**DRESDEN UNIVERSITY OF TECHNOLOGY**

# Analysis of discharge measurements at Vernagtferner, Ötz Valley, Austria

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Submitted by: Jessica Hanisch
Matr. No. 3472918
Kantstraße 3
73734 Esslingen
E-Mail: jessicahanisch@gmx.de
22.07.2011

Supervisors:

Dr. Ludwig Braun
Commission for Geodesy and Glaciology, Dept. Glaciology,
Bavarian Academy of Sciences and Humanities

Dr. Franz Lennartz
Institute of Hydrology, Dresden University of Technology

IHM

KfG

# Statutory Declaration

I declare on oath that I completed this work on my own and that information which has been directly or indirectly taken from other sources has been noted as such. This work or a similar one has not been published.

July 22, 2011 ______________________________________________

# Abstract

Discharge measurements are an important factor for the determination of the water balance. At the Vernagtferner the water level is continuously measured at a controlled cross section and the discharge is determined via a stage-discharge relation. Concerning the measurement techniques available, the discharge measurements are as reliable as possible. From a hydraulic point of view the discharge measurements are affected by a horizontal tilting of the water surface and an irregular distribution of the flow velocity. The investigation of these two phenomena with measurement data from several years showed that the tilting alone does not affect the determination discharge to a great extent. For the flow velocity a reliable analysis is not possible due to a lack of sufficient information on the velocity distribution throughout the measuring channel. For the area where flow velocity measurements exist, two phenomena are observed: The first phenomenon is that for the same stage the flow velocity doubles in regard to the lowest measured velocity. The second phenomenon is changing stages for the same flow velocity. It is concluded that this is associated with a change in flow regime. The determination of the discharge could be improved by considering the flow velocity in the stage-discharge relation. For a better understanding of the flow velocity measurements at different points would be necessary or a hydraulic model which could possibly determine the cause for the flow velocity phenomena.

# Abstract (German)

Abflussmessungen sind eine wichtige Komponente für die Bestimmung der Wasserbilanz. Im vergletscherten Einzugsgebiet des Vernagtferners wird der Pegelstand in einem kontrollierten Querschnitt kontinuierlich gemessen und der Abfluss mit Hilfe einer Wasserstand-Abfluss Beziehung bestimmt. Unter Berücksichtigung der Möglichkeiten der derzeitigen Messtechnik sind die Messungen des Abfluss als zuverlässig einzustufen. Bei genauerer Analyse, hingegen, zeigen die Messungen eine horizontale Verkippung der Wasseroberfläche im Messkanal und eine ungleichmäßige Verteilung der Geschwindigkeit über das Profil des Messkanals, was die Güte der Messung beeinträchtigt. Die Untersuchungen dieser beiden Phänomene mit Hilfe von Messdaten mehrerer Jahre, haben ergeben, dass die Bestimmung des Abflusses durch die Verkippung alleine nicht maßgeblich verfälscht wird. Für die Geschwindigkeitsmessungen kann keine eindeutige Aussage getroffen werden, da nur punktuelle Geschwindigkeitsmessungen vorhanden sind. In dem Bereich des Messkanals, in dem Geschwindigkeitsmessungen vorhanden sind, können zwei Phänomene beobachtet werden. Das erste ist, dass bei gleichbleibendem Wasserstand die Fließgeschwindigkeit stark schwankt. Das zweite Phänomen ist, dass die Fließgeschwindigkeit für unterschiedliche Wasserstände im gleichen Bereich liegen kann. Für eine genauere Bestimmung des Abflusses wäre es nötig die Geschwindigkeit in der Wasserstand-Abfluss Beziehung zu berücksichtigen und den Erfassungsbereich der Geschwindigkeit zu erweitern. Dies könnte durch zusätzliche Geschwindigkeitsmessonden erreicht werden. Zusätzlich könnte eventuell durch ein hydraulisches Modell die Ursache für die Phänomene der Fließgeschwindigkeit bestimmt werden.

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# 1 Introduction

The measurement of discharge is a key element in hydrology because it is essential for the determination of the water balance. There are many different ways to determine the discharge. However, depending on the location, the measurement of the discharge can be difficult. It is particularly difficult to determine the discharge of glacial catchment areas because of their inaccessibility and the specific characteristics of the discharge. There are only a few gauging stations worldwide where the discharge of a glacier is actually measured and not determined otherwise, for example through the mass balance of the glacier and precipitation measurements. One of these stations is located at the Vernagtferner in Austria. Apart from measuring discharge this gauging station also serves as climate station with direct measurements of precipitation and air temperature. With these as input variables into a runoff model, basin precipitation can be calculated. This approach is needed because it is hardly possible to get reliable measurements of precipitation in mountain regions due to the great variability of precipitation in intensity and space, together with a small monitoring network and large errors in precipitation measurements. The large errors in precipitation measurements are especially due to wind and a high proportion of snowfall (Escher-Vetter & Siebers, 2007)

Compared to measurements of discharge in low-land rivers the measurement of discharge at the Vernagtferner is more complex. The steep slope and the varying amount of discharge throughout the year cause a turbulent flow with high sediment transport and high flow velocities such as 3,5m/s. These conditions are not ideal for discharge measurements using flow anemometers, for instant. In addition the amount of discharge has generally increased over the last decades which made alterations at the gauging station inevitable. These components combined leave a wide range for measurement inconsistencies and unknown impacts on the discharge measurements. One of these impacts is the horizontal tilting of the water surface in the measuring channel. Depending on the amount of discharge the tilting of the water surface changes notably. Besides it seems that the flow velocity has no steady distribution within the measuring channel and that there are changes in the distribution within a day and during the year. The aim of this thesis is to investigate the impact of the tilting of the water surface and the changing distribution of the flow velocity on the discharge measurements on the basis of data from several years with the main focus on data from the years 2009 and 2010.

# 2 Materials and Methods

In this chapter the general measurement methods for the discharge at the Vernagtferner are described. This description is important to understand how and why the tilting of the water surface and the changes in the distribution of the flow velocity affect the measurements. The two phenomena themselves as well as the approach to the analysis will also be described.

## 2.1 Study Site

The Vernagtferner is located at 10°49’ E and 46°52’ W in the Oetz Valley Alps in Austria. The Oetz Valley Alps belong to the drier part of the Alps due to their geographical setting. The annual precipitation in the Oetz Valley Alps varies from less than 1000mm in the valley to 1500mm at high elevation, whereas the annual precipitation in the Bernese Alps, for example, reaches a maximum of 3000mm (Schwarb, et al., 2001). The catchment area extends from an elevation of 2635m to 3633m. The high point of the Vernagtferner is at 3598m, the low point at 2790m in the year 2006. The gauging station of the Vernagtferner is located below the glacier at 2635m (KFG, 2006). It marks the lower end of the catchment area. Figure 1 shows the geographic location of the Vernagtferner.

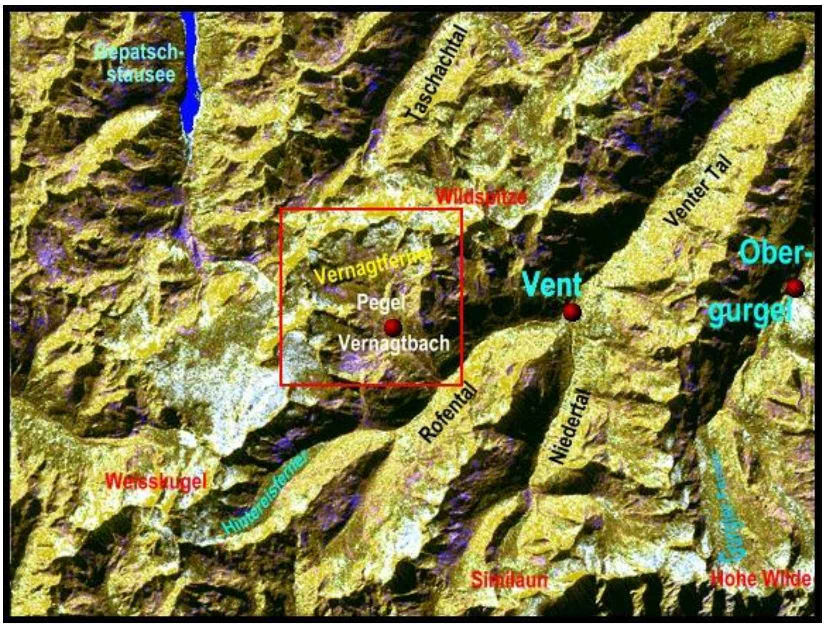


**Figure 1: geographic position of Vernagtferner (KFG, 2006).**

In Figure 1 the red square marks the position of the glacier and the gauging station. The gauging station was built in 1973 and is recording since the fall of 1973. Since then the inflow area of the measuring channel at the gauging station has been altered several times because of changes in the amount of discharge from the glacier and technical improvements (new measurement devices etc.). Table 3 on page 39 in the appendix summarizes the development of the gauging station since 1973.

## 2.2 General Methods

In this paragraph the measurement set up of the gauging station is described. The measuring channel is 2m wide in total, 2m high and has a trapezium profile. The length of the measuring channel is 4,20m not including the inflow area. The measurement principle is a continuous recording of stage level in the measuring channel, and occasional measurements of discharge. With pairs of stage and discharge, an annual stage-discharge relation is determined. There are two methods applied to determine the stage at the gauging station. The first method is via two standing pipes which operate as a system of communicating pipes. The second method is via three ultrasonic sensors which are placed over the profile of the measuring channel at different positions. The Figure 2 shows the measurement set up of the gauging station.

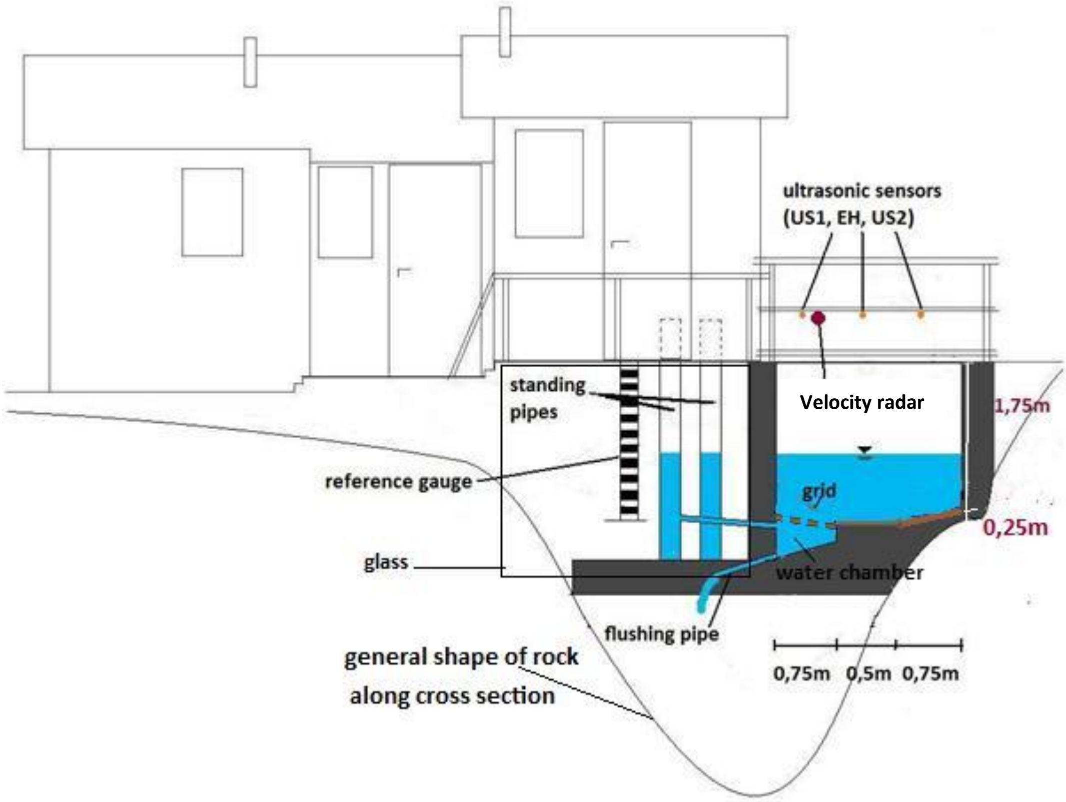


**Figure 2: Measurement principle of gauging station, cross section (Bergmann, 1976) (modified).**

The first method to determine the stage can be described as follows: The water in the measuring channel communicates through a metal grid with a water chamber which is connected with a pipe to two standing pipes, sharing the same water level as in the channel (see Figure 2). In the standing pipes the water level is recorded with a float, connected through a wire to a stage recorder via a deflection pulley and a counter weight. The reference gauge is used to ensure that the zero-point of the measuring channel and the zero-point of the pipes are the same. The metal grid prevents cobbles and stones from entering the water chamber. The flushing pipe is used to evacuate continuously the accumulation of sediment (primarily sand) in the water chamber. It is always open because otherwise the chamber would be silted up within hours. There are two different flushing pipes, a one-inch pipe and a two-inch pipe. In spring the one-inch opening is used, while later in the summer the two-inch pipe is used due to the higher discharge and higher bedload. A correction factor for the stage-measurements during the period using the two-inch pipe is applied to compensate the slightly lowered water level in comparison to the opening of the one-inch pipe. The standing pipes are behind a glass wall. The glass acts as Greenhouse and thus heating through solar radiation prevents early freezing of the water surface in the standing pipes.

The second method to record the stage is via three ultrasonic sensors. The ultrasonic sensors were originally installed to ensure the recording of the stage in case the recording via the standing pipes failed. As shown in Figure 2, the sensors are installed at the bridge which crosses the measuring channel and are directed vertically to the water surface. The sensors are installed at a height of 2.63m above the gauge zero-point, and are in line with the standing pipes. The first sensor is installed on the side of the measuring hut, the second in the middle of the measuring channel and the third on the opposite side of the measuring hut. The two sensors at the sides are CAMPBELL SR 50 sensors (US1 and US2). They have a measurement accuracy of 2cm and they measure the stage every 10 seconds. However, the data is recorded only every 5 minutes which means that the saved data consists of the arithmetic mean of the 10 second data. To ensure that splashes do not impact the arithmetic mean the data is filtered and outliers are not included in the arithmetic mean. The beam acceptance angle is approximately 22°. The middle sensor is an Endress and Hauser ultrasonic sensor. It has the same measurement accuracy. Although the manufacturer of the sensors differs, the operation mode is the same. The figure below shows the measuring principle of an ultrasonic sensor.

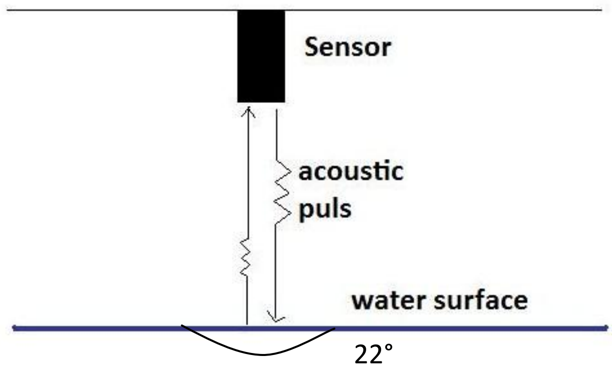


**Figure 3: measuring principle ultrasonic sensor.**

The sensor sends acoustic pulses to the water surface which are reflected by the water surface and reflected to the sensor. By measuring the time between the sending and receiving of the pulses the distance from the sensor to the water surface is determined (Maidment, 1993). Since the speed of sound varies with the air temperature it is necessary to measure the air temperature and to correct the signal (Campbell, 2003). To prevent an overlapping of the measuring signals of the sensors the sensors send their pulses at different times.

The flow velocity is recorded via the RG-24 flow velocity sensor manufactured by Sommer Mess- und Systemtechnik (Koblach, Austria). It faces the stream upward and is installed at the same height as the ultrasonic sensors. The measurement principle is based on the Doppler impact as shown in the Figure below.

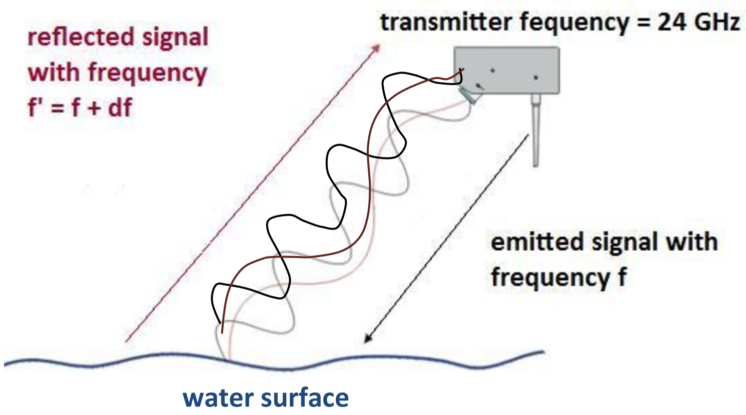


**Figure 4: Principle of the Doppler impact for RG24 Sensor (Sommer, 2009) (modified).**

The sensor sends a signal with a known frequency which is 24 GHz in the case of the RG24. When the signal hits the surface of the water it is reflected back to the sensor. Depending on the flow velocity the frequency is altered. Via the difference in the frequency the flow velocity can be determined. Due to the irregularity of the water surface the signals received vary. To determine a clear signal the raw data are being filtered and a spectral analysis is applied. In a final step certain statistical and mathematical methods are applied to achieve a reliable water flow velocity (Sommer, 2009).

In order to determine discharge continuously, a stage-discharge relation has to be defined to convert stage value (cm) to discharge ($m^3/s$). At the Vernagt gauging station the stage-discharge relation is determined by the “Slug” Injection Method (also called Integration Method) with table salt as a tracer. It is applied up to 50 times during the year to get discharge measurements for different stages which ensure a reliable stage-discharge relation. The Integration Method is based on an injection of a known value of a salt-water solution and the measuring of the electrical conductivity in the creek after a defined distance. Thereby the conductivity is directly related to the concentration of salt in the water. By integrating the concentration over time in relation to the concentration before and after the injection, the discharge is inversely related to the integral in Equation 1 (Herschy, 1999). Figure 5 shows the general schematic measurement principle of a discharge measurement via the Integration method. It shows only the general application of this method which differs in some details from the application of this method at the Vernagtferner due to special measurement conditions.

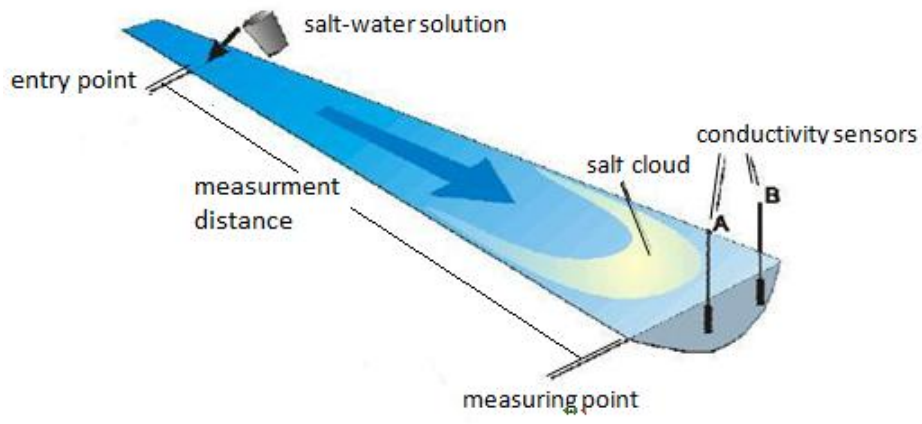


**Figure 5: schematic diagram of the slug injection (Grust, 2001) (modified)).**

At the entry point the entire salt-water solution is injected into the creek above the station. The amount of the salt needed for the solution is depending on the basic conductivity of the creek water and the expected amount of discharge. During the measurements the peak conductivity should be higher by 30-50% than the basic concentration, in order to receive an adequate measurement (Grust, 2001). Before the measurements take place the conductivity sensors need to be calibrated. The calibration coefficient (α) is determined to get the relation between the salt concentration and the electrical conductivity. It is assumed that this relationship remains constant with time; however, this should be checked repeatedly. Depending on the flow conditions of the creek the distance between the entry point and the measuring point varies. At the Vernagtferner the flow conditions are very turbulent which means that the mixing of the salt with the ceek water happens quickly and therefore the distance between entry point and measuring point is a set distance of 300m each year. Due to the high turbulence of the Vernagt creek the conductivity sensors cannot be placed directly in the ceek as shown in Figure 5, but in the outflow from the water chamber (area below the grid in the measuring channel) where the tubulence is reduced. Two sensors are used in parallel and are connected to data loggers which record the conductivity measurements and the time. For the measurements at the Vernagt creek one sensor is placed on the bottom of the inflow area of the water chamber.The second sensor is placed in a hopper where the conductivity sensor that constantly records the electric conductivity is installed. In the appendix on page 40-41 Figure 29-31 show the placement of the two sensors.

Depending on the reliability of the measurement either the measurement of the first or the second sensor or both are being used for the determination of the stage discharge relation. For example the measurements of the first sensor can sometimes not be used due to development of air bubbles during the measurment. The measurement can be terminated, once the coductivity is stable again and accordingly the initial conductivity is nearly reached again. For measurement at the Vernagt creek, however, the termination of the measurement depends on whether they take place during a rising stage level or not. In case of a rising stage level the dilution of the salt is higher, therefore the measurement cannot be terminated until the electric conductivity is below the initial electric conductivity. The calculation of the discharge is based on the following equation:

$$D = \frac{M}{\alpha \int_{t_0}^{t_1} (L_1 - L_0) dt}$$

**Equation 1 (Grust, 2001)**

D = discharge

M = amount of salt

α = calibration coefficient

$L_1$ = conductivity at measuring point

$L_0$ = inital conductivity

dt = measuring interval

$t_0$ = time at beginning of measurement

$t_0$ = time at end of measurement

To check the plausibility of the measurement, the calculated discharges as given by the two sensors are compared. The smaller the difference between the two sensors the more reliable is the measurement. For the determination of a pair of values for the stage-discharge relation the point of time at the maximum of the electric conductivity is allocated with the stage measurement at the same point of time. At the Vernagtferner the stage-discharge relation is defined over one year with about 20-30 pairs of stage and discharge, ideally covering the full range of discharge. To convert the stage into discharge the stage measurements of the standing pipes are used. The stage measurements of the ultrasonic sensors are only used to fill data gaps and to study surface tilting in the measuring channel. In the appendix on page 40 the stage-discharge relation of the year 2009 is as an example diagramed in Figure 28.

## 2.3 Data

All the data used for the investigation are based on the measurement methods described above. They are supplied by the Commission for Geodesy and Glaciology of the Bavarian Academy of Sciences and Humanities. In general the stage measurements of the standing pipes are considered the most reliable. They are used for the determination of the stage-discharge relation and for the overall determination of the annual discharge. For each recorded stage of the standing pipes, stage measurements from the three ultrasonic sensors and a flow velocity measurement from the velocity sensor can be assigned. Consequently each stage can be assigned to a tilting condition and a flow velocity.

The stage and flow velocity measurements that are recorded at the same time as the discharge measurements via the Integration method are used as reference measurements for the entire stage and flow measurements within the same year. They are the only measurements for which a measured discharge by a standard measurement method exists and which can be assigned to a certain tilting condition and a flow velocity.

Most measurements have a resolution of five minutes. However, the velocity measurements have a resolution of one minute and are transformed into five minute data which conform to the stage measurements in resolution and time of recording. The large amount of data used, as well as the calculations is included on a CD at the end of the appendix.

## 2.4 Phenomena Observed

With the measurement techniques available, the determination of the discharge at the Vernagtferner is as reliable as possible under the turbulent flow conditions and the changing conditions of the inflow area. From a hydraulic point of view there are some concerns in regard to the reliability of the measurements. In the following two phenomena that most likely affect the reliability of the discharge measurements will be described.

The first phenomenon observed in the measuring channel is a horizontal tilting of the water surface. In Figure 6 this tilting is diagrammed for August 18$^{th}$ 2009 at 05.30pm with red dots. The stage at the ultrasonic sensor US1 is 103cm, at the Endress and

Hauser ultrasonic sensor 106cm and at the ultrasonic sensor US2 110cm which creates a difference of 7cm between the US1 and US2 sensor. Besides the stage recorded for the same time at the standing pipes is 88cm and is included in Figure 6 with a blue line. Compared to the stage recorded at the ultrasonic sensor US1, there is a difference of 5cm between the standing pipes and the US1 ultrasonic sensor. These differences lead to the assumption that the stage recorded in the standing pipes is too low for the actual stage and that the stage is generally higher at the ultrasonic sensor US2 and therefore a general underestimation of the stage takes place.

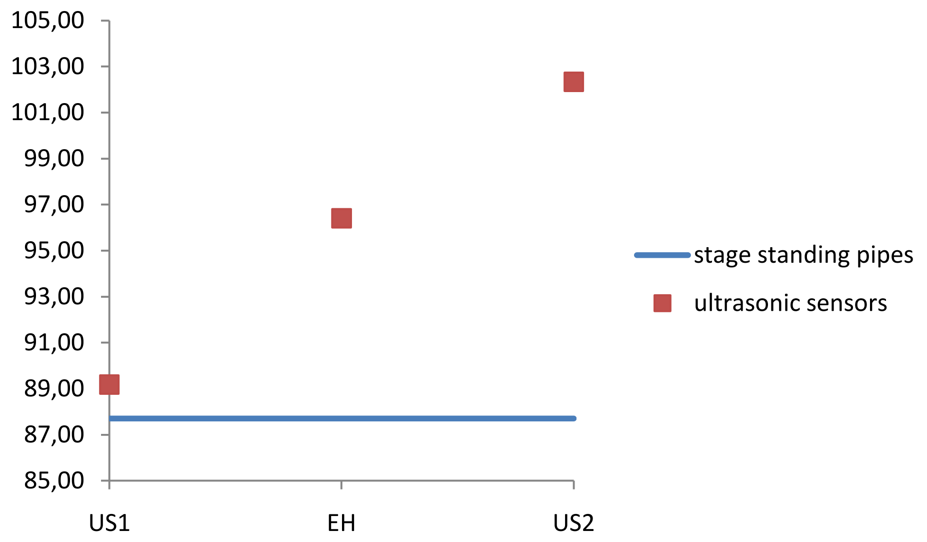


**Figure 6: Tilting in the respective measuring channels at 18.08.2009, 17:30.**

This assumption, however, does not apply for all stage measurements. Taking into account that the measuring reliability of both the ultrasonic sensors and the standing pipes is +/- 2cm, the stage measurement of the standing pipe and the ultrasonic sensor US1 becomes about the same. The stage measurements via the ultrasonic sensors show that in general the tilting of the water surface is not constant and is changing with no apparent regularity. Figure 7 shows the tilting for June 21$^{st}$, 2009.

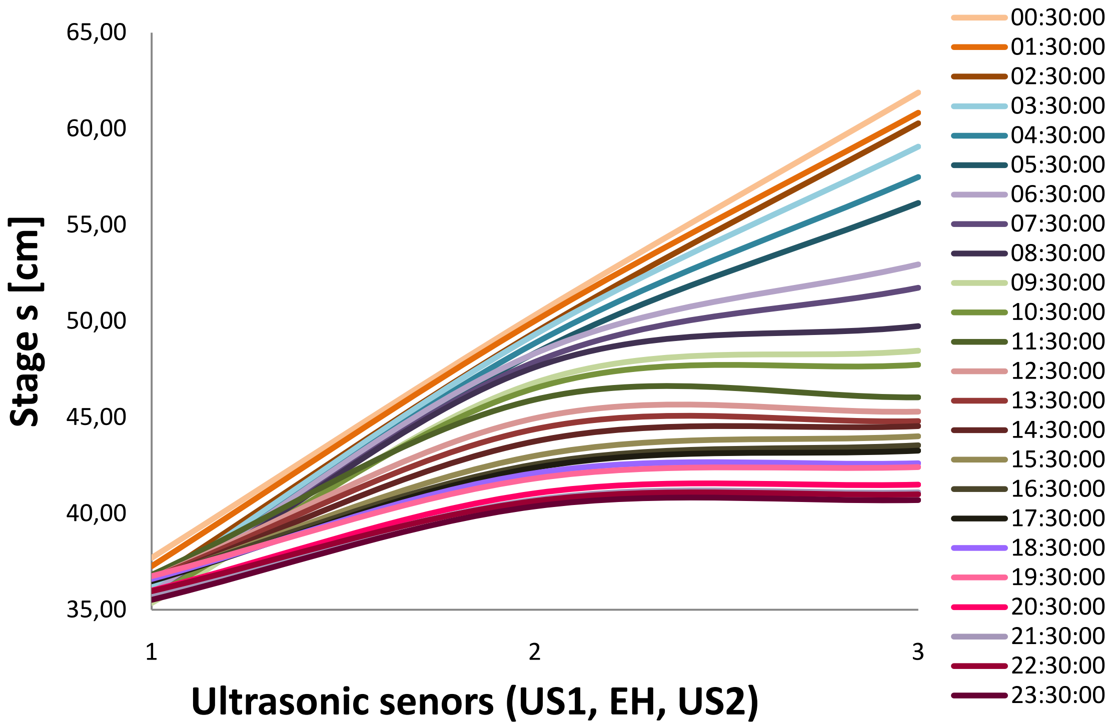


**Figure 7: Tilting of the water surface 21.06.2009**

The amount of tilting of the water surface varies throughout one day. Sometimes the difference between the ultrasonic sensor US1 and the ultrasonic sensor US2 are just 2 or 3cm. However, the difference can be as large as 45cm. In a few cases the stage at the side of the US1 sensor is higher than the stage at the US2 sensor but in most cases the stage is higher at the US2 sensor which is the opposite site of the standing pipes. In addition it is only possible to define the stage by the three measuring points of the ultrasonic sensors, and it is not possible to determine whether the stage runs as displayed in Figure 6 and 7 between the three points. In the appendix on page 42-44 Figure 32-37 show a variety of different cases of the tilting. The reason for the occurrence of the tilting cannot yet be clearly determined. Possible causes for the tilting will be discussed in Chapter 4.

The second phenomenon observed is an irregular distribution of the flow velocity. Unlike the usual distribution of flow velocity, the maximum of the flow velocity is not in the middle of the measuring channel but more to one side of the measuring channel. This phenomenon was first discovered in 1999 via velocity measurements with a hydrometric vane. This measurement showed that the maximum of the flow velocity is more to the left towards the side of the measuring hut. On the opposite side of the measuring channel the flow velocity was significantly smaller (Stätter, 1999). Figure 8 shows the velocity profile for August 15th 1999.

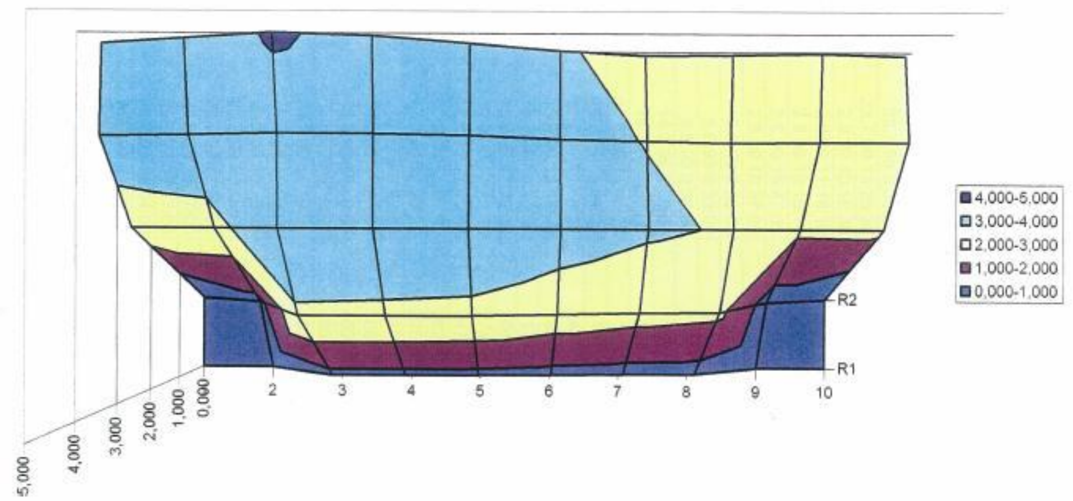


**Figure 8: velocity profile of cross section of measuring channel 15.08.2006 04.00 pm (Stätter, 1999)**

This is only a snapshot and the conditions of the flow velocity do not remain the same. It seems that there are two different velocities regimes, a faster one and a slower one. Whether the two flow velocity regimes cause changes from supercritical flow conditions to subcritical flow conditions is not yet determined. In order to get a better idea of the flow velocity at the water surface, the RG-24 velocity radar was installed in 2007. The data recorded by the RG-24 only capture a small spot of the water surface and do not give detailed information about the velocity distribution in the measuring channel. It allows, however, the investigation of the characteristics of the flow velocity for the captured spot.

## 2.5 Analysis

All measurements rely on the discharge measurements of the Integration method and by extension on the thereby determined stage-discharge relation. Therefore, the reliability of the stage-discharge relation is an important factor. The reliability of the stage-discharge relation depends on the sensitivity of the stage-discharge relation and the consistency of the measurement data. The sensitivity of the stage-discharge relation is investigated within this study by determining an eight year stage-discharge relation based on the measurement data of the annual stage-discharge relations from the year 2003 to 2010. For the determination of the eight year stage-discharge relation the pairs of values (stage, discharge) from the years 2003 and 2010 are included. Based on these pairs of values a fitting curve is applied and thereby the function of the eight year stage-discharge relation is defined.

By a recalculation of the annual amount of discharge with the eight year stage-discharge relation, deviations from the amount of discharge from the annual stage-discharge relation are determined. For the calculation the stage measurements of the standing pipes are used. Before the calculation of the discharge, all stage measurements need to be calibrated to the one-inch flushing pipe opening in order to provide the same measurement accuracy for all stage measurements. For this purpose, a correction factor of 0.7cm is added to all measurements recorded during the two-inch opening of the flushing pipe. The aim of the investigation of the stage-discharge relations is to show whether the application of an eight-year stage-discharge relation is reliable enough or if the determination of an annual stage-discharge relation is essential.

The investigation of the impact of the tilting on the determination of the annual discharge is performed for the years 2009 and 2010. To estimate the impact, the tilting conditions and stage measurements that are assigned to the discharge measurements of the integration method are analyzed and compared as reference values to the tilting conditions at similar stages within the same year. The tilting conditions and stage measurements of the discharge measurements can be used as reference values due to the fact that the measured discharge includes these specific tilting conditions and therefore are considered in the relationship. These specific tilting conditions and stage measurement are later referred to as “reference tilting condition” and “reference stage”. If the tilting conditions of the measured discharge are approximately even with the tilting conditions for similar stages, the impact of the tilting would be insignificant.

To assign each tilting condition with a reference tilting condition the stages of the reference tilting conditions are compared to similar stages. For this purpose the reference stages are divided into intervals of +/- 2cm. This interval conforms to the measuring accuracy of the standing pipes as well as the ultrasonic sensors. Consequently all stage measurements that fall within an interval can be compared to a reference tilting condition. Ideally, the intervals cover the full range of stages. If this is not the case the impact of the tilting of these stages cannot be determined. The aim of this investigation is to classify the data by the tilting conditions and to assess whether the tilting conditions conform to the reference tilting condition, or whether they are underestimated or overestimated by the reference tilting condition.

For the classification of the data from the years 2009 and 2010, the data is divided into three groups. The first group contains the data that can be assigned to a reference value. The second group contains the data that cannot be assigned to a reference value because there is no reference stage and the third group contains the data that cannot be assigned to a reference tilting condition because the stage height is below 25cm. If the data is below 25cm the ultrasonic sensors US1 and US2 can no longer record reliable data due to the trapezium profile of the measuring channel (see Figure 9).

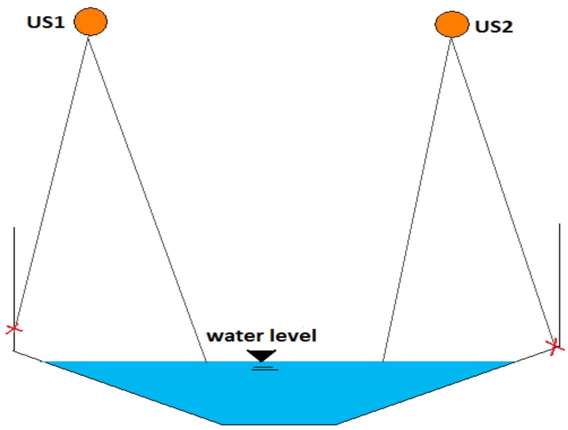


**Figure 9: 25cm boundary of US1 and US2.**

In a next step the data that can be assigned to a reference tilting condition will be further divided. This division is based on whether the tilting condition conforms to the reference tilting condition, is below the reference tilting condition or is above the reference tilting condition. For this division, the deviations between the reference tilting condition and the actual tilting condition are calculated in percent. The aim of this investigation is to determine whether the tilting is generally underestimated or overestimated.

The same classification as for the tilting conditions is performed for the flow velocity measurements for the year 2010. For the year 2009 the investigation is not possible due to a lack of velocity data for the entire year. Furthermore the flow velocity data is analyzed by a different approach for the years 2009 (starting July) and 2010 to investigate if there are significant inconsistencies that could affect the estimation of the discharge. This investigation is based on the visualization of the velocity data by plotting the velocity against the stage and the time. Together with the results of the first two analyses the impact caused by the two phenomena is estimated.

# 3 Results

## 3.1 Results of Analysis of the Stage-Discharge Relations

The analysis of the stage-discharge relation showed that the maximum deviation from the annual defined stage-discharge relation to the eight year stage-discharge relation is 13%. In Table 1 all the deviations from the eight year stage-discharge relation are summarized.

| year | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|
| Deviation [%] | 13,2 | 6,3 | 8,6 | 9,1 | 6,36 | -12,2 | -13,1 | 11,7 |

**Table 1: Deviations between the annual and eight-year stage discharge relation [%] from the mean of all 8 years**

In the years 2008 and 2009, the discharge would be underestimated by the mean eight year stage-discharge relation. For all other years, the discharge would always be overestimated. For four years the deviations between the annual stage-discharge relation and the eight year stage-discharge relation is below 10%. In the appendix on page 44 Figure 38 shows the eight year stage-discharge function including the equation which is the basis of these results. The calculations and data of the stage-discharge relation are included on the attached CD.

## 3.2 Results of Analysis of Tilting

The investigation of the tilting showed that the stage measured increases generally from the ultrasonic sensor US1 to the ultrasonic sensor US2. In comparison to the reference stage measurements in the standing pipes, the deviations were smallest to the US1 ultrasonic sensor. This indicates the problem addressed as tilting. The Figures 10 and 11 show the deviations between the stage measurements of the standing pipes and the three ultrasonic sensors for the years 2009 and 2010. All deviations from the reference stage measurements are in percent and plotted against the time.

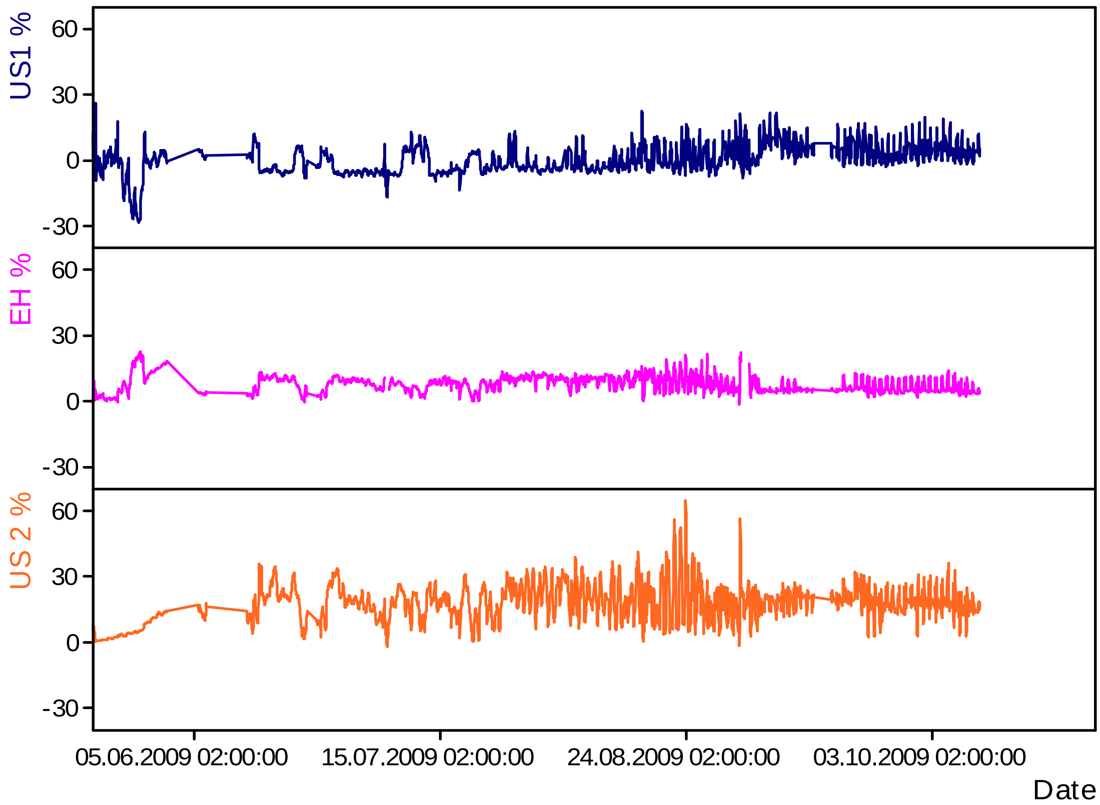


**Figure 10: Deviations in % from reference stage measurements for US1, EH, US2 during the year 2009.**

In Figure 10, the change of the deviations of the three ultrasonic sensors over time is shown for the year 2009. For the ultrasonic sensor US1 the main share of the values is within an interval of 5-15%. For the middle sensor EH the main share of the values is within an interval of 15-30%, and for the US2 sensor the main share of the values lies within an interval of 20-45%. Figure 10 shows the same for the year 2010, only here the deviations are greater than for the year 2009.

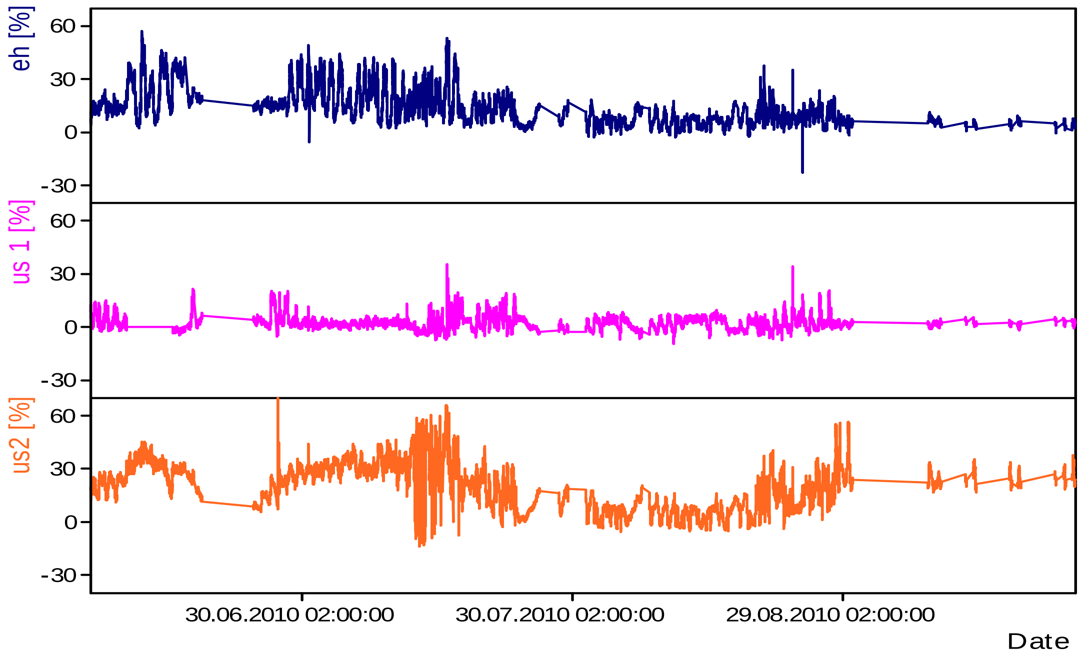


**Figure 11: Deviations from reference stage measurements in % for US1, EH and US2 during the year 2010**

In Figure 11, the main share of the values of the US1 sensor lies within an interval of 10-20%. For the EH sensor the main share lies within an interval of 20-40%, and for the US2 sensor within interval of 30-60%. Compared to the previous year the deviations are slightly greater. Nevertheless, in total the three sensors seem to correlate better with each other in terms of the occurrence of the deviations. (Note the deviations that remain constant for a long period of time are the result of the use of the ultrasonic sensor US1 as gap filler for missing stage measurements of the standing pipes)

Given that for the year 2009 the deviations between the reference stage measurements and the US2 sensor go up to 45% and for the following year up to 60%, the impact on the discharge measurements should be significant.

The next investigation of the impact of the tilting on the discharge measurements is to statistically analyze the measurement data of the year 2009 and 2010 in reference to the tilting conditions of the discharge measurements. For this purpose the data is first divided into data with a reference tilting condition (data that falls within an interval of a reference stage measurement), data with no reference tilting condition and data for which the tilting cannot be determined because the stage level is below 25cm. Figure 12 shows the percentage of the data of each group.

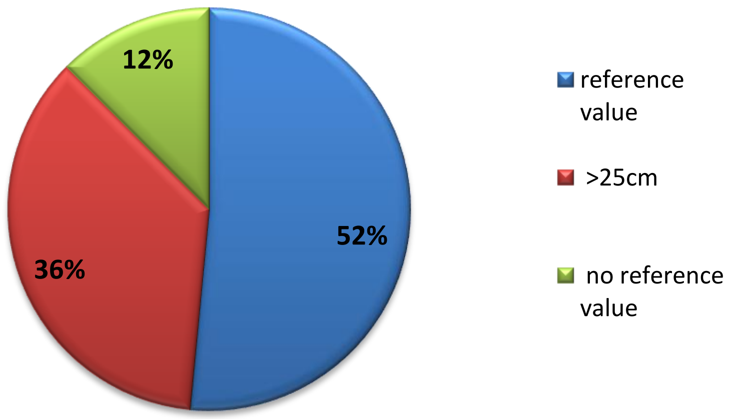


**Figure 12: Classification of the data in % for the year 2009.**

For the year 2009, 52% of all stage measurements were within an interval of a reference stage, 36% could not be classified because they are below 25cm, and 12% could not be classified because they did not have a reference stage measurement. In total more than half of the data could be classified. In the appendix on page 47 Table 5 shows the reference values from the stage-discharge relation of the year 2009.

For the year 2010, there are not as many reference values available and consequently the amount of data with a reference value is smaller. Only 17% of the entire data could be classified. 58% of the data were below 25cm and for 25% of the data there was no reference value. In the appendix on page 45 Figure 38 summarizes the classification of the year 2010 and on page 46 Table 4 summarizes the reference values.

After the classification of the data, the classifiable data was divided into three new groups. The first group contains the data where the deviation of tilting condition of the reference value compared to the actual value is between +/-10%. The second group contains the data that is below -10% and the third group contains the data that is above 10% of the data. Figures 13 and 14 show the results of this division for the years 2009 and 2010.

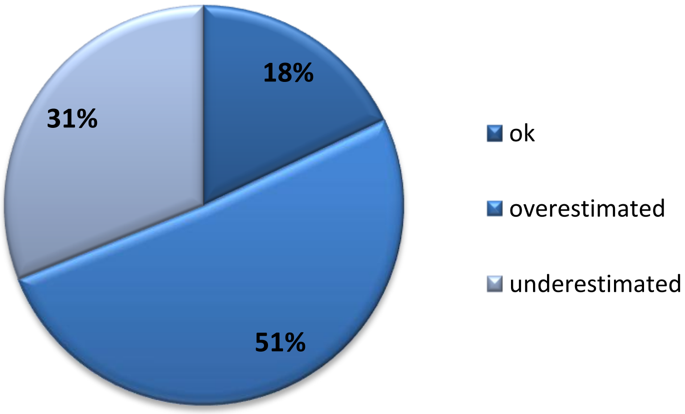


**Figure 13: Classification of tilting conditions for the data of the year 2009.**

Figure 13 shows that for the year 2009, 18% of the data fall into the interval with an acceptable deviation from the reference tilting condition. In 31% the tilting is underestimated by the reference tilting conditions. In 51% the tilting is overestimated. Consequently the amount of discharge should be lower if the tilting is taken into consideration for the calculation of the discharge. Figure 13 shows the same division of the values for the year 2010.

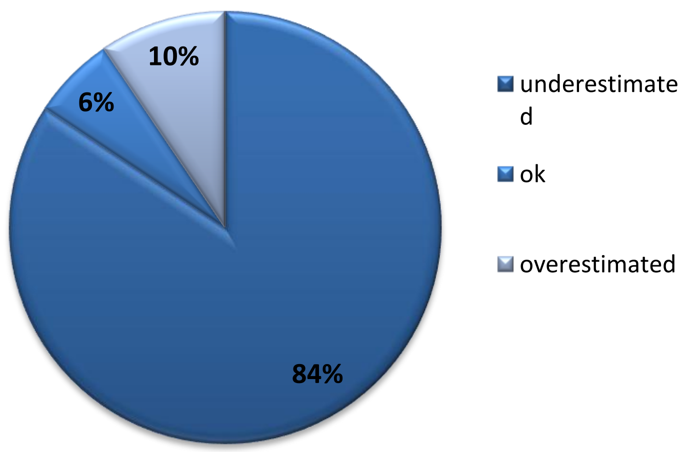


**Figure 14: Classification of tilting conditions for the data of the year 2010.**

For the year 2010, the tilting is underestimated in 84% by the reference tilting condition. In 10% of the data the tilting is overestimated and only 6% of the data conform to the tilting condition of the reference tilting condition. By underestimating the tilting, the discharge is most likely also underestimated.

The differences in over- and underestimation of the tilting between the two years are a result of different reference values. For the year 2009, the reference tilting conditions show a greater difference between the US1 and US2 ultrasonic sensor, than for the year 2010. In addition the amount of reference values for the year 2009 is higher. The stage-discharge relation of the year 2009 is based on 50 measurements with a maximum in difference of 24,6cm between the US1 and US2 ultrasonic sensor. The stage-discharge relation for the year 2010 is based on 27 measurements with a maximum of 13,5cm in difference between the US1 and US2 ultrasonic sensor. Besides in 15 out of the 27 measurements the maximum of the stage is not measured at the US2 sensor but at the US1 sensor. These differences become also noticeable when analyzing the distribution of the deviations of the actual tilting conditions from the reference tilting conditions. The following two pie charts show the differences between the two years in distribution of the deviation values in percent.

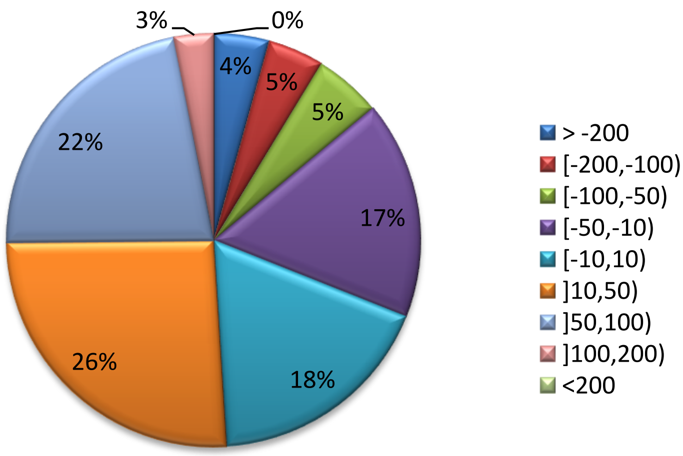


**Figure 15: Distribution of deviations from reference tilting in % for the year 2009.**

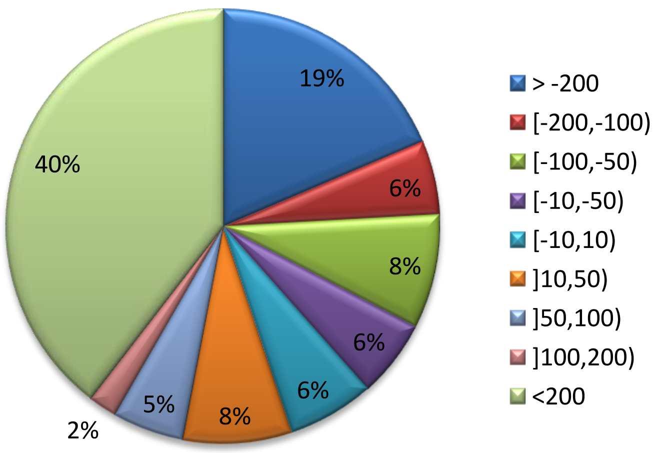


**Figure 16: Distribution of deviations from reference tilting in % for the year 2010.**

For the year 2009, 61% are within an interval of +/-50% from the reference tilting condition. 88% are within an interval of +/- 100% and only 12% deviate more than +/- 100-200%. In the year 2010 only 20% are within an interval of +/- 50% and 59% are higher or lower than +/- 200%. Consequently, the application of a correction factor for the calculation of the discharge should have a greater effect on the result for the year 2010 than for the year 2009.

For the estimation of the impact of tilting on the determination of the discharge, the discharge for both years is recalculated by applying a correction factor. By applying a correction factor the underestimation or overestimation of the tilting conditions will be corrected to the reference tilting condition. By correcting the tilting condition to the reference tilting condition the tilting does no longer impact the determination of the discharge since the reference tilting conditions are included in the discharge measurements.

The correction factor is based on the assumption that the tilting determined by the ultrasonic sensor US1 and US2 is approximately linear. In reality this is not the case. For the estimation of the impact on the determination of the discharge this approach can be justified due to the fact that a more precise approach is not possible since a reliable description of the water surface based on three measuring points cannot be achieved. The following photograph will show the roughness of the water surface. This shows that a more accurate definition of the run of the tilting would go beyond this analysis.

**Figure 17: Photography of measuring channel 18.07.2006 (Foto obtained from M. Siebers).**

The correction factor is determined by the percentage deviation from the actual tilting condition to the reference tilting condition. This deviation is converted in the cm value and divided by two. The division compensates the difference between the ultrasonic sensors US1 and US2. Depending on whether the tilting was underestimated or overestimated, the correction factor is either added or subtracted from the stage measurement. Based on the stage-discharge relation a new discharge with the corrected stage values is calculated. For the year 2009, the recalculation of the discharge showed a difference of -3% compared to the calculation of the discharge without the correction. For the year 2010, the recalculation of the discharge showed a difference of 5.4% compared to the calculation without correction. As indicated by the investigation of the data of the underestimation and overestimation of the tilting conditions, the discharge for the year 2009 was overestimated and for the year 2010 underestimated.

## 3.3 Results of the Analysis of the Flow Velocity Data

The analysis of the flow velocity data showed that there are two phenomena that could affect the discharge measurements. The first phenomenon is a wide spread of different flow velocities at one and the same stage. In Figure 18, the velocity data is visualized for the year 2010.

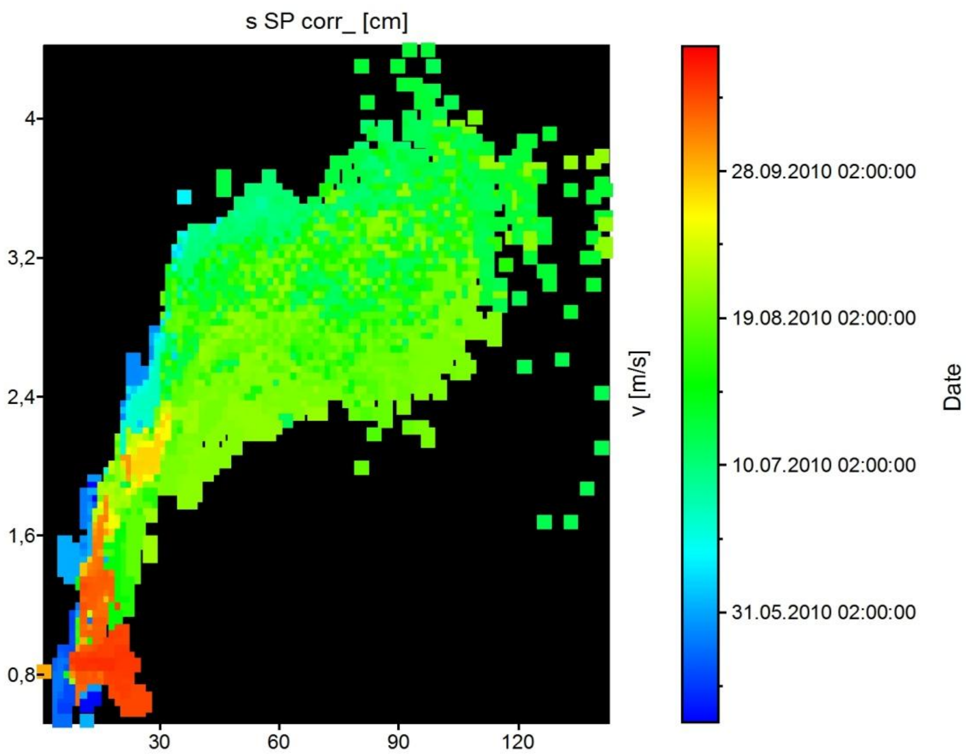


**Figure 18: velocity data plotted against time and stage for the year 2010.**

In Figure 18 the axis labeled *s SP corr_[cm]* represents the stage measurements of the standing pipes and *v* represents the velocity. Both quantities are plotted against the time. During the period of mid July until the end of August, the velocity data shows a wide range of different velocities for the same stages. If, for example, we examine the stage of 90cm, the range for the velocity data goes from about 2m/s up to 4m/s. At the given stage, the flow velocity can double in regard to the slowest measured velocity at that stage. It seem that the higher the stage, the higher the range of flow velocities. But even at lower stages a range of different flow velocities still exists. In the Figure below this phenomenon is visualized for two points in the year 2010.

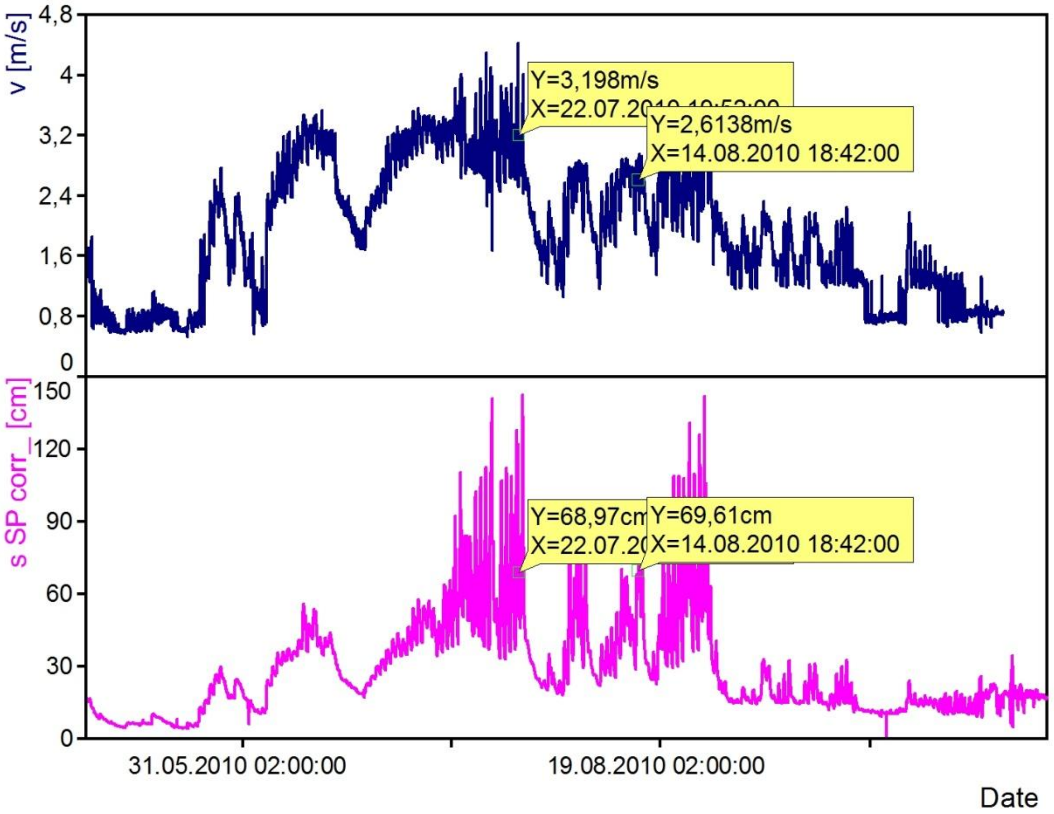


**Figure 19: same stages, different flow velocities in the year 2010**

In Figure 19 there are two points of time with approximately the same stage. For these two points of time the flow velocity differs by 0.7 m/s. (Note that the accuracy of the flow velocity data can only be determined by two decimal places and not by three or four as presented in the Figure 19 and the following Figures)

The second phenomenon is that while the stage changes the flow velocity remains the same. In Figure 20 this phenomenon is visualized.

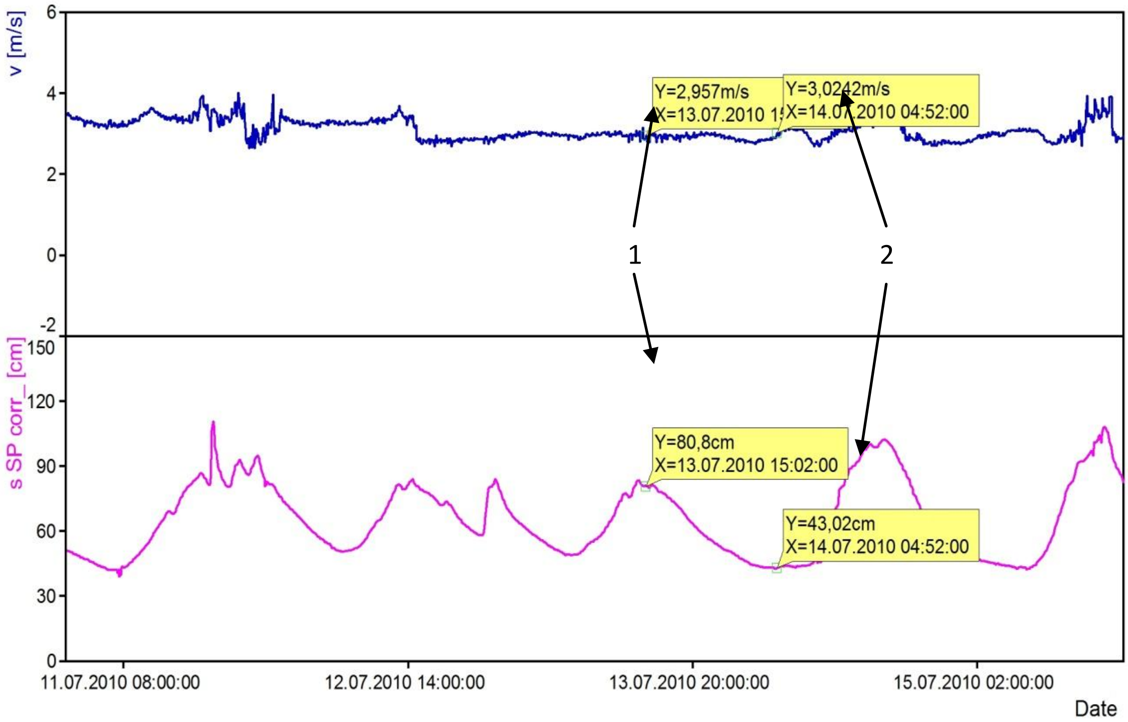


**Figure 20: Comparison of stage and velocity data 2010.**

Figure 20 shows the stage measurements and the velocity measurements for two chosen points of time in July. The fist point (1) has a stage of 80,8cm and a flow velocity of 2,957 m/s. The second point (2) has a stage of 43,02cm and a flow velocity of 3,0242 m/s. Although the stage is about half as high at the second point as at the first point, the flow velocitiy is practically the same. In addition the stage alternates significantly during the period from the 12.07.2010 to the 14.07.2010, unlike the flow velocity which nearly remains steady. In the appendix on page 48-49 Figure 39-40 show similar figures for the year 2009. This phenomenon, however, cannot be the only cause for the wide range in the flow velocity data since it only occurs at a few points.

In the following the results of the analysis of all flow velocity data of the year 2010 in connection with the stage-discharge relation will be displayed. In Figure 19, the deviation of the flow velocity from the flow velocity of the stage-discharge relation is shown.

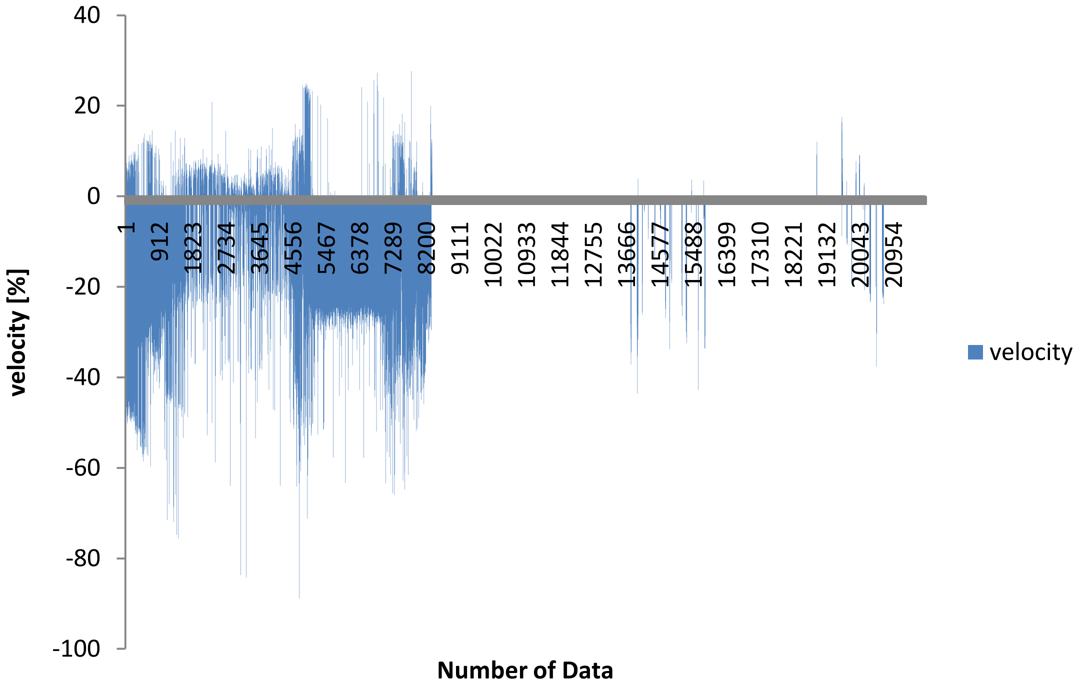


**Figure 21: Deviation in percent from the reference flow velocity of stage-discharge relation.**

Figure 21 shows that, while there is a deviation in most cases, it is not as high as the deviation of the tilting which went up to over 100 percent. For the flow velocity the deviation stays within a range of -100% and 30%, with a main accumulation of the values at -20%. It seems that in most cases the flow velocity is higher than the reference flow velocity. The next figure classifies the flow velocity data of 2010 by comparing all the flow velocity data to the reference flow velocity data of the stage-discharge relation and dividing the data into three groups.

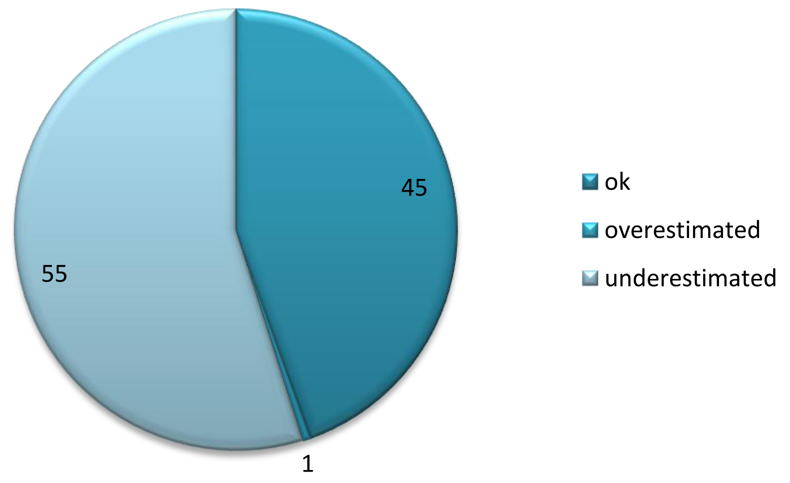


**Figure 22: Classification of velocity data with reference velocity data in percent 2010.**

The first group represents the data that fall within an interval of -+15% of the reference flow velocities of the stage-discharge relation. The second group contains the data that are more than 15% under the reference flow velocities and the third group contains the data that are more than 15% above the reference flow velocities. 45% of the data fall within the first group. Only 1% is overestimated by the reference flow velocity and 55% are underestimated. Consequently, for more than half of the entire data the flow velocity was higher than during the determination of the stage-discharge relation

## 3.4 Summary of Results

The analysis showed that for the stage-discharge relation the application of a mean eight year stage-discharge relation would be within an interval of +- 10%. Depending on the accuracy that is aimed for it would be possible to apply the eight year stage-discharge relation instead of defining a new stage-discharge relation every year. Given, however, that the tilting and the speed conditions seem to deviate significantly within one year as well as the conditions of the inflow area of the measuring channel the error developing by applying the eight year stage-discharge relation would go beyond 10%.

It was not possible to estimate the impact of the tilting conditions on the discharge measurements with absolute certainty. For the year 2010 there was only a small amount of data that could be classified within the year. For about 60% of the data a classification is under the given circumstances not possible because of the constrained measurement range. Taking into account that there is generally an increase in tilting with the level of the stage, the impact of tilting of the 60% may not be as significant. Nevertheless, there are 25% where the impact of the tilting is significant but cannot be classified due to a lack of a reference stage. The analysis of 17% of the data where a reference stage and tilting condition exists showed that although the tilting goes up to 45cm in difference between one ultrasonic sensor to the other, it only underestimates the entire water balance by 5.4 %. If the impact of the tilting conditions of the non classifiable 25% would be about equal to the impact of the classifiable 17%, the error occurring would be no higher than 15%. For the year 2009 the amount of classifiable data was higher and the error occurring with 3% smaller. Given that only 12% of the data (apart from the data below 25cm) was not classifiable with a reference value, the error developing through the different tilting conditions would unlikely be higher than 4%. The investigation of two years showed that depending on the reference tilting conditions of the discharge measurements, the discharge is generally underestimated for low reference tilting conditions and overestimated for high reference tilting conditions.

The analysis of the flow velocity data showed two opposed phenomena that could affect the discharge measurements and the determination of the discharge. The first phenomenon is that the flow velocity changes significantly while the stage remains the same. The second phenomenon is that the stage changes while the flow velocity remains the same. The first phenomenon seems to appear more often.

There is no knowledge of the velocity distribution in the entire measuring channel and therefore this statement that the flow velocity affects the determination of the discharge is only hypothetical. However, if the flow velocity recorded would approximately represent the flow velocity in the measuring channel the impact of the two phenomena would be significant. The table below shows the difference in discharge based on the assumption that the measured flow velocity approximately represents the flow velocity in the measuring channel.

| | | |
|---|---|---|
| Stage [m] | 0.9 | 0.9 |
| Flow velocity (v) [m/s] | 2.3 | 3.5 |
| Cross section (A) [m] | 1.61 | 1.61 |
| Discharge (D) [m³/s] | 3.71 | 5.64 |

| | | |
|---|---|---|
| Stage [m] | 0.8 | 0.43 |
| Flow velocity (v) [m/s] | 3.0 | 3.0 |
| Cross section (A) [m] | 1.41 | 0.67 |
| Discharge (D) [m³/s] | 4.24 | 2.02 |

**Table 2: Calculation of discharge for different flow conditions**

The calculations in Table 2 are based on the equation below. D stands for discharge, A for the cross section and v for the flow velocity. The flow velocity usually represents the mean flow velocity.

$$\boldsymbol{D = A \cdot v}$$ **Equation 2 (Bollrich, 2007)**

Table 2 summarizes the significance of the two phenomena concerning the flow velocity. For the first phenomenon the difference between the two discharges is about 2m³/s. For the second phenomenon the difference is almost 4m³/s. Although it is highly unlikely that the distribution of the flow velocity remains the same throughout the measuring channel there still could be an impact on the discharge measurements which would be worth investigating further.

# 4 Discussion

Neither for the tilting of the water surface nor for the unusual distribution of the flow velocity in the measuring channel clearly defined reasons could be determined through the investigation. In the following chapter reasons for both phenomena will be discussed.

## 4.1 Possible hydraulic causes of the two phenomena

There are in general two different phenomena that could influence the measurements at the Vernagt creek. The first phenomenon is impulse waves that go from one side of the measuring channel to the other, creating a tilting of the water surface and a change in the distribution of the flow velocity. Impulse waves could occur due to the changing conditions at the inflow area of the measuring channel as well as the asymmetric form of the inflow area. The figure below shows the inflow area at the gauging station.

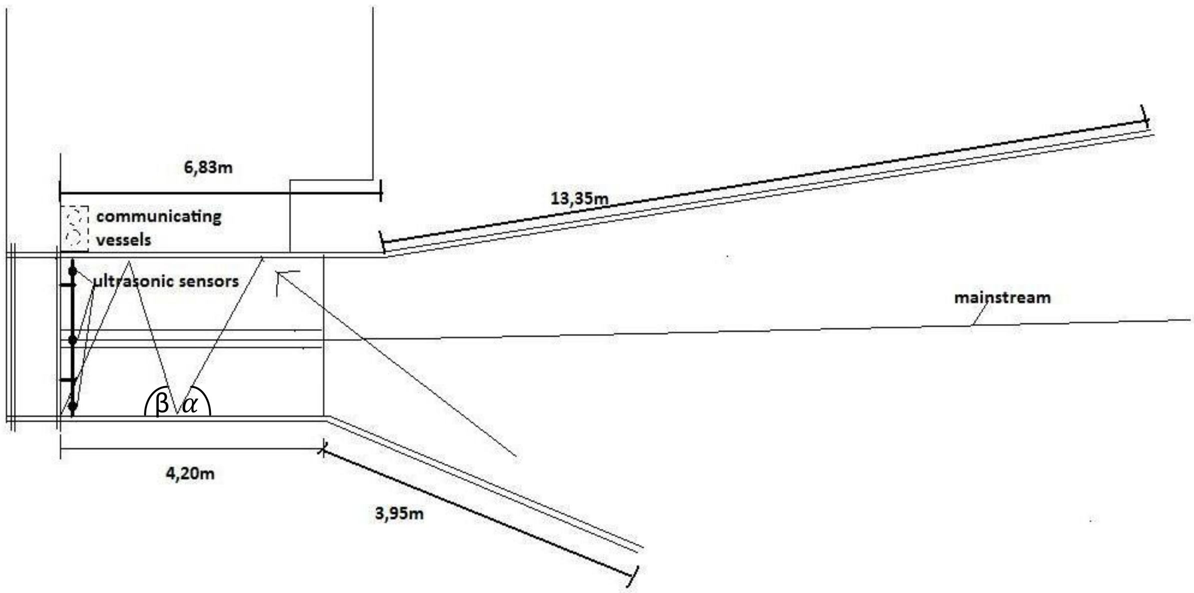


**Figure 23: Inflow area gauging station (Schmid, 1997) (modified).**

As shown in Figure 23, the inflow area of the gauging station is asymmetrical. This could lead especially for high discharge rates and in combination with the more sudden narrowing of the shorter side of the inflow area to the development of impulse waves. The impact angle (α) and the rebound angle (β) of the impulse waves as shown in Figure 23 are the same.

The photography below shows that impulse waves occur at the gauging station.

**Figure 24: Photography impulse waves 21.07.2006 (Photography L.Braun, 2006)**

The second phenomenon that could cause the impulse waves and consequently the spread of the flow velocities is a hydraulic jump in combination with standing waves. Hydraulic jumps are caused by obstacles such as stones, unevenness of the channel base, or a change in slope. They only occur in the direction from supercritical flow to subcritical flow but not the other way around. They can, however, also occur without a change in flow condition (supercritical to subcritical) if the flow cross section alters (Sigloch, 2006). Figure 22 shows a hydraulic jump with standing waves.

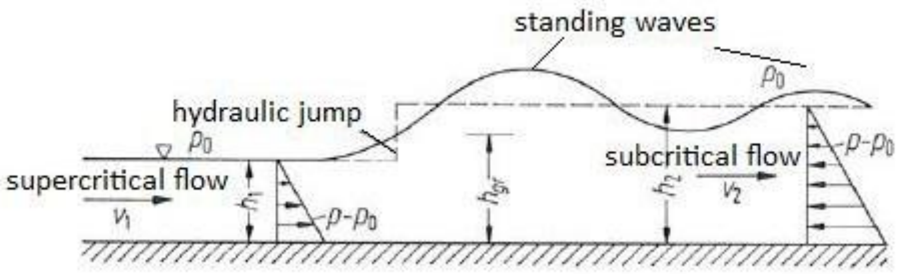


**Figure 25: Hydraulic jump with standing waves (Sigloch, 2006) (modified).**

At the Vernagt creek all conditions that could lead to the development of a hydraulic jump with standing waves are given: supercritical flow conditions, obstacles in form of stones and a change in the flow cross section (as shown in Figure 21). Due to the occurring flow velocities at the Vernagt creek, it is likely that there is no change from supercritical flow conditions to subcritical flow conditions. Nevertheless, the flow velocities would be affected by a hydraulic jump. The following photography shows the measuring channel at the Vernagt creek on the 21st of July, 2006. It indicates that the occurrence of a hydraulic jump is most likely the case.

**Figure 26: Photography of measuring channel 21.07.2006 09:13 (Photography, L.Braun, 2006).**

In the photography the two black arrows mark what appear to be two standing waves.

The flow velocity measurements at low stages could be affected by the stones in the inflow area of the measuring channel. This could be an explanation for the spread of flow velocities even at low stages. The following photographs show the measuring channel and the inflow area at the 18.07.2010. The first photography was taken in the morning the second photography in the afternoon from the same spot.

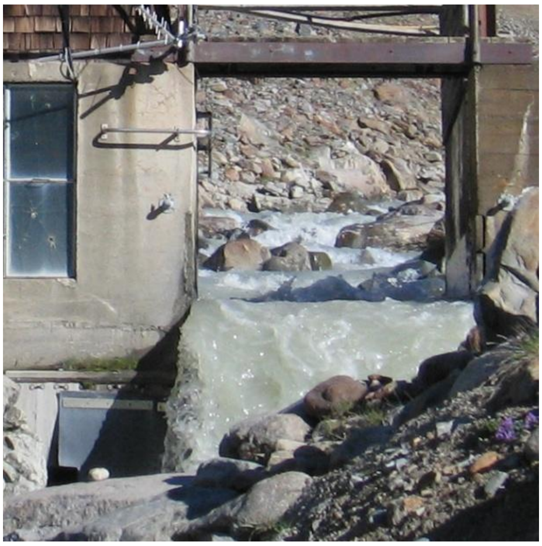

**Figure 27: Photographs of measuring channel 18.07.2006**

As shown in the two photographs the rocks are visible in the morning. However, in the afternoon, they have disappeared completely. In the morning, the flow velocity at the surface is slowed down by the stones. In the afternoon, when the stage is high enough, the stones should no longer affect the flow velocity at the water surface.

# 5 Conclusion

The study of the tilting of the water surface showed that it does not significantly affect the determination of the discharge. However, in combination with the inconsistent flow velocities the determination of the discharge is most likely affected significantly. In order to get more accurate results for the discharge measurements it is essential to include the flow velocity. The available information from the current flow velocity measurements is not enough to determine its effect. In order to get more information on the flow velocity at the water surface, the installation of at least a second flow velocity sensor at the other side of the measuring channel would be necessary. By observing the variation in flow velocities for known locations of rocks in the inflow area, the impact of rocks for low stages could be observed for selected days.

To further analyze the reasons of the tilting of the water surface as well as the flow velocity, a hydraulic model of the gauging station would be necessary. The realization of such a model would be rather complex due to the changing conditions of the inflow area and the turbulent flow conditions. A hydraulic model could lead to a deeper understanding of the processes taking place in the measuring channel but is not a guarantee for more reliable measurements.

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# 6 Appendix

| event | date |
|---|---|
| Beginning of operation of gauging station (Büdel, 1974) | September 1973 |
| Addition of measurement devices for meteorological data and recording of conductivity and temperature of creek water (Büdel, 1976) | 1976 |
| Automatic sample drawing for determination of discharge with isotope method (Büdel, 1979) | 1979 |
| Replacement of wooden base in channel with rubber coating to minimize erosion (Hagedorn, Kommission für Glaziologie, 1986) | 1986 |
| Damage of rubber coat by grid through flood in August (3-week disruption of measurements) (Hagedorn, 1987) | 1987 |
| No clear stage-discharge relation because of high discharge rates (Hagedorn, 1992) | 1992 |
| Reconstruction of measuring channel (elimination of huge rocks from floods) (Hagedorn, 1993) | 1993 |
| Damages through too high discharge, adaptation of gauging station to new flow conditions necessary (Hagedorn, 1994) | 1994 |
| Reconstruction of gauging station: new inflow area which is adapted to new flow conditions. New possibility to redirect water in case of flood (Hagedorn, 1995) | 1995 |
| Resuming of conductivity measurements (Hagedorn, Kommission für Glaziologie, 1997) | 1997 |
| Flood at gauging station, construction work necessary (Hagedorn, 1998) | 1998 |
| Construction at gauging station: new calibration of gauging station to avoid damages through floods (Hagedorn, 2000) | 2000 |
| Replacement of hydrological and metrological measurement devices (Hagedorn, Kommission für Glaziologie, 2001) | 2001 |
| Disruption of measurements because of sand filling (Hagedorn, 2002) | 2002 |
| Disruption of measurements due to high sedimentation which destroyed grid and led to sand filling (Hagedorn, Kommission für Glaziologie, 2003) | 2003 |

**Table 3: History of gauging station 1973-2003**

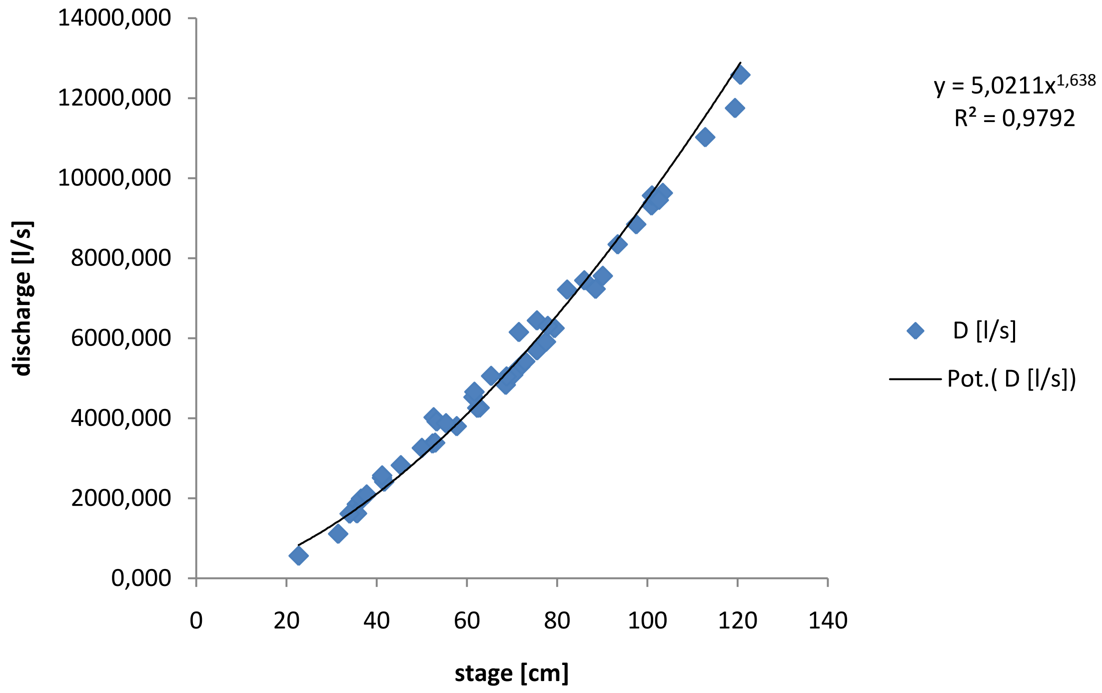


**Figure 28: Stage-Discharge relation 2009**

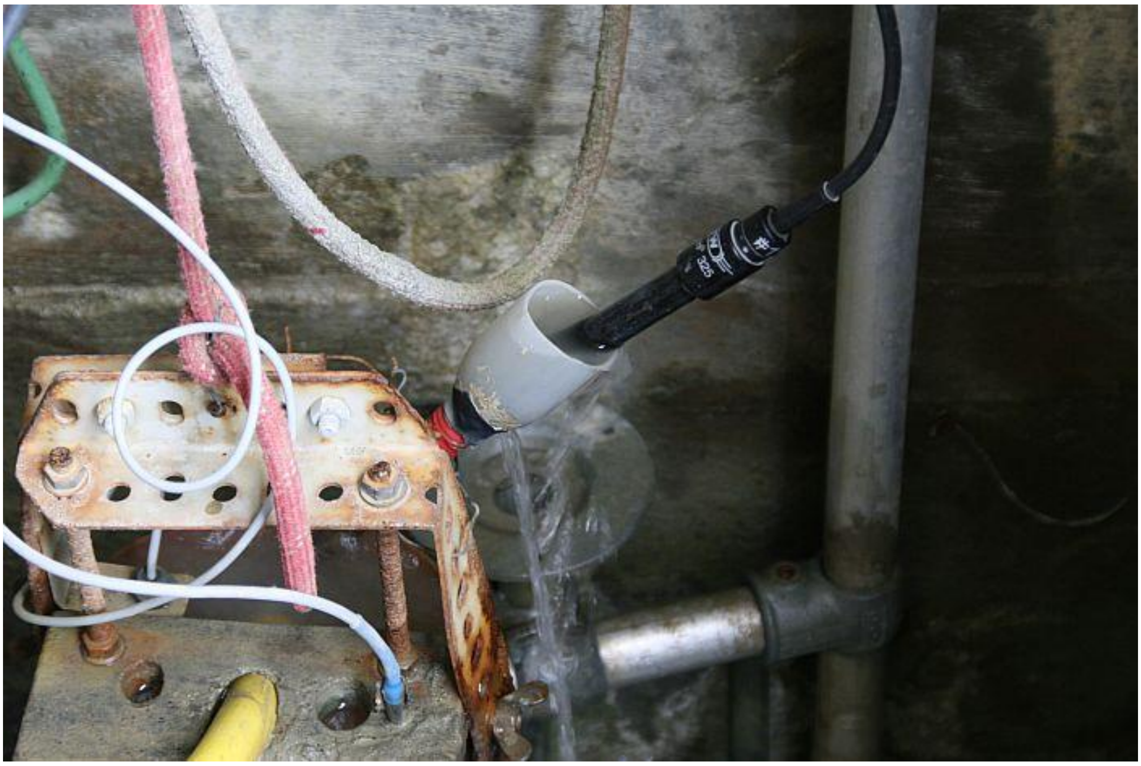

**Figure 29: Placement of second electric conductivity sensor**

**Figure 30: Placement of first electric conductivity sensor**

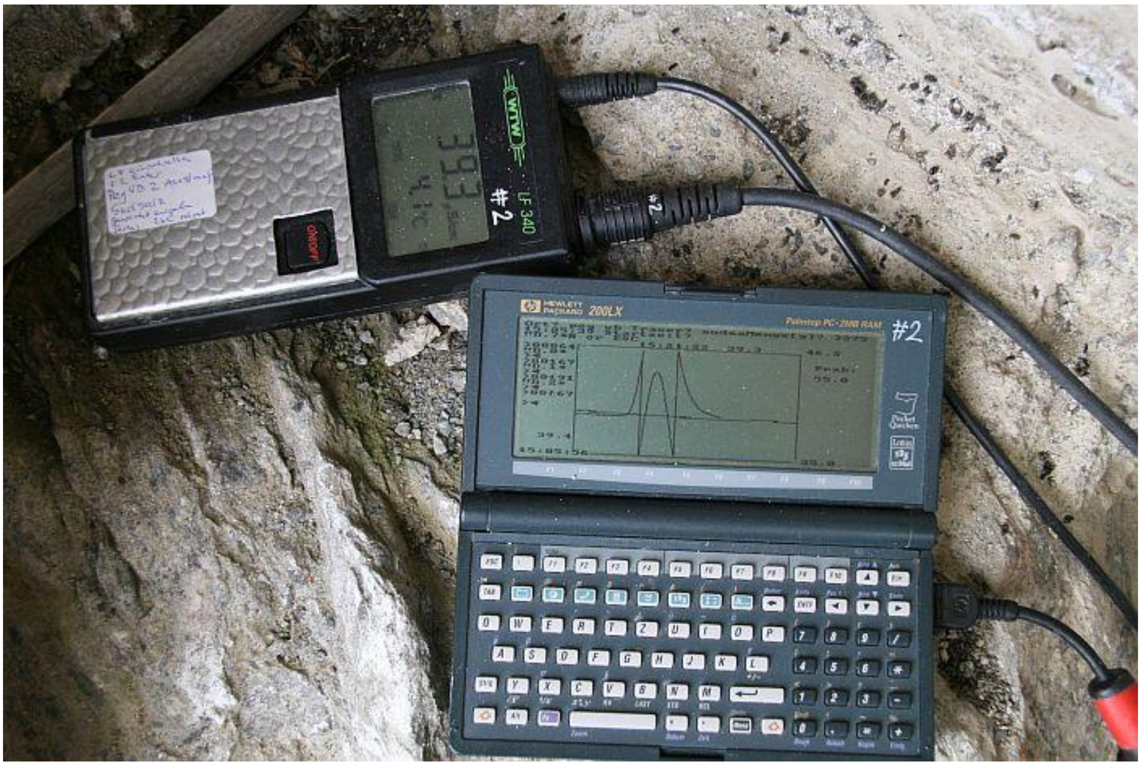


**Figure 31: Plotting of electric conductivity measurements**

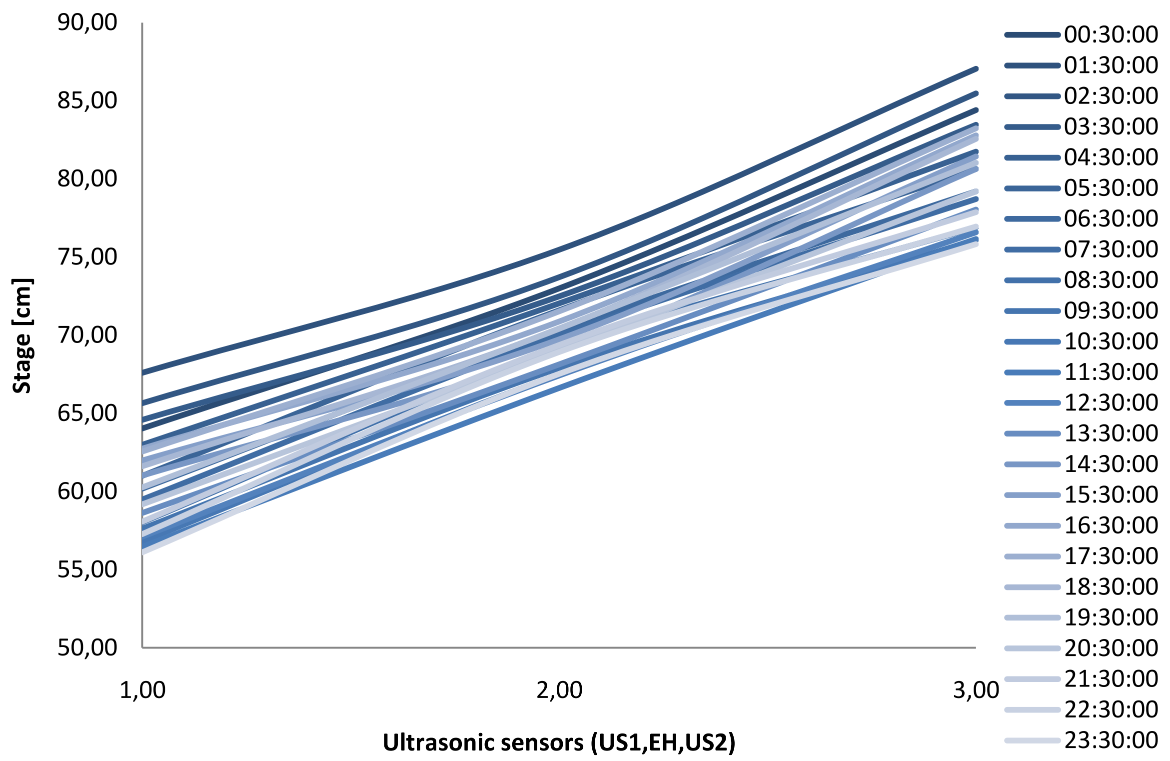


**Figure 32: Tilting of water surface 6.07.2009**

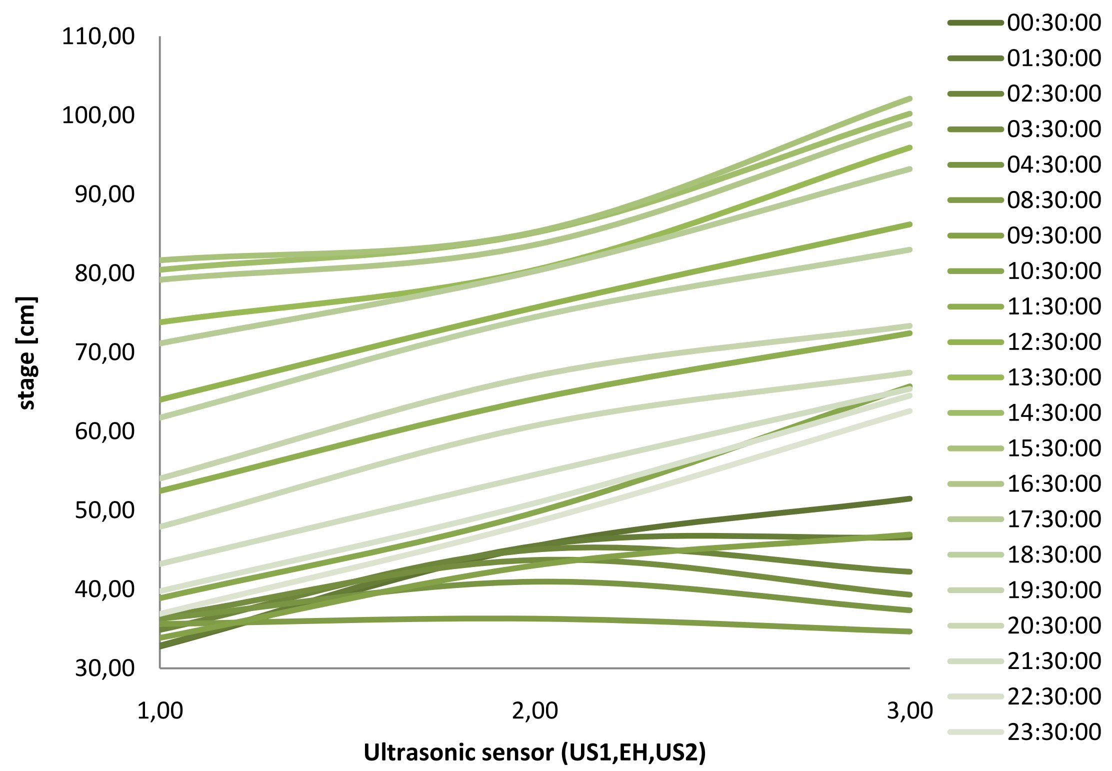


**Figure 33: Tilting of water surface 6.08.2009**

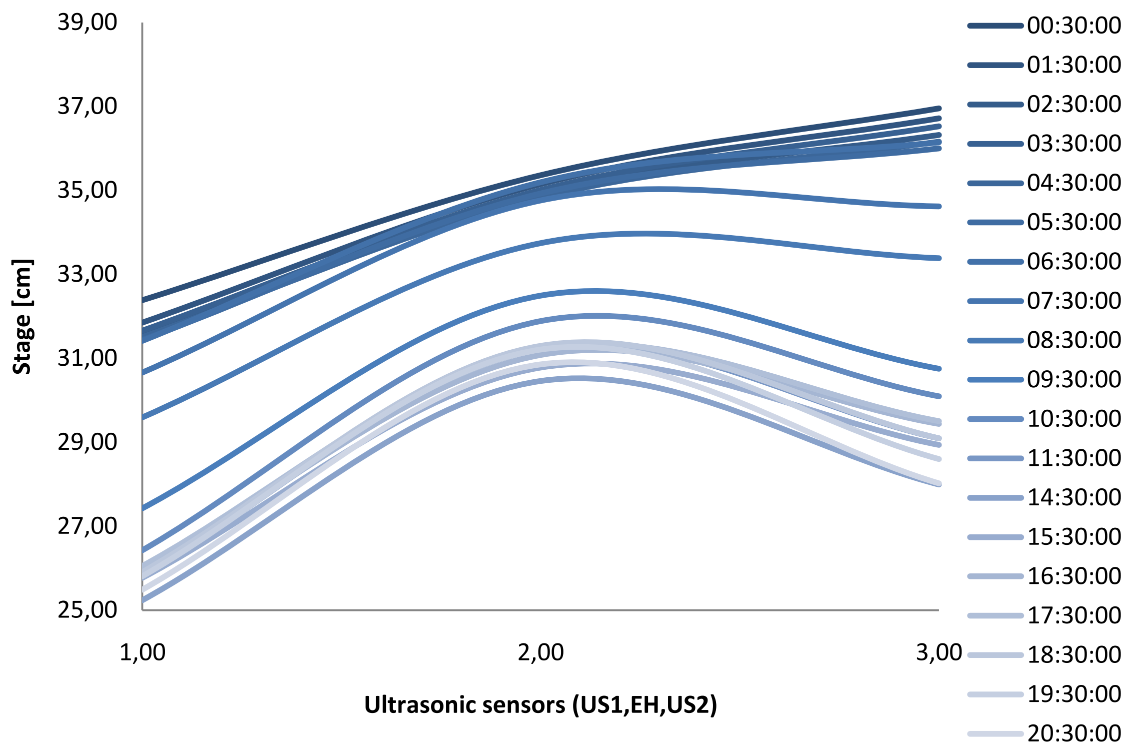


**Figure 34: Tilting of water surface 20.05.2006**

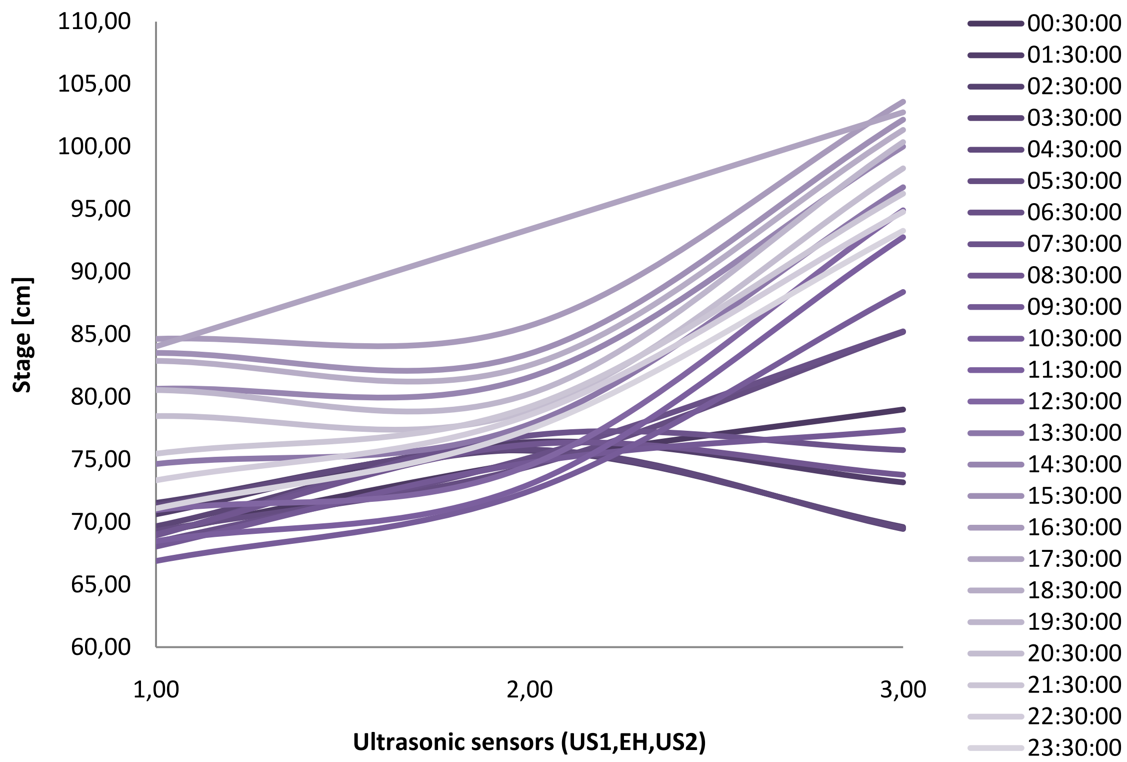


**Figure 35: Tilting of water surface 28.06.2006**

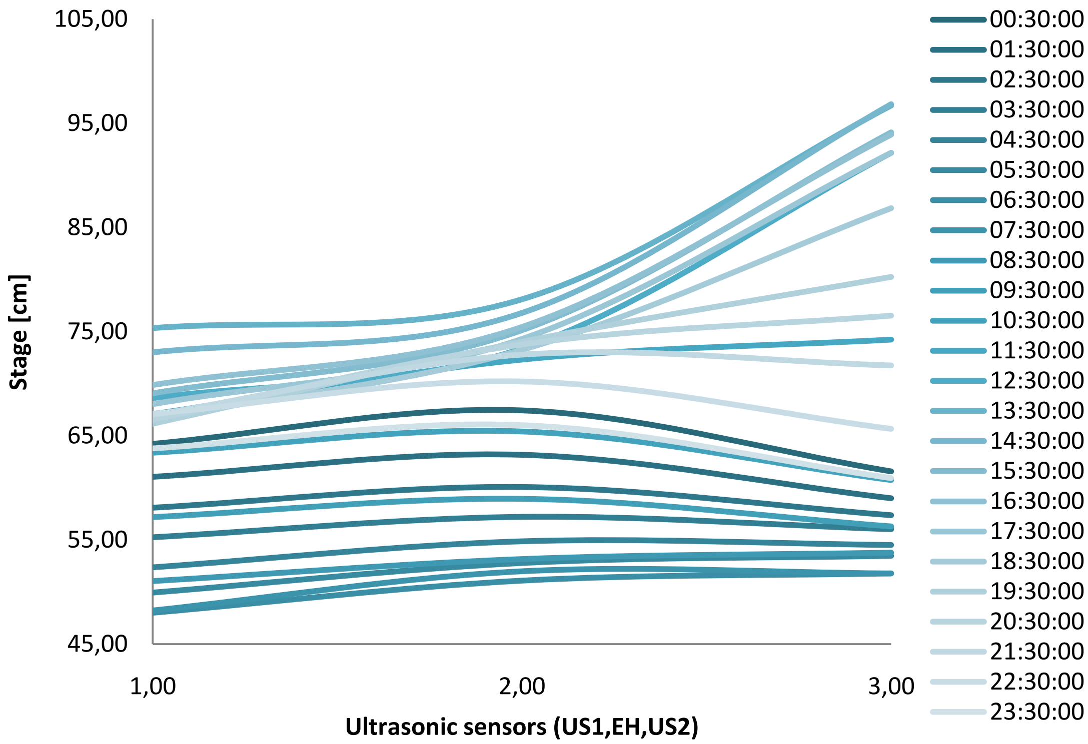


**Figure 36: Tilting of water surface 05.07.2006**

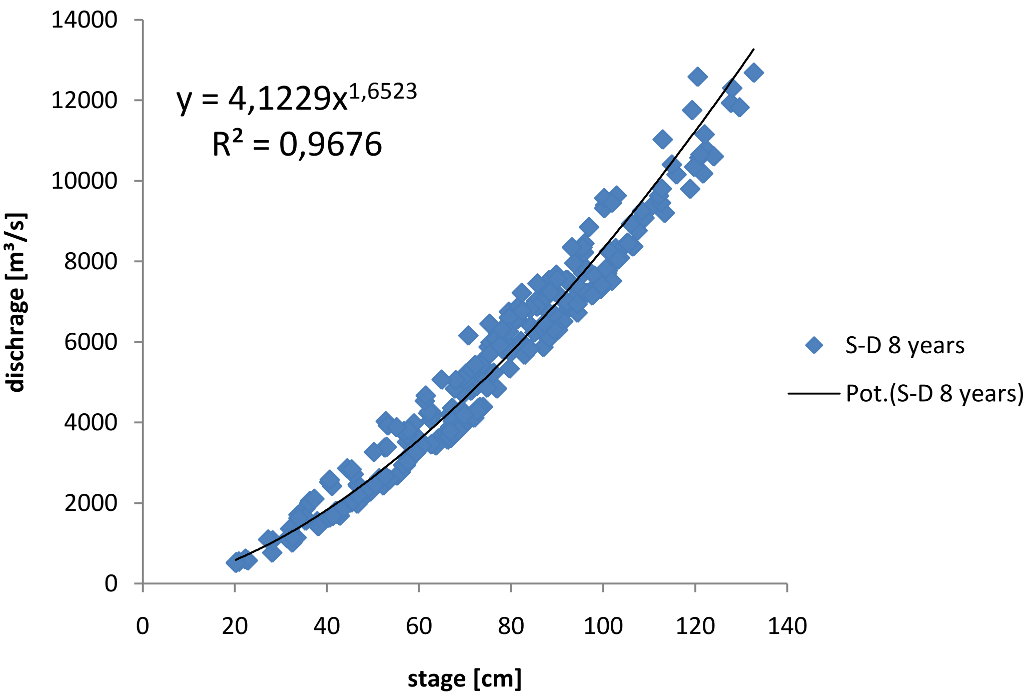


**Figure 37: 8-year stage discharge relation**

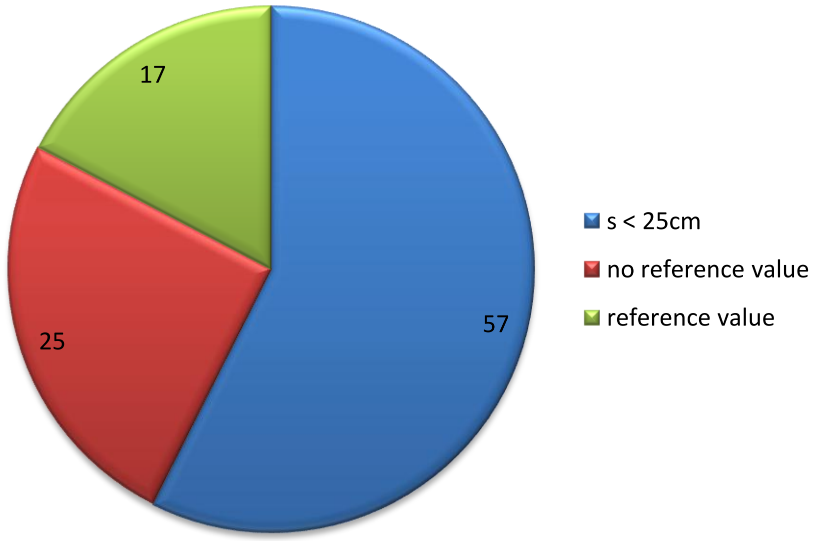


**Figure 38: Classification of the stage measurements 2010**

| Date | S_Poti [cm] | D [l/s] | S_US1 [cm] | S_EH [cm] | S_US2 [cm] | Tilting_max | v [m/s] |
|---|---|---|---|---|---|---|---|
| 27.07.2010 12:41 | 22,30 | 612,6 | 20,8 | 25,8 | 28,9 | 8,1 | 1,66 |
| 27.07.2010 13:24 | 22,20 | 599,5 | 20,9 | 25,2 | 28,8 | 7,9 | 1,674 |
| 28.07.2010 08:28 | 20,30 | 526,2 | 19 | 24,6 | 27,1 | 8,1 | 1,414 |
| 28.07.2010 09:28 | 20,20 | 507,4 | 19,6 | 24,3 | 28 | 8,4 | 1,401 |
| 28.07.2010 16:32 | 32,60 | 1141,4 | 33,7 | 34,2 | 35,1 | 1,4 | 2,178 |
| 18.08.2010 14:09 | 40,50 | 1626,7 | 42,6 | 39,9 | 39,3 | -3,3 | 2,54 |
| 18.08.2010 14:50 | 41,20 | 1668,9 | 43,6 | 40,9 | 40,4 | -3,2 | 2,536 |
| 23.08.2010 13:16 | 106,50 | 8367,2 | 116 | 116,9 | 116,7 | 0,7 | 2,776 |
| 23.08.2010 13:45 | 103,60 | 8090,1 | 113,7 | 114,3 | 110,9 | -2,8 | 2,752 |
| 23.08.2010 14:15 | 101,90 | 7512,1 | 112,5 | 111,7 | 110,7 | -1,8 | 2,679 |
| 23.08.2010 14:38 | 99,40 | 7307,5 | 109,3 | 109 | 106,3 | -3,0 | 2,421 |
| 23.08.2010 15:00 | 94,40 | 6721,5 | 102,7 | 103,3 | 98,8 | -3,9 | 2,386 |
| 23.08.2010 15:29 | 94,40 | 6938,2 | 102,4 | 102,8 | 98,2 | -4,2 | #NV |
| 23.08.2010 15:57 | 97,60 | 7150,3 | 107,5 | | 103,2 | -4,3 | 2,621 |
| 23.08.2010 16:36 | 89,20 | 6303,8 | 97 | 97,7 | 94,5 | -2,5 | 2,278 |
| 23.08.2010 17:04 | 82,90 | 5675,5 | 89,8 | 90,3 | 88,5 | -1,3 | 2,732 |
| 23.08.2010 17:35 | 74,80 | 4859,7 | 80,3 | 82 | 80 | -0,3 | 2,468 |
| 23.08.2010 18:13 | 69,80 | 4177,6 | 73,1 | 75,5 | 75,2 | 2,1 | #NV |
| 23.08.2010 20:28 | 57,50 | 3023,4 | 58,6 | 60,2 | 62,1 | 3,5 | 2,291 |
| 24.08.2010 07:58 | 59,30 | 3244,1 | 61 | 64 | 65,9 | 4,9 | 2,601 |
| 24.08.2010 09:44 | 87,20 | 6462,2 | 94,2 | 96,9 | 92,7 | -1,5 | 2,76 |
| 24.08.2010 10:03 | 84,10 | 5823,7 | 89,8 | 92,3 | 89,8 | 0,0 | 2,75 |
| 24.08.2010 11:10 | 99,70 | 7412,3 | 108 | 110 | 107,7 | -0,3 | 2,703 |
| 24.08.2010 11:41 | 103,20 | 8040,3 | 112,8 | 114,8 | 111,7 | -1,1 | 2,734 |
| 24.08.2010 12:28 | 105,50 | 8439,8 | 116,3 | 117 | 115,9 | -0,4 | 2,848 |
| 24.08.2010 13:45 | 112,70 | 9802,6 | 121 | 123,5 | 134,5 | 13,5 | 2,783 |
| 24.08.2010 14:15 | 114,90 | 10402,7 | 124,6 | 126,1 | 136,4 | 11,8 | 2,936 |

**Table 4: Tilting and velocity data of 2010 of stage-discharge relation**

| Date | S_Poti [cm] | D [l/s] | S_US1 [cm] | S_EH [cm] | S_US2 [cm] | Tilting_max | v [m/s] |
|---|---|---|---|---|---|---|---|
| 09.07.2009 11:02 | 31,45 | 1116,460 | 32,8 | 34,3 | 52,2 | 19,4 | 2,5 |
| 29.07.2009 08:32 | 35,59 | 1856,550 | 37 | 44,7 | 50,1 | 13,1 | 2,12 |
| 29.07.2009 09:04 | 36,51 | 1993,047 | 37,5 | 46,5 | 51,5 | 14,0 | 2,2 |
| 29.07.2009 09:33 | 37,77 | 2098,089 | 37,2 | 48,8 | 52,8 | 15,6 | 2,07 |
| 29.07.2009 10:20 | 41,16 | 2516,075 | 40,1 | 52,6 | 64,2 | 24,1 | 2,03 |
| 29.07.2009 10:55 | 45,34 | 2829,644 | 44,3 | 55,7 | 66,5 | 22,2 | 2,12 |
| 29.07.2009 11:45 | 52,36 | 3371,931 | 51,9 | 64,6 | 66,5 | 14,6 | 2,78 |
| 29.07.2009 12:24 | 57,72 | 3804,471 | 55,7 | 67 | 70 | 14,3 | 2,98 |
| 29.07.2009 13:00 | 62,79 | 4266,263 | 60,7 | 73,1 | 75,3 | 14,6 | 3,02 |
| 29.07.2009 14:01 | 68,59 | 4837,653 | 66,3 | 80,4 | 83,9 | 17,6 | 3,06 |
| 29.07.2009 14:40 | 71 | 5211,793 | 68,5 | 81,1 | 87,2 | 18,7 | 3,06 |
| 29.07.2009 15:13 | 71,8 | 5291,708 | 69,3 | 81 | 89,3 | 20,0 | 3,03 |
| 29.07.2009 15:47 | 72,9 | 5423,937 | 70,1 | 81,8 | 90 | 19,9 | 3,15 |
| 29.07.2009 17:05 | 70,24 | 5087,719 | 67,3 | 79,5 | 85,5 | 18,2 | 3,04 |
| 30.07.2009 08:55 | 41,66 | 2416,452 | 40,3 | 53,7 | 57,6 | 17,3 | 2,23 |
| 30.07.2009 10:17 | 52,94 | 3391,189 | 51,6 | 63,5 | 66,5 | 14,9 | 2,78 |
| 30.07.2009 11:09 | 62,28 | 4262,225 | 60 | 72,6 | 74,7 | 14,7 | 3,08 |
| 30.07.2009 12:09 | 68,77 | 5046,497 | 66,7 | 79,1 | 84,7 | 18,0 | 3,04 |
| 30.07.2009 13:08 | 75,5 | 5698,091 | 73,8 | 83,1 | 93,1 | 19,3 | 3,07 |
| 30.07.2009 14:09 | 79,4 | 6253,920 | 78,2 | 84,1 | 97,2 | 19,0 | 3,34 |
| 30.07.2009 14:54 | 77,5 | 5913,948 | 76,2 | 81,4 | 96 | 19,8 | 3,3 |
| 01.08.2009 14:45 | 88,5 | 7234,689 | 88,2 | 95 | 108,6 | 20,4 | 3,3 |
| 01.08.2009 15:30 | 90,1 | 7559,381 | 91,5 | 95,1 | 109,6 | 18,1 | 3,34 |
| 26.08.2009 10:35 | 52,61 | 4027,301 | 49,4 | 60 | 72,4 | 23,0 | 3,31 |
| 26.08.2009 11:21 | 53,28 | 3922,668 | 50,1 | 60,6 | 71 | 20,9 | 3,38 |
| 26.08.2009 12:27 | 75,5 | 6446,331 | 72,1 | 96,2 | 92,8 | 20,7 | 3,16 |
| 26.08.2009 13:01 | 93,4 | 8347,032 | 95,5 | 99,6 | 107,4 | 11,9 | 3,67 |
| 26.08.2009 13:39 | 77,9 | 6308,481 | 74,1 | 97,7 | 93 | 18,9 | 3,38 |
| 26.08.2009 14:47 | 65,35 | 5059,745 | 61,6 | 83,6 | 82,8 | 21,2 | 3,12 |
| 26.08.2009 15:45 | 61,45 | 4531,961 | 59,1 | 71,3 | 78,7 | 19,6 | 3,24 |
| 26.08.2009 16:41 | 61,65 | 4663,510 | 58,1 | 69,6 | 80,3 | 22,2 | 3,36 |
| 27.08.2009 08:53 | 35,42 | 1650,456 | 36,6 |  | 39,4 | 2,8 | 2,57 |
| 27.08.2009 10:44 | 71,5 | 6155,456 | 68,5 | 90,1 | 93,1 | 24,6 | 3,16 |
| 27.08.2009 12:26 | 86 | 7447,753 | 85,3 | 97,8 | 102,9 | 17,6 | 3,42 |
| 27.08.2009 13:21 | 97,5 | 8848,558 | 101,5 | 104,6 | 113,1 | 11,6 | 3,66 |
| 27.08.2009 13:55 | 101,2 | 9391,424 | 108,6 | 108 | 116,3 | 7,7 | 3,79 |
| 27.08.2009 14:51 | 100,9 | 9317,723 | 108,1 | 106,1 | 114,8 | 6,7 | 3,8 |
| 27.08.2009 15:34 | 103,4 | 9631,375 | 112,2 | 109 | 118 | 5,8 | 3,83 |
| 28.08.2009 08:04 | 35,62 | 1625,589 | 35,2 | 40,9 | 40,7 | 5,5 | 2,73 |
| 28.08.2009 10:43 | 82,2 | 7215,795 | 79,3 | 88 | #NV | #NV | 3 |
| 28.08.2009 11:39 | 101 | 9567,338 | 106,1 | 105,3 | 118,3 | 12,2 | 3,73 |
| 28.08.2009 12:09 | 102,5 | 9453,778 | 109,3 | 107 | 120 | 10,7 | 3,61 |
| 28.08.2009 13:14 | 112,8 | 11023,933 | 120,3 | 118,7 | 134,9 | 14,6 | 3,15 |
| 28.08.2009 13:46 | 119,4 | 11751,856 | 127,5 |  | 144,4 | 16,9 | 3 |
| 28.08.2009 14:16 | 120,6 | 12582,034 | 126,8 | 129,6 | 143,6 | 16,8 | 3,18 |
| 29.09.2009 15:19 | 55,35 | 3877,90018 | 54,9 | 63,45 | 71,4 | 16,5 | 3,42 |
| 29.09.2009 16:55 | 50 | 3261,71606 | 48,8 | 58,7 | 64,8 | 16,0 | 3,42 |
| 30.09.2009 07:35 | 22,7 | 568,162254 | 22 |  | 23 | 1,0 | 2,16 |
| 30.09.2009 11:13 | 34 | 1619,69108 | 35,8 | 38,1 | 41,4 | 5,6 | 2,77 |
| 30.09.2009 11:49 | 41,2 | 2574,26498 | 39,2 | 51,7 | 55,1 | 15,9 | 3,11 |

**Table 5: Tilting and velocity of stage-discharge relation 2009**

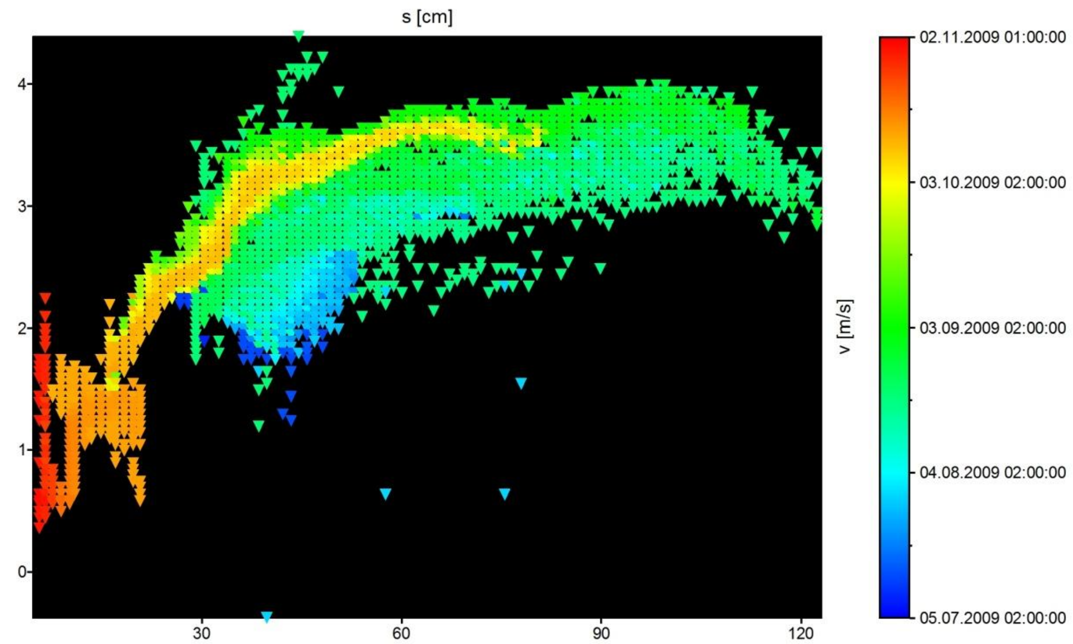


**Figure 39: Flow velocity plotted against time and stage 2009**

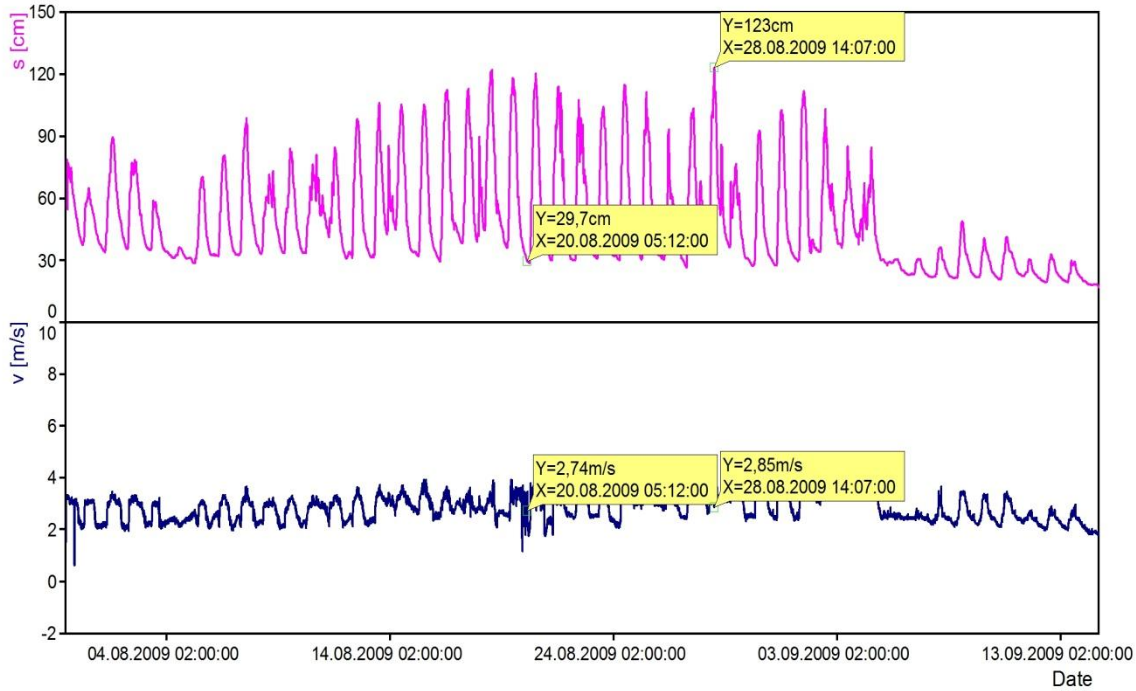


**Figure 40: Different stages with same flow velocity 2009**