Monitoring discharge continuously in the Geul

A feasibility study

Monitoring discharge continuously in the Geul
A feasibility study

Author(s)
Frans Buschman
Mike van Meerkerk

Disclaimer
The EMFloodResilience project is being carried out within the context of Interreg V-A Euregio Meuse-Rhine and is 90% funded from the European Regional Development Fund.

Monitoring discharge continuously in the Geul
A feasibility study

Client	Waterschap Limburg
Contact	de heer ing. P.H.J. Hulst
Reference	EMfloodResilience (Interreg)
Keywords	Stream, gauging, flow, measurement, Limburg

Document control	
Version	1.0
Date	06-11-2023
Project nr.	11209514-002
Document ID	11209514-002-ZWS-0001
Pages	39
Classification	
Status	final

Author(s)		
	Frans Buschman	
	Mike van Meerkerk	

The allowed use of this table is limited to check the correct order-performance by Deltares. Any other client-internal-use and any external distribution is not allowed.

Doc. version	Author	Reviewer	Approver
0.1	Frans Buschman	Klaas-Jan van Heeringen	Bianca Peters

Summary

Establishing a discharge-measurement station in the Geul that meets all requirements specified by Waterschap Limburg (WL) is not feasible. Nonetheless, our work presents a conceptual design for two stations to monitor across a wide range of discharge conditions, although they do not meet all the imposed requirements.

The Geul is a 60 km long stream. It drains a catchment area of approximately 340 km^2, situated for 40% in Belgium and for 60% in the Netherlands. Its source is at about 350 m above mean sea level. The Belgian part of the catchment exhibits thin soil layers and rocky subsurface, resulting in a rapid response of discharge to rainfall compared to the Dutch part. Damage in the upper regions is often due to local intense rainfall (flash floods), whereas in downstream parts damage typically occurs after prolonged and widespread rainfall. To forecast flooding and to assess the effect of measures, it is essential to monitor both the discharge peak and the duration of elevated discharge.

Especially during high-water conditions, discharge cannot be monitored accurately at existing monitoring stations. A challenge is that the Geul is morphodynamically active. During high-water the bed level may change substantially in parts of the Geul, making point-based discharge measurements within cross sections complicated. Additionally, the valley inundates at higher discharges, which complicates monitoring the discharge over the full width of the inundated valley. Finally, the Dutch part of the Geul valley has protected Natura2000 status, which means that restrictions apply for interventions in the stream bed and maintenance.

WL aims to implement or improve a measurement station where discharge can be monitored continuously, even under extreme high-water conditions. In addition to the requirements for the mentioned challenges, it is necessary to limit the error in discharge measurement. We conclude that a solution that meets all requirements is not feasible. However, we propose two improvements for existing monitoring stations:

1. **At Sippenaeken**, just 800 m upstream of the Dutch-Belgian border, we propose deploying flow velocity meters at two levels under the bridge. By applying the index-velocity method using the flow velocity measurements, the uncertainty during medium to high discharge conditions will be reduced substantially with respect to the discharge that is currently obtained from a stage-discharge relation.
2. **At Hommerich**, we recommend adding a radar surface flow velocity measurement to the existing station. This provides reference measurements for the stage-discharge relation during high discharge conditions, verifies camera-derived flow velocity, and operates reliably day and night, enhancing measurement continuity.

For each solution, one should perform additional on-site discharge measurements from a boat at a regular basis, particularly during higher discharge events. Furthermore, station maintenance and data validation are required on a regular basis.

Contents

1 Introduction

1.1 Background

1.1.1 Framework

Waterschap Limburg (WL) commissioned Deltares to advise on the feasibility of building a new or extending an existing discharge monitoring station in the Geul. The station needs to result in continuous measurements of the discharge, also during extreme conditions. Parallel to this study on the Geul, two similar feasibility studies were carried out: on the Gulp by Deltares and on the Roer by Wageningen University.

1.1.2 Motivation

In 2021 flooding of the Geul occurred as a result of an extreme rainfall event. In two days (13-7 10:00 to 15-7 10:00 2021) the average rainfall in the Geul catchment was 128 mm, resulting in very high discharge (occurring once in more than 100 years) and substantial damage (Asselman & Van Heeringen, 2023). Flooding occurred at several locations within the Geul valley. In some villages, like Valkenburg, the cross-sectional area is too small to accommodate the high discharge resulting in flooding.

Figure 1.1 presents the available discharge time series during the extreme discharge in 2021. To put this in perspective, the average discharge in the downstream part of the Geul is about 2 m^3/s. The peak discharge at Sippenaeken was observed to be 53 m^3/s, whereas a hydrological simulation model estimated a maximum discharge of about 90 m^3/s close to Sippenaeken and about 135 m^3/s in Valkenburg (Figure 1.2; Asselman & Van Heeringen, 2023). The peak measured at Sippenaeken is likely to be underestimated substantially, considering the high-water levels in the Geul valley. Moreover, the stage-discharge relation is based on a limited number of high discharge events, which limits the accuracy of the stage-discharge relation during high discharge conditions. At the other stations in the upstream part of the Geul, Cottessen and Hommerich, discharge could not be measured during the high discharge conditions (Figure 1.1). WL intends to implement or improve a station such that the discharge can be monitored continuously, also during very extreme high-water conditions.

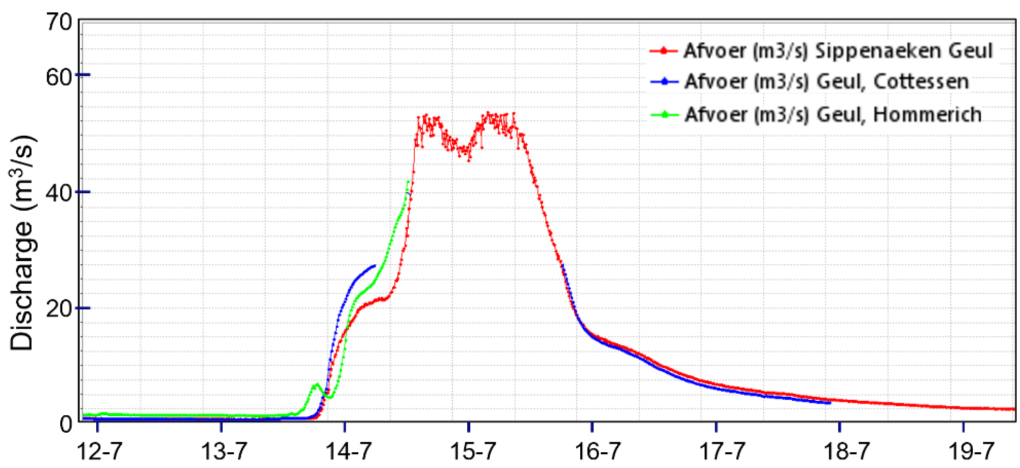

Figure 1.1 The monitored discharges at three locations along the Geul during the high discharge event in 2021. (source: (van Heeringen et al., 2022)).

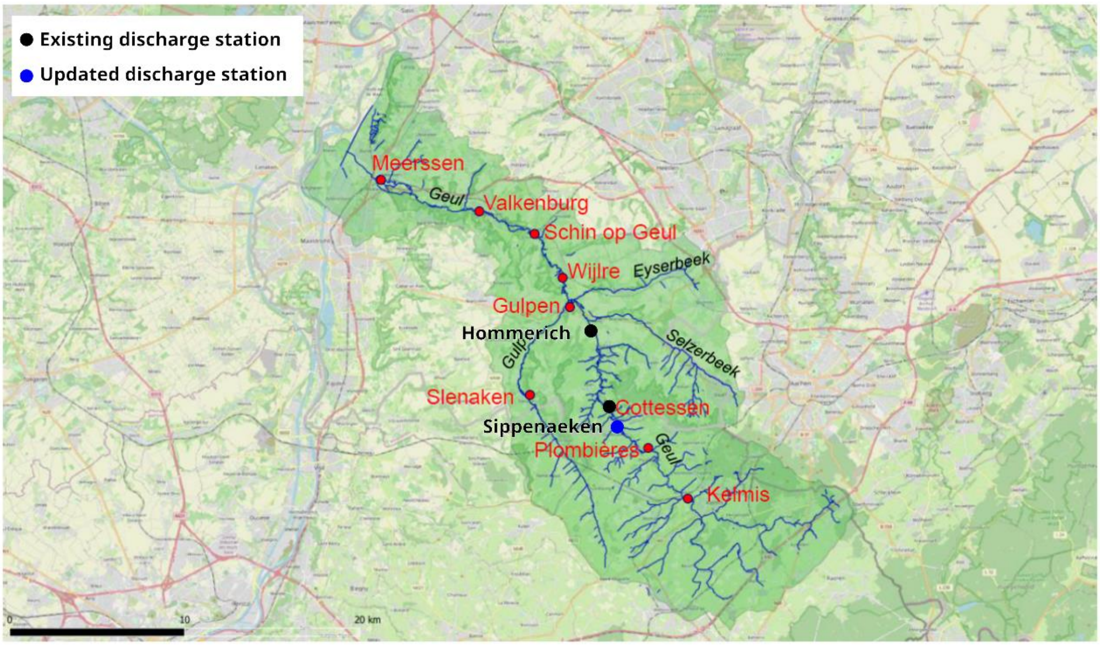

Figure 1.2 The catchment area of the Geul, with the discharge measurement stations indicated. (adapted from: Asselman & Van Heeringen (2023)).

1.1.3 Current measurement stations

1.1.1.1 Overview

In the upstream part of the Geul, the discharge is currently monitored at Sippenaeken, Cottessen and Hommerich. Service Public de Wallonie (SPW, Belgium) manages the station Sippenaeken, which is situated 800 m upstream of the Dutch-Belgian border. WL manages the other two stations in the upstream part of the Geul that are situated in the Netherlands. The Geul valley is situated in a protected Natura2000 area, except for the part upstream of the Dutch-Belgian border.

1.1.1.2 Sippenaeken

The water level is monitored every 10 minutes at Sippenaeken. The water level station is located upstream of a weir, as depicted in Figure 1.3. Due to the weir, the water depth is higher than in most parts of the Geul. Additionally, there are gates on the side of the weir. It is assumed that these gates are always closed; however, some water still leaks through the gates. The discharge is derived from a stage-discharge relation. During the high water of 2021, the peak water level was about 1.5 meters higher than the typical low discharge value.

Figure 1.3 Photo of the Geul at station Sippenaeken at low discharge on 15 May 2023, with a downstream view of the weir, a fish ladder, a gate to a side channel and a pedestrian bridge.

1.1.1.3 Cottessen

One kilometer downstream of Sippenaeken, a concrete flume was installed to monitor discharge in 1991 (Figure 1.4). The discharge can be derived from the water level measured directly upstream of the flume for a discharge range of 0.4 to 26 m^3/s. Boiten et al. (1995)estimated the relative measurement error to be within 5%, provided that no backwater effects or sedimentation on the flume occur. We note that vegetation (Figure 1.4) will result in a seasonal variation and error, although vegetation is removed regularly.

The water depth for the given discharge range is 0.2 to 2.0 m. During the extreme event 2021 a maximum water depth of 2.55 m was recorded. The valley was partly flooded, and no discharge could be derived from the water level observation.

Figure 1.4 Photo of the Geul at station Cottessen at low discharge on 15 May 2023.

1.1.1.4 Hommerich

The station at Hommerich is situated about 6 km downstream from the Dutch-Belgian border (Figure 1.5). Water level has been monitored near Hommerich since 1969, although the measurement station was situated somewhat further downstream than the current location for a few years. Discharge is derived from a stage-discharge relation. A consortium led by the TU Delft has recently set-up a video-system to explore discharge measurements with video systems.

During the flood event of 2021, the water level increased to almost 95.0 m with respect to the vertical datum used in the Netherlands, *Normaal Amsterdams Peil* (NAP), in the afternoon of the 13th of July. The water level sensor malfunctioned as the housing of the station was inundated. *WL* visited the site after the flooding and found flood marks at 95.7 m NAP. At this maximal level, the lower Geul valley was inundated for a large part and the water depth at the neighboring soccer fields was approximately 0.2-0.4 m. Directly after the 2021-flood, the water level housing was relocated to a higher point to avoid inundation during a next high water (see Figure 3.4b for a picture of the new housing).

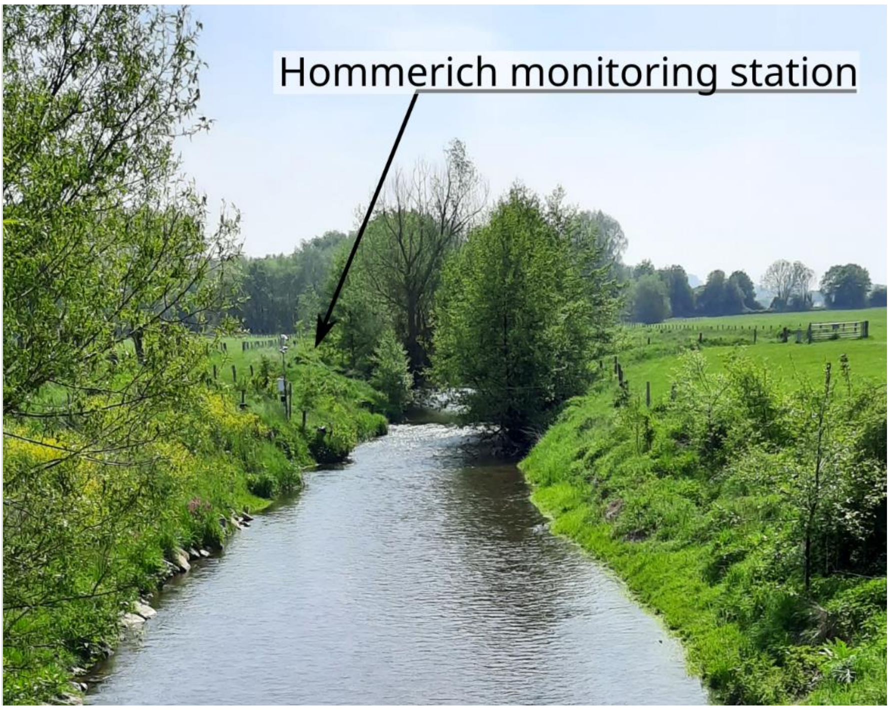

Figure 1.5 Photo of the Geul showing station Hommerich at low discharge on 15 May 2023.

1.2 Problem definition

1.2.1 Response time and damage

The Geul is about 60 km long. It drains an area of about 340 km^2, of which 60% in the Netherlands and 40% in Belgium. Its source is situated at 350 m NAP. The Belgian part of the catchment can be characterized by thin soil layers and sometimes rocky subsurface, resulting in a short response time of discharge to rainfall with respect to the Dutch part. As a result, damage occurs, generally, in the upper parts mostly due to local high intensity rainfall (flash flood), whereas lower in the Geul damage is more likely to occur after longer rainfall at a larger scale and longer rainfall (Asselman & Van Heeringen, 2023).

The extent of the flood in the valley largely determines the damage. In order to estimate the flood extent in the Geul valley (e.g. near Valkenburg and near Meerssen), it is important to know the volume of water for a particular high discharge event. Hence, not only the peak discharge, but also the duration of the elevated discharge need to be measured. Based on the forecast of the flood extent, inhabitants of the Geul valley can be informed timely and, if needed, evacuations can be started.

1.2.2 Challenges for implementing a discharge station

The implementation of a discharge station in the Geul faces several challenges:

1. The equipment and method need to be able to monitor discharge accurately from low to extreme flood levels.
2. The Geul overflows at a discharge of about 25 m^3/s. The discharge can then be distributed over the narrow main channel and wide shallow areas in the valley on both sides of the stream. It is challenging to measure or estimate the discharge in the inundated parts of the valley.
3. The Geul is morphodynamically active, due to its freely meandering and natural stream bed. The bed level in a cross section can change considerably during a flood, which complicates obtaining discharge from a measurement at a point in the cross section. As an example, for Hommerich the stage-discharge relation has been updated regularly to correct for bed level changes. It is expected that the discharge relation needs to be updated after each extreme discharge event.
4. The Dutch part of the Geul valley is designated as a protected Natura2000 area, which results in challenges for installing and maintaining a discharge station. Since alterations to the stream bed are restricted, it may be difficult to obtain permits for levelling or making structural modifications for the installation of a discharge station. The restrictions imply that it is no longer feasible to install a flume like the one at Cottessen in the Geul. Moreover, the protected status may also result in restrictions for the placement of poles or structures within the stream bed and the overall maintenance of the discharge station.

1.3 Objective

The objective of this study is to determine the feasibility of building or improving a station in the Geul to monitor discharge continuously, considering the requirements and preferences listed in Table 1.1.

1.3.1 Requirements and preferences

Considering the application of the discharge information and challenges for the implementation of a discharge station, the requirements and preferences are described in Table 1.1.

Table 1.1 Requirements and preferences, as given by WL and detailed further in a meeting on 15 May 2023 in Roermond.

	Minimal requirement	**Preference**
Discharge range	The range from 0.2 m^3/s to the peak value of 2021[1].	Up to a discharge even higher than occurred in 2021.
Temporal resolution	Continuously at an interval of about 5 minutes.	
Location	Within the Geul, upstream of the current station Hommerich	Within 2 km from the Dutch-Belgian border.

[1] The peak value of the discharge in 2021 is not known. It was most likely within the range 60-200 m^3/s.

	Minimal requirement	Preference
Maximal relative measurement error	15% assuming that the discharge from sailed transect is the true value.	10% assuming that the discharge from sailed transect is the true value.
Protected status	Interventions in the stream bed or surroundings are restricted in the Dutch part of the Geul.	No interventions in the stream bed or surroundings.
Bed level	The method to derive discharge is accurate, also when changes in bed level occur.	Changes in the rating curve for the station are limited.
Maintenance		Mowing and removing obstacles is only needed 1-2 times a year.

1.3.2 Research and practical questions

In case one of the three current locations or a new location is found to be suitable to improve or build a discharge station that meets most of the requirements, *WL* requested to answer the following research and practical questions:

A. What instrument(s) and mounting system can best be used for the high-water discharge measurement station?
B. What method can best be used to derive discharge from the measurements?
C. What is needed technically for the implementation (improvement) of the station?
D. What is the range of discharge that the station can monitor? And what is a realistic estimation for the uncertainty?
E. What are expected costs for the implementation of the station?
F. How can the station be maintained after implementation?

1.4 Measurement error and uncertainty

An important and difficult to quantify requirement is the relative measurement error. Measurement error is the difference between a measured value of a quantity and its true value. Often it is divided by the true value to result in a percentage, the relative measurement error. This relative measurement error is commonly presented for historical discharge measurements, due to its practicality. In this report, we estimate the expected uncertainty for each solution. Within the scope of this feasibility study, we cannot give an exact number or carry out a full uncertainty analysis for a proposed solution. For more details about uncertainty, we refer an interested reader to the work of Bertrand-Krajewski et al. (2021).

It is important to note that the measurement error does not distinguish between accuracy, trueness, and precision (see Figure 1.6). Measurement errors can be divided into two components: random and systematic errors. A random error is determined by chance and can be reduced by repeating the measurement and averaging the results (lower left in Figure 1.6). Systematic errors are errors introduced by repeatable processes inherent to the system. A systematic error results in a deviation from the true value (right panels in Figure 1.6). A measurement often has both a systematic error and a random error (lower right panel in Figure 1.6). In this work, the uncertainty (i.e., one standard deviation) is a combination of the random and systematic errors.

For example, consider the relative measurement error from sailing multiple transects with a boat-mounted ADCP. The discharge determined from each transect will have a random and systematic error. The discharges derived from each transect are usually averaged to reduce the random error. Furthermore, WL uses discharge derived from ADCP transect as the reference. This implies that it is assumed that the net systematic error of the discharge derived from multiple transects is zero. Although this assumption is commonly applied, it is not necessarily true for each discharge derived from multiple transects.

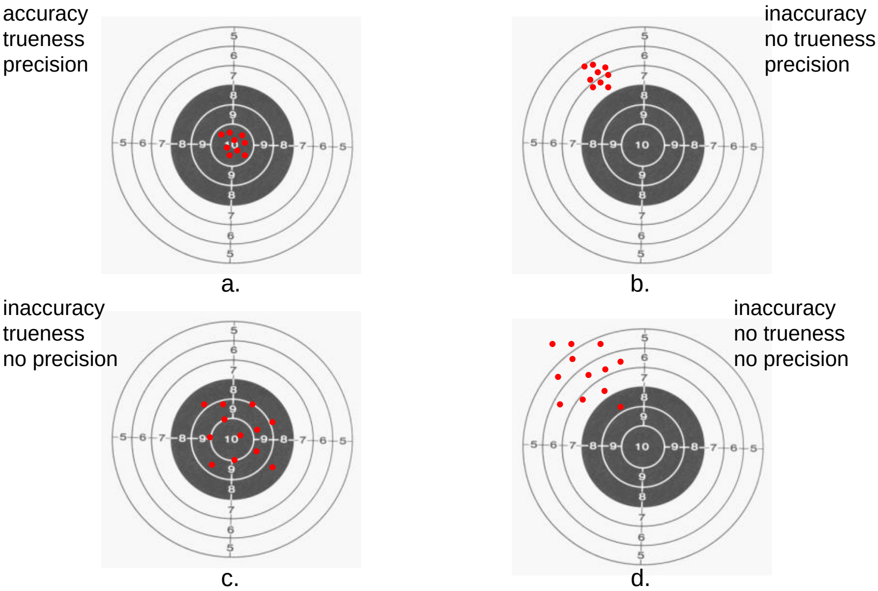

Figure 1.6 Characterization of accuracy, trueness, and precision in a set of measurements (source: (Bertrand-Krajewski et al., 2021)).

1.5 General approach and limitations

Generally, our approach was to select a suitable location along the Geul, to carry out a literature survey on equipment and methods that may be suitable and to determine the feasibility to install a discharge station that meets the requirements. Since it was clear beforehand that it is challenging to meet the requirements, we have made a conceptual design for two stations.

For each station we propose an improved design, aiming at meeting the requirements as good as possible. For the possible solutions, we have generally answered the research and practical questions. In a follow-up project, the questions can be answered in more detail, once a more detailed design of the monitoring station has been worked out.

1.2 Acknowledgements

We would like to acknowledge SPW for sharing the bed level observations and discharge observations in the Belgian part of the Geul. We thank the Wageningen University and Research centre for sharing insight on discharge monitoring in their parallel project on the Roer. We thank WL for sharing their knowledge on the Geul valley and the pleasant collaboration.

2 Methods and equipment

There are several different methods to determine the stream flow or discharge. The discharge is often derived from velocity or water depth measurements. In this section we will introduce the different methods to compute the discharge from the measurement of related quantities. These methods can be generally categorized in stage-discharge, velocity-area, dilution, or index-velocity methods. Thereafter, we will discuss different types of measurement equipment to determine the input required for the discharge computation, such as acoustic doppler current profilers, quantitative imaging, and other techniques.

2.1 Discharge methods

In this section, we will briefly introduce methods to compute the discharge from measurements of the velocity and/or water depth. In this section we limit ourselves to a general selection of methods that include: the stage-discharge, the velocity-area, the index-velocity, and the dilution method.

2.1.1 Stage-discharge method

The stage-discharge method, or so-called rating curve, describes an empirical fit between the head (h) and the discharge (Q) of a stream. The stage-discharge method is accurate for steady conditions within the calibration range. Calibration data is easily obtained for the most common conditions (i.e., low discharge conditions for streams). On the other hand, calibration data for high discharge conditions (i.e., rare conditions) are difficult to obtain, such that extrapolation methods are required. The extrapolation methods, combined with the hysteresis introduced during a flood event, negatively impact the accuracy of the discharge measurement during extreme conditions (Boiten et al., 1995).

A stage-discharge curve becomes inaccurate when there are morphological changes. Erosion and/or sedimentation may alter the bed, which negatively impacts the accuracy of the method. On the other hand, roughness changes of the bed, such as growth of vegetation (e.g., Kalinowska et al., 2023) or an extreme discharge situation that alters the local roughness can also negatively impact the accuracy. Additionally, the water depth variation introduced during a flood event (i.e., extreme conditions) limits the accuracy of the discharge estimate due to hysteresis on the stage-discharge curve (Boiten et al., 1995).

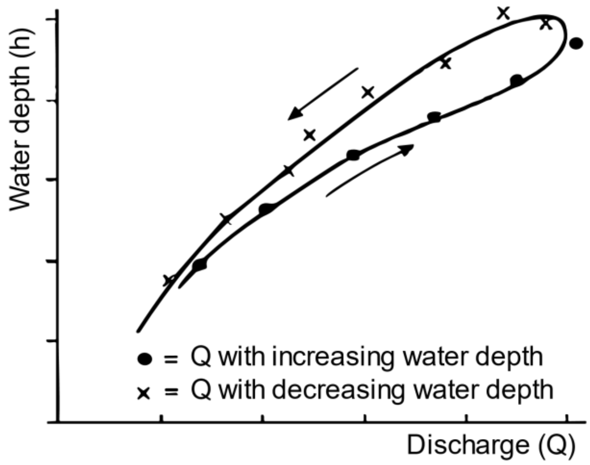

Figure 2.1 Hysteresis of the rating-curve during extreme conditions (adapted from Boiten et al., 1995).

2.1.2 Velocity-area method

The velocity-area method is a common method to estimate the discharge by integration of discrete velocity measurements over the cross-sectional area of the channel. The discrete velocity measurements are used to determine the vertical velocity profile at multiple locations (i.e., vertical sections) along sections across the channel. The discharge per section (Q_i) is derived by integration of the velocity (v_i) over both the depth and horizontal spacing between sections. The discharge is derived by summing the discharge of each section along the cross-sectional area of the channel and by accounting for the bank effects (Hauet, 2020a).

$$Q = Q_{bank} + \sum_{i=1}^{N} \iint v_i dxdy$$

The accuracy of the velocity-area method is defined by the assumptions associated with the velocity profile (Biggs et al., 2021; Dolcetti et al., 2022a; Hauet, 2020a; Welber et al., 2016a) and the choices in the measurement method. For example, there should be about 10 profiles across the stream for stable conditions and 16 or more when variations of the discharge are expected (Chen, 2013). The assumptions associated with the missing areas near the banks – see left and right area in Figure 2.2 - also impact the accuracy of the discharge estimate (Hauet, 2020a). Moreover, the accuracy of the velocity-area method also declines if the discharge is not stable during the measurements. For small streams, with rapidly varying flows, this could be an issue. Finally, the accuracy of the velocity-area method decays past the bankfull discharge (i.e., the discharge at which the water level barely overtops the floodplain) due to inundation of the floodplain.

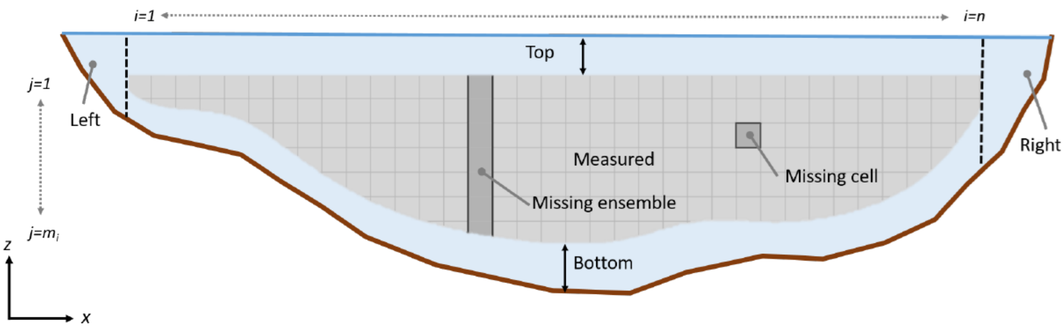

Figure 2.2 The velocity-area method uses the measured cross-sectional area (light gray) to determine the discharge. The measured cross-sectional area does not cover the entire wetted area, due to the blanking distance of an ADCP and a zone near the bed where interference occurs (see section 2.2.1). Furthermore, a boat mounted ADCP can often not reach the banks on the left and right of the domain. (source: Hauet, 2020b)

The assumptions associated with the velocity profile can have a significant impact on the accuracy of the velocity-area method. In general, a log-law velocity profile is used with a velocity coefficient to account for a reduced velocity at the surface. The maximum velocity of the profile does not necessarily coincide with the surface due to wind effects, and non-uniformities (e.g., momentum redistribution over the depth) of the velocity field (Biggs et al., 2021). The velocity coefficient can typically attain values between $0.7 \leq \alpha \leq 0.95$ with a default value of approximately 0.85 (Biggs et al., 2021). An uncertainty of 10% on the velocity coefficient may introduce an uncertainty of up to 16.8% of the discharge (Dolcetti et al., 2022a).

2.1.3 Index-velocity method

The index-velocity method uses the velocity at a specific point in the cross-section of the stream combined with a stage-area (i.e., water depth versus surface area) curve to determine the discharge. The stage-area and index-velocity curves can include multiple linear combinations to accurately determine both low and high discharge conditions (see Figure 2.3 which is reproduced from Figure 23 of Levesque & Oberg, 2012). This method is comparable with the stage-discharge method but uses the velocity instead of the water depth to determine the discharge. Furthermore, this method can be used in situations with variable backwater or unsteady flow conditions (Levesque & Oberg, 2012a).

The method assumes that the velocity distribution over the cross-section remains constant within the multiple linear combinations that span the discharge range. Consequently, the discharge measurement becomes more uncertain when the velocity distribution is altered due to bathymetry and/or vegetation changes.

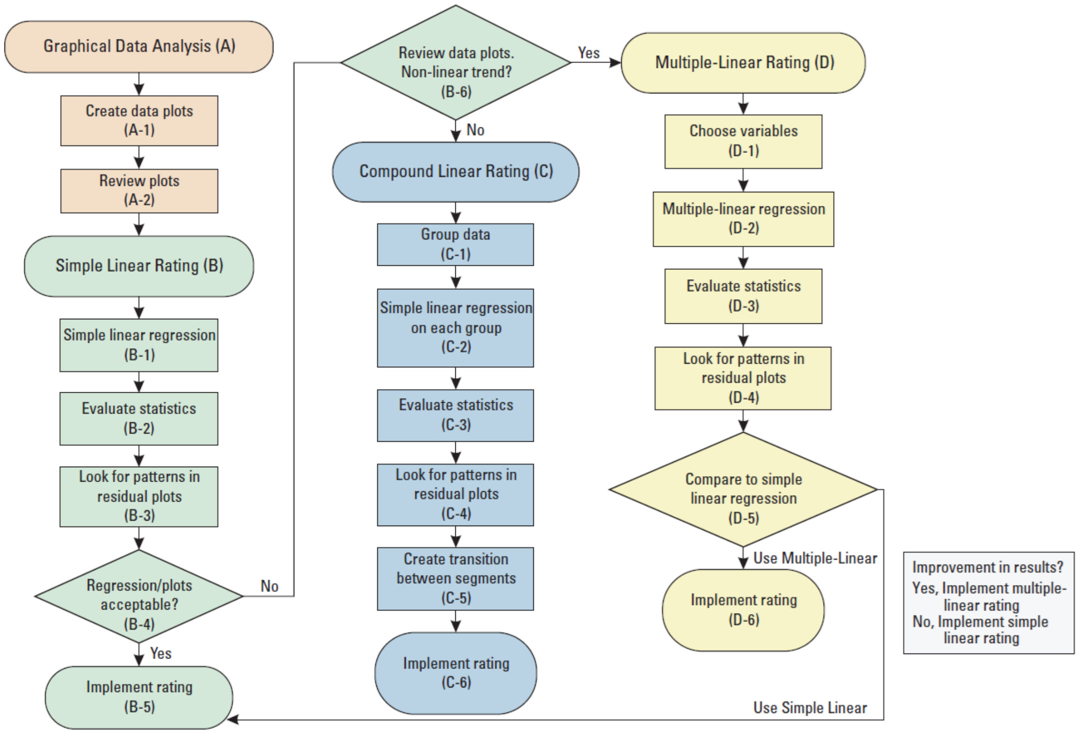

Figure 2.3 A schematic to determine the index rating (source: Figure 23 from Levesque & Oberg, 2012b).

A gauging station that applies the index-velocity method should satisfy the following points:

1. The gauging section should be placed at a location where the streamlines in the flow are relatively parallel and uniform.
2. The location should be free of any flow disturbance due to obstacles (e.g., wake separation behind pillars) or branching flows. The flow at the gauging station should also be free of air entrainment.
3. The gauging sections should be straight for approximately 5 and 10 channel widths upstream and downstream.
4. The bathymetry at the gauging station should be relatively stable and free of vegetation.

Not all criteria can be met at each gauging station, but care must be taken to select a location with a velocity distribution that is a as uniform as possible (Levesque & Oberg, 2012a).

2.1.4 Dilution methods

Dilution methods rely on mass conservation between an injection point and measurement point downstream of the injection point. The principle of mass conservation is used to determine the travel time of the tracer. The discharge of the stream can be calculated from measurements of the tracer concentration at the downstream location (Boiten et al., 1995).

The tracer material can be injected into to the system with a *continuous* or *sudden (i.e., slug)* rate. The *continuous* method derives the discharge from the difference between the injected tracer and the steady tracer concentration at a downstream location. On the other hand, the *sudden* method derives the discharge from the integral of the measured tracer concentration curve at a downstream location.

The dilution method imposes several requirements on the tracer material and the gauging section. The tracer material must dissolve easily but should not be adsorbed by the environment. Furthermore, the background concentration of the tracer material at the injection point should be known. Additionally, the impact of the material on the environment should be minimal (i.e., a material that breaks down in a natural environment after the gauging section). The gauging section should have sufficient length and should be free of branching streams. Furthermore, the fluid flow in the gauging section should be turbulent to allow for efficient mixing of the tracer material, as the method requires a well-mixed tracer material at the gauging point. An optimal design of the dilution method results in a discharge uncertainty (i.e., one standard deviation) of approximately 3 – 6% (Boiten et al., 1995). While this method can be manually applied at regular time intervals, creating a continuous measurement station utilizing a dilution method is a challenging endeavour in practice.

2.2 Measurement equipment

In this section, we will introduce measurement equipment that might be appropriate for discharge measurements at the Geul. For each technique, we will briefly describe its measurement principle and possible sources of measurement uncertainty.

2.2.1 Acoustic Doppler Current Profiler (ADCP)

An acoustic doppler current profiler (ADCP) measures the velocity of particles in the water, using the Doppler-shift from the returning soundwaves. The device usually has multiple transducers. The recorded velocities in each of the beams can be used to derive all three-components of the velocity. A gyroscope and compass are typically used to convert the velocity components to a world referenced coordinate system. If the ADCP is mounted on a vessel, the measured velocity is corrected for the movement of the boat with a bottom-tracking or a GPS-based reference velocity (Mueller et al., 2013).

An ADCP has two specific limitations, namely: unmeasured areas in the profile; and problems with high levels of sediment. The velocity profile cannot be determined near the ADCP (i.e., up to the blanking distance) and near the bed (i.e., due to side-lobe interference). Figure 2.4 depicts the blanking distance and side-lobe interference as function of the beam angle. The accuracy of an ADCP can quickly decay in areas where sediment concentrations are high. First, the high amount of sediment can attenuate the acoustic signal and limit the available profile depth. Furthermore, suspended sediment near the bed can limit the accuracy of the bottom-tracking of boat mounted ADCPs and depth estimate (Mueller et al., 2013).

Accurate discharge measurements (i.e., standard deviation of approximately 5 – 10%) can be derived with a traversed (e.g., boat-mounted) ADCP using the velocity-area method. This method to derive instantaneous discharge is often used to establish a stage-discharge relation. However, when the flow velocity is too high, it may be practically impossible to carry out boat-mounted observations. As an alternative, Chen (2013) obtained accurate discharge measurements during high-flow conditions with approximately 7- 16 velocity profiles using a crane from a bridge. The accuracy (i.e., standard deviation) of the boat mounted ADCP measurements can be improved by increasing the number of transects (e.g., typically more than 10 are advised) over the cross-section of the stream.

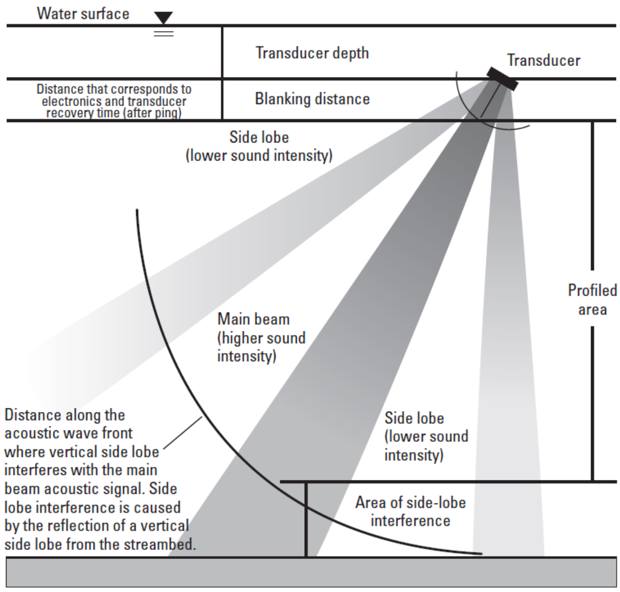

Figure 2.4 The main and side lobe from a single transducer, with zones indicated in the vertical where measurements are biased and should not be used (i.e., due to blanking and side-lobe interference) in an ADCP profile (source: Figure 4 of Mueller et al., 2013).

2.2.2 Side looking Doppler instruments

Aiming to monitor discharge continuously, side looking instruments are available that measure the flow velocity at one level in the river (Figure 2.5). Such instruments are normally installed from a riverbank or a bridge pier and measure the flow at the level at which they are installed. The instrument is ideally installed at 40% of the water depth in the deepest point of the cross section, considering that it is insensitive to the hydraulic roughness and gives the depth-averaged flow directly. Typically, a horizontal ADCP (HADCP) is developed for a river and smaller side looking instruments with higher sound frequency are available for streams. An index-velocity method is usually applied for both groups of instruments (Le Coz et al., 2008a; Schroevers, 2013).

The side looking instruments have generally the same uncertainty sources as the vertical ADCP, although uncertainty can be reduced by averaging the continuous signal over time. Typical for a deployment across a river or stream is that water depth is often small with respect to the width. The main beam may intersect with the water surface further away from the instrument, due to the widening with typical 1-2 degrees (Figure 2.4). In addition, the side lobes of a beam may intersect with the riverbed and water surface substantially closer to the instrument. Particularly when the low energy side lobes reflect on the bed, they can possibly generate a bias in the observed flow velocity.

Le Coz et al. (2008b) found for their specific implementation in a river that the HADCP flow measurements tend to underestimate the flow velocity up to 50% in the second half of the cross section furthest away from the sensor. In all other cases, the horizontal ADCP measurements were reliable with velocity measurements within 5% of vertical ADCP measurement. Moore et al. (2010) evaluated another HADCP deployment and found a similar underestimation of the flow further away from the instrument (Figure 2.6). They found that the echo intensity measured by the HADCP diverges from the theory with distance from the instrument. They suggest that reflection from the bed or from roughness at the water surface may explain the underestimation of the flow further away from the instrument. The bias at the site could not be explained from the geometry, variations in roughness or variation in sediment concentration.

Considering the bias found at several (relative low depth to width ratio) sites with a side looking Doppler instrument, the flow velocity profiles measured with such an instrument need to be evaluated (e.g., using boat mounted ADCP observations). However, discharge is currently monitored successfully at hundreds if not thousands of sites, using one or several side-looking Doppler instruments. The discharge can be estimated from the unbiased part using the index-velocity even when only the first part of the horizontal profile is unbiased. However, the accuracy of the discharge derived from a IVM is limited when the location of the maximum flow is not within the unbiased range.

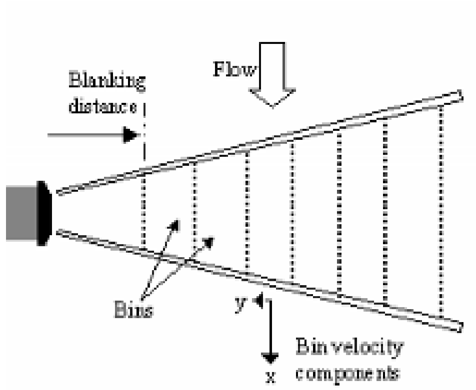

Figure 2.5 Example of a side looking instrument with 2 beams, showing the widening of the main beam. (source: usgs.gov2).

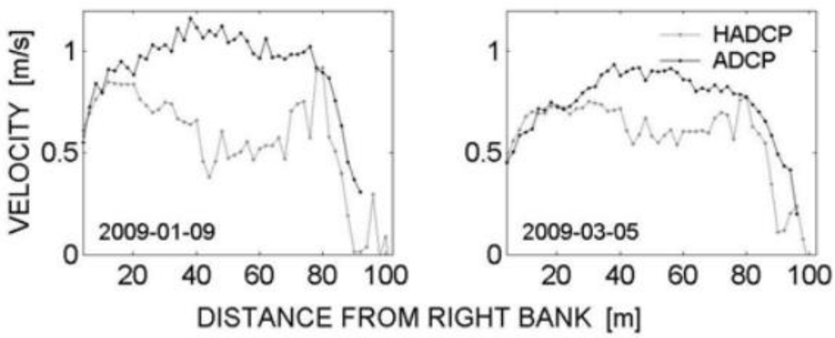

Figure 2.6 Horizontal profiles of streamwise velocity measured by a vertically oriented boat-mounted 600 kHz ADCP (black) and a fixed 300 kHz HADCP (grey) in a roughly 4 m deep French river at two moments. (source: (Moore et al., 2010)).

[2] OSW Hydroacoustics: Index-Velocity Instruments (usgs.gov), visited on 5 September 2023

2.2.3 Quantitative imaging (QI)

In this review, we have combined measurement equipment that uses an image of the free surface to determine the surface velocity as quantitative imaging (QI). These techniques track image features – that could be particles or free surface features – to determine the free surface velocity. For example, Large Scale Particle Image Velocimetry (LSPIV) determines the free surface velocity in small sub-windows of an image with a correlation-based procedure (e.g., Le Coz et al., 2010). On the other hand, optical tracking velocimetry (OTV) or particle tracking velocimetry (PTV) follow individual features in the images of a free surface (e.g., Tauro et al., 2017, 2018). The benefit of QI systems is their ability to determine the free surface velocity over substantial areas of a stream or river.

A disadvantage of QI systems is their dependence on visible features on the free surface. First, the application of the technique during the night is complex due to limited visibility. There are several manufacturers of QI (see for example the Discharge Keeper system) that support infrared measurements during the night. The accuracy of infrared systems can be limited due to non-uniform illumination with (infrared) lights. In addition, thermal infrared cameras are well-suited to detect image features during the night, but during the day the visible features on the thermal infrared cameras were limited due to solar irradiance (Puleo et al., 2012). Second, the QI techniques require traceable (i.e., particles) on the free surface. These features should be well-distributed and of sufficient quality to obtain velocity measurements over a substantial area of the stream (Jolley et al., 2021). Finally, the weather can have a negative impact on the accuracy of the method due, but not limited to, wind induced drift, specular reflection with varying solar zenith angles, and visibility limitations induced by rain and/or mist.

The discharge can be computed with the velocity-area or index-velocity method using the free surface velocity at a local transect in the measured area. This requires an appropriate assumption for the velocity profile. However, the velocity profile assumption can have a negative impact on the accuracy of the discharge estimate as discussed in section 2.1.2. In addition, a site-specific calibration is required for methods that depend on surface velocity measurements, which imposes requirements on the stability of the gauging section (Dolcetti et al., 2022b).

The accuracy of the discharge measurements derived with QI systems can be limited in specific situations. Nonetheless, the technique is valuable as it can provide data during fast flood events when conventional techniques are difficult to deploy (Le Coz et al., 2010). Some manufacturers also sell pan-tilt QI systems, which allow for QI measurements over even larger areas. A QI system could therefore be used to extend the validation range of stage-discharge curves if the uncertainty of the QI discharge measurement is low. In addition, the technique can also supplement other techniques that require regular inspection of the gauging station and or section. For example, the images provided by the QI methods can be used to remotely inspect the growth of weeds or operational state of a gauging station.

2.2.4 Radar

There are multiple types of radars available on the market. In this review, we will limit ourselves to small-scale Surface Velocity Radars (SVR) applicable to streams such as the Geul and the Gulp. The radar emits a radio signal that is backscattered by short surface waves (Welber et al., 2016a). A specific wavelength is required to scatter the radio signal, which is based on the Bragg condition. The velocity is derived from the difference in frequency of the back-scattered wave (i.e., the Doppler effect).

The radar determines the average velocity over an area (i.e., the radar footprint) that depends on the angle and the height of the sensor with respect to the water level. The surface velocity in the radar footprint should be uniform to limit errors due to averaging of the velocity. Consequently, a radar cannot be applied near the banks of a stream or in areas with vegetation growth.

The SVR velocity measurement can be converted to a discharge with either a velocity-area (Plant et al., 2005) or index-velocity (Welber et al., 2016b) based method.
On the other hand, the velocity-area discharge computation from a SVR essentially uses a single velocity measurement and is thereby an index-velocity method.

The typical requirements for an index-velocity method also apply to SVR based discharge measurements (OTT HydroMet, 2006). In addition, site locations with macroturbulence (e.g., foam and/or boils) and obstacles should be avoided. The macroturbulence can complicate the signal evaluation whereas obstacles alter the velocity distribution (Welber et al., 2016a). On the other hand, the method requires small-scale surface waves to allow for Bragg scattering.

Another uncertainty source of the SVR methods is wind that can induce drift on the surface (Alimenti et al., 2020; Plant et al., 2005). The velocity measured by the SVR could be corrected for wind induced drift by measuring the local wind vector (Plant et al., 2005).

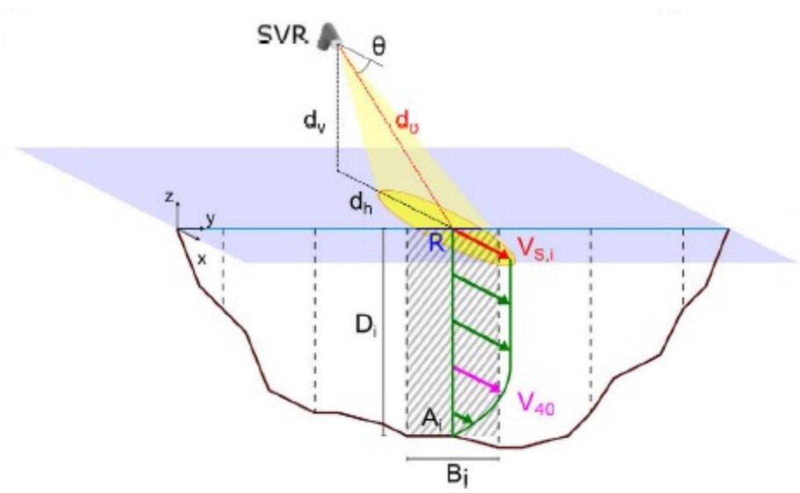

Figure 2.7 Surface Velocity Radar measurement principle. The surface velocity ($V_{s,i}$) is determined over an area denoted in yellow (i.e., the beam footprint). A velocity profile assumption (i.e., log-law) is used to derive a velocity profile. The bulk-velocity (i.e., integral of the velocity profile) or velocity at a specific depth (i.e., velocity at 40% of the maximum velocity V_{40}) is used to derive a discharge with the index-velocity method. (adapted from Welber et al. (2016)).

2.2.5 Acoustic transit-time

An acoustic transit-time system measures the propagation time of an acoustic pulse between an acoustic emitter and receiver (Marushchenko et al., 2016). The acoustic travel time is altered by the magnitude of the fluid velocity along the acoustic path (Figure 2.8). This path should not be perpendicular to the mean flow direction, but rather at an angle with respect to the mean flow direction. The optimal angle is approximately between $30°$ and $65°$ with respect to the mean flow direction (ISO 6146, 2004). A combination of a forward and backward facing acoustic (i.e., crossed-path) transit-time system allows for accurate average-velocity measurements over the acoustic path even when the transverse velocity component is non-negligible (Bertrand-Krajewski et al., 2021; ISO 6146, 2004).

These transit-systems are generally accurate and reliable when the length of the acoustic path is sufficient. Additionally, these systems have a wide measurement range both in terms of their averaged-velocity and their measurement width (Marushchenko et al., 2016). The averaged-velocity derived over the acoustic path is also perfectly suited for index-velocity methods. A transit-time system can be acquired from for example Flow-Tronic[3].

A disadvantage of the transit-time system, and side looking instruments, is their fixed measurement depth. In some cases, the velocity at a single depth might not be sufficient to determine a discharge relation for the complete measurement range (ISO 6146, 2004). Additionally, the submergence depth, which is dependent on the acoustic path length and transducer frequency, should be sufficient to avoid reflection from the water surface (ISO 6146, 2004). Consequently, multiple measurement depths might be necessary to limit reflections from the water surface and to increase the measurement range.

These systems – like other acoustic methods – also suffer from air entrainment in the water column. For example, weed growth on the banks can negatively affect the accuracy of the system as these weeds tend to collect air in their plant structures (ISO 6146, 2004). If the banks tend to accumulate weeds, a transit-time system could be installed on frames away from the banks to reduce their impact on the system accuracy. In addition, the maintenance costs of a transit-time system can be high, as the transmitter and receiver of the system need to be perfectly aligned.

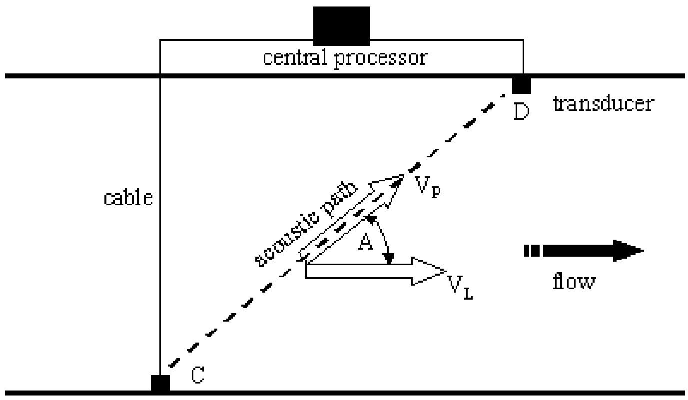

Figure 2.8 Acoustic transit time set-up with one pair of transducers. Sound pulses are emitted at C to D, and from D to C. The flow velocity can be derived from the difference in travel time. (source: usgs.cov4).

[3]https://www.flow-tronic.com/products/flo-sonic-ocfm, visited on 13 October 2023
[4]https://hydroacoustics.usgs.gov/indexvelocity/instruments.shtml, visited on 5 September 2023

3 Conceptional design for the Geul

3.1 Location selection

We have identified two locations where a discharge station could meet (most of the) imposed requirements (Table 1.1). Near the border, the potential of Sippenaeken is highest since a weir results in a relatively high water depth locally and helps to stabilize the stream bed. The relatively high depth to width ratio is beneficial for flow measurements. Although it is possible that the weir may be altered or removed for ecological purposes, we assume that the weir and fish trap will remain. Furthermore, the Geul valley upstream of the Dutch-Belgian border does not have the Natura2000 protection status, which may simplify getting permits for the installation of equipment and maintenance of the station. Our decision was not influenced by the absence of the Natura2000 status, as the location is interesting from a hydraulic point of view. Nonetheless, the location is still challenging due to the variable flow through and over the construction near the weir (Figure 1.3) and the non-uniform flow due to a mild bend upstream of the station. We propose an improvement of the station, particularly for the high discharge range.

At Hommerich, discharge is already derived using two methods. For decades, the discharge has been derived from stage-discharge relations. It is valuable to continue this time series, although the station is 6 (not less than 2 km as required) from the border. Two requirements are met at this station: the Geul is rather straight and the bed level has been rather stable the past decades. Although vegetation cover can result in a systematic error of the derived discharge, the location still allows for accurate discharge measurements until inundation of the valley. A connection for electricity and telemetry is available at Hommerich.

For each of these two locations we describe relevant details and propose a conceptional design to improve the discharge station.

3.2 Sippenaeken

3.2.1 Details of current situation

A bridge is situated at Sippenaeken, which has a sufficiently large cross-sectional area to accommodate the discharge of the Geul, even during extreme conditions (Figure 3.1). This makes the bridge a perfect location to install a discharge station. Furthermore, at this station, a discharge time series has been consistently generated over many years through a stage-discharge relation. However, during the high water period of 2021 the observed discharge was probably underestimated substantially (section 1.1.2).

WL provided 1/500 scale maps containing detailed geometry data, including bridge elevation information (as depicted in Figure 3.2, originating from SPW). These maps have served as valuable resource for the bed level, which we used for the conceptual design. It is worth noting that the vertical reference used in these maps is TAW[5], which is situated 2.33 m lower than the Dutch reference level NAP.

[5] Tweede Algemene Waterpassing (TAW) is the vertical datum used in Belgium

In subsection 1.1.1.2, we highlighted the potential variability in flow over certain structures, such as gates and fish ladders. To ensure the stability of the discharge measurement, it is important that there are no alterations in the height of the gate opening over time. As a precautionary measure, we recommend the permanent closure of this section to mitigate uncertainties in the discharge derivation method that we will propose in the following section. Additionally, there is a channel branching off from the Geul, located just upstream from the weir. This channel is connected to a mill. The provided map shows that the Geul is relatively straight, without sharp bends within five times the width of the bridge.

Figure 3.1 Photos with upstream view of the road bridge over the Geul at Sippenaeken at low discharge on 15 May 2023 from (top) the weir and (bottom) the stream bank, showing the water level station on the other side of the stream.

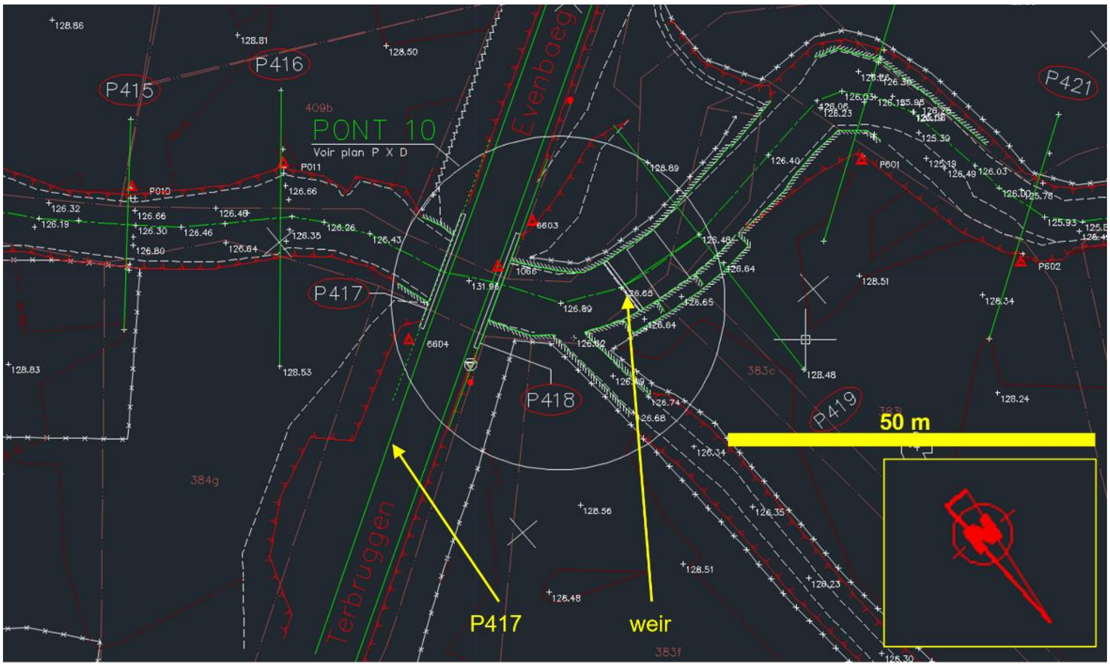

Figure 3.2 Map of the Geul at Sippenaeken, flow being from left to right. The road bridge is situated upstream of the weir. A channel branches off the Geul in between the bridge and the weir, which is usually closed with gates. (Source: Ministere de la region Wallonie, SPW, 1/500 map, dated: March 1994).

3.2.2 Conceptual design

3.2.2.1 Medium to high discharge range

For the medium to high discharge range, we propose an improvement of the station. We propose to install flow meters at two levels on the sidewall under the bridge, as indicated in Figure 3.3. The flow meters determine flow over a large part of the width at their installation level. According to the available information on bed level and minimal water level, the lower instrument will always be at least 0.5 m below the water surface. The upper flow meters are at about 128.9 m TAW, about 75% of the water depth at high discharge, and will only measure the flow when it is submerged. We propose to install the upper flow meters so high to avoid any interference with the bed. However, in the design phase it can be considered to install the upper instrument at a lower position (e.g. at 0.4 times the water depth at yearly occurring maximum water level). This choice will require further support and validation during the detailed design phase. Discharge is obtained from the measured flow velocities from both levels and the water level, using the index-velocity method.

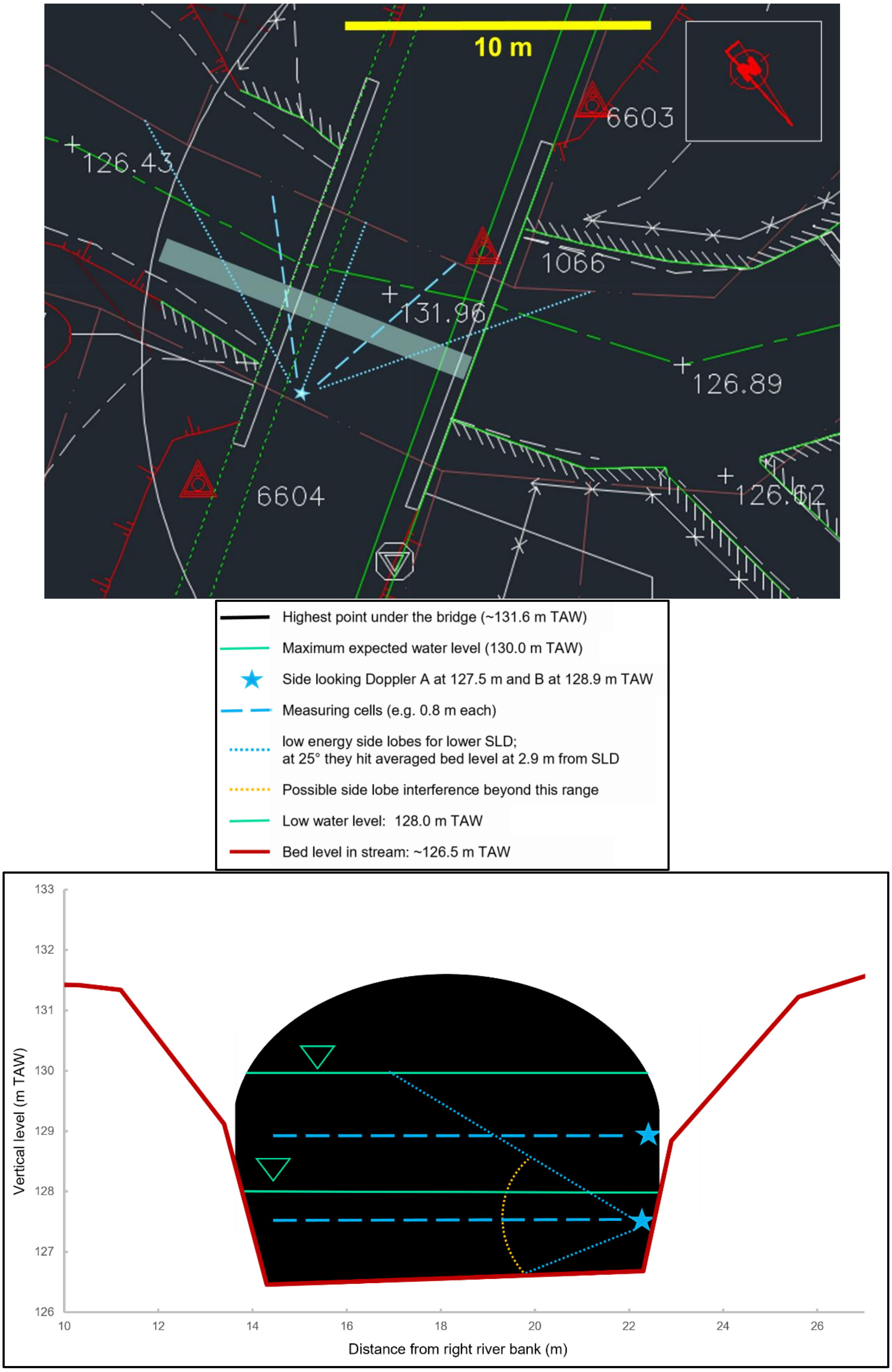

Figure 3.3 Conceptual design of a possible station set-up with two side looking Doppler systems deployed under the road bridge, with (top) a detailed map of the area around the bridge (as in Figure 3.2), (middle) a legend, and (bottom) a cross sectional area. The bed level profile is obtained from profile P417 in Figure 3.2.

3.2.2.2 Equipment

We found three potentially suitable instruments that are currently available (Table 3.1). All three can be mounted on the side wall of a bridge to measure flow in a large part of the stream width. The first two in the table are Side Looking Doppler instruments and the last is a transit time instrument. Given that the thickness of all three instruments is small compared to their width, their impact on the flow is minimal. The flow measurement for all three can be disturbed due to interference with the bed or water surface, high sediment concentration or obstacles (e.g. vegetation). Based on the information we obtained for these instruments in this feasibility study, we cannot yet select one as the best option.

All three instruments may be suitable, but we have a slight preference for one of the Doppler instruments. The required length along the channel is smaller than required for the transit-time instrument. Furthermore, when an obstacle is in the water the Doppler instruments still result in an observation up to the obstacle, whereas a transit-time instrument will have a data gap at such a moment. However, a drawback associated with side-looking Doppler instruments is the potential occurrence of side-lobe interference. Sontek makes a noteworthy claim about side-lobe suppression, but we were unable to find specific information on their website regarding the implications and the effect on the range with valid flow measurements. Side-lobe interference has been noted with several side looking Doppler instruments, although it was not observed at all monitoring stations (Le Coz et al., 2008b; Moore et al., 2010).

To illustrate, we provided an example solution with cells measuring 0.8 meters, resulting in a total of 8 cells across the width. In the case of the lower instrument, as depicted in Figure 3.3, we have designed with the assumption that the first side-lobe is present at an angle of 25°. Under this configuration, it can be confirmed that for the lower flow meter only observations within approximately 3 meters from the instrument location are guaranteed to be free from side-lobe interference with the streambed. However, we anticipate that the range unaffected by side-lobe interference will be larger in practice.

The upper panel of Figure 3.3, with cell 4 highlighted, indicates that the assumption of uniform flow within each beam may be questionable when using the available geometry. Consequently, during a more detailed design phase, it’s required to carefully select the optimal location and orientation, considering bed level observations. After installing the instruments, it’s essential to evaluate the measured flow velocities and ensure that side-lobe interference or reflections with the water surface do not occur. This verification can be achieved through standard boat-mounted ADCP observations.

Table 3.1 Examples of side looking Doppler instruments that may be feasible, and some specifications (Sources Sontek6, Ott 7 and Flow-Tronic8).

Type	Instrument (Manufacturer)	Range (m)	Angle with line across (°)	Accuracy	Thick-ness (m)	Remarks
Doppler	SL1500 (Sontek)	0.2-20	25	1% + 5mm/s	0.06	They claim to apply side lobe suppression, but unclear how they do that and what the implications are
Doppler	Side looking Doppler 2.0 (Ott)	0.1-10	Not available on website	1% + 5mm/s	0.07	Maximum is 9 cells
Transit time	Flo-Sonic Open Channel Ultrasonic transit-time flow meter (Flow-Tronic)	N.A. on website	Free to choose, 30-65 (section 2.2.5)	Min(1%, 5mm/s)	0.14	

3.2.2.3 Low to medium discharge regime

The stage-discharge relation is well-suited for low to medium discharge. However, the flow measured by the lower flow meter could potentially be used with IVM to decrease the discharge uncertainty. According to Ott, one of the manufacturers, accurate discharge can be derived in a section with a depth over width ratio of at least 1:10. This condition is met at the lowest water level, assuming that rocks do not protrude higher than 16.5 m TAW. We suggest evaluating the flow measured by the lower flow meter. If this evaluation confirms a valid flow velocity, we recommend applying IVM. Alternatively, an up-to-date stage-discharge relation can be used to derive the discharge for low to medium levels.

3.2.3 Estimation of uncertainty

We estimated the uncertainty for the medium to high discharge range with a simplified uncertainty propagation (see also section 1.4). In our simplified uncertainty propagation, we neglect correlation of errors.

A first source is the uncertainty in the flow measurement. Both manufacturers mention a measurement uncertainty (i.e., one standard deviation) of 1% of the measured flow +/- 5 mm/s. When the flow velocity is 0.5 m/s under the bridge, the uncertainty due to the flow measurement is then 2%. However, this uncertainty holds for optimal conditions, with uniform flow. Considering the irregularities as the mild bend and rocky bed under the bridge, we expect that the flow in both main beams differ both in magnitude and direction (the upper panel of Figure 3.3). The resulting uncertainty is difficult to estimate, but can be 5 times higher than the 2% mentioned, being 10% at low discharge regime.
Note that during high discharge regime the uncertainty relative to the observation is expected to be lower, due to the higher level at which flow is measured and the smaller contribution of the absolute uncertainty (+/- 5 mm/s).

---

[6] https://www.xylem.com/en-us/products--services/analytical-instruments-and-equipment/flowmeters-velocimeters/sontek-sl3000-side-looking-doppler-current-meter/specifications/, visited on 31 August 2023
[7] https://www.ott.com/products/water-flow-3/ott-sld-side-looking-doppler-sensor-970/, visited on 31 August 2023
[8] https://www.flow-tronic.com/products/flo-sonic-ocfm, visited on 13 October 2023

A second source is the uncertainty in the geometry observation. The manufacturers deliver water level sensors that can be deployed in the side looking Doppler instrument. They provide an uncertainty (one standard deviation) of +/- 2 mm, which is lower than 1 % of the lowest water depth. An uncertainty of 1 % in the depth will result in an approximate uncertainty of 1 % of the surface area and consequently in the discharge. In addition, the uncertainty in measuring the bed level (which is assumed to be stable in time) and the bridge should be accounted for. It needs to be assumed that the cross-sectional area is the same along the section where flow is measured (the main beams in the upper panel of Figure 3.3). Irregularities due to rocks or changes in geometry along this section will lead to a substantial uncertainty in the discharge. The combination of measurement uncertainties and uncertainties due to geometry changes is challenging, but for the proposed station their sum will probably result in a discharge uncertainty larger than 5%.

The last uncertainty source is the application of IVM. Considering the mild bend of the stream upstream of the bridge, we expect that the flow velocity distribution will change for the medium to high discharge range. Again, this uncertainty source is challenging to quantify. We expect that it can easily result in an uncertainty of 5% averaged over the discharge ranges. The flow velocity distribution over the cross section may be well known from several boat-mounted observations during the most common (medium discharge range) conditions, whereas for high discharge range less boat-mounted observations will be available, which may result in a higher uncertainty for applying IVM at high discharge.

The total discharge uncertainty is computed with a simplified uncertainty propagation. The IVM relies on the mean velocity and the wetted cross-sectional area. The mean velocity (V_b) often depends on the streamwise index velocity, and the stage. The total uncertainty of the mean velocity is assumed to be approximately 11%. The wetted cross-sectional area (A_b) depends on the stage and channels cross-sectional shape. The total uncertainty of the wetted cross-sectional area is assumed to be approximately 5%. For the combined uncertainty propagation, we assume that the mean velocity, cross-sectional area, and all parameters in between are propagated as products. Consequently, we can compute a simplified propagated uncertainty that neglects cross-correlations between the uncertainties as:

$$\frac{\sigma_Q}{Q} = \sqrt{\left(\frac{\sigma_{v_b}}{V_b}\right)^2 + \left(\frac{\sigma_{A_b}}{A_b}\right)^2}$$

All in all, we expect that the uncertainty for the medium to high discharge is approximately 13% (i.e., one standard deviation) when we assume optimal site conditions. This means that for these site conditions the relative measurement error, from the comparison with the discharge derived from multiple transects with a boat-mounted ADCP, is expected to be higher than the required 15% for some individual comparisons. However, most of the relative measurement errors are expected to be within 15%.

3.2.4 Steps and expected costs

For the installation of the conceptual design, we foresee the following steps:

1. **Design**: Measure the actual bathymetry in the whole width and a stretch along the stream and use this to make a detailed design, considering the best configuration to limit side lobe interference.

2. **Installation**: Install the instruments and log water level, flow velocity and echo intensity. To avoid water level changes due to opening or leakage at the construction close to the weir and decrease uncertainty, we recommend to permanently close existing gates and openings.

3 **Calibration**: Carry out boat-mounted observations at various discharge levels when the side looking Doppler instrument is operational. The calibration period can last several years, since it is limited by the occurrence of high discharge events. A proper calibration curve can only be obtained if the environmental conditions, such as the bed profile, backwater, and vegetation growth, remain stable.

4 **Maintenance**: The station should be maintained regularly, which includes removal of vegetation (e.g., mowing) and bed level measurements at least after every high water. In case the bridge gets clogged by large debris (e.g. by trees transported in the Geul during high discharge), the debris needs to be removed, in order to obtain discharge from the index-velocity method.

The sensors should be calibrated regularly (e.g., annually). Sensor maintenance should be performed carefully to prevent misalignment of the equipment, but re-calibration of the station is advised after maintenance.

5 **Data validation and analysis**: data validation is required to ensure that the continuous data adheres to the data quality standards of WL. Otherwise, a sensor that malfunctions could not be noticed for a long time, which results in missing data in the validated discharge time series. The data validation procedure should be checked on a regular basis (e.g., twice a year) to detect gradual variations or trends. These trends may stem from either instability in the monitoring system or from changes in the conditions at the monitoring station.

For step 2, we estimate the total costs at € 42,000, - excluding VAT, being roughly € 24,000,- for the two instruments and € 30.000,- for cabling and telemetry. Perhaps an additional electricity connection is needed, which is not included in this estimate. The cost estimates do not include the costs associated with a design of the discharge measurement station and the civil engineering works. Furthermore, the staff costs for maintenance and data validation may be substantial and are not included.

3.3 Hommerich

3.3.1 Details of current situation

Figure 3.4 displays an overview of the discharge measurement station near Hommerich. Seasonal changes of the hydrodynamic conditions, such as variations in bathymetry and vegetation growth, are limited near Hommerich. Consequently, the location has a long history as a reliable and stable discharge measurement station that relies on a rating-curve derived from a water level sensor.

A deficit of the location is the wide valley (i.e., floodplain) that inundates for high discharge conditions. In addition, the discharge measurement can be biased due to backwater effects induced by the downstream bridge, or vegetation. Consequently, during high discharge conditions, the accuracy of the discharge measurement station is impaired.

During the flood of 2021, the old water level sensor was damaged which limited the available measurement data. *WL* installed a new water level sensor at a higher level compared to the floodplain. The new location of the water level sensor does not improve the accuracy of the rating curve during high discharge conditions.

Measurements during high discharge conditions could improve the accuracy of the rating curve. The rating-curve is currently limited to discharge conditions lower than approximately 25-35 m^3/s. Calibration measurements are conducted with a boat mounted ADPC that is pulled along the stream with a pulley system. However, these measurements cannot be performed during extreme discharge conditions, as the valley inundates for water levels higher than 95.0 m NAP. The highest reference measurement was at approximately 32 m^3/s. The rating-curve and reference measurement had a difference of 5% (de Graaff & Hagedooren, 2021).

Figure 3.4 also indicates a camera system that is used to derive discharge measurements with a QI (i.e., LSPIV) method (subsection 1.1.1.4). The camera system is a pilot project of a consortium with amongst others the TU Delft, Waterboard Limburg, and Rainbow Sensing. The initial results of the pilot project are promising, for example see Winsemius et al. (2023) and results obtained during the flash flood of 2021[9].

In this work, we did not find a solution that improved the accuracy during high discharge conditions. However, we propose a supplementary measurement system that allows for continuous day and night reference measurements.

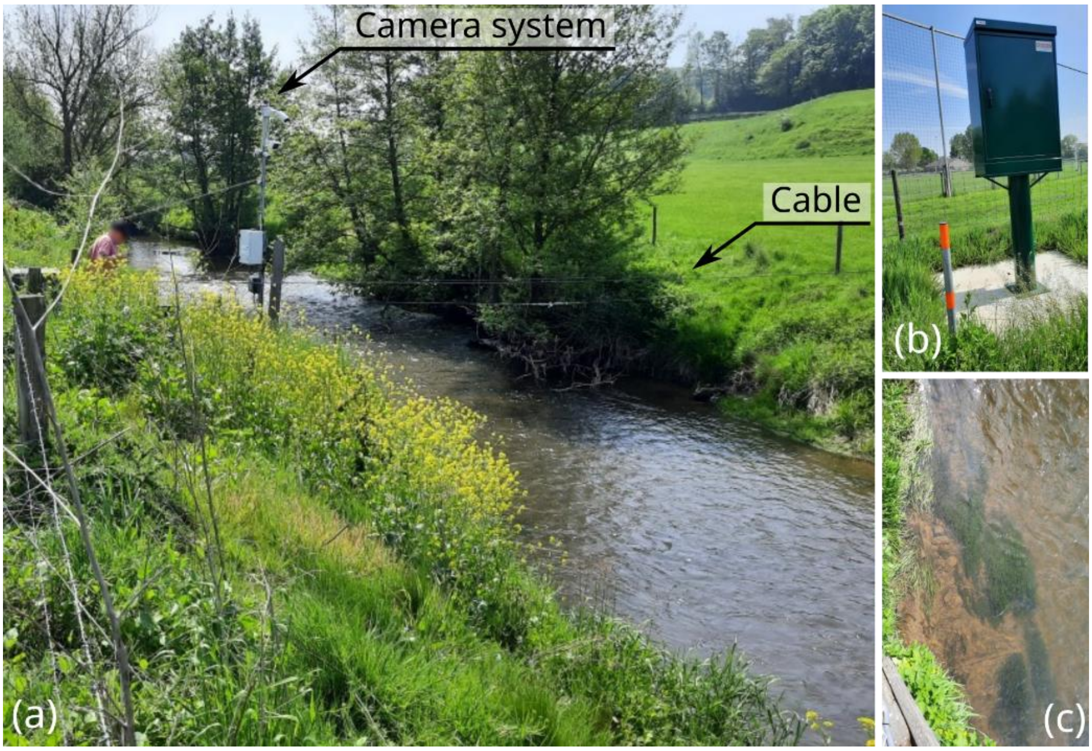

Figure 3.4 (a) Overview of the discharge measurement station in the Geul near Hommerich. Discharge measurements are derived with a rating-curve, and a camera system. In addition, the measurement station is regularly calibrated with moving boat ADCP measurements along a cable. (b) A reliable rating-curve is obtained with the water level sensor. (c) The bottom is relatively stable in the Geul near Hommerich. However, there is still growth of vegetation on the bottom of the Geul.

[9] *Capturing the July 2021 Meuse Flood with OpenRiverCam, see https://rainbowsensing.com/index.php/capturing-the-july-2021-meuse-flood-with-openrivercam/ accessed on 12th of September 2023.*

3.3.2 Conceptional design

The rating-curve at the discharge measurement station near Hommerich is reliable up to about 35 m³/s due to the stable environmental conditions and straight flow path. The regular calibration measurements that the *WL* performs with a boat mounted ADCP should continue. The calibration measurements guarantee a reliable and up-to-date rating curve. However, measurements are difficult to obtain during high discharge conditions. The camera system could be invaluable for calibration of the rating-curve at higher discharge conditions.

However, the measurements of the camera system during high discharge conditions should be interpreted with care as the conditions could not be optimal for surface velocity measurements (see section 3.2.1 for more details). In addition, camera measurements cannot be obtained during the night. An additional measurement system could be defined if a reference measurement should also be available during the night.

A surface velocity radar (SVR) as a supplementary measurement system offers the distinct advantage of continuous day and night monitoring. However, it's important to acknowledge the limitations of an SVR in terms of a velocity bias induced by variations over the measurement area or radar spot size (e.g., non-uniform velocity fields or vegetation) (Welber et al., 2016b). Unlike the optical measurement system, which can readily identify and address these issues, the SVR lacks this capability. Furthermore, since the SVR also relies on the surface velocity, it shares similar challenges with the optical measurement system.

Nonetheless, an SVR can also function as a validation measurement alongside the existing discharge measurement station. To delve deeper into the practical application of SVR technology, refer to OTT HydroMet (2006) for comprehensive insights. When implementing the SVR, careful placement is essential. It should be positioned above the stream's centreline, set at an angle ranging from 30° to 45° relative to the horizontal axis (see Figure 3.5). To achieve this, a robust cantilever arm is mandatory to ensure stability and minimize any potential disturbances caused by wind-induced vibrations or sway.

Orient the SVR in the upstream direction, ensuring that the water flows directly towards the sensor. Additionally, consider the sensor's mounting height, keeping it above 0.5 meters but within a maximum height difference of 3 meters relative to the water level. Notably, when the height difference reaches 3 meters, the radar spot size expands to 2.7 meters in length and 0.9 meters in width when positioned at a 30° angle to the horizontal axis.

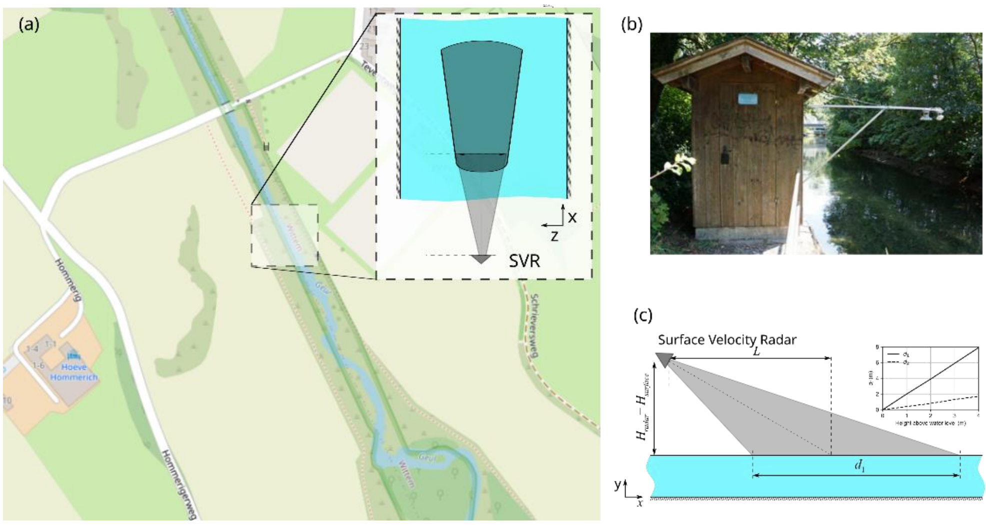

Figure 3.5 (a) Conceptual design for Hommerich. (b) A sensor mounted on a cantilever beam (adapted from:OTT HydroMet (2006)). (c) The SVR spot size depends on the height above the fluid level.

The discharge can be derived from the measured surface velocity at the centre line with an index velocity method (IVM). The location of the current discharge measurement station is well suited for an SVR measurements, as the course is rather straight, and the cross section is stable.

3.3.3 Estimation of uncertainty

It is worth noting that SVR measurements are most effective when surface velocities exceed 0.1 m/s, and minimal surface features are present (i.e., minimum feature height of 3 mm). If these conditions are met, the surface velocity can be determined with an uncertainty of approximately 2% (i.e., one standard deviation).

For the surface velocity measurements, a calibration of the site-specific velocity coefficient (i.e., a rating curve for the velocity coefficient) is required. However, Welber et al. (2016) show that a default velocity coefficient of 0.85 is valid for gauging sections with a relative roughness between 0.001 and 0.05. The discharge can be determined with an uncertainty of 10% during discharge conditions wherein the requirements of the SVR method are met. However, the accuracy of the SVR discharge measurement quickly declines when, amongst others, the water surface is too smooth (Welber et al., 2016b) or when the vegetation growth is too extensive (i.e., within the radar spot area).

3.4 Requirements and preferences

3.4.1 Sippenaeken

In Table 3.2 we present our evaluation of the requirements and preferences for the measurement system in the Geul near Sippenaeken.

Table 3.2 Summary to what extend the criteria from Table 1.1 are met for both the proposed solutions (medium-high and low-medium discharge regime).

Requirements and preferences	Explanation
Discharge range	The complete discharge range can be determined with the improved station.
Temporal resolution	A temporal resolution lower than 5-minutes is possible.
Location	The location is within 1 km from the Dutch-Belgian border. Closure of the construction next to the weir may reduce the uncertainty of the measured discharge.
Maximal relative measurement error	The gauging section near Sippenaeken fulfils most of the requirements for a gauging station. Nonetheless, we estimated the uncertainty (one standard deviation) to be 13 % at optimal site conditions. In practise, it is likely that the relative measurement error is higher for some of the moving-boat derived discharges.
Protected status	Sippenaeken is situated in Belgium, where the Geul valley has no protected status.
Bed level	The method does not consider bed level changes. However, bed level variations are expected to be limited due to the weir that and rocky bed.
Maintenance	The preference for doing maintenance maximally 1-2 times a year can be met.

3.4.2 Hommerich

In Table 3.3 we present our evaluation of the requirements and preferences for the supplementary measurement system in the Geul near Hommerich.

Table 3.3 Summary to what extend the criteria from Table 1.1 are met for the proposed solution.

Requirements and preferences	Explanation
Discharge range	The discharge range remains the same in the Geul near Hommerich (up to 35 m^3/s). The supplementary measurement system can improve the calibration of the rating-curve for higher, up to bankful, discharge conditions.
Temporal resolution	A temporal resolution lower than 5-minutes is possible. However, the user should be aware of the limitations of surface velocity based IVM methods. The uncertainty of the method quickly increases when the water surface is exposed to wind, resulting in a data gap. In addition, the method cannot determine the discharge when the surface velocity is below 0.1 m/s.
Location	The location is not within 2 km from the Dutch-Belgian border. The proposed location is near an already existing discharge measurement station in the Netherlands which is approximately 5 km from the Dutch-Belgian border.
Maximal relative measurement error	The gauging section near Hommerich fulfils most of the requirements for a gauging station. Nonetheless, the results from surface velocity measurements must be interpreted with care. In optimal conditions the discharge can be derived with an uncertainty (one standard deviation) of 10%.
Protected status	Apart from installing equipment that spans the stream no additional work is needed. If possible, the system could be installed on one of the existing poles.
Bed level	The method does not consider bed level changes. However, bed level variations are limited in the Geul near Hommerich.
Maintenance	The preference for doing maintenance maximally 1-2 times a year can be met.

4 Conclusion

For a location within the required 2 km from the Dutch-Belgian border, we could not specify a solution that meets all requirements. However, we propose two methods that could improve the quality and continuity of the discharge monitored at two existing stations:

At **Sippenaeken**, situated 800 m upstream of the Dutch-Belgian border, we propose to deploy flow velocity meters at two heights under the bridge. Medium to high range discharge can be derived from the continuous flow velocity measurements and water level measurements, using the index velocity method. As a result, the uncertainty of the obtained discharge can be reduced substantially.

At **Hommerich**, situated about 6 km downstream from the border, we propose to improve the existing station with a radar surface flow velocity measurement. These measurements can be used to obtain reference measurements for the stage-discharge curve during high discharge conditions. The method can also be used to verify the camera-derived flow velocity. In addition, the radar does not depend on the light conditions, and as such can provide velocity measurements during the night. This improves the continuity of the discharge measurements.

For each solution, one should perform station maintenance and data validation on a regular basis. Regular on-site discharge measurements from a boat are required for calibration purposes, particularly during high discharge events.

5 Literature

Alimenti, F., Bonafoni, S., Gallo, E., Palazzi, V., Vincenti Gatti, R., Mezzanotte, P., Roselli, L., Zito, D., Barbetta, S., Corradini, C., Termini, D., & Moramarco, T. (2020). Non-Contact Measurement of River Surface Velocity and Discharge Estimation with a Low-Cost Doppler Radar Sensor. *IEEE Transactions on Geoscience and Remote Sensing*, *58*(7), 5195–5207. https://doi.org/10.1109/TGRS.2020.2974185

Asselman, N., & Van Heeringen, K.-J. (2023). *Een watersysteemanalyse - wat leren we van het hoogwater van juli 2021?*

Bertrand-Krajewski, J. L., Clemens-Meyer, F., & Lepot, M. (2021). *Metrology in Urban Drainage and Stormwater Management: Plug and pray* (J. L. Bertrand-Krajewski, F. Clemens, & M. Lepot, Eds.). IWA Publishing.

Biggs, H., Smart, G., Holwerda, N., Doyle, M., McDonald, M., & Ede, M. (2021). *River discharge from surface velocity measurements A field guide for selecting alpha*.

Boiten, W., Dommerholt, A., Soet, M., Waterhuishouding, V., Kanaal, N., & Wageningen, P. A. (1995). *Handboek debietmeten in open waterlopen*.

Chen, Y. C. (2013). Flood discharge measurement of a mountain river-Nanshih River in Taiwan. *Hydrology and Earth System Sciences*, *17*(5), 1951–1962. https://doi.org/10.5194/hess-17-1951-2013

de Graaff, B., & Hagedooren, H. (2021). *Meetpunt Hommerich: vebeteren nauwkeurigheid hoogwaterafvoeren (PR4419.10)*.

Dolcetti, G., Hortobágyi, B., Perks, M., Tait, S. J., & Dervilis, N. (2022a). Using Noncontact Measurement of Water Surface Dynamics to Estimate River Discharge. *Water Resources Research*, *58*(9). https://doi.org/10.1029/2022WR032829

Dolcetti, G., Hortobágyi, B., Perks, M., Tait, S. J., & Dervilis, N. (2022b). Using Noncontact Measurement of Water Surface Dynamics to Estimate River Discharge. *Water Resources Research*, *58*(9). https://doi.org/10.1029/2022WR032829

Hauet, A. (2020a). *Uncertainty of discharge measurement methods: a literature review*. www.nve.no

Hauet, A. (2020b). *Uncertainty of discharge measurement methods: a literature review*. www.nve.no

ISO 6146. (2004). *Hydrometry-Measurement of discharge by the ultrasonic (acoustic) method*.

Jolley, M. J., Russell, A. J., Quinn, P. F., & Perks, M. T. (2021). Considerations When Applying Large-Scale PIV and PTV for Determining River Flow Velocity. In *Frontiers in Water* (Vol. 3). Frontiers Media S.A. https://doi.org/10.3389/frwa.2021.709269

Kalinowska, M. B., Västilä, K., Nones, M., Kiczko, A., Karamuz, E., Brandyk, A., Kozioł, A., & Krukowski, M. (2023). Influence of vegetation maintenance on flow and mixing: case study comparing fully cut with high-coverage conditions. *Hydrology and Earth System Sciences*, *27*(4), 953–968. https://doi.org/10.5194/hess-27-953-2023

Le Coz, J., Hauet, A., Pierrefeu, G., Dramais, G., Camenen, B., & Dramais, G. (2010). Performance of image-based velocimetry (LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers. *Journal of Hydrology*, *394*, 42–52. https://doi.org/10.1016/j.jhydrol.2010.05.049ï

Le Coz, J., Pierrefeu, G., & Paquier, A. (2008a). Evaluation of river discharges monitored by a fixed side-looking Doppler profiler. *Water Resources Research*, *46*(4). https://doi.org/10.1029/2008WR006967

Le Coz, J., Pierrefeu, G., & Paquier, A. (2008b). Evaluation of river discharges monitored by a fixed side-looking Doppler profiler. *Water Resources Research*, *46*(4). https://doi.org/10.1029/2008WR006967

Levesque, V. A., & Oberg, K. A. (2012a). *Computing discharge using the index velocity method*. U.S. Dept. of the Interior, U.S. Geological Survey.

Levesque, V. A., & Oberg, K. A. (2012b). *Computing discharge using the index velocity method*. U.S. Dept. of the Interior, U.S. Geological Survey.

Marushchenko, S., Gruber, P., & Staubli, T. (2016). Approach for Acoustic Transit Time flow measurement in sections of varying shape: Theoretical fundamentals and implementation in practice. *Flow Measurement and Instrumentation*, *49*, 8–17. https://doi.org/10.1016/j.flowmeasinst.2016.03.004

Moore, S. A., Le Coz, J., Paquier, A., & Hurther, D. (2010). Backscattered intensity profiles from horizontal acoustic doppler current profilers. *River Flow*.

Mueller, D., Wagner, C. R., Rehmel, M. S., Oberg, K. A., & Rainville, F. (2013). Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat. In *Surface-Water Techniques* (2nd ed.). https://doi.org/10.3133/tm3A22

OTT HydroMet. (2006). *OTT SVR 100 - BEST PRACTICES*. OTT HydroMet.

Plant, W. J., Keller, W. C., & Hayes, K. (2005). Measurement of river surface currents with coherent microwave systems. *IEEE Transactions on Geoscience and Remote Sensing*, *43*(6), 1242–1257. https://doi.org/10.1109/TGRS.2005.845641

Puleo, J. A., McKenna, T. E., Holland, K. T., & Calantoni, J. (2012). Quantifying riverine surface currents from time sequences of thermal infrared imagery. *Water Resources Research*, *48*(1). https://doi.org/10.1029/2011WR010770

Schroevers, M. (2013). *Advies inzet WUR-methode bij RWS*.

Tauro, F., Piscopia, R., & Grimaldi, S. (2017). Streamflow Observations From Cameras: Large-Scale Particle Image Velocimetry or Particle Tracking Velocimetry? *Water Resources Research*, *53*(12), 10374–10394. https://doi.org/10.1002/2017WR020848

Tauro, F., Tosi, F., Mattoccia, S., Toth, E., Piscopia, R., & Grimaldi, S. (2018). Optical tracking velocimetry (OTV): Leveraging optical flow and trajectory-based filtering for surface streamflow observations. *Remote Sensing*, *10*(12). https://doi.org/10.3390/rs10122010

van Heeringen, K.-J., Asselman, N., Overeem, A., Beersma, J., & Philip, S. (2022). *Analyse overstroming Valkenburg*.

Welber, M., Le Coz, J., Laronne, J. B., Zolezzi, G., Zamler, D., Dramais, G., Hauet, A., & Salvaro, M. (2016a). Field assessment of noncontact stream gauging using portable surface velocity radars (SVR). *Water Resources Research*, *52*(2), 1108–1126. https://doi.org/10.1002/2015WR017906

Welber, M., Le Coz, J., Laronne, J. B., Zolezzi, G., Zamler, D., Dramais, G., Hauet, A., & Salvaro, M. (2016b). Field assessment of noncontact stream gauging using portable surface velocity radars (SVR). *Water Resources Research*, *52*(2), 1108–1126. https://doi.org/10.1002/2015WR017906

Winsemius, H., Annor, F., Hagenaars, R., Van De Giesen, N., Luxemburg, W., & Hoes, O. (2023). *Towards Open Access and Open Source Software for Image-Based Velocimetry Techniques*. https://doi.org/10.20944/preprints202308.0896.v1

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl