding axis (Whiting and Dietrich, 1990). The bed roughness height for elements in the stream can, as an alternative, be back calculated by using a single measurement of discharge and the corresponding water surface slope (Kean and Smith, 2005).

Flow model

At any given cross section, streamflow in the channel in the most basic sense is the product of the average water velocity through the channel cross-sectional area. However, along a channel reach, both the velocity and the cross-sectional area can vary. As such, the Kean and Smith (2005, 2010) rating curve method models streamflow (Q) in a channel reach approximately by solving a version of St. Venant equations for steady, non-uniform flow in one-dimension for shallow water. The model calculates the water surface profile that simultaneously satisfies both the continuity and momentum equations:

$$\partial Q / \partial x = 0 \quad (1)$$

and

$$\frac{1}{2} \frac{\partial (u^2)_{av}}{\partial x} + g \frac{\partial E}{\partial x} + \frac{1}{2} \frac{(\tau_b)_{av}}{R} = 0 \quad (2)$$

where $(u^2)_{av}$ is the square of the downstream velocity component averaged over the cross section, E is the surface water elevation, ρ is water density, $(\tau_b)_{av}$ is the perimeter-averaged shear stress, and R is the hydraulic radius given by the ratio of the cross-sectional area of the flow to its wetted perimeter (Kean and Smith, 2005). While the first term of equation (2) describes the crosswise change of velocity, the second term expresses how the forces change due to crosswise change of elevation. The third and last term in the equation contributes with a mathematical expression for the resistance factors.

As a starting point to simultaneously satisfying equations (1) and (2), the vertically velocity (u) at any point in the stream reach is calculated as

$$u = (\tau_b / \rho)^{1/2} \times \beta_r = u_* \times \beta_r \quad (3)$$

Here, β_r is a non-dimensional roughness coefficient and u_* is the shear velocity, which is directly related to the shear stress (τ_b). In streams with steady flow conditions the shear stress is given by

$$\tau_b = \rho g h S_f \quad (4)$$

where g is acceleration of gravity, h is the local flow depth, and S_f is the friction slope.

Under such conditions (Kean and Smith, 2005), β_r will have the form

$$\beta_r = \frac{\ln(h/z_0) - 0.74}{\kappa} \quad (5)$$

where κ is the von Karman constant equal to 0.408 (Long et al., 1993). By combining equation (3), (4), and (5), the vertical velocity at any point can be calculated as

$$u = \sqrt{ghS_f} \times \frac{\ln(h/z_0) - 0.74}{\kappa} \quad (6)$$

Equation (6) is thus used to solve the flow field for the entire reach in an iterative manner. This solution can be related to the stage in the stream reach and, repeating the procedure for several stages or flows, a rating curve can be modeled.

In practice, for a given stage, the model initially guesses a corresponding flow (Q). This guessed Q is used to back calculate the friction slope. The calculated slope is then compared to measured slope obtained from field observation. If calculated friction slope differs from the measured friction slope, the model guesses another Q for a new calculation of friction slope. The model iterates these guesses and calculations until calculated slope approximately equals measured slope for that stage. This procedure is

repeated to calculate flow over the whole range of defined stages to model a rating curve.

LiDAR

LiDAR technique is based on emission of light of a certain wavelength and frequency (laser technology) and on collection of the backscatter from an illuminated surface. The general principle for LiDAR is measurement of the time it takes for pulses of light to travel from emission to collection of the backscatter. Since speed of light is known the distance to the illuminated object can be calculated. In combination with the technology of Global Positioning System (GPS) and inertial navigation system, LiDAR allows for accurate positioning of illuminated objects. In an early publication Collis (1956) describes the potential of the LiDAR technology for meteorological studies and the observation of clouds. Recently, terrestrial LiDAR scanning techniques that works with laser pulses in the near infrared spectral range (~1064 nm) has gained popularity for the collection of topographic data to derive digital elevation models. LiDAR data have been used to examine patterns of depth-to-water and topographic wetness index (Hopkinson, 2011; Murphy, 2011) as well as for studies of climate change impacts on sea level rise (Coveney, 2011; Zhang, 2011; Zhang et al., 2011), investigations and inventories of forested areas (Huang, 2011; Soycan, 2011), and river network studies (Cheung 2011; Liu and Zhang, 2011a; Liu and Zhang, 2011b; Wilkins and Snyder, 2011). The wavelength 1064 nm is important since it allows for penetration of the canopy, which results in backscatter from both ground surface and vegetation, however, it does not penetrate through water. This allows for the positioning of objects and for estimation of for example vegetation density. An often-used system is the aircraft

mounted TopEye MkII S/N 425 (Blom Swe AB), emitting laser pulse at a frequency of 50,000 Hz. This instrument is equipped with a dual channel receiver to collect the backscatter, and an integrated differential GPS, which allows for accurate positioning of the scanned topography relative to the position of a reference station.

Proof of Concept: the Krycklan catchment

Study area

The proof of concept and fieldwork considered in this study to combine the modeling approach of Kean and Smith (2010) with LiDAR data was conducted as part of the interdisciplinary Krycklan Catchment Study (KCS), located in the vicinity of Vindeln Experimental Forests, Svartberget Research Station ($64^{\circ} 14' N$, $19^{\circ} 46' E$), about 60 km northwest of Umeå in northern Sweden (Figure 1).

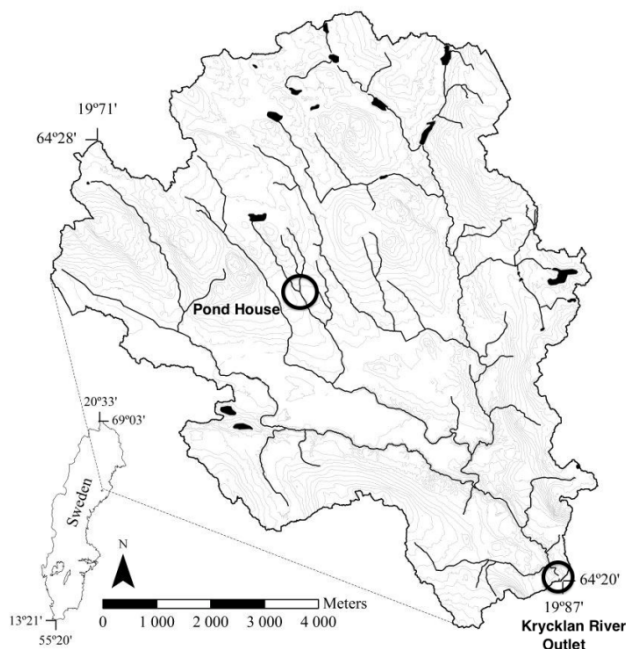


Figure 1. Showing the Krycklan River Catchment, the location of the outlet of the Krycklan River where the study for this thesis was conducted, and the location of the regularly monitored pond house.

Growing from three decades of small-scale catchments studies (Bishop et al., 1990), the 67 km² KCS today is host for research integrating water quality (Agren et al., 2007; Bjorkvald et al., 2008; Buffam et al., 2007; Cory et al., 2006), hydrology (Grabs et al., 2009), aquatic ecology (Petrin et al., 2007; Serrano et al., 2008) and climate effects (Lyon et al., 2010) in running water in the boreal landscape.

The landscape of the Krycklan River catchment is gently undulating, with the topography ranging from 130 to 370 m asl. The upper part in northwest consists mainly of coniferous-forest on glacial till with elements of wetlands, while the lower part in southeast of the landscape is characterized by mixed forest on sand and silt. Well-developed iron-podzol overlying the gneissic bedrock is common throughout the whole catchment. Small agricultural fields are common features in the landscape especially in the lower part of the catchment, where deciduous shrubs and trees characterize the riparian zones along larger streams. The stream network in the area comprises 15 sub-catchments, with areas ranging from 0.03 km² to 67 km². The meandering streams are of first order headwater streams in upper part of the catchment, to the fourth order stream at the mouth of the Krycklan River where this proof of concept study was carried out.

Short summers and long winters characterize the climate in the area. Mean annual temperature is 1°C, and mean annual precipitation is 600 mm whereof approximately 30% falls as snow. On average, the ground is snow covered 171 days, from the end of October to the beginning of May. Commonly, the turn of month from April to May is the starting point for the yearly most dominant hydrologic event, the spring flood. During a 3- to 6-week period approximately half of the annually runoff (mean runoff is approximately 325 mm) occurs due to snowmelt. During periods of low flow conditions

in autumn discharge at the 8 m wide Krycklan River outlet is approximately 0.6 m³/s, while measurements have shown discharge peaks exceeding 8 m³/s in springtime.

Surveys and data collection

The Krycklan River was surveyed upstream from its outlet and serves as the study site for the work in this thesis (Figure 2).

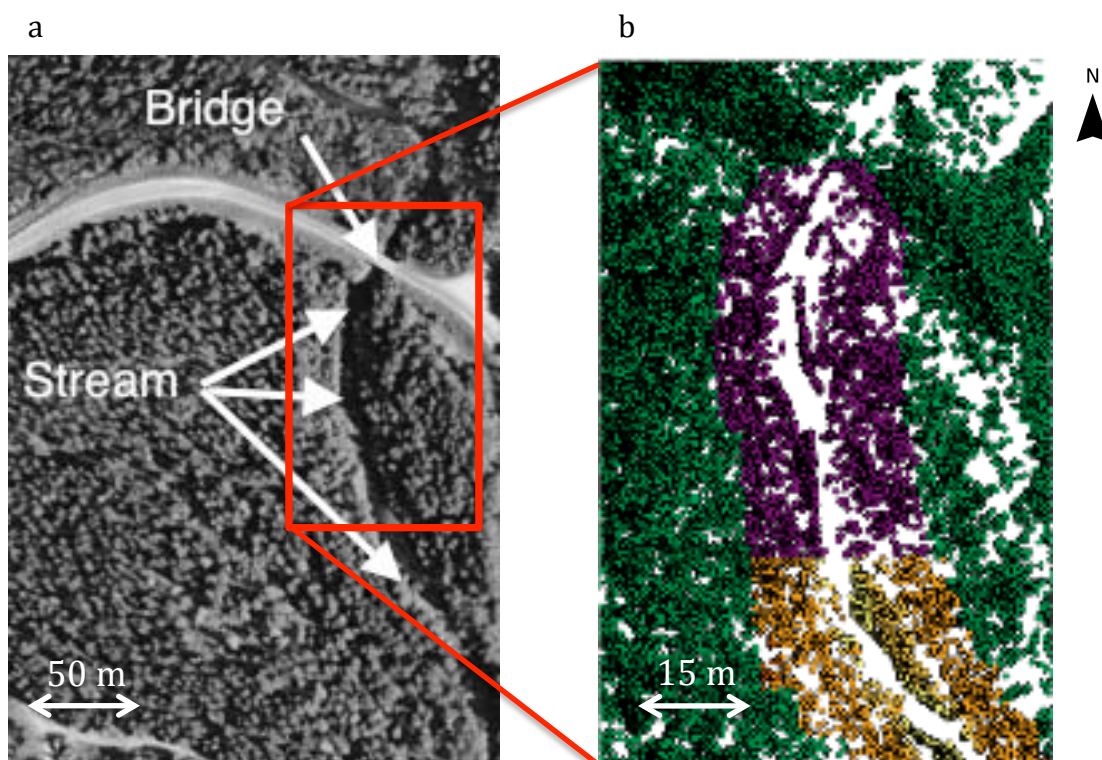


Figure 2. The fieldwork for this thesis was conducted downstream of the bridge and before the Krycklan Catchment river outlet. Insert in (a) shows location of the study site. The red box in (a) outlines the region of LiDAR details shown in (b). In (b), purple is the surveyed reach, yellow is the extension of the channel, and green are outer areas not included in the study. The span of the bridge is such that it does not have any influence on flow other than at very extreme situations.

This includes fieldwork involving the collection of flow data and geometric measurements for rating curve modeling and deskwork processing data from the field survey, and an airborne LiDAR survey conducted in August 2008.

Flow data

Flow data were collected over a three-year period, 2008 through to 2010, using both the current meter method (Herschy, 1993b), and the salt dilution method (Moore, 2005). The measurements were conducted over a wide range of stages (and thus flows) from very low to very high water surface elevation. A rating curve for the stage-discharge relationship at the site was established as a power relation using a standard least squares fitting method for the measured stage and the measured flow (Figure 3). This observed rating curve (hereafter referred to as the empirical rating curve), was established to serve as the control or validation for the modeled rating curves prepared in this study.

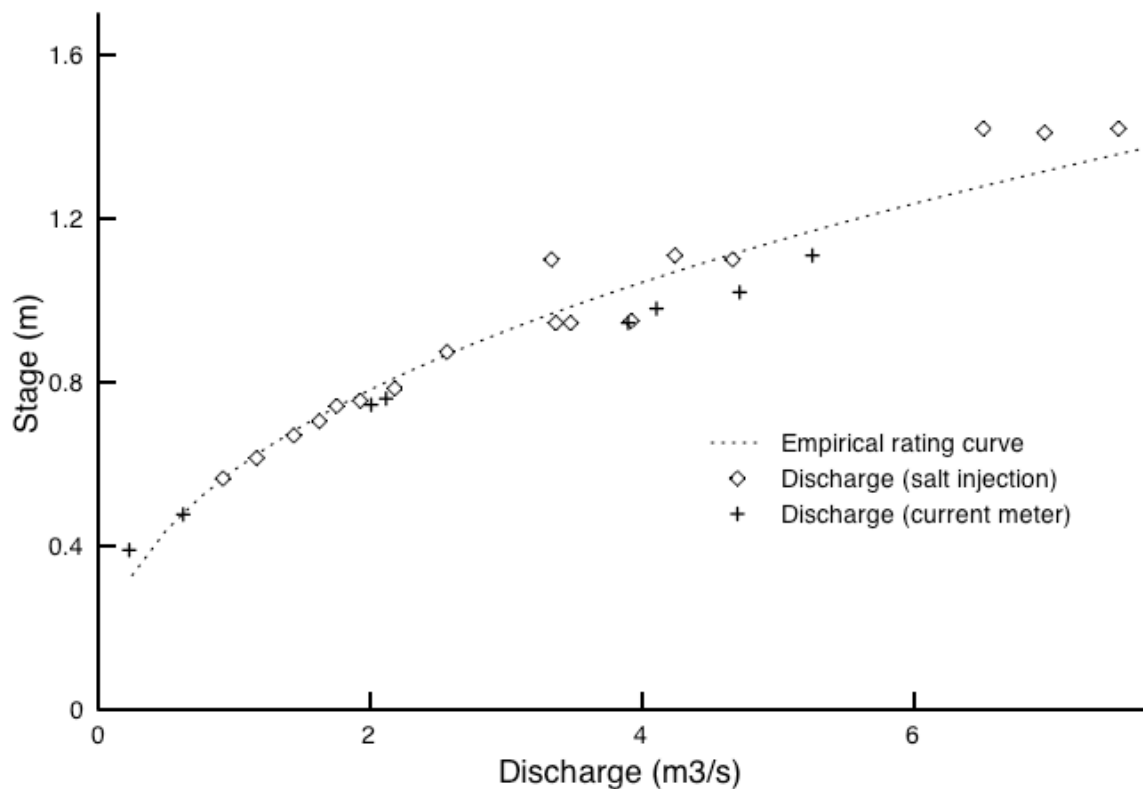


Figure 3. The empirical rating curve with the power relation $stage = 0.6 \times discharge^{0.4}$ serves as a control for modeled rating curves.

Geometric measurements

The geometric information about the stream channel necessary for modeling rating curves with the Kean and Smith (2010) method was obtained from detailed ground surveys conducted during the period April 2009 through to October 2009. These surveys were performed using a robotic total station, which is an instrument for geodetic measurements with an integrated electronic distance meter. The total station surveys included measurements of water surface slope and channel geometry, which were conducted as described by Kean and Smith (2005, 2010). Measurements of the water surface slope were undertaken at both high stage (spring flood) and low stage (autumn low flow), and revealed no difference in water surface slope between the two stages. The channel geometry was established from cross-sectional measurements of the streambed topography. The channel-bed roughness height was back calculated from a single water surface slope measurement and the corresponding flow measurement. This approach to establish the roughness height was taken since the water level along the studied reach was too high to perform accurate pebble counts. As mentioned in the previous section, vegetation roughness was not included in this current study since only herbaceous vegetation is represented on the stream banks along the studied reach and no overbank flow was modeled in this study.

LiDAR data

The company Blom AB on behalf of the Swedish University of Agricultural Science (SLU) and the Swedish Defense Research Agency (FOI) conducted a LiDAR survey of the KCS area in August 2008. Data of high resolution obtained from this survey was initially preprocessed by SLU. This preprocessing involved computational classification routines

that allowed for the exclusion of vegetation influence. The resulting geometric data, considered to reflect the ground topography for the surveyed area of interest, was then used as input data to the Kean and Smith (2010) method for modeling rating curves.

Survey and LiDAR data processing

All geometric information, consisting of topographic points from the total station survey and the LiDAR survey required further processing prior to modeling. A first step was to obtain a common coordinate system. This was done by transformation of the data to the SWEREF 99 TM coordinate system using ArcGis (ESRI, Redlands, CA).

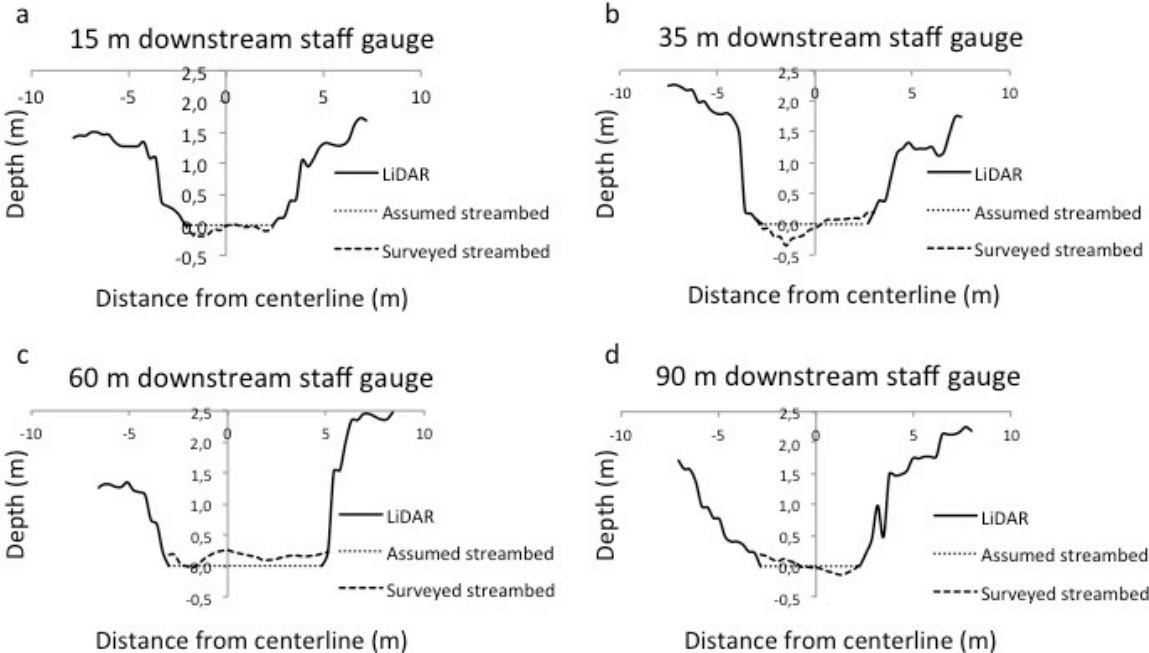


Figure 4. Examples of estimated and surveyed streambed topography at cross sections a) 15 m, b) 35 m, c) 60 m, and d) 90 m downstream the staff gauge.

A second step was to estimate the cross sectional topography in the missing areas of the streambed topography where the LiDAR was unable to penetrate the water surface. Two approaches were considered to fill in these LiDAR blank spots (Figure 4). The first approach was to create an elevation model from a simple assumption of a flat streambed with its elevation corresponding to zero at the staff gauge. This model is hereafter referred to as the LiDAR model. A second approach in step 2 was to merge the cross-sectional topographic data from the total station survey and the LiDAR survey, to create a combined or hybrid model (hereafter referred to as the hybrid model). This second step of the processing work was done using software for Multi-Dimensional Surface-Water Modeling System (MD_SWMS) by the US Geological Survey (USGS) to interpolate between topographic points.

A third step was to implement processed data into the flow model of Kean and Smith (2010) for quantification of resistance factors and calculation of rating curves.

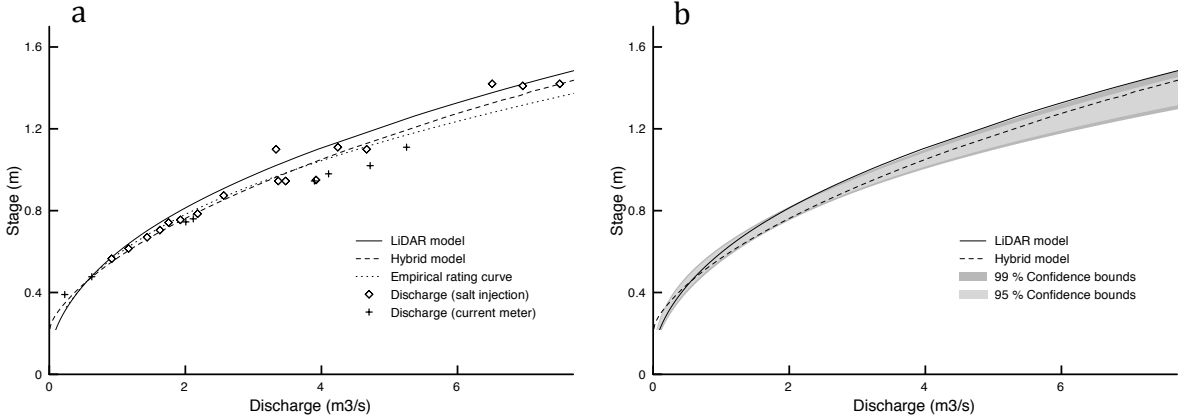


Figure 5a (left), the modeled rating curves and the empirical rating curve have equally good fit to measured flow. Figure 5b (right), shows the modeled rating curves fit within the 99% confidence bounds calculated for the empirical rating curve.

The two modeled rating curves were compared to both the flow measurements (Figure 5a) and to the calculated 95% and 99% confidence bounds for the empirical rating curve (Figure 5b). Also, both modeled rating curves and the empirical rating curves were assessed using the root mean square error (RMSE) relative to flow measurements (Table 1).

Discussion of the proof of concept

The aim of this thesis was to explore the following question: is data from high-resolution LiDAR scans suitable information to constrain a flow model for calculation of rating curves? A general answer to that would be: yes, so it seems. The modeled LiDAR curve and the modeled hybrid curve have good fit to measured flow (Figure 5a). At higher stages the modeled rating curves have better fit to measured flow than the empirical rating curve.

Table 1. Summary of the agreement between predicted discharges and measured flow calculated as root mean square error (RMSE).

Root Mean Square Error (m³/s)		
LiDAR model predicted	Hybrid model predicted	Empirical rating curve
0.63	0.47	0.74

The difference in the rating curves relative to flow measurements is seen by the RMSE (Table 1), where the rating curve from the hybrid model has the lowest RMSE and the empirical rating curve has the highest. A probable explanation is that there are only a few measurements at high flow represented when calculating the empirical rating and that no weighting was considered when the calculation was done. At lower stages, all rating curves show reasonably good fit to measured flow; however, the curves diverge

when at stages below the lowest flow measurement. This difference between the LiDAR curve and the hybrid curve (Figure 5a), at medium to higher stages, is due to the difference in the resolution of the streambed topography (Figure 4). Both modeled curves were constrained with high-resolution LiDAR data reflecting the topography above the water surface (i.e. stream banks and the part of the streambed that was not covered with water during the LiDAR scan). The LiDAR curve was assumed to have a flat streambed, which results in shorter roughness length and thereby less resistance to flow. This is true for all stages relevant in this study, but with limited impact on flow at higher stages. The hybrid curve on the other hand, reflects a more realistic situation, thereby resulting in a higher roughness length, which gives this curve a fit closer to the empirical rating curve.

Although the modeled rating curves vary in their agreement to each other, they both clearly fall within the confidence bounds calculated for the empirical rating curve (Figure 5b). From a statistical point of view, both modeled curves are equally good at representing the empirical rating curve and, therefore, it cannot be determined which one is most accurate. As such, in spite of potential limitations and drawbacks, LiDAR data appear to provide sufficient information to run the physically-based Kean and Smith (2010) method for modeling rating curves.

Future perspectives

This study demonstrates a possibility to constrain the Kean and Smith (2010) method for modeling rating curves with topographic information obtained by airborne LiDAR scans. However, there are drawbacks to overcome and questions to be addressed with

future research. For example, are water-penetrating LiDAR techniques or bathymetric LiDAR, operating at blue-green wavelengths, a more attractive alternative to conventional LiDAR that operates in the near infrared region of light? And, what is an optimal data resolution during the LiDAR scan such that the data can be used in flow modeling? Taking up some of these questions and outlining future potential research concludes this thesis.

First, other scanning methods can be considered. For example, preliminary results (Figure 6) demonstrate that the LMS111 Laser Measurement System sensor from SICK, Inc., USA, is capable of scanning the entire pelvic geometry and channel bed in small river systems. This equipment is working in the spectral range around 905 nm, operates at close range, and requires a temporary installation above the investigated surface. The results (Figure 6) derived from a survey in a small creek within the KCS (named Pond House in Figure 1), suggest that filtering parameters of this camera system can be optimized so that high resolution topographical information from the entire streambed, including the portion of the streambed below the water, can be obtained. This opens an exciting realm for exploration of the viability of the Kean and Smith (2010) method to manage high-resolution LiDAR data derived onsite to model rating curves.

In addition to such onsite techniques, there is good potential for the use of bathymetric LiDAR to obtain data. This technique has been shown to be useful in the study of marine ecology (Chust et al., 2010; Valle et al., 2011), and bathymetric elevation (Monfort and Lippmann, 2011). By working in the blue-green wavelengths, this technique may offer chances to map the streambed geometry in a truly remote sense. Of course, there are potential limitations associated with the turbidity of the water and the resolution at which the bathymetric LiDAR can be collected.

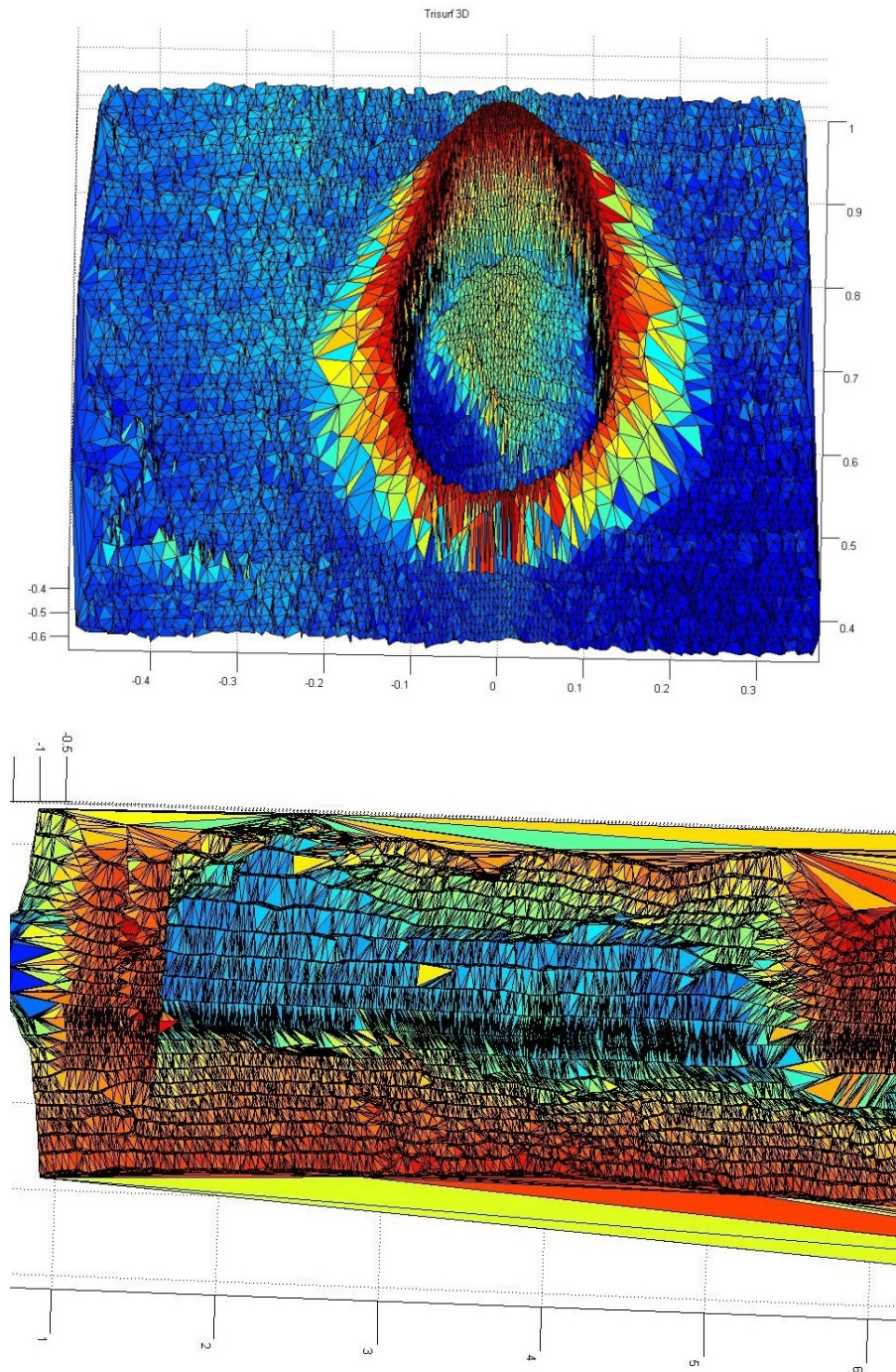


Figure 6. Top, a submerged boulder scanned with the LMS111 camera system. All scales shown in the image are relative, where blue is deeper regions and red is shallower. Bottom, a 6-meter section of a small stream in the Krycklan River scanned with the LMS111 camera system. The scales shown in the image is relative, blue is deeper parts of the streambed, and red are shallower parts. The brown areas at the beginning and end of the scanned area show fallen tree logs, which is just across the brook

One key issue associated with using LiDAR information in stream-discharge modeling is identifying the optimal resolution of the topographic data required to adequately represent the channel geometry. The density of the LiDAR data used in this study was approximately 5-10 points/m². In the next phase of this research, a systematic filtering will be conducted to synthetically reduce the LiDAR and hybrid data to identify the relationship between data resolution and the performance of the rating curve model. This may allow for scaling of coarse LiDAR data (such as that collected in the ongoing national scan of Sweden, which is conducted at the resolution of 0.5 points/m²) to a resolution relevant for modeling streamflow.

Based on the results presented in this thesis, it was possible to establish relevant stream channel geometric information via LiDAR scans to constrain the Kean and Smith (2010) method for modeling theoretical rating curves at the outlet of the 67 km² Krycklan catchment. Moving upstream to smaller catchments, however, implies more narrow streams of lower order. These low order streams represent the overwhelming majority of the running water in streams worldwide. These small streams, which are seldom monitored, form a blank space on the map creating a region of *aqua incognita* (Bishop et al., 2008). Therefore, more work is needed to determine the limiting spatial scales and stream sizes for which the Kean and Smith (2010) method can use LiDAR information. Currently, LiDAR data (explicitly near infrared LiDAR) exists covering the entire Krycklan catchment. Furthermore, the Krycklan catchment consists of 18 sub catchments ranging from 0.03 to 67km² with continuously monitored stream gauges. Direct flow measurements at various flow conditions have been made at each of these sites over several years. This provides data of the stream-discharge relationship for all sites within the catchment and makes the Krycklan Catchment a good test bed for investigating many of the questions outlined in this section.

Acknowledgement

First and foremost, I thank my supervisor Steve Lyon for all assistance and support and inexhaustible patience to put up with my questions, I think you know what I mean. Also, great thanks to my co-supervisors Jerker Jarsjö for important and valuable lunch talks and support, to Jan Seibert for introducing me to the exciting but difficult field of hydrology, and to Hjalmar Laudon and Kevin Bishop for encouragement and all constructive comments during presentations at seminar and conference and the process of writing the first paper. I would also like to extend special thanks to Jason Kean for providing expertise and never-ending patience and generosity. This study was funded by the Ministry of Education and Research at the Swedish Government, and supported by the Education Administration at the City of Stockholm and Åsö vuxengymnasium, which is gratefully acknowledged. There is a whole list of people whom have contributed so much in the fieldworks, but special thanks to Thomas, André, Peder, Viktor and Peng. Jan-Olov Persson (Statistiska forskningsgruppen, Matematisk statistik, Stockholms Universitet), is acknowledge for help with statistical calculations, Julienne and Malin for help with images, and Hildred Crill for linguistic assistance. The staff at Trimtec in Umeå is greatly acknowledged for support and technical assistance. Finally, all my family and especially my dearest life mate Tova, without your support and belief in me this would never have happened.

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Paper I

Nathanson M, Kean JW, Grabs, TJ, Seibert J, Laudon H, Lyon SW
Modeling rating curves using remotely sensed LiDAR data

Accepted in *Hydrological Processes* (*in press*)

Please cite this article as:

Accepted Article, doi: 10.1002/hyp.9225

Modeling rating curves using remotely sensed LiDAR data

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Abstract: Accurate stream discharge measurements are important for many hydrological studies. In remote locations, however, it is often difficult to obtain stream flow information because of the difficulty making the discharge measurements necessary to define stage-discharge relationships (rating curves). This study investigates the feasibility of defining rating curves using a fluid mechanics-based model constrained with topographic data from airborne LiDAR scanning. The study was carried out for an 8-m wide channel in the boreal landscape of northern Sweden. LiDAR data were used to define channel geometry above a low flow water surface along the 90-m surveyed reach. The channel topography below the water surface was estimated using the simple assumption of a flat streambed. The roughness for the modeled reach was back calculated from a single measurement of discharge. The topographic and roughness information was then used to model a rating curve. To isolate the potential influence of the flat bed assumption, a “hybrid-model” rating curve was developed based on data combined from the LiDAR scan and a detailed ground survey. While this hybrid-model rating curve was in agreement with the direct measurements of discharge, the LiDAR-model rating curve was equally in agreement with the medium and high flow measurements based on confidence intervals calculated from the direct measurements. The discrepancy between the LiDAR-model rating curve and low flow measurements was likely due to reduced roughness associated with unresolved submerged bed topography. Scanning during periods of low flow can help minimize this deficiency. These results suggest that combined ground surveys and LiDAR scans or multi-frequency LiDAR scans that see “below” the water surface (bathymetric LiDAR) could be useful in generating data needed to run such a fluid mechanics-based model. This opens a realm of possibility to remotely sense and monitor stream flows in channels in remote locations.

1. Introduction

Stream flow is one of the most important hydrological variables, but monitoring continuous flow remains challenging. Flow in an open channel is a function of the water surface elevation (stage) in the stream and the usual approach for monitoring stream flow is to transform measured stage heights using stage-discharge relations (i.e. rating curves) (Hersch, 1993a). Such rating curves can often be physically based equations when controlled sections, e.g. V-notch weirs or flumes, are used. In natural sections, flow is more commonly estimated using either a velocity-area method derived from field measurements of water velocity (e.g. using a mechanical or acoustic current meter) over a cross sectional area of the stream (Hersch, 1993b) or a tracer injection method like the commonly applied salt slug injection method (Moore, 2005). These flow measurements allow for the estimation of empirical rating curves. Establishing such rating curves, however, can be time consuming because flow has to be measured over a range of stages and especially high stages do not occur frequently. Furthermore, obtaining measurements at high flows can often be hazardous. In environments where stream morphology changes over time, additional uncertainty is included because rating curve parameters change over time (Westerberg et al., 2011).

Rating curves can also be modeled from theoretical calculations. The Manning equation (Manning, 1891) or other similar expressions have been used for more than a century for modeling open channel flow. One often-identified drawback of such approaches is their reliance on an empirical coefficient (here the Manning

coefficient) of roughness, which can vary with stage (e.g. Comiti et al., 2007; Lopez et al., 2007). More recent techniques allow for modeling rating curves without such empirical estimates of roughness. For instance, the two-stepped, physically based Kean and Smith (2005, 2010) theoretical rating curve method uses basic geometric measurements to establish flow resistance. In the first step, contributing factors such as the shape of the channel, physical roughness of the streambed, banks and floodplain, and vegetation density on the banks and floodplain are quantified. Secondly, the quantified roughness is embedded into a flow model for calculation of the stage-discharge relation. Regardless of how roughness is treated, modeling rating curves requires knowledge of channel geometry that can often be time intensive or logistically difficult to obtain in remote areas. This highlights the need for new ways for measuring channel bed topography and roughness.

Recently, LiDAR scanning techniques have gained popularity for the collection of topographic data and for remote sensing of river channels (Snyder, 2009; Wobus et al., 2006), landslide detection (McKean and Roering, 2004), and investigation of forest age as well as ecological surveying in rivers and coastal zones (Brock et al., 2002; Kinzel, 2009; Kinzel et al., 2007; McKean et al., 2008). The objective of this study was to test the use of LiDAR-derived topographic information for modeling rating curves in a boreal stream. Terrestrial geometric information from an airborne LiDAR-scan was used in the physically based Kean and Smith (2010) theoretical rating curve method for modeling rating curves. As LiDAR, specifically near infrared (NIR) LiDAR like that

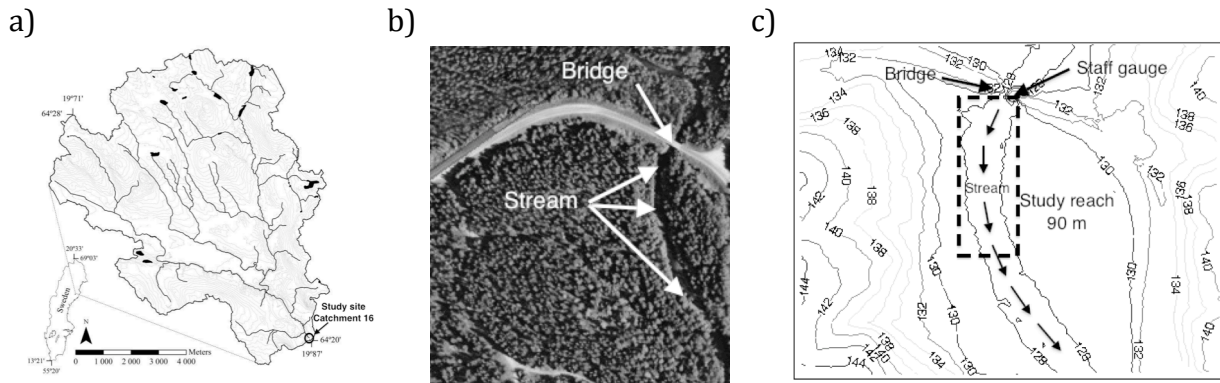


Figure 1. (a) Map of the Krycklan River Catchment (illustration by Anneli Ågren); (b) aerial photo over the study site at the outlet of Krycklan River; and (c) map of the study reach including location of bridge and staff gauge.

considered in this study, cannot detect the submerged portions of the channel bed due to strong absorption of the laser pulses by the water, a simple linear stream bottom assumption was made to represent the streambed geometry. To test the influence of this assumption, the LiDAR data were also combined with topographic data derived from a conventional ground survey of the streambed. Both modeled rating curves were compared with direct measurements of discharge to estimate their ability to predict the empirical rating curve. This study serves as a proof-of-concept for the utility of LiDAR derived channel geometry in a physically based rating curve model.

2. Site description, flow measurements and empirical rating curve

The Krycklan Catchment Study (KCS) is a 67 km² area located within the Vindeln Experimental Forests, Svartberget Research Station (64°14'N, 19°46'E), approximately 60 km northwest of Umeå in northern Sweden (Figure 1 a). The KCS has grown from three decades of small-scale catchments studies (Bishop et al., 1990) to a multi-scale project including catchments spanning close to 2000 times in scale (Laudon et al. 2011). In the area a number of multidisciplinary research projects have been conducted, including topics such as integrating water quality (Ågren et al., 2007; Bjorkvald et al., 2008; Buffam et al., 2007; Cory et al., 2006), hydrology (Grabs et al., 2009), aquatic ecology (Petrin et al., 2007; Serrano et al., 2008) and climate effects (Lyon et al., 2010) in streams in the boreal landscape.

The gently undulating landscape of the KCS ranges from 369 to 130 m above sea level, where the upper part mainly consists of a boreal-forested landscape on glacial till with elements of wetlands. Forests on sand and silt characterize the lower part of the landscape. Well-developed iron-podzol overlying the gneissic bedrock is common throughout the whole catchment. Small agricultural fields are dispersed throughout this boreal landscape and are common features in the lower part of the catchment. Complete descriptions of the KCS landscape and settings can be found in Buffam et al. (2007) and Cory et al. (2006).

The work in this study was performed at the main outlet of the KCS (Figure 1 b). This site is the largest of the 15

sub-catchments considered in Laudon et al. (2007) and Lyon et al. (2010), where it has been referred to as catchment 16. The topography along the west side of the stream at the site is steep while the area to the east is relatively flat. The floodplain on both sides is approximately 1.5 m above low-flow water level with dense deciduous shrubs and small trees close to the stream.

A 90-m long area stretching downstream from a staff gauge (installed in a stilling well) was chosen for the study (Figure 1 c). The wetted width of the stream along the studied reach is approximately 6.5 m at low flow and 8 m at high flow. The streambed consists of sand and sand ripples and the along-channel profile is regular with some pools between sand dunes. The average water surface drop of the surveyed reach is 0.004 m/m. This drop was measured at both high flow and low flow. During low flow the discharge is approximately 0.6 m³/s. Salt slug-injection measurements have shown peak discharge exceeding 8 m³/s during spring flood.

Flow measurements were conducted during 26 occasions covering a range of flow conditions including spring flood and base flow from April 2008 to May 2010. These measurements were made using both velocity-area method (Herschy, 1993b) and salt slug injection method (Moore, 2005). No measurements were carried out during winter when the river was ice covered because measurements during such conditions are difficult to make and can be fairly uncertain. Water levels were measured automatically during flow measurements using a staff gauge at the stilling well. From these flow measurements and stage recordings, a rating curve was determined for the site as a power relation using a standard least squares fitting method. For the remainder of this study, this will be referred to as the empirical rating curve.

3. Physically based modeling of rating curves

This study used the method proposed by Kean and Smith (2010) to model rating curves for the study site. This was done using measurements from both airborne LiDAR scanning and a detailed ground survey to represent channel geometry. The following sections provide a brief overview of the method to model rating curves and the required information (section 3.1),

information on how LiDAR data were gathered (section 3.2), description of how the detailed ground survey was carried out (section 3.3), and an overview of the data processing requirements to bring these data into the modeling environment (section 3.4).

3.1 Model overview

The fluid mechanics-based flow model of Kean and Smith (2010) has been developed for calculating rating curves for relatively straight reaches having: (1) gravel bed roughness elements that are small compared to the depth of flow, (2) rigid bank or floodplain vegetation, and (3) width to depth ratios of 10 or greater (see Kean and Smith (2005) for a model appropriate for narrow channels). The rating curve is generated by computing discharge over the full range of stage at a given site using the flow model. The model is constructed for a reach of channel approximately 10 times longer than the width. Velocity profiles are computed for every submerged grid point on a two-dimensional curvilinear grid that follows the centerline of the channel (an even grid spacing of 30 cm in the cross-stream and streamwise directions was used in the current study). Although the model yields a three-dimensional representation of the velocity field, spatial flow accelerations are only resolved in the streamwise direction as in one-dimensional step-backwater models (e.g. Hydrologic Engineering Centers River Analysis System, HEC-RAS).

The main difference between the approach of Kean and Smith (2005, 2010) and standard one-dimensional flow models used for rating curve estimation (e.g. HEC-RAS) is the way in which channel roughness is specified. Channel roughness in the Kean and Smith (2005, 2010) model is specified directly from field measurements of the geometry of the roughness elements on the bed, banks, and floodplain of the channel - specifically, the grain size of the bed material, the size and spacing of the stems of woody vegetation, and the size and spacing of small-scale topographic features on the banks and floodplains. In contrast, channel roughness in standard one-dimensional models is specified through a bulk roughness coefficient (e.g. the Manning coefficient), which lumps the effects of all sources of roughness into a single parameter. A difficulty with using bulk roughness coefficients for rating curve estimation is that the roughness coefficient (unlike roughness element geometry) typically varies with stage, especially over low to moderate flow heights (e.g. Limerinos, 1970; see also Kean and Smith, 2005, 2010). Accurate determination of this variation is difficult without multiple discharge calibration points, which can be difficult to obtain at remote sites.

In this study, the stage range of interest is below the vegetated floodplain, so the bed roughness is the dominant source of flow resistance controlling the rating curve. The flow resistance of the grass-covered banks is neglected, because the flexible grass stems offer little flow resistance, and the channel is sufficiently wide that the lateral flow resistance of the banks is small compared to the resistance of the channel bed. The roughness of the bed is specified in terms of a roughness height, z_o , which

for a gravel bed is related to the particle size distribution by $z_o = 0.1 D_{84}$, where D_{84} is the 84th percentile of the grain size distribution for the nominal axis (Whiting and Dietrich, 1990). In both Kean and Smith (2010) and this study, the bed roughness is sufficiently uniform that a single value of z_o is used for the entire reach; however, the model can accommodate spatial non-uniformity in roughness by permitting z_o to vary throughout the computational grid. At our study site, the flow depth at the time of the field survey was too deep to permit accurate grain size determination, so z_o was determined empirically using the model and a measured low-flow discharge measurement and water surface profile made at the time of the field survey. It is important to note that this single value of z_o is used for the calculation of discharge over the entire stage range.

3.2 LiDAR data for defining channel geometry

Airborne LiDAR scanning over the study area was carried out during low-flow conditions on 5 August 2008 and 6 August 2008 by Blom Swe AB, Gothenburg, Sweden (formerly TopEye AB, Sweden, <http://www.blomasa.com>) on behalf of the Swedish Defense Research Agency (FOI) using a helicopter mounted TopEye MkII S/N 425 system (Blom, 2008). The TopEye MkII system uses a Laser Range Finder emitting laser pulses (infrared light (IR) spectrum range is 1064 nm) at a frequency of 50,000 Hz and a Dual Channel Receiver to collect the backscatter. An integrated differential global positioning system (GPS) enables positioning of the scanned surface topography. The system is also equipped to compensate for flight deviations in yaw, pitch, roll, slide slip, speed and altitude. The spectrum range 1064 nm is important because it allows for penetration of the canopy to detect the ground topography, but not through water, which for this study led to loss of information about the streambed topography.

The main flight altitude was 500 m and the crosswise direction flight altitude was 250 m. This procedure was taken to ensure that the accuracy of the topographic information did not differ too much between the two flight directions. As reference point during the scanning the SWEPOS reference station in Vindeln was used. The distance between the helicopter and the reference station never exceeded 15 km during the scanning. The software Applanix POSGNNs was used for calculations of GPS coordinates in the RT90 2.5 gon West 0:-15 / RH70 coordinate system.

Raw LiDAR data were collected with a density of approximately 5-10 points/m². Researchers at the Swedish University of Agricultural Sciences (SLU) initially processed and classified the collected data. A routine to evaluate the intensities and numbers of echoes from each emitted laser pulse was used for classification. This process allowed for filtering backscatter caused by vegetation from that caused by ground topography. It should be noted here that this is a somewhat rough method, meaning that it can be difficult to distinguish small trees from rocks (or boulders). Fortunately the ground surface topography along the surveyed reach is

smooth, which facilitated the process of separating ground topography from vegetation. After classification the set of LiDAR-derived data consisted of 472,000 topographic ground points, which gives approximately 30-cm average point spacing in the plane of the 160 m by 160 m area that was used in this study. ArcGis (ESRI, Redlands, CA) was used to identify and select the LiDAR-based topographic information for the same reach of the stream that was surveyed in the detailed ground survey (see following section). The selected data consisted of more than 31,000 topographic points covering the 90 m reach (Figure 1 c) that was modeled in this study. The general accuracy of the LiDAR data was assessed relative to detailed ground survey transects for overlapping locations. The average absolute difference between the two sets of data was 0.35 m over the entire study reach with a standard deviation of 0.23 m.

3.3 A detailed ground survey for defining channel geometry

A detailed ground survey was conducted on 7 August 2009. At the time of the survey, the stage was 0.5 m at the gauge and the discharge was 0.6 m³/s established using the velocity-area method. The ground survey consisted of 617 topographic measurements of the wetted perimeters of 29 cross sections along a 90 m long reach of the stream extending downstream from the staff gauge (Figure 1). The survey was made at an average density of 3.2 points per meter along each cross section, using a Trimble S6 DR robotic total station and an adjustable prism rod. This equipment combination has an angular precision of 0.1 milligrad and a distance measurement precision of $\pm 3 \text{ mm} + 2 \text{ ppm}$ root mean square (RMS). Given a maximum distance of $< 50 \text{ m}$ in the survey the maximum error in the plane is $\pm 3 \text{ mm}$ and $\pm 0.5 \text{ mm}$ in height. Reference points were set using a high resolution Trimble R8 Global Navigation Satellite System receiver with an accuracy horizontal of $\pm 10 \text{ mm} + 1 \text{ ppm}$ (RMS) and vertical of $\pm 20 \text{ mm} + 1 \text{ ppm}$ RMS. Topographic data

were collected with a handheld field computer (Trimble CU Controller or Trimble TSC2 Controller) as points in the SWEREF 99 (zone 20 15) coordinate system to facilitate their import to a geographical information system for preprocessing.

3.4 Data preprocessing

Data from both the LiDAR scan ($> 31,000$ topographic points) and the detailed ground survey (617 topographic points) required some preprocessing to be used in the model of Kean and Smith (2010). To obtain a common coordinate system data were transformed to the SWEREF 99 TM coordinate system using ArcGis (ESRI, Redlands, CA).

Because the LiDAR technique (TopEye MkII) used in this study was unable to penetrate through the water surface, some method must be used to fill in for the missing streambed topography. This was treated in two different ways in this current study. The first was to create a model with estimated streambed topography (hereafter referred to as the LiDAR model). This was done using the simple assumption of a flat streambed with the lowest elevation corresponding to zero (0 m) at the staff gauge (Figure 2). The water level over the period of the LiDAR scan was 0.3 m at the staff gauge but discharge was not measured at this time. The second approach to represent the streambed topography was to merge the LiDAR data and detailed ground survey data to create a model with a combined topographic representation (hereafter referred to as the hybrid model). Data from both approaches were then interpolated using curvilinear regression onto a common computational grid that could be imported into the flow model. Once both sets of data were preprocessed, the model of Kean and Smith (2010) was used to calculate flow rates at different stages and, thus, to generate rating curves.

In this current study, the roughness of the streambed was the primary source of flow resistance. The low-flow

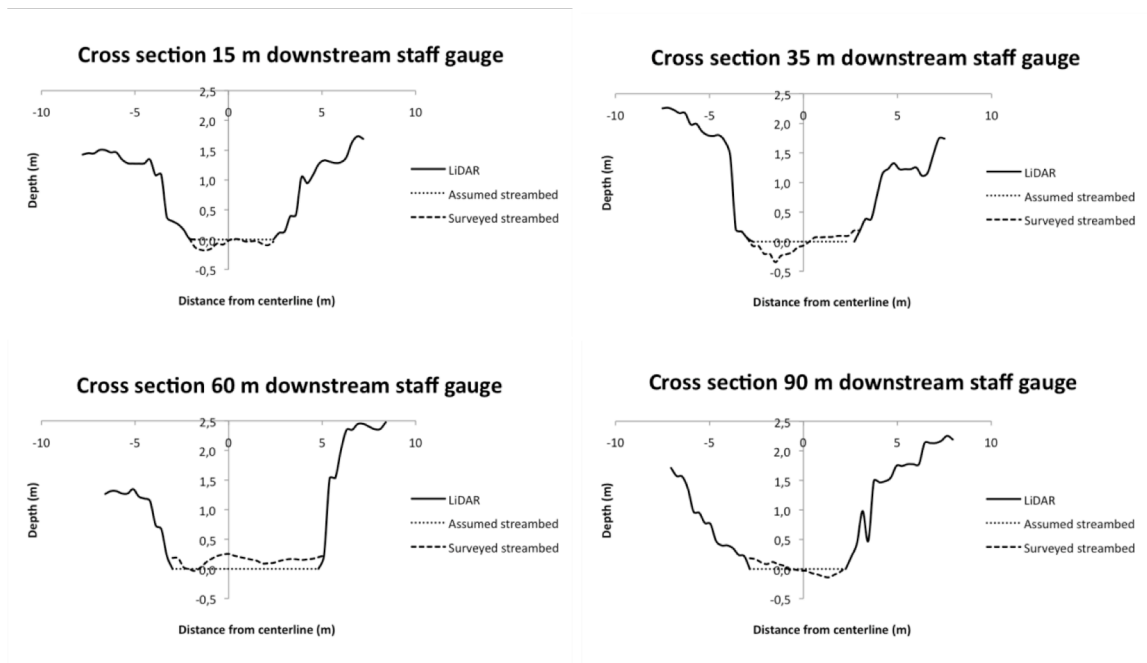


Figure 2. Cross sections showing topography from the LiDAR scan (solid line), measured streambed from the detailed ground survey (dashed line), and the estimated “flat” streambed (dotted line).

discharge and the water surface slope used to estimate the roughness height in each model were 0.6 m³/s (current meter measurement) and 0.004 m/m (measured with a total station), respectively, and were performed on same day as the detailed ground survey. Once specified, the roughness height was held fixed during the computation of the rating curves. Separate bed roughness heights were determined for the modeled reaches in the LiDAR model ($\tau_o = 0.027$ m) and the hybrid model ($\tau_o = 0.023$ m). The minor differences between these two values reflect differences in the bed topography in the two models: the unmeasured bed surface (in the LiDAR model) was assumed to be flat, whereas the hybrid model (from the detailed ground survey) contained measurements of the bed surface. The calibrated bed roughness height for the LiDAR model was slightly larger than for the hybrid model, because the LiDAR survey does not account for the additional roughness provided by the gradually varying bed topography.

4. Results

4.1 Empirical rating curve

Observations from 26 flow measurements in 2008-2010 were used to estimate an empirical rating curve (Figure 3). The empirical rating curve is a fitted power function ($y = 0.6x^{0.4}$; $r^2 = 0.91$) that shows the relationship between stage and discharge. There was good agreement between the empirical rating curve and measured flow (Table 1). This is particularly true at low to medium stages whereas the rating curve deviates somewhat at higher stages.

Table 1: Agreement between model-predicted and measured flow calculated as root mean square error.

Root Mean Square Error (m ³ /s)		
LiDAR model rating curve	Hybrid model rating curve	Empirical rating curve
0.63	0.47	0.74

4.2 Modeled rating curves

In general, the modeled rating curves were in agreement with measured flow (Figure 3). The LiDAR-model rating curve (solid line in Figure 3) was in agreement with measured flow at most stages; however, it seems to slightly overestimate flow at the lowest stages. This overestimation is not seen as much in the hybrid-model rating curve, which included data from a detailed ground survey (dotted line in Figure 3).

4.3 Rating curve comparisons

General statistical characterizations (Figure 4) were used to compare each modeled rating curve to both the measured stream flow data and the empirical rating curve.

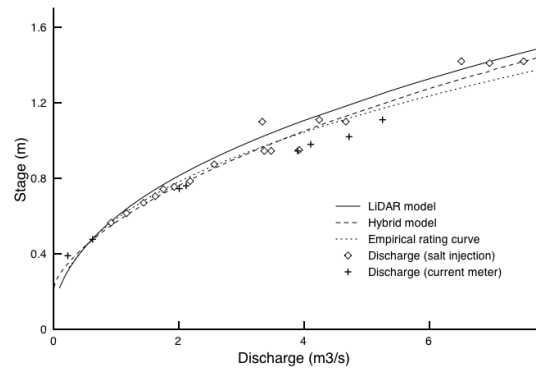


Figure 3. Measured discharge from salt measurements (white diamonds), from current meter measurements (black cross), and the empirical (fitted) rating curve (dotted line). Modeled rating curves using the LiDAR model (solid line) and the hybrid model (dotted line) are also shown.

Confidence bounds for the empirical rating curve were calculated for this comparison (Figure 4). Most of the LiDAR-model rating curve is within the 95 % confidence bounds except for a small portion at stages between approximately 0.8 m and 1 m (where Q is approximately 2-3 m³/s). The hybrid-model rating curve is within the calculated 95 % confidence bounds at all stages. The LiDAR-model rating curve, however, seems to track better with the three highest flow observations (Figure 3).

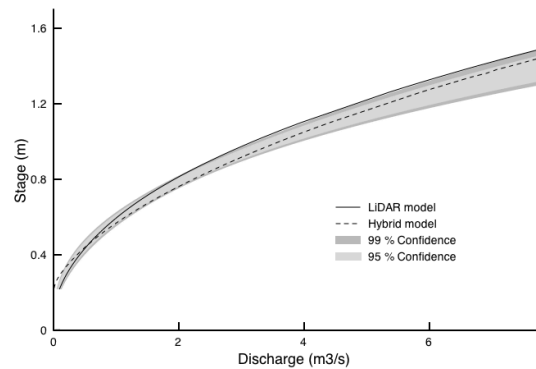


Figure 4. LiDAR model rating curve (solid line) and hybrid model rating curve (dotted line) in relation to the 95 % (light gray area) and the 99 % (dark gray) confidence bounds of the empirical rating curve.

5. Discussion and concluding remarks

Both modeled rating curves showed relatively good agreement with measured discharge (Figure 3; Table 1). In addition, both modeled rating curves matched the empirical rating curve. That is, for the most part, both modeled rating curves are within the 95 % confidence bounds calculated for the empirical rating curve (Figure 4). This indicates that the modeled rating curves (independent of assumptions regarding the representation of the streambed) accurately estimate the stage-discharge relationship for this site assuming the empirical rating curve can be thought of as the ‘true’ rating curve. The empirical rating curve was fit using a standard least squares approach to measured discharge without any weighting of discharge measurements. Thus, there is a potential over-representation of the more frequent low

discharge measurements made at the site. A fitted weighting applying more value to the high discharge measurements could potentially offset this and would lead to a better agreement between the empirical rating curve and the modeled rating curves. However, since physical flow measurements are subject to uncertainties (Herschy, 2002) and weighted rating curves are not necessarily commonplace in hydrological practice, such weighting was not considered in this study.

The LiDAR-model rating curve (solid line in Figure 3) shows good fit to measured flow at stages where water level is exceeding approximately 0.5 m. This curve seems to slightly overestimate flow at the lowest stages, probably due to unresolved streambed topography. The assumption of a flat streambed produces a relatively lower bed roughness that will have greater impact at lower flows and less influence at higher flows. This effect is not seen in the hybrid-model approach where the data from the detailed ground survey better reflect the actual roughness of the streambed topography.

While based on only one location, the results obtained in this study indicate that the Kean and Smith (2010) method can use the LiDAR derived data to model rating curves that are as likely as rating curves modeled using data from discharge measurements (Figure 4) or rating curves developed using topographic data from conventional ground survey methods (Figure 3). Of course, this may not be true in regions or reaches with more complex geometries or flow conditions. This warrants further investigation into using LiDAR to run the Kean and Smith (2010) method at different positions in a stream network to find potential limitations.

The TopEye technique used for the LiDAR scan in this study could not penetrate the water surface. It was therefore unable to obtain data regarding the streambed topography necessary for running the Kean and Smith (2010) method to generate rating curves. This was compensated for in this study by an assumption of the actual streambed topography. Fortunately, there are other new techniques that can potentially overcome this problem. For instance, the HawkEye technique (bathymetric LiDAR) uses a combination of NIR and green light that can provide both terrestrial and bathymetric topographic information (Bailly et al., 2010); however, this technique has a coarser resolution, which may limit potential usefulness, especially in small streams. Flow depth or water surface elevation can also be determined using object-based classification of topographic data (Hofle et al., 2009) obtained from airborne LiDAR scanning. This technique, or workflow, allows for separation of water and non-water points in the LiDAR data point cloud, thereby giving the possibility to map river bathymetry with higher accuracy. Yet another approach for mapping accurate river bathymetry, especially in shallow river channels, is to apply the algorithm of Optimal Band Ratio Analysis (Legleiter et al., 2009) on data retrieved from passive optical remote sensing. Nevertheless, the hybrid-model rating curve presented in this study, for example, could provide an approximation of the potential rating curves available

using such bathymetric LiDAR techniques. Since this hybrid approach is completely within the 95 % confidence bounds of the empirical rating curve and fits well with the discharge measurements, there appears to be some potential for development of rating curves from bathymetric LiDAR-derived data.

The use of LiDAR-derived data as input for modeling theoretical rating curves opens a realm of possibility to remotely sense and monitor stream discharge in channels in remote locations. This approach might also be beneficial in cases where stream morphology is changing over time and, thus, frequent updates of the rating curve are necessary. However, airborne LiDAR scanning today is still quite expensive. The high cost might be partially compensated by the ease with which rating curves and stream monitoring could be performed even at remote locations using the methodology outlined in this study. Future studies will be needed to investigate limitations linked to the resolution of the LiDAR information. How much information is needed from the LiDAR scan to modeled rating curves accurately? In particular, can low-resolution scans (similar to those currently being carried out at the national scale in Sweden (i.e. 0.5 points/m²)) be used to estimate stage-discharge relationships? Regardless, the potential of LiDAR-based techniques for obtaining geometric measurements for use in modeling rating curves opens an exciting realm of potential for monitoring and measuring discharge in the multitude of ungauged streams sometimes called Aqua Incognita (Bishop et al., 2008).

7. Acknowledgements

The lead author (MN) was funded by the Ministry of Education and Research at the Swedish Government and by the Education Administration at the City of Stockholm. We also acknowledge support in the form of funding from the Swedish Research Council (VR Grant No. 2011-4390). The Krycklan infrastructure is funded by Formas (ForWater), VR, SKB and others. The LiDAR scan was organized by the Swedish Defense Research Agency (FOI) and financed by The European Space Agency (ESA). Great thanks to Jörgen Wallerman at the Swedish University of Agricultural Sciences (SLU) for providing LiDAR data. Also, great thanks to Paul Kinzel (USGS) and Kevin Bishop (SLU) for pre-review of this manuscript, to Jim (James Dungan) Smith (USGS) for helpful conversations, and Bijan Dargahi at Swedish KTH Royal Institute of Technology that provided constructive comments on this paper, as did two anonymous reviewers. MN greatly acknowledges the staff at Trimtec (Umeå, Sweden) and the field staff at SLU for all support with equipment, help and advice whenever needed. Any use of trade or product names does not constitute endorsement by the US government.

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