Monitoring discharge continuously in the Gulp

A feasibility study

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Disclaimer

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Summary

Establishing an ideal discharge measurement station in the Gulp that meets all requirements specified by Waterschap Limburg (WL) is not feasible. Observations by WL have confirmed the challenges posed by seasonal variations in the level of the streambed and vegetation growth, making a stable stage-discharge curve implausible. Nonetheless, our work outlines a conceptual design that provides continuous discharge measurements along a stretch of the Gulp, from the Dorpsstraat to the wooden bridge in Slenaken. While not meeting all the imposed requirements, the conceptual design, using two measuring techniques, may provide a discharge estimate at the Gulp near Slenaken.

Spanning approximately 21 kilometres with a catchment area of 46.7 square kilometres, including Belgian plateaus exceeding 300 meters above datum (NAP[1]) at the drainage divide, the Gulp flows into the Netherlands near Slenaken and converges with the Geul at Gulpen, with a bed level around 91 m NAP. The rapid response to rainfall in its upper reaches can result in flash floods, contrasting with a relatively more delayed response downstream in Gulpen. Both discharge peak and elevated discharge duration are therefore essential to obtain an accurate forecast of the flood extent and its impact in the valley.

Existing monitoring stations in the Gulp cannot accurately monitor discharge during extreme conditions, particularly during high-water levels—a critical aspect for effective water management. Consequently, WL seeks to implement or enhance a station in the upstream part of the Gulp capable to measure discharge continuously, even under extreme high-water conditions. Implementation of a discharge station in the Gulp faces several challenges. When the Gulp overflows at higher discharge levels, accurately assessing discharge over the full width in the inundated valley presents a challenge. Additionally, the stream is morphological active. Especially during floods, this leads to significant bed level changes in large parts of the Gulp, complicating point-based discharge measurements within cross sections. A final challenge stems from the protected Natura2000 status of the Gulp valley, which places restrictions on streambed interventions and maintenance.

To address these challenges, we have selected a location in Slenaken where the bed level is assumed to be rather stable since 2021. Our conceptual design for a discharge measurement station at this location employs a combination of two measurement techniques for two discharge regimes:

1 **Low to medium discharge**: Developing a stage-discharge curve for the existing water level sensor and incorporating a camera measurement system to measure surface velocity and to monitor bed profile and vegetation growth. The camera system offers adaptability to seasonal changes, ensuring stage-discharge curve accuracy.
2 **Medium to high discharge**: Installing a side-looking Doppler instrument under the Dorpsstraat bridge to measure flow velocity continuously and derive discharge using the index-velocity method.

For any 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.

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[1] NAP means “Normaal Amsterdams Peil”, the generally utilized reference level (datum) in the Netherlands.

Contents

1 Introduction

1.1 Background

1.1.1 Framework

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

1.1.2 Motivation

WL currently monitors the discharge of the Gulp stream. The discharge observations are used to forecast the water level and to implement measures against flooding downstream in the Gulp and in the Geul (Figure 1.1). Extreme rainfall events in the catchment of the Gulp resulted in flooding in 1998, 2012 and 2021.

In 2012 a flash flood occurred in a summer night, and resulted in substantial damage (Van Heeringen et al., 2012). The maximum recorded discharge at the downstream station (Azijnfabriek Gulpen) in 2012 was 11.7 m^3/s. However, in the upstream part of the Gulp the peak during this flash flood was probably substantially higher. For this flood event, several estimates were given for the peak discharge. For example, Van Heeringen et al., 2012 estimated the peak discharge to be 20 m^3/s. Peak values at various locations in the Gulp are often debated due to the absence or inaccuracy of discharge observations in the high discharge regime.

Currently, no discharge measurement station is present in the upstream part of the Gulp near the Dutch-Belgian border. Especially during high-water levels, accurate discharge observations in the upstream part of the stream are important for water management purposes. To forecast the flood extent, the volume of the discharge peak in the upstream part needs to be known. Therefore, *WL* intends to implement or improve a station near the border where discharge can be derived continuously, also during very extreme high-water conditions.

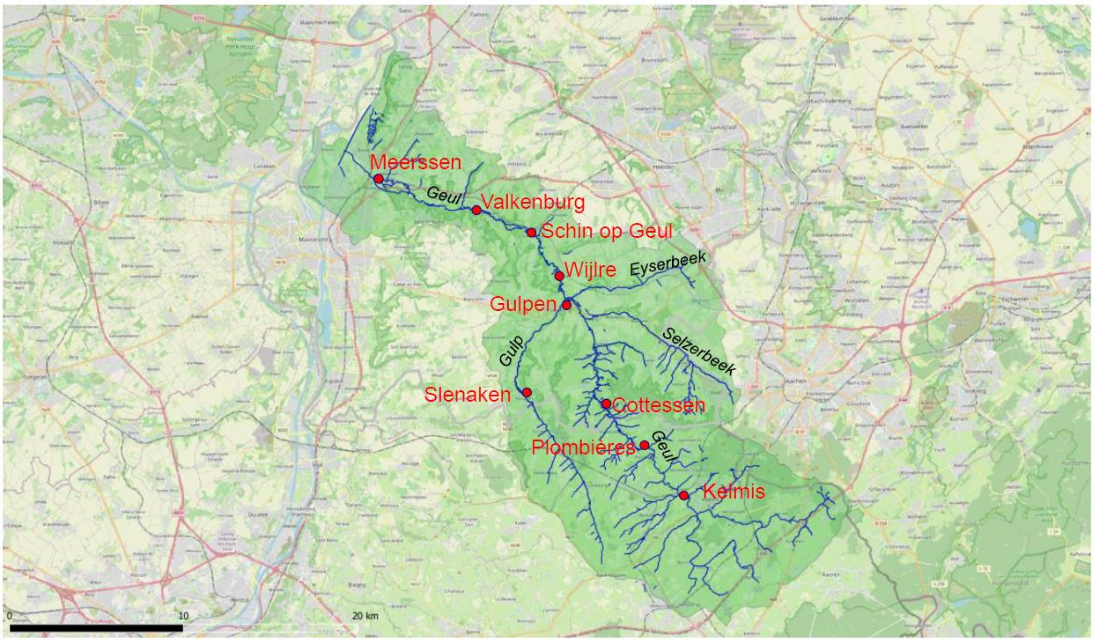

Figure 1.1 The catchment area of the Geul, with the Gulp as one of the main tributaries.

1.1.3 Current measurement stations

Discharge is monitored at station Azijnfabriek in Gulpen since 1972. At first, a Crump weir was used. After the weir was removed for ecological purposes in 1994, a stage-discharge relation was determined using water level measurements. A vertical profile of flow velocity is also measured using an Acoustic Doppler Current Profiler (ADCP). Especially during high-water levels, discharge is derived from the ADCP measurements.

The water level is also recorded at Slenaken since 1978. Currently a radar instrument is mounted on a wooden bridge over the Gulp starting from Slenakerpad, from which the photos in Figure 1.2 were taken. The location of the wooden bridge is about 750 m from the Dutch-Belgian border. A reliable stage-discharge relation could not be established, due to bed level variation and vegetation growth.

A second water level station was built in 2013 at Teuven, which is about 1250 m upstream of the Dutch-Belgian border. The bed level varies too much to obtain a stable stage-discharge relation. Hence, monitored discharge time series are only available downstream in the Gulp at Gulpen.

1.2 Problem definition

1.2.1 Response time and damage

The Gulp is about 21 km long. The catchment area is 46.7 km^2, including plateaus in Belgium with elevations that exceed 300 m above datum (NAP) at the drainage divide. The Gulp flows into the Netherlands close to Slenaken and joins the Geul at Gulpen, where its bed level is about 91 m NAP.

Due to thin soil layers in the upper parts of the catchment and a limited infiltration capacity of the soil, the response time of discharge to rainfall is short relative to the downstream part of the catchment. As a result, damage occurs, generally, in the upper parts mostly due to local high intensity rainfall (flash flood), whereas lower in the Gulp damage is more likely to occur after longer rainfall at a larger scale and longer rainfall (Asselman & Van Heeringen, 2023). To be able to forecast the discharge and water levels in the Gulp and its effect in the lower part of the Geul, both the discharge peak and the duration of the elevated discharge need to be known in the upstream part of the Gulp.

As an example of the short response time, the peak discharge at Gulpen in 2012 occurred within two hours after its base level of around 0.3 m^3/s (Van Heeringen et al., 2012). This flood can be characterized as a flash flood, and resulted in considerable damage (e.g., in Slenaken). The discharge during such a peak discharge event can vary considerably along the Gulp. After the flooding in 2012 various measures have been implemented to reduce damage due to flooding, such as widening the stream and removing depositions and vegetation (e.g. in the bend of the section in Figure 1.2). These measures were implemented before the flood of 2021 and have reduced the flood extent. However, flooding still occurred in the 2021 event at locations along the Gulp (e.g., in Slenaken).

Figure 1.2 The Gulp in Slenaken upstream (left) and downstream (right) of the current water level station on 15 May 2023 at low discharge.

1.2.2 Challenges for implementing a discharge measurement station

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

1. The equipment and method need to be able to monitor discharge accurately from low to extreme flood levels.
2. The Gulp overflows at higher discharge levels, meaning that the discharge can 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 Gulp 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 deriving discharge from a measurement at a point in the cross section.

4 Due to the short response time to rainfall, a manual observation of the peak discharge using a boat is only possible when the peak discharge was foreseen. Often the surveyor arrives too late and cannot measure the maximal discharge, meaning that it is difficult to obtain accurate discharge observations for a verification of the stage-discharge relation.
5 The Dutch part of the Gulp valley is a protected Natura2000 area. As a result, restrictions apply for changing the stream bed. The bed level cannot be fixed for the implementation of a discharge station. Also, the protected status can have implications for the installations of poles or constructions within the stream bed or 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 Gulp to monitor discharge continuously, considering the requirements and preferences listed in Table 1.1.

1.3.1 Requirements and preferences

Considering the objectives 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 full range should be covered, being 0.05 to 25 m^3/s.	
Temporal resolution	Continuously at an interval of about 5 minutes.	
Location	Within the Gulp, upstream of the current station Azijnfabriek	Within 2 km from the Dutch-Belgian border.
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	Restricted interventions in the stream bed or surroundings. The Natura2000 status needs to be respected for the installation of equipment.	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

If the location for a station is found to be feasible, the request was 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 stream discharge from the measurements?
C. What is needed technically for the implementation (improvement) of the station?
D. What is the range of discharges that the station can monitor? And what is a realistic estimation for the accuracy?
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 1.3). 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 1.3). 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 1.3). A measurement often has both a systematic error and a random error (lower right panel in Figure 1.3). 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.

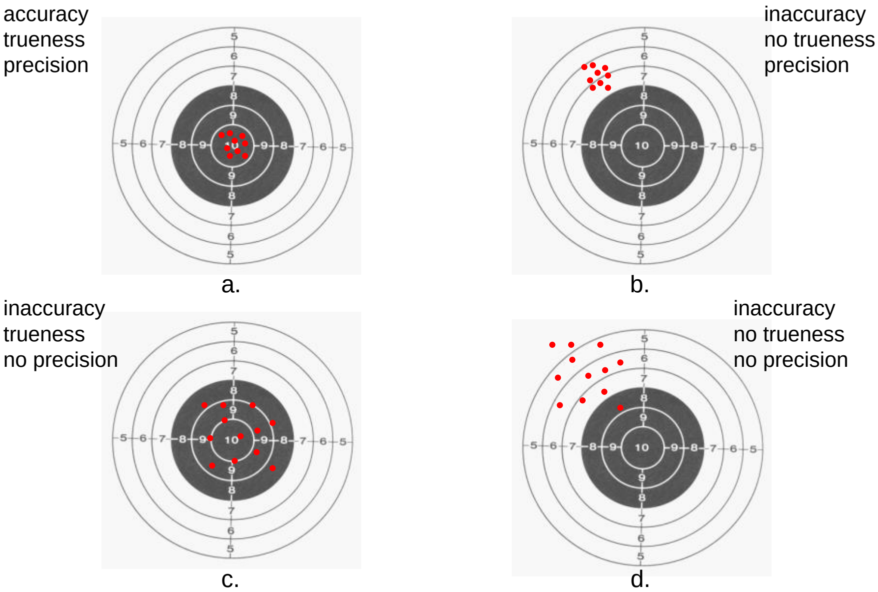

Figure 1.3 Characterization of accuracy, trueness, and precision in a set of measurements (source: Bertrand-Krajewski et al., 2021).

1.5 General approach and limitations

Generally, our approach was to select a suitable location along the Gulp, to carry out a literature survey on equipment and methods that may be suitable for the Gulp 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 a station, aiming at meeting the requirements as good as possible. For that possible solution, 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.

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).

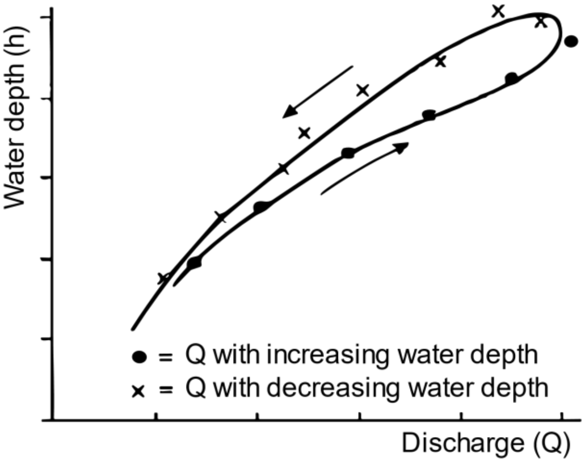

Figure 2.1 Hysteresis of the rating-curve during extreme conditions (adapted from Boiten et al., 1995).

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, 2020b).

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

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, 2020b; 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, 2020b). 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.

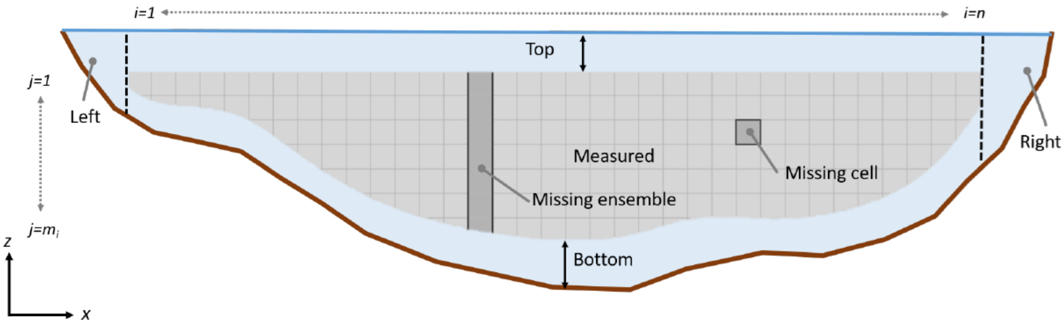

Figure 2.2 The velocity-area method uses the measured cross-sectional area (light gray) to determine the discharge. The measured cross-sectional area does not cover the entire wetted area, due to the blanking distance of an ADCP and a zone near the bed where interference occurs (see section 2.2.1). Furthermore, 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.

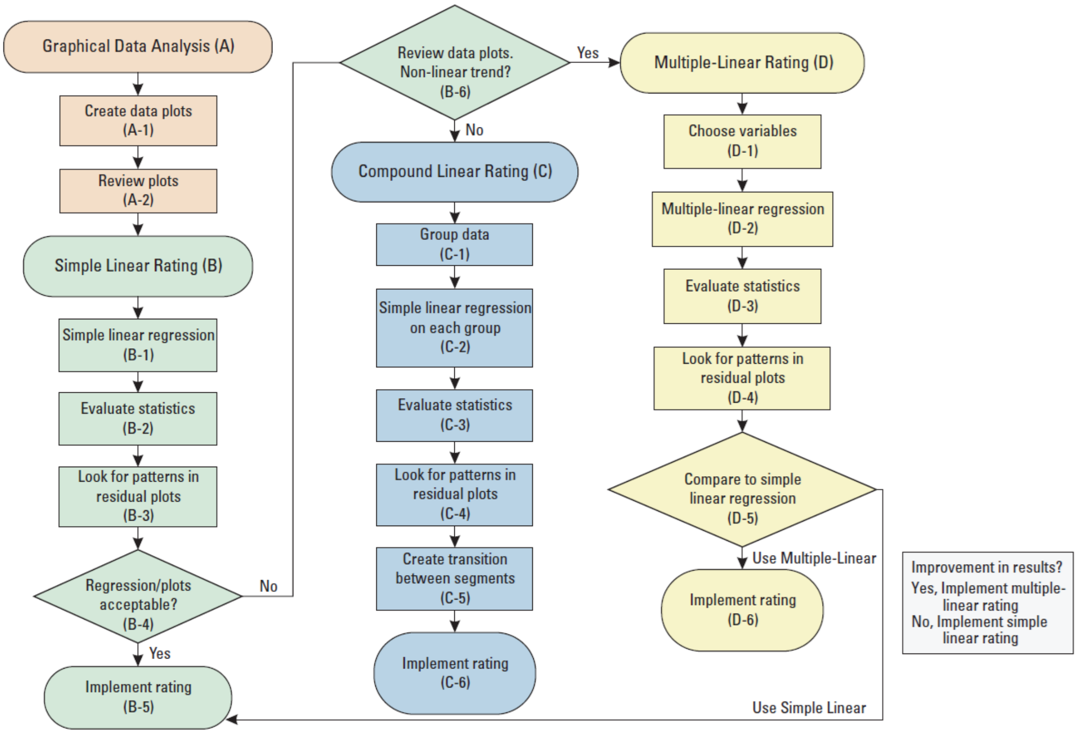

Figure 2.3 A schematic to determine the index rating (source: Figure 23 from Levesque & Oberg, 2012b).

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 Gulp. 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.

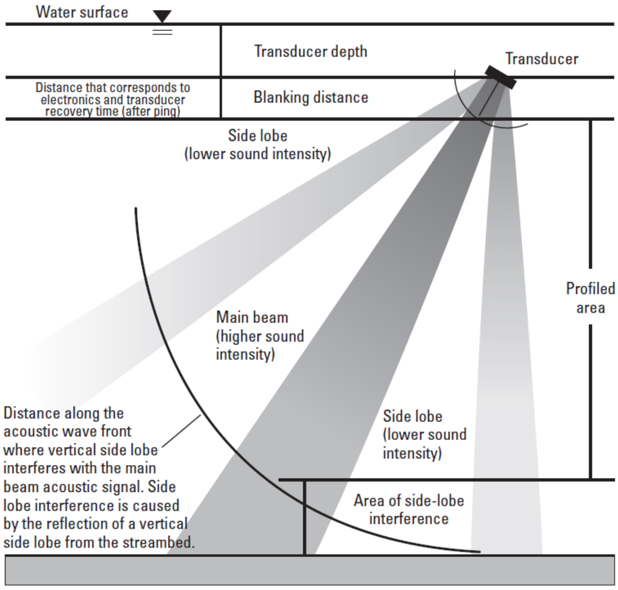

Figure 2.4 The main and side lobe from a single transducer, with zones indicated in the vertical where measurements are biased and should not be used (i.e., due to blanking and side-lobe interference) in an ADCP profile (source: Figure 4 of Mueller et al., 2013).

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.

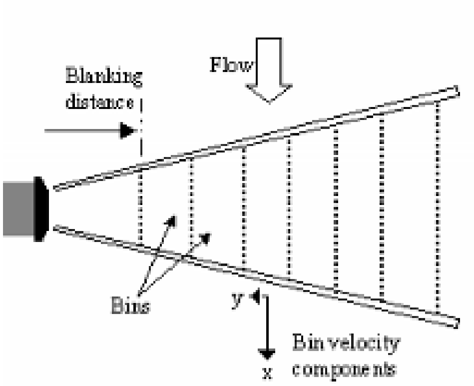

Figure 2.5 Example of a side looking instrument with 2 beams, showing the widening of the main beam. (source: usgs.gov2).

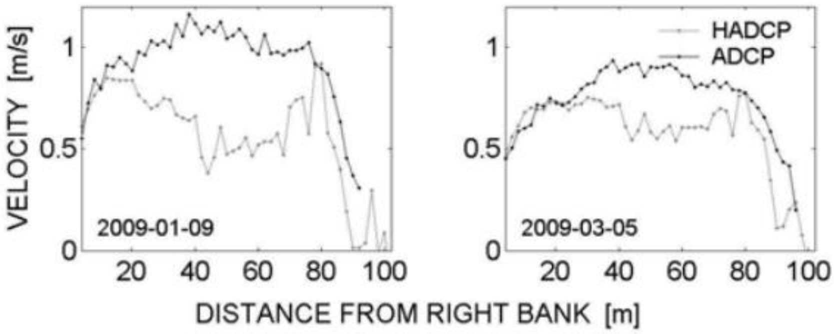

Figure 2.6 Horizontal profiles of streamwise velocity measured by a vertically oriented boat-mounted 600 kHz ADCP (black) and a fixed 300 kHz HADCP (grey) in a roughly 4 m deep French river at two moments. (source: (Moore et al., 2010)).

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[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).

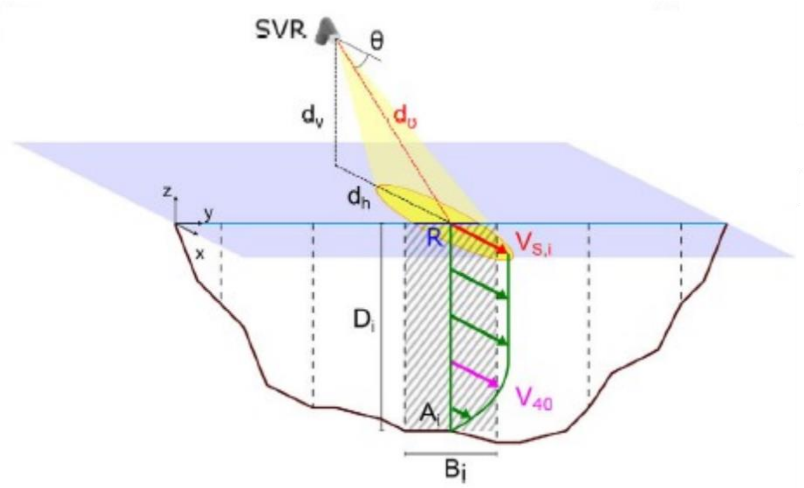

Figure 2.7 Surface Velocity Radar measurement principle. The surface velocity ($V_{s,i}$) is determined over an area denoted in yellow (i.e., the beam footprint). A velocity profile assumption (i.e., log-law) is used to derive a velocity profile. The bulk-velocity (i.e., integral of the velocity profile) 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.

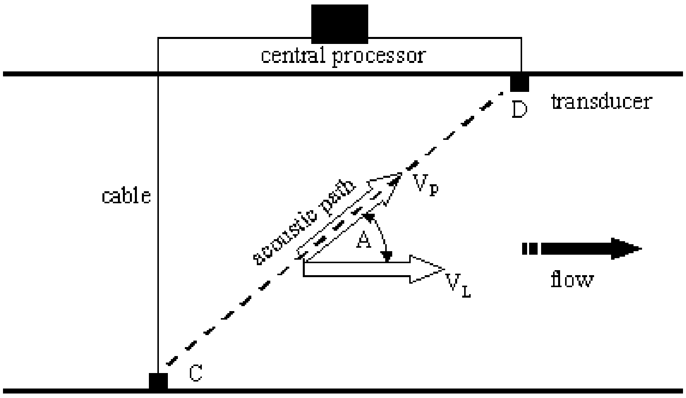

Figure 2.8 Acoustic transit time set-up with one pair of transducers. Sound pulses are emitted at C to D, and from D to C. The flow velocity can be derived from the difference in travel time. (source: usgs.cov4).

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[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 Slenaken

3.1 Location selection

Considering the short response of discharge to rainfall events and measures to increase retention, the character of the discharge time-series near the border can differ considerably from that at the existing station in Gulpen. The best location to monitor the discharge continuously was found to be in Slenaken, following the requirements and preferences (Table 1.1). Particularly the stretch in between the bridge of the Dorpsstraat and a wooden bridge for pedestrians seems suitable (Figure 3.1 and Figure 1.2), because the bed is rather fixed in this stretch of the Gulp. A connection for electricity and telemetry is available. From studying maps and using the experience of WL, other sections of the Gulp within 2 km of the border are either very steep with limited water depth or have a moving bed, making them unsuitable for a discharge monitoring station.

The location in Slenaken also provides challenges, such as seasonal variation of the hydraulic roughness due to vegetation growth. Therefore, we propose to install a side looking Doppler system under the bridge of the Dorpsstraat, where we assume that vegetation cover is limited. A side looking Doppler needs sufficient water depth (i.e., submergence), which is only realizable for the medium to high discharge regime. A combination of a stage-discharge relation with an optical monitoring system is seen as a possible solution for the low to medium discharge. The optical monitoring system can be used to both measure the local surface velocity and to monitor the seasonal vegetation and bed profile changes. The combination of methods for the low to medium discharge regime could result in a reliable stage-discharge relation.

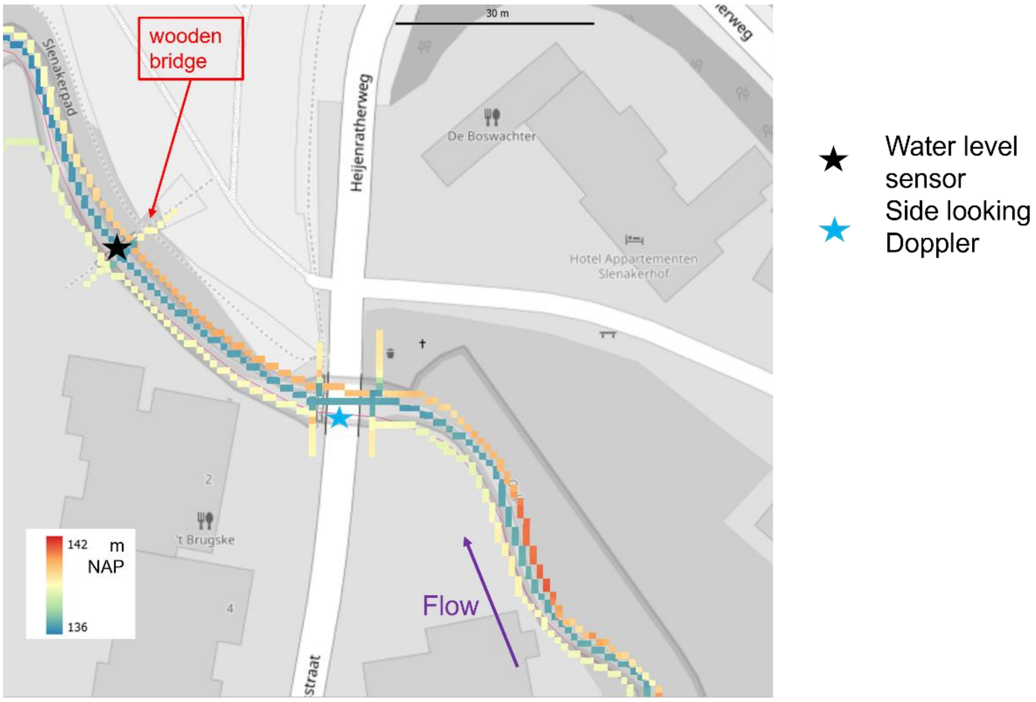

Figure 3.1 Overview of the Gulp section with bed level profiles along and across the stream, the bend upstream of the Dorpsstraat bridge and the water level sensor on the wooden bridge.

3.2 Medium to high discharge regime

3.2.1 System design

When the water level is sufficiently high, a horizontal flow profile can be measured over a large part of the width of the stream. Suitable instruments that can be mounted on the bridge wall are side looking Doppler instrument (section 2.2.2) and transit-time instruments (section 2.2.5). We have a preference for a side looking Doppler instrument, mainly because the required length along the channel is smaller than required for the transit-time instrument. This is important since the straight section under the bridge is limited (Figure 3.1). In fact, it is sufficient long to have the sensors and main beam within the straight part under the bridge, but the undisturbed flow length upstream of the instrument is limited in both cases. As the beams of a Doppler instrument require a smaller channel length, the undisturbed length upstream of the instrument is longer than for a transit-time instrument. Therefore, we propose to install a side looking Doppler instrument at the sidewall under the bridge, as indicated in Figure 3.2. An advantage of a SLD over a single point flow meter or an ADCP that looks upwards from the bed is that a SLD monitors flow velocity arrays. As a result, a SLD normally measures flow at the point in the width where it is maximal, whereas the maximal flow may not always occur at the point in the width where maximal flow occurs. Using the Doppler derived flow velocity vectors, discharge can be derived with the index-velocity method (Figure 2.3).

A disadvantage of a side looking Doppler instrument is that side-lobe interference may occur (section 2.2.2). To limit side-lobe interference, we propose to install the instrument at 136.9 m NAP. At that level, it can monitor flow when the water level exceeds about 137.5 m NAP, which is the annual mean maximum level (Van Heeringen et al., 2012). Figure 3.2 includes a conceptual design of the first side-lobe assumed to be present at 25°. For this configuration, only the observations up to about 1.5 m from the instrument are guaranteed to have no side-lobe interference with the bed. We expect, though, that the range where measurements are not biased due to interference with this side-lobe will be larger. Side-lobe interference has been observed for several side looking Doppler instruments but did not occur at all stations (Le Coz et al., 2008b; Moore et al., 2010). This is something that needs to be verified after installation of the instrument, using the usual boat mounted ADCP observations.

Manufacturer Ott states that the discharge can be derived accurately in a section with at least a 1:10 depth over width ratio. At a water level of 135.5 m NAP, this ratio is about 1:5. Hence, following these specifications, a side looking instrument is likely to result in a flow profile that is not biased by side-lobe interference up to the point where maximal flow occurs. Shall the evaluation show that this is not the case, the flow up to 1.5 m from the instrument (top panel of Figure 2.3) can still be used to obtain discharge using IVM at a higher uncertainty. Alternatively, a vertical upward looking ADCP could be installed in the bed on the centre line of the stream under the bridge. The flow disturbance will be limited when the ADCP is installed such that its transducers are aligned with the level of the stream bed. In case this additional ADCP is needed, velocity observations from both instruments can be used to obtain discharge. A challenge for the installation of the ADCP is that it should not change the flow and at the same time sediment deposition on the ADCP should be limited.

Details for two possible side looking Doppler instruments are listed in Table 3.1. Either of the two is suitable to mount on the sidewall of the bridge, having limited effect on the flow considering their size. The Sontek instrument has a lower opening angle and more freedom to select a larger number of cells. Sontek makes an interesting claim on side lobe suppression, but we could not find on their website what this implies and what the effect on the range with valid flow measurements is. Both instruments can be equipped with a pressure sensor to monitor water level. Ott specifies that water level is monitored when the water level is minimally 0.15 m higher than the instrument. Generally, their specifications are similar. As an example, we have schematically drawn a solution with cells of 0.5 m, resulting in 8 cells across. In the lower panel of Figure 3.2 (cell 4 is highlighted), it can be seen that the uniformity of the flow is questionable, considering the bend directly upstream of the bridge and the limited (absent) straight section upstream of the side looking instrument. This solution seems the best possible for this location, but it will not meet all requirements.

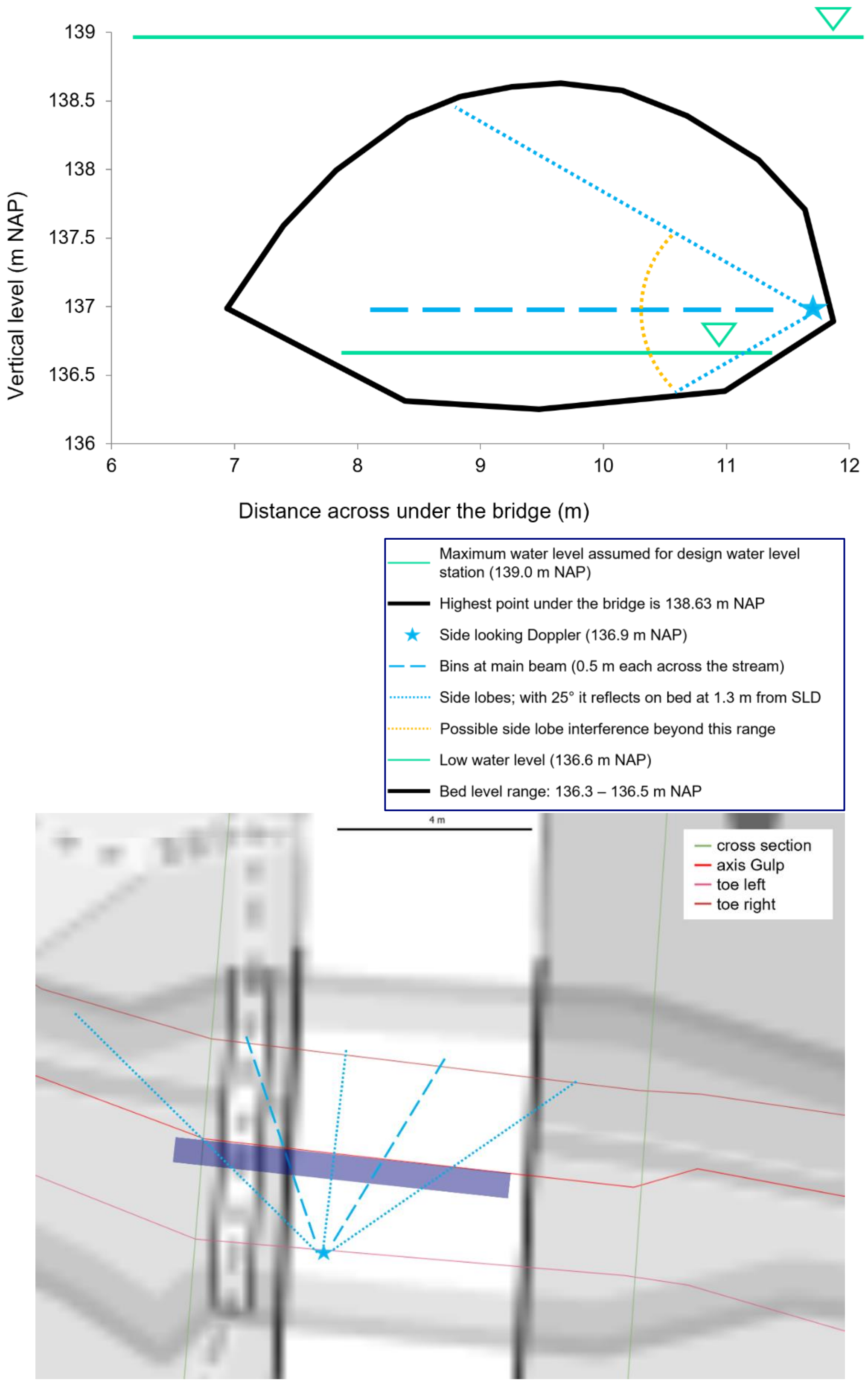

Figure 3.2 Conceptual design of a possible discharge measurement station set-up with a side looking Doppler system deployed under the Dorpsstraat bridge, with (top) a cross-section under the bridge, (middle) a legend, and (bottom) a top view. The bridge profile is obtained using de Jong & van Heeringen (2019).

Table 3.1 Examples of side looking Doppler instruments that may be feasible, and some specifications (Sources Sontek5 and Ott 6).

Instrument (Manufacturer)	Range (m)	Angle wrt centerline (°)	Opening angle (°)	Thick-ness (m)	Remarks
SL3000 (Sontek)	0.1-5	25	1.4	0.04	They claim to apply side lobe suppression, but unclear how they do that and what the implications are
Side looking Doppler 2.0 (Ott)	0.1-10	Not available from website	2.1	0.07	Maximum is 9 cells

3.2.2 Uncertainty estimate

We estimated the uncertainty for the medium to high discharge range roughly with a simplified uncertainty propagation (see also section 1.4). As WL expects that after the measures taken in 2021 no flow will go over the bridge at the investigated discharge range, we assume that the entire discharge flows underneath the bridge. In our simplified uncertainty propagation, we neglect correlation of errors.

A first source is the uncertainty in the velocity measurement. Both manufacturers mention a measurement error of 1% of the measured flow +/- 5 mm/s. At the minimal water level (137.5 m NAP) to obtain discharge from the side looking Doppler instrument, the cross section averaged flow velocity at the bridge is expected to be about 0.5 m/s. Hence, the uncertainty (i.e., one standard deviation) due to the flow measurement is then 2% according to this specification of the manufacturer. However, this uncertainty holds for optimal conditions, with uniform flow. Considering the small straight length under the bridge, we expect that the flow in both main beams differ both in magnitude and direction (the lower panel Figure 3.2).

The uncertainty of the averaged velocity over the cross-section is difficult to estimate. For example, Bertrand-Krajewski et al. (2021) show an uncertainty analysis for an idealized case where a small uncertainty of the velocity measurement can amount to a significant uncertainty of the averaged velocity of up to 10% (i.e., one standard deviation). The uncertainty of the averaged velocity increases substantially due to the compound uncertainties of the water depth measurement, the translation from water depth to cross-sectional area, and the integration constant associated with the velocity profile assumptions (Bertrand-Krajewski et al., 2021). Consequently, in the current situation, where the conditions are sub-optimal an uncertainty of the velocity measurements may result in an uncertainty of the averaged velocity of approximately 20 up to 30%.

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 error of +/- 2 mm, which is lower than 1% of the lowest water depth. An error of 1% on the depth will result in an approximate uncertainty of 1% of the surface area and consequently on the discharge. In addition, the error made in measuring the bed level (assumed stable in time) and the bridge should be accounted for.

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[5] 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

[6] https://www.ott.com/products/water-flow-3/ott-sld-side-looking-doppler-sensor-970/, visited on 31 August 2023

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 lower panel of Figure 3.2). Irregularities due to rocks or changes in geometry along this section will lead to a substantial uncertainty in the discharge. The combination of water level measurement uncertainty and uncertainties due to geometry changes is challenging. Considering the limited depth at the proposed station, their sum will easily result in a discharge uncertainty larger than 5%.

The last uncertainty source is the application of IVM. Considering that the stream is straight for a much shorter length than required, we expect that the flow velocity distribution will change for the medium to high discharge range. Furthermore, variations in the backwater curve are to be expected due to variations in vegetation cover. Again, this uncertainty source is challenging to quantify. Also considering its limited size, it can easily result in an uncertainty of 10%.

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 between 20 and 30%. 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 neglect 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 discharge uncertainty is approximately 25% (i.e., one standard deviation) when we assume optimal site conditions. This is high with respect to the required maximal relative measurement error of 15%, meaning that a considerable number of the individual relative measurement errors with respect to the discharge from multiple ADCP transects is expected to be higher than 15%.

3.2.3 Steps and cost estimate

For the installation of the sketched system, 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 instrument and log water level, flow velocity and echo intensity.

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, as it depends on the number of medium-high discharge situations that occur during the calibration period. 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 branches during high discharge), the debris needs to be removed, in order to obtain discharge from the index-velocity method and to avoid flooding.

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 followed on a regular basis (e.g., twice a year) to detect gradual variations or trends. These trends may stem from wear and tear of the instrument, instability in the monitoring system or from changes in the conditions at the monitoring station.

For step 2, we estimate the total costs at € 32,000,- excluding VAT. A specification for only this step 2 is € 12,000,- for the instrument, and € 20,000,- for cabling and making it operational. The cost estimates do not include the costs associated with telemetry (perhaps limited), staff costs of WL and costs associated with a design of the discharge measurement station and the civil engineering works.

3.3 Low to medium discharge regime

3.3.1 System design

For the low to medium discharge regime, we propose to extend the current water depth measurement station near the wooden bridge with an optical discharge measurement system (see Figure 3.3). The optical measurement technique will use a velocity-area method to determine the discharge (see section 2.1.2). It must be noted that, the proposed combination of methods does not fulfil all the requirements defined in Table 1.1! The proposed combination of methods may improve the reliability of the discharge measurement derived using only a rating curve of which the uncertainty is largely unknown. However, we cannot guarantee an effective and accurate discharge station with the proposed solution. If possible, we advise to first test a QI system at the specified location before permanently installing it.

A reliable rating curve can currently not be established using only the water depth measurement station, due to the growth of vegetation and variations of the bathymetry. A rating curve that accounts for the seasonal variation of the vegetation growth did not improve the accuracy. The combination of an optical discharge and water depth measurement system could result in an improved rating curve, as the optical system allows for adjustments to the rating curve based on the current situation.

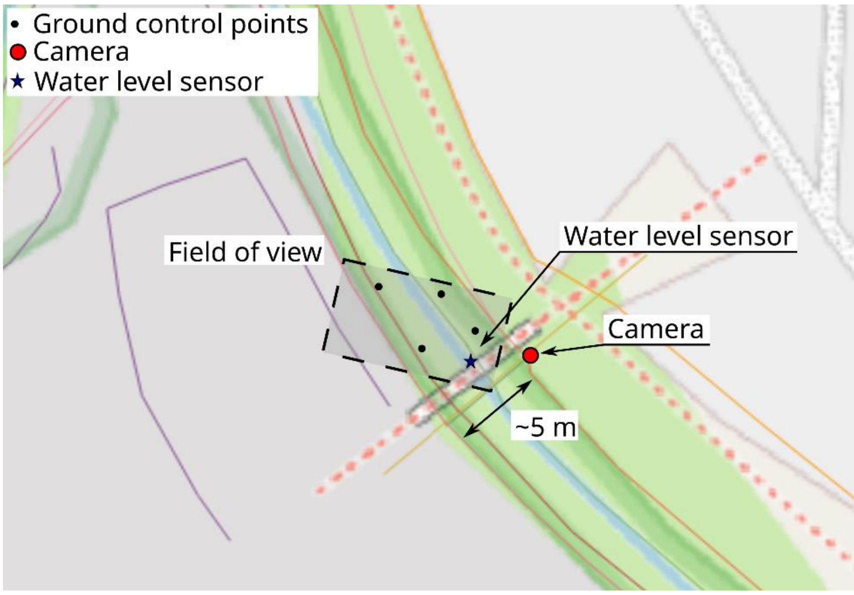

Figure 3.3 Low to medium discharge system overview. A rating curve uses the (current) water level sensor mounted on a wooden bridge. The field of view of the camera system needs to be near the location of the water level sensor.

The camera system needs to be regularly calibrated to maintain its accuracy. For this procedure, we require several reference points – or so-called ground control points (GCPs) - that are in the field of view of the camera (see Figure 3.3). A simple calibration requires at least 4 GCPs at/or near the water level. A full camera calibration requires at least 6 GCPs spanning the entire three-dimensional measurement volume. The full camera calibration can handle water level variations with a water level sensor as reference. The calibration of the camera can be automatically adjusted if the GCPs are continuously in the field of view of the camera.

The combination of methods can continuously acquire discharge measurements for the low to medium discharge regime if a reliable rating curve can be determined. It must be noted that the optical method cannot acquire measurements during the night. The system cannot be extended with a (visible) light source due to the protected status of the area (i.e., Natura2000). A thermal (infrared) camera could be installed (see for example the Discharge Keeper system by Photrack AG), but the accuracy during the night may be limited (see for example Puleo et al., 2012).

The combination of methods will still be impacted by significant change in the bed level or growth of vegetation. However, we expect that small changes in the bed level or growth of vegetation can be accounted for in an adjusted rating curve – in part - derived from the camera measurements. In addition, the camera system allows WL to monitor the location and to plan calibration measurements for the rating curve. Nonetheless, the proposed system does not meet all the requirements due to the inherent challenges of the location. WL is aware of these challenges as it is unable to determine a stable and reliable discharge curve at the proposed location.

3.3.2 Uncertainty estimate

The accuracy of quantitative imaging (QI) methods has been discussed in section 2.1.2. The discharge derivation from surface velocity measurements relies on assumptions of the velocity profile.

The uncertainty of QI methods is significant (see section 2.2.3) and even small variations in the monitoring or environmental conditions may have a negative impact on the uncertainty of the obtained results. For example, a small variation of the velocity coefficient can already lead up to a discharge uncertainty of 16.8% (see section 2.2.3).

For stable situations, without changes to the bed or vegetation growth, the QI method can be calibrated to limit the impact of the velocity coefficient. Nonetheless, for these calibrated situations, the uncertainty of the discharge estimate is estimated to be at least 10% for reported measurements (e.g., Winsemius et al., 2023) or specifications[7] supplied by manufacturers.

3.3.3 Steps and cost estimate

For the installation of the sketched system, 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 determine the field of view that can be derived with the selected camera equipment. Select an appropriate height of the camera system.

2 **Installation**: Install the instrument and connect to the existing electrical cabinet near the wooden bridge.

3 **Calibration**: Carry out boat-mounted observations at various discharge levels when the camera system is operational to calibrate the velocity coefficient. The optical system will function properly when 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.

5 **Data validation and analysis**: data validation is required to ensure that the continuous data adheres to the data quality standards of the 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 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. Especially, for QI methods, these changes can continuously occur, so data validation is paramount.

When considering a camera system for your needs, it's crucial to evaluate both the initial investment and ongoing costs associated with different suppliers. Here are some options to consider:

- **Budget-Friendly Option**: Some suppliers offer camera systems at an initial cost as low as € 7,000,- excluding VAT. However, it's essential to note that these systems come with a yearly fee of € 8,000,- excluding VAT. While the initial investment is lower, the annual fees can add up significantly over time.

- **Mid-Range Alternatives**: On the other hand, there are suppliers offering camera systems with a broader cost range, ranging from € 15,000,- up to € 30,000,- excluding VAT. The advantage here is that these systems do not require a yearly fee, which can result in cost savings in the long run.

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[7] Specifications of the *DischargeKeeper* by *SEBA hydrometrie*, see https://www.wetec.com.sg/our-products/water/product-listing/dischargekeeper accessed on the 11th of September.

Regardless of the system you choose, it is wise to explore maintenance options. Many manufacturers provide yearly maintenance contracts for an additional € 1,200,- excluding VAT per year. This can ensure the reliability and longevity of your camera system, reducing the risk of unexpected downtime or repair costs. Additionally, WL will have staff costs particularly for maintenance of the station and data validation.

The cost estimates do not include costs associated with a design of the discharge measurement station and the civil engineering works.

3.4 Requirements and preferences

Table 3.2 gives our evaluation of the requirements and preference for both the side looking Doppler instrument solution and the stage-discharge solution. Not all criteria are met, although this seems the best location in the Gulp close to the Dutch-Belgian border. We conclude that a solution that meets all criteria is not available.

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	After following the steps for an index-velocity, discharge can be derived for a medium-high range. The stage-discharge relation for low-medium discharge range could still be hindered by too much vegetation growth.
Temporal resolution	A temporal resolution lower than 5-minutes is possible.
Location	The location is within 1 km from the Dutch-Belgian border.
Maximal relative mesurement error	Due to the bend, the short length under the bridge and the seasonal changing vegetation the uncertainty is estimated to be substantially higher than 15%.
Protected status	Apart from installing equipment under the bridge and on poles, no interventions in the stream.
Bed level	The method does not consider bed level changes. However, this may not be needed as the bed level in the proposed section of the Gulp is claimed to be stable.
Maintenance	The preference for doing maintenance maximally 1-2 times a year can be met. However, considering the disturbance on the flow, we recommend to perform monthly maintenance (i.e., mowing) when the vegetation growth is too large to increase accuracy.

4 Conclusion

Given the currently available technologies, a discharge measurement station that meets all criteria is **not feasible** for the Gulp. The outcome is not unexpected, as WL already identified that a stable stage-discharge curve could not be derived due to seasonal variations in the bed profile and vegetation growth. Nonetheless, we have detailed a conceptual design that could provide discharge observations in a stretch of the Gulp near the wooden bridge and the bridge over the Gulp (Dorpsstraat Slenaken).

The conceptual design of the discharge measurement station for the Gulp uses a combination of measurement techniques for respectively the low to medium and medium to high discharge regimes:

- **Low to medium discharge**: A stage-discharge curve should be developed for the existing water level sensor. In addition, a camera measurement system could be installed to both measure the surface velocity and to monitor the development of bed profile and vegetation growth. The camera system could provide the flexibility to fine-tune the stage-discharge curve in response to seasonal vegetation growth or changes in the bed profile, ensuring the accuracy of the stage-discharge curve.
- **Medium to high discharge**: A side-looking Doppler instrument should be installed under the Dorpsstraat bridge to obtain discharge measurements using the index-velocity method.

For any 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

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