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Abstract

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Hydrological models are used widely and they demand for multiple input variables and observations. One of those variables is Manning’s roughness coefficient. In the current literature the variability of the coefficient poses an unknown uncertainty. This study examines a small river channel located in central Sweden, and aims to determine the variability and uncertainty of the roughness coefficient during diverse vegetation conditions within the channel. During multiple field visits to the location, slope, water level and cross-section examination is performed. With numerical simulation, discharge and roughness coefficients are obtained. With the hydraulic model (HEC-RAS), stage-discharge rating curves are produced and extrapolation is applied to obtain high flows. Manning’s roughness coefficients and their uncertainties are assessed by two different approaches. Determining the coefficient in a simplified sensitivity analysis by using Manning’s equation and calibrating HEC-RAS while applying Mean absolute error (MAE) calculation. The calculated roughness coefficients presents higher range when using Manning’s equation (summer vegetation conditions – 0.2, winter vegetation conditions – 0.095). On the contrary MAE provides values closer to each other (summer – 0.15, winter – 0.11). The obtained results indicate a high variance between summer and winter vegetation conditions, producing 38 cm water level differences during high flows using Manning’s equation and 6 cm difference using the calibration of the model in HEC-RAS. These results confirm that the roughness coefficient cannot be assumed to be constant throughout different seasons as had been assumed widely when applying hydrological modelling. Throughout the study innovative approaches and methods (e.g. back-calculating from Manning’s equation and calibrating HEC-RAS based on observed water levels) are used in order to determine the consequences of ignoring the variability of the roughness coefficient. Due to the study, one can derive that vegetation needs to be considered in having an important impact on the varying roughness coefficient value and it cannot be left as a constant value within hydrological models.

Keywords: Manning’s roughness coefficient, vegetation, HEC-RAS, Tärnsjö, uncertainty, rating curve

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Introduction

Flooding events have become a major concern in modern day society as a growing number of people live on or near floodplains. Moreover, the general flood risk is increasing due to climate change (Nicholls et al., 1999). One method to mitigate hazards due to flooding events is the prediction of such events with numerical modelling of the respective streams and their flooding areas (Di Baldassarre and Claps, 2011). However, hydrological models are not only a widely used tool for the forecast of floodings in order to minimise the danger of such events to society. Since they simplify complicated Earth systems, hydrological models also provide a powerful means to study the driving processes of flooding events in detail. The investigation of the various factors influencing the behaviour of natural streams and channels on the basis of numerical models helps understanding the nature of flooding events and hence reduce their threat to society. However, further research is required in order to strengthen the reliability of such models by determining the uncertainty levels of the parameters used (Di Baldassarre and Montanari, 2009). There are multiple commonly applied possibilities to compute flood models of natural channels. Depending on the approach, the uncertainties of the hydrodynamic models may differ widely. Understanding how the parameters affect the model is the first step to decrease model uncertainty.

Hydrological modelling and management of water resources demands observations of high and low river flows. These data from multiple measurements at different water levels during a certain time span are then used to establish so-called rating curves, which consists of water levels corresponding to an appropriate discharge value. These rating curves may be used to estimate extreme flows. However, the uncertainties associated with river flow measurements and calculations are often disregarded in hydrological modelling (Di Baldassarre and Claps, 2011). There are multiple factors causing uncertainties in rating curves. One of these factors is the variability of Manning’s roughness coefficient due to seasonal changes in vegetation. Manning’s roughness coefficient describes the channel's resistivity to flow. Though several publications mention the roughness coefficient to impact the reliability of the models, it has not been studied in more details when it comes to considering the changing vegetation conditions. This makes it an important factor to be considered since so far no uncertainty range has been established for the roughness coefficient. Specifically the influence that vegetation has on the roughness factor and thus ultimately on model uncertainty has barely been studied before, although the roughness factor and hence model uncertainty is known to be profoundly affected by the vegetation condition at the time of the measurement. This owes to the fact that Manning’s roughness coefficient characterizes the channel's resistivity to flow. Resistivity in this context implies vegetation conditions within the channel inhibiting the flow. Several other factors such as shape and size of a channel, sediment grain size also influence the coefficient. In this study, however the main focus will be on vegetation. Determining the uncertainty of Manning’s roughness coefficient poses a challenge to hydrologists since there is no established way or a method to derive the coefficient. Normally, a rating curve for a specific stream is calibrated from multiple water level and discharge
observations. To get the full range of flow variations, extrapolation of the observations is often applied. However, the vegetation conditions in a stream change seasonally, resulting in discharge values temporarily deviating from the calibrated rating curve. Due to the seasonal changes in Manning’s roughness coefficient values, different discharges may correspond to the same stage conditions. Thus, understanding the processes for changes in Manning’s roughness coefficient is of major concern when trying to refine hydrological models based on measurements of this parameter. In this thesis, the variation of Manning’s roughness coefficient is analysed by examining the aquatic vegetation in-situ during different seasonal conditions at an exemplary channel. This channel is located in Tärnsjö, approximately 50 km northwest of Uppsala, Sweden. A hydrodynamic numerical model of the channel is applied to the collected field data. Two different approaches are applied to derive the roughness coefficient in order to evaluate the suitability of the approaches to produce reliable hydrological models. Within the first approach, Manning’s equation is applied to back-calculate the coefficient. However within the second approach, while using a constructed cross-section within a hydrodynamic model, Mean absolute error (MAE) calculation is applied to compare observed water levels with simulated ones. These results are further used as an input for Hydrologic Engineering Center River Analysis System (HEC-RAS) hydrodynamic model to produce rating curves. Hence, variations between the roughness coefficients determined with the two different approaches can be evaluated.

**Aim**

The objective of this thesis is to investigate how the uncertainty of Manning's roughness coefficient influences the validity of hydrological models. As model uncertainty depends on the quality of field data and the method used to analyse the data, this thesis aims at evaluating how choosing a method impacts the uncertainty of hydrological simulations. To do so the variability of Manning’s roughness coefficient, \( n \), and its dependence on the changing vegetation conditions within a natural channel in Tärnsjö is investigated.

This study is an important step towards improving understanding the roughness coefficient uncertainty, since in the current literature investigations of the coefficient are not that commonly seen.
Background

The Irish hydraulic engineer Robert Manning is best known for presenting the widely used Manning’s equation in 1889 (Chow, 1959). The formula was later modified several times to derive to its current form:

\[ Q = \frac{1}{n} A R_h^{2/3} S^{1/2} \]

Here \( Q \) describes discharge \([\text{m}^3/\text{s}]\), \( n \) is Manning’s roughness coefficient, \( A \) the cross-section area, \( R \) the hydraulic radius calculated as the cross-sectional area against the wetted perimeter \( P \) and \( S \) represents the surface energy slope (in the thesis will be referred to as slope and hydraulic gradient). For practical purposes Manning’s coefficient is accepted as a dimensionless variable. Due to its simplicity, Manning’s equation is one of the most widely used equations for uniform flow conditions in open-channel calculations and simulations. Manning equation is sometimes acknowledged as a variation of Chezy formula (Chow, 1959).

According to Graf (1998) a flow is considered steady and uniform when the depth of the flow is remaining constant within its direction and time. In a uniform flow bed slope, water surface slope and hydraulic gradient are considered to be the same. Also other hydraulic parameters of the channel such as discharge, channel slope, roughness and average velocity remain unchanged within different reaches. Although uniform flow in natural or artificial streams is rare, the foregoing assumptions of these conditions is often taken as a reference for theoretical or experimental simulations and considerations. This is done to simplify the set-up of hydrological models as defining unsteady flow would introduce new levels of uncertainty due to additional parameters.

Chow (1959) emphasizes that the biggest difficulty when applying Manning’s equation is the determination of the roughness coefficient since there is no established way or method to determine the coefficient. So far, the coefficient has been defined as the resistance of flow in a channel. At the current stage, the estimation of the coefficient is based solely on the experience of the person setting the value (Chow, 1959).

In Chow (1959) four steps are presented to help determining the coefficient. Firstly, and most importantly, one has to recognize the factors affecting the coefficient and to acquire basic knowledge about the channel and its characteristics. Secondly, starting values of the coefficient are presented in literature that may be used as a reference level for different types of channels. As the third step is advised to be familiarized with various types of channels whose roughness coefficients are known. From this a solid foundation to adjust the value can be achieved. And finally, with the help of analytical methods, the value of the coefficient can be determined based on theoretical knowledge and measurements on the velocity distribution across the channel (Chow, 1959).
Rating curve
With regard to discharge measurements, recording higher flows often comes as a challenge due to the large extent of the possible flooding and many risk factors especially when it comes to large rivers. Flooding events are a danger to be present at, and to get accurate measurements and observations come at an even higher risk level. The term stage is defined as the water level and is often specified as water depth and is one of the most important observations to be done when performing hydrological field measurements. Whereas discharge is a volume of water flow through a given cross-sectional area and is usually expressed in m³/s. Further, discharge is one of the most important parameters in the evaluation of a catchment water balance and water control as well as in the construction of flood models and preparation of precautions for such events. Although direct measurement system can be applied and monitored in small channels and streams, indirect approaches are most often used in medium and large streams. When estimating discharge values, stage – discharge relationship is established. Several pairs of recorded stage and discharge values yield the so-called rating curve by numerically fitting a curve through these data points. To compute discharge and stage values during high flows and flooding that cannot be measured, the rating curve is extrapolated beyond the end of the data set. Once the rating curve is established it is possible to measure solely the stage and obtain the corresponding discharge value from the curve.

In most hydraulic models an option to produce rating curves is often applied, as that is the most common product presented for natural streams and channels. And as an input for the models, Manning’s coefficient is applied. Therefore without correctly adjusting this parameter or even leaving it to be constant throughout different seasonal vegetation conditions, the produced rating curves can end up with high and often unknown uncertainty levels.

A comprehensive analysis on rating curve uncertainty was performed by Di Baldassarre and Montanari (2009) on the River Po, listing potential sources of errors and uncertainty. Errors during the collection of river stage and discharge measurements range as one of the most important ones, since these are the main input parameters when creating a rating curves. Usually extrapolation beyond the measurement range is applied to adjust the collected data to extreme cases. However, this causes a considerable uncertainty in modelling flooding events. The authors further detected that due to extrapolation, errors in rating curves comprised up to 14% at 95% confidence level. Assuming a steady and uniform flow during modelling despite having unsteady flow conditions in reality is another error source for hydrodynamic modelling. Another factor adding to the uncertainty of hydrological simulations are seasonal vegetation variations leading to roughness changes (Di Baldassarre and Montanari, 2009). Moreover, the river geometry which is assumed unchanged with time, in fact varies temporally, leading to a varying roughness coefficient. The authors emphasize that the roughness coefficient can hardly be reliably determined, since it is affected by such a large number of other factors, all varying either with time or locally along the course of the stream. They thus conclude it to be the main reason for uncertainties in the established rating curve. Di Baldassarre and Claps (2011) performed
a numerical study in which they analysed the uncertainty of the HEC-RAS model parameters by running three simulations with varying Manning’s coefficient. Slight differences of the modelled discharge values are observed, leading them to the conclusion that this factor should be accounted for when using hydraulic modelling approach to reduce uncertainty of rating curves (Di Baldassarre and Claps, 2011).

Several hydraulic models might apply slightly different methods to produce rating curves. Dottori et al (2009) in their research propose multiple techniques to obtain rating curves. Their study showed that for one data set, different methods lead to considerably different rating curves. This indicates that significant variations between rating curves may in fact not result from different flow parameters but maybe due to the chosen calculation approach.

On the contrary a study by Westerberg et al (2011) emphasizes the importance of evaluating the uncertainty of discharge measurements before analysing or working with the data. The authors examined a field site in Honduras and attempted to determine the uncertainty levels concerning dynamic and non-stationary rating curve conditions. Considering the varying situation within the field site due to erosion or sedimentation within the channel, or due to seasonal variations of other parameters, the authors assigned different uncertainty levels to low, medium and high flows. Recognizing the uncertainty of discharge observations and introducing them into hydrodynamic models, increases the accuracy of the overall uncertainty estimate of the model. This results in more reliable simulations, since the estimated uncertainties become more realistic. Therefore, this factor may not be disregarded when considering non-stationary rating curve locations (Westerberg et al., 2011).

Factors Affecting Roughness Coefficient
For simplicity it is often assumed that a channel has a single value of roughness coefficient throughout time. In reality, however, this is not the case – the coefficient fluctuates due to many factors. Therefore the understanding of how the roughness coefficient is impacted becomes imperative (Chow, 1959). In this section, factors influencing the roughness coefficient are described and possible interdependencies are discussed.

Several factors influencing the roughness coefficient have been mentioned by Chow (1959). One of these factors being surface roughness. It represents the material forming the wetted perimeter, such as the size and shape of the grains on the bed and banks of a channel. While fine grained material will result in a low value of the Manning’s coefficient, a coarser material will indicate an increase of the value.

The next factor that is mentioned by Chow and of great importance for this study is vegetation. It is also often referred to as the surface roughness, and can change the capacity of a channel and retard the flow in it (Chow, 1959). Floodplains as well as the channel itself can be covered with brush or trees and other living or dead plants. It is challenging to determine the impact of vegetation within a stream, but size, shape, spacing of the plants and their submergence or unsubmergence in a channel is considered. Dingman (2009) mentions that due to anthropogenic increase of nutrients that are present in
runoff, height and spacing of water plants can vary a lot seasonally, influencing the roughness of a channel. Several laboratory experiments have been carried out to try and identify the importance of vegetation in a channel in terms or roughness changes. For example, Wilson and Horritt (2002) did an experimental study, using common garden grass of average height and density to represent vegetated conditions in a flume design experiment. The results showed that the hydraulic resistance of the grass reached its maximum when the flow depth was similar to the grass height. From this point, with increasing flow depth, resistance decreases. Furthermore, if cross-sectional flow area is to increase, resistance, and therefore roughness coefficient decreases. Wilson and Horritt (2002) emphasize, however, that information and roughness values provided by various studies are contradictory to each other. It could be seen from the reported results in Wilson and Horritt (2002) that the Manning’s coefficient values were 40% greater than those given for a similar grassy floodplain (Chow, 1959), but were noticeably lower that values mentioned in the handbook United States Department of Agriculture (1947). The vegetation in a channel can also be characterized by the percentage of the wetted perimeter covered by vegetation, by the density of submerged water plants or by the alignment of vegetation with respect to the flow (Aldridge and Garrett, 1973). The U.S. Soil Conservations Service presented studies that dealt with different estimates of roughness coefficients in small and shallow channels. Comparing two variant channels a higher coefficient value was prescribed to the channel with a smaller average depth (Unites Stated Department of Agriculture, 1947). The reason for this is that the channel is being affected by vegetation, affecting the ability for the flow to move freely. Likewise, deeper channels would not be affected by deep vegetation as much. A steeper slope also provides flattening and submerging of vegetation (Chow, 1959). As for low flows, where vegetation is unsubmerged, the roughness coefficient has a tendency to decrease with increasing flow depth and vice versa. Conditions change when vegetation is submerged, driving the roughness coefficient up to increase to a certain stage (Wu et al., 1999). It has been argued, whether vegetation changes on roughness should only be considered up to a certain discharge and stage levels (Chow, 1959), and when these levels are exceeded, the presence of vegetation within a channel is no longer an important factor to consider. On that occasion, when high flooding levels occur, a fixed value of $n$ could be assumed.

Other factors affecting the roughness coefficient are channel irregularities in channel geometry. These irregularities correspond to bumps and holes in the channel bed that may strongly affect the bed roughness. Another factor influencing the flow is the channel alignment, where sharp curves and twists in a channel may increase the roughness coefficient. Within open channel hydraulics two of the most studied variables are stage and discharge. An increase of both stage and discharge results in a decreasing roughness coefficient. On the contrary, a lower stage indicating shallow waters leads to an increase of the roughness coefficient due to the fact that when the channel bottom is more exposed so that irregularities and vegetation will inhibit the flow more strongly. A different situation is observed at very high discharge values, where a stream flows over the banks and part of the flow occurs on the floodplain.
In most cases, the roughness coefficient is considerably larger on the floodplains, depending on the roughness and the vegetation present. Only if the banks of the river as well as its bed, can be characterized with a similar vegetation conditions, the coefficient may have minor variations or even remain unchanged for various stages and discharges (Chow, 1959).

Chow (1959) also mentions seasonal change as a factor influencing the growth of aquatic plants, grass, weeds and willows, which leads to an increasing value of the roughness coefficient in the growing season and a decreasing one in winter and dormant season.

Wilson and Horritt (2002) emphasize that while many technical hydrodynamic models are deeply analysed and well established, the presence of vegetation and its variability poses an important and significant factor to be considered within the models.

Furthermore, suspended material and bed load may affect the roughness coefficient. Material moving downstream with the flow or conversely material resisting the flow by remaining stationary may have opposite effects on the coefficient.

All of the factors mentioned need to be considered when estimating the roughness coefficient of a certain channel or stream.

**Methodology**

**Study area**
The study area is located within Tärnsjö catchment, situated in central Sweden, ~50 km northwest of Uppsala, Sweden. It forms a part of Tämnarån outlet to the Baltic Sea (SMHI, 2017) (see Fig. 1 and 2).
Further, in Figure 2, a more detailed field location set-up is presented. In order to account for the validity of the field data, they were compared to publicly available data sets recorded at the Tärnsjö monitoring station. The monitoring site is located on Tämnarån river, on a Stalbobäcken river section (station number of 2299) which lies roughly 50 m upstream from the measurement location of this study. The total catchment area is estimated to be 13.70 km² (SMHI, 2017).

Figure 2. Field layout describing the set-up of the measurements location. Source: Lantmäteriet, 2017.

Field work

For numerical and statistical analysis of the data, multiple field surveys were carried out. Field visits in the scope of the project were executed during a period of six months between September 2016 and March 2017. The first field survey took place on 5 September, 2016, when four metal rods were placed in the main channel that would be used to record readings on every field visit. The distance between the first and second pole was measured to be 18.20 m, between the second and third pole it was measured to be 17.49 m and between the third and fourth the distance was 19.05 m. All the pole locations can be seen in Figure 2, marked with the appropriate numbers and the colour yellow. The total length of the
examined channel section is 54.74 m. The distances between the poles were measured with a measuring tape.

In the course of the project a levelling instrument-tripod was used. Due to the factors such as ice melting or instability of the channel bottom, the placement of the poles may have been slightly shifted either further downstream or deeper within the sediments on the channel bed. In order to account for these changes, levelling was performed. The procedure was repeated six times to exclude measurement, reading or processing errors.

The reference point for the levelling was located at an easily identifiable, stable object and can be seen in Figure 2 coloured in red and located south of the channel. The levelling was repeatedly performed six times in order to minimize measurement errors and to detect whether adjustments to the pole placement and original height and therefore hydraulic gradient (slope of the water table) and water level measurements had to be done. A consistent shift of the levelling throughout the course of the project would indicate a shift present within the poles. The GPS coordinates and the absolute elevation of the poles and the reference point were determined with the Trimble R7 GPS Receiver (Trimble R7/R8 GPS Receiver, 2003). This data was recorded to get the exact elevation above sea level for the top of the poles and further to be calculated as elevation above sea level of the water table.

A detailed cross-section examination was performed on 3 October, 2016 by the third pole (Fig. 2). In order to characterize the cross-section within the main channel and on the banks up until the floodplain, measurements of the depth and the width of the channel were recorded by using measuring tape and stick. For further water level observations, the level at which the poles are submerged within water were recorded. The start of the floodplain was determined visually. The depth of the channel and its width were determined using measurement tape and stick. A few samples (roughly 5-6) were taken to determine approximate length of the vegetation within the channel.

On every field location visit the following measurements were performed. For hydraulic gradient and water level values the height of the poles that is unsubmerged is recorded. By each of the poles, an individual photographic/visual analysis on the current vegetation conditions is performed. To be certain that the photos are taken on the same spot each time, the poles can be seen within the photos. An on-site water level reading is performed by the stationary SMHI station. The station, as mentioned above, is located roughly 50 m upstream of the inserted poles and in Figure 2 is referred to with blue colour and lies next to the outlet of a small pond. By the station, water level monitoring is done by the set-up triangle wire method, providing consistent water level readings for further discharge calculations (SMHI, 2017). Due to this recording, a specific discharge calculations could be performed to derive at an accurate value of discharge. For the calculation, water level readings from the station were incorporated in the following equation:

\[ Q(W) = \frac{8.0}{15.0} \times 0.575 \times \tan \left( \frac{90}{360.0} \times \pi \right) \times \sqrt{2.0 \times 9.81} \times (W - 10)^{\frac{5.0}{2.0}} \] equation 2
Here $Q$ represents the discharge value [m$^3$/s] and $W$ variable corresponds to the water level reading at the SMHI station [cm]. Furthermore, a rating curve, established in 1981 and lastly adjusted in 15th of April, 2009, was obtained from SMHI (SMHI, 2017). Together with the rating curve, equation 2 was presented, that was specifically designed to fit the current monitoring station at Tärnsjö. The equation had been designed so that accurate discharge calculation may be completed from the on-site readings of water levels. Daily average discharge values are provided by SMHI, and could be used for accuracy cross-checking for the calculated data (SMHI, 2017).

Measurements performed in September and October 2016 represent the growing season and summer period of the channel. Measurements for dormant season and winter period were recorded within months from November 2016 till March 2017. All field measurements were carried out in the first part of the day, approximately between 9 am and 1 pm.

**Numerical Simulation**

The flow in the examined channel was simulated using the HEC-RAS modelling software. For accuracy of the simulated flow, a detailed cross-section model was constructed. In Figure 3, a detailed cross-section of the channel constructed within HEC-RAS is shown. The vertical extent of the cross-section examined ranges from 52.17 m above sea level at the deepest point of the channel bed and 53.60 m above sea level when the cross-section reaches the floodplain. The total width examined is 8.1 m. The length of the simulated channel section is 54.74. m. Since in this simulation the channel geometry is assumed not to change within the whole examined channel reach, the cross-section established is fitted along the entire simulated length of the stream. An assumption is made for simplifying the analysis and complexity of the study that the main channel roughness is the same as the one on the banks of the channel (Fig. 3).

![Figure 3. Characterized cross-section model constructed within HEC-RAS.](image-url)
Estimation of Manning’s roughness coefficients

Two different approaches were applied for obtaining Manning’s coefficient. Both are explained further.

Determining Manning’s coefficient in a simplified sensitivity analysis

This approach includes using Manning’s equation (equation 1) to back-calculate the roughness coefficient. Equation 2 is applied for discharge calculations, hydraulic gradient variable is calculated as the relationship between length of the examined channel reach [cm] and the overall difference of elevation within the reach [cm], producing a dimensionless value, and cross-section parameters and hydraulic radius is calculated from recorded cross-section measurements by the third pole. For the simplicity of the equations and calculations, in this approach, the shape of the channel is assumed to be trapezoidal. This shape was visually determined and accepted to be true for the whole cross-section where Manning’s equation calculations are considered.

With assuming trapezoidal shape of the channel and from the specifics of Manning’s equation, uniform flow is accepted to represent the situation within the channel. By knowing these variables, a reciprocal roughness coefficients could be obtained. The size, form and characteristics of the channel are assumed to be constant over time and over the examined length of the stream. As floodplain is indicated to begin from visual determination, on the field it coincided with fenced infrastructure made for the field next to the stream (Fig. 2). For further calculations, as mentioned above the roughness coefficient is accepted to be the same for the main channel, the banks and the floodplain itself as well. Table 2 in results section provides parameters for area-cross section and hydraulic radius calculations.

For each field visit an individual values of discharge and hydraulic gradient is calculated. Then, using the previously described methods, the roughness coefficients can be derived. This results in four values characterizing growing period vegetation period and four for the dormant season accordingly. An average values of the roughness coefficient, discharge and hydraulic gradient were produced for summer and winter conditions.

To account for the range of uncertainty concerning equation 1, ±2% of the average discharge is considered together with ±2 cm changes in the slope and therefore the gradient of it. This in turn can indicate the sensitivity of the parameters. The chosen ±2% for the discharge is based on the reliability of the SMHI established station and the readings that had been done on it (SMHI, 2017). Slope measurement uncertainty is set for ±2 cm due to the precision of the levelling instrument and measurements done on the field. All of the possible combinations for uncertainties were performed by numerical simulations with MatLab software to obtain the upper and lower/most extreme range estimates of the roughness coefficient.

To account for the variations of the roughness coefficient due to vegetation changes, multiple rating curves needed to be produced. Also the uncertainty levels were established to account for the collected field measurements. For this part of the analysis, HEC-RAS software was applied. By adjusting only
the Manning’s coefficient, rating curves were presented. To construct an accurate model, field measurements for cross-section characterization were used. For the channel profile that was used in total of 54.74 m, and the four cross-sections considered within the model, an average hydraulic gradient was calculated to account for both summer and winter conditions, resulting in a value of 0.0025. This value was used to characterize the channel reach from the first pole located upstream to the fourth pole, located downstream of the channel (see Figure 2). Introducing this value allowed to simulate conditions closer to the real situation. Within HEC-RAS model, and option of Steady Flow Data was used, to describe the assumed behaviour of the channel. Within the option multiple flow profiles could be implemented. An important detail was Steady Flow Boundary Conditions, and depending on whether the channel is considered to have a fast and rapid flow (supercritical flow) or slow flow (subcritical flow), the implied boundary conditions differ. For the examined channel, the flow was characterized to be subcritical and was indicated so within HEC-RAS as well. For this, only downstream boundary conditions were necessary to be described. This parameter was set for normal depth, indicating that the measured hydraulic gradient value would be used. To run the model, Steady Flow simulation was chosen due to the assumptions made above. To obtain the differences in rating curves, Manning’s coefficient values were chosen based on the uncertainty of discharge and slope mentioned above. The same methodology was repeated for both, summer and winter conditions, to allow one to see the differences that roughness coefficient can produce. Extrapolation of the observed values was applied up to the discharge values of 2 m$^3$/s based on the rating curve spread, obtained for the SMHI station at the field site.

To account for uncertainties and the variations of the roughness coefficient, another method to determine the coefficient is applied. To be able to see the variations of the coefficient using slightly different approach could give a better understanding on which approach could be more reliable and accurate.

**Determining Manning’s coefficient by calibrating HEC-RAS**

For this approach to estimate the roughness coefficient, is the so-called inverse modelling using HEC-RAS software. This indicates that the model would be calibrated with the calculated values observed on the field. Within this approach, the observed water levels within the measured cross-section are compared with the modelled water levels in HEC-RAS. Since, the detailed cross-section measurements were recorded specifically for the situation by the third pole, the water levels are compared for this section of the channel reach. All observed discharge values were used as an input for the simulations, to find the best correspondence between observed and modelled values. Same boundary conditions were used as described for the first approach. Multiple individual simulations were executed separately for summer and winter vegetation conditions. At first, the Manning’s coefficient values were chosen based on the results from the first approach, to cover any possibilities on the occasion that the best fit values would correspond for both methods chosen. However, from the obtained results from each of the simulations, after applying equation 3, the input value of the roughness coefficient was manually
adjusted to fit better with the observed values accordingly. As objective function the *Mean absolute error* (MAE) equation was implemented:

\[ MAE = \frac{1}{n} \sum_{i=1}^{n} | \hat{h}_i - h_i | \]

Here, \( n \) corresponds to the number of observations or variables, \( \hat{h}_i \) is the modelled value and \( h_i \) is the observed water level.

MAE is separately calculated for winter and summer conditions. In this approach therefore, the lowest MAE value would correspond to the best fit for all of the observations (equation 3). Further, from these calculations, two individual rating curves are produced for both conditions as described above.

Due to the narrow focus of the project, an assumption is made, that roughness is only influenced by the vegetation. The characterized and developed cross-section represents the whole river reach studied within the project.

## Results

### Levelling/accuracy of the results

To ensure the accuracy of the results, levelling data were analysed first. As described before, four metal rods were positioned in the channel within the first field visit. The levelling data are displayed in Figure 4. As can be clearly observed in the plot the positions of the rods were measured at almost the same position on most of the measurements dates. The inaccuracy of a levelling measurement is considered to be 1-2 cm (STANLEY, 2004), if no other measurement error is present. The levelling is calculated as the absolute elevation determined at the reference point and that of the relative height between the poles and the reference point. This was achieved with combining the levelling data with the ones obtained from using *Trimble R7 GPS Receiver* providing centimetre accuracy and real-time positioning (Trimble R7/R8 GPS Receiver, 2003). Considering the inaccuracy level, two curves representing data from the 14 September 2016 (red curve) and the 14 February 2017 (light blue curve) differ notably from the data recorded on the other days. Especially the data recorded on 14 September 2016 deviate strongly from the other levelling data sets. This appears to be a measurement error. Although measurements correspond to the first and second pole, the following readings are not considered as a natural change in the situation within the channel since on the following field days, the rods positions are again to be measured to be on their previous positions. Another reading drawing attention was recorded on 14 February 2017, where the overall readings indicate higher levelling results. This means that the poles would have risen higher in elevation, instead of sinking down into the sediments. This observations does not correspond with the expectation, which is that the poles would be buried deeper in the sediment over time. Therefore, it is also considered to be a measurement error. A likely explanation for this is that the initial reference point measurement had not been chosen exactly the same for all the visits, and especially the one on 14 February 2017. This would imply that the chosen spot on the reference point had been
identified several cm higher in elevation than on other field visits, therefore shifting all the proceeding levelling results for that particular measurement reading. This situation may have occurred on the other field visits as well, impacting their accuracy from the first reading on the reference point while keeping the trend of the levelling unchanged. Taking into account the inaccuracy of the levelling measurements, the remaining measurements confirm that the rods have not considerably moved from their original place, and no adjustments to the water level readings is necessary (Fig. 4).

Figure 4. Levelling results for the carried out surveys displayed on top of the poles corresponding to absolute elevation. Measurement/reading errors present on 14 September, 2016 and 14 February, 2017.

**Numerical analysis**
The discharge values calculated for the water level readings at the SMHI station according to equation 2, are summarized and presented in Table 1 along with distinctive slope and water level. In Table 1 are further listed the roughness coefficient values calculated with equation 1. As mentioned before, the first four measurements in September and October 2016 correspond to summer vegetation conditions. The following measurements from late November 2016 to March 2017 represent winter conditions. The hydraulic gradient varies slightly from 0.042 to 0.029 during growing season vegetation conditions. However, in dormant period it ranges much wider from 0.119 to 0.031. A correlation between slope and discharge variable is observed such that a higher slope indicates high discharge values. The roughness coefficient can be observed to show similar characteristics as the slope, when varying slightly for the first four measurement surveys from 0.159 to 0.222, and showing more relevant changes within the last four field surveys from 0.064 to 0.180. For the growing season, an average value from all observations was calculated to be 0.003, and as for the dormant season the results pointed out to a decrease, to the value – to 0.002.
Table 1. Main variables and parameters observed, measured or calculated for the field visits.

<table>
<thead>
<tr>
<th>Date</th>
<th>Water level (h)</th>
<th>Calculated discharge (Q)</th>
<th>Hydraulic gradient (dimensionless)</th>
<th>n calculated from Manning equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.09.2016</td>
<td>1.2480</td>
<td>0.0416</td>
<td>0.0030</td>
<td>0.1592</td>
</tr>
<tr>
<td>14.09.2016</td>
<td>1.2200</td>
<td>0.0308</td>
<td>0.0030</td>
<td>0.2121</td>
</tr>
<tr>
<td>23.09.2016</td>
<td>1.2180</td>
<td>0.0301</td>
<td>0.0031</td>
<td>0.2217</td>
</tr>
<tr>
<td>3.10.2016</td>
<td>1.2160</td>
<td>0.0295</td>
<td>0.0029</td>
<td>0.2207</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurements during summer/growing season (field days 1-4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.11.2016</td>
<td>1.3780</td>
<td>0.1193</td>
<td>0.0022</td>
<td>0.0470</td>
</tr>
<tr>
<td>26.01.2017</td>
<td>1.2870</td>
<td>0.0599</td>
<td>0.0021</td>
<td>0.0911</td>
</tr>
<tr>
<td>14.02.2017</td>
<td>1.2200</td>
<td>0.0308</td>
<td>0.0021</td>
<td>0.1795</td>
</tr>
<tr>
<td>3.03.2017</td>
<td>1.3150</td>
<td>0.0756</td>
<td>0.0016</td>
<td>0.0637</td>
</tr>
<tr>
<td>Measurements during winter/dormant season (field days 5-8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 provides a graphical overview of the calculated discharge values in respect to the four field days carried out in both vegetation periods. A clear difference can be observed between summer and winter time. The water level and hence discharge varies only slightly for summer conditions, from 0.029 to 0.042 m³/s, whereas the difference is higher in the winter period with values ranging from 0.031 to 0.119 m³/s (Table 1). The difference between summer and winter conditions mainly is explained with the varying atmospheric conditions governing during the respective periods. Water inflow into the channel is mainly due to precipitation in summer and snow melting in winter. Since no major changes were recorded during September and October 2016 for water levels and discharge, it could be argued that major precipitation events did not occur close to the field survey dates. However, during the period from November, 2016 to March, 2017, higher values were recorded. This in turn could point out to precipitation event in November to January, and snowmelt during February and March (Fig. 5).
The calculated roughness coefficient reveals a clear variations with time, with higher values being assigned to the summer and a lower to the winter period as displayed in Figure 6. Furthermore, the coefficient varies more notably for winter conditions. However, when analysing the calculated data in more detail, one of the calculated roughness coefficients in winter period (field day 7 in Fig. 6 representing 14 February 2017) exceeds one of the values for summer conditions (field day 1 in Fig. 6 representing 5 September 2016) with 0.180 and 0.159 accordingly. Considering these two days, a slightly higher discharge has been recorded for summer conditions (0.0042 to 0.031 m$^3$/s). Combining the results from Figures 5 and 6 it is implied that increasing discharge would decrease the roughness coefficient.

![Figure 6. Calculated roughness coefficient, using Manning equation.](image)

**Determining Manning’s coefficient in a simplified sensitivity analysis**

In Table 2 basic characteristics of the channel that were recorded on October 3, 2016 are presented (Table 2). These values were used for equation 1 calculation to obtain the roughness coefficient.

<table>
<thead>
<tr>
<th>Table 2. General characteristics of the channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bottom width, m</td>
</tr>
<tr>
<td>Water depth, m</td>
</tr>
<tr>
<td>Channel top width, m</td>
</tr>
</tbody>
</table>

To further execute the tasks for the first approach, several input values had to be calculated for the model to obtain the corresponding rating curves. For the summer period the average hydraulic gradient is identified to be 0.003, which is used as the downstream boundary condition as mentioned previously in the methodology chapter. This value decreased overall with winter conditions to 0.002 and therefore was adjusted in HEC-RAS software for any winter simulations that were performed.
The average roughness coefficient value for summer was calculated to be 0.2034 with an uncertainty range varying from 0.1834 to 0.2157. The minimum value was obtained from combination of increased slope and decreased discharge, +2 cm and -2 % accordingly. The chosen critical values for the uncertainty simulations were chosen based on the reliability and accuracy of the acquired field data as mentioned in methodology chapter above. Decreased slope and increased discharge values presented the upper range value. To carry out the first approach, numerically determined values were implemented into the model. The rating curves within HEC-RAS were produced by simply adjusting the calculated Manning’s coefficient (Fig. 7). In Figure 7 both, summer and winter produced rating curves can be seen. However, for winter conditions simulations, the average calculation points out to a value of 0.0954. As for the calculated range, unusual view was observed, since the upper range was calculated to be 0.0834, which is still a lower than the average value. This, however is due to the fact that one field recording (24 November) was noticeably higher in terms of value range. This value could be also named as an outlier, presenting very different conditions and results. This one value, in turn changes the calculations done further. However, it is still considered within the results and discussion, due to providing a wider range of the analysed data allowing to have more trust in the extrapolated values. The upper range value was obtained from the simulation with +2 cm for the slope and -2 % of the discharge variable. As for the lower range, a value of 0.0666 was obtained. For these simulations a combination of – 2 cm for slope and +2 % for discharge gave the most fitting result.

The produced rating curves regarding the first approach mentioned above are displayed in Figure 7. In the Figure 7, rating curves are provided, including the uncertainty levels, based on the variability of the Manning’s roughness coefficient. When considering high flows for summer conditions, in Figure 7 we can observe that the range did not reach 2 m³/s due to the fact that at this point, water would over top the channel and would flow onto the floodplain. This is based on the combination of the modelled water levels in Figure 7 and the constructed cross-section in Figure 3. However, we can consider differences at 1 m³/s, where the average value produces a water level of 53.35 m. Here, with the lower roughness coefficient providing water levels of 53.28 m, and at the maximum coefficient value of 53.39 m, indicates an 11 cm difference only considering uncertainty based on the same vegetation conditions. From HECRAS extrapolation of the observed values was possible. Keeping in mind that the observed discharge values during vegetated period stayed between 0.029 and 0.042 m³/s, extrapolated values increase the uncertainty levels during high flows. Also in Figure 7 rating curve with uncertainty levels are produced for winter conditions. Even higher differences in high flows can be seen as for the winter vegetation conditions. At 1 m³/s, the average value produces 52.97 m, lower range value indicates a 52.87 of water level, and 53.03 regarding upper range. This indicates as high as 16 cm difference (see Figure 7). Hence, when both summer and winter vegetation conditions are considered simultaneously for the high flows (at discharge of 1 m³/s), the differences increase up to 52 cm (from 52.87 m corresponding to lower range value of winter period and 53.39 m corresponding to the upper range of the summer period). This is when the most extreme scenario is exploited. As the flow is decreasing the
range of uncertainty also decreases due to the values in the rating curves, approaching the observed values on the field. Also, we could also consider simply the average calculated roughness coefficient applied, without the range of added uncertainty. This again, considered at 1 m$^3$/s points to 38 cm variations (Fig. 7).

![Figure 7. Rating curves with uncertainty levels produced by using HEC-RAS.](image)

**Determining Manning’s coefficient by calibrating HEC-RAS**
As for the second approach, same calculated discharge, hydraulic gradient and water level values were used as an input for HEC-RAS simulations. Calculated *Mean Absolute Error* (equation 3) produced results are displayed in Figure 8. Once the lowest MAE values from HEC-RAS were found for both vegetation conditions, comparison for both periods could be displayed. The best fit of the roughness coefficient within MAE calculation for summer conditions indicated a value of 0.15. As for winter vegetation conditions, roughness coefficient decreased to 0.11 (Fig. 8). After applying equation 3 for the data, for summer period the value decreased to 0.015. However for winter period the result did not drop lower than 0.030.

![Figure 8. The best result for roughness coefficient, by using MAE calculation.](image)
In Figure 9, the produced rating curves with HEC-RAS are displayed, corresponding to the best fit values obtained from MAE calculations. When comparing visually from the results of Figure 7, less variance is observed in the latter results. Extrapolation again, was done up to 2 m$^3$/s, and before displaying the figure were cross-checked with Figure 3 and the range of the actual cross-section not to over top the banks of the channel. For better comparison purposes, high flows at discharge of 1 m$^3$/s are considered. For summer conditions water level correspond to 53.16 m, but as for winter conditions lowering to 53.10 m (Fig. 9). This converts to 6 cm differences (Fig. 9). The differences between the two conditions decrease slowly when shifting towards lower discharges. However, also shortly considering the upper extrapolation value of 2 m$^3$/s the difference is still 6 cm between the both conditions.

![Figure 9. Rating curves from MAE calculations and modelled with HEC-RAS](image)

**Vegetation**

**Growing season**

Throughout the first four field survey days, vegetation conditions within the channel are considered to represent the growing season or summer period as mentioned before. Since on the every field visit, photos of the current vegetation conditions were taken, Figure 10 is provided to display conditions that can best characterize the situation during September and October 2016. For further display of summer vegetation see Appendix A figures A1 to A3. On the first field visits, characteristics of the vegetation in the channel were slightly variable between the poles. Vegetation is unsubmerged and stands well above the water surface between the first and the second pole. The length was recorded to be ~0.9-1 m, providing enough material to be present above the water levels concerning summer period for the project. The vegetation type changed between the second and the third pole to a submerged vegetation lying within the channel, corresponding with the flow direction. Unsubmerged tall grass vegetation type returned again shortly after the third pole and continued on until the fourth pole. Some small trees were
also present between poles the third and the fourth pole, temporarily providing narrower channel space for the flow. The banks of the channel were heavily vegetated with different length and type of vegetation.

![Image 1](image1.png)  ![Image 2](image2.png)  ![Image 3](image3.png)  ![Image 4](image4.png)

**Figure 10.** Summer vegetation conditions captured by each of the poles (1-4) within the channel on the 14th of September, 2016. The positions of the poles are highlighted by arrows.

**Dormant season**

With the field visits from 24 November 2016 till 3 March 2017 the conditions within a stream are considered to represent dormant season or winter period concerning vegetation. Figure 11 provides an overview of the channel characteristics representing these conditions. As observed on the field and can be seen in Figure 11 also, the vegetation is still present on the river bed. However, when comparing situation with the conditions during September and October, the vegetation has noticeably changed colour, and all through the main channel lies parallel to the bed. For further display of winter vegetation conditions see Appendix A Figures A4 and A5.
When comparing both approaches used to determine the roughness coefficient, a larger range is observed from the Manning’s equation. However the second approach with calibrating HEC-RAS, provides a more narrow range for the values (Table 3).

Table 3. Calculated/modelled coefficient values with both approaches applied.

<table>
<thead>
<tr>
<th></th>
<th>Manning’s equation</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>summer</td>
<td>0.2 [0.18;0.22]</td>
<td>0.15</td>
</tr>
<tr>
<td>winter</td>
<td>0.095 [0.067;0.08]</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The roughness coefficient when compared with the water level readings pose a view pointing out that different roughness coefficient values can correspond to the same water level read from the SMHI station (see the marked area in Figure 12). The water levels represented in Figure 12 are noticeably higher than the ones actually present on the stream due to the set-up monitoring station specifics. A correlation between water levels and the Manning’s coefficient is observed, as water level increases, a decrease of the coefficient is observed. This, in turn points out for correlation between discharge and the roughness coefficient in the same manner, as the stage at the SMHI station is monotonically related to discharge (Fig. 12). Further, it indicates that a constant roughness coefficient cannot be assumed in any case.
Figure 12. Recorded water levels vs calculated Manning’s coefficient. With the squared area representing several roughness coefficient for the same water level.

Discussion

Although there are many factors influencing Manning’s roughness coefficient, presence and variability of vegetation within a channel is possibly one of the least studied ones. Multiple authors such as Chow (1959), Wilson and Horritt (2002), Di Baldassarre and Claps (2011) mention the importance and significance that vegetation may have on the discharge and water level calculations, while turning more attention to other variables. This study may help to understand the importance of seasonal changes in terms of vegetation presence in a channel and give a chance to further exploration or variance of Manning’s coefficient to improve hydrological model simulations.

Currently in the scientific literature there is a gap regarding the variability of the roughness coefficient. However, in multiple studies, claims have been made that the coefficient should be considered and studied in more detail (Di Baldassarre and Claps, 2011; Wilson and Horritt, 2002).

For more accurate analysis, the temporarily existing ice layer on top of the channel should be considered within the model. However, in this thesis, due to the number of measurements recorded, it was not sufficient enough to base our assumptions on. Together with this, the ice layer within the channel was unevenly distributed therefore making it more difficult to account for this.

The accuracy of the field measurements was evaluated based on the consistency of the levelling data. The reference point identified on the field as the rock by the stable (Fig. 2) is assumed not to have shifted from its place throughout the field survey period. This would imply that the starting point for each levelling would be fixed in its place. The latter data obtained, however indicates that some sort of a shift or inaccuracies are present for the data recorded on the field, regarding levelling (Fig. 4). In regards to the data analyzed in this thesis, it is important to note, that after analyzing the results presented from levelling, the elevation recordings were calculated from the levelling that was carried out on 5
September 2016. Two levelling readings as mentioned in the previous chapter is seen to highly vary from the other ones, 14 September 2016 and 14 February 2017 (Fig. 4). One could argue that for better combined results, an average of the remaining four consistent measurements may be used for further elevation calculations. However, this could cause inaccuracies and inconsistencies for all the field measurements due to it not fitting any of them after all. The slight deviations in the four remaining recordings may have resulted from the reference point itself. Although it was assumed to stay at the exact same spot, the measurement stick, depending on the person holding the measurement tool, may not have been held at the exact same spot each time, providing slight inaccuracies at the starting point already. Further, since no clear evidence was spotted that the poles had moved from their original spot, it was decided for higher accuracy, to consider the measurements obtained on 5 September to be valid.

A clear relation between the roughness coefficient and water level and therefore discharge is present (Fig. 12.). Almost identical discharge and stage conditions were recorded, however varying roughness coefficients were calculated. Therefore it can be discussed that use of constant coefficient values should not be applied in model simulations. This indicates the importance of evaluating vegetation changes within a stream. Still, the only other variable being different for this situation is the changing slope variable throughout summer and winter conditions. But when considering the slope, the vegetation presence is an important factor, therefore again, enhancing the effect of it. For a water level of 1.22 m, multiple roughness coefficients were calculated (Fig. 12). Yet, other variables such as discharge should be considered.

Due to the simplicity of the models, a number of assumptions were made at the start of the thesis. As mentioned above in methodology part, one of them was, that discharge has no influence on roughness. This assumption was made, so the focus of the study may stay only on the roughness coefficient. Relationship between the calculated discharge and Manning’s roughness coefficient values strongly disregard this assumption (Fig. 12). The trend is clear with an increase in discharge, a decrease in the coefficient is present. Clearly within a higher discharge, no matter what vegetation conditions would be present in a channel, the overall coefficient value would be lower. This is explained by the fact that with higher water levels and discharge, greater strength is given to the river, being able to disregard obstacles and therefore vegetation, rocks, pebbles etc. This relationship works both ways, meaning that both variables are relying on each other, and have to be considered as such. This points out, that previously stated assumption that roughness coefficient is only influenced by vegetation changes for further research should be disregarded. Same can be applied to the assumption that discharge has no influence on the roughness coefficient.

Another assumption that had been made in the beginning of the project was that the roughness coefficient is accepted to be the same for the main channel, the banks and the floodplain itself as well. This is not realistic nor true, therefore the sensitivity of the differences between the main channel and the floodplain should be further addressed in a more detailed study with additional and more continuous measurements.
For the modelling part of this thesis, an average slope determined for four field visits in summer and four in winter was used as an input for the model. However, when deriving the roughness coefficient with the first approach an individual slope measurement was used for each field measurement. For this reason, it is important to verify whether the slope has a crucial impact on the roughness calculations. A trend of the slope decreasing while water level and discharge is increasing was produced from the observed data (Fig. 13). This trend corresponds with the speculations mentioned above, the less resistant the channel gets without vegetation, the smaller the slope gradient becomes. As higher discharge is present within a channel, the slope is gradually decreased. Within the summer vegetation observations, slope is varying slightly as are the water levels in Figure 13. However, when high variations are present for winter observations (in Figure 13 5-8 field days), the changes within slope are not immediately recorded to follow. For the later field measurements, although water levels on the 7th field day return close to the observations during summer conditions, the slope variable is still lower than the ones recorded earlier (Fig. 13). This would indicate the importance of vegetation within a channel.

**Figure 13.** Slope variable plotted together with calculated roughness coefficient.

Besides the already mentioned factors to cause uncertainty in the results produced, the occasional presence of ice on the channel should be considered. In Figure 14 a situation can be observed, where the channel reach is partly covered with an ice layer. This represents the situation on the field on 26 January. Similar conditions were observed until mid-February. Ice thickness although was recorded for descriptive purposes, its presence was not considered within HEC-RAS model. Ice thickness was varying throughout the whole examined channel reach, in some parts covering most of the channel with up to 10 cm of ice. In other parts, the channel was free from ice or only 2-3 cm of ice cover was present. Presence of snow cover on the banks of the river was recorded on multiple field surveys, however this was also a variable not taken into considerations within the modeling analysis. The water was recorded to flow under the ice layer, and no additional ice blocks were present within the channel, but more field data needs to be collected in order to do more detailed analysis on this. Hence, though the ice and snow
could possibly have influenced the results of this thesis, due to the narrow focus of the study, it was not considered as an influential factor.

Figure 14. Winter vegetation conditions partly covered with an ice layer observed on the 26th of January by each of the poles (1-4) within the channel. The positions of the poles are highlighted by arrows.

As for the results presented from applying the Manning’s equation, extremely high differences are presented in terms of the different vegetation conditions. From figure 7, all uncertainty levels considered, the differences rose up to 52 cm in water levels during flow of 1 m³/s. This uncertainty decreases to 38 cm, if only average values are considered (Fig. 7). If we look closely on Figure 9, at MAE calculation, i.e. second approach, only one value for each of the vegetation periods is provided. Therefore this approach presents a difference of 6 cm (examining values at the flow of 1 m³/s). Considering that in most cases, the Manning’s roughness coefficient is left unchanged no matter the season or vegetation conditions, the differences between the two conditions periods presented in Figures 7 and 9, would indicate that this should not be the case, when relying on the hydrological models for accurate simulations on the flood levels. When we look at the different results that the approaches are presenting, one could argue that 6 cm differences presented by MAE does not seem so critical and this method could be applied for further model calculations. However, the uncertainty levels that for further studies needs to be added for MAE calculation. This would further indicate a wider range of values. This could be done by applying ±2 cm error bar around the water level. This would provide that a range could be obtained from HEC-RAS simulations for these variables as well. For further studies and analysis this uncertainty should be implemented to achieve a better understanding on the accuracy on the approach.
With the constructed cross-sections model in HEC-RAS, multiple rating curves extrapolated beyond the observations up to the edge of the constructed cross-section are displayed in Figure 7, characterizing the results from the first approach mentioned previously. These results were mostly compared at the high flows (1 m³/s), indicating up to 52 cm variability of the water levels. Uncertainty this high inevitably questions the accuracy, inputs and the characteristics of the models and methods used. However, the accuracy of the parameters obtained on the field, regarding slope parameter was identified to be ±2 cm (based on the accuracy of levelling procedure and equipment mentioned in methodology). As for the shape of the channel, for the initial roughness coefficient calculations when applying Manning’s equation, it was simplified according to the characteristics of the equation. The calculated discharge variable, with the uncertainty of ±2% was fixed due to the accuracy of the SMHI station located at the field location. Therefore, when producing the appropriate rating curves, a more precise cross-section model was constructed within HEC-RAS, increasing the trustworthiness of the results. All above factors considered, the variability of Manning’s coefficient that has been found during this study poses an important question of how accurate can our models be, if the roughness coefficient, that has been assumed not to change over the scope of different seasons, produces such high variable water levels.

Comparing the approaches applied
In order to be able to compare the two approaches applied within this thesis, Table 3 summarizes the main values produced by both approaches. One of the main differences between the two approaches is that with Manning’s equation, the shape of the channel is simplified and assumed to be trapezoidal as mentioned in the method chapter. However, when using simulations with HEC-RAS a detailed cross-section is used instead, which would presumably yield more accurate results. When comparing the results produced in this study and the ones mentioned in the literature, second approach, where equation 3 was applied displayed slightly closer values. For example, Di Baldassarre and Claps (2011) mention more widely used roughness coefficient values corresponding to 0.005, and similar values are reported by Chow (1959). The results presented in Table 3 imply that the Manning’s equation provides a wider range of the roughness coefficient, when comparing the different conditions (from 0.095 to 0.2). However, this would mean that the uncertainty of the results would increase as well. On the other hand from MAE calculations, the provided range is smaller (from 0.11 to 0.15). With the results produced by the Manning’s equation (equation 1) extrapolation up to 2 m³/s produced results that were displayed out of the constructed cross-section, indicating that the water would flow onto the floodplain. Due to this reason, most of the results are discussed and compared at the high flows of 1 m³/s for the channel. Without performing more extensive field study it is difficult to be exact in determining which of the two approaches is closer to the true value of the coefficient, but this can be an important step in the right direction in finding it out.
Conclusions

The main objective of this thesis was to investigate the influence of vegetation on the Manning’s roughness coefficient. The changing vegetation conditions within two seasonal periods are considered to be the main focus of this study. Two different approaches were applied to reach the estimates of the roughness coefficient, in order to test these approaches as well as to test the accuracy of the hydrological models itself. The uncertainty levels produced indicates that the assumption made within most hydrological models to use a constant Manning’s coefficient should be reconsidered.

Although there are many factors influencing Manning’s roughness coefficient, presence and variability of vegetation within a channel is possibly one of the least studied ones. Multiple authors such as Chow (1959), Wilson and Horritt (2002), Di Baldassarre and Claps (2011) mention the importance and significance that vegetation may have on the discharge and water level calculations, while turning more attention to other variables. This study may help to understand the importance of seasonal changes in terms of vegetation presence in a channel and give a chance to further exploration or variance of Manning’s coefficient to improve hydrological model simulations.

Applying Manning’s equation, at flows of 1 m$^3$/s, between the growing and dormant vegetation conditions extrapolation simulations produced 38 cm differences. At the same flow rate, calibrating HEC-RAS model and using MAE calculation, the differences were lowered till 6 cm variance. The main difference between the approaches was mentioned as using constructed or simplified cross-section. As a conclusion from the results and discussion above, one can observe that vegetation does have an important influence on the roughness coefficient and in turn until now poses an unknown uncertainty in rating curves. From the produced results one could argue that MAE approach would be more suitable to achieve the highest accuracy, due to using observed water levels within the model to fit the best coefficient (in addition producing values closer to each other in comparison to the first approach). However to claim one approach over the other, more detailed analysis needs to be done. Firstly, more field measurements need to be collected, recording data for longer periods of time, providing a solid base of diverse recordings. This would inevitably increase the trustworthiness of the results. Secondly, analysis and examination of the data could be done, with combining the two approaches that are mentioned within this thesis. MAE calculations could be applied, with considering the same uncertainty levels as mentioned for Manning’s equation approach.
Acknowledgements

First of all, I would like to express my gratitude to my supervisor Giuliano Di Baldassarre for advice, encouragement and help when I needed it. Thanks also goes to Allan Rodhe for suggesting the field site and assisting within the first field visit. Also to Kaycee, thank you for assisting me on the field visits even though it gets cold in Sweden during the winter months and also while figuring out how to further process the data.

Secondly thanks to Laura, for assisting with advice on organizing the written text and Tyra, for helping with the Swedish translation. And finally, thanks to the house owners of the field location in Tärnsjö for allowing me to invade their property and entertain the little horses with my presence.
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Appendix A: Vegetation conditions

Figure A1. Vegetation conditions by the poles (1-4) on the 5th of September, 2016.

Figure A2. Vegetation conditions by the poles (1-4) on the 23rd of September, 2016.
Figure A3. Vegetation conditions by the poles (1-4) on the 3rd of October, 2016.

Figure A4. Vegetation conditions by the poles (1-4) on the 26th of November, 2016.
Figure A5. Vegetation conditions by the poles (1-4) on the 14th of February, 2017.