Graz University of Technology
Institute of Hydraulic Engineering and Water Resources Management

Influence of vegetation on the Manning values in rating curves

Master Thesis

Christoph GLANZER

Provided to obtain the
Academic degree
Master of Science (Diplomingenieur)

Graz, October 2017

Supervisor of the Master Thesis:
Ass. -Prof. Dipl.-Ing. Dr.nat. techn. Josef SCHNEIDER

……………………………………………………

Statutory Declaration

I hereby confirm that I have written the accompanying thesis by myself, without contributions from any sources other than those cited in the text and acknowledgements. This applies also to all graphics, drawings, maps and images included in this thesis.

I assure that the thesis hasn’t been used or any audit work in this country or abroad.

Graz, October 2017 ………………………………………………

Acknowledgement

At this point I want to thank everyone who supported me during the creation of this master thesis. It was an interesting part of my time at the Graz University of Technology. At first, I want to thank Josef Schneider, who was the supervisor of this thesis, for giving me all the support I needed. He always had time for me and provided helpful advices. Furthermore, I want to appreciate the backing of the people around me who always supported and motivated me in their own way. Namely these people are Julia Holzer, Carolin and Iris Amann, Andreas Glanzer, Langer Bernhard, Florian and Philip Schitzelhofer, Philip Lanz and Christina Simmerer. Another person I want to thank is Dipl.-Ing. Dr. Robert Schatzl, who was so kind to share his knowledge about river rating in Austria with me, which makes it possible to find similarities and differences between the USA and Austria, concerning the river rating topic. Last but not least I want to thank the USGS for providing the data for the investigation.

Abstract

The purpose of this thesis is to find correlations between the vegetation of rivers and the Manning factors. In this context, the stage to discharge relationship, also called rating curve, is investigated. Gaining knowledge of the vegetational influence on rating curves is the first step for a refinement of the basic streamflow data, which is provided for every river. This streamflow data is used for designing hydraulic structures, which are protecting artificial and human resources. This means that the security measures for flood events can be planned more accurate to reduce the financial and human losses.

In order to investigate such influence, three gaging stations in the USA were observed. The “Clear Creek”, “Duck Creek” and “Walnut Creek” gaging stations, operated by the USGS, are located in Iowa, USA. For these gaging stations, field measurements and autonomous recorded stage data are available at the website of the USGS since the late 19th century.

Before the actual analysis began, the data have been filtered to eliminate failures due to low-flow and peak-flow conditions, as well as ice. Furthermore, only measurements which has been taken at steady flow conditions have been used for the analysis.

The analysis aimed at the occurrence of loop effects and the shifting of the rating curve itself. Furthermore, it was investigated how the autonomous collected measurements are influenced by such effects and how reliable they are. It has been shown that loop effects are occurring at every gaging station due to changes of the riverbed and unsteady effects, like storage potential of the channel and the flood plains. Additionally, the shifts of the rating curves for several years have been analyzed with respect to the Manning factors and the field measurements. It has been shown that seasonal changes are occurring at all three gaging stations. However, their amounts are different for every year. This may have the reason, that the degree of vegetation is different for every year and additional effects, which distort the results, cannot be completely ruled out.

The shifting of the rating curve is directly related to the changes of the Manning factors which makes such shifts to a central topic of the investigation. The main

effect, which falsify many results, is that many field measurements have not been taken at steady flow conditions. As the field measurements are used to shift the rating curve, such shifts are also distorted by loop effects. As a result, all autonomous measurements, which used such distorted shifted rating curve, are also suffering from a constant failure. Nevertheless, if the knowledge concerning the flow condition for every field measurement is taken in account, the interpretation of the results leads to satisfying results. This means that the Manning factors are tendentially higher in the summer than in spring and autumn.

Zusammenfassung

Der Zweck dieser Masterarbeit ist es eine Korrelation zwischen dem Pflanzenbewuchs von Flüssen und der Veränderung von Manning Faktoren zu finden. In diesem Kontext werden Abflusskurven näher untersucht, welche den Zusammenhang zwischen Pegelhöhe und Durchfluss wiedergeben. Den Einfluss der Vegetation auf diese Abflusskurven zu ermitteln, ist ein erster Schritt um die Genauigkeit von Abflussdaten, welche für die Bemessung verschiedenster wasserbaulicher Anlagen benötigt werden, zu verbessern. Diese wasserbaulichen Maßnahmen dienen zum Schutz von materiellen und menschlichen Ressourcen, welche durch genauere Abflusskurven noch sicherer gemacht werden können.

Um diese Einflüsse auf Abflusskurven zu untersuchen wurden die Daten dreier Messstationen in der USA herangezogen. Die Messstationen „Clear Creek“, „Duck Creek“ und „Walnut Creek“ befinden sich in Iowa und werden betrieben von der USGS. Für diese Stationen sind Feldmessungen und autonom aufgezeichnete Pegeldaten verfügbar, welche auf der Webseite der USGS abgerufen werden.

Bevor mit der eigentlichen Analyse begonnen werden konnte, mussten die Daten gefiltert werden, um Einflüsse von sehr niedrigem Durchfluss, sehr hohen Spitzenabfluss und Eis zu vermeiden. Des Weiteren wurden für die Analyse nur der Teil der autonom aufgezeichneten Messungen herangezogen, welcher unter gleichförmigen Abflussbedingungen aufgezeichnet wurde.

Die Analyse zielte auf das eventuelle Auftreten von Hysterese und den Anpassungen der Abflusskurven. Weiters wurde die Richtigkeit der autonom aufgezeichneten Daten untersucht und wie Sie von einer auftretenden Hysterese betroffen sind. Es wurde durch die Analyse aufgezeigt, dass alle Messstationen von Hysterese betroffen sind, aufgrund von Änderungen des Flussbettes oder Speichereffekte von Retentionsflächen im Flusslauf. Als nächstes wurden die Anpassungen der Abflusskurven untersucht, wobei die Manning Faktoren und die Feldmessungen miteinbezogen wurden. Für alle Messstationen wurden saisonale Veränderungen festgestellt, welche sich jedoch von Jahr zu Jahr unterscheiden. Die Gründe dafür könnten sein, dass die Dichte der Vegetation nicht jedes Jahr

gleich ist und zusätzliche Einflüsse, welche die Ergebnisse verzerren, nicht immer vollständig eliminiert werden konnten.

The Anpassung der Abflusskurven haben einen direkten Effekt auf die Manning Faktoren, was diese Anpassungen zu einem zentralen Thema macht. Die stärkste Beeinträchtigung der Ergebnisse ergibt sich dadurch, dass die meisten Feldmessungen nicht bei gleichförmigen Fließbedingungen durchgeführt wurden. Dadurch das die Feldmessungen zur Anpassung der Abflusskurve herangezogen werden, sind diese genauso fehlerbehaftet wie die Feldmessung bei ungleichförmigen Abfluss. Daraus folgt, dass auch die abgeleiteten Durchflüsse der autonom aufgezeichneten Pegelmessungen fehlerbehaftet sind. Wenn jedoch diese Eigenschaft der Feldmessungen in die Interpretation der Ergebnisse einbezogen wird, können dennoch brauchbare Schlussfolgerungen gezogen werden. Für die Analyse bedeutet das, dass die Manning Faktoren im Sommer tendenziell größer sind als im Frühling und im Herbst.

Table of content

1. Introduction

Rivers are complex systems whose physical properties are changing constantly over time. Therefore, the behavior of streams is difficult to predict, which is necessary to minimize the risk potential due to flood events. Reasons for the change of physical properties can be:

- Flood events
- Ice formations
- Vegetational growth
- Sedimentation

All these influences change the resistance of a stream and therefore the possible discharge. To gain knowledge about the different behaviors under those conditions, existing monitoring data should be analyzed to get an idea of the risk potential and the needed measures for flood prevention and maintenance (Rantz, 1982, a).

The Institute of Hydraulic Engineering and Water Resources Management of the Graz University of Technology has a long-lasting research history in river management and flood prevention. Therefore, the influence of vegetation on these systems are a point of interest.

1.1 Motive of this Thesis

This thesis aims on the changing effect of vegetational growth on the resistance of a river. Numerical and empirical studies have shown, that a general statement for every river cannot be made. Nevertheless, it is indisputable that seasonal changes affect the flow regime. In this thesis, the influence of vegetation on the river resistance will be analyzed by using historical measurements, although many previous studies tried to use numerical approaches. The difficulty about empirical determination is that the streamflow is influenced by many different factors. This makes it difficult to extract only the part which is corresponding to the vegetation.

1.2 Task

This master thesis deals with the influence of vegetation on the Manning values in rating curves. As the vegetation changes with the season, all other seasonal, temporal and long-term influences must be considered while performing the data analysis. Otherwise the plane influence of the vegetation cannot be extracted. For understanding the available measurement data, a detailed knowledge of the measurement process and the characteristics of the autonomous collected stage data and field measurements is significant. Therefore, the development and maintenance of rating curves should be investigated to understand the development process and find ways to reconstruct historical data. Although this knowledge will help to analyze the data, the problem of spatial informations about the site and the amount of vegetational growth at the gaging sites makes it hard to interpret the available historical stage data.

To investigate such changes of the river properties, three measuring stations in the USA are investigated. For these stations, field and autonomous measurements of stage, discharge, a.s.o. have been carried out since the late 19th century. This was done by the United States Geological Survey, also called the USGS. The USGS stores streamflow measurements and provides them free of charge to the public. Stage data is recorded every 15 minutes which are validated by field measurements performed every 2 months. By using these measurements, trends and seasonal changes should be able to be observed. The gaging stations are:

- Clear Creek near Oxford
- Duck Creek at DC Golf course at Davenport
- Walnut Creek at Des Moines

All these stations are operated and maintained by the USGS. The huge amount of recorded data should now be filtered and analyzed to get an idea about the vegetational influence on the flow regime.

Points of interest are:

- Changing of Manning values
- Discharge – Stage correlation (Rating Curve)
- Changing of bed forms

For analyzing of the data MS Excel and a curve editor is used.

1.3 Goal

This master thesis should find correlations between the changing Manning values and the growth of the vegetation, gained from historical and actual data. To achieve this, the topic of river rating should be examined. Furthermore, the amount of similarities and differences between the USA and Austria concerning the river rating process should be found. Additionally, the deviations between theory and practice, concerning the river behavior in different seasons, should be investigated.

2. Background

In this chapter of the master thesis, parts of various fields of expertise, which are important to fulfill the given tasks, will be specified.

2.1 Analysis of the problem

The main things to be investigated are the seasonal changes, the validity of existing rating curves and the change of the Manning values over time. To achieve this, expert knowledge in hydraulic engineering, physics of streamflow, biological condition in rivers and the special topic of river rating is needed.

2.2 Hydraulic basics

The following hydraulic basics, which are derived out of physical regularities, are essential to deal with the problem of vegetation driven shifts in rating curves.

2.2.1 Equation of streamflow

The relationship between the discharge *Q* and the water depth, which adjusts itself due to specific channel roughness and geometry, is one of the main topics in open channel hydraulics. Many different equations have been developed since the 18th century, but only a few are used until today. The most important historical equation was developed by the French hydraulic engineer Antoine Cezy (1775) (Jirka & Lang, 2009).

$$\boldsymbol{v = C\ R^{\frac{2}{3}}\ I_0^{\frac{1}{2}}} \tag{1}$$

With:	v	….. streamflow velocity	[m/s]
	C	….. constant	[-]
	R	….. hydraulic radius	[m]
	I_0	….. bed slope	[‰]

The hydraulic radius *R* describes the geometric properties of the channel, like shape and the water depth, while the constant value *C* defines the roughness of the channel. Additional the following equation is valid which defines a steady flow regime.

$$\boldsymbol{I_0 = I_e = \frac{h_l}{D}} \qquad (\mathbf{2})$$

With:	I_e	….. slope of the energy line	[‰]
	h_l	….. energy height losses	[m]
	D	….. longitudinal distance	[m]

In modern hydraulic engineering two extensions to the Cezy equation are important. At first, the equation of flow according to Darcy-Weißbach is used to describe the flow in pipes. However, this equation can also be approximately used for other geometries too, like river reaches with open channel flow (Jirka & Lang, 2009).

$$\boldsymbol{v = \left(\frac{8\,g}{\lambda}\right)^{\frac{1}{2}} R^{\frac{1}{2}} \quad I_0^{\frac{1}{2}}} \qquad \mathbf{(3)}$$

With:	g	….. gravitational acceleration	[m/s²]
	λ	….. roughness coefficient	[-]

The roughness coefficient λ is defined through the Reynold´s number and the roughness of the river bed. This relationship is shown in the so called “Moody diagram”, displayed in Figure 1 (Jirka & Lang, 2009).

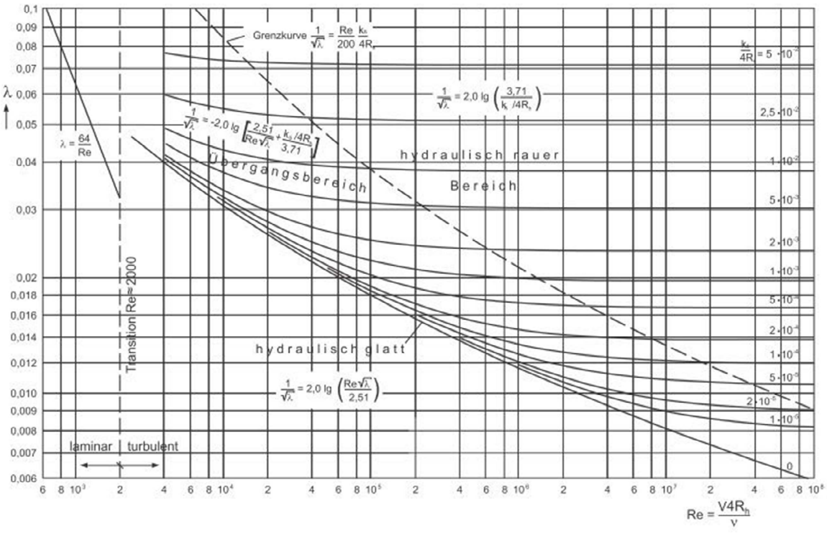


Figure 1 Moody Diagram for open channel flow (Jirka & Lang, 2009)

When dealing with open channel flow, mainly the hydraulic rough section is important. Furthermore, the coefficient λ changes with water level. The second common used equation to describe open channel flow was developed by Manning-Strickler

$$\boldsymbol{v = k_{st}\ R^{\frac{2}{3}}\ \ I_0^{\frac{1}{2}}} \tag{4}$$

With: k_{st} ….. “Strickler” – coefficient $[\mathrm{m}^{\frac{1}{3}}/s]$

This equation is more empirical than the equation according to Darcy-Weißbach, which can be used in many different cases like small scale flumes up to big scale rivers. Nevertheless, it has been proven, that for hydraulic rough channels with high Reynold´s numbers the Manning-Strickler equation leads to satisfying results. To proof the validity of this equation, their results has been compared to many field measurements. Furthermore, the roughness coefficient after Manning-Strickler, k_{st}, is not depending on the water level which makes it easier to handle. Due to this property this roughness coefficient is often used in the practical part of hydraulic engineering (Jirka & Lang, 2009).

The equation of streamflow can be expressed in different ways. The differences are resulting in the way the roughness coefficient is expressed. While in Europe mostly the roughness coefficient according to Strickler, called k_{st}, is used, other countries, including the USA, are using the roughness coefficient according to Manning, which is called n. Since these coefficients are proportional to each other, the equation of streamflow leads to the same result with both coefficients.

$$\boldsymbol{n = 1/k_{st}} \tag{5}$$

With: **n** ….. "Manning" – coefficient $[s/m^{\frac{1}{3}}]$

Nevertheless, the quantitative value of n and k_{st} for the same river are highly different which leads to failures if the wrong equation is used (Jirka, 2007).

$$\boldsymbol{v = \frac{1}{n}\ R^{\frac{2}{3}}\ \ I_0^{\frac{1}{2}}} \tag{6}$$

2.3 Flow conditions

The flow conditions in open channels can have various characteristics, which makes it possible to qualify different types of streamflow. Uniform flow exists when the water depth is constant in a specific part of a channel. Therefore, the water level is parallel to the river bed. If some properties of the reach like roughness, geometry or bed slope are changing, also the water depth is changing in a specific area of the channel. In this area, non-uniform flow condition occurs. For a more detailed analysis non-uniform flow can be separated into strongly non-uniform flow and slightly non-uniform flow. In contrast to strongly non-uniform flow, which occur due to weirs or large changes of the cross section, slightly non-uniform flow appears where the roughness or the slope are changing (Jirka & Lang, 2009).

Apart from uniform and non-uniform flow conditions, another flow classification is important, which deals with changes of flow rates over time. If the flow rate stays constant at a specific section of a river in a specific period, steady flow occurs. When the flow rate changes within a specific period, the flow condition is unsteady. Unsteady flow conditions occur when a flood wave is propagating through a channel or due to operating weirs and gages (Jirka & Lang, 2009).

Flow condition can also be defined using the geometric and physical properties of a cross-section. The subcritical and supercritical flow conditions are a central topic to describe flow conditions. Basically, the physical properties of every cross-section lead to a water depth, which marks the border between sub- and supercritical flow condition. This criterion is called critical depth. The water depth which adjusts itself with a specific discharge, at a cross-section, is called normal water depth. If the normal water depth is higher than the critical water depth, subcritical flow condition occurs. On the other hand, if the normal water depth fell below the critical depth, supercritical flow occurs. The physical properties, which define the flow state, are the roughness, slope and geometry. To determine the critical depth the basic equation according to Bernoulli is used.

$$\boldsymbol{h_E = z + \frac{p}{\rho\, g} + \frac{v^2}{2\, g}} \tag{7}$$

With:	h_E	….. energy height	[m]
	z	….. geodetic height	[m]
	p	….. pressure	[N/mm²]
	ρ	….. density of water	[kg/m³]

The Bernoulli equation is based on the theory of conservation of energy and defines that the energy height h_E above some energy horizon is equal to the sum of geodetic height z, which stands for the potential energy, the pressure height $p/\rho g$, which stands for the internal energy, and the velocity height $v^2/2g$, which stands for the kinematic energy. Subcritical flow occurs in deep streams with low flow velocity and low slope, while supercritical flow occurs where streams have low depths, high flow velocities and high slope. The most common flow condition in rivers is subcritical although supercritical flow can occur repeatedly. An easy and fast way to determine sub- or supercritical flow conditions is to throw a stone into the water and monitor the propagation of the generated waves like it is shown in Figure 2 (Bollrich, 2013).

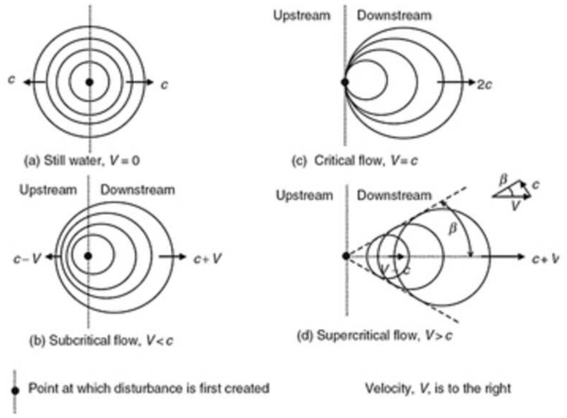


Figure 2 Wave propagation subcritical and supercritical flow (globalspec, 2017)

Alternatively, the flow state can be described by using the nondimensional Froude number

$$\boldsymbol{F_r = \frac{v}{\sqrt{g\,H}}} \tag{8}$$

With: H ….. water depth [m]

If Froude's number is below 1, the flow state is subcritical, and if the number is above 1, the flow state is supercritical. The minimum energy and therefore the critical depth occurs when Froude's number is equal to 1. Subcritical and supercritical flow state is very important when it comes to the shear stresses at the riverbed and therefore the sediment transport of a stream. The effects, generated from sediment transport, are having a big influence on the change of roughness and the bed degradation (Bollrich, 2013).

The previous descriptions does not offer specifications about what happens underneath the water surface. Water particles follow some specific way through the streamflow which are called stream-lines. Such stream-lines can be seen as small pipes in which all particles are travelling with the same velocity. The approach, that natural water particles travelling straight on stream-lines from one cross-section to another, is in many cases too simple. Nevertheless, if the velocity of the streamflow is low, the particles follow such stream-lines and are separated to each other. This flow condition is called laminar flow, where particles travelling side by side on separated stream-lines, without penetrating each other. If laminar flow conditions occur, the velocity orientation of each particle fits to the general direction of the streamflow. If the streamflow velocity is higher, the particles does not follow uniform stream-lines anymore and penetrate each other's stream-lines. This flow condition is called turbulent flow. A mixture of the water layers is created and the velocity orientation of the particles differs strongly from the general flow direction of the stream. Turbulent and laminar flow conditions are important when it comes to the velocity distribution of a cross-section, or for predicting shear stresses at the riverbed (Bollrich, 2013).

2.3.1 Riverbed and sediment transport

Sediments are brought into the stream by erosion processes at the surrounding areas, from steep upstream sections of the river or dynamic processes concerning the riverbed. A cross-section of a natural channel is separated into a riverbed and the river banks, which are both subject to mobile effects due to erosion and accumulation. Under the circumstances that a stream transports and deposits material, the riverbed is constantly changing. Therefore, also the hydraulic properties are changing constantly which makes it difficult to develop models for calculations. As it can be seen, this research area is complex and can be, in most cases, only solved by using empirical approaches and model tests. In order to do this, one must understand how solid materials behave when they are travelling in a stream. The total amount of solid materials, which are carried by the stream, are further separated into suspended loads and bed loads. In most cases these loads where detached from the riverbed by the streamflow. At one hand, the amount and velocity of the streamflow is responsible for the mobility of the riverbed, and on the other hand, the amount and velocity of the streamflow is highly influenced by the riverbed. The most important properties of the riverbed, which influences the streamflow, are the distribution and size of the grains as well as the shape of the riverbed which influences the velocity distribution (Aigner & Carstensen, 2015).

To describe the erodibility of a riverbed, some terms has been defined to make a calculation possible. At first, the critical velocity is the velocity where the erosion and transport of solid material begins. This velocity has been defined by using many laboratory test and is increasing with higher water depth. If the velocity of the stream is lower than the critical velocity, theoretically no erosion takes place at the riverbed. Another possibility is to describe the resistance of the riverbed by using the critical shear stress of the riverbed. Values for the critical stress and velocity has been defined by laboratory tests. Many tables and approaches has been developed but they can never be totally accurate due to the constant natural changes (Bollrich, 2013).

The effects which are having the largest influence on the streamflow, concerning sediments and riverbed, are bed degradation and changing forms of the riverbed due to erosion and accumulation of sediment. However, the roughness of a channel is not only influenced by the grain size distribution. Different effects like ripples, dunes and anti-dunes, as shown in Figure 3, also effects the roughness significantly. If the velocity is higher than the critical velocity, or the shear stress is higher than the critical shear stress, grains begin to dissolve from the riverbed and move along the surface of the riverbed. Thus, smaller grains of the dissolved load are forming ripples, which have a wavy but smooth appearance. If the velocity is getting higher, bigger grains get dissolved and therefore dunes can be formed. Dunes are not as symmetric as the ripples. In the direction of the flow, the slope of a dune is small until the maximum elevation is reached. After that point, the slope gets very steep and the elevation drops quickly. If the velocity is still getting higher, eventually reaching supercritical flow conditions, the surface of the riverbed is smoothened again but anti-dunes can appear. These anti-dunes are symmetrically shaped and are moving upstream due to erosion on the upstream side of the anti-dune and accumulation at the downstream side (Aigner & Carstensen, 2015).

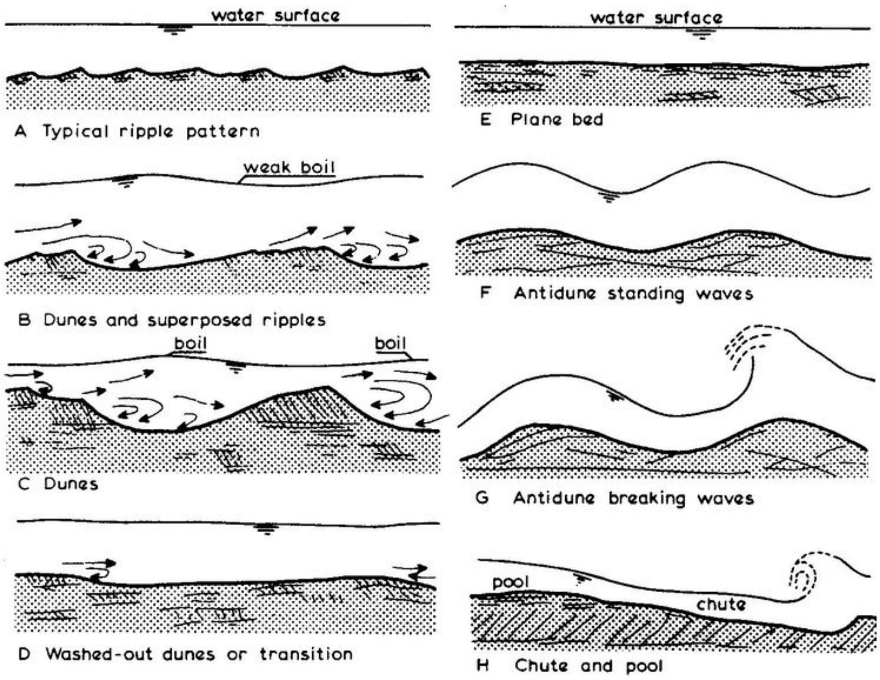


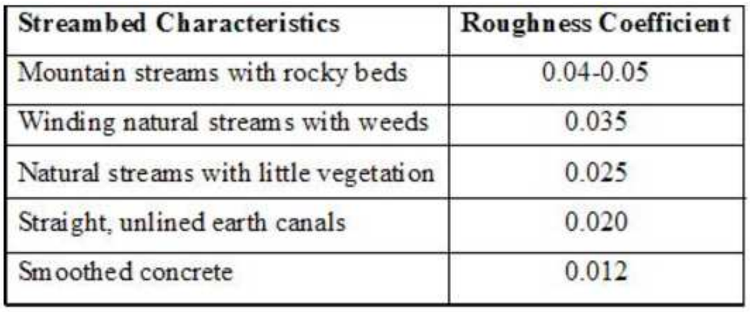
Figure 3 Changing bed forms when velocity is increased (marinespecies, 2017)

2.3.2 River roughness

As it has been mentioned before the roughness of the riverbed is depending on the grain size distribution and the form of the riverbed. In addition to this, different roughness coefficients can occur over the whole cross-section. For example, when the banks of a channel are secured with stone blocks, the roughness differs from the riverbed. To take care of such effects, an averaged roughness coefficient can be used, if the channel is not separated in different sections. This is done by separating the sections with different roughness and measuring their length. By using the length and roughness of the different sections compared to the total length, a mean roughness can be determined. In case of high discharge, the main channel is overtopped and the flood plains are used. For such conditions, the roughness of the channel cannot be estimated by using averaged coefficients. Since the flood plains are often vegetated, the main discharge follows the original riverbed and no significant discharge occurs at the flood-plains. Such effect can only occur if the water depth at such flood-plains is small enough. Nevertheless, the discharge is kind of stored at the banks and influences the main streamflow. To get realistic results such cross-sections must be separated and every section should be analyzed due to its discharge and roughness. The degree of influence of such vegetated flood-plains is dependent on the degree of vegetation and the water depth. If trees or something similar are situated at such sections, the roughness increases rapidly. Due to this effect the velocity of the water on the flood plains and in the main channel is reduced. This is caused by reacceleration effects of the water volume brought back into the main channel from the flood plains. As this effects increases the water depth, it must be taken in account for flood prevention management (Bollrich, 2013).

With a large amount of field measurements and laboratory tests, reference values have been defined to describe the roughness of different rivers and streams. This coefficients are called Manning values. Without field observations, these reference values can differ strongly from the real values because of seasonal changes, vegetation and riverbed formations. Examples for roughness coefficients in different streams are listed in Table 1.

Table 1 Manning values for different types of streams (Fetter, 2001)



Streambed Characteristics	Roughness Coefficient
Mountain streams with rocky beds	0.04-0.05
Winding natural streams with weeds	0.035
Natural streams with little vegetation	0.025
Straight, unlined earth canals	0.020
Smoothed concrete	0.012

Vegetation is having big influences on the roughness coefficients. Although these values are considered as static, laboratory tests and numerical simulations have shown that, under the influence of vegetation, the roughness coefficients are growing as the velocity decreases. Furthermore, if the water depth increases, the roughness coefficients are also growing. Roughness estimations of vegetated areas must also be divided into two parts. The influences of the original riverbed and the additional influences due to vegetation.

2.3.3 Flood hydrographs

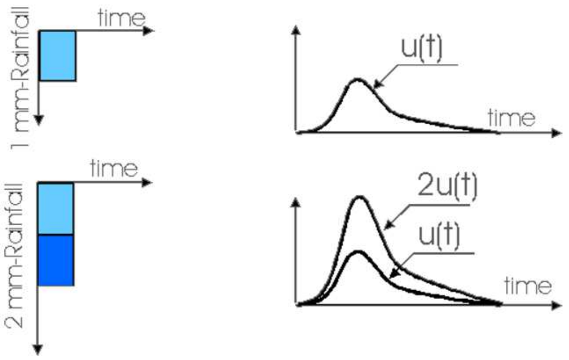


Figure 4 Example of the proportionality of the unit hydrograph (echo2, 2017)

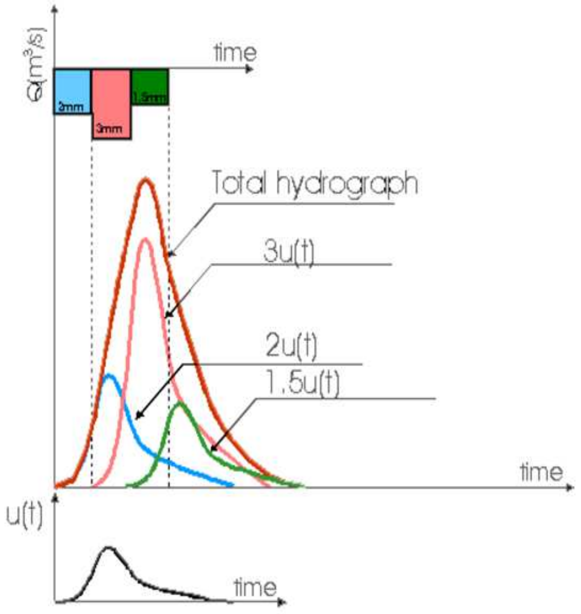


Figure 5 Principle of building a total hydrograph from different rainfall intensities (echo2, 2017)

A flood event indicates a change in the flow regime of a river. This means that the amount of streamflow changes with time, like it is shown in Figure 4. A relatively simple possibility to display such runoff scenarios, is the unit hydrograph approach. For using this approach, some assumptions must be made. The total amount of rainfall that actually reaches the river reach, also called effective rainfall, is equally distributed over the whole catchment area. The duration of such a rainfall event is called unit duration and in that period, the rainfall is constant. The direct runoff hydrograph is having the same time base as the effective rainfall. Furthermore, the effective rainfall is proportional to the runoff hydrograph. It is also assumed that all special properties of the drainage area are covered by the shape of the surface runoff hydrograph. These assumptions lead to the suspicion that such unit hydrograph does not properly display flood events because rainfall is not linear and uniform. Nevertheless, this approach leads to satisfying results when it is correctly applied. In fact, the unit hydrograph represents the direct runoff which is generated by one millimeter of rainfall in a specific drainage area and period. If higher rainfall occurs, every value on the ordinate of the hydrograph is multiplied with a factor which is representative for the amount. For two millimeters rainfall, the multiplication value is two, which is shown in Figure 4. If the amount

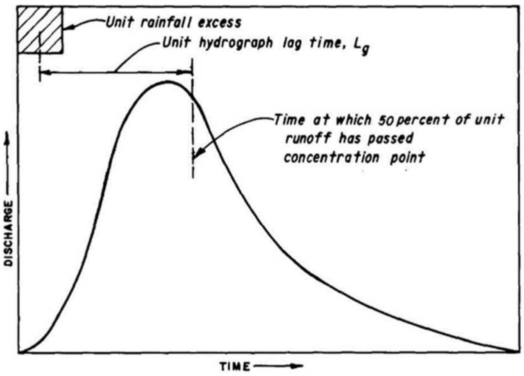


Figure 6 Definition of the lag time (Cudworth, 1992)

of rainfall changes in a storm event, which is always the case in nature, the different amounts are multiplied with the unit hydrograph. Then these amounts are plotted including a specific time delay, the lag time, which produces a hydrograph for every rainfall intensity which is shown in Figure 5. To get the total hydrograph, the different hydrographs are summed up. Figure 4 and Figure 5 does not consider the lag time which 50 percent of the effective amount of rainfall needs to get from the drainage area into the river reach. This lag time, like it is shown in Figure 6, is different for any catchment area and can be defined with field observations (Cudworth, 1992).

The hydrographs which has been described before can only be valid for a channel where no storage effects occur. Storage effects occur due to riverbeds with flood plains or retention basins which, when submerged, mitigate the peak discharge in the channel and reduces the risk of flooding at downstream regions. If such retention effect occurs the hydrograph is changed like it is displayed in Figure 7. Therefore, if the stage in the channel reaches a specific height, the flood plains are submerged which means that a specific volume of water is temporary stored and the discharge downstream is reduced. After the water level is decreasing, the water from the flood plains flows back to the main channel and is emptied (Blöschl, et al., 2015).

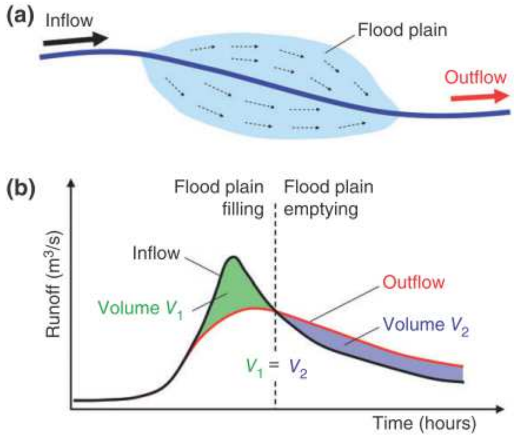


Figure 7 Mitigation of a flood wave due to retention volume, (Blöschl, et al., 2015)

2.4 Vegetation in rivers

Vegetation in rivers is an important task of this thesis. In general, it is a significant but complex topic when discussing open channel flow. The main vegetational influence on the river roughness results of vegetation on riverbanks or flood plains, although some rivers are also subject to aquatic vegetation in the main channel section. The knowledge of how vegetation influences the streamflow is important to adjust cost intense and environmental harming maintenance work at flood plains and banks with the goal to gain the necessary flood capacity (Camporeale, et. al. 2013).

2.4.1 Properties of riparian vegetation

Flood plains and banks can be vegetated with various types of plants. As a result, the roughness at these areas increases with the side effect of increased robustness regarding erosion processes. These plants can be weeds with different height, bushes, trees and other riparian vegetation (Camporeale, et. al. 2013).

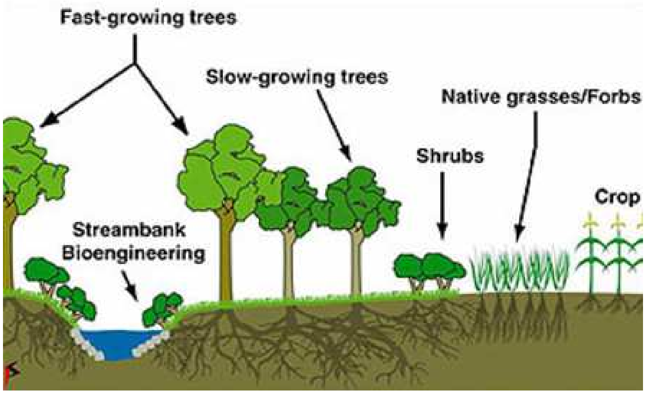


Figure 8 Types of riparian vegetation (missouri, 2017)

The variety of riparian vegetation is shown in Figure 8 but as important as the kind of plants is the degree of vegetation. In general, vegetational growth is influenced due to seasonal changes and the river itself. The river transports seeds, water, organic and mineral materials into and off riparian sections of the rivers, like banks or flood plains. These process is triggering the growth of vegetation and differs from one cross-section to another. This condition makes it difficult to find regularities. Furthermore, vegetation can have a passive or active influences on a stream. The environment at riparian zones of rivers are heterogeneous and their properties are changing constantly due to flood events, different discharges and changing amount of available soil moisture. This makes it very hard for plants to grow and survive for along time at such locations. If plants resist all these harmful influences, they can be considered as highly robust. To describe the properties, which are important for riparian plants, they can be defined as invaders, endurers, resisters or avoiders. Invaders secure their existence by producing huge amounts of seeds which are brought by wind or water into new riparian areas. In contrast to invaders, endurers regrow out of their broken or burned leftovers. Resisters are very robust and can withstand extreme external influences like fires and flooding, in opposite to the avoiders, who are only growing at their ideal location. Plants which are growing well in riparian areas must own two or more of the first three properties. As examples for such plants poplars and willows can be mentioned which are growing very fast, develop asexually and are producing seeds in spring and summer which can be easily spread through wind and water. The growth rate of the plants and their roots can vary due to the available soil moisture. Usual grow rates of these plants vary from 3 to 15 mm/day and roots can grow 10 to 30 mm/day. These values differ due to available soil moisture and type of the plant, and influences their initial and long-term resistance to environmental influences (Camporeale, et. al. 2013).

2.4.2 Influence of vegetation

The influence of vegetation on the river roughness is a difficult topic especially when general regularities and mathematical approaches should be created. It is obvious that vegetation influences the streamflow but, so far, no mathematical approach could describe this effect satisfactorily. Most methods which were developed to define this relationship used flume experiments with natural, synthetic or rigid vegetation prototypes. These approaches where proofed and calibrated by additional field measurements. As it was mentioned before many types of plants exist and every single one has different influences, which makes it very difficult to compare different investigations and find unique regularities (Defina & Bixio, 2005).

To clarify the problem of determination the vegetational influence, some of these methods will be described hereafter. These methods use mathematical approaches to gain the velocity distribution inside and above flooded vegetation. For both models the assumptions of uniform flow and no correction of density due to vegetation-water mixture was made. However, this might have an influence at very dense vegetated areas. In addition, the effect of bed and wall roughness are neglected because it is small compared to the effect of the vegetation. Both methods are using a two-layer model, like it is shown in Figure 9, which separates the cross-section into a vegetation layer and an upper layer (Defina & Bixio, 2005).

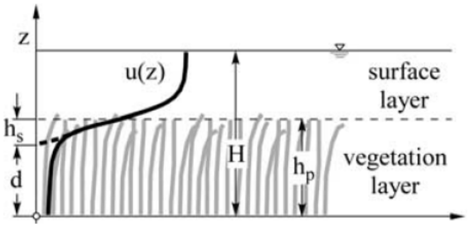


Figure 9 Velocity profile at the vegetated and upper layer (Defina & Bixio, 2005)

Therefore, the momentum equation below is solved for the vegetation layer while the upper layer keeps a logarithmic shape (Defina & Bixio, 2005).

$$\frac{\partial u}{\partial t} = g\, I_0 + \frac{1}{\rho}\frac{\partial \tau}{\partial z} - f_D \tag{9}$$

With:	u	….. average flow velocity	[m/s]
	t	….. time	[s]
	τ	….. shear stress	[N/mm²]
	f_D	….. drag force per unit mass	[m/s²]

This equation of momentum contains the variable f_D which stands for the drag force per unit mass due to vegetation. These force is defined by

$$f_{D\,(z)} = \begin{cases} C_D\, a\, u^2/2, & z \le h_p \\ 0, & z > h_p \end{cases} \quad ; a = A_z\, m \tag{10}$$

With:	C_D	….. drag coefficient	[-]
	a	….. projected plant area per unit volume	[1/m]
	h_p	….. vegetation height	[m]

A_z ….. frontal area of vegetation per unit depth [m]

m ….. number of stems per unit area [1/m^2]

Therefore, this drag force is influenced by the mean velocity, drag coefficient and the vegetation density while the force is limited to occur only in the vegetation layer. Furthermore, the total shear stress is defined by using the eddy viscosity model according to Boussinesq and is written as

$$\boldsymbol{\tau = \rho\,(\upsilon + \upsilon_t)\frac{\partial u}{\partial z}} \qquad \textbf{(11)}$$

With: υ ….. fluid viscosity [kg/m*s]

υ_t ….. eddy viscosity [kg/m*s]

Due to the calculation of the eddy viscosity υ_t, the models differ now from each other due to different approaches in dealing with the closure problem. At this point, reference is made to Defina & Bixio (2005) where the $\kappa - \varepsilon$ model and the two-layer model is derived and described in more detail, because in this thesis the mathematical background is not the main topic. In general, the $\kappa - \varepsilon$ model uses two transport equations to describe the turbulent part of the flow condition, where κ is the budget of the kinetic energy and ε the dissipation rate. The two-layer model on the other hand describes the velocity profile for each layer and solves the closure problem due to the eddy viscosity by using the flow velocity and a specific length scale, which was developed empirical. Both models are able to describe the velocity and shear stress profile in both layers, with only small deviations compared to laboratory tests. The turbulence characteristics on the other hand couldn’t be accurately described with both models (Defina & Bixio, 2005).

Many mathematical approaches have been developed using the two methods described above. For all these approaches, various types of plants and different boundary conditions where used which makes it hard to compare the results (Defina & Bixio, 2005). Apart from the mathematical approaches, these thesis tries to detect the influences triggered by vegetation using big amounts of stage-discharge measurements.

2.4.3 Seasonal changes

Seasonal changes can cause deviations of the rated discharge to the real discharge due to changes in seasonal changes, sediment and debris transport or ice. These effects must be monitored and brought into the continuous development process of the rating curves. In the northern hemisphere vegetation in rivers tendentially starts between March and April, and is reaching a maximum in the summer months, August to September, and are minimum in January to February. Although the streamflow in the winter month are not mainly influenced by vegetation, ice formations can strongly effect the autonomous measurements at gaging stations. Furthermore, in autumn, large amounts of dead leaves can be brought into the streams which cause problems at some gaging stations where thin-plate weirs or natural section controls are used, which are described in 2.6.5 (Rantz, 1982, a).

2.5 River Rating

River ratings (rating curves) are defined by the relationship between streamflow (discharge) and the water level elevation (stage) of a specific measuring station at a river. These curves are mainly used to determine the discharge of a river reach where only automatic measurement devices are used. These devices can only measure the stage. The discharge cannot be measured directly therefore additional variables are measured like stage, velocity and rate of change in stage. By using these variables in various models, in order to get the amount of streamflow, a rating is made (Holmes, 2016).

2.5.1 Simple ratings

Simple ratings relate the discharge directly to a specific stage measurement. This means that only the stage must be measured to gain the corresponding discharge. The relation between the stage and discharge is defined as rating curve which is necessary for autonomous river monitoring. Those rating curves are mostly hand drawn to fit field measurements which are made at various stages, like it is shown in Figure 10. This rating method can only be fully accurate if the streamflow is completely uniform at all stages and in the transition zones. This is normally not the case because every stream develops some sort of hysteresis also known as loop effects like it is explained in chapter 2.5.2 (Holmes, 2016).

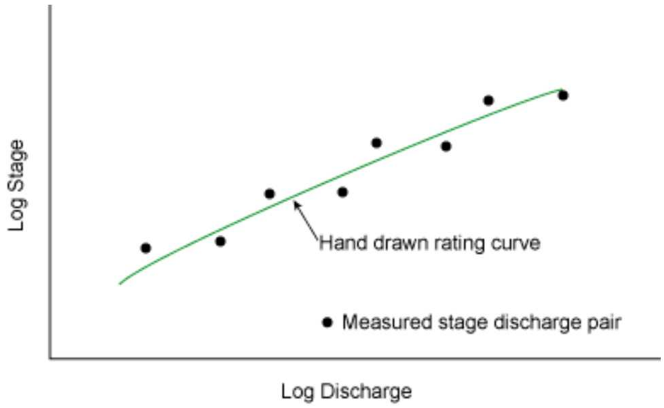


Figure 10 Simple hand drawn rating curve (gallatin, 2017)

Apart from the local influences and properties of these rating curves, also the changing seasons have a big influence. Due to the growth of vegetation in summer, the discharge capacity is much lower than in the winter. This means that if you compare the height of the water level in winter and summer, by using the same amount of discharge, the height in summer and therefore the channel resistance is higher. If stage measurements should be compared, they must be separated with respect to the season, otherwise the variation of the measurement would be too high (Gunawan, 2010).

2.5.2 Loop ratings

Loop ratings occur when the discharge on the rising and falling limp of a hydrograph at the same stage are different. This means that if a flood wave propagates through a specific river reach the discharge capacity on the rising limb is lower than the capacity on the falling limb. These special behavior is caused by reducing the river flow resistance by flattening of the vegetation, removing of debris out of the channel and eventually smoothed grain structure of the river bed. Often this hysteresis effect is relatively small. This means that simple ratings are accurate enough. This is not the case for low-gradient streams, streams with storage effects and mobile beds, other rating methods should be used (Holmes, 2016).

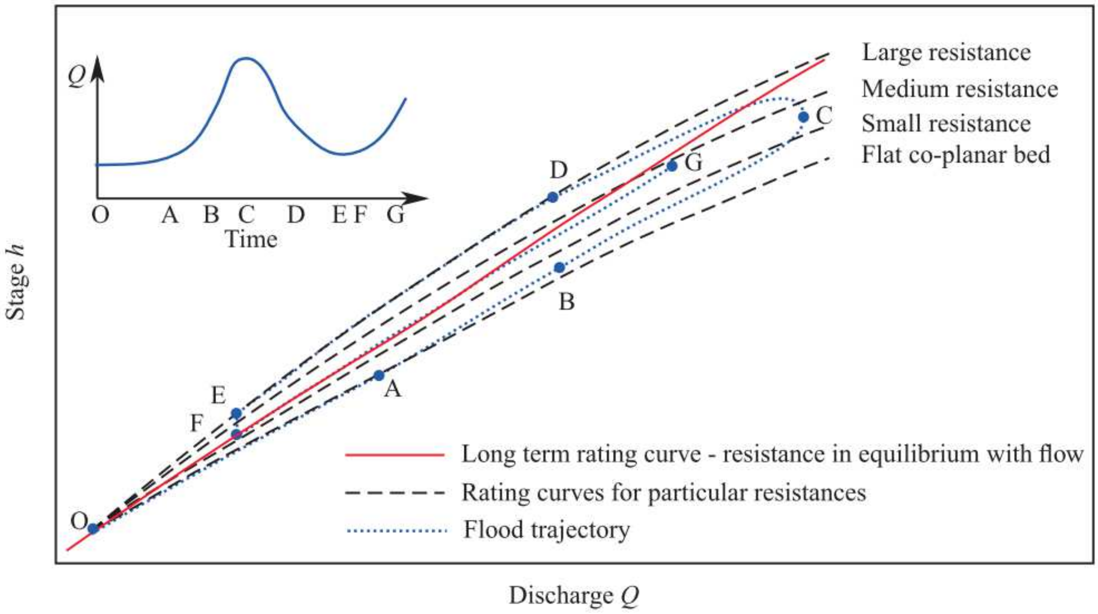


Figure 11 Detailed visualization of a loop rating separated into development-sections, (Fenton, 2015)

If such a loop rating for bed mobility is analyzed in detail a few characteristics of this curve can be defined with respect to the inflow hydrograph like it is displayed in Figure 11. Between point O and A the flow rate increases but cannot change the resistance of the riverbed. At point B, the flow rate is high enough to mobilize grains from the riverbed which changes his form and therefore the resistance increases which continues to point D. There can be seen that the resistance has been increasing and the flow rate started to decrease after the peak flow at point C. Between the point D and E the flow rate is decreasing but the riverbed needs more time to adjust itself so the resistance stays at a high level. After uniform-flow has occurred for some time, the riverbed is flattened to a specific degree, which marks point F. If now another flood event occurs the loop curve starts from a different resistance level than at the first flood event due to a different bed form and grain distribution. This effect shows that the rating curve itself is an approximation between different measurements with different bed resistances due to different time between the last high-flow event. But in general, the measurements fit more to the rating curve if uniform flow has occurred for a long time (Fenton, 2015).

2.5.3 Complex ratings

The relation between discharge and stage is often by discontinuities like the mobility of the riverbed, unsteady flow conditions, backwater effects and channels with large storage capacity. At sites were no simple stage to discharge relationship is valid, complex ratings are needed which relate the discharge to the stage and to some other variable. If some stream is effected by storage effects, which causes loop ratings, the additional variable for the stage discharge relationship is the rate of change in stage. Another unsteady condition, the variable backwater, can be considered by using slope ratings. Furthermore, an index-velocity rating can also determine some special conditions in ratings. However, this method uses mechanical and electrical devices and is very accurate but also complex. It is only used when other complex ratings are not enough to get satisfying results. To develop complex ratings, generally more discharge measurements are needed to evaluate the ratings than for simple ratings (Kennedy, 1984).

2.5.4 Detecting of rating complexity

The equation of streamflow according to Manning is valid for steady uniform flow. If the physical properties, like changing channel width and roughness, are changing, the Manning equation for open channel flow must be adapted like it was done in equation *(13)*. This is made by using the one dimensional unsteady equation of motion in equation *(12)* and the theory of conservation of mass in equation *(14)* (Holmes, 2016).

$$\boldsymbol{S_f = S_0 - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial y}} \tag{12}$$

$$\boldsymbol{Q = \frac{k}{n} A R_h^{\frac{2}{3}} \sqrt{S_0 - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial y}}} \tag{13}$$

$$\frac{\partial \boldsymbol{Q}}{\partial \boldsymbol{x}} + \boldsymbol{T}\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{t}} = \boldsymbol{0} \qquad \textbf{(14)}$$

With:	S_f	….. friction slope	[‰]
	A	….. area	[m²]
	k	….. constant	[-]

The equation *(12)* covers all unsteady effects. Using this modified Manning equation, the hydrodynamic effects are covered but effects like bed mobility must be investigated separately to enable satisfying results (Holmes, 2016).

Deriving complex flow condition has been shown with equation *(13)* but to detect these conditions, for example in the autonomous recorded discharge measurements of the USGS database, other approaches must be used, otherwise the measurement would not fit to the simple rating curves. In order to detect such complexity, scrips have already been developed which can analyze large amounts of data. These scripts are using the change in stage height per time unit (dH/dt) and the percent difference to the base rating *(PDIFF)* (Holmes, 2016).

$$\boldsymbol{PDIFF} = \left(\frac{\boldsymbol{Q_m} - \boldsymbol{Q_r}}{\boldsymbol{Q_r}}\right) * \boldsymbol{100} \qquad \textbf{(15)}$$

With:	Q_m	….. measured discharge	[m³/s]
	Q_r	….. rated discharge	[m³/s]

In equation *(15)* $Q_m - Q_r$ gives the difference between the measured discharge and the rated discharge. With respect to the rated discharge, the deviation to the original rating curve is determined. The rate of stage changing can be used to determine the time in which a flood wave is propagating through a specific cross section. If a flood event should be monitored by field measurements, this information is essential. Otherwise it could happen that some parts of the hydrograph are not fully monitored. If the rate of change in stage is put into a relationship with the PDIFF, discontinuities at the falling or rising limb of the hydrograph can be detected, like the occurrence of hysteresis effects due to storage effects (Holmes, 2016).

2.6 Developing of rating curves

To develop a rating curve, different tasks must be accomplished. At the beginning a location is selected which enables good local conditions to gain a satisfying stage to discharge relationship. This means that the gaging station should be positioned were undisturbed uniform flow conditions occur and discontinuities like variable backwater and storage effects are as small as possible. For the continuous measurement and recording of stage data, instruments are installed which monitor the stage of the water level. For example, at the gaging stations, which are mentioned in this thesis, stage records are made every fifteen minutes. In addition to the stage measurements, discharge measurements are made at different water-surface elevations to develop a unique stage to discharge relationship. With this relationship, the rating curve, the continuous stage measurements can be related to a specific discharge. To consider effects like change in the geometry of the channel, roughness or vegetation, monthly discharge measurements are made to proof or modify the curve (Rantz, 1982, a).

2.6.1 Selection of gage location

To select a proper location for a gaging station, the reason for gaining measurements at this location must be defined. The gaging station could be a control station for monitoring the outflow of a reservoir or it can be a pure hydrological measuring station. The selection of a site for both examples happens under different criteria. What both examples have in common is, that the flow condition should be uniform and not influenced by effects which are caused by up- and downstream conditions. By considering this, normally some specific part of a stream is usable for implementing a gaging site. Furthermore, some important site properties are listed below which should be fulfilled for a good gaging location (Rantz, 1982, a).

- The steam should be straight for at least 100 m up-and downstream

- There is only one riverbed with no bypasses at all stages
- The riverbed is not suffering from effects due fill, scour and aquatic growth
- In case of flood events the banks are high enough to store them
- The site is accessible for installing and controlling of the measuring instruments
- A natural low water control section is available

Most sites do not fulfill all properties of an ideal location to measure a stable stage to discharge relationship. Therefore, the properties of the different locations must be analyzed, evaluated and the most suitable one is chosen. To prepare a gaging station the low-flow and high-flow conditions are investigated. In this context, the possible gaging location should be analyzed due to section and channel control properties. Section control means that an artificial or natural narrowing of the riverbed is forcing the streamflow to reach the critical depth and creates a unique stage to discharge relationship for all stages. In contrast to this, channel control means that the physical properties, like geometry and roughness, of a long part of the channel downstream the gaging station defines the stage to discharge relationship. In most cases a combination of section and channel control is used. For low-flow conditions section control and for high-flow conditions channel control is used to define the rating curve at all stages. Furthermore, peak streamflow, out of historical records, should be reviewed to determine the minimum height of the measuring device to avoid damages. Furthermore, the possibility for other discharge measurement methods, when a measurement by wading is not possible, must also be considered. Therefore, a site where a bride is available or the installation of a cableway is possible should be preferred. Otherwise the measurement must be made from a boat (Rantz, 1982, a).

2.6.2 Measuring of stage

The stage, or gage height, is defined as the height above some reference datum. It should not be mistaken with the water depth. The reference datum must be always below the deepest point of the riverbed to assure that no negative values occur. Therefore, the elevation of zero flow is not zero. For one gaging station, only one datum should be used over the whole lifetime, except if negative stage values occur. The reference datum can be the sea level elevation or some other defined datum. The measuring of stage is the basic step to develop rating curves and further the deriving of discharge. Therefore, the accuracy and reliability of this measurements is, assuming a completely correct rating curve, directly related to the accuracy and reliability of the derived discharge. Stage records are made by field measurements (nonrecording gages) or autonomous by installed monitoring devices (recording gages) (Rantz, 1982, a).

The most common ways for autonomous measuring of stage are the float gage, bubble gage, pressure gage, radar or ultrasonic water level detection (Morgenschweis, 2010).

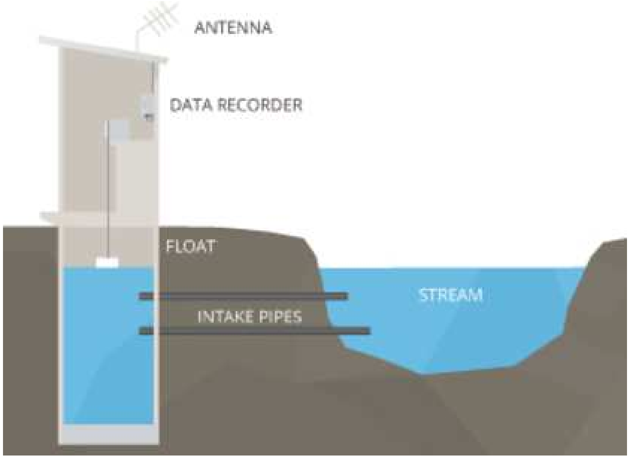


Figure 12 Principle of a gaging station using a float sensor (fondriest, 2017)

A float sensor consists of a cable on a pulley which is attached at one side with a float in a stilling well and on the other side with a counterweight, which can be seen in Figure 12. If the water surface elevation changes, this movement can be recorded by attaching the pulley to a water-stage recorder (Rantz, 1982, a).

A bubble gage is measuring the pressure head in a stream by pumping gas, most of the times nitrogen, via a tube to an orifice at a fixed underwater elevation. The gas is bubbling out freely and the pressure in the tube is corresponding to a specific gage height at any stage. The recorded stage measurements are then transmitted via telemetry to a central receiving station where they are stored. In Figure 13 the principle setup of a bubble gage is displayed (Rantz, 1982, a).

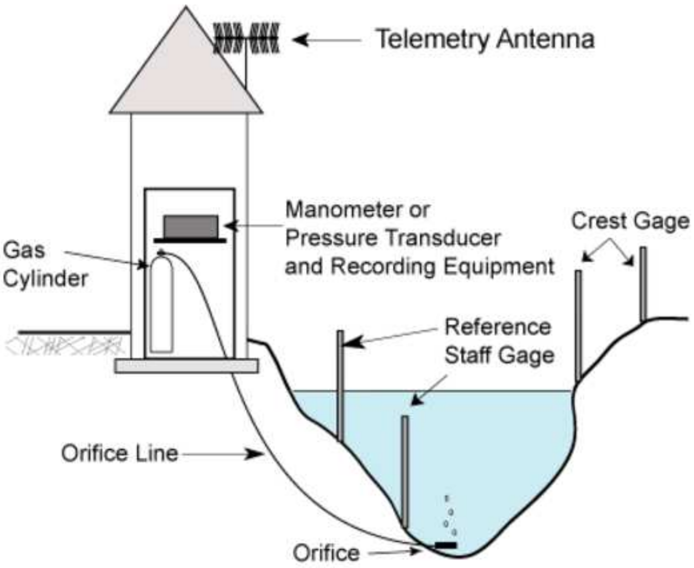


Figure 13 Setup of a bubble gage (gallatin, 2017)

The pressure gage uses the same hydrostatic principle as the bubble gage. The difference to the bubble gage is that the pressure gage uses a closed system to determine the pressure height with the help of a pressure transducer. These pressure probes are situated underwater and converts the water pressure into an electric signal which is corresponding to some pressure height (Morgenschweis, 2010).

The previous gaging systems using the direct contact to the water for their measurements. At sites were a direct contact to the water is not possible, like in narrow channels, large amounts of debris could occur or if the gaging station should only be installed temporary, indirect gaging methods can be used. Such systems are installed above the water surface where they cannot be submerged or damaged. The measurement technique is based on a runtime measurement between the emitting and receiving of a reflected signal. The different indirect measurement systems differ from each other in the kind of the emitted signal. Ultrasonic gages using soundwaves for the measurement, while radar gages are using microwaves. Differences occur due to the characteristics of the signal itself. Soundwaves suffer from high deviations when temperature changes occur which must be compensated from the measuring device. Microwaves are much easier to handle since the effect of temperature on the runtime is very small. Since all signals are reflected at the water surface, scattering of the reflected signal can occur which can distort the measurement results (Morgenschweis, 2010).

2.6.3 Measuring of discharge

The measurement of discharge at a gaging station is made to define the stage to discharge relationship. The frequency of these field measurements is strongly depending on how stable the rating is. When a gage station is implemented, discharge measurements are carried out at many stages. With these stage and discharge measurements, basis rating curves are developed. These rating curves are validated and fitted by performing field measurements in a period of, for example, two months. The discharge can be measured using different methods like the current-meter method, the moving-boat method, tracer dilution or some other methods (Rantz, 1982, a).

A traditional, but often used method for determining the discharge is the measurement with the conventional current-meter, which is displayed in Figure 14. In general, this method is based on continuous velocity measurements with respect to the location, width and depth in a stream. The measurement can be either made by wading, or if the stream is too deep, by using a bridge, cableway or a boat. The discharge is computed with $Q = \sum(a\ v)$ where a is a subsection of the cross-section and v the associated longitudinal mean velocity. Therefore, the summation of discharge at all subsections leads to the discharge of the stream. Limitations for this measurement method are that the velocity close to boundaries cannot be measured and turbulent flow can cause damage at the instrumentation. The instrumentation consists of a current meter, which measures the velocity by counting the revolutions of a build-in rotor, mounting and operation equipment, which depends on the site location. Operation equipment can be rods, sounding weights, sounding reels, or sonic sounder. In addition, for special conditions, bridge-, ice-, boat- or cableway equipment is necessary (Rantz, 1982, a).

Figure 14 Example of a current meter (chmibrno, 2017)

For locations where the conventional current-meter method is not possible or cost efficient, like for large streams, the moving-boat method can be useful, which is exemplary shown in Figure 15. This method also needs no further installations and the measurement can be made rapidly. This can also be interesting when it comes to unsteady flow conditions. Like the conventional current-meter method, the moving-boat method also uses the subarea to velocity relationship to determine the discharge. For this method, a small boat, a current-meter, a vane with angle indicator and a sonic sounder is needed. The boat is crossing the stream, normal to the flow direction, several times. Due to the vane, the current-meter turns itself into the flow direction triggered by the movement of the boat as well as by the direction of the streamflow. Then the velocity is measured with the current-meter at specific positions, while a sonic sounder measures the profile of the cross-section. Additional, an angle indicator shows the orientation of the vane. With these instruments, the discharge can be computed. Usually 30 to 40 measurement positions are used to define a discharge properly. The main difference between the conventional current-meter and the moving-boat method is that by using the moving-boat method the measurements are made under dynamic and not static conditions, like with the conventional method. This means that for the measured values, the dynamic effect must be filtered out (Rantz, 1982, a).

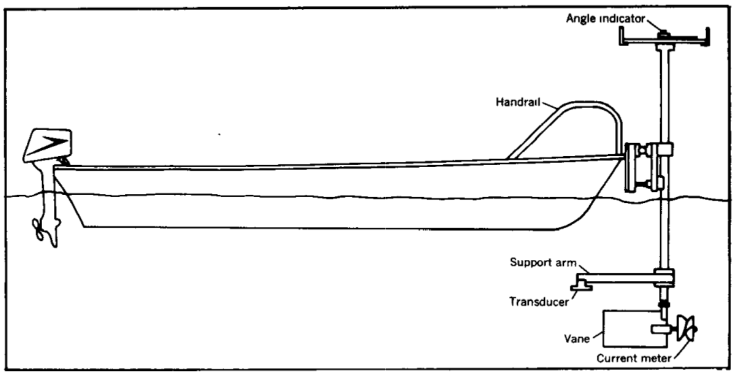


Figure 15 Concept of a moving-boat method installation (Rantz, 1982, a)

Another possibility to measure the discharge is by tracer dilution. It is used when methods like the conventional current-meter and moving-boat method are not suitable. This can be the case for rough channels with highly turbulent flow conditions. To gain the discharge from a tracer measurement, a tracer solution, often salt solution (NaCl) or dyes, are injected into the stream. By measuring the concentration of the tracer at a specific cross-section, with respect to the original concentration of the tracer fluid, the discharge can be derived. Through the rate of injection of the tracer, two methods are differentiated. The first possibility is to inject the fluid constantly over a specific time, so that a stable concentration at the measurement cross-section is reached. The second possibility is to suddenly inject a specific amount of the tracer solution and repeat it several times. The second method can be used for measuring the velocity, if the cross-section is constant (Rantz, 1982, a).

In addition to the previous mentioned methods for measuring the discharge of different streams, some other methods exist which can be separated into methods for high-, low- and unstable-flow. For high-flow situation, like flood events, sometimes a current-meter measurement or tracer dilution measurement cannot be performed. To measure the velocity anyway, floats can be used. These floats can be anything from sand filled plastic bottles, to pieces of wood. The measurement is made by measuring the time that a float needs to get from one control section to another (downstream) control section. The cross-sectional area is than measured when the streamflow conditions are becoming steady. To gain the discharge of the flood event, the measured velocity of the floats is referred to the cross-sectional area at the stage of the flood event. For low-flow situations, direct volumetric measurements can be implemented which determine the discharge very accurate. For this method, only a container and a stopwatch is needed. The container is filled either to a calibrated mark or the container is placed on a scale to determine the weight of the container. Both methods lead to a specific volumetric amount of water flowing into a container in a specific time, which is the discharge of the river. To perform such measurement, the channel must have some natural or artificial narrowing to lead the discharge into a pipe, like a v-notch weir or a narrow natural cross-section where a dam can be build. Additionally, a v-notch weir can also be used to measure small discharges by placing it in the riverbed and ensure that the whole discharge is flowing over the weir. Then the head above the zero point of the notch can be measured which leads to the discharge due to a unique relationship between the head and the flow rate (Rantz, 1982, a).

Today, measuring the discharge using acoustic doppler current profiler (ADCP) is the state of the art. By using these devices the complete velocity profile, from the riverbed to the water surface, is recorded. ADCPs can be compared to a sonar. Build in piezoelectric transducers are sending out acoustic signals. The signal is reflected and the time difference, between emitting and receiving of the signal, leads to the water depth. Additionally the shift in the frequency of the received signal allows to derive the velocity along the path of the signal. The emitter can be mounted on a boat and transfer the real time velocity profiles to a computer, while the boat is moved along a specific way through a cross-section. The discharge can be derived by using the velocity profiles and the corresponding cross sectional area (Morgenschweis, 2010).

2.6.4 Curve plotting

To develop a rating curve, many field measurements must be carried out at different discharges/stages. To gain a satisfying accuracy, no or at least very little gaps between different discharges should occur. After the stage and discharge field measurements has been done, the data is plotted on rectangular or logarithmic scaled paper. Therefore, the stage is applied to the ordinate and the discharge to the abscissa, which is made for every stage and discharge measurement. If this has been done, the points are connected via a curved line by hand. Therefore, no actual equation lies behind the basic rating curves and they are fully empirical. The use of logarithmic or rectangular scales is depending on the state of development of a rating curve. Curve-shaping in logarithmic scale is easier and can be done more accurately but when the curve development is finished, rectangular scale should be used because then the occurrence and magnitude of shifts can be easier detected. Furthermore, the point of zero flow, which is important to detect bed degradations, can be better monitored by using rectangular scales. In some cases, also a combination of logarithmic and rectangular scales is used but not in general (Rantz, 1982, b).

2.6.5 Section control

As it was mentioned before, the stage to discharge relationship for low-flow conditions can be described by using artificial or natural control sections. These control sections describe the lower part of the rating curve. Therefore, the control section acts like a dam at the gaging station and defines a unique stage to discharge relationship, which gives the rating curve its shape. To gain this relationship, the characteristics of different types, especially artificial sections, must be known. Artificial section controls can be thin-plate weirs, broad-crested weirs or flumes. All of them has their own characteristics and fields of use. Thin-plate weirs are used for river with low discharge, no expected debris, very low sediment transport and at locations where constant maintenance is possible. These weirs are consisting, like it can be seen in Figure 16, of metal plates at the bottom, to hold back some

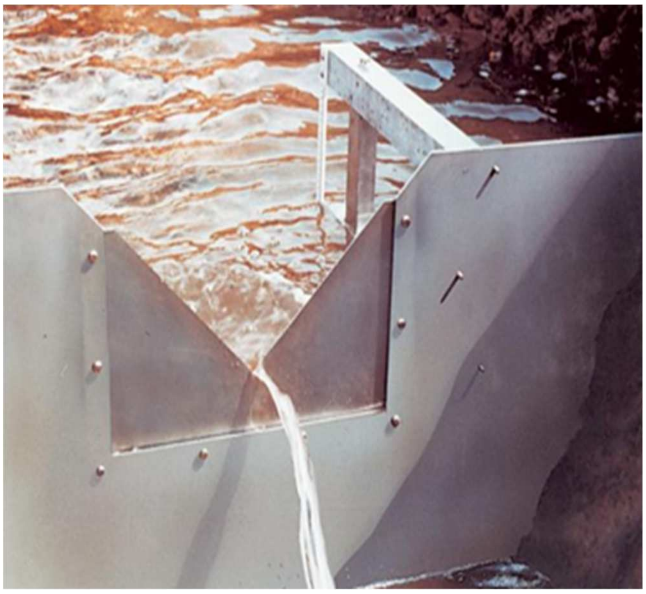


Figure 16 Thin-plate weir (armfield, 2017)

specific amount of water, and rectangular, triangular, trapezoidal or V-notch profile at the top to gain a controlled outflow with respect to the backwater stage. This type of section controls is very accurate, if they are intact and maintained, which makes it possible to use them for laboratory tests as well as for field observations. The shape of the crest defines a unique mathematical relationship between water level behind the weir, the stage and the discharge which defines directly the rating curve. Broad-crested weirs, like in Figure 17, are used where thin-plate weirs are not possible. They are more robust and due to the gentle upstream slope of the structure, sediments can pass the section control and does not influence the stage to discharge relationship (Rantz, 1982, b).

Figure 17 Example of a broad-crested weir (hydrocad, 2017)

The crest shapes of these dam structures can differ due to national preferences and the location of the site. Some examples are the flat-crested rectangular weirs, notched flat-crested rectangular weirs, Trenton-type controls or Columbus-type controls. The first types are identical with the difference that the notched flat-crested weir owns a gap positioned in the crest, which makes it more sensible to low discharges. In general, the crest of rectangular flat-crested weirs is horizontal and rectangular along the whole cross-section. Because of the inaccuracy at low-flow conditions, the crest can be slightly inclined over the cross-section, which theoretically leads to a triangular crest shape for low flow. This increases the sensibility to low discharge and has no effect on the behavior when the discharge is increasing. For the sake of completeness, the Trenton-type control is also a broad-crested weir, with the difference that the overflow is optimized by the shape of the dam body, and the Columbus-type control is having a crest with a parabolic notch. Apart from the broad-crested weirs, flumes are another possibility for section control. Using these control sections, critical or supercritical flow conditions are performed by using artificial changes in width or slope of the channel. The most common type is the Parshall-flume, which has been developed with respect to the Venturi-flume. It consists of three sections which can be seen in Figure 18. At first, the width of the channel is narrowed constantly and the slope is flat, while the second section is parallel in width but slopes downward. In the third section, the channel is widened again and the slope is uprising to an elevation which must be less than the elevation at the beginning of the flume. The stage discharge relationship is then defined by the water height in the flume by using stilling wells in all sections (Rantz, 1982, b).

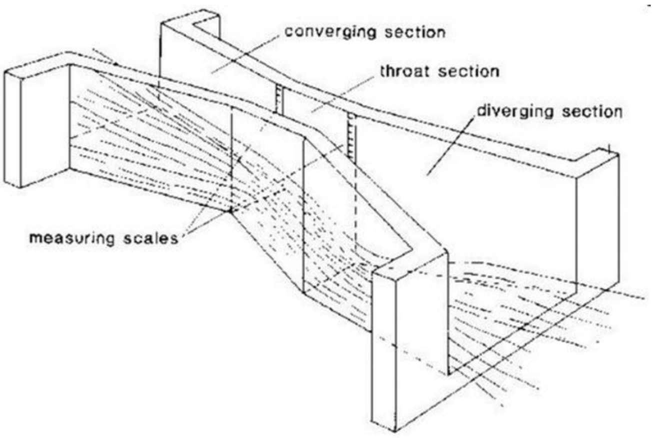


Figure 18 Principle of a Parshall flume (tankonyvtar, 2017)

Natural section controls are developing unique flow conditions without installing weirs or other flow-disturbing structures. These can be sections where bedrock or gravel banks narrows the channel. To gain rating curves from these sections, field measurements at various stages must be performed and plotted on logarithmic scales. The biggest problem with using natural sections is the shape of the crest which can be highly irregular. This makes it difficult define the height of zero flow (Rantz, 1982, b).

2.6.6 Channel control

Channel control is used for channels where no section control is possible. This could be at large rivers or to measure high-flow conditions, in case the channel control is submerged. For this kind of measurement, the cross-sectional area at a specific location at the channel is measured, with respect to the stage measurement. It is necessary to get all physical information at such cross section, except the channel roughness *n*, to define the stage to discharge relationship using Manning's equation for open channel flow. The Manning coefficient *n* can be determined using field measurements at one stage or by using more field measurements at different stages to define an averaged coefficient which may be more accurate. This coefficient can cause large deviations if no proper adjustments are made over the year (Rantz, 1982, b).

2.6.7 Curve shaping

As it has been mentioned before, rating curves are defined in most cases by a combination of section and channel control and the corresponding field measurements. Because field measurements, in practice, do not cover the whole range of stages at a gaging station, the shape of the rating curve between those measurements must be extrapolated. Figure 19 defines, theoretically, the sections of a rating curve with respect to their degree of definiteness. As it can be seen in Figure 19, the section of medium flow is the part which is sufficiently described with field measurements. This section do not need further extrapolations. In contrast to this, the low-flow and the high-flow part of the rating curve are not well described with field measurements. This means that these parts has to be defined using other methods (Rantz, 1982, b).

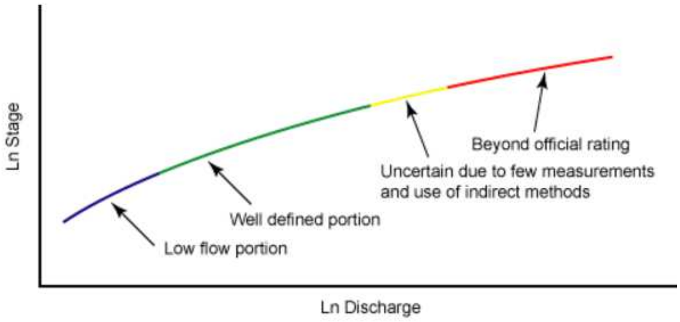


Figure 19 Typical rating curve divided in sections due to their definiteness (gallatin, 2017)

The low-flow part of the curve is fitted smoothly by hand, from the last known field measurement to the known point of zero flow, like it was done in the left diagram in Figure 20. This may not be completely accurate but in most cases, it is done this way, also because low-flow conditions are not that important as high-flow conditions according to their accuracy. If no indirect measurements are available, like explained in 2.6.3, often only a few field measurements can be used to define high-flow conditions. This makes it difficult to describe that part with respect to the importance of this section due to flood prevention. To extrapolate this part of the rating curve, some methods can be used like the conveyance-slope method, areal comparison of peak-runoff rates, the step-backwater method or flood routing. To show how such an extrapolation is done, the conveyance-slope method is nearly described. The conveyance-slope method is based on Manning's equation of open channel flow. The area and wetted perimeter is measured for all relevant stages and the roughness coefficient is estimated. The manning equation is separated into two part which is the geometric part, $\frac{1}{n}AR^{2/3}$, and the square root of the energy gradient $S^{1/2}$. The geometric part can be gained from field measurements and the energy gradient can be derived with the Manning equation, if the discharge is measured. Both parts are now plotted with respect to the stage, with the knowledge that the energy gradient become constant at higher stages. Both curves are shown at the right diagram in Figure 20, with whom the rating curve can be extrapolated at each stage. Uncertainties due to roughness estimation, assumption of constant geometry in the channel and uniform flow at higher stages makes this method not completely accurate, but for an estimation often satisfying (Rantz, 1982, b).

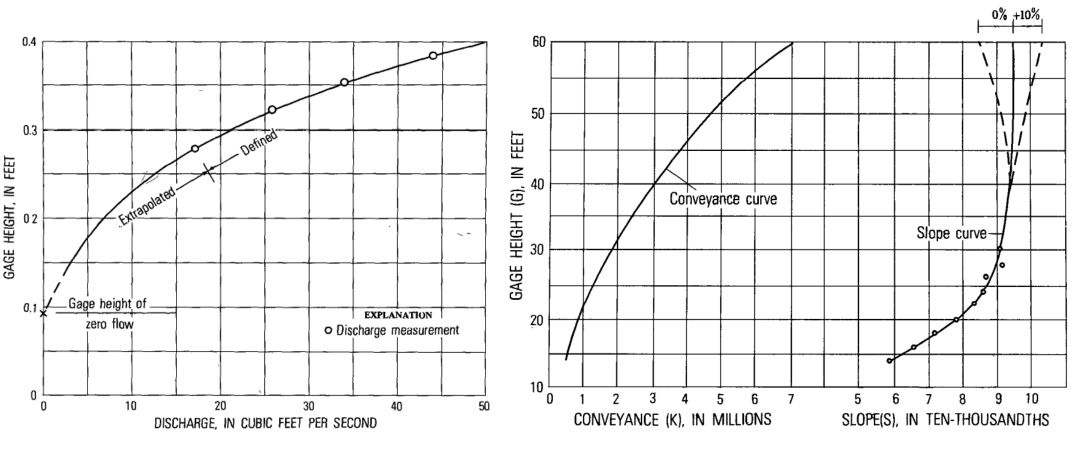


Figure 20 Extrapolation of rating curves for low-flow (left) and high-flow (right) (Rantz, 1982, b)

2.6.8 Shifts in rating curves

Rating curves for specific cross-sections are changing over time due to seasonal or permanent changes. Furthermore, these shifts can also be caused by damage or deviations of the measuring equipment. When temporary changes occur, which leads to a change in the stage to discharge relationship, the rating curve is adjusted to fit the new conditions. Although, if such changes last longer than a few months, the rating curve may not be valid anymore and a new one must be established. The frequency of creating new rating curves is very much depending on the properties of the observed river. For example, rivers with high mobile beds needs new rating curves after nearly every high-flow event, while coarser grained riverbeds may not need new rating curves for years. Apart from the development of new rating curves, the shift adjustments are now explained in more detail. To explain shifts easily, one example is presented here. If, for example, some vegetation has been growing at a control section, the stage to discharge relationship has changed. The amount of these deviation is determined using field measurements. For this case, the stage is recorded 0.1 m higher than is would be correct for such a discharge. To take care of these changed relationship, the recorded stage is adjusted with the deviation of -0.1 m. With this adjustment the autonomous stage measurements can provide the correct discharge by using the shifted curve. To detect shifts out of field measurements, some range of fluctuations must be defined due to the peculiarity of water which are not be considered as shifts. Furthermore, a shift can be better detected by using many measurements, which shows an offset, than one measurement at its own, which could theoretically be an error reading. In the USA, the detection of shifts follows the approach, that all discharge measurements, which are within a ±5 % deviation range to the rated discharge, is proofing the actual rating curve. If some measurements exceed these ±5 % and are all plotting on the same side of the rating curve, a shift may have occurred. Another measure to ensure the accuracy of the measurements is that the hydrographer plot the measurement, which has been just made, on the rating curve to control their fitting. If the deviation is too high, the measurement is repeated (Rantz, 1982, b).

The reason for shifts is also dependent on which type of control is used to gain the stage data. Therefore, different shifts can occur for different section or channel controls. Artificial section controls develop shifts by scour or fill deposit in the upstream reservoir of the weir, which leads to a relatively small parallel shift to the original rating. This means that at same stages, the discharge is reduced due to deposits in the reservoir. The approach that the amount of deviation is the same for every stage may not be completely correct, because scour and fill does not affect the low-flow part of the rating curve. This is resulting, like shown in Figure 21, in a rating curve whose low-flow part is still the same as the original but as the amount of discharge rises, the deviation rises too. After reaching a specific amount, the deviation stays constant. The two different shifted curves in Figure 21 are resulting from scour and fill. If scour appears the discharge capacity is reduced due to reduced velocity. On the other hand, fill increases the discharge capacity by increasing the velocity. Fill occurs on the recession and scour on the rising limb of the hydrograph. The shifted curve is plotted to the right, with respect to the original curve, if fill occurs and to the left if scour occurs. If the discharge reaches an amount at which the section control is submerged but shifts due to scour or fill has occurred, the curve must be fitted to the curve due to channel control, to gain a consistent curve without gaps. Another reason for shifts at artificial controls can be aquatic vegetation. This vegetation can also lower the velocity in the reservoir and even reduce the capacity of weirs, if they are growing on the crest. This would lead to a shift left of the original rating curve. This could happen if aquatic vegetation, like moss, is growing at weir crests which increases the gage height of zero flow. Such an effect would lead to a parallel shift left of the rating curve. If the artificial control section is a flume, shifts can also happen when large rocks or debris blocks contracting parts of the flume. This would cause a shift to the left because the stage is raised to a higher level that is should be (Rantz, 1982, b).

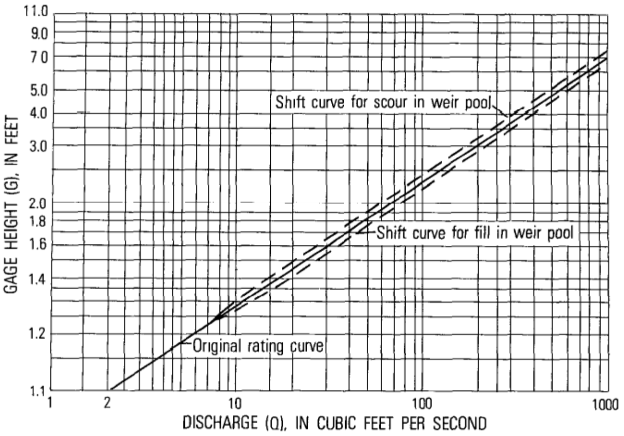


Figure 21 Shift at an artificial section control (Rantz, 1982, b)

Natural section controls underlie the same shift-causing problems as artificial weirs, with the exception that if flood events occur, the natural control sections can be destroyed more likely. Of course, rock ledge outcrop or similar sections would not be effected by such high-flow events but sections controls like gravel or sand banks can be easily eroded. After a flood event, these sections must be controlled and evaluated. If they were destroyed, new ones must be found and calibrated using discharge measurements, like is was explained in 2.6.3. Since such natural section controls, like gravel bars, have rough crests, fallen leaves can get stuck at such weirs which causes an increase of the gage height of zero flow, just like moss at artificial weirs (Rantz, 1982, b).

Additional to shifts at section controls, which are mostly used for the low-flow part in a channel, deviations from the rating curves at high-flow regime can be caused by changes in the physical properties of the channel. The most important reasons for such changes are the occurrence of fill and scour as well as changes of roughness due to vegetation, especially at medium size streams. Fill and scour influences the streamflow in another way that it influences the rating curves in section controls. While scour indicates a plus shift and fill a minus shift for section control, this relationship is turned around for channel control. Therefore, the discharge capacity at a channel control is increased by scour, which indicates a minus shift, and reduced by fill, which causes a plus shift. Shifts due to scour and fill are difficult to forecast. The reason for this is that these effects are not only depending on the flow velocity, but on the sediment load of the streamflow, which can be highly irregular. A special behavior of shifts in channel control, due to fill and scour, is that the shift decreases when stage increases, like it is shown in Figure 22. Because in most case no information about whether the measurement was taken at the rising or falling limb of the hydrograph, this relationship can be seen as idealized (Rantz, 1982, b).

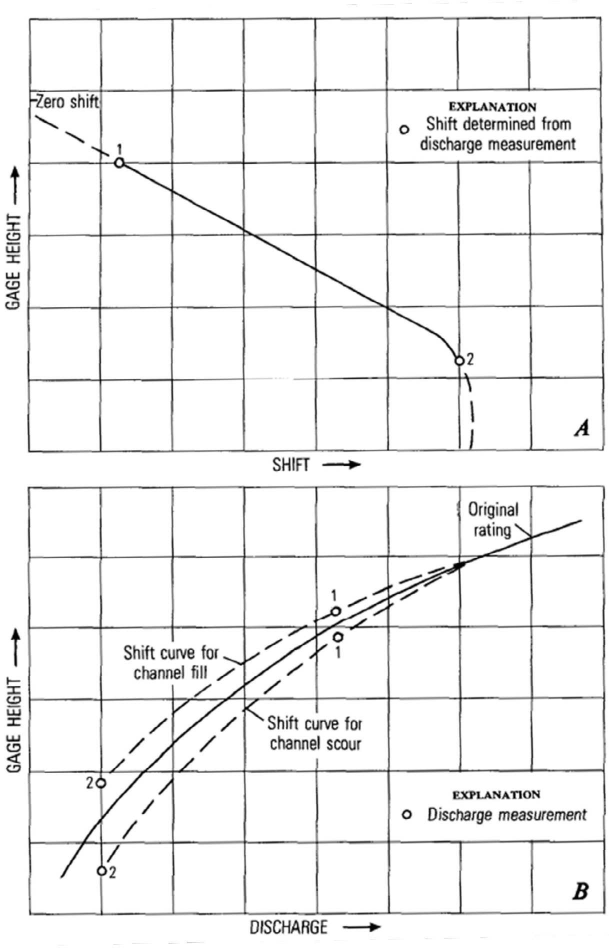


Figure 22 Shifts in channel control due to fill and scour (Rantz, 1982, b)

As this thesis deals with the vegetational influence on rating curves, vegetation of course also indicates shifts in rating curves, due to the effects which has been explained in chapter 2.4. Vegetation reduces the discharge capacity. This means that the derived rated discharge for a given stage is higher than it really is. Such shift is, just like a shift due to scour in channel control, a minus shift. Apart from the increased roughness, vegetation can also narrow the channel. Both effects lead to a shift which is, in most cases, parallel to the original rating curve. This means that the effect of vegetation does not change with stage. Using this approach may not always be appropriate, because weeds or low plants are overtopped at a specific stage, which reduces their effect. If then the stage rises to an amount that the crowns of larger trees like willows are submerged, the effect of vegetation surely changes with stage too. The most important characteristic of vegetational driven shifts is, that they are constantly changing with time, which needs some afford to constantly fit the rating curve. Because these fittings are only made every two months, the accuracy of the rating curve, concerning the vegetation, is limited (Rantz, 1982, b).

2.6.9 Alternative curve development from existing data

To analyze and draw rating curves out of existing stage and discharge data, very little systematic numerical approaches have been defined. Mostly curve approximations have been developed from simplified hydraulic formula, which plot as single power functions or by hand, like it was explained in 2.6.7. Using such approaches can be very time intensive, complicated and sometimes far away from the reality. Better possibilities are the use of piecewise linear interpolation, cubic splines, least-squares approximation or global polynomial. In this chapter, the problems are evaluated which distort the development of rating curves but are mostly accepted (Fenton, 2015).

The problem starts with curve shaping using the common assumptions, regarding the basic hydraulic equations. The power function in equation *(16),* which is based on the Manning´s equation for open channel flow, is often used to define the stage to discharge relationship (Fenton, 2015).

$$\boldsymbol{Q = C(h - h_0)^{\mu}} \tag{16}$$

With:	C	….. constant	[-]
	h_0	….. reference elevation	[m]
	h	….. water surface elevation	[m]
	µ	….. constant (1.5 – 2.5)	[-]

For natural rating curves, no actual reason exist why these curves should follow such power function. This equation is considered as rough estimation, but on the other hand it is used for most rating curve developments, rather than finding better ways to approximate curves to the given data. A method to develop a more accurate curve through the mass of measurements, is to use piecewise interpolation. This can be made either with two-point interpolation or splines. The first method is based on the minimizing the sum of the squared deviations from the interpolated curve, which is reasonable when a curve should be fitted to a large amount of data points. The second method, the splines, forms a curve which goes through all data points, using low order polynomials to gain a smooth curve between two points. These two interpolation methods perform well in developing curves but needs additional human adaptions of the data points. Another method is to use global polynomials which means that the whole curve is described with one function of an order between 3 and 10. Such polynomials are described like it is shown in equation *(17)*. To develop such global polynomials, the user must vary the order of these equation to gain the best fitting (Fenton, 2015).

$$\boldsymbol{Q = a_0 + a_1 h + a_2 h^2 + \ldots + a_m h^m} \qquad \textbf{(17)}$$

To ensure that global polynomials leads to satisfying results, large gaps between data points should be avoided which occurrence can be seen in Figure 23 (Fenton, 2015).

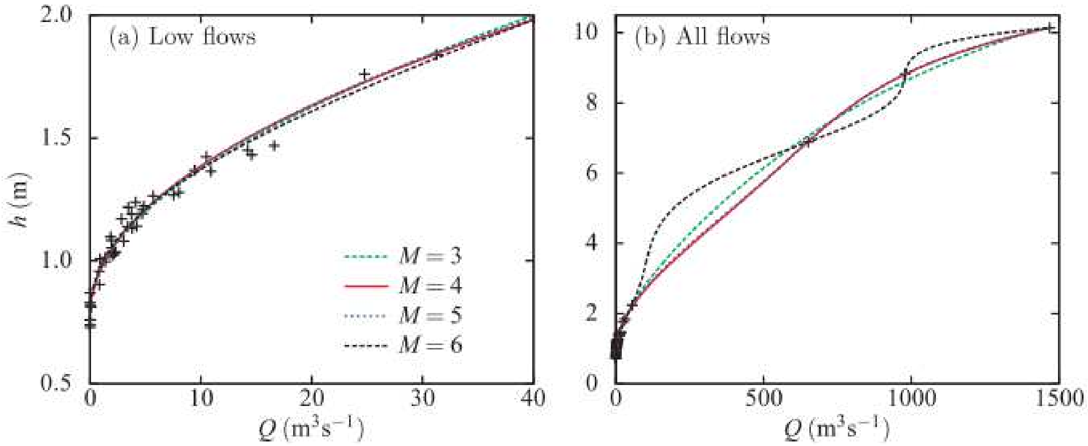


Figure 23 Global polynomials different order for different flow states and with gaps (Fenton, 2015)

Like in Figure 23, the occurrence of gaps causes fluctuations which are getting worse with higher polynomial order. This behavior makes it hard to always use the same order. For every point-cloud, different orders give the best results, which makes the implementation into autonomous scripts kind of difficult. Furthermore, it has been proofed that if the square root of the discharge is used for plotting the data, fluctuations in the low-flow and high-flow part can be reduced. This effect can also be achieved using log scales, which on the other hand focuses too much on the low-flow part. In Figure 24 a comparison between the two most relevant methods, splines and global polynomials, are made which shows that both methods are leading to satisfying results and can both be used for developing rating curves. The main advantage is that the global polynomials method need less calibration than splines (Fenton, 2015).

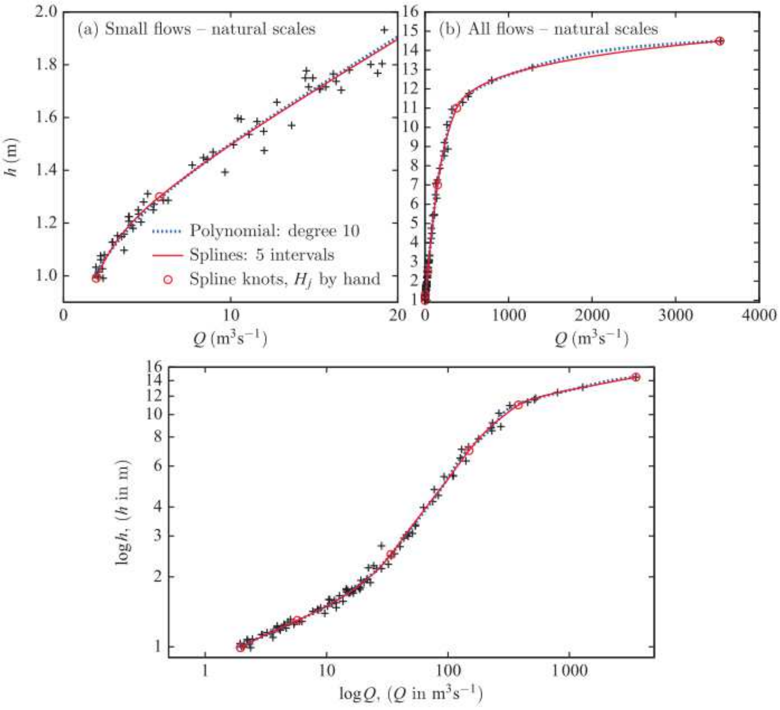


Figure 24 *Polynomial and spline approximation for USGS Station at Noxubee River near Geiger of the year 1970 for low-flow (a), complete flow(b) and on complete flow on log scale(c) (Fenton, 2015)*

A further theory may consider that the rating curve should not be imagined as a thin line with unique stage to discharge relationships either than a curve with upper and lower boundaries, due to different bed heights and resistances (Fenton, 2015).

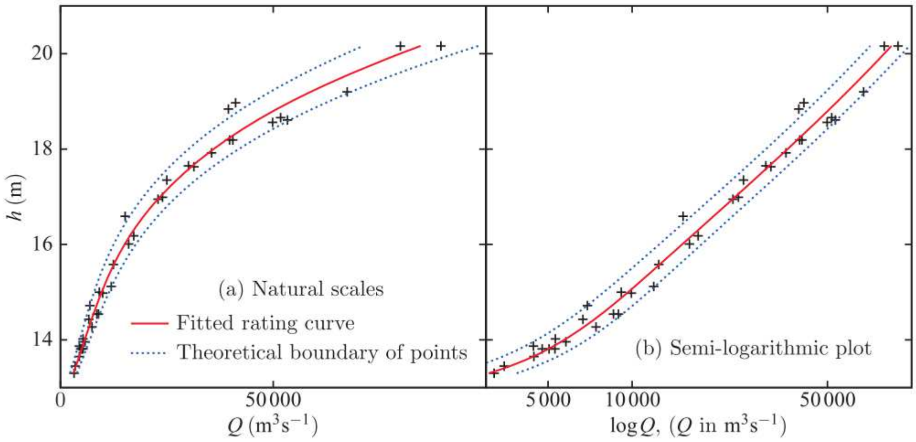


Figure 25 Further development of a rating curve to separate scattered data from errors, (Fenton, 2015)

Figure 25 shows the principle of a further development of a rating curve to define boundaries in which a measurement can be considered as correct. Such boundaries make it easier to analyze scattered data. Additionally, this approach may also detect loop-effects, like described in 2.5.1 (Fenton, 2015).

2.7 The United States Geological Survey (USGS)

The United States Geological Survey is a part of the Department of Interior and was founded in 1879. It is a science agency which deals with gaining experience in natural science and collecting data in various fields of research. The fields of research are water, earth and biological science as well as civilian mapping. The consequence of such a central management of different research disciplines, is that the USGS can manage large, multidisciplinary and complex tasks using their nearly 9000 employees. The range of provided material and documents spreads from real time data to scientific papers and publications. Furthermore, all these resources are free of charge for the public (USGS, 2017).

USGS
science for a changing world

Figure 26 Logo of the United States Geological Survey (USGS, 2017)

Some of the most important services which are provided by the USGS are:

- Collecting and providing of real-time data from a wide range of different specialist areas

  - Developing and maintaining of geographic and topographic maps
  - Provide and collect publications
  - Developing and providing of software to analyze the monitored data of the USGS

The resources, which are provided for the major topics of the USGS, are briefly described in the following paragraph. The importance of the major topics is defined by the economical and human risk and danger. The first topic deals with the change of climate and land use, which effects our lives. Research in this field is important to provide sufficient facts to build up the public and economic awareness, when using resources and how it will change on local and global scale. The most popular, although important, part of this topic is the potential which lies within the various forms of carbon sequestrations and their consequences on different parts of the environment. Apart from this, also long-term observations of climate history, land-use and land-cover are provided. The next main topic tries to understand complex Earth and biological systems and processes. This can be achieved due to the multidisciplinary competence of the USGS like it was mentioned before. Conservation and observation of ecosystems is another main topic which deals with wildlife and their living environment. Furthermore, resources like water, energy, mineral and land are managed. Observing the location, amount and quality of mineral resources, which can be used for energy production, is the next main mission of the USGS. This also includes research in environmental friendly extraction and production of these materials. Protecting the environmental health of the United States is another major topic and aims on the control, monitoring and minimization of harmful substances in the environment. The next topic deals with the risk of natural hazards, which causes every year high human and economic losses. Understanding these hazards is the first step to reduce the risk when they occur. To achieve this, research must be performed and provided to officials and the public. Natural hazards include earthquakes, volcanos, hurricanes, landslides and floods. Finally, analyzing and monitoring of water resources is also a main mission and it deals with surface water, groundwater and water quality as well as their availability. Furthermore, these observations increase the quality of life by protecting the public and their properties (USGS, 2017).

This thesis uses data from the USGS water-data archive, which is free of charge to the public and online available (https://waterdata.usgs.gov/nwis). Since the late Nineteenth century, the USGS is collecting stream stage data, like it was described in 2.6.2, every 15 minutes at many gaging stations scattered all over the United States. The data is analyzed by using rating curves which are developed and maintained using field measurements done by staff of the USGS.

2.8 River rating in Austria

All previous investigations, concerning river rating methods, has been based on standards of the USGS. The topic of river rating in Austria is handled in different ways, but the purpose stays the same. To show these differences, it will be explained how the Austrian government deals with river rating.

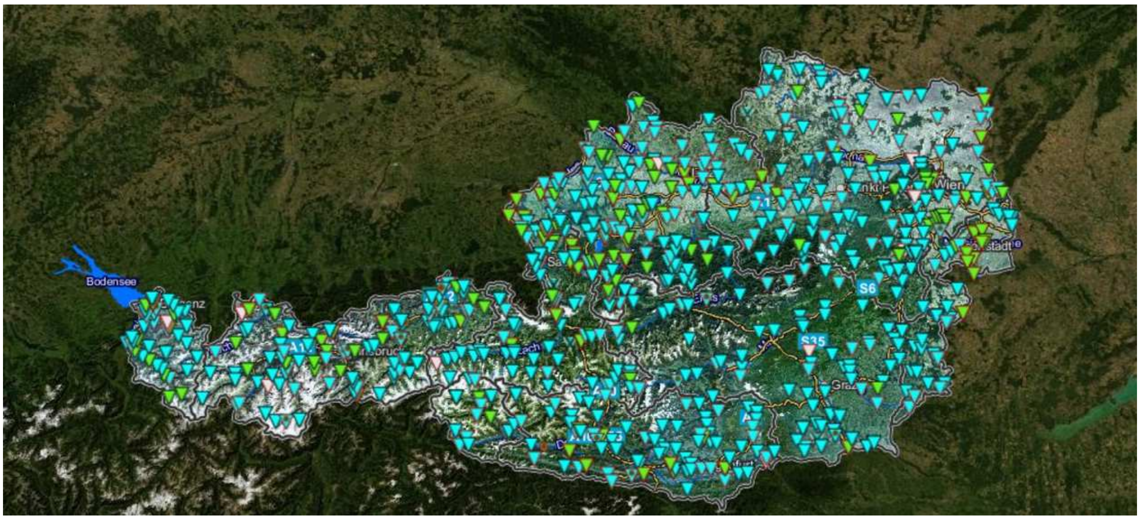


Figure 27 Location of all open channel gaging stations in Austria operated by the government (ehyd, 2017)

The installation and operation of the gaging stations in Austria, which are displayed in Figure 27, is done separately by the government of every federal state of Austria. According to the water rights act, the “Federal Ministry of Agriculture, Forestry, Environment and Water Management” is developing masterplans, which includes the frequency of field measurements and submit these to the governments of the federal states. Despite from the federal gaging stations also private stations are installed, specially to perform measurements at specific locations which are interesting for hydro power plants or other purposes. In this thesis, these private stations will not be discussed since these companies are operating them in their very own way (bmvit, 2017).

The following informations are based upon an interview with Dipl.Ing.Dr. Robert Schatzl, who is the head of the hydrographical service of the Styrian government. The operation, field surveys and maintenance of the federal gaging stations lies in the responsibility of every federal state administration, but is funded by the federal ministry. Staff of the hydrology department of every federal state are performing field measurements every two month at every federal gaging station, according to the masterplan provided by the federal ministry, if the resources are available. The discharge measurements, performed by the staff, are done by using current meters and ADCP measurements, which is equal to the methods used by the USGS. The federal ministry is providing a central processing software where all staff member can upload their measurement results and are able to access all previous recorded data. Apart from the field measurements, the autonomous recorded stage data is also implemented into this central processing software. These autonomous recorded stage data have been recorded for a long time. The usage of the recording interval of 15 minutes, which is now the standard, started in 1976 and was then successively implemented at all gaging stations. At some gaging stations measurements are performed every 5 minutes. Nevertheless, also at this gaging stations the 15-minute data is created out of the mean gage height of these measurements. In the central processing software, current and previous rating curves are stored for processing the autonomous stage measurements. If deviations occur, due to changes of the physical properties of the riverbed, limitations have been defined for every gaging station which helps to detect a shift in the rating curve. In the USA, the limitations are the same for every gaging stations. The biggest difference to the USGS is that, in most cases, the rating curves are implemented in the program about one year after the measurements has been made. Although the autonomous recorded measurements are provided from the government in real time, the data will be changed one year later, because of the implementation of the corresponding rating curve. In the meantime, the previous rating curve is used to create the discharge values. The reason therefore is that the creation of the water year summary from the ministry (BMLFUW, 2017) where every gaging station is listed with their important data and informations, takes some time. When such water year summaries are made, also the rating curves are defined and fitted due to changes in streamflow. Nevertheless, in some cases, the rating curves are also created during the year. Reasons for such additional investigations can be the creation of flood reports and monthly reports as well as for providing online gaging data. However, these rating curves are additionally controlled when the water year summaries are created (Schatzl, 2017).

Just like in the USA, the seasonal influence on the physical properties of the riverbed are not especially investigated. This influence is covered within the adjustment of the rating curve, according to the field measurements. Unlike many rivers in the USA, rivers in Austria tend to be less influenced by seasonal changes and vegetational growth.

3. Investigation of the available data and creating of assumptions

This chapter deals with the assumptions that should be made for analyzing the historical data of three gaging stations in the United States, provided by the USGS.

3.1 Available data

The data, provided by the USGS, can be downloaded on their website (www.waterdata.usgs.gov) for example in CSV-file format. The data consists of three data set. The first two are autonomous recorded and represents the stage measurements and the corresponding rated discharge. These data have been recorded every 15 minutes since the late nineteenth century. The stage data have been collected mainly with a float gage and containing the date, time and stage measurement. The third data set contains field measurements which has been carried out from the USGS, at an interval of about two months. The field measurements are containing all informations which are needed to get an idea of the cross-sectional properties of the stream. The most important parameters are:

- Gage height and discharge
- Number of the corresponding rating curve and the current shift adjustment
- Channel -width and -area
- Measurement method of the velocity and the discharge

These field measurements have been used to validate and maintain the stage to discharge relationship and therefore making autonomous data recording useful. These data are provisional and subject revision which means that the data were not published by the USGS. Concerning the rating curves, only the most recent one, for every gaging station, is available online (https://waterwatch.usgs.gov).

3.1.1 Gaging station "Clear Creek near Oxford", Iowa

The gaging station Clear Creek, with the ID of 05454220, is located 4.5 km east of Oxford, Iowa, 0.3 km west of Kent Park and 21,7 km upstream from the mouth into the Iowa River. The coordinates are Latitude 41°43'06'' and Longitude 91°44'24'' referenced to the North American Datum of 1927 (NAD27) which is the geodetic reference system for north- and central America established in 1927.

Figure 28 Location map of the gaging station „Clear Creek" near Oxford, Iowa (waterdata.usgs, 2017)

The drainage area, referred to this station, covers about 151.26 km², which leads to a mean discharge, from 1994 to 2016, of 1.60 m³/s. Autonomous stage recordings has been made since the November of 1993. This means that about 800,000 records have been made and stored by this gaging station. The field measurements were made by wading through the river, except for higher discharge, where the measurements were made from a bridge near the measuring station. From 1993 until 2016, overall 219 field measurements have been performed in a frequency of about two months.

Figure 29 View upstream Clear Creek (waterdata.usgs, 2017)

Figure 30 View downstream Clear Creek (waterdata.usgs, 2017)

Figure 29 and Figure 30 show the up- and downstream channel and its vegetation. The gaging station is located near the bridge from whom the photos has been made. The datum of the gage is 212.29 m above the National Geodetic Vertical Datum of 1929 (NGVD29) also called the sea level datum of 1929. The riverbed, at this gaging station, has decreased since the first measurements in 1993. These changes do not affect the stage measurements because the rating curves have been fitted constantly to the changing conditions, using the field measurements. Nevertheless, it must be assured that the gage height of zero flow is always above the reference gage height.

Figure 31 Photo of the gage at Clear Creek (waterdata.usgs, 2017)

3.1.2 *Gaging station "Duck Creek at DC Golf at Davenport", Iowa*

The gaging station Duck Creek, with the ID of 05422600, is located 0.15 km upstream from Kimberly Road in Davenport, 30 m upstream from the golf cart bridge, 0.8 km downstream from Pheasant Creek and 7.2 km upstream from the mouth into the Mississippi river. The coordinates are Latitude 41°43'06" and Longitude 91°44'24" referenced to the NAD27 which is the North American Datum of 1927.

Figure 32 Location map of the gaging station „Duck Creek at DC Golf at Davenport" (waterdata.usgs, 2017)

The drainage area referred to this station covers about 148.41 km² which leads to a mean discharge, from 1993 to 2016, of 1.59 m³/s. Autonomous stage recordings have been made since the November of 1993, which means that about 800,000 records have been made and stored by this gaging station. The field measurements were made by wading through the river, except for higher discharge, where the measurements were made from a bridge near the measuring station. From 1993 until 2016, overall 212 field measurements have been performed in a frequency of about two months.

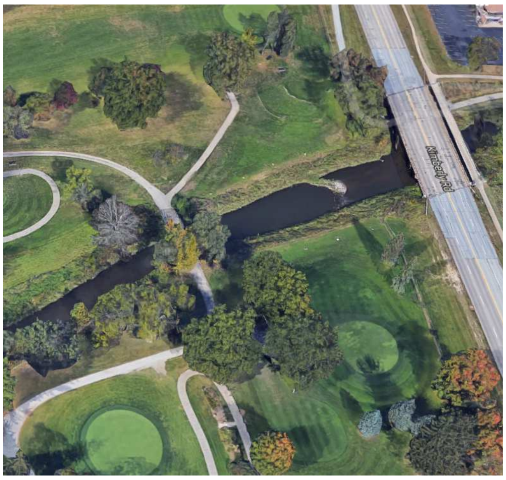


Figure 33 Satellite image of the gaging station „Duck Creek" (google.maps, 2017)

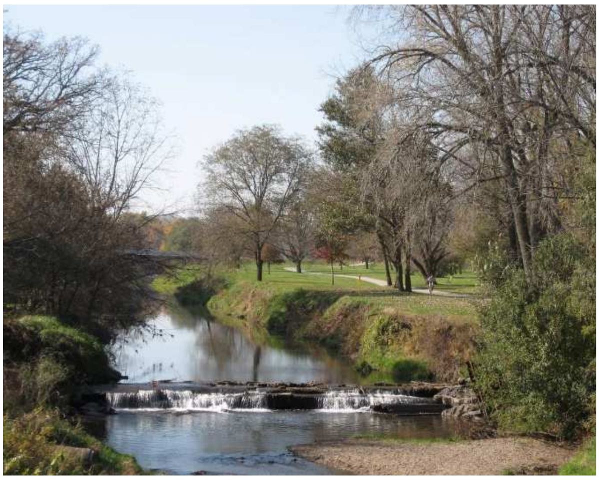


Figure 34 View from a location downstream from the "Duck Creek" gaging station (tedvillaire, 2017)

Figure 32 and Figure 33 show location and properties of the channel around the gaging station at Duck Creek. The gaging station is located near a golf bridge, which makes it possible to perform discharge measurements without wading. The datum of the gage is 182 m above NGVD29. The riverbed at this gaging station has suffered from a degradation of about 0.45 m since the first measurements in 1993. These changes do not affect the stage measurements because the rating curves has been fitted constantly to the changing conditions, using the field measurements. Nevertheless, the measurements can only be valid if the gage datum is always beneath the gage height of zero flow.

3.1.3 Gaging station "Walnut Creek at Des Moines", Iowa

The gaging station Walnut Creek, with the ID of 05484800, is located 8 m downstream from the bridge on the 63rd Street in Des Moines and 3.54 km upstream from the mouth into the Raccoon River. The coordinates are Latitude 41°35'14" and Longitude 93°42'11"referenced to the NAD27, which is the North American Datum of 1927.

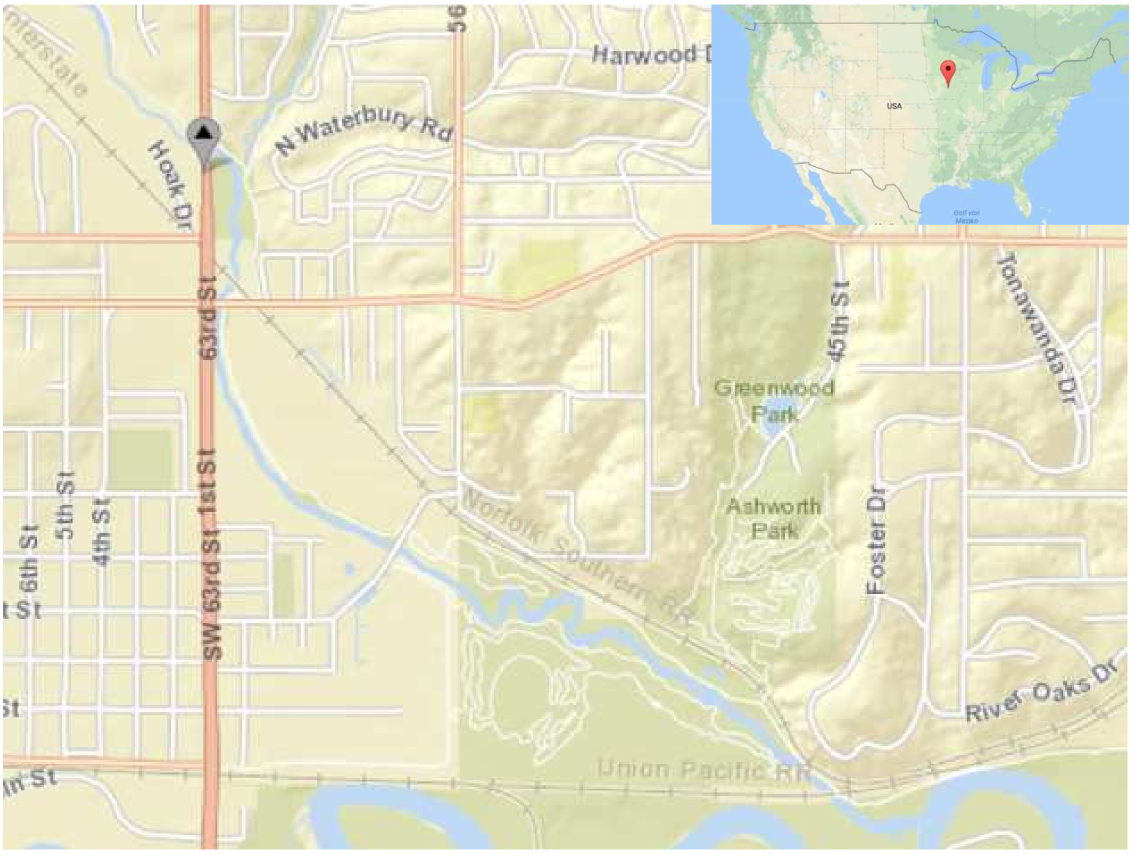


Figure 35 Location map of the gaging station „Walnut Creek at Des Moines" (waterdata.usgs, 2017)

The drainage area referred to this station covers about 203.05 km², which leads to a mean discharge, from 1993 to 2016, of 2.40 m³/s. Autonomous stage recordings have been made since the October of 1990, which means that about 900,000 records have been made and stored by this gaging station. The field measurements were made by wading through the river, except for higher discharge, where the measurements were made from a bridge near the measuring station. From 1990 until 2016, overall 255 field measurements have been performed in a frequency of about two months. For this station, also field measurements exist before 1990, but these measurements will not be taken in account, since the field measurements are used to validate the autonomous stage data, which are not available before 1990.

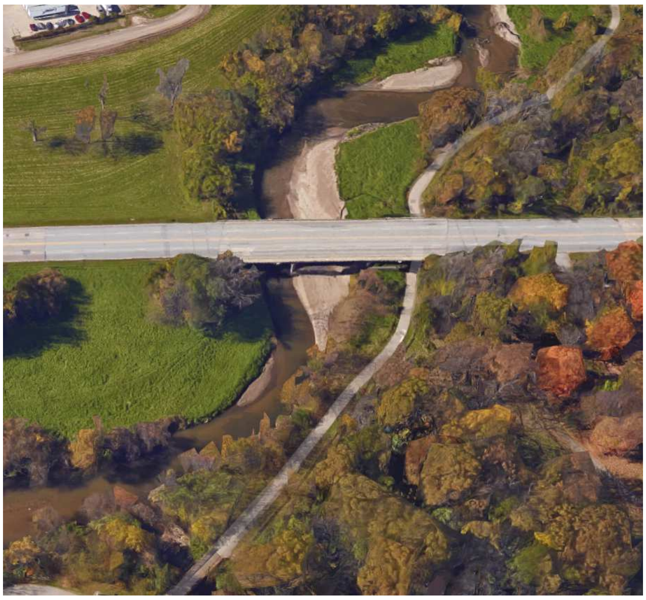


Figure 36 Satellite image of the gaging station „Walnut Creek at Des Moines” (google.maps, 2017)

Figure 36 shows the location and properties of the channel around the gaging station at Duck Creek. The gaging station is located near a golf bridge which makes it possible to perform discharge measurements without wading. The datum of the gage is 244.16 m above NGVD29. The riverbed at this gaging station has suffered from a degradation of about 0.12 m since the first measurements in 1990, although the riverbed has changed over time and temporary higher degradations has occurred. These changes do not affect the stage measurements because the rating curves have been fitted constantly to the changing conditions using the field measurements. Nevertheless, the measurements can only be valid if the gage datum is always beneath the gage height of zero flow.

3.1.4 Basic analysis of the data

As mentioned before, the autonomous recorded stage and discharge data provided by the USGS is provisional which means that deviations triggered by ice formations are not sorted out. Furthermore, flood events are recorded, but for the investigation of the influence of vegetation on the river resistance, these events are not decisive since many other factors, additional to the vegetation, are influencing the streamflow in these cases. However, before any calculations are performed with the data sets, they must be thinned out to get proper results and minimize distortions. Because of the large amount of the data, the assumption was made that for every year the winter months are neglected and deleted from the data sets. The reason for this is that in these months the deviations are too high. Furthermore, finding only the days where ice formations occur is not possible.

3.2 Processing steps performed on the data sets

To extract the influence of vegetation on the rating curves and manning factors, the data obtained from the USGS must be prepared. Furthermore, the USGS could not submit all previous rating curves of the gaging stations which makes it very difficult to reconstruct these rating curves and all the shift adjustments. Another difficult topic is that, apart from the field measurements, no further information about the sites are available. This is problematic when it comes to the determination of the channel area, width and slope. Because of these circumstances, some assumptions must be made, to analyze the autonomous recorded data by using the field measurements as calibration.

3.2.1 Elimination of ice data

As it has been mentioned before, stage measurement can be inaccurate due to ice formations. Although this is not always the case, the measurements during the winter period are neglected and deleted from the data. To be sure and achieve the same number of recordings for every year, all data sets which were recorded between the 22nd of December and the 21st of March are removed.

3.2.2 Approximation of the cross-section geometry

The wetted area and width of a cross-section, with respect to the water level, is changing constantly over time. Such changes are caused by erosion and accumulation processes as well as changes in the riverbed elevation. The cross-sections of these gaging stations have not been constantly monitored which makes it difficult to obtain a relation between the stage, area and width. A proper way to gain such relationships, anyway, is to approximate it by using polynomial functions and the stage to area relationship of the field measurements. Due to the constant changing cross-section, these functions should be developed using small periods in order to gain a satisfying correlation to the area which has been measured in field measurements. These functions can then be applied to the autonomous recorded data. The USGS often simplifies the determination of the area by multiplying the water depth with the channel width, which is nearly accurate for large streams.

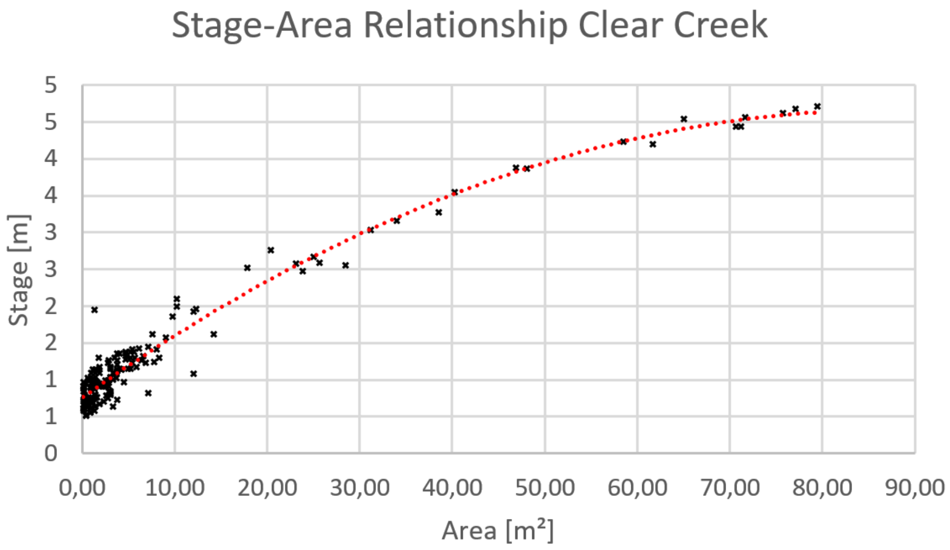


Figure 37 Stage-Area relationship for all available field measurements at the Clear Creek gaging station

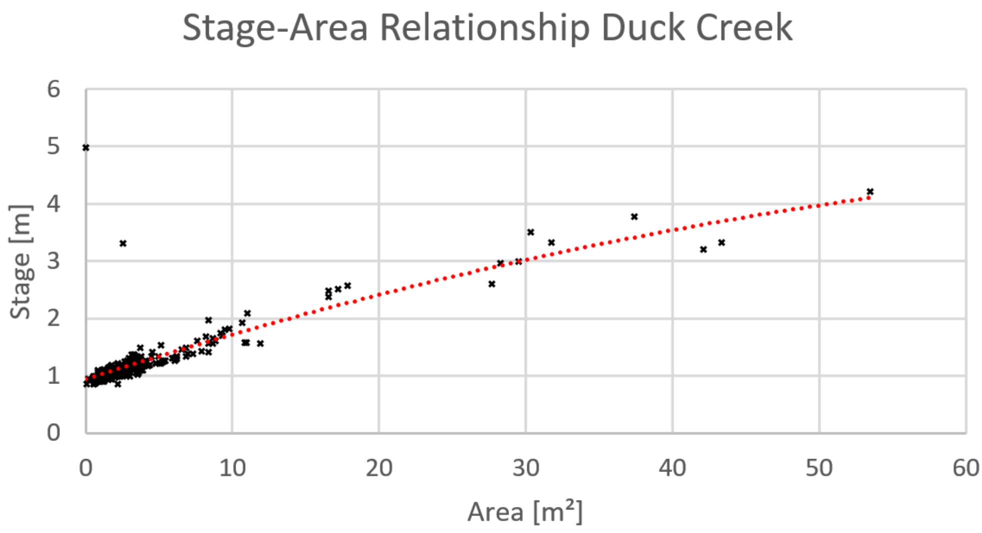


Figure 38 Stage-Area relationship for all available field measurements at the Duck Creek gaging station

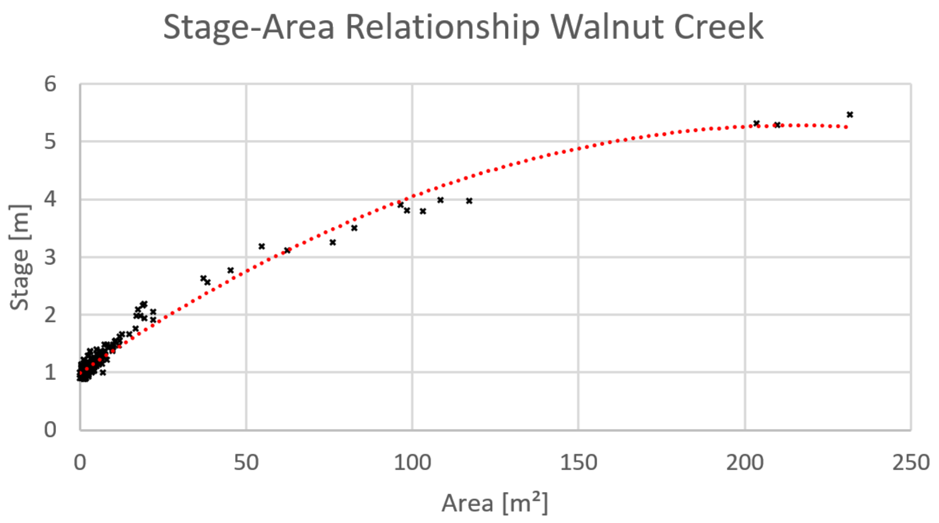


Figure 39 Stage-Area relationship for all available field measurements at the Walnut Creek gaging station

As it can be seen in Figure 37, Figure 38 and Figure 39, the area of the cross-section with respect to the water level is not constant over time. These diagrams of stage to area relationships for the three USGS gaging stations are based on 170 measurements at the Clear Creek gaging station, 211 measurements at Duck Creek gaging station and 240 measurements at the Walnut gaging station, from 1991 to 2016. The low-flow part of the curve is well defined through many measurements in contrast to the high-flow part which may allow deviations at high stages. By using the diagrams displayed above, it can be observed that the cross-section at Clear Creek suffers the most of time-dependent changes. Furthermore, the cross-section at Walnut Creek has changed the least. The scattering of the data, as a result from time-dependent changes of the cross-section, is now removed by separating the field measurements into periods of three years and generateing polynomial functions for each of these periods. These functions are then used to reconstruct the autonomous recorded data.

The same analysis as it has been made for the stage to area relationship must now be made for the stage to width relationship. This is also made by using polynomials and the channel widths from the field measurements.

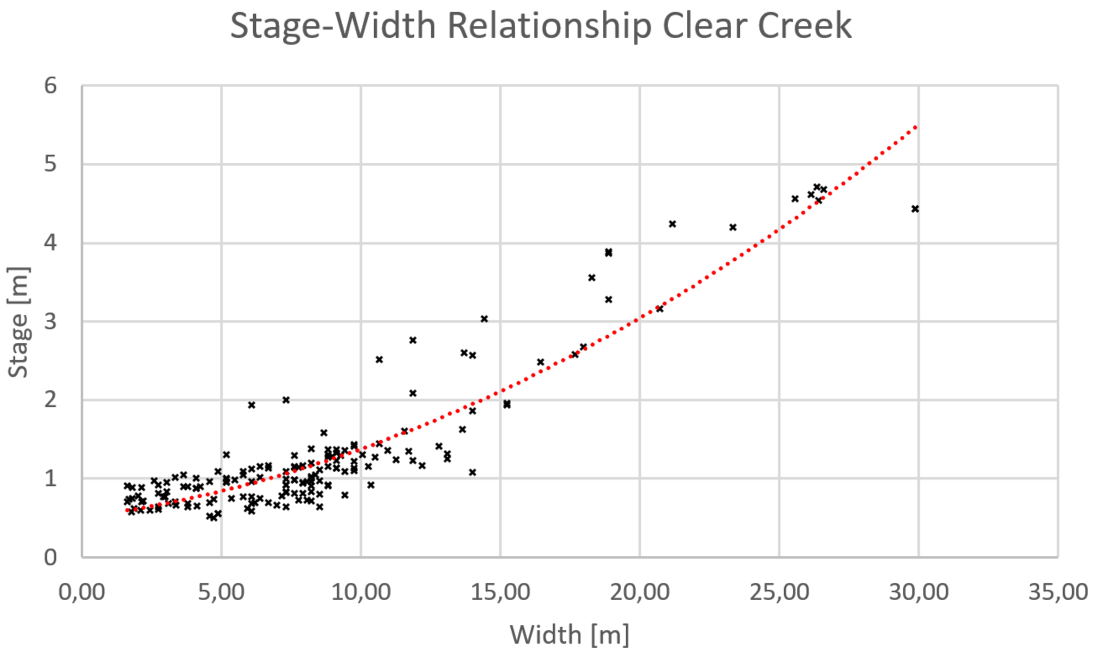


Figure 40 Stage-Width relationship for all available field measurements at the Clear Creek gaging station

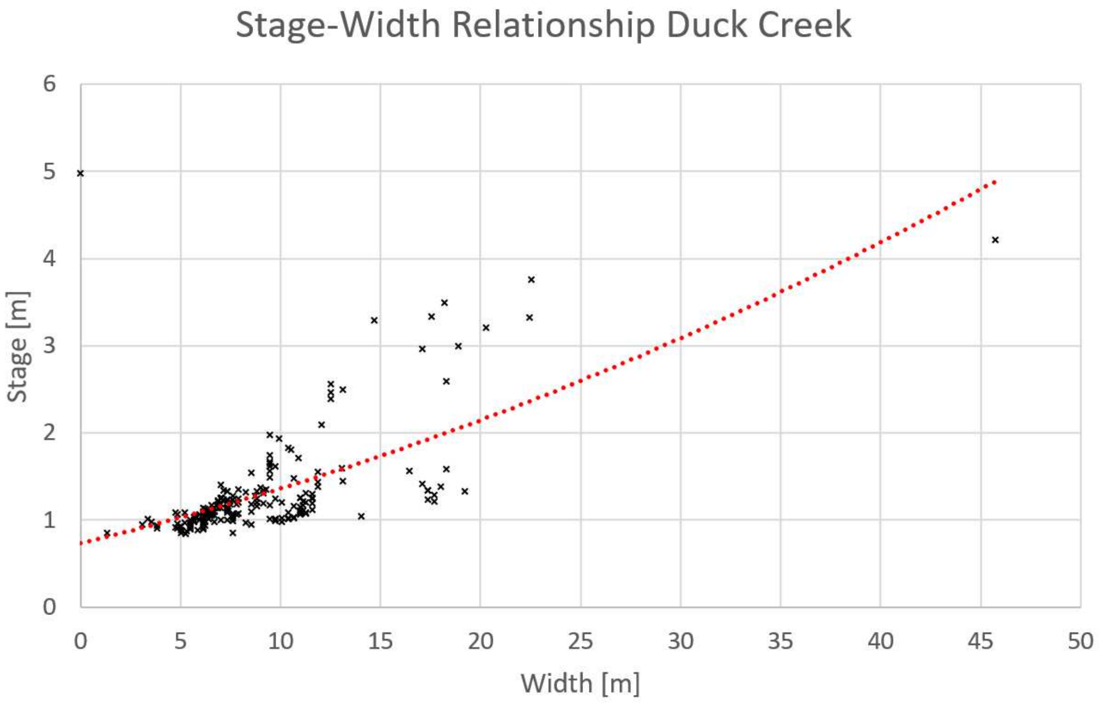


Figure 41 Stage-Width relationship for all available field measurements at the Duck Creek gaging station

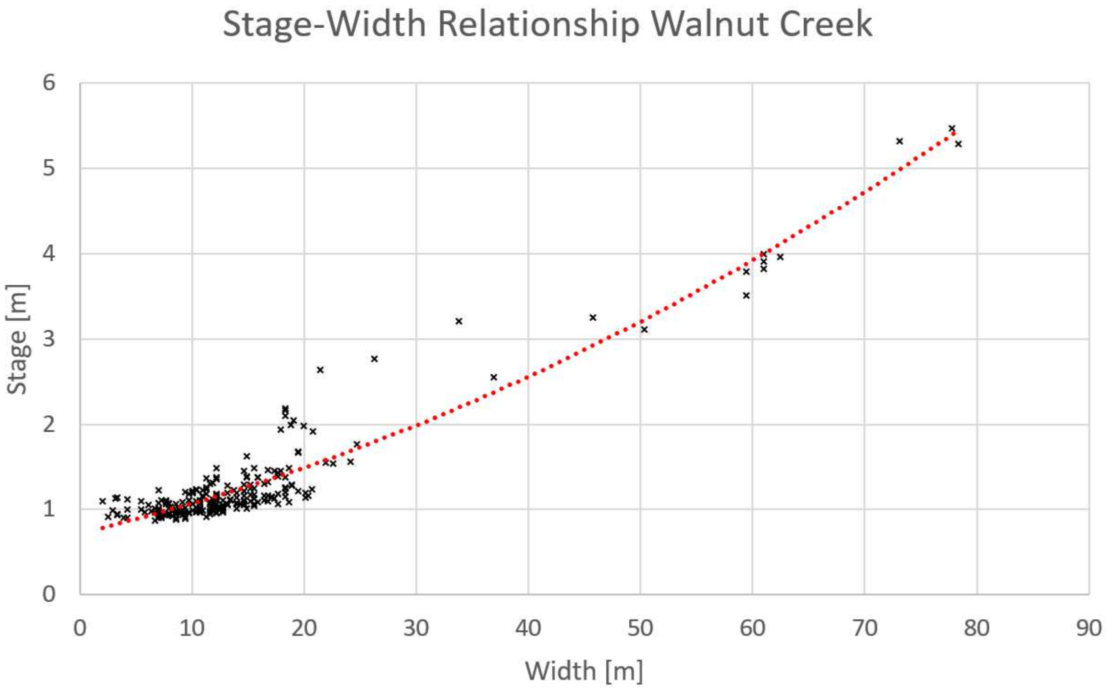


Figure 42 Stage-Width relationship for all available field measurements at the Walnut Creek gaging station

The scatterings in the stage to width relationships are much higher than it have been at the stage to area relationships. This may cause in vegetation of the banks, inaccuracies of the measurements or deviations caused by measurements at slightly different positions in the channel. Figure 40 to 42 indicate that the Clear Creek gaging station shows the highest scattering in the measurements while the Walnut Creek gaging station seems to have a relative stable stage to width relationship.

In 2016 some geodetic field measurements were performed to determine accurately different cross-sections around the Clear Creek gaging station. These cross-section profiles are defining a stage to area relationship which can be used to calculate the corresponding area to the autonomous recorded stage data. For the development of a stage to area relationship, the cross-section XS2 has been used because it is positioned right after the bridge where the field measurements are performed, as it can be seen in Figure 43. The banks are strongly vegetated, as this survey has been performed in July, and the riverbed contains of sand and silt as shown in Figure 44.

Figure 43 Location of the cross-section surveys near the Clear Creek gaging station

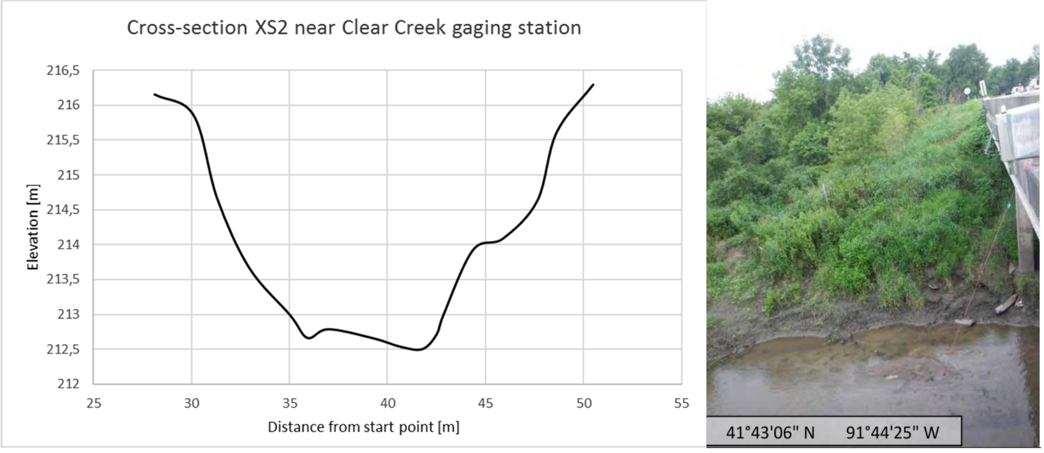


Figure 44 Cross-section XS2 near the Clear Creek gaging station

Although this relationship is accurate, it is only valid for a specific period because of time-dependent cross-sectional changes and bed degradation.

Because such geodetic survey is only available for the Clear Creek gaging station, this kind of gaining the area with respect to the stage is only used to validate the method of approximation using polynomial function like it was described before. Additionally, the calculated cross-sectional area has been fitted to the field measurements to eliminate the time-depended effect of bed degradation, which otherwise would lead to a significant error. Field measurements were divided up into 3 year periods to gain these functions. Those leads to a minimal deviation from the calculated values (see Figure 45). Differences to the calculated values getting higher for high-flow conditions and fit very well for mid-flow conditions. Because of this investigation at the Clear Creek gaging station, the method of the area approximation can be also used to gain satisfying results for the Duck Creek and Walnut Creek gaging stations.

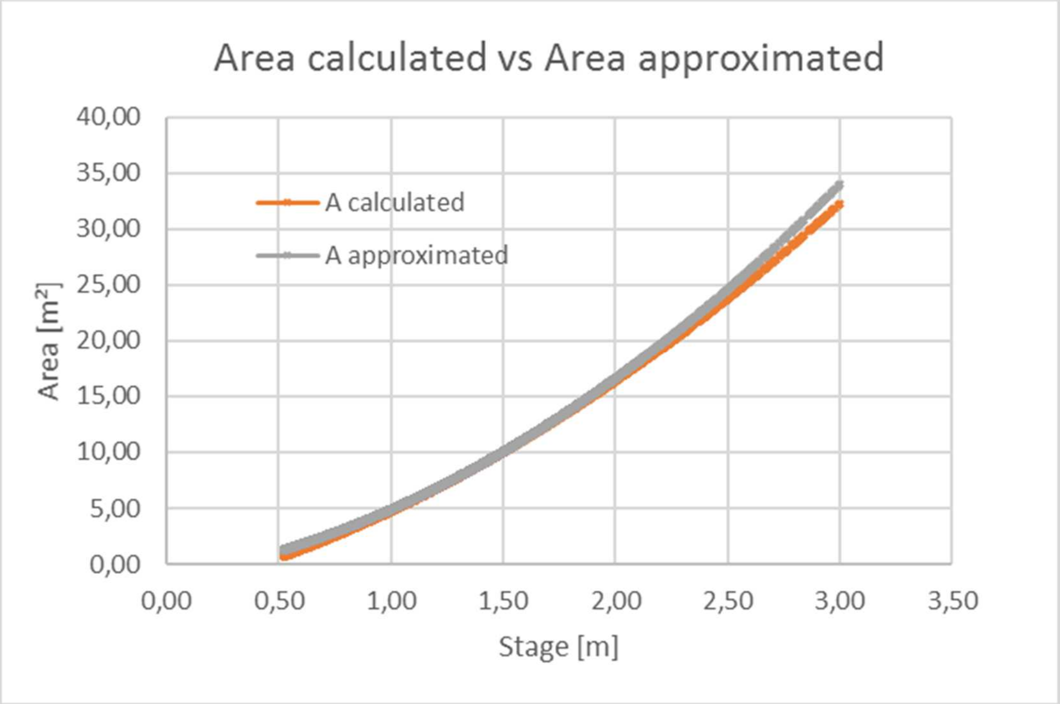


Figure 45 Difference between calculated area and approximated area from 2013 to 2016 at the Clear Creek gaging station

It can be summarized that the cross-section at the Clear Creek gaging station suffers the most from geometric changes in width and area, while relatively stable conditions are occurring at the Walnut Creek station. The cross-section at the Duck Creek gaging station also suffers from geometric changes but mainly when it comes to the changes in channel width.

3.2.3 Approximation of the channels steady slope

A more difficult topic is the determination of the bed- and energy-slope of a channel, without personally measuring it, which is also not easy due to constant changes in discharge. Slope measurements have not been performed by the USGS, which means the slope, necessary for the determination of the Manning roughness, must be derived using alternative methods. A possibility for estimating the bed slope of a river is by measuring it in Google Earth. In order to do this, a path, following the riverbed for a specific length, is defined. Google Earth can calculate a height profile and the corresponding slope for every section of a path. This is not always accurate due to strong vegetation, like trees near the riverbed. To eliminate these inaccuracies, only the height difference between the start and the end of this path, which are located in the bed without vegetation, are determined. This height difference leads, with the corresponding length of the path, to a mean geodetic slope. For the Clear Creek gaging station, the steady slope has been determined with 0.39 ‰, which gives the possibility to control the measured slope with the approximated Google Earth slope. For the Clear Creek station bed slope in Google Earth has been calculated along a 3.5 m long path which leads to a slope of 0.45 ‰. Compared with the measured slope, the Google Earth slope can be used for the calculation of the Manning roughness because small deviation can always occur due to changes in the riverbed. Furthermore, this slope can only be used if steady flow conditions occur, which means that the water level line and the energy line are parallel to the river bed. The determination of the water level slope for unsteady flow conditions, which occur if the hydrograph of the river is rising or falling, is not possible with the available data. This means that only data is used where steady flow conditions occur. Limitations for steady flow criteria are defined by only selection data after the slope of the hydrograph stays horizontal for two hours. This leads to an elimination of every unsteady flow condition and steady state flow can be assumed. By only using steady state data, loop effects and inaccuracies due to flood events are also eliminated which reduce the deviations in the roughness estimations.

3.2.4 Approximation of the hydraulic radius

The problem with the determination of the cross-section geometry has already been discussed in 3.2.2 and therefore it is obvious that the determination of the hydraulic radius causes problems as well. The USGS deals with this problem by calculating the hydraulic radius with the assumption, that the hydraulic Radius R is equal to the water depth in the channel (Rantz, 1982, a). This approximation is only valid for very wide streams. Otherwise the hydraulic radius is significant smaller than the water depth. A better assumption may be, that for natural rivers, the hydraulic radius is often assumed to be equal to the mean water depth of the channel (Jirka & Lang, 2009). For the Clear Creek gaging station, the current hydraulic radius has been defined for every stage height, which can be used to proof the accuracy of the assumptions for determining the hydraulic radius of the other stations. The calculated values are now compared to the approximated values due to the following formula.

$$\boldsymbol{R = D = \frac{A}{W}} \tag{18}$$

With:	D	….. water depth	[m]
	W	….. width of the channel	[m]

Additionally, these calculated values are compared to values from the assumption that the hydraulic radius equals to the water depth D.

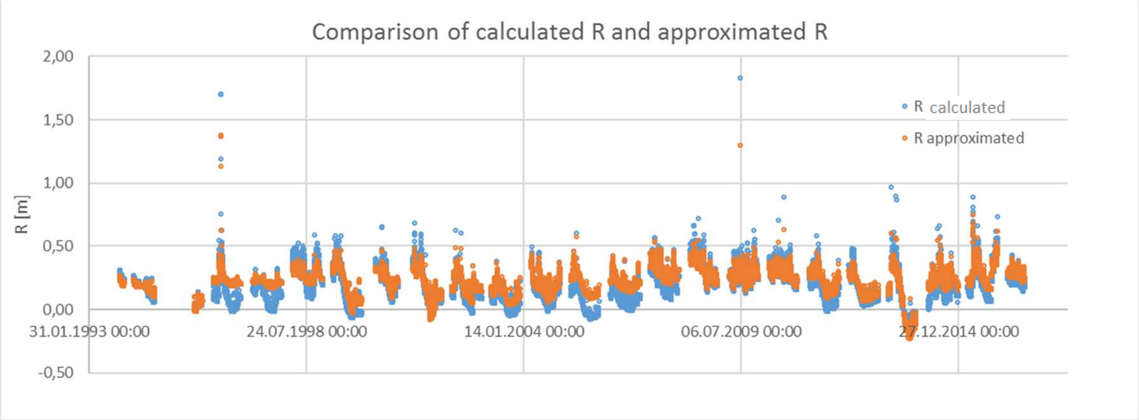


Figure 46 Comparison of calculated R values from field survey and approximated R values by using R=D=A/W

Figure 46 shows the relationship between the calculated and approximated values for *R,* using the equation *(18).* It is obvious that the deviation between these two methods are too high and cannot be used to calculate the hydraulic radius R at other stations. The second method for determining *R* needs the values for the water depth, which are calculated by subtracting the gage height of zero flow, determined for every year, from the recorded stage heights. Furthermore, these values are set equal to the hydraulic radius.

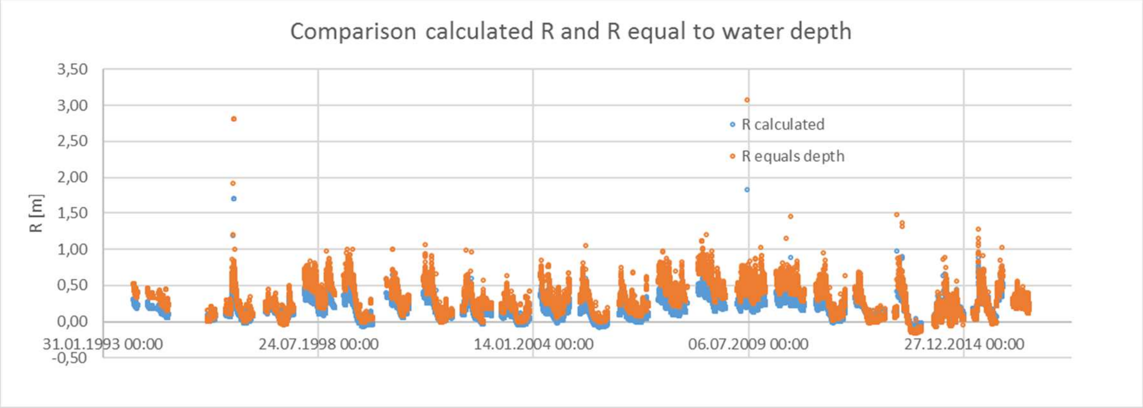


Figure 47 *Comparison of calculated R values from field survey with R values equal to the water depth*

Figure 47 shows that this assumption leads to better results than using the equation *(18).* However, the *R* values equal to the water depth are tendentially higher than the calculated values. As it has been mentioned before, a good approximation for *R* should use the mean water depth as the hydraulic radius.

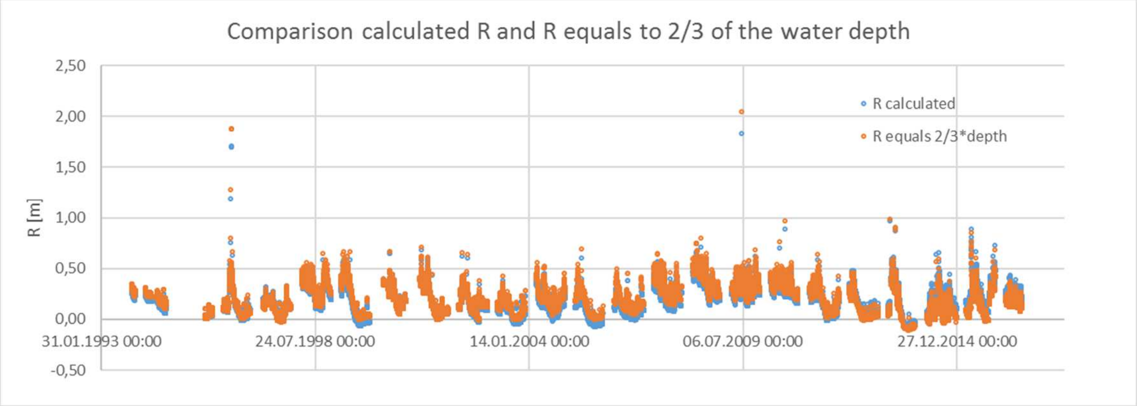


Figure 48 *Comparison of calculated R values from field survey with R values equal to the 2/3 of the water depth*

In Figure 48 the comparison of the calculated *R* values with the values equal to two third of the water depth is made, which leads to satisfying results. The assumption, that the mean water depth is two third of the highest depth, is realistic and necessary since the real value cannot be determined.

For the other gaging stations, the assumption of *R* equals to two third of the water depth is used, which should be a good approximation and more accurate than using the approximated values for the area and the wetted circumference.

3.2.5 Dealing with changing rating curves and shift adjustments

Due to different rating curves and shift adjustments, the daily changes of vegetation or other factors, like dead wood in the channel, cannot be monitored. In fact, such constant observations are not reasonable and would cause too much costs for the advantages which would be gained. The rating curves are controlled and, if necessary, adjusted every two months, which can lead to a proper data basis for detecting possible seasonal changes. To determine the influence of vegetation on rating curves, out of existing data, the rating curves themselves must be available. For the three gaging stations of interest, only the very current rating curve is available for every gaging station. This makes it necessary to reconstruct all previous rating curves out of the autonomous recorded data. For the gaging stations, different numbers of rating curves have been valid since the beginning of autonomous recording of the stage data. At the Clear Creek gaging station 9 rating curves, for the Duck Creek gaging station 3 rating curves and for the Walnut Creek gaging station 6 rating curves have been applied. For every field measurement, the shift adjustment is provided. These adjustments give the possibility to reconstruct the rating curves with the measurements in a period where the shift adjustment is zero. This was done for all previous rating curves which was fortunately possible due to enough periods with zero shift adjustment.

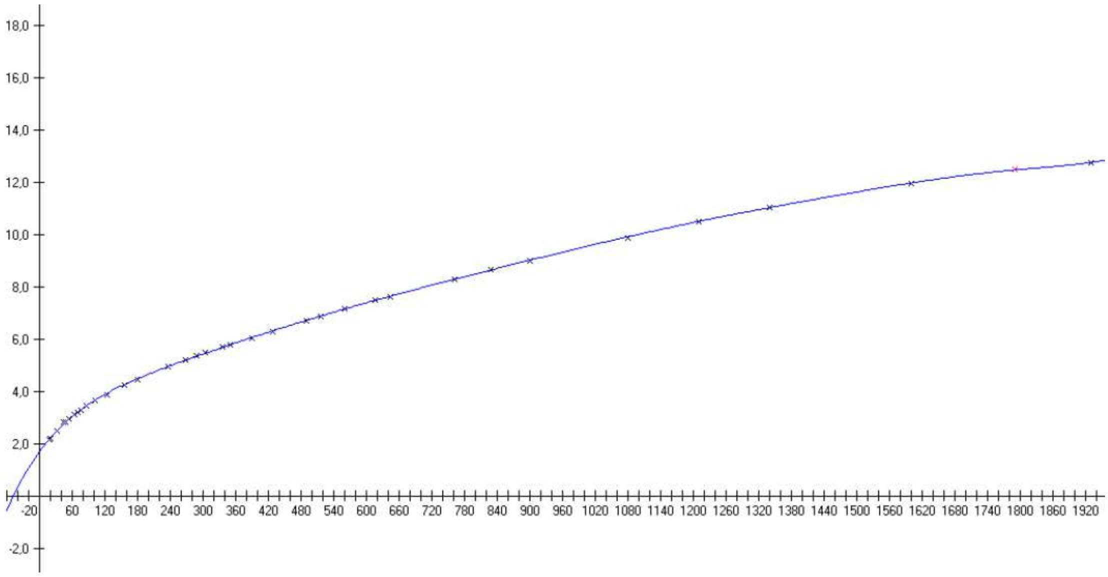


Figure 49 Rating curve of the gaging station Clear Creek from 16.04.2013 until 01.07.2014; horizontal axis=Q[ft³/s]; vertical axis=stage[ft]

Figure 49 shows exemplarily the base rating curve No. 7 for the Clear Creek gaging station, from 16.04.2013 until 01.07.2014. It was created using a small program, “kurvenanpassung.exe”, which allows to create a proper function out of the available data-points. This method is more accurate than the trend-function in excel and can use polynomials of higher order. The order of the polynomial functions varies between 6 and 10, which is depending on the density of the data points. The order that leads to the most satisfying results has been graphically selected, without using any mathematical criteria. The abscissa scales the discharge in cubic feet per second while on the ordinate the stage in feet is plotted. Although the curve is extended into the negative area, caused by limitations of the curve editing program, the curve ends at the ordinate at the stage height of zero discharge, which was explained in 2.6.2. Such plots were made for every rating curve and their function have been implemented into MS Excel to calculate the discharge values for all stage measurements, like no shifts have occurred. Later these values will be related to the data of the USGS to describe the shifts.

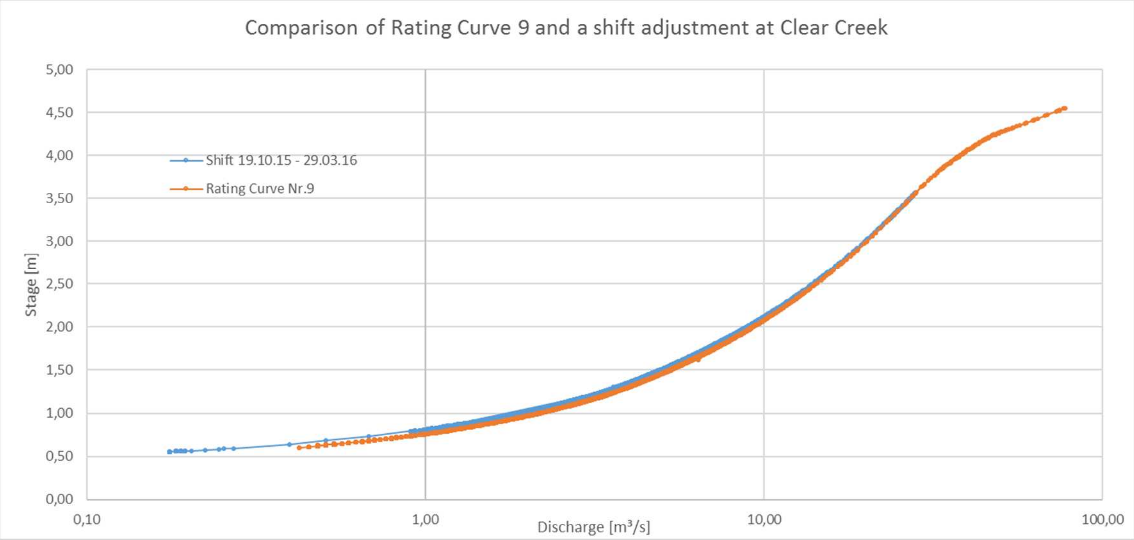


Figure 50 Comparison of the RC 9 and the shifting period between 19.10.15 and 29.03.16

The relationship of the RC 9, from the Clear Creek gaging station, and the shifted curve between the 19.10.2015 and the 29.03.2016 is visualized in Figure 50. The shift adjustment for this period was a plus shift of 5.18 cm, at a discharge of 1.10 m³/s. Furthermore, Figure 50 is representative for the shape of most shift adjustments. This means that usually the low-flow part of the rating curve is shifted and the high-flow part stays the same. This is characteristic for changes in the roughness of the riverbed which can be measured and determined easier for low-flow conditions than for high flow conditions, which are less common.

For determining the seasonal changes at the gaging stations, the corresponding base rating curves are used and compared to all shifted or not shifted values of the autonomous recorded datasets. The deviations, which are resulting out of this comparison, are providing information about the exact amount, date and time of changes in the properties of the riverbed, like it is shown in Figure 51.

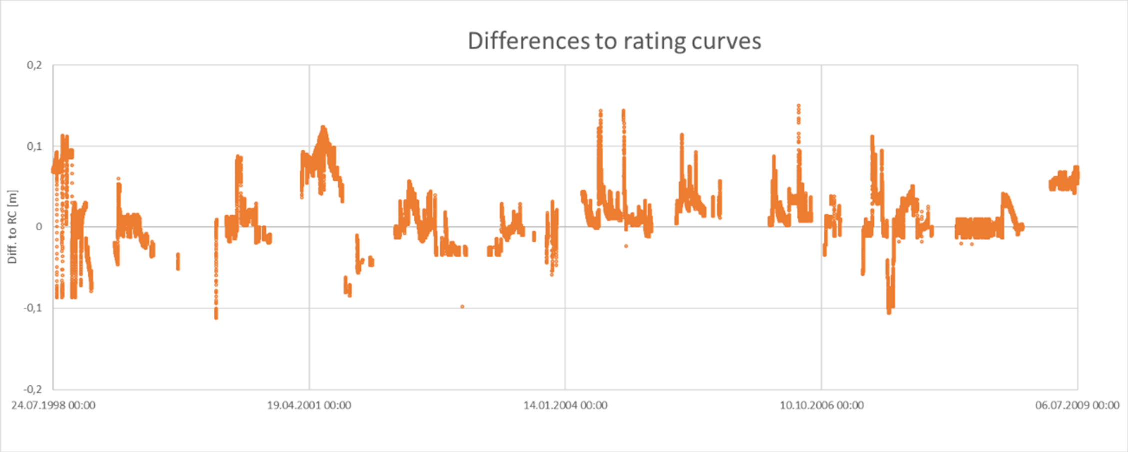


Figure 51 Deviations of the autonomous recorded datasets to the corresponding base RC at the Clear Creek gaging station

3.2.6 Delimitate the range of valid discharge

To gain satisfying results for the Manning factors, limitations concerning the flow rate must be defined. Peak high-flow conditions during flood events can often not be satisfactorily monitored. Furthermore, the influence caused by an expansion of the riverbed are unpredictable. Because of this, the determination of accurate Manning values would not be possible. Another problem is, that if low-flow conditions occur also no realistic values can be gained. The reason therefore is, that if the Manning factors are calculated with the use of the approximated geometry, negative values can occur if the discharge is close to zero, due to deviations of the geometry. Therefore, the following limitation has been used in thus thesis.

- Clear Creek 0.1 – 20.0 m^3/s

• Duck Creek	0.1 – 30.0	m³/s
• Walnut Creek	0.1 – 40.0	m³/s

3.2.7 *Detecting of complex effects*

Unsteady and complex effects in a channel, such as loop ratings and variable backwater effects, can have a misleading influence on rating curves. Such effects sophisticate and scatter the data, which makes it harder to develop unique stage to discharge relationships. If such effects are detected for a specific gaging station, counter-measures can be set to gain satisfying results. A good possibility to do this is to create plots where the percent difference from the base rating curve of the measurement (PDIFF) is compared with the rate of how the stage changes with time (dH/dt).

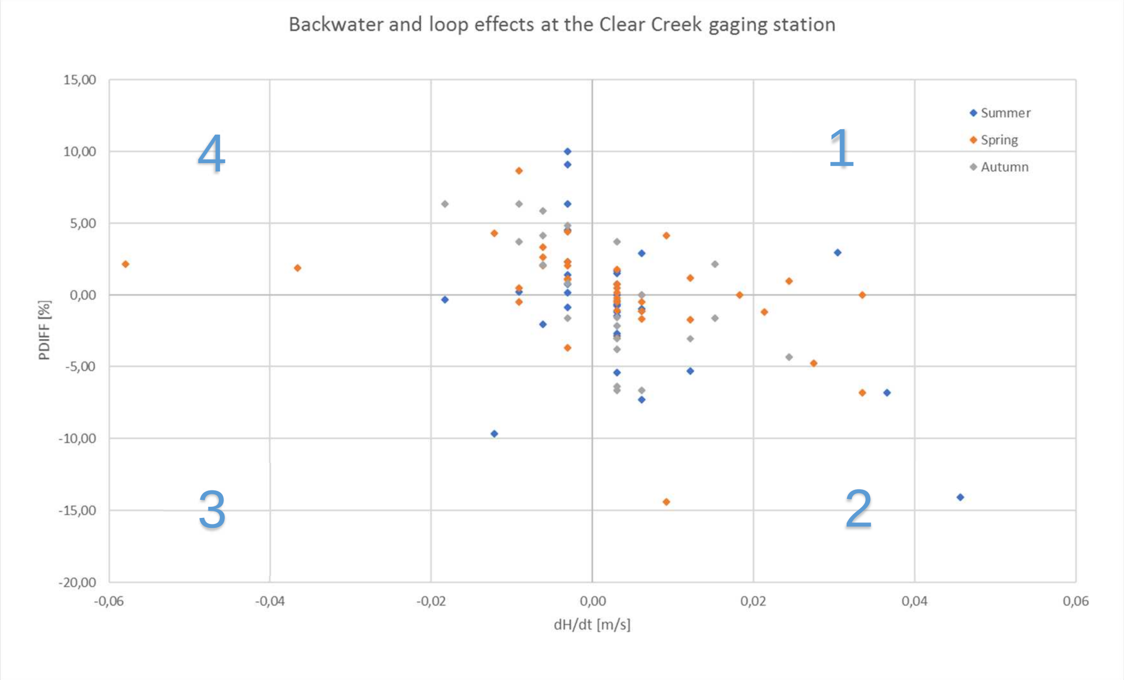


Figure 52 PDIFF vs dH/dt plot for the Clear Creek gaging station

In Figure 52 such a plot has been created by using the field measurements and the autonomous record at the same time. To get the difference from the valid rating curve, the field measurement is referred to the corresponding rating curve, which can be shifted or not. To get the rate of change in stage, the autonomous recorded measurements are used in a close interval to the field measurement.

The plot then consists of four quadrants. If most of the measurements plot in the quadrant one and three, variable backwater effects are occurring in the channel. This means that some structure or property of the channel downstream of the gaging station increases the recorded stage. On the other hand, if most of the measurements plot in the second and fourth quadrant, loop effects may occur due to a change in roughness of the riverbed if a flood wave is propagating through the channel.

4. Results of the investigation

After the assumptions, limitations and computation steps were defined in chapter 3, the results for the three gaging stations will now be presented. The results consisting of two parts, where every part deals with the topic of vegetational influence in its own way. The first part investigates the loop and backwater effects at the gaging stations, while the second part is analyzing the shifting of the rating curves. Together these investigations should provide a satisfying base to evaluate the occurrence and magnitude of vegetational influences on the streamflow properties.

As it was mentioned before, the Clear Creek gaging station is the first station for which the analysis has been performed. The reason is the available field survey data that is used to validate the computation steps, performed on the datasets. This makes it possible to get accurate results also for the Duck Creek and Walnut Creek stations. Additionally, the field measurements, which are, compared to the amount of autonomous recorded measurements, rare but accurate, are used for a fine calibration of the data.

4.1 Detection of backwater and loop effects

The occurrence of loop or backwater effects, which falsify the rating curves, should be known for every gaging station. If such effects occur, measures can be prepared which compensate them. Furthermore, limitations for valid field measurements can be adjusted, with additional focus on the rising and falling limb of the hydrograph. Nevertheless, compensating of such effects can be very difficult because of irregular occurrence and variable magnitude.

To eliminate these effects, the autonomous collected datasets are filtered with respect to steady state flow. All data which are collected under unsteady conditions are filtered out.

4.1.1 Loop and Backwater effects at the Clear Creek station

The course of the Clear Creek is natural and meandering with little impoundments. According to the field measurements of the USGS, sand and silt are the dominating grain sizes of the riverbed while beneath this upper layers, cobbles and boulders occur. These layers are only a few times uncovered due to the erosion of the upper layer, caused by flood events.

Figure 52 shows the results of the backwater and loop effect analysis. As most of the data points are plotted in the second and fourth quadrants of the diagram, loop effects are occurring at this gaging station. A reason for that can be, that the upper layer of the riverbed can be easily eroded and transformed like it was explained in 2.3.1 and 2.5.2. Furthermore, the bed degradation of the riverbed has not been remarkable high since the beginning of the data collection, which means that also a high sedimentation capacity seems to occur. Additionally, influences from unsteady flow conditions, like storage effects of the channel and flood plains, may also affect the loop rating. In the first and third quadrant of this diagram, less data points are occurring, which indicates that variable backwater does not have a strong influence on the rating curve of this station. Nevertheless, the backwater effect should not be neglected because even small magnitudes effects the rating curve. Seasonal influences, visualized in Figure 52, cannot be clearly determined, but it seems that loop effects tend to occur more frequently in spring. The reason for this can be that during the winter months no high-flow conditions occur which allows a higher accumulation of sediments.

4.1.2 Loop and Backwater effects at the Duck Creek station

The course of the Duck Creek is less natural than the course of the Clear Creek. The reason for this is, that the gaging station is located in urban area where the course is straightened. Most of the time the bed material consists of cobbles and boulders, while sometimes also gravel and sand layer covers the riverbed due to sedimentation. This can be taken from the field measurements of the USGS, where, apart from stage and discharge measurements, also the grain size of the upper layer is recorded.

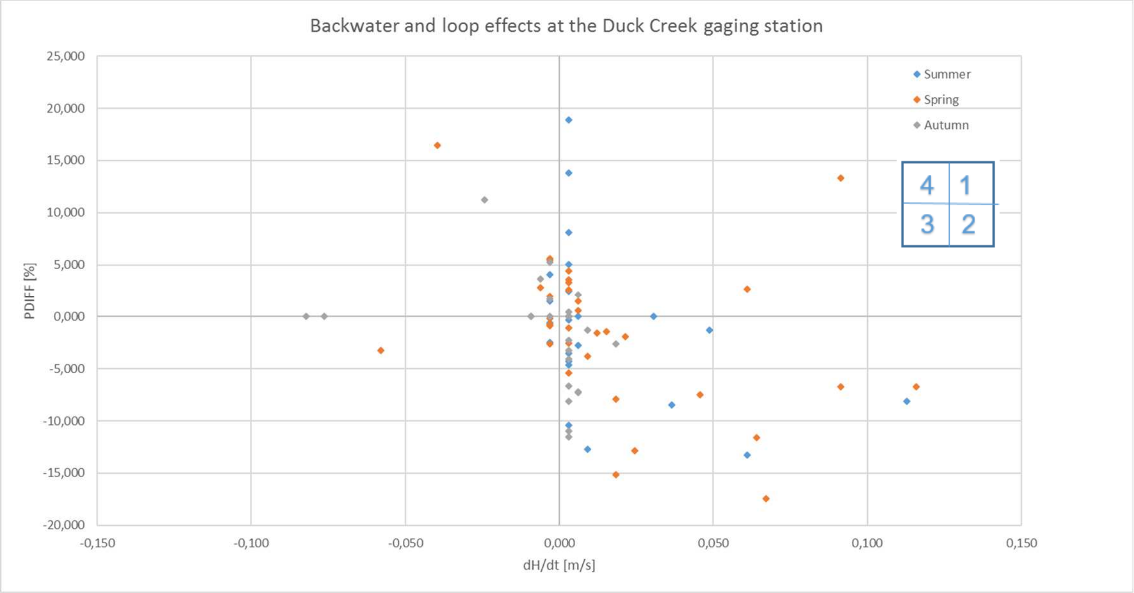


Figure 53 PDIFF – dH/dt diagram of the Duck Creek gaging station

As it can be seen in the results of the backwater and loop effect analysis, visualized in Figure 53, most of the data points are plotted in the second quadrant, which means that some sort of loop effect occurs at this gaging station, due to changes of the riverbed like explained in 2.3.1 and 2.5.2. The difference to the results of the Clear Creek gaging station can be referred to a coarser grained upper layer of the riverbed, which increases the resistance due to erosion and changing of the bed form. The grain size of the riverbed was monitored by the field measurements of the USGS. On the other hand, the riverbed may not need to build up some upper silt or sand layer to gain its original roughness, which become noticeable since very little data points are plotting in the fourth quadrant. Additionally, influences from unsteady flow conditions, like storage effects of the channel and flood plains, may also affect the loop rating. Apart from the loop effects, nearly no backwater effects are occurring at this gaging station, because very little data points are plotting in the first and third quadrant. From the seasonal point of view, most of the larger loop effects are occurring in spring and some in summer. The loop effects in spring can also have the reason explained in 4.1.1, while the loop effects in summer may results from high flood events.

4.1.3 Loop and Backwater effects at the Walnut Creek station

Walnut Creek is a partly regulated and straightened river with a partly meandering course. It flows through urban areas. Therefore, some regulating hydraulic structures are positioned. The upper layer of the riverbed consists most of the times of sand and very seldom of gravel, due to erosion processes. This can be taken from the field measurements at the website of the USGS (www.waterdata.usgs.gov).

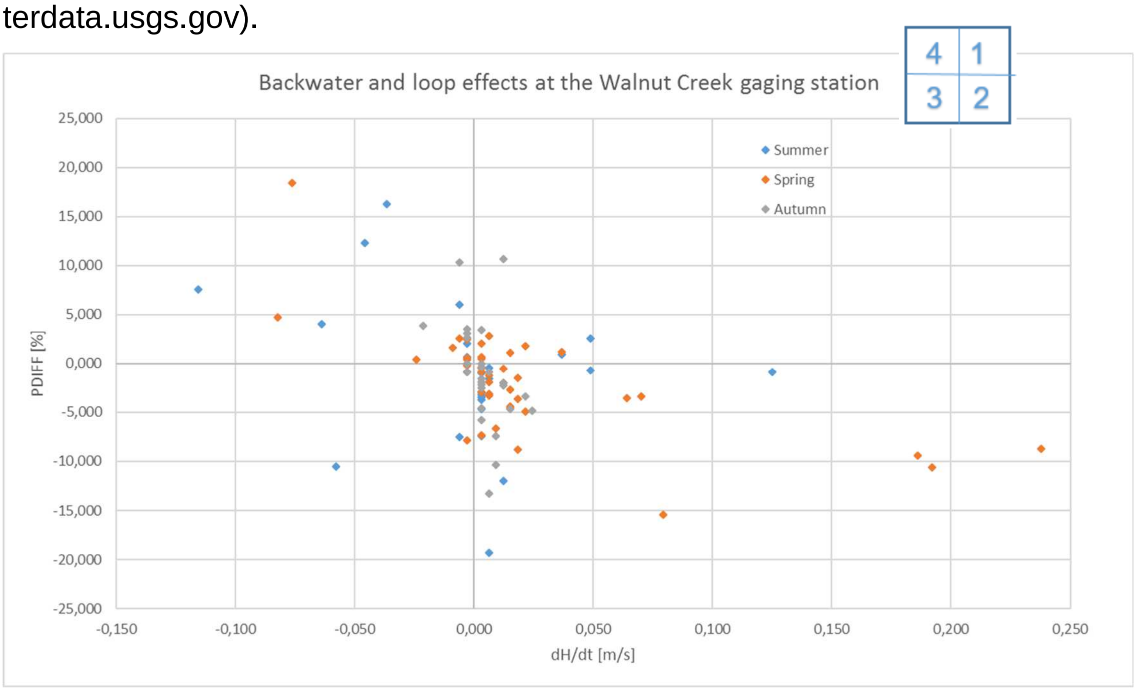


Figure 54 PDIFF – dH/dt diagram of the Walnut Creek gaging station

Figure 54 shows the results of the backwater and loop analysis of the Walnut Creek station. The most data points are plotting in the second and fourth quadrant of the diagram, which indicates the occurrence of loop effects. Just like at the other stations, such effects can occur due to erosion and changing of the riverbed like explained in 2.3.1 and 2.5.2. Because the upper layer of the riverbed at the Walnut Creek gaging station consists only of easy erodible sand, the form of the riverbed can be easily changed. This property allows significant changes in the river roughness, if flood waves are propagating through the channel. Additionally, influences from unsteady flow conditions, like storage effects of the channel and flood plains, may also affect the loop rating. As very little data points have plotted into the first and third quadrant, no or at least little backwater effects occur at this gaging station. By differentiating between seasons, the likelihood of the occurrence of loop effects is high in spring and, although less high, in summer.

4.2 Relationship between Manning factors and rating curve adjustments for steady flow conditions

Due to the elimination and filtering of data sets, which could be influences by loop and backwater effects, the Manning´s roughness coefficients at the different gaging stations should theoretically be higher in summer and early autumn than in spring. As the determination of physical properties of rivers is a sensible topic, especially when it comes to the roughness coefficients, the results may not be completely accurate, but allow to gain an idea of their behavior. The following chapter deals with the changing roughness coefficients with respect to the shifts in the corresponding rating curves. This relationship is determined separately for every year, because otherwise no meaningful results could be gained. The reason therefore is that rivers are changing with time which causes high scatterings. As it was mentioned in 3.2.3, only datasets which has been recorded at steady flow conditions are used. In order to filter the data due to steady flow conditions, every measurement was evaluated due to its position on the hydrograph (rising/falling limb). This means that for some periods, little or no measurements are available for performing the analysis. However, for most years the available data are sufficient and an interpretable analysis can be performed.

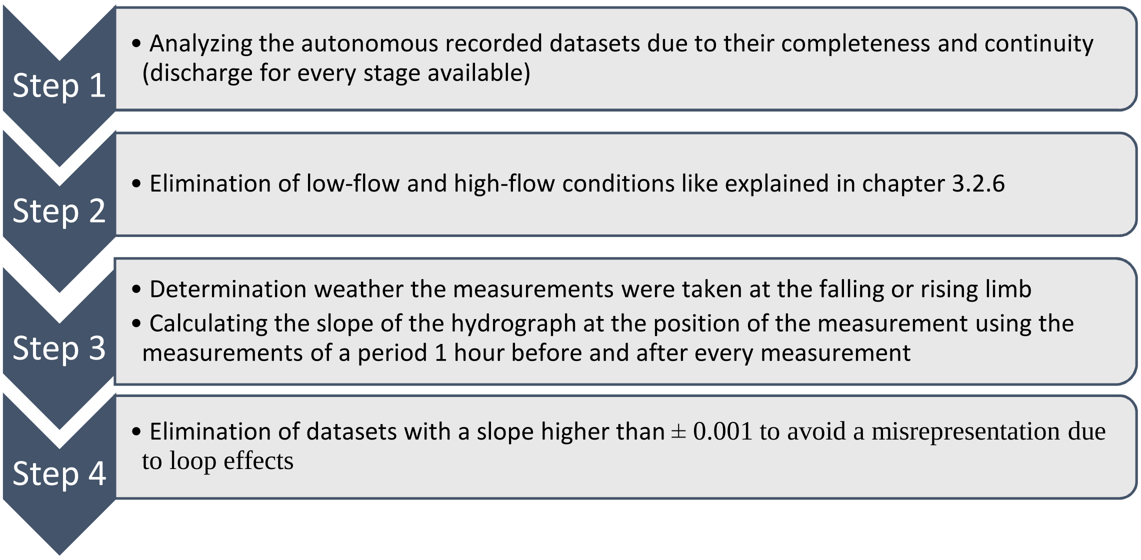
The results of the chapter 4.1 are helping to evaluate the analysis performed at this chapter. The knowledge about the behavior according to loop effects of every station is necessary, because the field measurements, which are used to create the shifts of the rating curve, are mainly made at unsteady conditions. Filtering out the periods where the shifts have been created using field measurements which was made at unsteady conditions, is not possible. Otherwise very little periods would remain for the analysis and this makes it difficult to gain proper results.

For the three gaging stations, overall 72 years of autonomous data recording and field measurements are available which, if interpreted, would go beyond the scope of this work. To gain proper results, some years were selected which represents, if they are existing, the seasonal influences and the limitations as well as unexpected results of the analysis. The following results are aiming on the low- and mid-flow part of the rating curve since the high-flow part suffers from high deviations and often cannot be properly described. Further graphical analysis of several water years are provided in the Appendix.

4.2.1 Overview of the processing steps performed on the datasets

To gain meaningful results, the autonomous recorded data must be edited. These processing steps are now listed to gain an overview about what data is used for the analysis and which has been sorted out. Furthermore, by providing this overview, the diagrams of the following investigation, starting at chapter 4.2.2, should be more comprehensible.

As mentioned before, the available data from the USGS consists of autonomous recorded data and field measurements. The main processing steps are now displayed in the flow chart below.



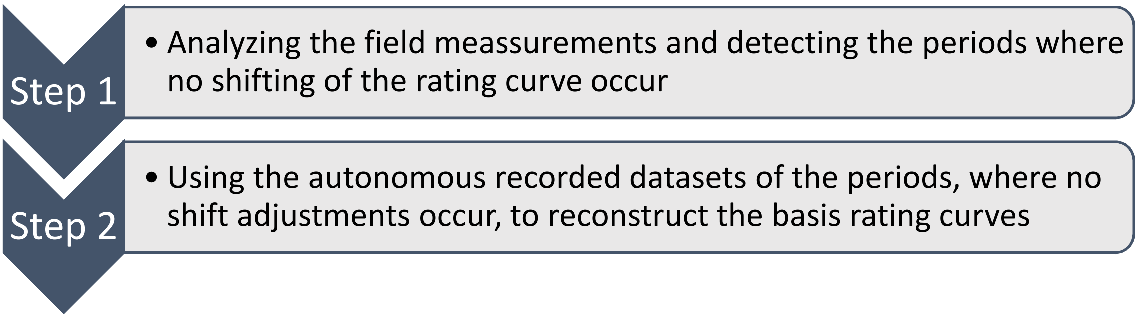
Step 1
- Analyzing the autonomous recorded datasets due to their completeness and continuity (discharge for every stage available)

Step 2
- Elimination of low-flow and high-flow conditions like explained in chapter 3.2.6

Step 3
- Determination weather the measurements were taken at the falling or rising limb
- Calculating the slope of the hydrograph at the position of the measurement using the measurements of a period 1 hour before and after every measurement

Step 4
- Elimination of datasets with a slope higher than ± 0.001 to avoid a misrepresentation due to loop effects

With these computation steps, the raw data is now able to be analyzed. To gain the final results, these datasets must be compared to the corresponding non-shifted basis rating curve. Since these basis rating curves are not available, they have to be created. The steps which have been performed to achieve this are displayed in the following flow chart.



Step 1

- Analyzing the field meassurements and detecting the periods where no shifting of the rating curve occur

Step 2

- Using the autonomous recorded datasets of the periods, where no shift adjustments occur, to reconstruct the basis rating curves

Now the modified autonomous recorded datasets and the corresponding reconstructed rating curves can be displayed and analyzed which is made in the following chapters.

4.2.2 Rating curve and Manning factors at the Clear Creek gaging station

At the Clear Creek gaging station, overall nine base rating curves have been valid since 1993. This indicates a high mobile bed which makes it harder to extract the plane influence on the rating curves due to the vegetation. Nevertheless, some trends and peculiarities can be observed for this gaging station.

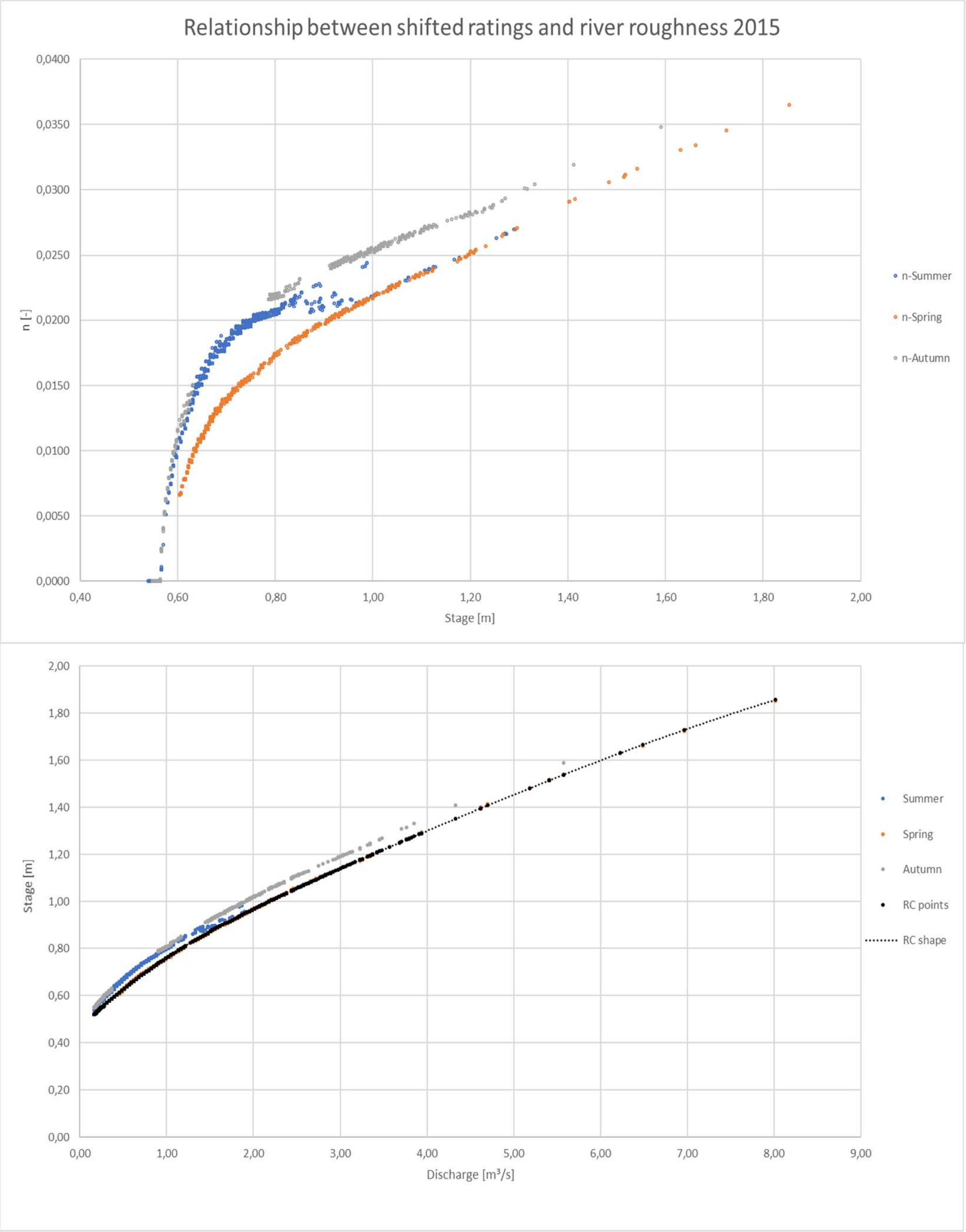


Figure 55 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Clear Creek gaging station in 2015*

Table 2 *Shift adjustments and flow state at Clear Creek station in 2015*

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
03.12.2015 11:02	autumn	9	-0,052	1,31	3,60	-0,005	falling limb
19.10.2015 08:00	autumn	9	-0,052	0,56	0,18	-0,044	falling limb
09.09.2015 11:33	summer	9	-0,043	0,59	0,27	-0,083	falling limb
21.07.2015 17:07	summer	9	-0,043	0,78	0,91	-0,071	falling limb
16.06.2015 15:20	spring	9	0,000	1,62	6,40	-0,019	falling limb
12.06.2015 17:36	spring	9	0,000	4,20	45,59	0,020	rising limb
12.06.2015 16:24	spring	9	0,000	4,24	48,42	0,051	rising limb
10.04.2015 08:15	spring	9	0,000	0,64	0,54	0,074	rising limb

In Figure 55 the analysis of the Manning values, with respect to shifts in rating curves, at the Clear Creek for 2015 is given. The analysis of the year 2015 leads to results which would be desirable for every year, because the seasonal influence on the Manning factors can be clearly observed. However, one problem can be seen in the analysis of this year. The Manning values at lower stages are too small. This may occur out of errors in the determination of the geometry. The roughness coefficients of the different seasons are separated to each other. The rating curve is shifted to the left in summer and autumn, which can be taken from Table 2. The data points in spring mainly fits to the base rating curve number nine, which means that no, or at least very little shift adjustments has been necessary for this season. At the beginning of summer, a minus shift has been performed on the rating curve and stayed constant over the whole summer. Additionally, the stage to Manning diagram also shows that the roughness values in spring are significantly smaller than the values in summer. At the end of the summer, the rating curve is shifted a bit more to the left side, but stays nearly the same. This change in the rating curve can also be observed in the Stage-Manning diagram, where the roughness coefficients in summer are slightly higher. Finally, the roughness coefficients and shifting of the rating curve stays constant until the end of the year. This may indicate a permanent change of the riverbed or vegetation, which does not lose their roughness-increasing influence until winter.

2007 is the next year which will be analyzed. At this year, apparently large deviations have occurred in summer like it is shown in Figure 56. In spring, some slight plus shifts has occurred, which may result in a rearrangement of the riverbed. The deviations in summer can be partly linked to the fact that, as shown in Table 3, the measurements have been taken at the falling limb of the hydrograph. This means that the field measurement could suffer from some loop effect, as investigated in 4.1.1. Therefore, the discharge capacity could be reduced due to bed formation after high-flow conditions. Nevertheless, compared to measurements in spring, the roughness coefficients tend to be higher in summer, even if the effect of a possible loop rating is considered. In autumn, the Manning factors decrease to values which can be compared to the values in spring.

Table 3 Shift adjustments and flow state at Clear Creek station in 2006

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
05.11.2007 08:50	autumn	5	0,000	1,03	1,23	-0,031	falling limb
18.10.2007 13:09	autumn	5	0,000	3,04	21,61	-0,024	falling limb
02.10.2007 08:55	autumn	5	0,030	0,82	0,50	-0,017	falling limb
20.08.2007 08:56	summer	5	0,000	2,56	13,88	-0,127	falling limb
20.08.2007 08:30	summer	5	-0,140	2,60	13,28	-0,217	falling limb
08.08.2007 13:40	summer	5	0,000	1,12	1,53	-0,087	falling limb
26.06.2007 13:40	summer	5	-0,094	1,58	3,88	-0,080	falling limb
23.06.2007 11:26	summer	5	0,000	4,54	86,37	0,051	rising limb
22.06.2007 13:12	summer	5	0,000	2,51	14,24	0,076	rising limb
15.05.2007 08:50	spring	5	0,040	1,16	1,95	0,083	rising limb
25.04.2007 10:25	spring	5	0,122	2,00	10,14	0,096	rising limb
10.04.2007 10:50	spring	5	0,000	1,11	1,52	0,080	rising limb

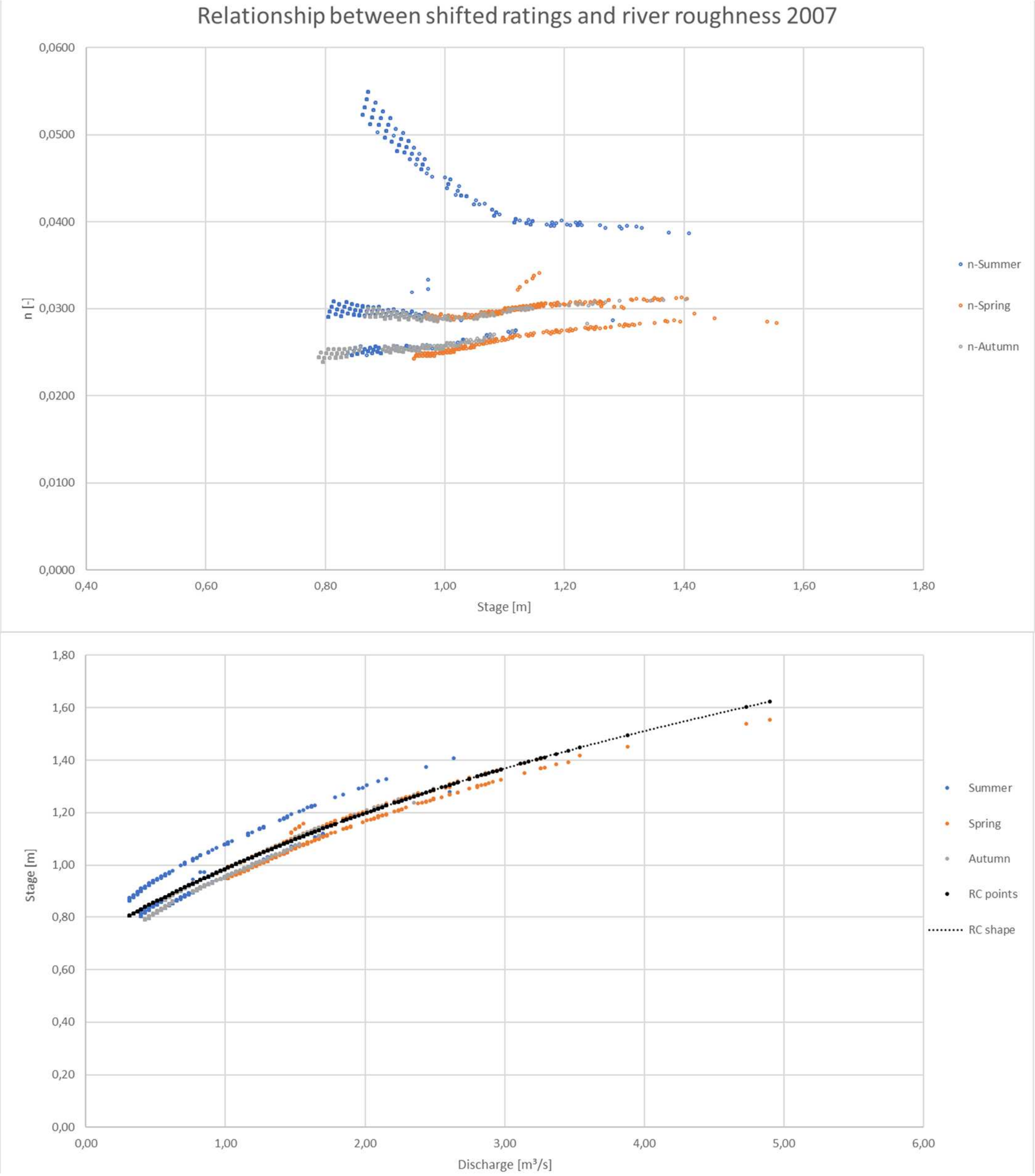


Figure 56 Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Clear Creek gaging station in 2007

The seasonal changes are not the same for every year due to different flood events and different density of the vegetation. Because of this reason, the data of some years leads to opposite results than in most other years. This is the case in 1997 and a few other years, where the roughness coefficients in summer are significantly lower than for spring and autumn. None of the field measurements have been taken at completely steady conditions. Nevertheless, no highly unsteady conditions occurred during the measurements, as listed in Table 4, so that loop effects may not affect the shifts of the rating curve. As shown in Figure 57, the distribution of the roughness coefficients is different from Figure 55 and Figure 56. The rating curve is shifted to the right and therefore the discharge capacity in spring and autumn is lower than in summer. This should, theoretically, be the opposite. Finding reasons for this unusual behavior of the river is difficult without further information, but as all the field measurements has been performed at very low discharge, no influence of bank vegetation has been taken in consideration within the analysis. Due to this, all autonomous recorded stage data may suffer from a failure, caused by shifting the rating curve with respect only to such low-flow conditions. As a result of shifts at low-flow conditions, the point of zero flow is also shifted.

Table 4 Shift adjustments and flow state at Clear Creek station in 1997

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
17.11.1997	autumn	2	0,067	1,04	0,55	0,003	rising limb
07.10.1997	autumn	2	0,055	0,84	0,04	0,004	rising limb
28.08.1997	summer	2	0,131	0,81	0,07	0,003	rising limb
14.07.1997	summer	2	0,091	0,96	0,32	0,002	rising limb
03.06.1997	spring	2	0,067	1,17	1,16	0,000	steady

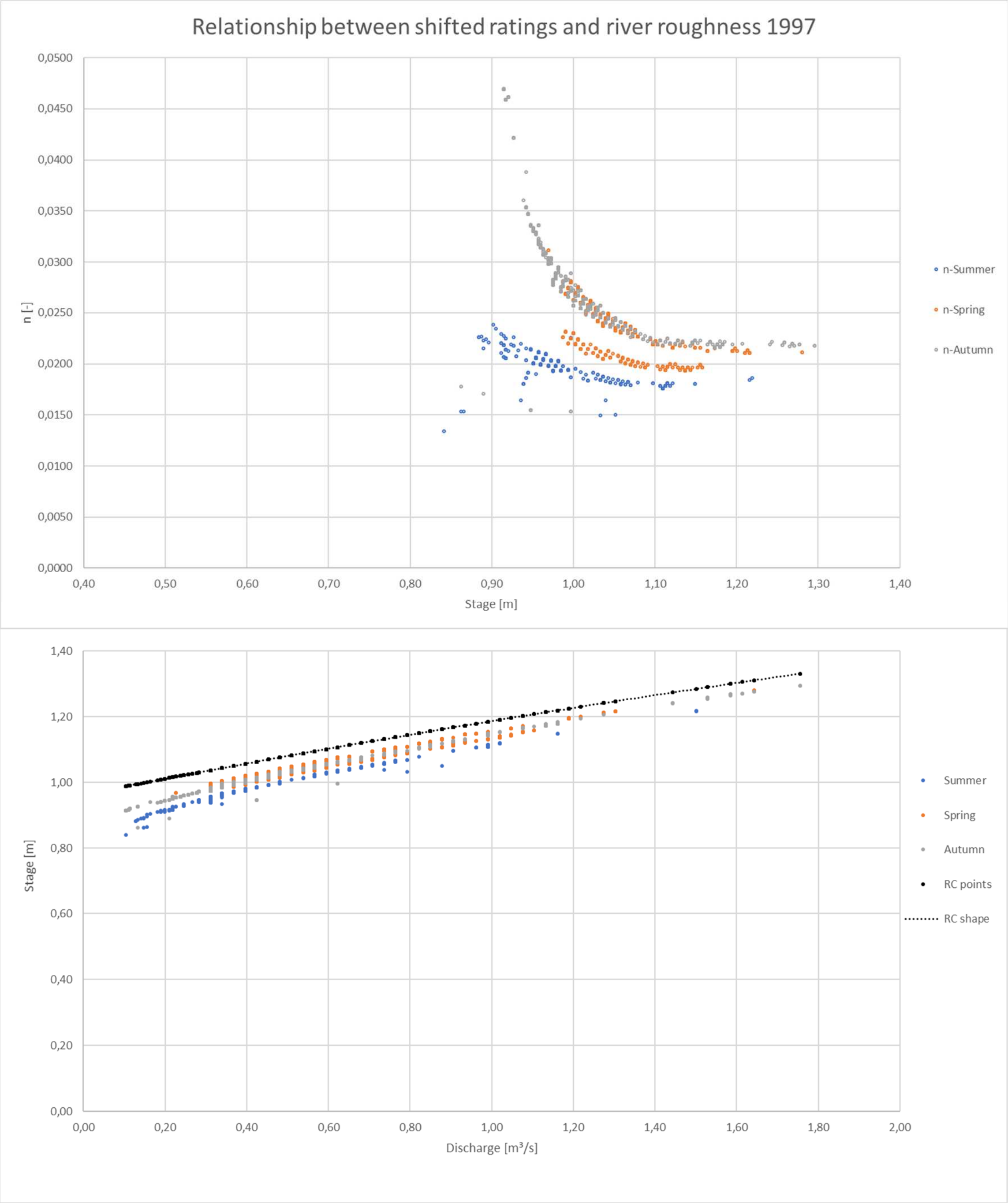


Figure 57 Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Clear Creek gaging station in 1997

4.2.3 Rating curve and Manning factors at the Duck Creek gaging station

The next station which is analyzed is the Duck Creek gaging station. After filtering the data due to meanings of steady flow conditions and valid discharge, about 76,000 datasets are available for the analysis.

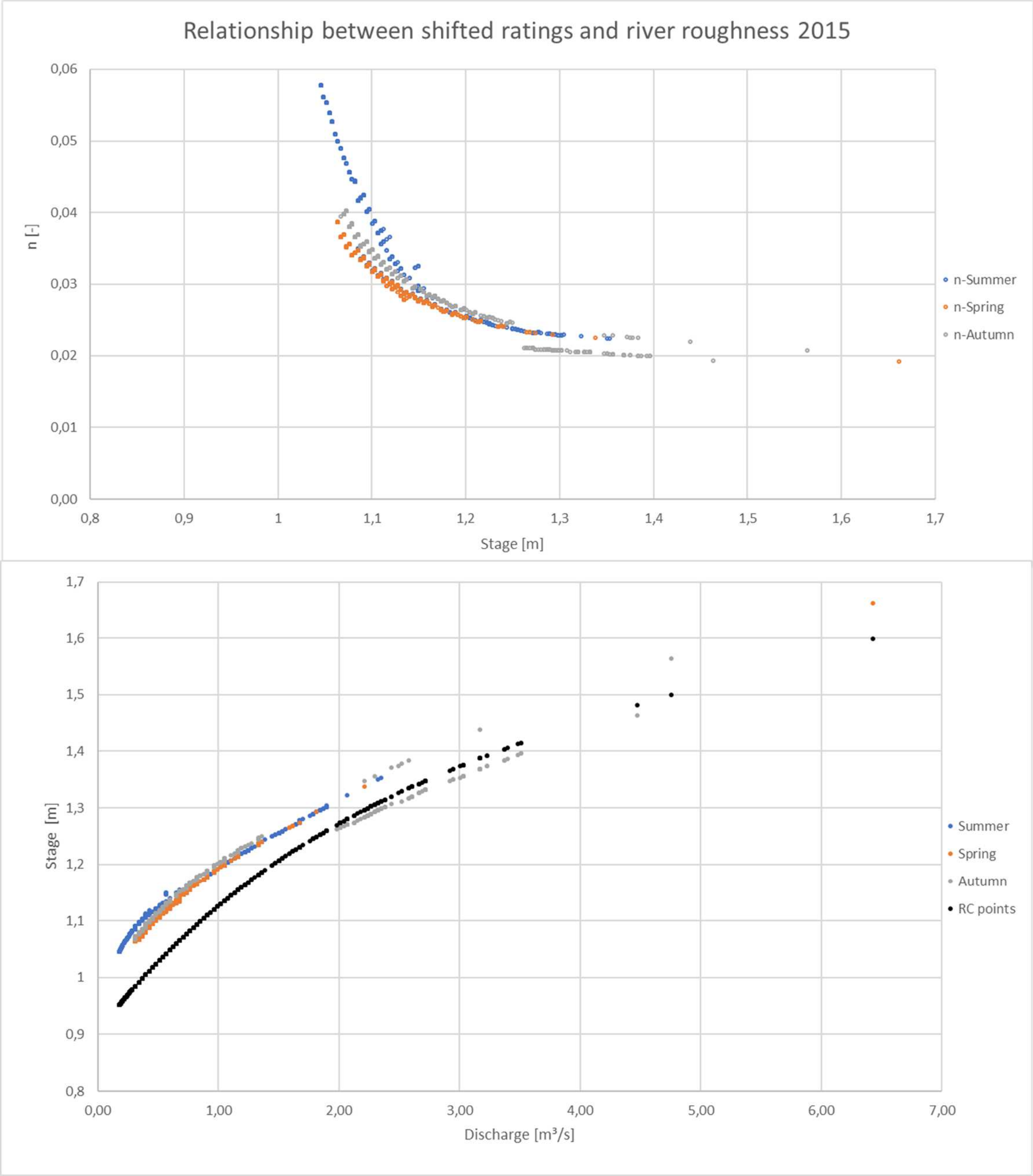


Figure 58 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Duck Creek gaging station in 2015*

The results which have been developed using those filtered data are visualized in Figure 58. In this diagram, the roughness coefficients plotted like it would be expected. Since the deviations to the rating curve did not change in spring, but the slope at which the measurement was taken was not the same, long term changes of the riverbed may occur. In the middle of summer, the roughness coefficients start to rise, although the slope of the hydrograph was nearly the same for both field measurements. The field measurements are shown in Table 5. This behavior indicates changes of the roughness due to vegetation. The Manning factors stays at the magnitude of summer until a strong reduction happens around December.

Table 5 Shift adjustments and flow state at Duck Creek station in 2015

Date and Time	Season	Rating Curve	Horiz. Shift adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
14.12.2015 11:11	autumn	3	0,073	2,09	19,68	0,001	rising limb
05.11.2015 13:49	autumn	3	-0,058	1,17	0,80	0,010	rising limb
11.09.2015 11:58	summer	3	-0,076	1,11	0,38	0,017	rising limb
24.07.2015 15:49	summer	3	-0,049	1,21	1,16	0,018	rising limb
18.06.2015 16:16	spring	3	-0,049	1,48	3,99	0,023	rising limb
08.04.2015 16:42	spring	3	-0,049	1,10	0,48	0,002	rising limb

The results for the year 2015 are satisfying but not every year leads to such good results. For some years, at the Duck Creek gaging station, roughness coefficients do not change much for different seasons. In 2000 such effects occur. The shift adjustment of the rating curve was not changed during the whole year. This circumstance may indicate, that the physical properties of the riverbed did not change at this gaging station. As all field measurements have been made at nearly steady flow conditions, the shift adjustments can be seen as accurate. Although the change of roughness at higher stages due to vegetation could not be considered.

Table 6 Shift adjustments and flow state at Duck Creek station in 2000

Date and Time	Season	Rating Curve	Horiz. Shift adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
22.11.2000 14:00	autumn	1	0,027	1,01	0,20	0,004	rising limb
11.10.2000 11:20	autumn	1	0,027	1,01	0,22	-0,002	falling limb
28.08.2000 10:25	summer	1	0,027	1,19	1,15	-0,002	falling limb
18.07.2000 11:25	summer	1	0,027	1,13	0,77	-0,003	falling limb
07.06.2000 06:40	spring	1	0,027	1,25	1,76	0,000	steady
25.04.2000 10:55	spring	1	0,027	1,34	2,52	0,002	rising limb

Just like the shifting of the rating curve has not changes over the year, the roughness coefficients are also the same for different seasons, as displayed in Figure 59. Such effects could be observed for some years.

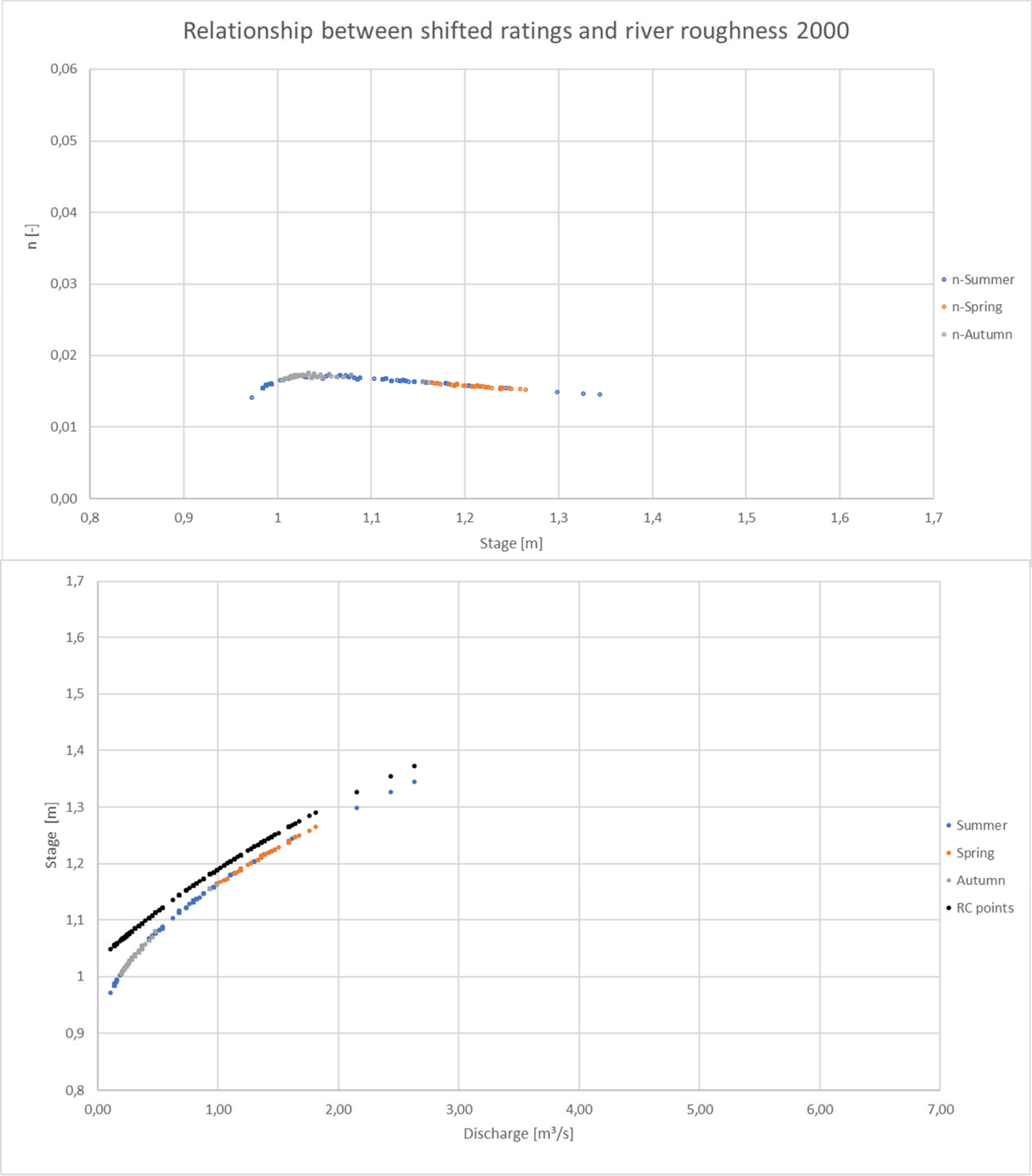


Figure 59 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Duck Creek gaging station in 2000*

Apart from the expected behavior in 2015 and the not definable behavior in 2000, another unexpected development of the Manning values occurs for some years. In spring 2002, a negative shift of about 0.04 m appears which affects the Manning coefficients significantly, like it is shown in Figure 60. As in Table 7 apparent, the field measurement was made at the rising limb of a flood wave. This shift may results from temporary changes of the riverbed.

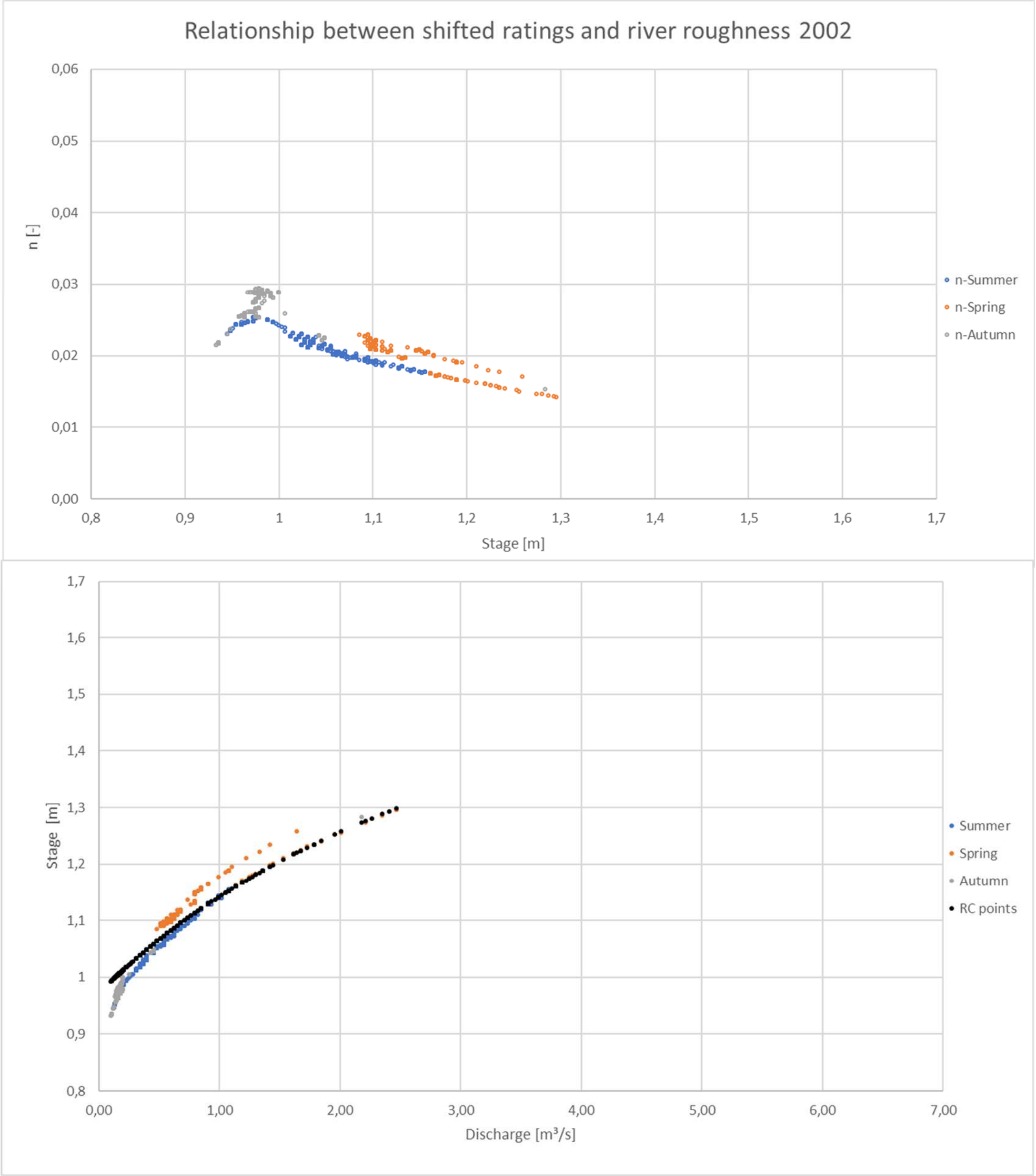


Figure 60 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Duck Creek gaging station in 2002*

Table 7 *Shift adjustments and flow state at Duck Creek station in 2002*

Date and Time	Season	Rating Curve	Horiz. Shift adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
18.12.2002 09:55	autumn	2	0,000	1,308	2,676	0,000	steady
31.10.2002 11:50	autumn	2	-0,024	0,975	0,147	-0,382	falling limb
17.09.2002 14:56	summer	2	-0,012	0,954	0,134	-0,326	falling limb
13.08.2002 15:30	summer	2	0,006	1,100	0,770	-0,244	falling limb
01.07.2002 10:19	summer	2	0,000	1,082	0,648	-0,138	falling limb
04.06.2002 12:00	spring	2	0,000	4,980	244,940	-0,004	falling limb
21.05.2002 11:13	spring	2	0,000	1,247	1,948	0,100	rising limb
08.04.2002 10:40	spring	2	-0,037	1,372	2,803	0,182	rising limb

4.2.4 Rating curve and Manning factors at the Walnut Creek gaging station

The Walnut Creek gaging station is the last one which has been analyzed. The available datasets are reduced to 47,000 by filtering due to steady flow state and discharge limitations. At this gaging station loop effects and, due to six different valid rating curves, mobile bed effects are occurring.

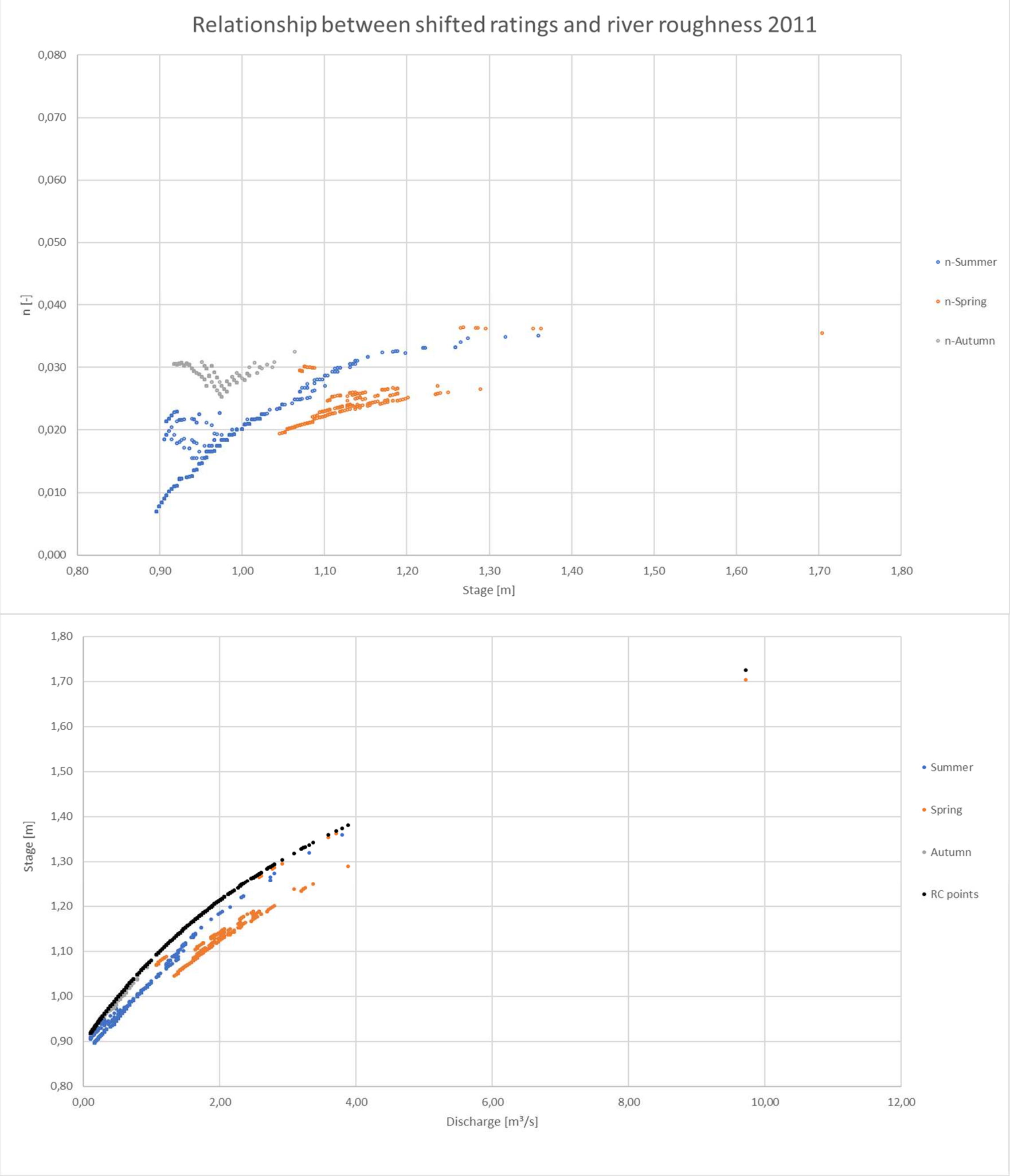


Figure 61 Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Walnut Creek gaging station in 2011

2011 is the first year which should be analyzed here. In Figure 61 the results are plotted like it would be expected due to seasonal changes. The roughness coefficients are low in spring and higher in summer and autumn which can be an indicator of vegetational influence on the physical properties. Nevertheless, some field measurements have been made during strongly unsteady conditions, which is shown in Table 8. This means that the shift adjustments are influenced by the occurrence of scour and fill, or other changes of the riverbed, especially at the end of spring.

Table 8 Shift adjustments and flow state at Walnut Creek station in 2011

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
19.12.2011 16:15	autumn	4	0,015	0,97	0,34	0,00	steady
15.11.2011 15:10	autumn	4	0,018	0,95	0,26	-0,08	falling limb
05.10.2011 11:37	autumn	4	0,018	0,90	0,05	0,00	steady
09.09.2011 12:27	summer	4	0,030	0,92	0,15	-0,04	falling limb
14.07.2011 14:27	summer	4	0,055	1,07	1,29	-0,12	falling limb
10.06.2011 09:39	spring	4	0,265	3,20	65,98	22,34	rising limb
09.06.2011 11:04	spring	4	0,064	1,67	9,71	414,83	rising limb
25.04.2011 10:09	spring	4	0,085	1,17	2,47	-0,28	falling limb

Although some of the field measurements in 2011 where made at unsteady conditions, sufficient data is available and some trends can be observed. For other years, only few suitable datasets exists. An example for this is the year 2004, where it is hard to observe meaningful trends. In Figure 62, the results of the analysis of the year 2004 are given and it can be observed that some discharge ranges are not sufficiently described. For example, in spring, nearly no usable datasets are available, which would describe the low-flow part of the rating curve. Nevertheless, some trends can be extracted for 2004, which also indicates the same seasonal changes as in 2011, but with different magnitudes. In spring two field measurements have been made during flood events which distort the shift adjustments for this period, just like it is shown in Table 9. However, the river roughness seems to be higher in summer and autumn than in spring, even if some deviations concerning the field measurements have occurred.

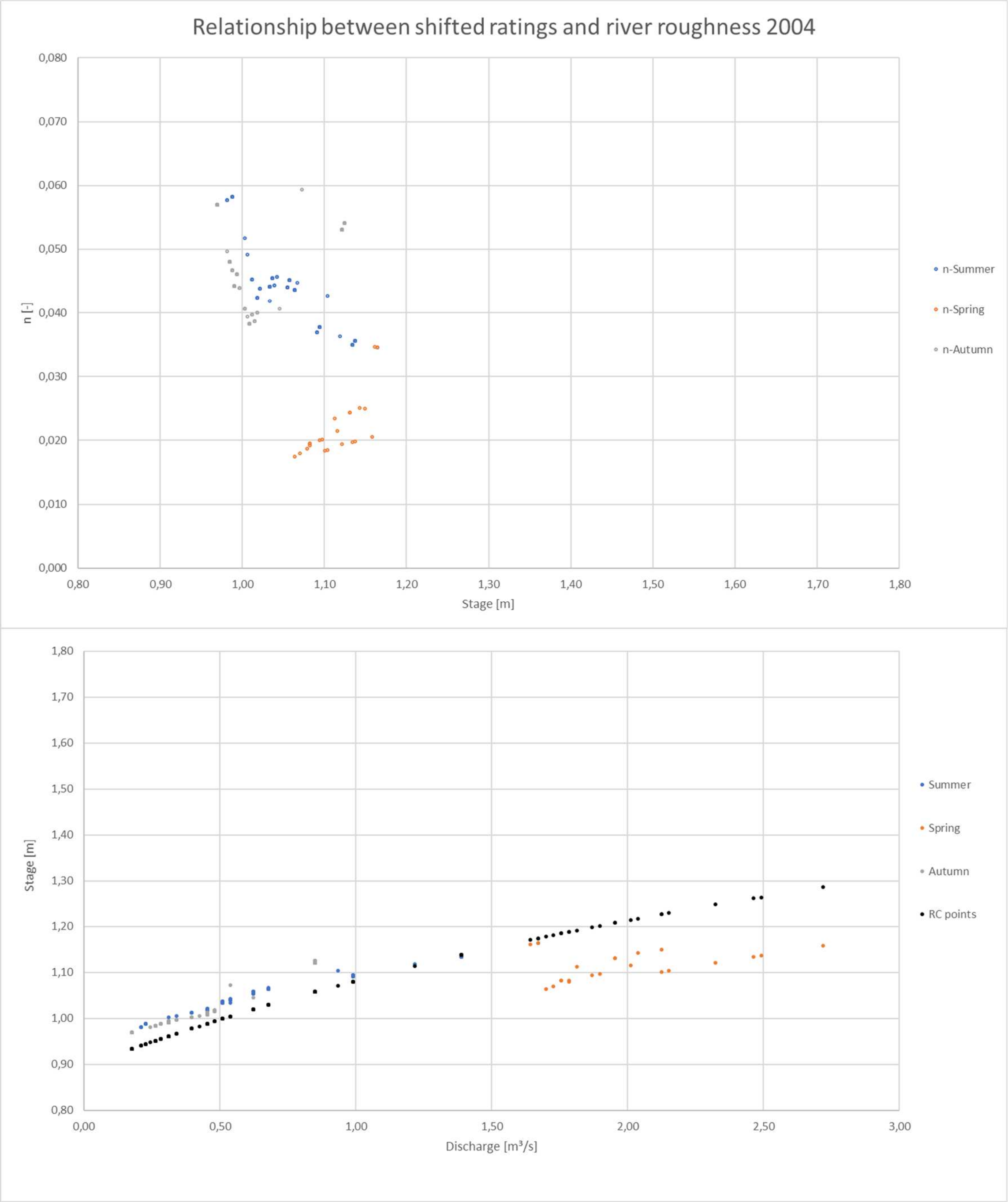


Figure 62 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Walnut Creek gaging station in 2002*

Table 9 Shift adjustments and flow state at Walnut Creek station in 2004

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
20.12.2004 15:40	autumn	4	-0,030	0,98	0,16	-0,02	falling limb
17.11.2004 15:45	autumn	4	-0,015	0,97	0,17	0,00	steady
05.10.2004 11:22	autumn	4	-0,070	0,98	0,05	0,01	rising limb
05.10.2004 12:05	autumn	4	-0,070	0,99	0,04	0,00	steady
31.08.2004 16:05	summer	4	-0,021	0,98	0,19	-0,11	falling limb
19.07.2004 12:45	summer	4	-0,027	1,06	0,67	0,00	steady
08.06.2004 12:20	spring	4	0,021	1,19	2,00	-0,05	falling limb
25.05.2004 07:40	spring	4	-0,070	3,91	83,25	76,07	rising limb
25.05.2004 08:10	spring	4	-0,070	3,82	79,29	65,47	rising limb
21.04.2004 13:35	spring	4	0,119	1,62	9,77	6,43	rising limb

Even if the results for 2011 and 2004 are kind of different, the seasonal changes can be extracted and their characteristics are as one would theoretically expect. For some years, however, the results are the opposite of what would be expected. One of them is the year 1995, where the river roughness tends to be higher in spring than in summer and autumn, like it is shown in Figure 63. One shift adjustment was made by using a field measurement which was taken at highly unsteady conditions. This could be the reason for the high Manning factors in spring, as shown in Table 10 and Figure 63. The field measurements in summer have been made at the falling limb of the hydrograph which may be the reason for the low roughness coefficients in the summer.

Table 10 Shift adjustments and flow state at Walnut Creek station in 1995

Date and Time	Season	Rating Curve	Horiz. Shift Adj. [m]	Stage [m]	Discharge [m³/s]	Slope	Flow State
13.12.1995 14:30	autumn	1	-0,094	1,10	0,17	0,00	steady
02.11.1995 10:15	autumn	1	-0,073	1,26	1,53	0,00	steady
20.09.1995 16:20	summer	1	0,006	1,01	0,25	-0,35	falling limb
03.08.1995 08:00	summer	1	0,024	1,14	1,36	-0,10	falling limb
22.06.1995 16:00	summer	1	0,000	1,13	1,05	0,00	steady
16.05.1995 16:50	spring	1	0,009	1,56	6,20	9,43	rising limb
05.04.1995 17:45	spring	1	-0,034	1,10	0,54	0,58	rising limb

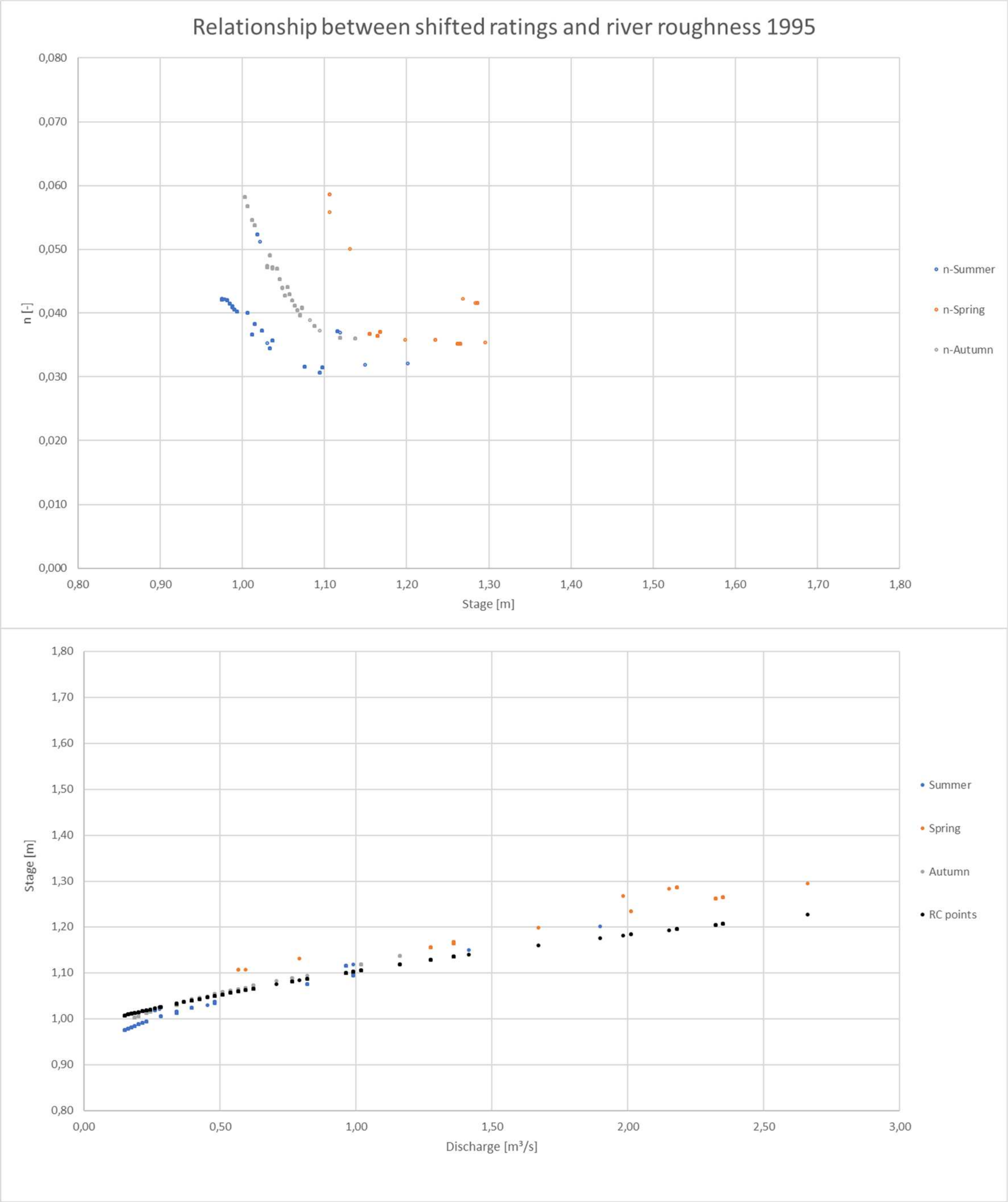


Figure 63 *Stage-Manning value relationship (upper diagram) and stage-discharge relationship (lower diagram) at the Walnut Creek gaging station in 1995*

5. Comparison of the gaging stations

The three gaging stations have now been analyzed due to loop effects, backwater and vegetational influences. With respect to these topics, all three gaging stations have shown different behaviors. Some comparisons have already been made during the analysis in chapter 4. This chapter gives an overview of the differences and similarities which occurred during the analysis.

For all three gaging stations, seasonal differences were detected. For many investigated years, the Manning factors have been higher in summer and the early autumn, than in spring. However, deviations from the expected results have also occurred. A quantitative comparison of the Manning factors between the gaging stations is not reasonable, because for some periods, the approximation of the geometric parameters is not as accurate as for the other periods which leads to unrealistic Manning factors. Nevertheless, the shifts in the rating curves can be detected and evaluated, although sometimes only qualitative. No general relationship between the three stations can be formulated since every year leads to different results that are hard to compare.

The highest loop effects are occurring at the Clear Creek gaging station. Although loop effects also occur for the other gaging station, the amount and magnitude of loop ratings are lower. For the Duck Creek gaging station, some additional behavior has been detected. While the loop ratings for the Clear Creek and Walnut Creek gaging station are appearing at the rising and falling limb of the hydrograph, the Duck Creek gaging station is only influenced at the rising limb. The reason might be, that the riverbed usually contains of coarse grained material. Nearly no large backwater effects appear at all stations, therefore no downstream structures or properties influence the stage measurement.

The number of previous rating curves is also a possibility to compare different stations. A large number of previous rating curves indicates a higher bed mobility and leads to discontinuities in the measurement results. Such stations must be observed carefully to avoid incorrect measurements. At the Clear Creek gaging station, nine rating curves has been valid since 1993, which is the highest number of all three stations, followed by the Walnut Creek station with 6 valid curves. For the gaging station at Duck Creek, only three rating curves had been valid which means that the riverbed is very stable and not easily erodible.

Concerning the flow conditions, discontinuities can cause fluctuations in stage measurements and characterize the gaging station. Such flow conditions have been filtered out of the available data, which influences the results of the investigation due to less data. For the Clear Creek and Duck Creek station, about one third of the existing data was filtered out. Two third of the data remain for further investigation, which is enough for a continuous analysis of the data. The Walnut Creek station suffers from higher fluctuations than the other two stations. This means that half of the stage data was filtered out. The analysis could be performed satisfactorily but for some years, too little data sets has been available to gain proper results.

6. Conclusion

River rating is a complex topic, especially when it comes to the influence of the vegetation. To get the plane influence of the vegetation, all other disturbing factors must be eliminated. In order to do this, detailed informations about the site and the surrounding area should be given, especially for the determination of the Manning factors which are very sensitive to geometric changes.

The determination of the geometry was performed with an approximation that is calibrated by field measurements. This approximation fits for many datasets. However, for some measurement periods these approximation leads to incorrect results which distort the depending Manning factors. This makes no difference for a qualitative investigation, but if quantitative results should be provided, further informations must be available. Nevertheless, the seasonal differences could be observed for many years at different gaging stations.

The greatest problem which occurred during the analysis is, that the field measurements have not been referred to a specific position on the rising or falling limb of the hydrograph. This leads to an error in the field measurements that are used to calibrate the rating curves. The error is caused by not considering loop effects. If a field measurement was made while loop effects occur, the whole rating period, where this field measurement was used for the calibration, suffers from a constant failure. The influence of vegetation can be only determined constantly if the field measurements are made at steady flow conditions. Nevertheless, the influence of vegetation can be observed for many years, since the field measurements have not always been made at highly unsteady flow conditions. To be aware of these loop effects, the analysis of every year must be evaluated by considering the corresponding field measurements.

Further investigations may try to find a way to gain field measurements always at steady state flow. In order to do this, the staff of the USGS should observe the autonomous recorded data, find periods where steady flow conditions occur which fits in the measurement period of the field measurements, and perform the field measurement at this steady conditions. Performing the field measurements always at steady flow conditions at every gaging station in the USA is hard, because especially in summer the probability of rainfall is high which means that the flow conditions are unsteady most of the times. Another possibility would be to create mathematical approaches, which could take care of these loop effects. For developing such approaches, large amounts of field measurements must be performed, to gain the influence of loop effect at different rivers. Furthermore, it should be investigated if this is cost efficient for every river or if such deviations are acceptable.

References

Aigner, D., & Carstensen, D. (2015). *Technische Hydromechanik 2.* Berlin: Beuth Verlag GmbH.

armfield. (2017, July 9). Retrieved from http://discoverarmfield.com/en/products/view/fex26/flumes-and-gauging-weirs

Blöschl, G., Gaal, L., Hall, J., Kiss, A., Komma, J., Nester, T., . . . Viglione, A. (2015, March). Increasing river floods: fiction or reality? *Wiley Interdisciplinary Reviews: Water*, pp. 329-344.

BMLFUW. (2017, August 10). *Hydrologisches Jahrbuch.* Retrieved from https://www.bmlfuw.gv.at

bmvit. (2017, August 16). Retrieved from https://www.bmvit.gv.at

Bollrich, G. (2013). *Technische Hydromechanik 1.* Berlin: Beuth Verlag GmbH.

Camporeale, C., Perucca, E., Ridolfi, L., & Gurnell, A. (2013). Modelling the Interaction between River Morphodynamics and Riparian Vegetation. *Reviews of Geophysics*, 379–414.

chmibrno. (2017, July 9). Retrieved from http://www.chmibrno.org/ENG/pristroje.php

Cudworth, A. G. (1992). *Flood Hydrology Manual.* Denver: United States Goverment Printing Office.

Defina, A., & Bixio, A. C. (2005). Mean turbulent flow in vegetated open channel flow. *WATER RESOURCE RESEARCH*, 1-12.

echo2. (2017, July 18). Retrieved from http://echo2.epfl.ch/VICAIRE/mod_1b/chapt_4/main.htm

ehyd. (2017, August 16). Retrieved from http://ehyd.gv.at/?g_card=pegelaktuell#

Fenton, J. D. (2015, 11 4). *http://johndfenton.com*. Retrieved from Generating stream rating information from data: http://johndfenton.com/Alternative-Hydraulics/08-Generating-stream-rating-information-from-data.pdf

Fetter, C. W. (2001). *Applied Hydrogeology.* New Jersey: Prentice-Hall.

fondriest. (2017, July 9). Retrieved from http://www.fondriest.com/environmental-measurements/equipment/hydrological-measurements/streamflow-measurements/

gallatin. (2017, July 9). Retrieved from http://gallatin.humboldt.edu/~brad/nws/lesson4.html

gallatin. (2017, July 13). Retrieved from http://gallatin.humboldt.edu/~brad/nws/

globalspec. (2017, June 29). Retrieved from http://www.globalspec.com/reference/24097/203279/4-3-SIGNIFICANCE-OF-FROUDE-NUMBER-IN-GRADUALLY-VARIED-FLOW-CALCULATIONS

google.maps. (2017, July 20). Retrieved from https://www.google.at/maps/

Gunawan, B. (2010). *A study of flow structures in a two-stage channel using field data, a physical model and numerical modelling.* University of Birmingham.

Holmes, R. R. (2016). River rating complexity. In G. Constantinescu, M. Garcia, & D. Hanes, *River Flow 2016* (pp. 679 - 686). London: Taylor & Francis Group.

hydrocad. (2017, July 9). Retrieved from https://www.hydrocad.net/weir1.htm

Jirka, G. H. (2007). *Einführung in die Hydromechanik.* Karlsruhe: Universitätsverlag Karlsruhe.

Jirka, G. H., & Lang, C. (2009). *Einführung in die Gerinnehydraulik.* Karlsruhe: Universitätsverlag Karlsruhe.

Kennedy, E. (1984). *Discharge ratings at gaging stations.* Washington: United states goverment printing office.

marinespecies. (2017, October 2). Retrieved from http://marinespecies.org/introduced/wiki/Bedforms_and_roughness

missouri. (2017, July 9). Retrieved from http://extension.missouri.edu/p/AF1009

Morgenschweis, G. (2010). *Hydrometrie: Theorie und Praxis der Durchflussmessung in offenen Gerinnen.* Heidelberg: springer-Verlag Berlin.

Rantz, S. (1982, a). *Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge.* Washington: United states goverment printing office.

Rantz, S. (1982, b). *Measurement and Computation of Streamflow: Volume 2. Computation of Discharge.* Washington: United States Goverment Printing Office.

Schatzl, R. (2017, August 3). Oral information from Dr. Schatzl, goverment of the province Styria. (C. Glanzer, & J. Schneider, Interviewers) *tankonyvtar*. (2017, July 9). Retrieved from http://www.tankonyvtar.hu/en/tartalom/tamop425/0032_hidrologia/ch08s06.html

tedvillaire. (2017, July 20). Retrieved from http://www.tedvillaire.com/road-biking-illinois/quad-cities-challenge/

USGS. (2017, July 17). *www.usgs.gov*. Retrieved from https://www.usgs.gov/

waterdata.usgs. (2017, July 20). Retrieved from https://nwis.waterdata.usgs.gov/nwis/uv

List of Figures

List of Tables

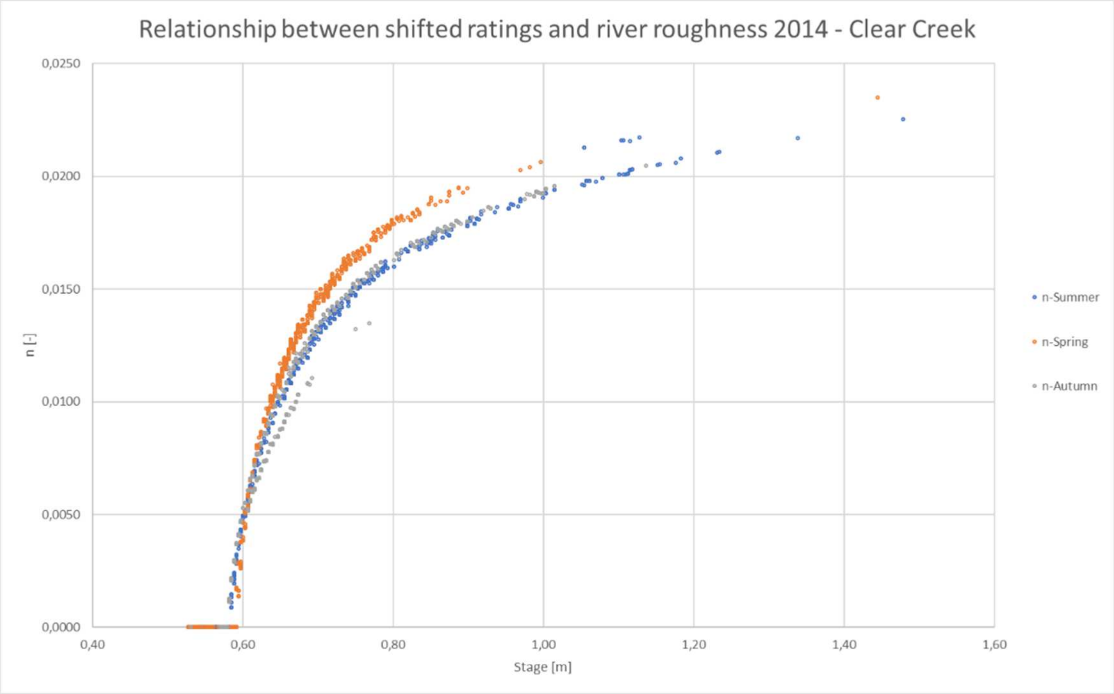
List of Abbreviations

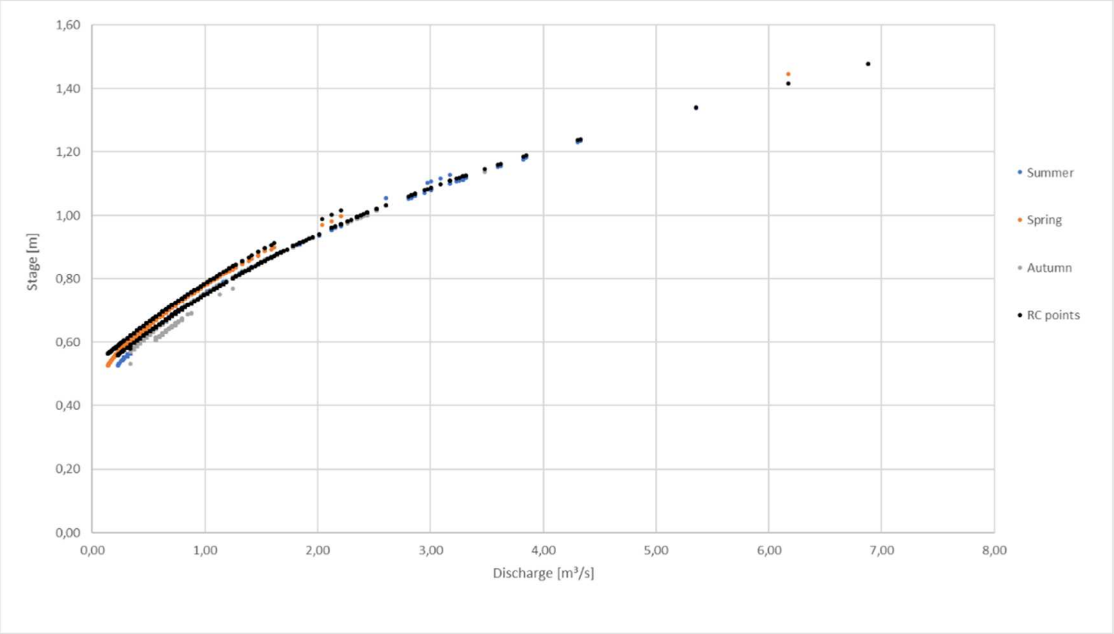
A	Two-dimensional area	[m²]
A_z	Frontal area of vegetation per unit depth	[m]
a	Projected plant area per unit volume	[1/m]
C	Coefficient	[-]
C_D	Drag coefficient	[-]
D	Longitudinal distance	[m]
f_D	Drag force per unit mass	[m/s²]
g	Gravitational acceleration	[m/s²]
H	Water depth	[m]
h_E	Energy height above some reference height	[m]
h_l	Energy height losses	[m]
h_p	Vegetation height	[m]
I_o	Bed slope	[‰]
I_e	Slope of the energy line	[‰]
k_{st}	Strickler-roughness coefficient	$[m^{1/3}/s]$
m	Number of stems per unit area	[1/m²]
n	Manning factor	$[s/m^{1/3}]$
p	*Pressure*	[N/mm²]
Q	Discharge or mass-flow per time unit	[m³/s]
Q_m	*Measured Discharge*	[m³/s]
Q_r	*Rated Discharge due to stage*	[m³/s]
R_h	Hydraulic radius, $R_h = A/U_h$	[m]
t	Time	[s]
τ	Shear stress	[N/m²]
U_h	Wetted circumference	[m]

u	Averaged velocity	[m/s]
v	Velocity	[m/s]
υ	Fluid viscosity	[m²/s]
υ_t	Eddy viscosity	[m²/s]
W	Channel Width	[m]
z	Geodetic height	[m]
λ	Roughness coefficient	[-]
ρ	Density of water	[kg/m³]

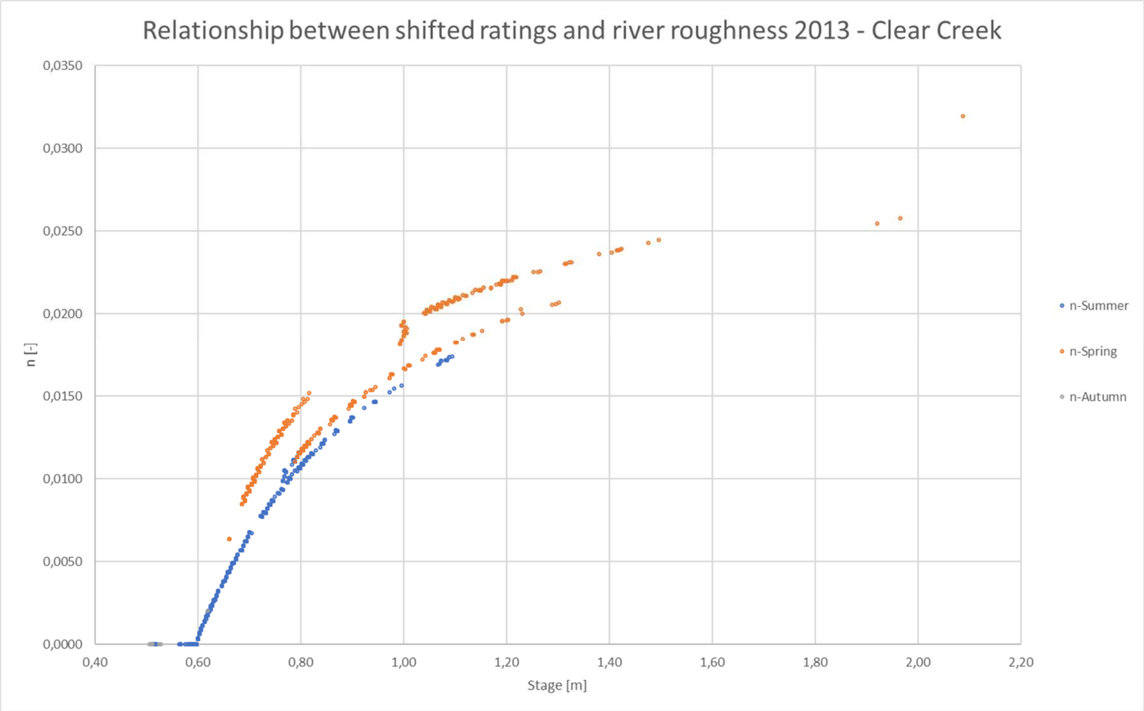
Appendix

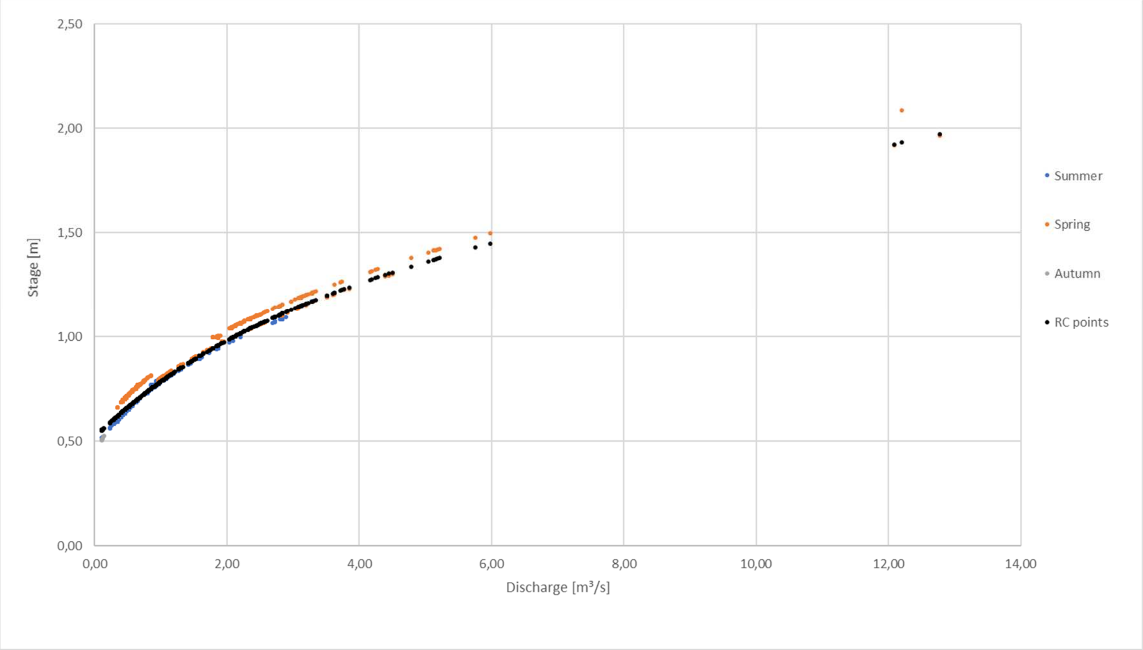
Appendix 1 Analysis of several years at the Clear Creek gaging station



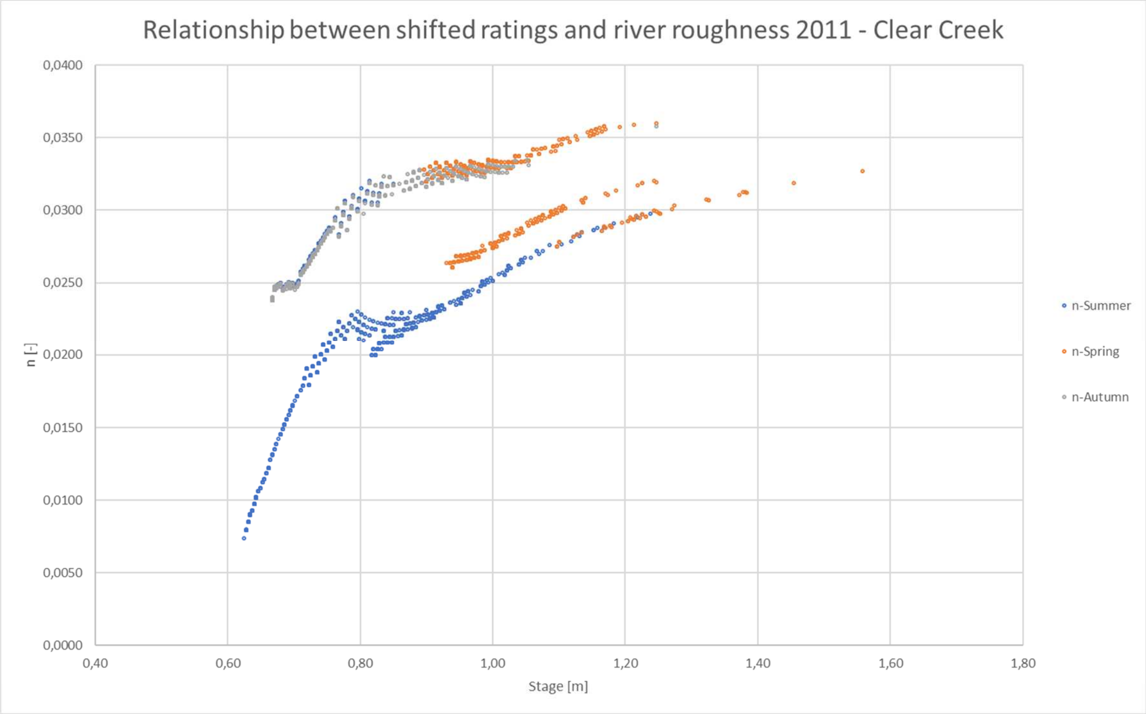


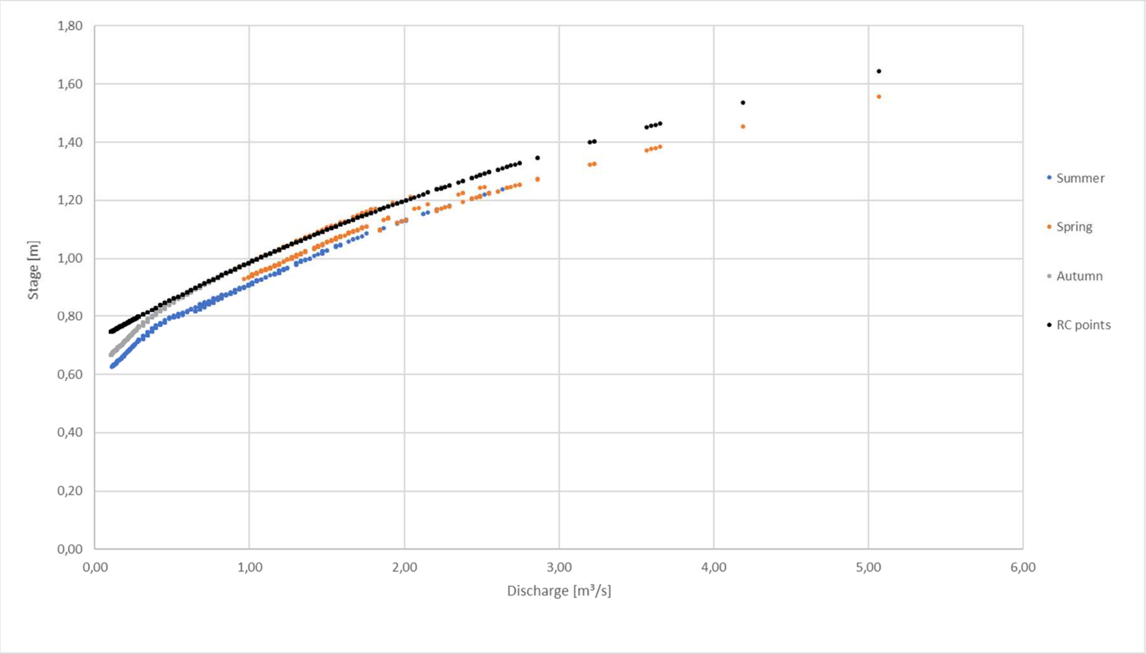
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
15.12.2014 15:52	autumn	0,64	0,66	8	0,265	-0,020	falling limb
05.11.2014 13:32	autumn	0,73	0,86	8	0,232	-0,083	falling limb
17.09.2014 10:04	summer	0,82	1,23	8	0,232	-0,086	falling limb
30.07.2014 08:02	summer	0,75	0,98	8	0,232	-0,127	falling limb
01.07.2014 14:53	summer	4,68	95,99	8	0,000	-0,009	falling limb
01.07.2014 14:16	summer	4,71	108,45	8	0,000	0,059	rising limb
16.06.2014 08:25	spring	0,67	0,55	7	0,204	0,102	rising limb
02.04.2014 08:04	spring	0,55	0,19	7	0,192	0,136	rising limb



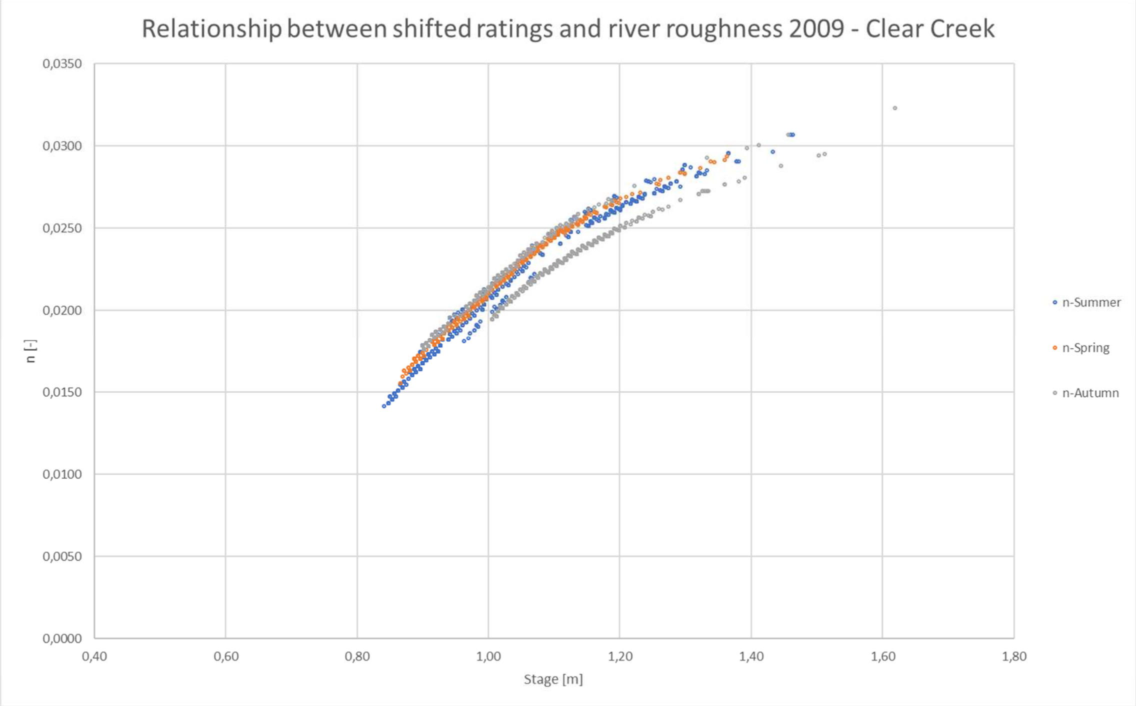


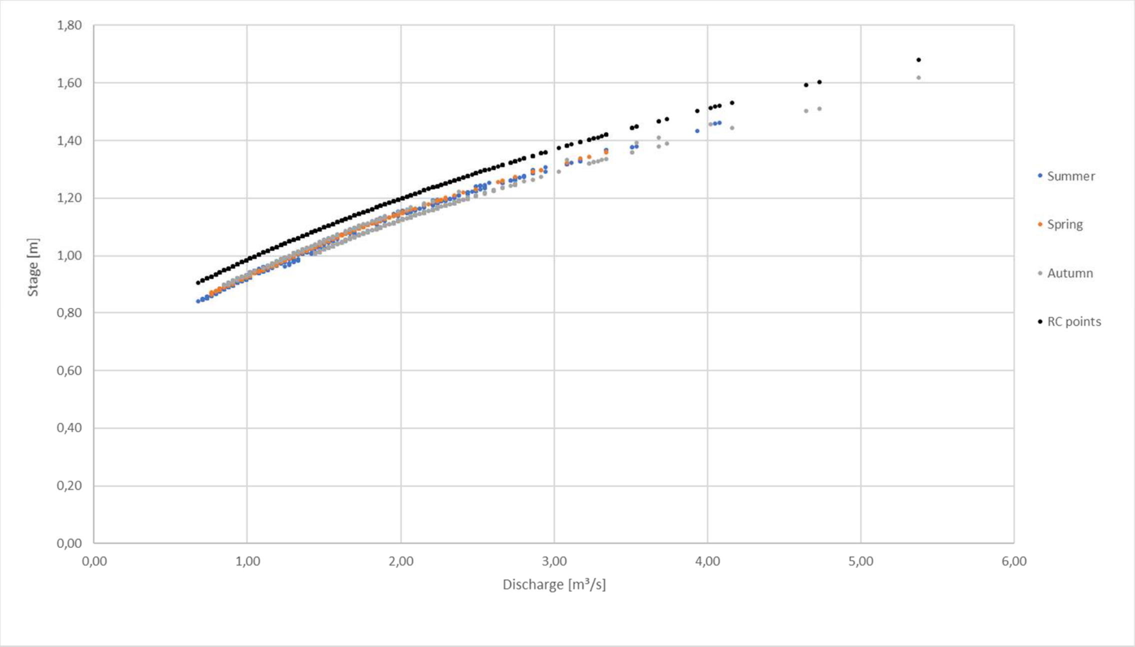
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
07.11.2013 11:54	autumn	0,50	0,10	7	0,192	0,033	rising limb
12.08.2013 15:05	summer	0,52	0,12	7	0,186	0,002	rising limb
23.07.2013 11:58	summer	0,62	0,39	7	0,201	-0,066	falling limb
18.06.2013 12:57	spring	0,83	1,14	7	0,183	-0,031	falling limb
18.04.2013 09:53	spring	4,61	139,88	7	0,000	0,012	rising limb
16.04.2013 12:09	spring	1,16	2,86	7	0,134	0,052	rising limb



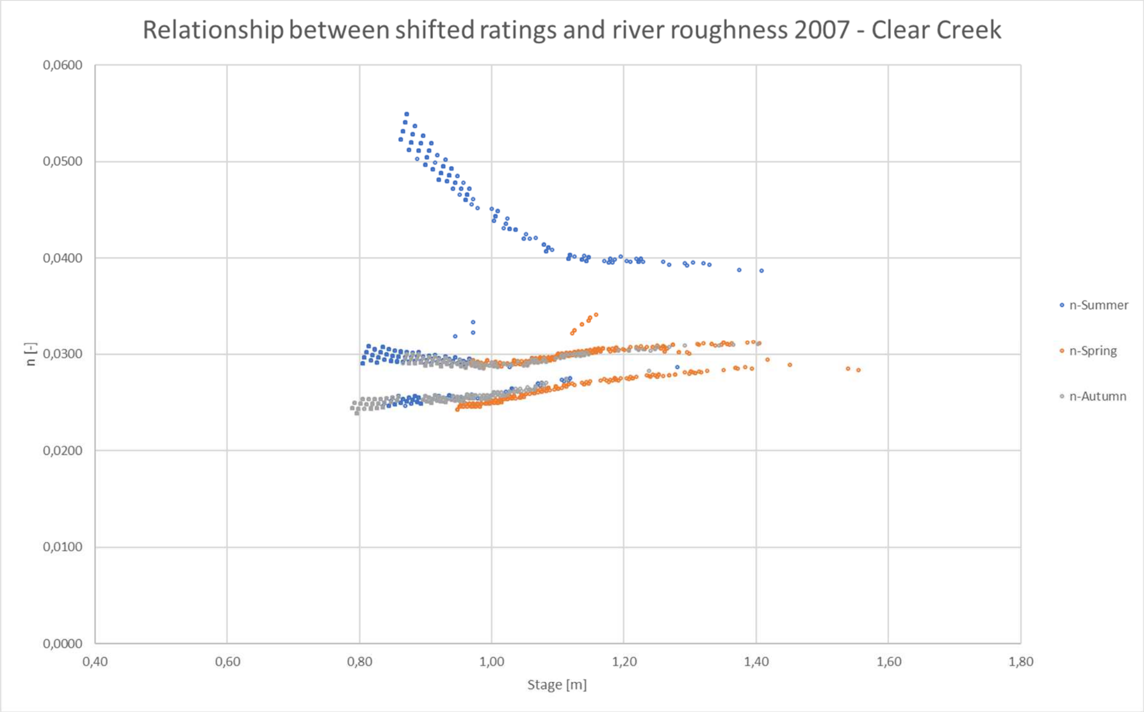


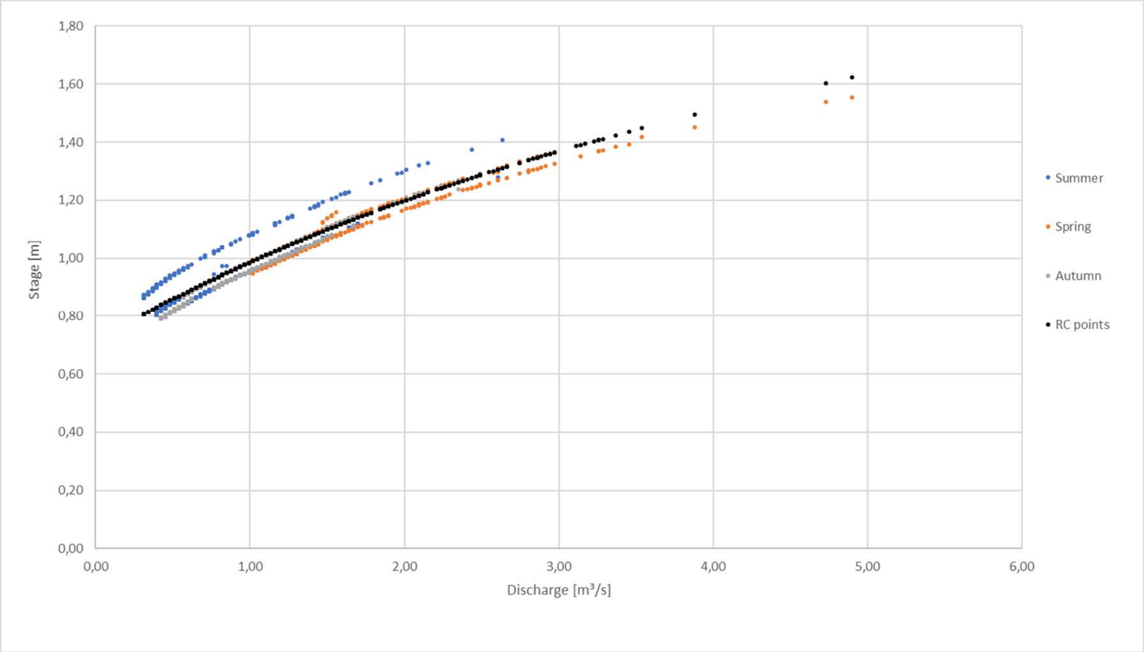
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
01.11.2011 08:46	autumn	0,66	0,09	5	0,000	-0,002	falling limb
20.09.2011 11:33	summer	0,68	0,12	5	0,000	-0,001	steady
09.08.2011 10:38	summer	0,77	0,41	5	0,046	0,000	steady
27.06.2011 10:00	summer	1,17	2,22	5	0,076	-0,001	falling limb
16.05.2011 09:41	spring	0,99	1,24	5	0,049	-0,005	falling limb
05.04.2011 09:08	spring	0,92	0,75	5	0,000	-0,005	falling limb



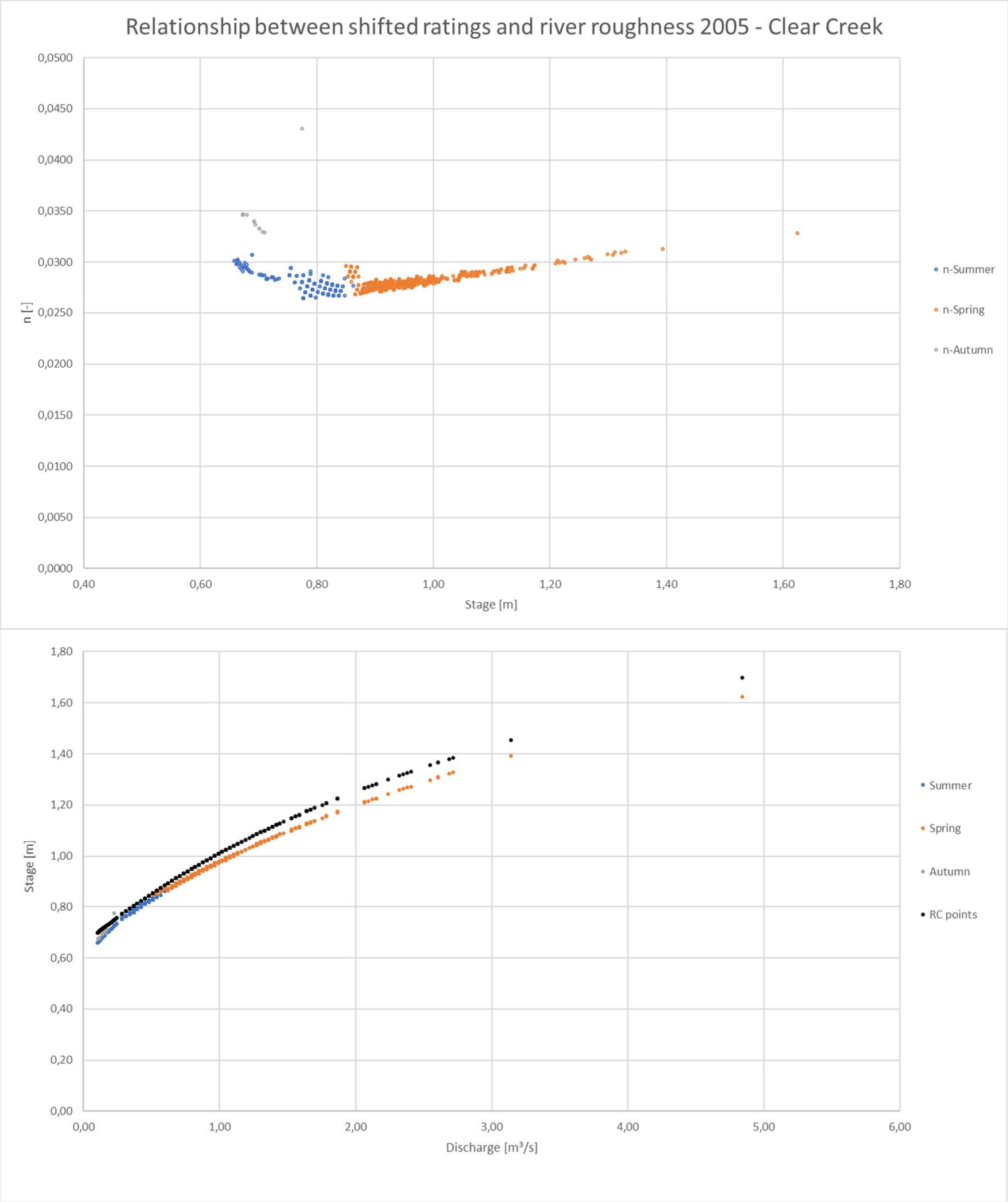


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
09.11.2009 10:26	autumn	1,22	2,59	5	0,082	-0,058	falling limb
06.10.2009 11:30	autumn	1,24	2,50	5	0,052	-0,040	falling limb
28.08.2009 08:53	summer	4,56	81,84	5	0,000	-0,019	falling limb
24.08.2009 10:40	summer	1,02	1,48	5	0,079	0,014	rising limb
21.07.2009 10:08	summer	1,13	1,94	5	0,064	0,046	rising limb
26.05.2009 10:11	spring	1,10	1,73	5	0,058	0,056	rising limb
14.04.2009 11:15	spring	0,97	1,18	5	0,058	0,066	rising limb

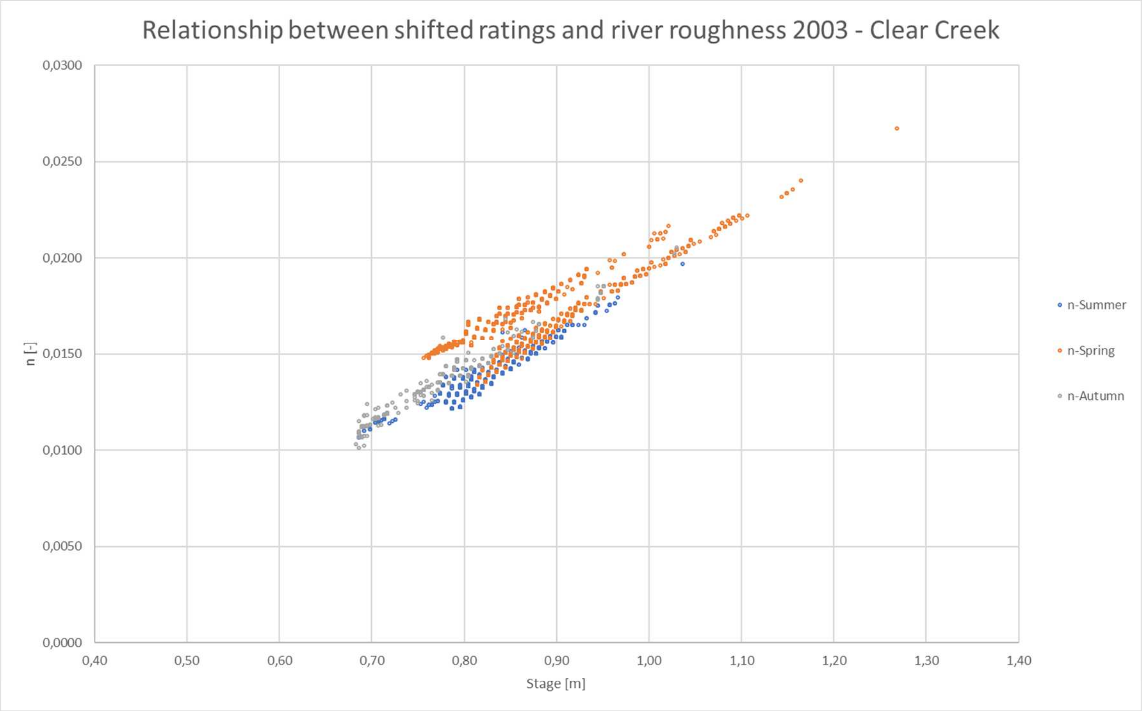


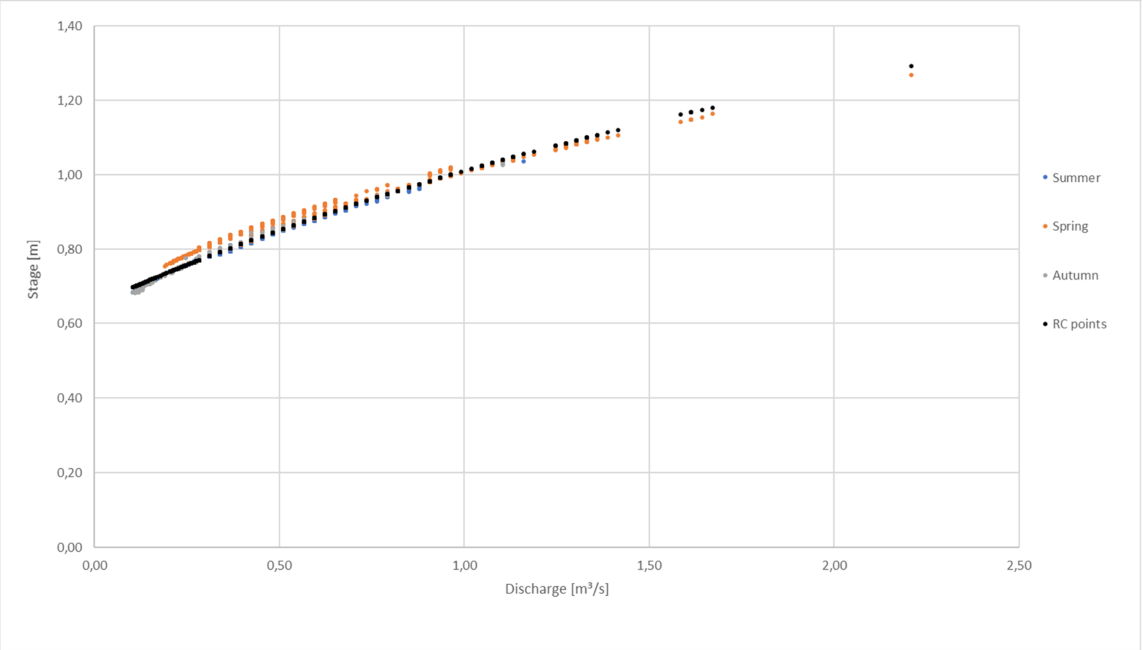


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
05.11.2007 08:50	autumn	1,03	1,23	5	0,000	-0,031	falling limb
18.10.2007 13:09	autumn	3,04	21,61	5	0,000	-0,024	falling limb
02.10.2007 08:55	autumn	0,82	0,50	5	0,030	-0,017	falling limb
20.08.2007 08:56	summer	2,56	13,88	5	0,000	-0,127	falling limb
20.08.2007 08:30	summer	2,60	13,28	5	-0,140	-0,217	falling limb
08.08.2007 13:40	summer	1,12	1,53	5	0,000	-0,087	falling limb
26.06.2007 13:40	summer	1,58	3,88	5	-0,094	-0,080	falling limb
23.06.2007 11:26	summer	4,54	86,37	5	0,000	0,051	rising limb
22.06.2007 13:12	summer	2,51	14,24	5	0,000	0,076	rising limb
15.05.2007 08:50	spring	1,16	1,95	5	0,040	0,083	rising limb
25.04.2007 10:25	spring	2,00	10,14	5	0,122	0,096	rising limb
10.04.2007 10:50	spring	1,11	1,52	5	0,000	0,080	rising limb

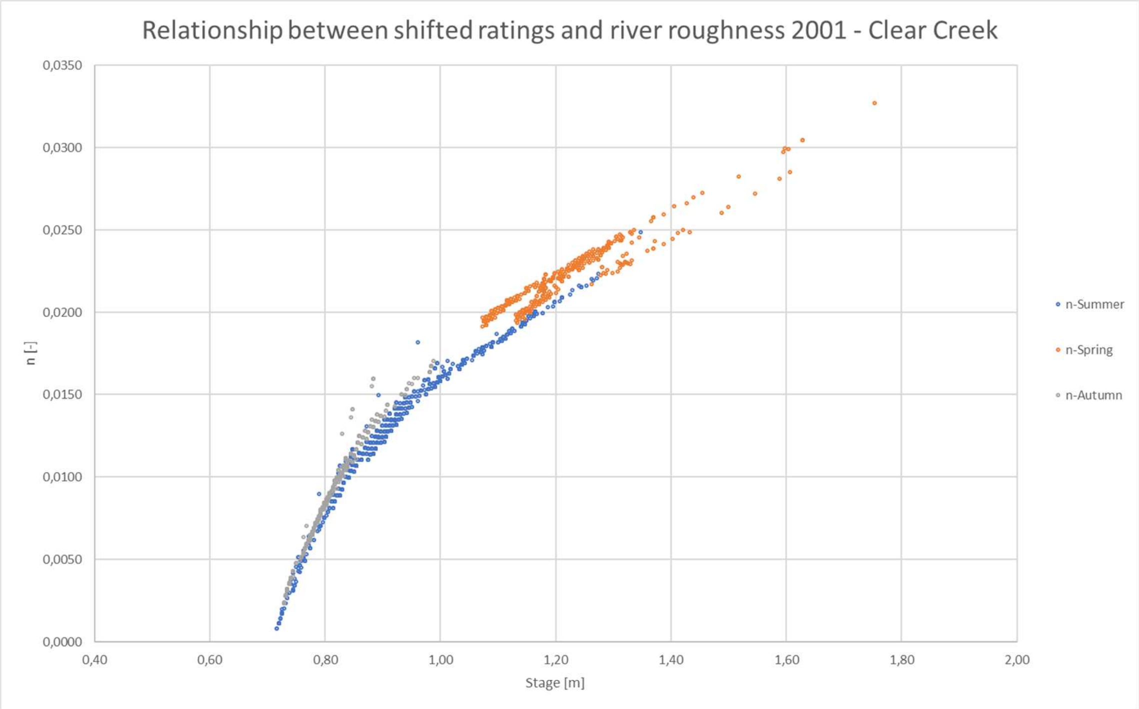


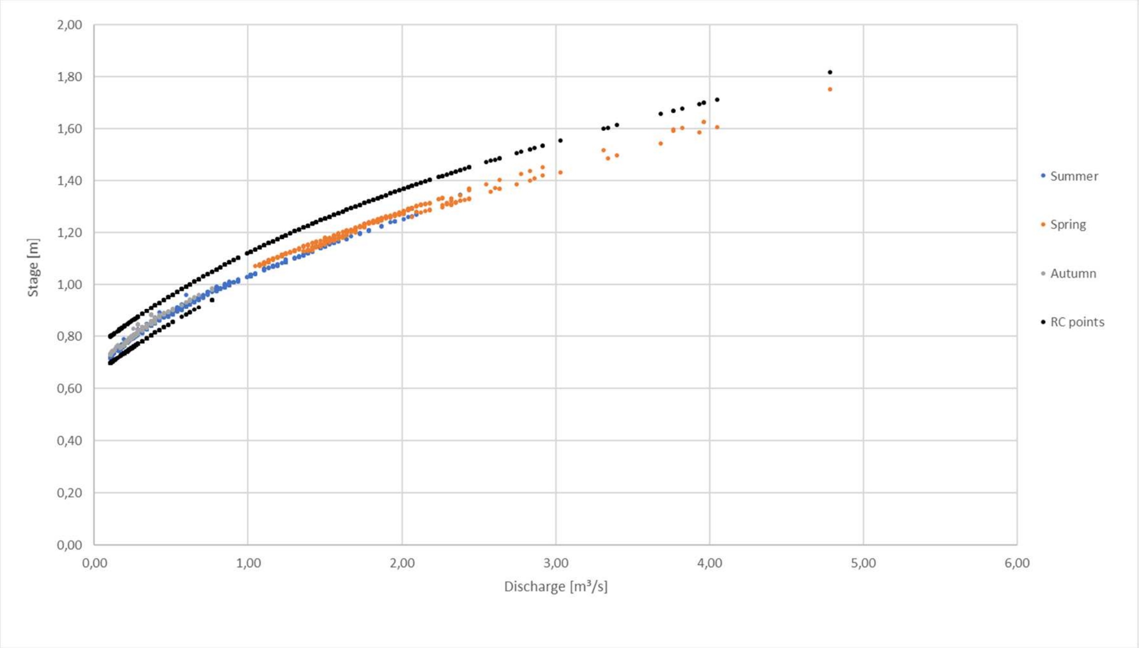
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
05.12.2005 13:00	autumn	0,70	0,03	4	-0,027	0,024	rising limb
03.11.2005 08:45	autumn	0,60	0,02	4	0,055	0,003	rising limb
03.10.2005 13:30	autumn	0,60	0,03	4	0,070	0,004	rising limb
08.09.2005 09:50	summer	0,58	0,02	4	0,049	0,004	rising limb
25.07.2005 11:55	summer	0,64	0,08	4	0,067	-0,003	falling limb
14.06.2005 10:40	spring	0,91	0,77	4	0,070	-0,002	falling limb
10.05.2005 11:50	spring	0,91	0,76	4	0,067	-0,003	falling limb
28.03.2005 13:30	spring	0,92	0,77	4	0,067	-0,002	falling limb



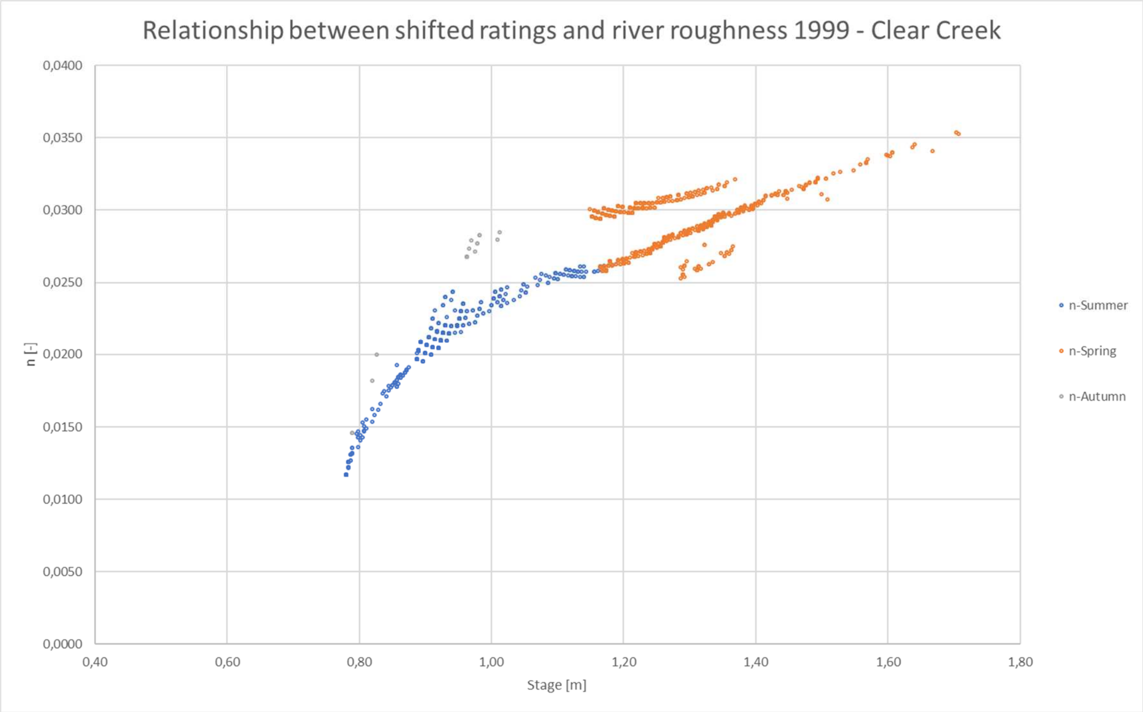


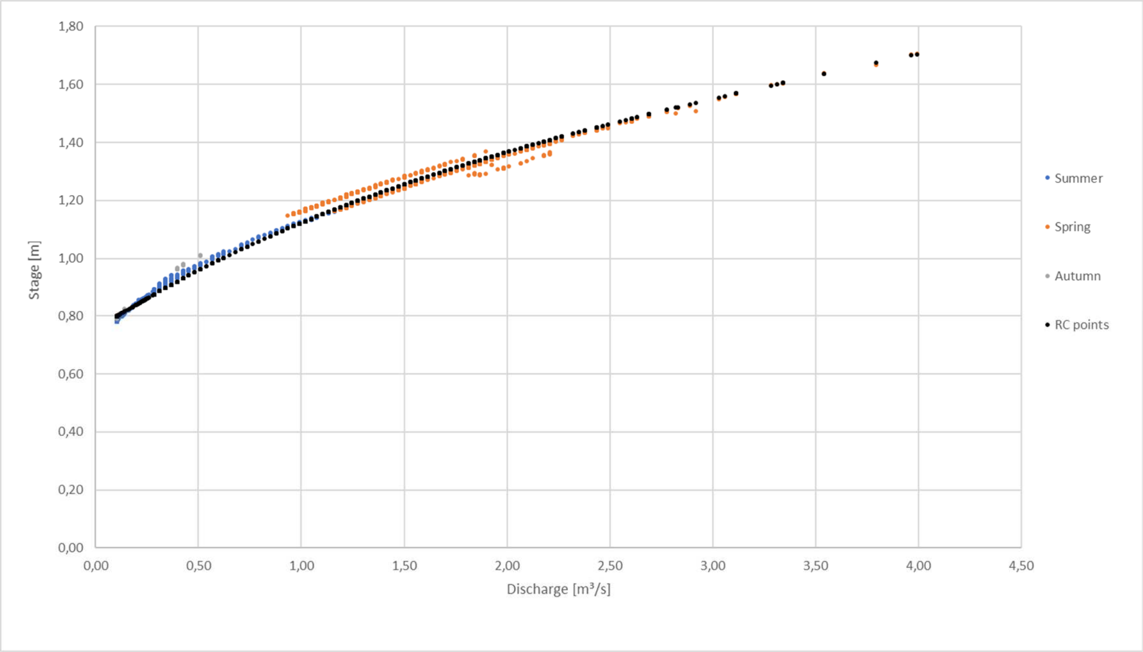
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
13.11.2003 11:45	autumn	0,68	0,10	4	0,043	0,002	rising limb
25.09.2003 12:30	autumn	0,62	0,02	4	0,015	0,001	rising limb
18.08.2003 11:45	summer	0,65	0,05	4	0,037	0,001	rising limb
03.07.2003 11:40	summer	0,81	0,39	4	0,052	0,000	steady
28.05.2003 11:00	spring	0,87	0,53	4	0,037	-0,001	steady
15.04.2003 12:20	spring	0,77	0,22	4	0,018	-0,001	falling limb





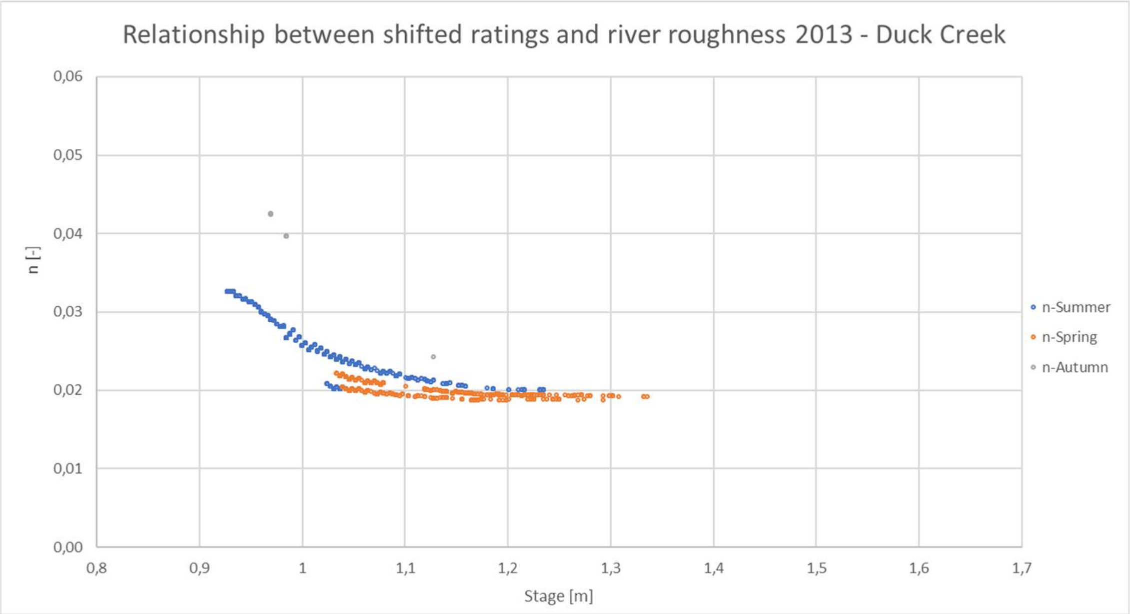
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
26.11.2001 12:45	autumn	0,77	0,18	4	0,006	0,000	steady
09.10.2001 09:55	autumn	0,71	0,07	4	-0,006	0,000	steady
31.08.2001 09:30	summer	0,71	0,10	3	0,064	0,001	rising limb
24.07.2001 08:16	summer	0,95	0,67	3	0,104	0,000	steady
11.06.2001 12:35	spring	1,37	2,63	3	0,128	0,000	steady
02.05.2001 09:30	spring	1,09	1,13	3	0,088	0,001	steady

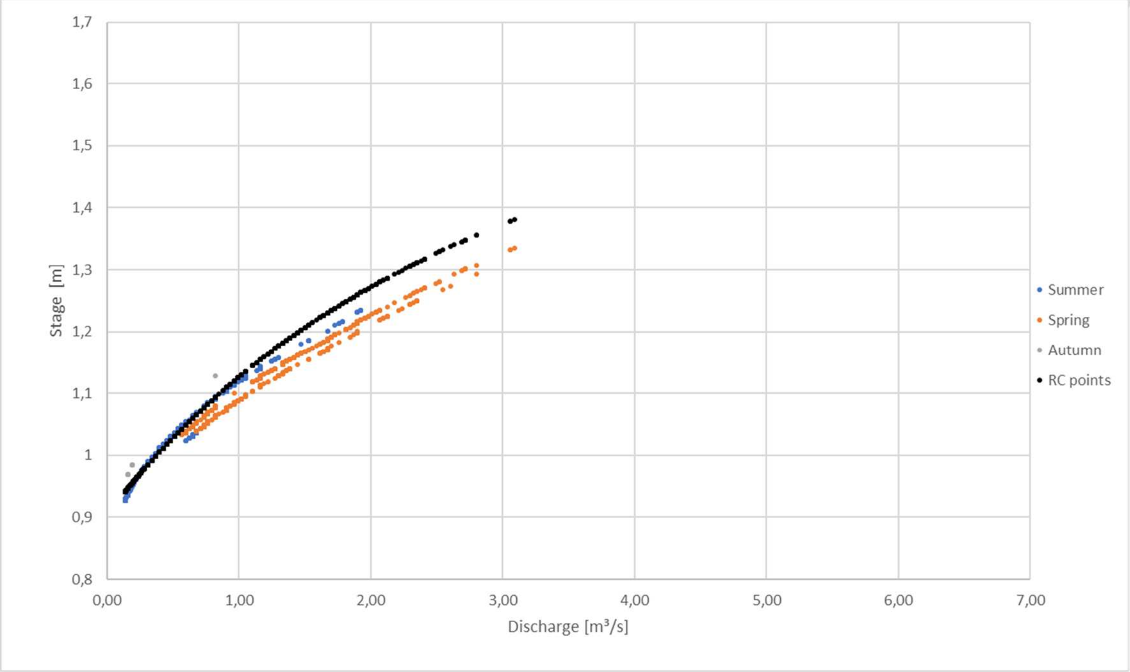




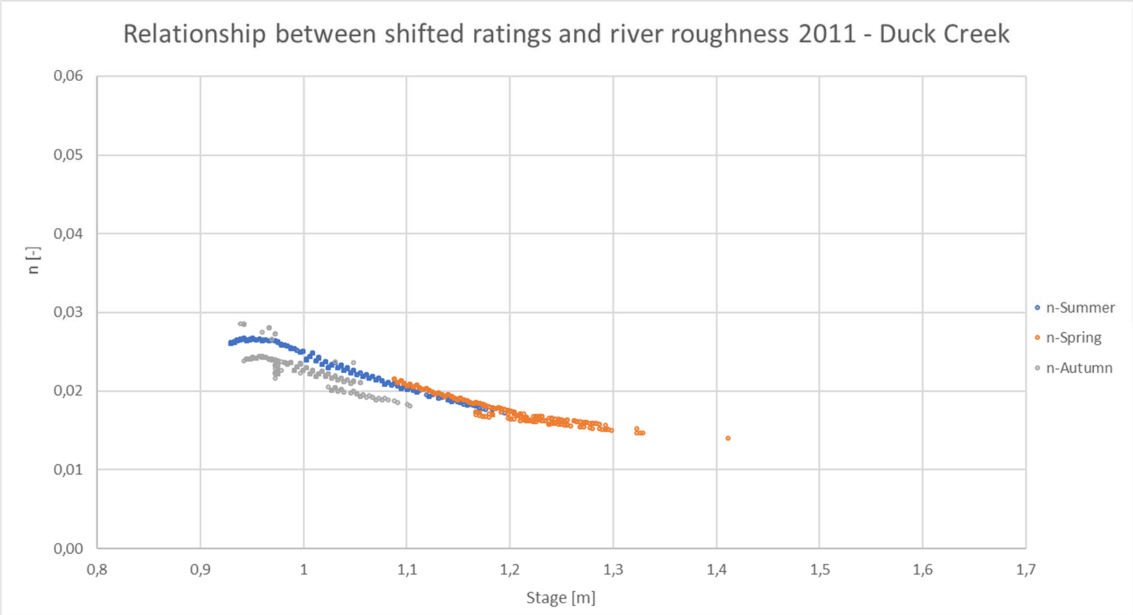
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope	Flow state
13.12.1999 10:40	autumn	0,75	0,04	3	-0,024	0,054	rising limb
02.11.1999 10:45	autumn	0,73	0,03	3	-0,024	0,027	rising limb
20.09.1999 12:10	summer	0,70	0,02	3	-0,009	-0,001	falling limb
09.08.1999 11:15	summer	0,78	0,11	3	0,000	-0,003	falling limb
22.06.1999 09:50	summer	1,15	1,12	3	0,024	-0,012	falling limb
19.05.1999 13:55	spring	1,61	3,43	3	0,009	-0,043	falling limb
05.04.1999 13:10	spring	1,29	1,93	3	0,070	-0,032	falling limb

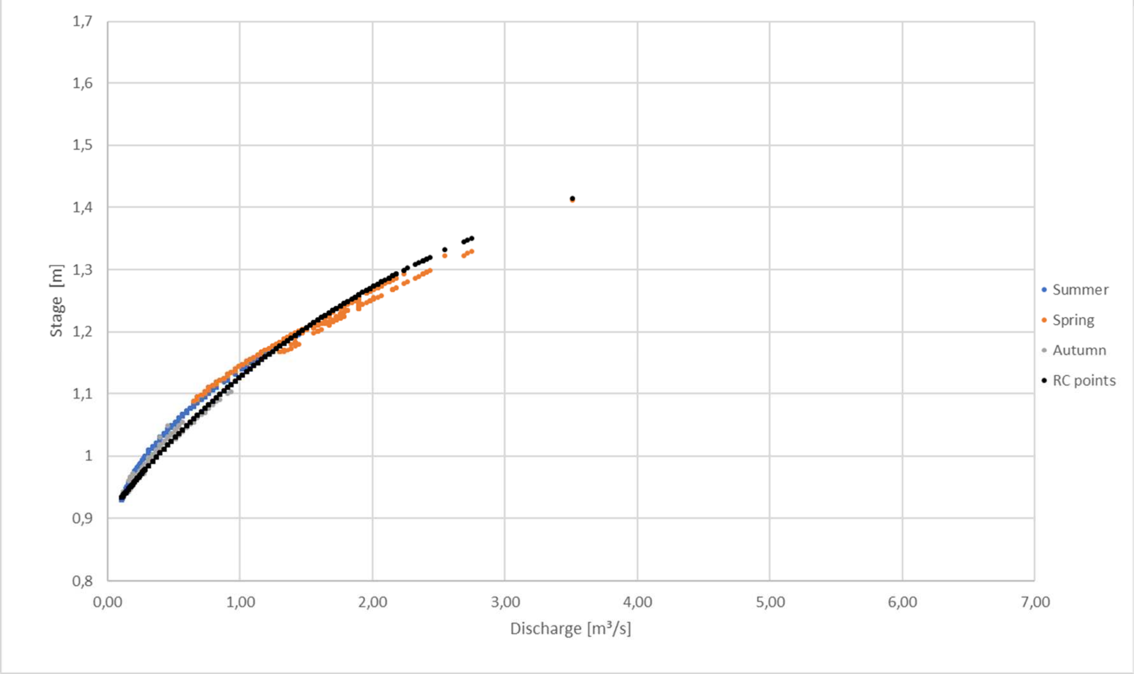
Appendix 2 Analysis of several years at the Duck Creek gaging station



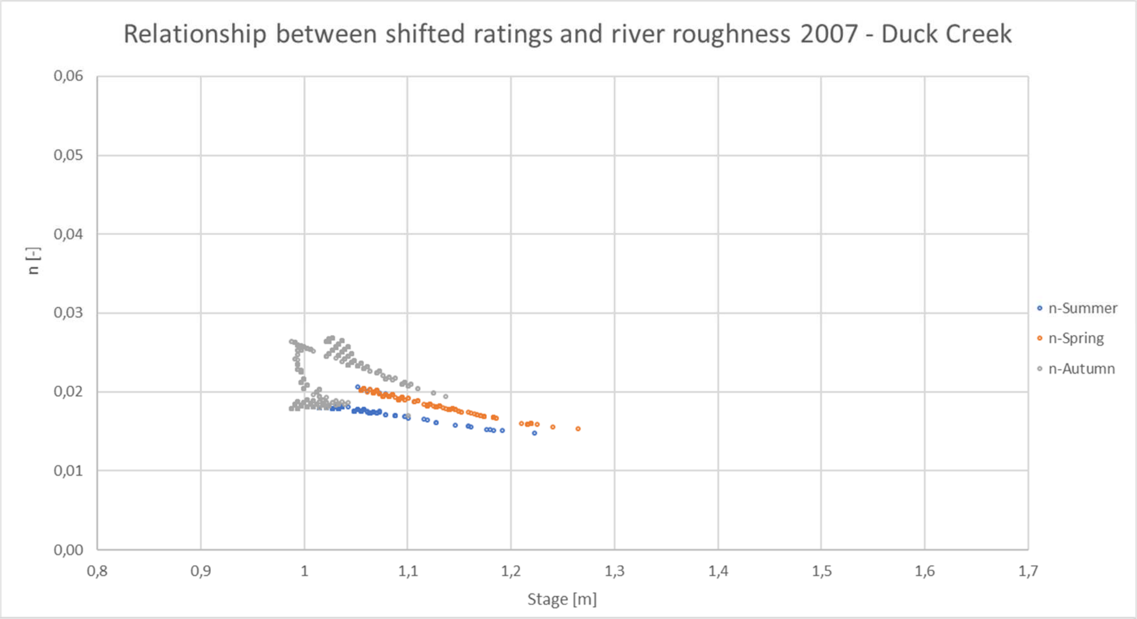


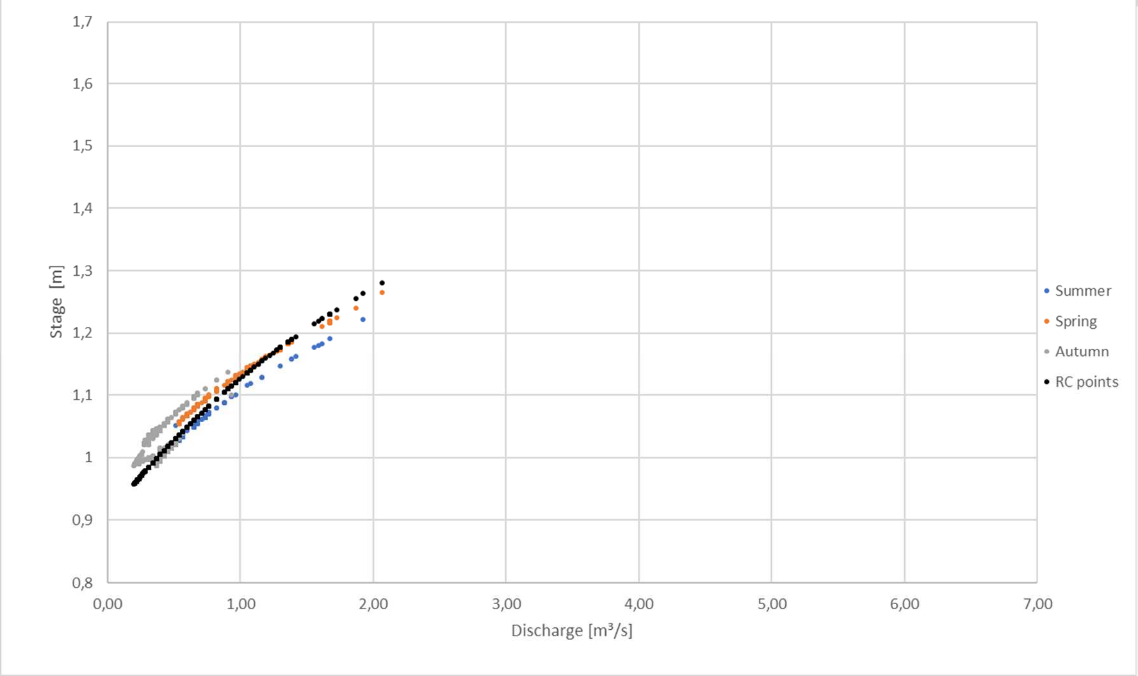
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
21.10.2013 16:24	autumn	0,86	0,01	3	-0,009	-0,004	falling limb
17.09.2013 09:05	summer	0,89	0,08	3	0,030	-0,003	falling limb
19.08.2013 17:06	summer	0,90	0,08	3	0,024	-0,001	steady
25.06.2013 19:28	summer	1,43	4,53	3	0,055	-0,001	falling limb
15.05.2013 16:39	spring	1,18	1,61	3	0,040	0,001	steady
27.03.2013 15:46	spring	1,07	0,78	3	0,040	0,003	rising limb



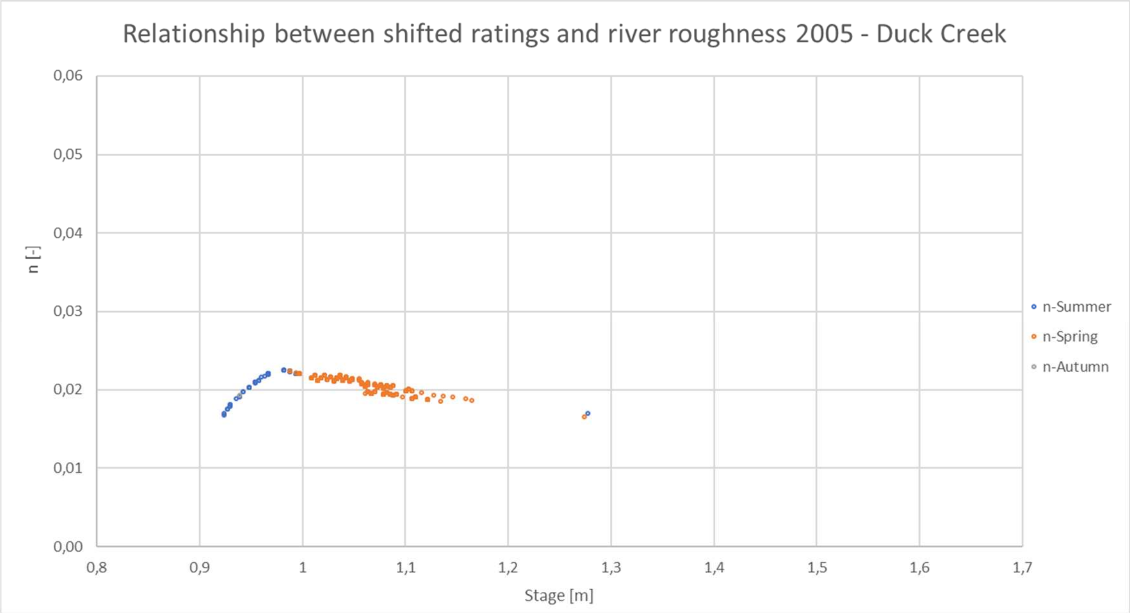


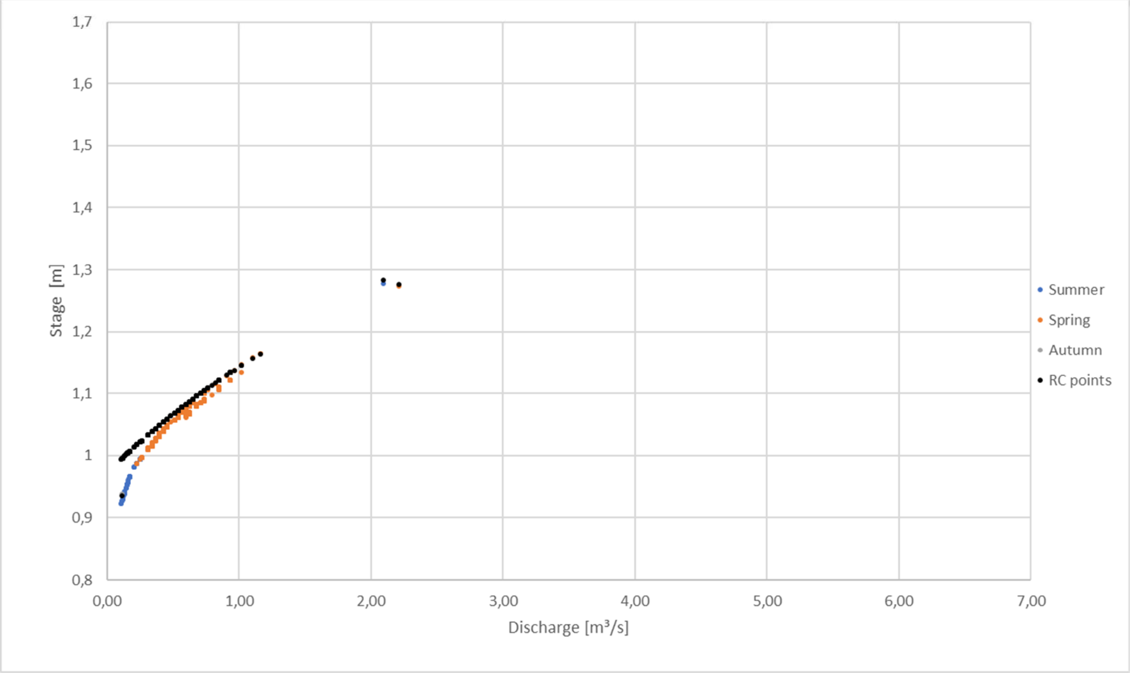
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
09.11.2009 09:53	autumn	1,21	1,65	3	0,009	-0,075	falling limb
13.10.2009 13:41	autumn	1,10	0,73	3	0,000	-0,102	falling limb
01.09.2009 14:41	summer	1,28	2,31	3	0,027	-0,085	falling limb
10.07.2009 16:53	summer	3,21	69,94	3	0,000	-0,058	falling limb
09.06.2009 14:17	spring	1,36	3,17	3	0,027	-0,003	falling limb
30.04.2009 11:01	spring	2,59	37,38	3	0,000	0,046	rising limb
28.04.2009 13:57	spring	1,31	2,77	3	0,027	0,089	rising limb



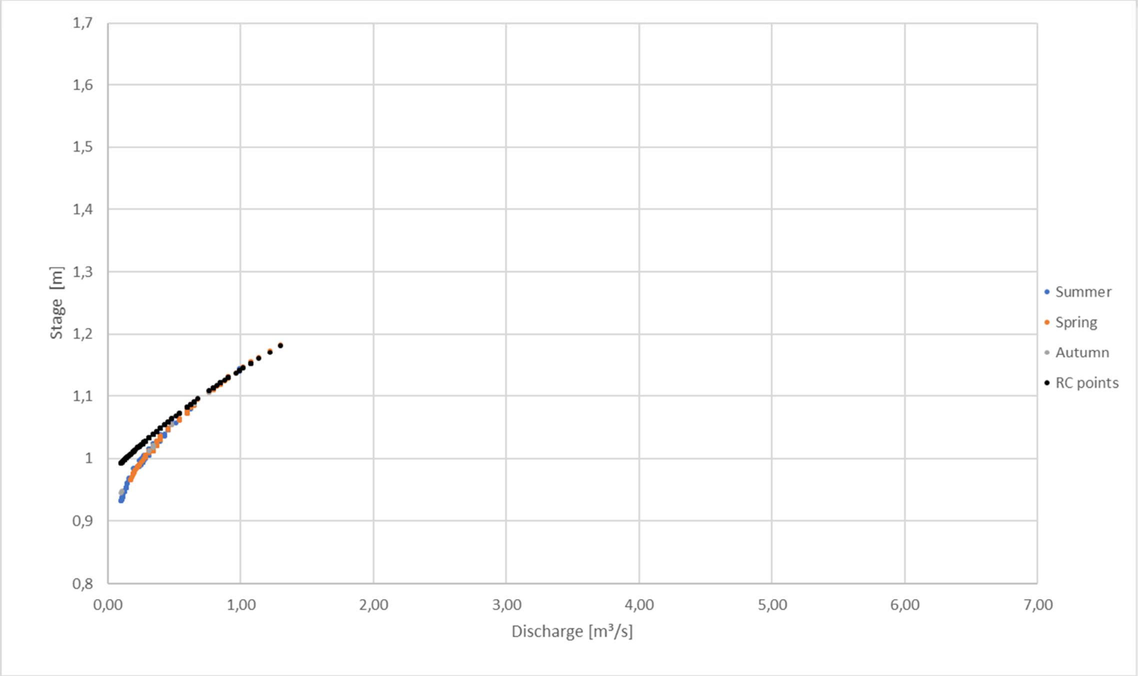


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
13.11.2007 12:11	autumn	1,03	0,29	3	-0,021	0,000	steady
09.10.2007 13:33	autumn	1,00	0,24	3	-0,009	-0,001	falling limb
14.08.2007 09:36	summer	1,71	9,00	3	0,037	-0,001	steady
02.07.2007 11:30	summer	1,06	0,56	3	0,009	-0,073	falling limb
21.05.2007 12:42	spring	1,08	0,63	3	0,009	-0,169	falling limb
02.04.2007 13:16	spring	1,41	3,71	3	0,009	-0,126	falling limb

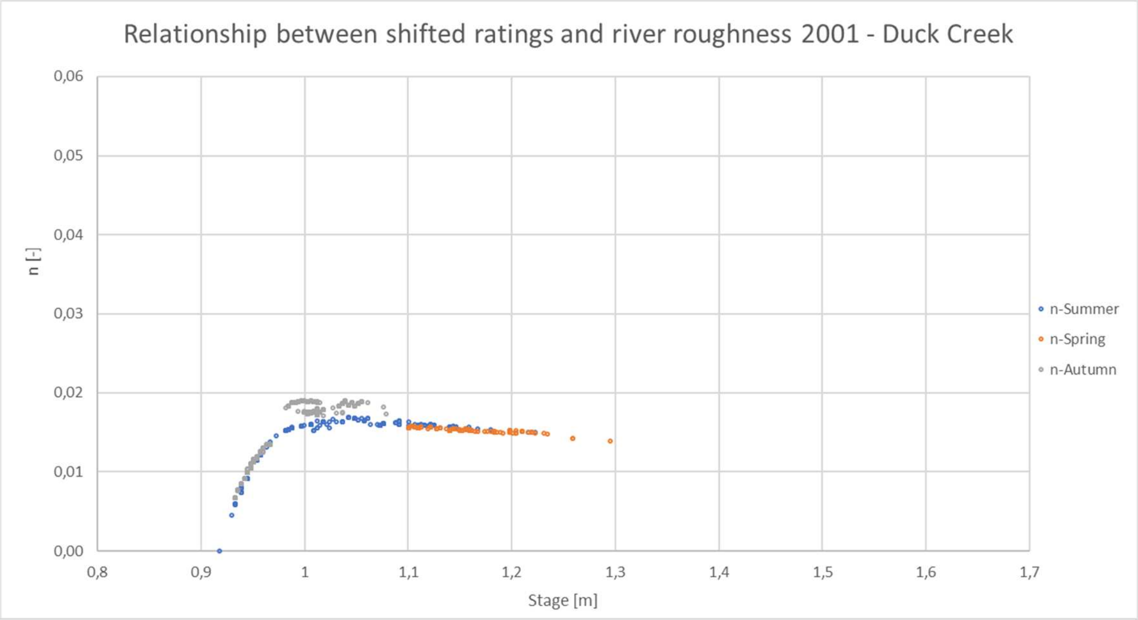


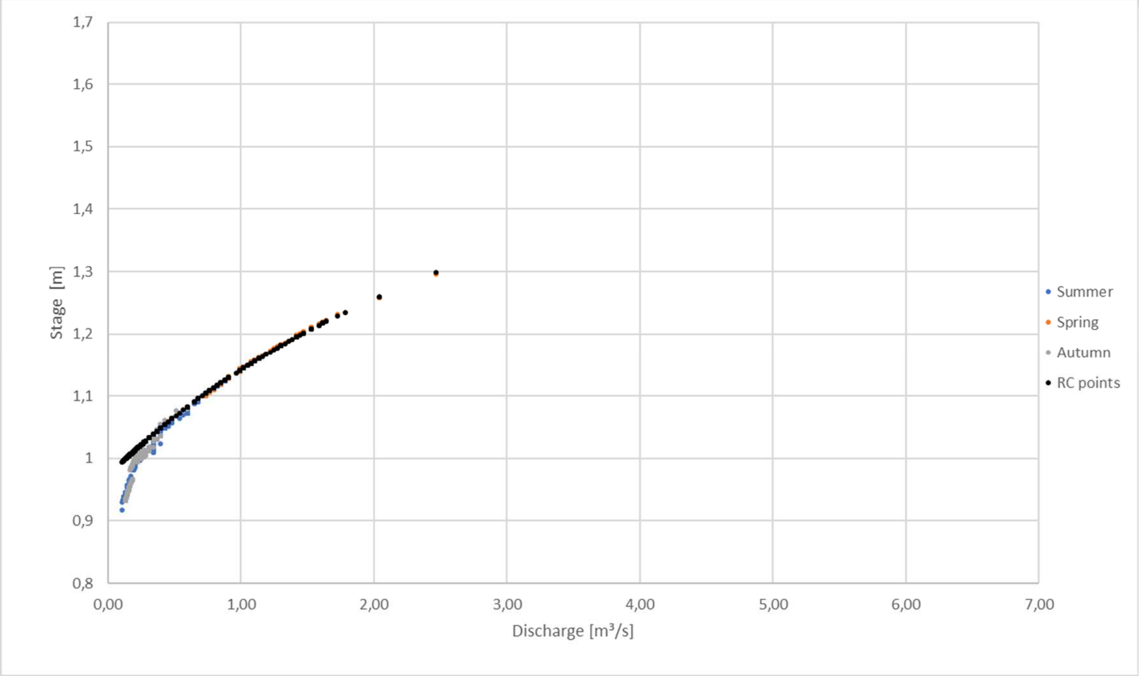


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
13.12.2005 12:10	autumn	0,90	0,05	3	-0,009	0,003	rising limb
08.11.2005 10:33	autumn	0,90	0,05	3	0,000	0,004	rising limb
12.10.2005 09:24	autumn	0,84	0,01	3	0,003	0,003	rising limb
06.09.2005 10:57	summer	0,85	0,01	3	0,000	-0,002	falling limb
01.08.2005 11:38	summer	0,87	0,03	2	0,000	-0,004	falling limb
21.06.2005 11:02	summer	0,99	0,25	2	0,000	-0,004	falling limb
09.05.2005 08:02	spring	1,17	1,23	2	0,000	-0,003	falling limb
28.03.2005 12:01	spring	1,12	0,91	2	0,012	-0,001	steady

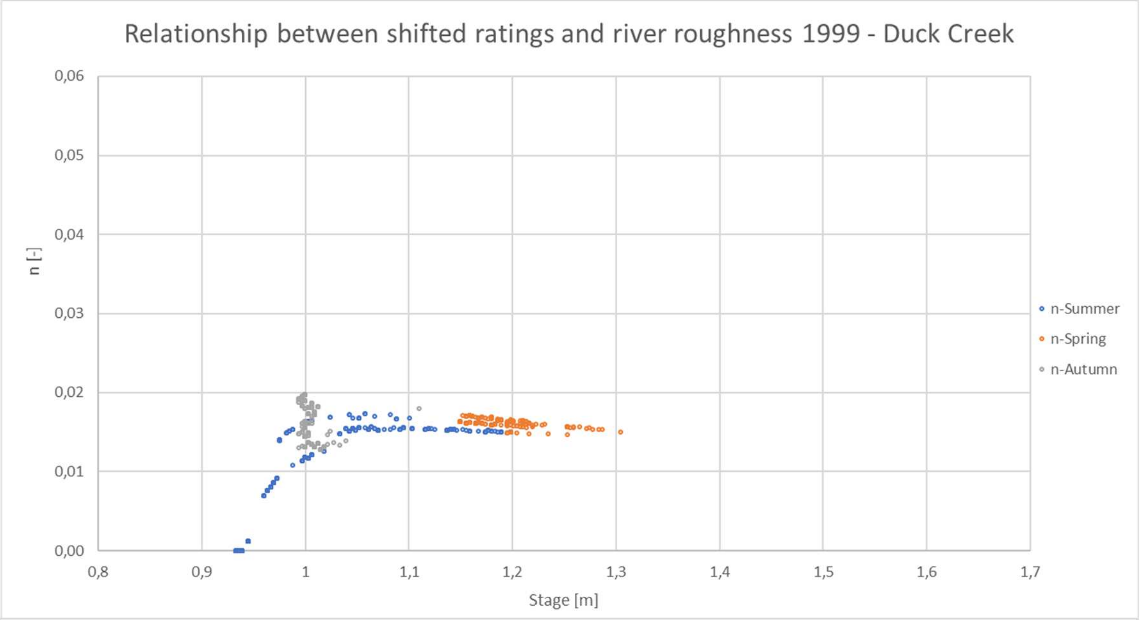


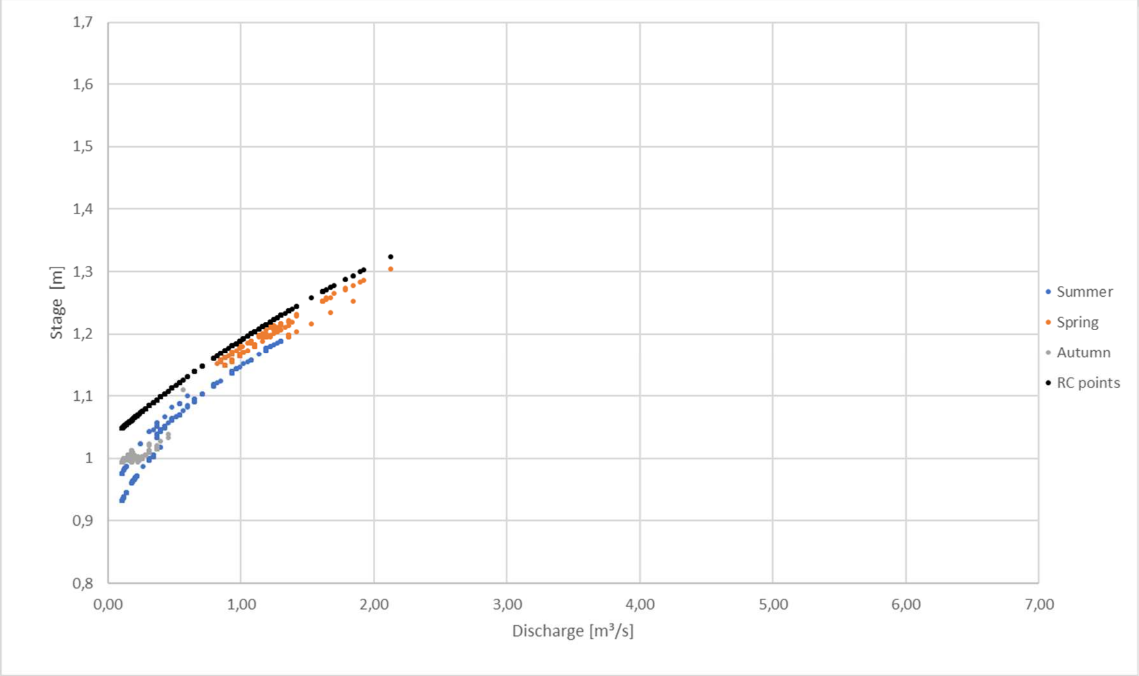
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
16.12.2003 10:28	autumn	1,07	0,59	2	0,000	0,006	rising limb
12.11.2003 11:56	autumn	0,93	0,07	2	-0,027	-0,007	falling limb
29.09.2003 11:54	autumn	0,88	0,03	2	-0,009	-0,009	falling limb
09.09.2003 09:48	summer	0,86	0,01	2	0,003	-0,009	falling limb
18.08.2003 11:43	summer	0,91	0,06	2	-0,015	-0,005	falling limb
09.07.2003 12:09	summer	1,54	6,40	2	0,000	-0,002	falling limb
07.07.2003 11:47	summer	0,99	0,26	2	0,003	0,002	rising limb
27.05.2003 12:02	spring	1,11	0,77	2	0,000	0,000	steady
14.04.2003 11:17	spring	0,97	0,19	2	0,000	0,004	rising limb


Relationship between shifted ratings and river roughness 2001 - Duck Creek

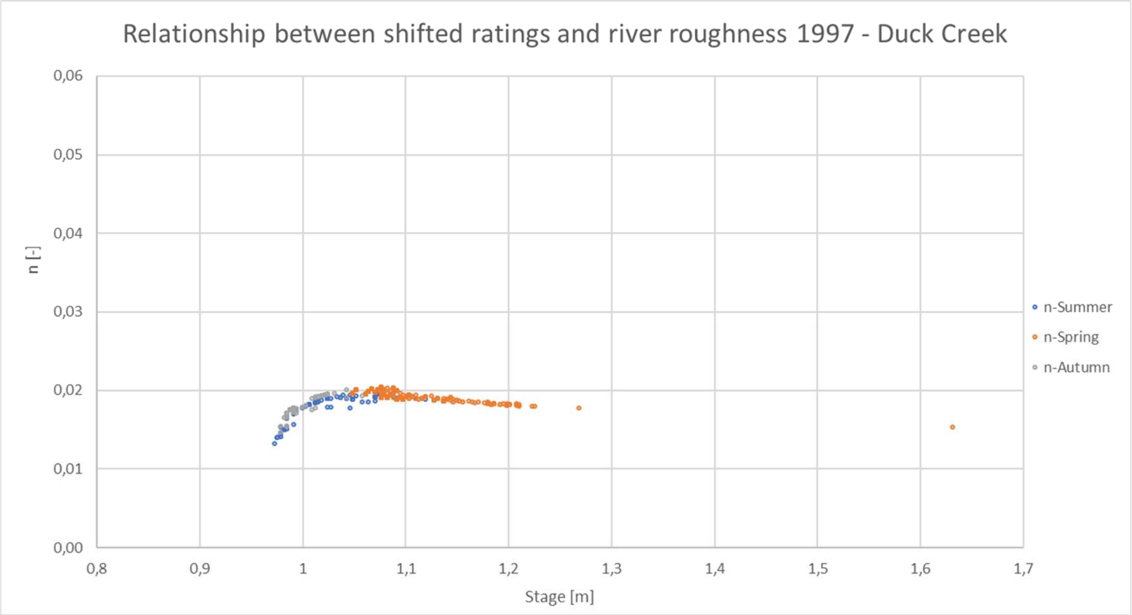


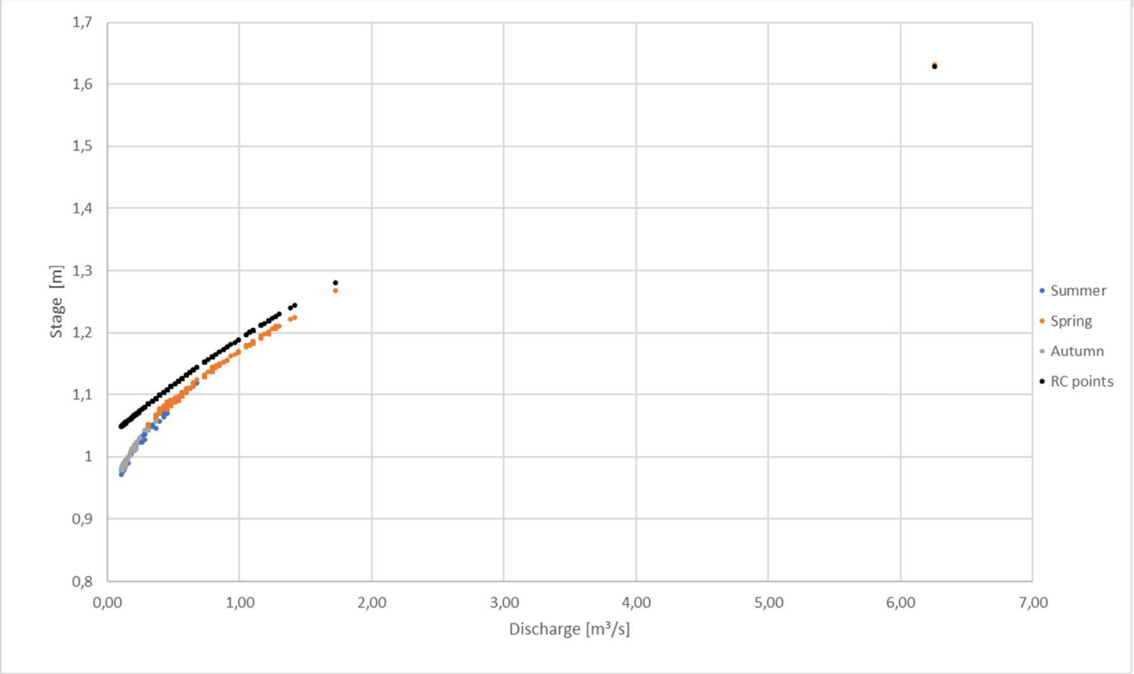
Date and Time	Season	Stage [m]	Discharge [m^3/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
11.12.2001 14:52	autumn	1,00	0,24	2	-0,006	0,303	rising limb
24.10.2001 14:58	autumn	1,32	2,58	2	-0,018	-0,072	falling limb
10.09.2001 13:05	summer	0,98	0,24	2	0,006	-0,132	falling limb
30.07.2001 10:15	summer	1,01	0,27	2	-0,006	-0,135	falling limb
20.06.2001 11:55	spring	1,20	1,49	2	0,000	-0,121	falling limb
14.05.2001 11:35	spring	2,97	58,62	2	0,000	-0,067	falling limb
14.05.2001 12:07	spring	3,00	59,47	2	0,000	0,007	rising limb
09.05.2001 07:10	spring	1,34	3,03	2	0,000	0,084	rising limb
27.03.2001 12:15	spring	1,21	1,58	2	0,000	0,137	rising limb



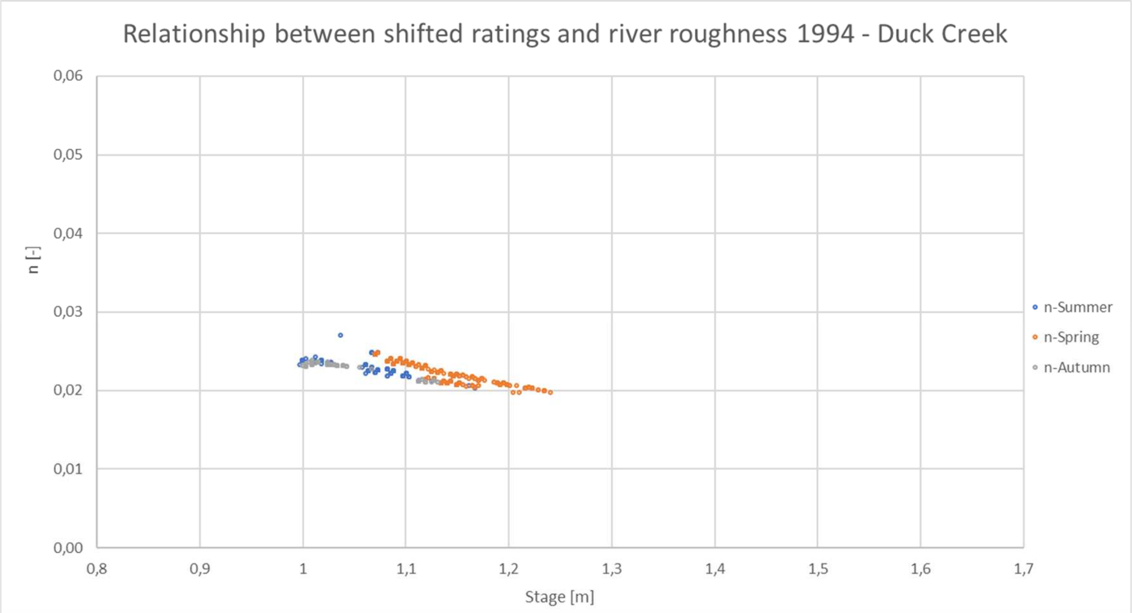


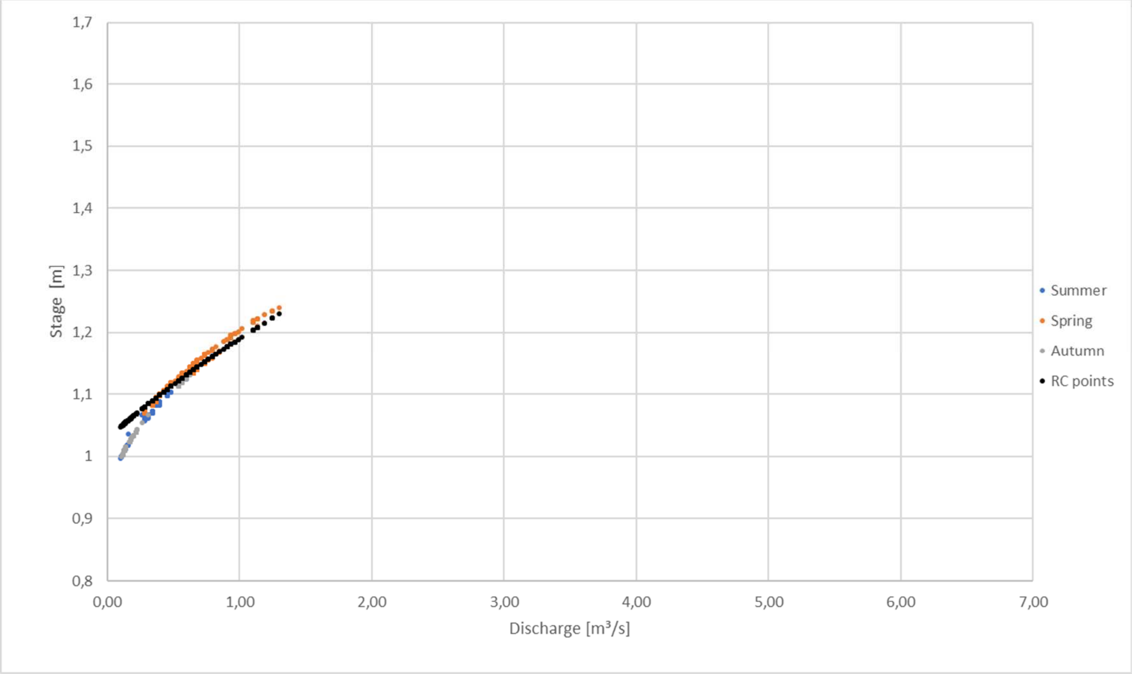
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
15.12.1999 11:15	autumn	1,01	0,19	1	0,015	-0,007	falling limb
15.11.1999 10:35	autumn	0,99	0,10	1	0,006	-0,003	falling limb
28.09.1999 10:45	autumn	1,98	14,89	1	0,067	-0,002	falling limb
16.08.1999 10:00	summer	0,98	0,13	1	0,024	0,002	rising limb
28.06.1999 10:55	summer	1,14	0,91	1	0,043	0,006	rising limb
26.05.1999 11:15	spring	1,18	1,01	1	0,012	0,013	rising limb
12.04.1999 11:05	spring	1,21	1,38	1	0,024	0,020	rising limb





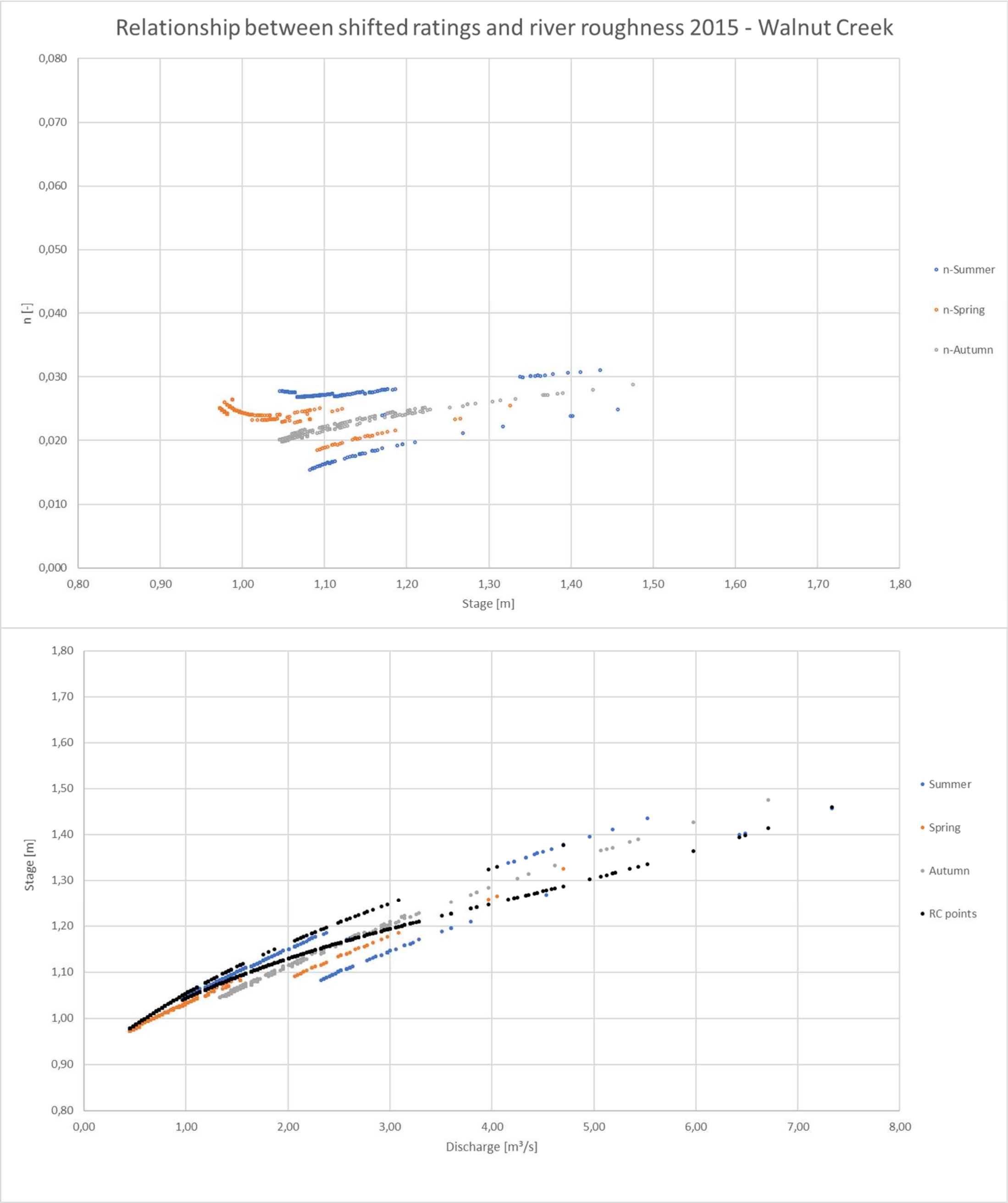
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
26.11.1997 10:35	autumn	0,99	0,13	1	0,018	0,020	rising limb
16.10.1997 10:50	autumn	0,95	0,06	1	0,024	0,005	rising limb
04.09.1997 11:45	summer	0,98	0,14	1	0,030	0,005	rising limb
23.07.1997 13:00	summer	1,02	0,22	1	0,021	0,003	rising limb
11.06.1997 12:50	spring	1,17	0,97	1	0,021	-0,001	steady
30.04.1997 09:50	spring	1,11	0,63	1	0,021	0,000	steady



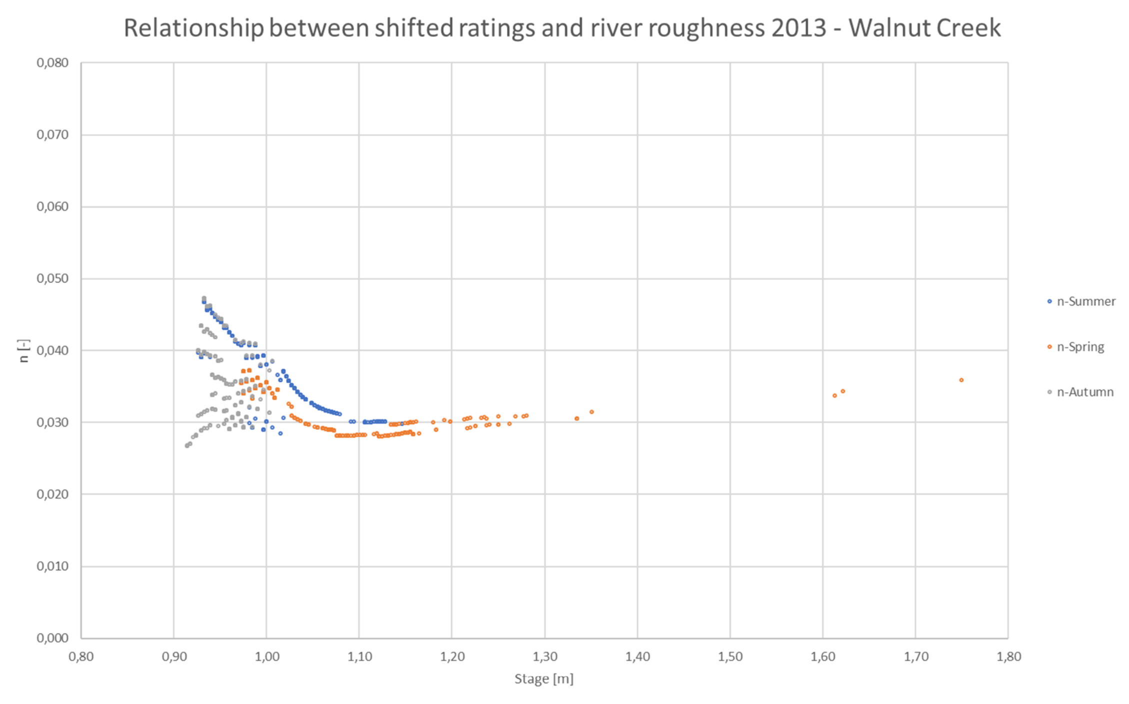


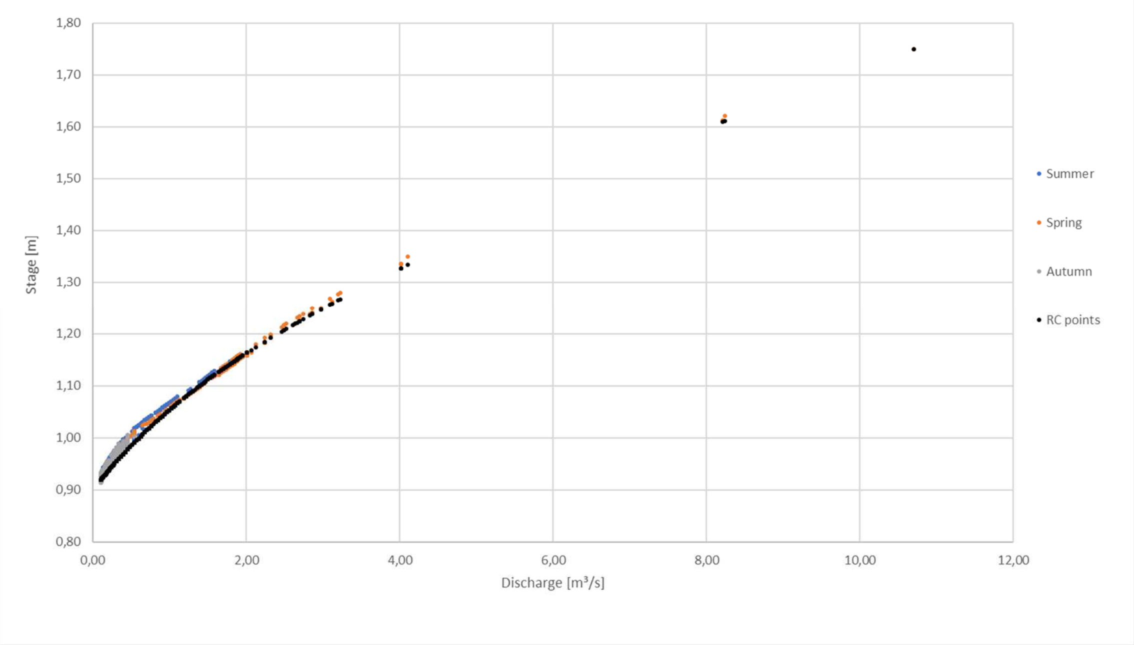
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
22.11.1994 16:25	autumn	1,04	0,23	1	0,000	0,027	rising limb
05.10.1994 11:15	autumn	0,94	0,02	1	0,000	0,011	rising limb
24.08.1994 12:05	summer	1,00	0,08	1	-0,015	-0,009	falling limb
11.07.1994 14:11	summer	1,05	0,26	1	0,000	-0,019	falling limb
11.07.1994 16:10	summer	1,05	0,29	1	0,000	-0,020	falling limb
17.05.1994 14:00	spring	1,16	0,69	1	-0,012	-0,017	falling limb
12.04.1994 11:45	spring	1,62	6,71	1	0,043	-0,006	falling limb
12.04.1994 12:20	spring	1,57	5,95	1	0,043	0,000	steady
04.04.1994 10:00	spring	1,14	0,65	1	0,000	0,000	steady

Appendix 3 Analysis of several years at the Walnut Creek gaging station

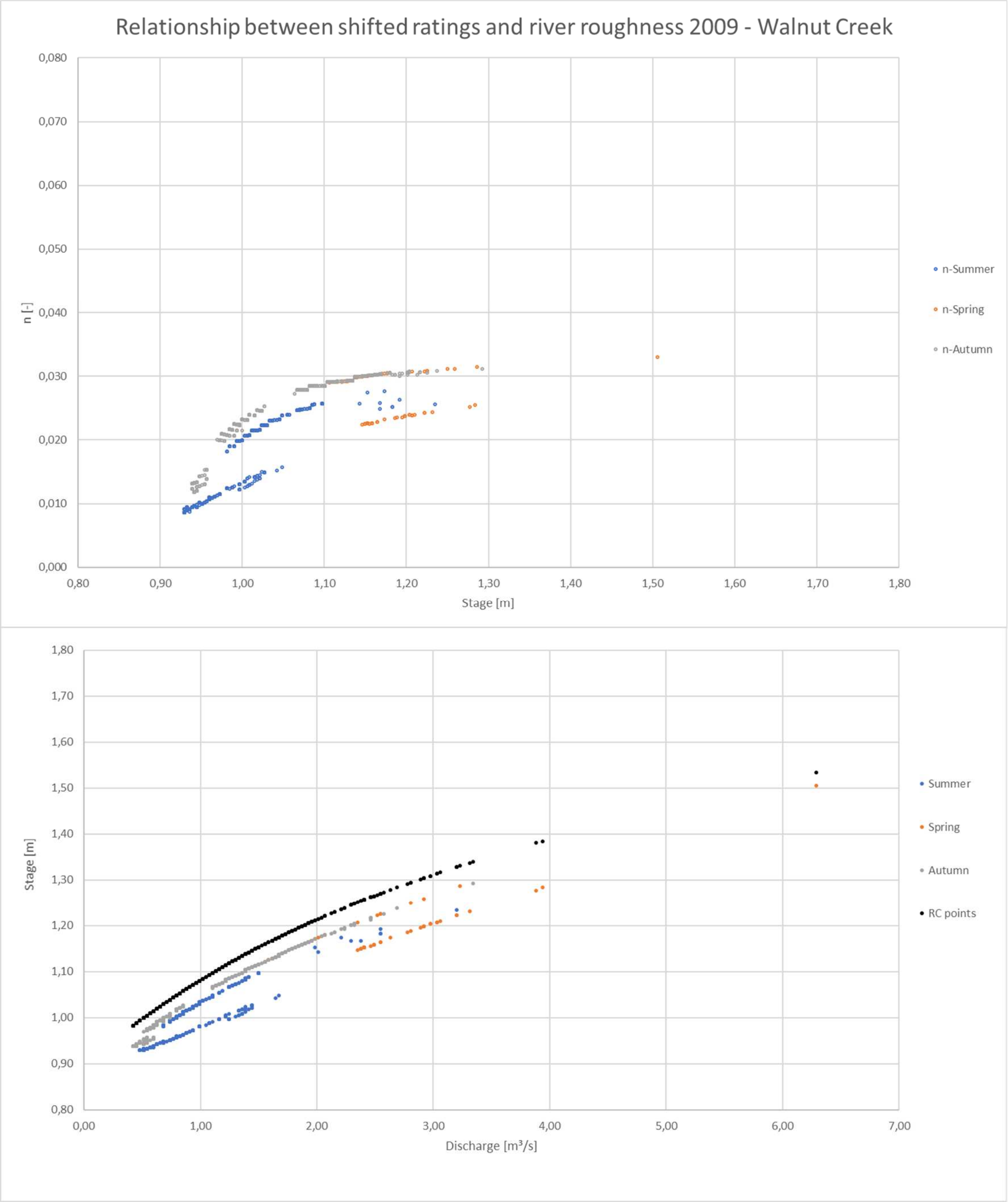


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
17.11.2015 14:57	autumn	1,22	3,20	6	0,040	0,22	rising limb
06.10.2015 11:12	autumn	1,13	2,17	6	0,034	-0,07	falling limb
26.08.2015 11:16	summer	1,09	1,35	6	0,000	0,00	steady
15.07.2015 12:02	summer	1,19	3,57	6	0,098	-0,56	falling limb
25.06.2015 11:23	summer	5,32	186,89	6	0,000	-975,09	falling limb
25.06.2015 10:37	summer	5,47	210,39	6	0,000	-600,71	falling limb
15.06.2015 14:54	spring	2,55	35,40	5	0,210	860,86	rising limb
01.06.2015 14:48	spring	1,12	2,39	5	0,064	-0,05	falling limb
26.05.2015 12:25	spring	1,98	19,20	5	0,165	6,82	rising limb
26.05.2015 11:40	spring	1,98	18,94	5	0,165	3,69	rising limb
22.04.2015 09:55	spring	1,06	1,20	5	0,021	-0,62	falling limb

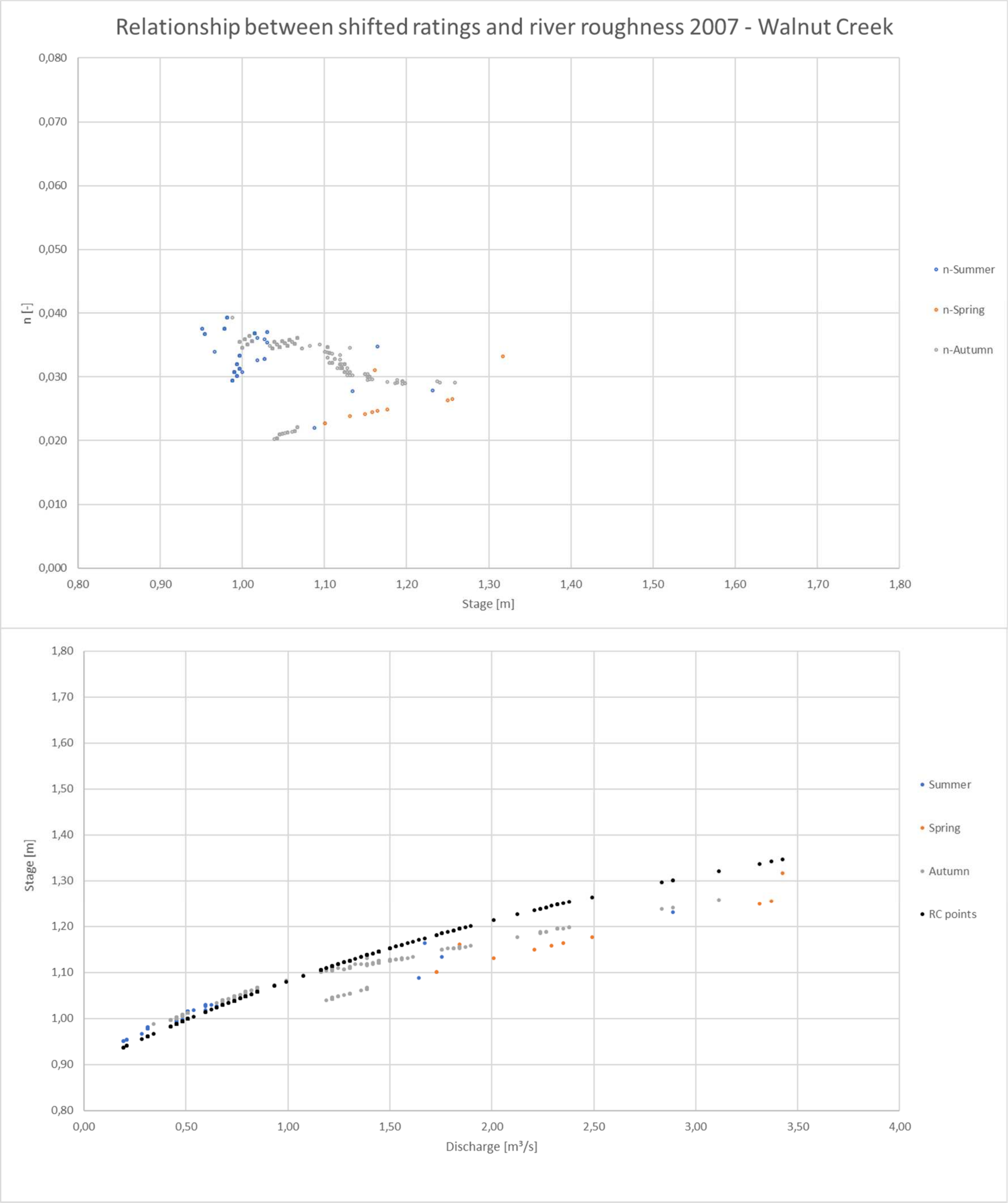




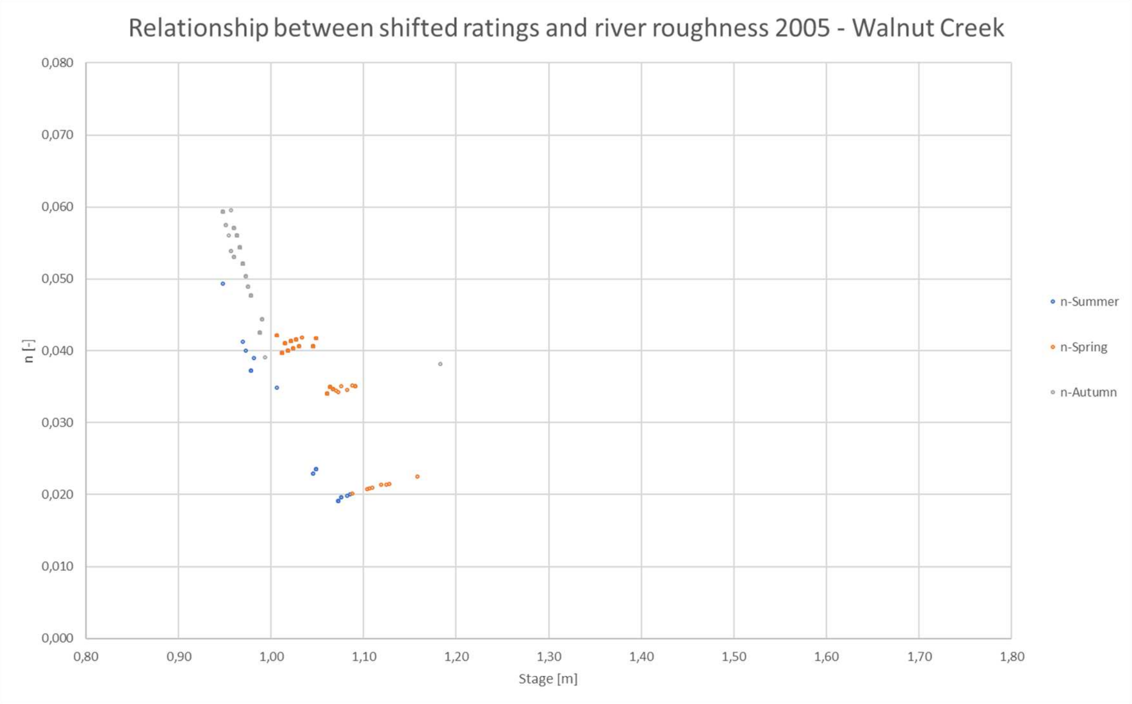
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
19.11.2013 10:59	autumn	0,97	0,24	5	-0,018	-1,21	falling limb
22.10.2013 12:28	autumn	0,91	0,08	5	0,000	0,03	rising limb
04.09.2013 17:31	summer	0,92	0,09	5	-0,012	-0,08	falling limb
23.07.2013 10:00	summer	1,20	2,34	5	-0,018	-3,55	falling limb
29.05.2013 14:29	spring	1,54	6,54	5	-0,034	573,82	rising limb
25.04.2013 13:10	spring	1,15	1,90	5	-0,009	-4,26	falling limb

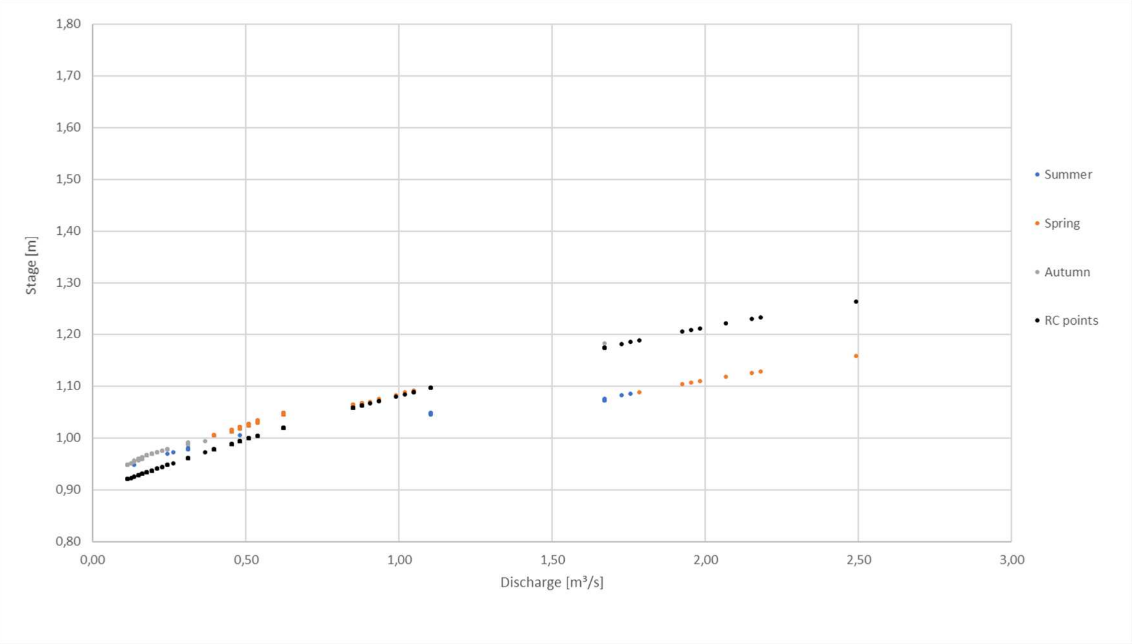


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
16.11.2009 14:40	autumn	1,08	1,20	4	0,037	2,45	rising limb
06.10.2009 15:45	autumn	1,09	1,28	4	0,040	-1,42	falling limb
26.08.2009 14:42	summer	1,43	6,46	4	0,125	19,52	rising limb
13.07.2009 16:38	summer	1,13	1,79	4	0,055	-0,29	falling limb
02.06.2009 06:57	spring	1,38	5,27	4	0,098	-7,57	falling limb
15.04.2009 09:09	spring	1,16	1,86	4	0,037	-0,44	falling limb

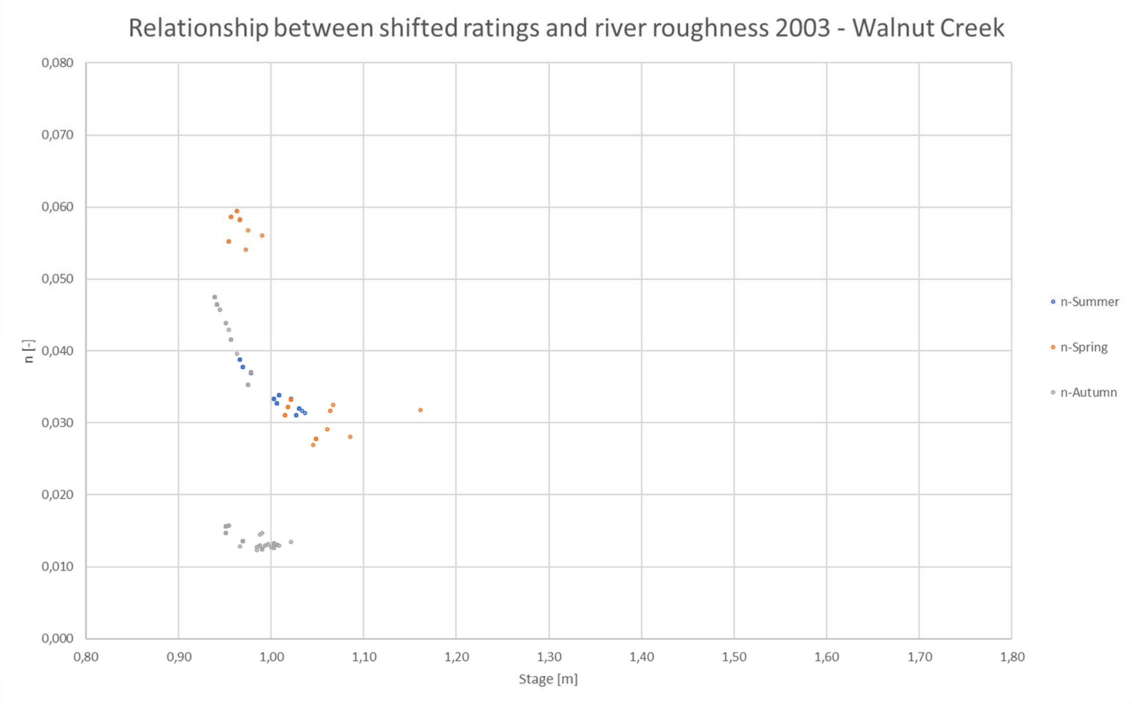


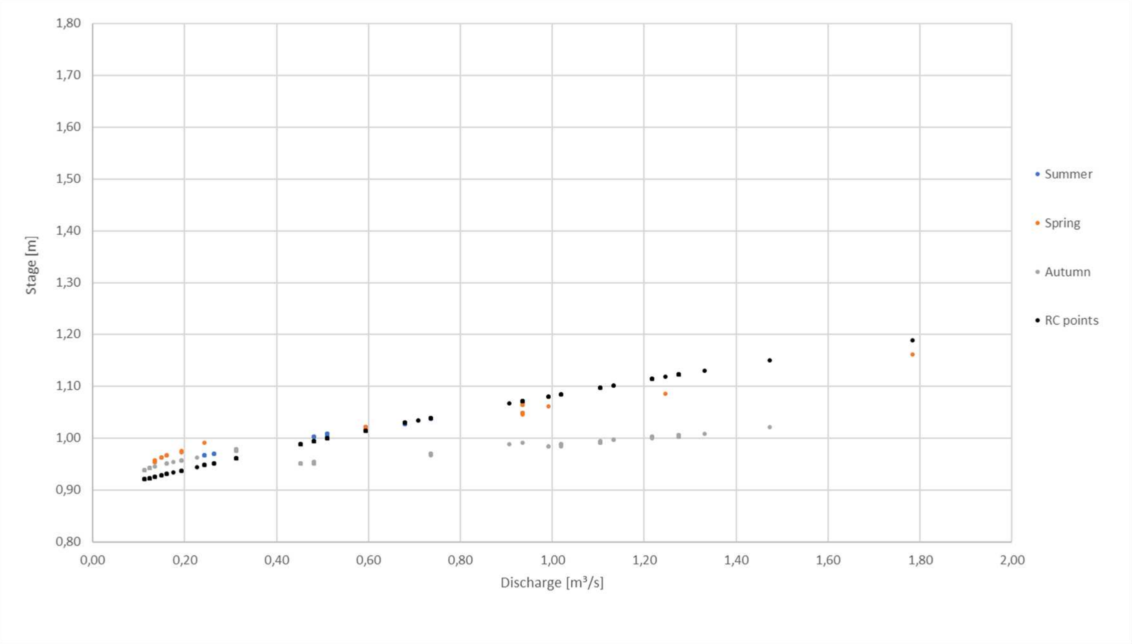
Date and Time	Season	Stage [m]	Discharge [m^3/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
19.12.2007 16:08	autumn	1,14	0,67	4	0,000	0,03	rising limb
14.11.2007 06:59	autumn	1,07	0,85	4	0,000	0,06	rising limb
03.10.2007 11:30	autumn	1,22	2,89	4	0,073	-2,02	falling limb
28.08.2007 11:02	summer	1,01	0,52	4	-0,006	-0,01	falling limb
09.07.2007 16:56	summer	1,03	0,65	4	0,006	-0,04	falling limb
30.05.2007 09:07	spring	1,29	3,77	4	0,079	-0,90	falling limb
25.04.2007 14:11	spring	3,51	63,15	4	-0,107	59,31	rising limb
18.04.2007 08:21	spring	1,21	2,37	4	0,030	0,01	rising limb



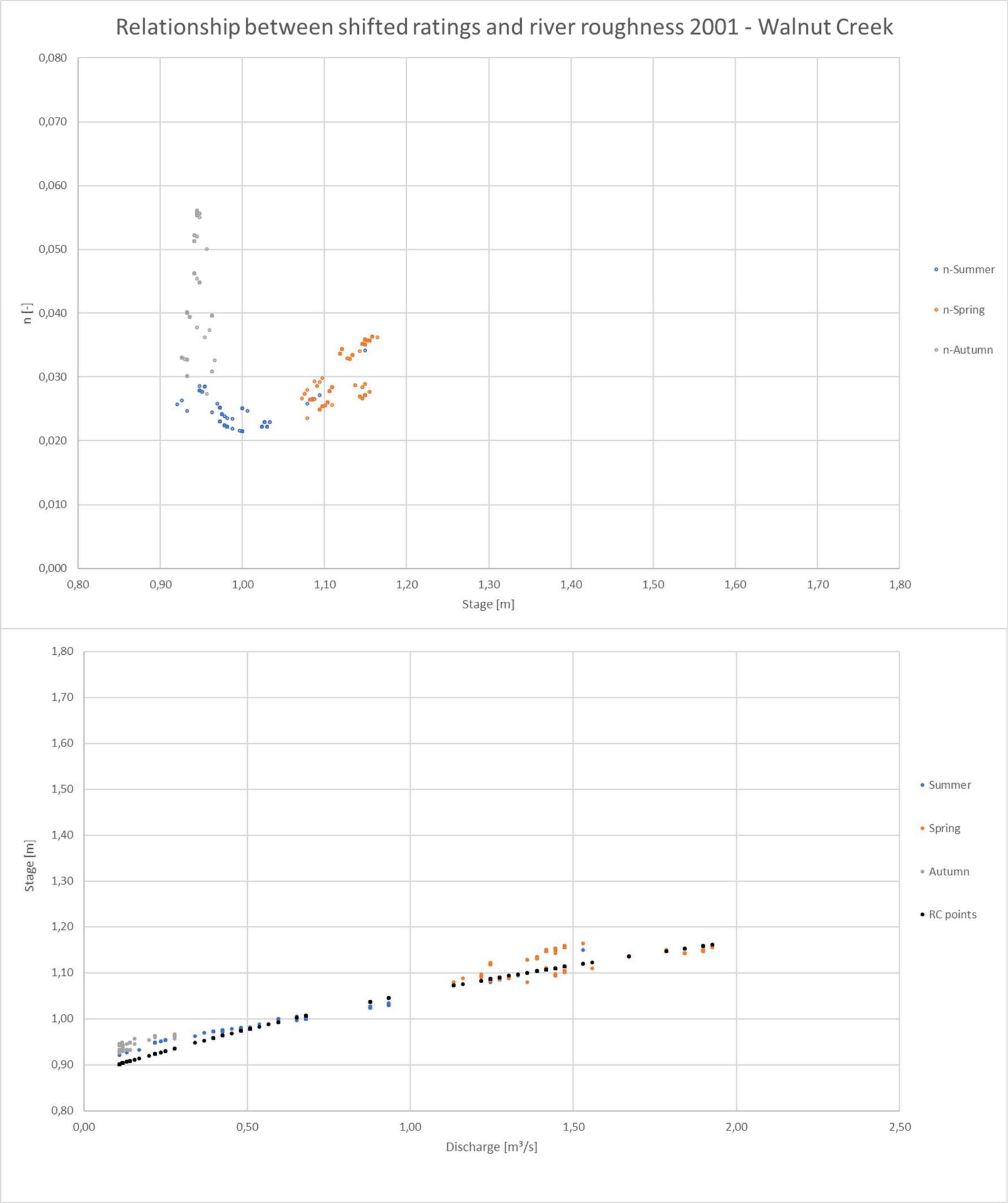


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
17.11.2005 16:39	autumn	0,99	0,14	4	-0,043	-0,05	falling limb
12.10.2005 09:11	autumn	0,95	0,10	4	-0,012	0,00	steady
30.08.2005 13:31	summer	0,93	0,07	4	-0,006	-0,03	falling limb
27.07.2005 14:22	summer	1,06	0,84	4	0,003	-1,47	falling limb
14.06.2005 10:21	spring	1,30	4,11	4	0,098	-0,18	falling limb
02.05.2005 11:40	spring	1,08	0,93	4	0,003	-0,06	falling limb
21.03.2005 16:03	spring	1,01	0,39	4	-0,018	0,00	steady

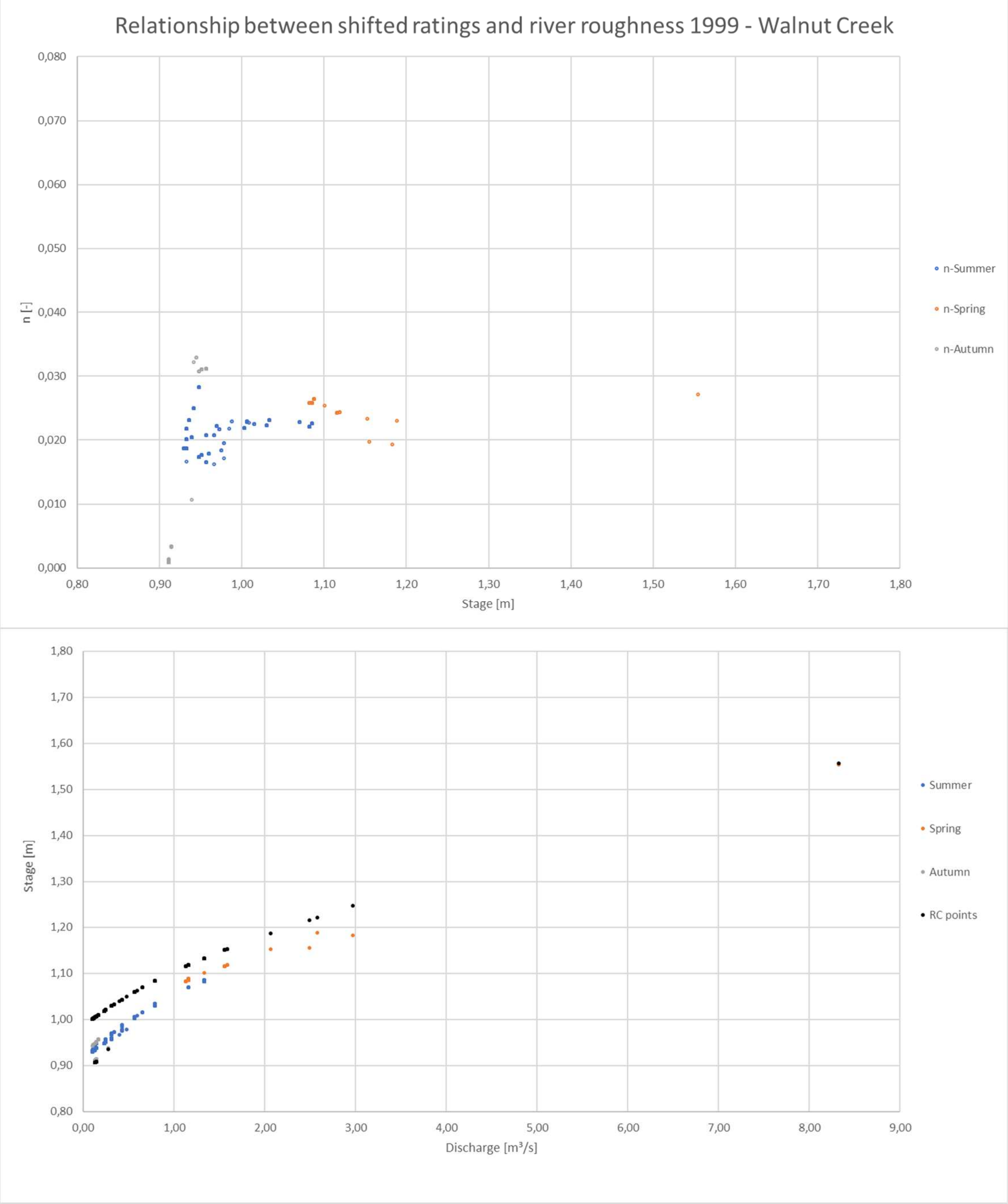




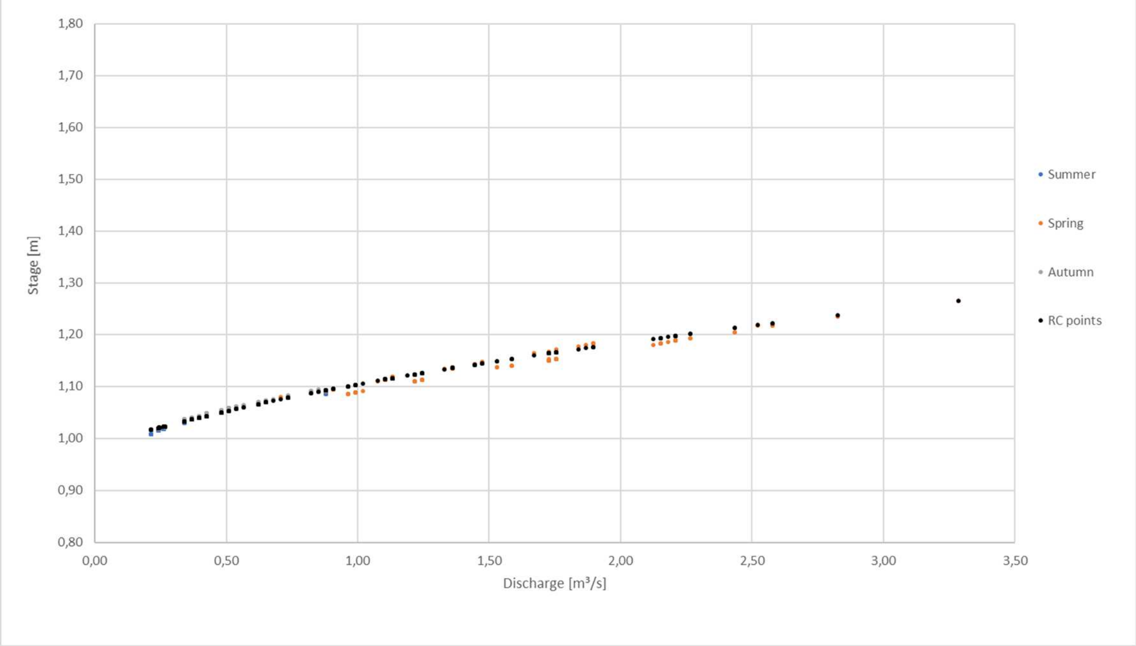
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
15.12.2003 14:00	autumn	0,99	0,23	4	-0,024	0,00	steady
04.11.2003 16:20	autumn	1,36	5,61	4	0,143	51,07	rising limb
01.10.2003 17:15	autumn	0,90	0,02	4	0,000	0,00	rising limb
11.08.2003 16:05	summer	0,95	0,18	4	0,000	0,77	rising limb
01.07.2003 08:28	summer	1,02	0,56	4	0,000	-0,03	falling limb
21.05.2003 11:25	spring	1,14	1,80	4	0,043	0,00	steady
15.04.2003 09:00	spring	0,97	0,19	4	-0,015	-0,10	falling limb



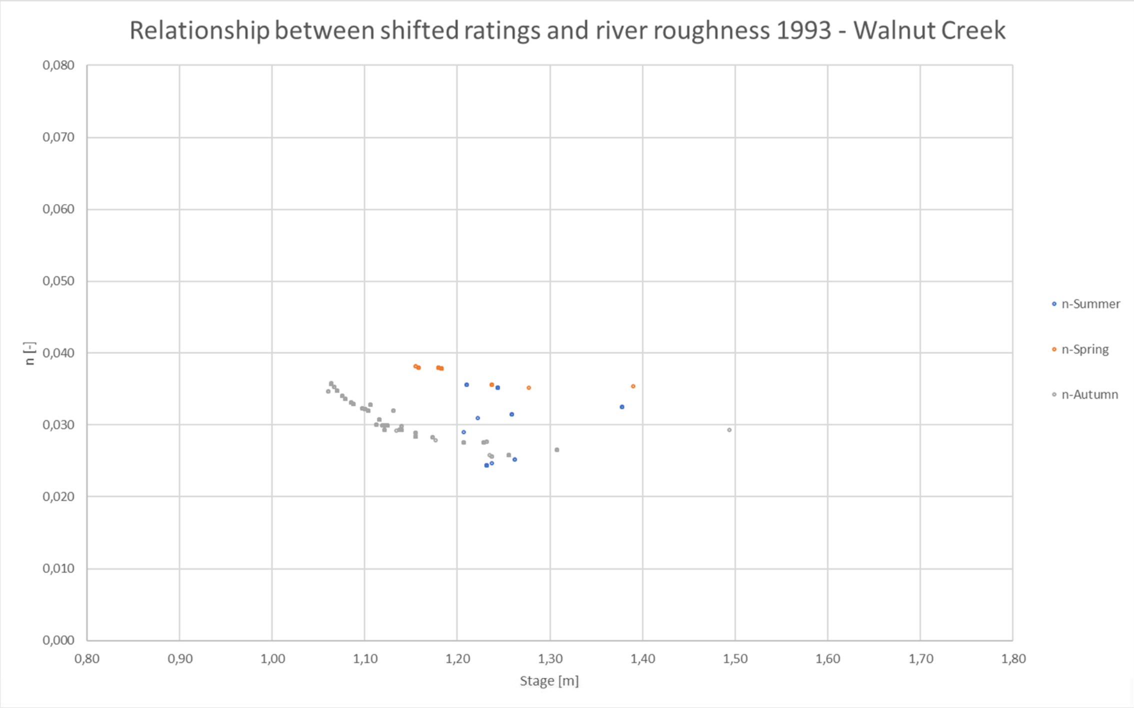
Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
13.11.2001 12:30	autumn	0,97	0,24	3	-0,043	-0,01	falling limb
02.10.2001 09:00	autumn	0,92	0,09	3	-0,024	0,00	steady
22.08.2001 08:35	summer	0,90	0,06	3	-0,015	-0,01	falling limb
10.07.2001 15:30	summer	0,96	0,31	3	-0,021	0,00	steady
23.05.2001 11:25	spring	1,10	1,58	3	0,024	-0,29	falling limb
11.04.2001 08:50	spring	1,45	5,89	3	-0,009	0,43	rising limb

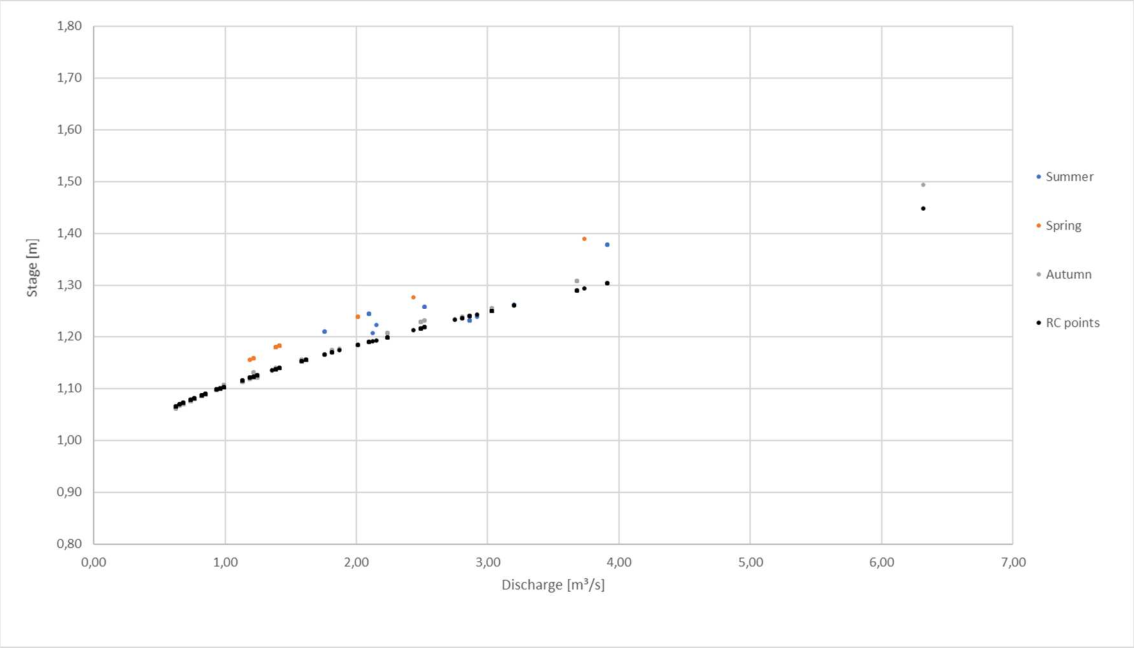


Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
13.12.1999 11:50	autumn	0,91	0,10	3	-0,003	0,00	steady
08.11.1999 11:00	autumn	0,94	0,09	2	0,043	0,00	steady
27.09.1999 14:30	autumn	1,20	2,62	2	0,027	15,41	rising limb
17.08.1999 14:50	summer	0,96	0,42	2	0,082	-0,10	falling limb
28.06.1999 12:15	summer	1,11	1,77	2	0,061	-0,35	falling limb
25.05.1999 11:25	spring	1,37	6,23	2	0,061	-0,31	falling limb
09.04.1999 13:20	spring	1,55	8,24	2	0,000	-69,63	falling limb



Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
18.11.1997 10:45	autumn	1,03	0,33	2	0,000	0,62	rising limb
08.10.1997 11:00	autumn	1,09	0,03	2	-0,143	0,00	steady
21.08.1997 14:00	summer	1,00	0,17	1	0,006	0,00	steady
08.07.1997 10:55	summer	1,07	0,66	1	0,012	0,00	steady
04.06.1997 10:00	spring	1,19	2,21	1	0,067	0,10	rising limb
21.04.1997 14:00	spring	1,16	1,67	1	0,040	0,35	rising limb





Date and Time	Season	Stage [m]	Discharge [m³/s]	Rating Curve	Horiz. Shift Adj. [m]	Slope [-]	Flow State
16.11.1993 16:15	autumn	1,11	0,99	1	0,015	0,00	steady
29.09.1993 11:05	autumn	1,45	5,66	1	0,085	0,37	rising limb
30.08.1993 10:30	summer	2,76	33,70	1	0,000	-102,91	falling limb
25.08.1993 08:50	summer	1,25	2,51	1	0,040	-0,24	falling limb
29.07.1993 10:00	summer	1,37	3,96	1	0,037	-0,30	falling limb
29.07.1993 09:30	summer	1,37	3,82	1	0,027	-0,02	falling limb
02.06.1993 15:50	spring	1,49	5,10	1	0,000	-6,25	falling limb
23.04.1993 13:05	spring	1,31	2,86	1	0,000	-0,27	falling limb