Improving discharge measurement range on the lower Roer

A scoping study for flood flow discharge measurement options prepared for Waterschap Limburg by the Hydrology and Environment Hydraulics Group, Wageningen University & Research, funded by the Interreg EMfloodResilience project (Deliverable D.T2.2.1).

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*https://www.wur.nl/en/research-results/chair-groups/environmental-sciences/hydrology-and-environmental-hydraulics-group.htm

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Executive Summary

This report investigates options for measuring discharge over the range 5 to 500 m^3s^{-1} on the lower Roer river in the Netherlands. The research need was identified by Waterschap Limburg, and the work has been conducted by staff from the Hydrology and Environmental Hydraulics Group of Wageningen University & Research. This research was initiated in response to the July 2021 floods in the Ruhr region during which it was found by river monitoring authorities that the measurement range of the existing flow gauging infrastructure was too small and too uncertain or inaccurate through the high-flow range for accurate estimates of discharge to be made. In the Roer catchment, data from the gauging station at Stah, located upstream of Roermond, is used by Waterschap Limburg for monitoring and modeling purposes, specifically to mitigate against flood risk in that town. However, the Stah gauge can only accurately measure discharge for in-bank flows up to 135 m^3s^{-1}, whereas the discharge at this point during the July 2021 event was estimated to be as high as 300 m^3s^{-1}. Therefore, it was identified that there is a pressing need to be able to monitor and record flows which are currently not accurately measured by the Stah gauge because they pass downstream on the floodplain itself where it is in fact much harder to measure flow magnitude accurately. In the scoping document for this research Waterschap Limburg identified that the main aim of the investigation should be to, 'Explore the possibilities of measuring flows over a wide measurement range (5 to 500 m^3s^{-1}) in the Ruhr river basin' (specifically, in this instance, in the Roer river) and to tackle the following research sub-questions:

- What does a measurement site need to meet to deliver good continuous flow measurement? This includes taking into account the infrastructure, accessibility and land ownership present.
- Are there any other site conditions to consider?
- Conduct a site survey to identify the best measurement location.
- Is an existing measurement site suitable or adaptable for this flow measurement?
- Which measurement system or combination of measurement systems can best be used?
- What is technically required to adapt or set up a flow measurement system?
- A cost estimate for setting up the measurement system.
- What measurement range and measurement error can be expected and is realistic?
- Advice on how to perform maintenance of the station to guarantee a good quality of the measurement.

The authors of this report, who were commissioned to investigate methodologies for measuring flood flows in the lower Roer catchment, identified four techniques at the outset of the project that might offer the potential to measure floodplain flows, these being: 1) Fluvial Acoustic Tomography; 2) Image-based surface velocimetry; 3) Radar-based surface velocimetry, and; 4) the use of numerical model simulation results. A site visit was conducted in July 2023 and the lower catchment traversed between Roermond and the Stah gauging station to investigate current, and to explore the possibility of selecting new, discharge monitoring stations. Through that site visit, and a desk-based exercise examining flood inundation maps for the catchment, four possible discharge monitoring sites were identified, one being the Stah gauge itself, the other three being located further downstream. A detailed review of the literature associated with each technique identified was then undertaken and consultation sought with individuals identified as experts in the different methodologies. Based upon the review of techniques and the field and desk-based analysis of the catchment, a series of eight options for extended flow measurement are outlined in this report across the four potential field gauging sites. First, four different approaches that could be applied at the Stah gauge site are identified (Site 4), comprising: 1) extension of the current rating curve using field data combined with numerical model simulation results; 2) the use of image-based water-surface velocimetry to estimate discharge through two bypass culverts; 3) the use of surface velocity radar to estimate discharge at these culvert sites, and; 4) the use of water-surface

velocimetry to estimate discharge in the main Roer channel through a bridge section at the gauge site. Second, two approaches are identified as being applicable to a site on the outskirts of Roermond itself (Site 1) that have the potential to capture the full range of flows specified, these being: 1) the use of Fluvial Acoustic Tomography, and; 2) the use of image-based velocimetry. Third, a site between the above two is suggested for application of a combination of both a standard rating-curve technique to measure flow in the river channel itself, and the use of either image or radar-based water-surface velocimetry to monitor a secondary channel that is predicted to carry the majority of flood flows (Site 3). Finally, an option for measuring in-channel flows is given for a fourth site which is located a few kilometres upstream of the town of Roermond (Site 2). Technique limitations are discussed, estimates given for the discharge / stage range that the chosen system can measure over, and an assessment made of the level of uncertainty expected with each technique. Costings are also provided for the hardware involved in each technique based upon quotes obtained from Dutch suppliers where possible. In the final chapter the authors present recommendations for the implementation of one of the eight options outlined in Chapter 5, that associated with Site 3. This site is located where the N293 road bridge crosses the Roer between Sint Odilienberg and Melick (51.14876144°N, 6.00349374°E) and has been recommended for implementation of a new gauging station because it represents a compromise location in that it is expected that a large proportion of flood flows can be accurately measured here, although not as high a proportion as at Site 1, but is located eight kilometres upstream of that Site and thus affords some lead-in time for the purpose of flood warning in the town of Roermond. It is recommended that a standard stage-discharge rating curve be developed for the main Roer river channel at this site, as the channel appears suitable for such a technique, and that a small side stream which runs parallel to the main river here, the Melicker Leigraaf, be instrumented with a camera-based surface velocity measurement system to determine discharge through this channel which is predicted to carry a large proportion of out-of-bank flow coming from the Roer. A combination of the use of these two techniques at this point on the lower Roer will therefore, it is believed, best satisfy both the requirement to measure as wide a range of flows as possible in this river, and also provide some warning time for flood risk management purposes in the town of Roermond.

Acknowledgements

The authors would like to thank Bart van der Aa and Helena Pavelkova of Waterschap Limburg for their advice on steering this project and for joining us on our field visit of the lower Roer in July 2023. The authors would also like to thank Dr Kiyoshi Kawanishi of Hiroshima University for advice regarding fluvial acoustic tomography, Dr Issa Hansen of SEBA Hydrometrie for background information and siting guidelines for the DischargeKeeper system, Dr Hessel Winsemius of Rainbow Sensing for technical input on camera-based velocimetry and Dr Frans Buschman of Deltares for discussion regarding discharge measurement options and their application on the Geul river. We also acknowledge the support of RMA Hydromet (www.rmahydronet.nl), SEBA Hydrometrie (https://www.seba-hydrometrie.com/), Aqua Vision (https://aquavision.nl/), Viatronics (https://www.viatronics.fi/), and AEM (https://aem.eco/) who provided us with quotations and advice. Finally, the authors would like to thank Interreg for commissioning this research through the EMfloodResilience project, which is 90 % funded from the European Regional Development Fund.

Contents

1. Introduction

During the July 2021 floods in the Ruhr region, it was found by monitoring authorities that the measurement range of the existing flow gauging infrastructure was too small and the measurement technique too uncertain or inaccurate in the high-flow measurement range for accurate estimates of discharge to be made. Waterschap Limburg, who operate gauging stations that lie in the region affected by this high flow event therefore initiated research to investigate the possibilities for improving continuous flow measurement in the Ruhr region together with German partners Landesamt fur Natur, Umwelt und Verbraucherschutz Nordrhein-Westfallen (LANUV) and Wasserverband Eifel-Rur (WVER).

One of the rivers which Waterschap Limburg has control over, and monitors, is the lower reach of the river Roer which has its source in Germany and runs, over its lower course, through the Netherlands and confluences with the River Meuse in the town of Roermond. Although the vast majority of flow measurement infrastructure on the Roer lies in Germany, and is operated by German water authorities, Waterschap Limburg currently obtain gauge readings using their own infrastructure at the Stah gauge site which lies in Germany but is only a few kilometres from the Dutch-German border. From the Stah gauge flood peak travel times to the town of Roermond are approximately 8 to 15 hours, which provides some lead-in time for flood management in this town. The main challenges, identified by Waterschap Limburg, for flow measurement in the Ruhr region include:

- The largest part of the catchment area is in Germany.
- Waterschap Limburg mainly use data from the LANUV but do have two measurement locations running in parallel (Stah and Julich gauges).
- The Roer floods at high discharges.
- The Roer has a dynamic morphology and meanders.

Measurement of discharge at the Stah gauging station is acceptable up to a discharge of approximately 135 m^3s^{-1} beyond which flow goes out of bank at the gauge site and the rating curve cannot simply be extrapolated. During the July 2021 flood event it was estimated that the peak discharge at Stah was 300 m^3s^{-1} and Waterschap Limburg considered that, to have insight into flood flows through the system, research was required to increase the effective range of flow measurement at their gauging sites. The key objective stated for this research package was therefore to investigate methods for flow measurement on the lower Roer that can operate accurately over a measurement range of between 5 and 500 m^3s^{-1}.

The Hydrology and Environment Hydraulics Group at Wageningen University and Research (WUR) were tasked with investigating this research objective, the funding for which has come from the Interreg EMfloodResilience project. In the scoping document for this research Waterschap Limburg identified that the main aim of the investigation should be to, 'Explore the possibilities of measuring flows over a wide measurement range (5 to 500 m^3s^{-1}) in the Ruhr river basin' (specifically, in this instance, in the Roer river), and to tackle the following research sub-questions:

- What does a measurement site need to meet to deliver good continuous flow measurement? This includes taking into account the infrastructure, accessibility and land ownership present.
- Are there any other site conditions to consider?
- Conduct a site survey to identify the best measurement location.
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- A cost estimate for setting up the measurement system.

- What measurement range and measurement error can be expected and is realistic?
- Advice on how to perform maintenance of the station to guarantee a good quality of the measurement.

The geographical scope for this research was set as running from the Stah gauging station downstream to the point where the Roer meets the Meuse in Roermond and a site visit by the research team was specified as one of the requirements in the research scoping document. The final deliverable was identified as being a report, written in English, which explores the research questions set out above. This research was initiated in June 2023 and the report deliverable date set as November 2023.

The approach, proposed by Dr. Nick Wallerstein and Prof. dr. ir. Ton Hoitink of the Hydrology and Environmental Hydraulics Group, WUR, was that of a combined desk and field-based research campaign, the work comprising a detailed investigation of potential techniques available to measure the stated target discharge range at current, or newly proposed, gauging sites on the lower Roer. At the outset of the investigation the researchers stated their intention to investigate the following measurement techniques as these were identified to offer the potential, at least, to satisfy the demands set in the project scope:

1. The use of a numerical model to extend a current, or to aid the development of a new, stage-discharge rating curve in combination with the collection of field data for calibration purposes.
2. The use of camera-based imaging technology to determine flow surface velocity and thence to derive discharge (Large Scale Particle Image Velocimetry (LSPIV) and derivatives thereof).
3. The use of radar technology to detect flow surface velocity and thence to derive discharge (Surface Velocity Radar (SVR)).
4. The use of Fluvial Acoustic Tomography (FAT) to determine cross-section averaged flow velocity and thence to derive discharge.

In carrying out this research activity the authors undertook a field site investigation in July 2023, accompanied by staff members from Waterschap Limburg, and then conducted an extensive literature review of the four techniques described above. Experts in these sensing technologies were contacted and advice sought on their field application at gauging sites identified on the lower Roer by the authors. Costs for each type of technology that requires hardware have been sought (from local, Dutch, suppliers where possible) and these costs are given in the report findings.

The structure of this report is as follows:

- Chapter 2 discusses background factors that must be considered when identifying discharge measurement techniques for the lower Roer including the current infrastructure that is in place, the discharge measurement requirements outlined by Waterschap Limburg, practical constraints on discharge measurement infrastructure in the catchment imposed by site conditions / local regulations, and the influence of channel geomorphological characteristics upon discharge measurement activities.
- Chapter 3 presents results of the desk and field study campaign from which four potential sites have been identified as suitable for measuring discharge on the lower Roer. One of these sites is the current Stah gauging station location, the three others are located further downstream. The type of measurement technologies that could be applied at each site are also initially identified and reasons given for their selection.
- Chapter 4 presents a summary of the theory behind each technology proposed, based upon a thorough review of the available academic and commercial sector literature. The academic and practical application of each technology type is identified along with the factors required for the technology to operate correctly such as spatial operating range, velocity range constraints, and uncertainty associated with each type of instrument. A summary is also given of the availability

of each technology type in the commercial sector with datasheets, obtained from manufacturers, provided in the report Appendices.

- Chapter 5 gives eight options for discharge measurement on the lower Roer. In the course of undertaking this research it was identified that the Stah gauging station was not the optimal site to monitor if one wishes to capture flows in the range of 5 to 500 m^3s^{-1}. However, because this site gives the greatest lead-in time with regards to flood warning downstream in Roermond, the authors have divided recommendations into four sub-sections. First four possible gauging options, using different technologies, are outlined for the Stah gauge site that have a range of hardware costs and different uncertainty characteristics. Second, two possible gauging options are identified for the most downstream site on the Roer, as this location is optimal in terms of being able to capture the full range of flows specified. Third, a discharge measurement option is given for an intermediate site, where the potential to capture extreme flows is not as effective as at the downstream site, but which provides a degree of lead-in time in terms of flood warning. Finally, and for completeness, an option is given for measuring in-channel discharge at the fourth potential gauging site that was identified from the field visit. For each option identified, the following sub-sections are included in order to satisfy the remit of the research scoping document:
    - Actions: Management actions required to implement the suggested option.
    - Site considerations: The physical factors of the discharge measurement site that must be considered along with suggested siting options for the hardware itself.
    - Discharge measurement rate: An estimate is given of the discharge or stage range over which the chosen technology can be used to measure flow.
    - Cost: Costs are given for the hardware required in each option (in euros) along with identification of other costs involved in setting up the technology such as field survey campaigns (the latter costs are not given a monetary value).
    - Limitations: The limitations of the proposed technology in general, and specific to the site in question.
    - Uncertainty estimate: For each technology measurement uncertainty values are given based upon manufacturers technical specifications along with identification (but not always a numerical estimate) of the uncertainty associated with processing and converting the data into discharge readings. The full set of uncertainties that must be taken into account with each technology are explored in Chapter 4.
    - Robustness of approach: An assessment is made of the overall likelihood of this option being successful taking into account the technology used and the time needed to implement the option.
- Chapter 6 presents recommendations for implementation of one of these options, as a priority, based upon the authors consideration of factors including the scientific robustness of the technique, the ability for it to be physically deployed, the discharge range which can be measured, and the likely degree of uncertainty associated with the measurements obtained. This option comprises the development of a standard stage-discharge rating curve at Site 3 (51.14876144°N, 6.00349374°E), which will enable good estimates of in-bank flows to be made, along with the use of image-based velocimetry or radar to capture flood flows in a secondary channel at this site that is predicted to convey the majority of out-of-bank flows.

It should be understood that this report represents a scoping study and the infrastructure siting recommendations made in Chapter's 5 and 6 are speculative and based upon the limited site information held to date. Therefore, specifics including CAD drawings of the operational setup for each technology are not given; that task would have to be undertaken in an advancement of this research activity when specific options are selected and refined.

2. Background

2.1. Lower Roer measurement infrastructure

Waterschap Limburg's jurisdiction in the Roer catchment runs from the point where the river crosses the German-Dutch border southeast of the town of Roermond at 51.12188925°N, 6.08070957°E downstream to the point where the river meets the Meuse. The Roer joins the Meuse at two locations within Roermond, the main channel at 51.19727568°N, 5.98122387°E and a subsidiary bypass channel upstream on the Meuse at 51.18772360°N, 5.97184567°E.

Figure 1 shows the downstream extent of the Roer displaying the spatial range which Waterschap Limburg asked to be considered with respect to installing new or improved discharge measurement infrastructure. Over this extent of the river there are currently two gauging stations at which discharge is actively monitored, the Stah gauge (51.09767898°N, 6.10449473°E) which actually lies just over the Dutch-German border within Germany, and the Hambeek gauge (51.18495759°N, 5.98030975°E) which lies on a bypass channel of the Roer within the town of Roermond.

Currently the Stah gauge rating curve is accurate up to 135 m^3s^{-1} beyond which the flow goes out of bank and the Q-H rating curve relationship is no longer valid. Figure 2 shows the Roer discharge measured at the Stah gauge, developed from stage-discharge rating relationships spanning the period from 1st July 2021 to 1st August 2021 during which time a major flood event occurred. Data is plotted for rating relationships developed by both Waterschap Limburg and the German authority, Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV). The Hambeek gauge is located on a bifurcation of the Roer within Roermond and does not capture the complete discharge of the river and has consequently been ruled out as a suitable location for new or updated discharge measurement infrastructure.

Waterschap Limburg also receive continuously monitored water stage data at 13 gauges between the Stah gauge and the confluence of the Roer with the Meuse. The location of these gauges is displayed in Figure 1 and their corresponding geographical reference given in Table 1. During a field visit made by the authors of this report a number of these gauge sites were visited in person to check on their precise location and suitability for flow monitoring. The locations visited are also denoted in Table 1.

Figure 3 shows recordings for the stage gauges on the lower Roer covering the flood event of July 2021 with data shown between the 1st of July and 1st August. It is interesting to note that the time of travel for the discharge peak between the Stah gauge (16th July at 18:45) and gauge 2.H.4 which is located at the railway crossing over the Roer at the upstream side of the town of Roermond (17th July at 10:15) was 15 and ½ hours. Note that gauge 2.H.169 failed to record any data during this period and gauge 2.H.3 ceased recording above a stage height of 21.598 m. The latter issue was picked up by the Waterschap Limburg and the gauge re-sited to enable recording at higher stages.

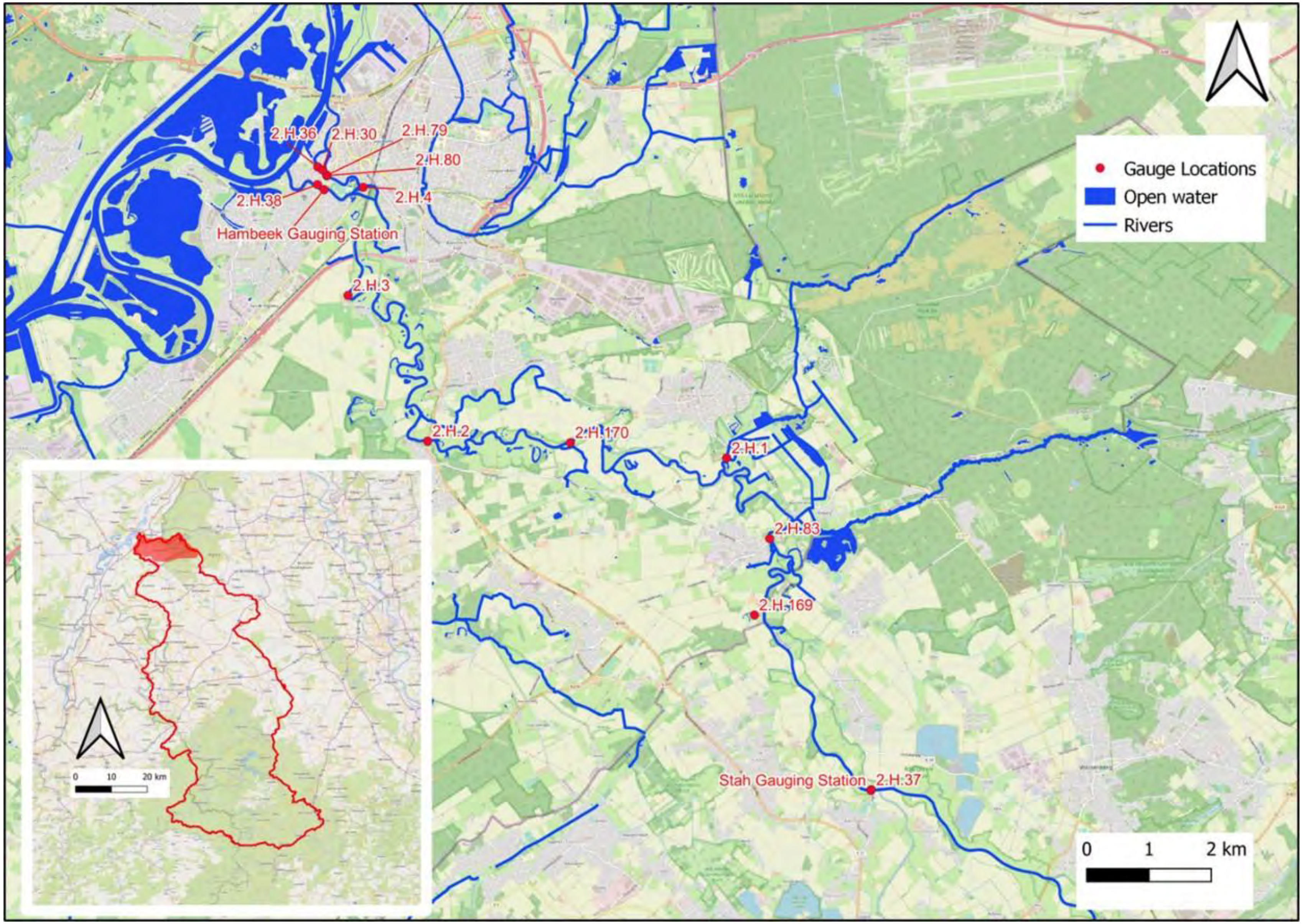


Figure 1. Lower Roer location map showing position of gauges.

Table 1. List of gauging stations on the lower Roer operated and continuously monitored by Waterschap Limburg.

Gauge ID	Gauge type	Location	Location (Lat./Long.)	Site visit*	Function**
2.Q.4: Stah	stage-disch.	Roer channel	51.09770918°N, 6.10450155°E	✓	Full data
2.H.37	stage	Roer channel	51.09781844°N, 6.10455939°E	✓	Full data
2.H.169	stage	tributary channel	51.12314101°N, 6.07814555°E	×	No records
2.H.83	stage	Roer channel	51.13410103°N, 6.08177126°E	✓	Full data
2.H.1	stage	tributary channel	51.14582910°N, 6.07217017°E	×	Full data
2.H.170	stage	Roer channel	51.14821801°N, 6.03629141°E	×	Full data
2.H.2	stage	Roer channel	51.14861817°N, 6.00349733°E	✓	Full data
2.H.3	stage	Roer channel	51.16972472°N, 5.98547119°E	✓	Peak lost
2.H.4	stage	Roer channel	51.18527262°N, 5.98921137°E	✓	Full data
2.H.80	stage	Roer channel	51.18694464°N, 5.98088272°E	✓	Full data
2.H.79	stage	Roer channel	51.18711426°N, 5.98097911°E	✓	Full data
2.H.30	stage	Roer tributary	51.18784121°N, 5.97995731°E	✓	Full data
2.H.36	stage	Roer tributary	51.18827737°N, 5.97883911°E	✓	Full data
2.Q.6: Hambeek	stage-disch.	Hambeek channel	51.18496971°N, 5.98022722°E	✓	Full data
2.H.38	stage	Hambeek channel	51.18573304°N, 5.97870416°E	×	Full data

* Site visit refers to whether the location was inspected on 5th July 2023 by the authors of this report.
**Function refers to whether the gauge was actively recording and whether it recorded all stage levels during the July 2021 flood event.

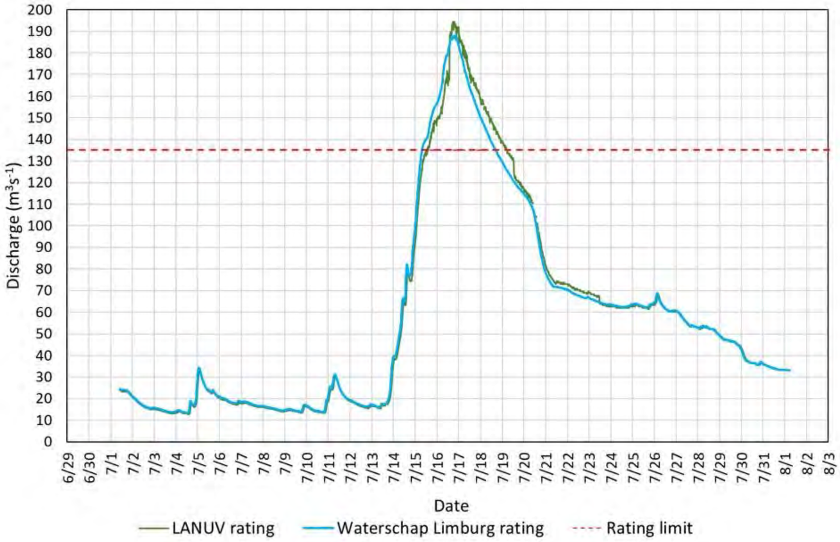


Figure 2. Discharge at the Stah gauging station developed from Waterschap Limburg and LANUV rating relationships for the July 2021 flood event. Also shown is the limit of the rating relationship above which flow goes out of bank.

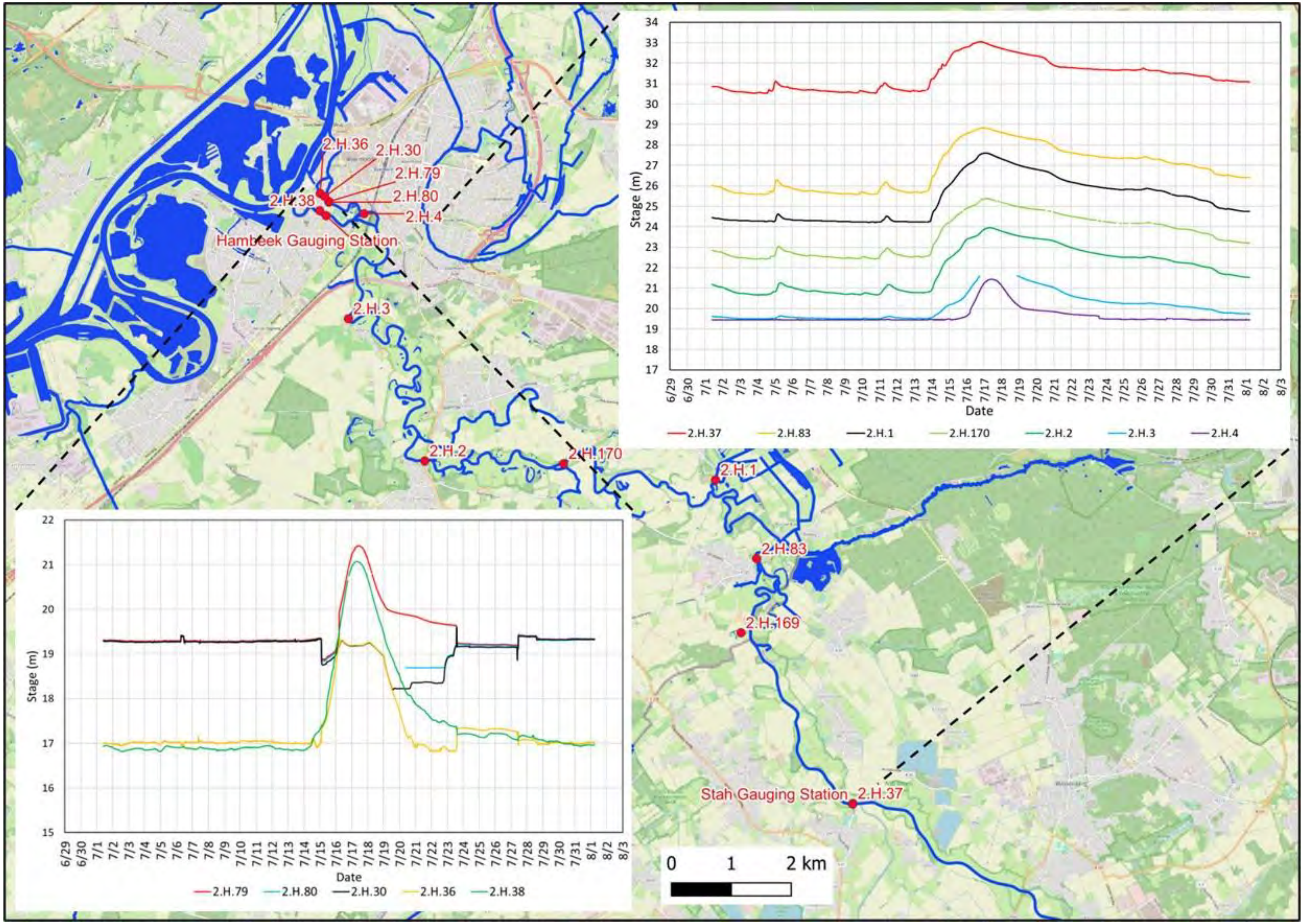


Figure 3. *Stage records for gauges on the lower Roer between 1st July 2021 and 1st August 2021.*

2.2. Discharge measurement requirements

Waterschap Limburg specified that they would like to be able to measure discharges between the range of 5 and 500 m^3s^{-1} on the lower Roer in order to capture out-of-bank flood flows. The Stah gauge is of importance to Waterschap Limburg because this represents the furthest upstream point on the Roer that they actively monitor. Also of significance is the fact that this location is immediately downstream of the last significant tributary to enter the Roer within the catchment, the Wurm tributary joining approximately 100 m upstream of the gauge. Therefore, this gauge measures the total flow of the lower reach of the Roer as, between this point and the rivers confluence with the Meuse, there are no further significant additions to the total flow. Discharge data from this site is primarily acquired for flood modeling purposes the results of which are then used for planning regarding flood risk assessment on the lower Roer, especially for the town of Roermond. Note that the travel time of the flood peak from Stah to the outskirts of Roermond was calculated to be 15 ½ hours based upon the July 2021 gauge data and this order of magnitude of delay was also mentioned by staff from the Waterschap Limburg. This delay therefore provides some lead in time for flood risk management downstream of the gauge location. It is for this reason that the Waterschap Limburg are keen to continue to use the Stah gauge as a primary monitoring point on the Roer, as the use of points further downstream on the river would mean a reduction in the lag time between detecting a flood event and its arrival in the town. Therefore, while the Waterschap Limburg initially left open the question of where an extended discharge measurement system might be sited, we are now aware that they are specifically interested in having as much lead-in time as possible, monitoring-wise, between detection of flows and their arrival in the Roermond urban area. Thus, the Stah gauge, which is located approximately 24 river kilometres from where the Roer enters Roermond, represents the site operated by the Waterschap Limburg from which they would primarily wish to receive improved discharge measurement capabilities.

2.3. Practical constraints on discharge measurement equipment

An important factor that needs to be considered regarding the potential siting of a new measurement system is that there is currently a management policy in place in the lower Roer, within Waterschap Limburg's jurisdiction, which stipulates that the channel must be allowed to freely meander within its floodplain upstream of Roermond's town limits. The implications of this are that the construction of a fixed structure for discharge measurement such as a weir, would not be permitted in this zone unless the structure could be moved if the river were to naturally meander away from its current path. This stipulation has led the authors not to consider the use of a fixed weir as one of the viable options for discharge measurement in this scoping report.

2.4. Geomorphological impacts upon discharge selection method

A factor to consider when investigating gauging methods, especially those that rely on a stage-discharge relationship, is the vertical and lateral stability of the river channel in question. The Roer is known to be geomorphologically quite active in terms of bed elevation change and has an actively meandering channel along its lower course, responding in part to human activities in the catchment over the past 200 years (Wolf et al., 2021; Wolf et al., 2022). Such activity means that stage-discharge relationships will change over time and repeat field measurement of stage and discharge are therefore necessary in order to maintain a reliable rating relationship. Indeed, the rating relationship for the Stah gauge, for example, as derived on 01-01-1994 was adjusted slightly five years later, on 15-11-1999, presumably as a consequence of local changes in channel geometry at the site (data obtained from Waterschap Limburg, July 2023). Direct evidence of the dynamic natural of the channel is available from the fact that, following the construction of the A73 road tunnel under the Roer (due south of Roermond at 51.17537146°N, 5.98754024°E) repeat surveys were made of the channel bathymetry above the tunnel (to ensure that sufficient ground cover existed between the tunnel top and the bed of the Roer) which showed considerable changes in both channel width and depth, especially in response to the July 2021 flood event. Figure 4 shows an example of cross-section data surveys taken just downstream of the tunnel itself between 2011 and September 2022. A summary of this repeat survey work concluded that, 'Between 2011 and 2018, approximately 12 cm of soil erosion occurred' (beneath the bridge) while, 'Between 2018 and 2021, an average of 33 to 90 cm of soil erosion has occurred (that) probably happened during the summer high water of 2021, but that cannot be said with certainty'. Then, 'Between 2021 and 2022, an additional 0 to 38 cm of additional soil erosion has occurred' and finally that, 'In 2022, subsidence will have come to a standstill and sedimentation will have occurred up to a few decimetres' (data and text provided by Waterschap Limburg, July 2023). Therefore, the dynamic nature of the Roer needs to be taken into account when selecting a new gauge site, or when changing the monitoring method at an existing site, as any method that relies upon pre-surveyed bathymetry and/or a fixed roughness coefficient will necessarily mean that repeat surveys will have to be undertaken in the future to account for morphological adjustment. Best practice states that if a discharge measurement obtained during a rating verification test deviates by more than 5 % from the value indicated by the rating, corrections and/or a shift to the rating curve is required (Rantz, 1982a) and it is worth noting that the results of two calibration tests conducted in 2011 and 2023 by Waterschap Limburg for the Stah gauge show deviations of 5% and 6% respectively between the rating relationship and directly measured flow values (data obtained from Waterschap Limburg, July 2023).

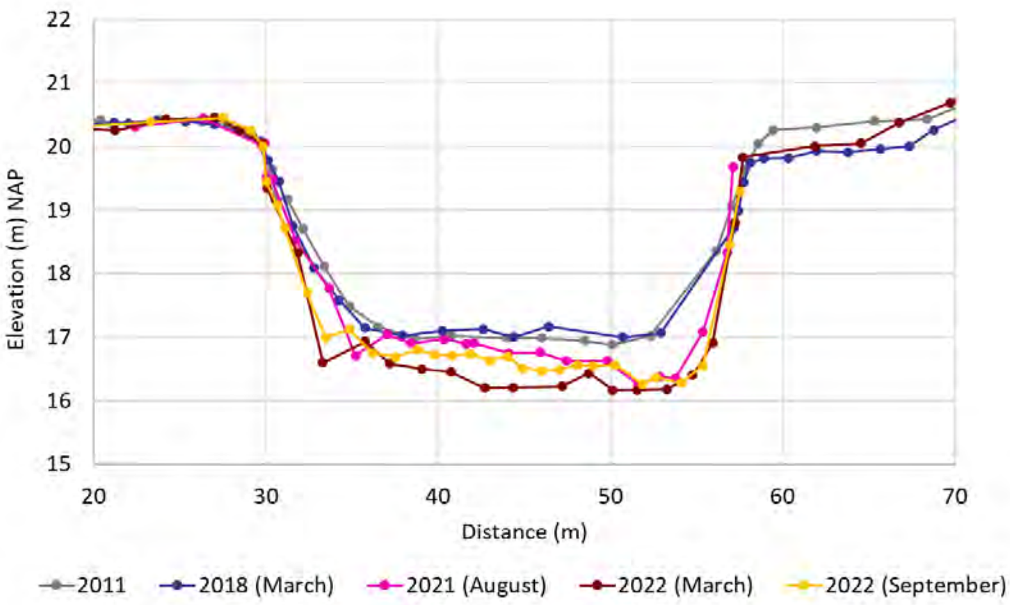


Figure 4. Repeat channel cross-section surveys taken at the A73 road highway tunnel crossing of the Roer (data provided by Waterschap Limburg).

3. Desk and field investigation of potential discharge measurement sites

3.1. Introduction

Potential sites for new/improved gauging were considered and investigated during a field trip undertaken by the authors of this report in conjunction with staff from Waterschap Limburg on 5th July 2023. Initial site selection was primarily based upon prior assessment of GIS data including the mapped extent and depth of a simulated 500 m^3s^{-1} flow event for the lower Roer. This discharge was selected because Waterschap Limburg wished to know the possibilities of implementing a flow measurement system in the Roer that could measure flows over a wide range from 5 to 500 m^3s^{-1}. This upper value was therefore modelled, and the output inundation map used to determine the maximum extent to which flows might spread across the floodplain in the study area. This simulation was generated from a SOBEK 1D flow model of the Roer developed by Waterschap Limburg. The form of the inflow hydrograph used for this simulation is shown in Figure 5. The flood inundation extent used in the mapping exercise was extracted for the time point at the end of the 1-day 500 m^3s^{-1} simulation.

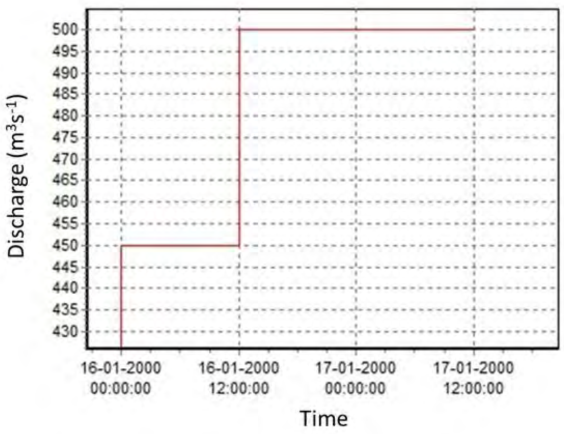


Figure 5. Hydrograph used in the SOBEK model simulation of a 500 m^3s^{-1} flood event on the lower Roer.

This flood extent was overlain on a 0.5 m resolution digital surface model for the catchment obtained from the PDOK digital data repository (www.pdok.nl). Potential target sites to visit in the field were selected on the basis of the degree of lateral constraint of the flood by both topography and structures and the potential for accessing the site in the field. The rational for this was that the narrower the lateral extent that has to be monitored, perpendicular to the primary flow direction, the better, regardless of the type of monitoring equipment used along with the requirement of ready site access for installation and maintenance of any measurement devices. Figure 6 displays the lower Roer with the 500 m^3s^{-1} inundation extent overlain. From the combined field trip and desk-based study four sites were identified as having the potential for discharge measurement across the range of flows prescribed by Waterschap Limburg. These are detailed in Table 2 and marked in Figure 6. Locations downstream of Site 1, such as the Hambeek gauge were not considered suitable for continuous monitoring of the Roer because the river splits into two channels within Roermond which would thus necessitate two separate gauging stations. These four potential sites will now be discussed in a little more detail providing information on the potential width over which flow would have to be monitored under worst-case conditions (i.e., a 500 m^3s^{-1} discharge), access to the site, and possible issues associated with the location.

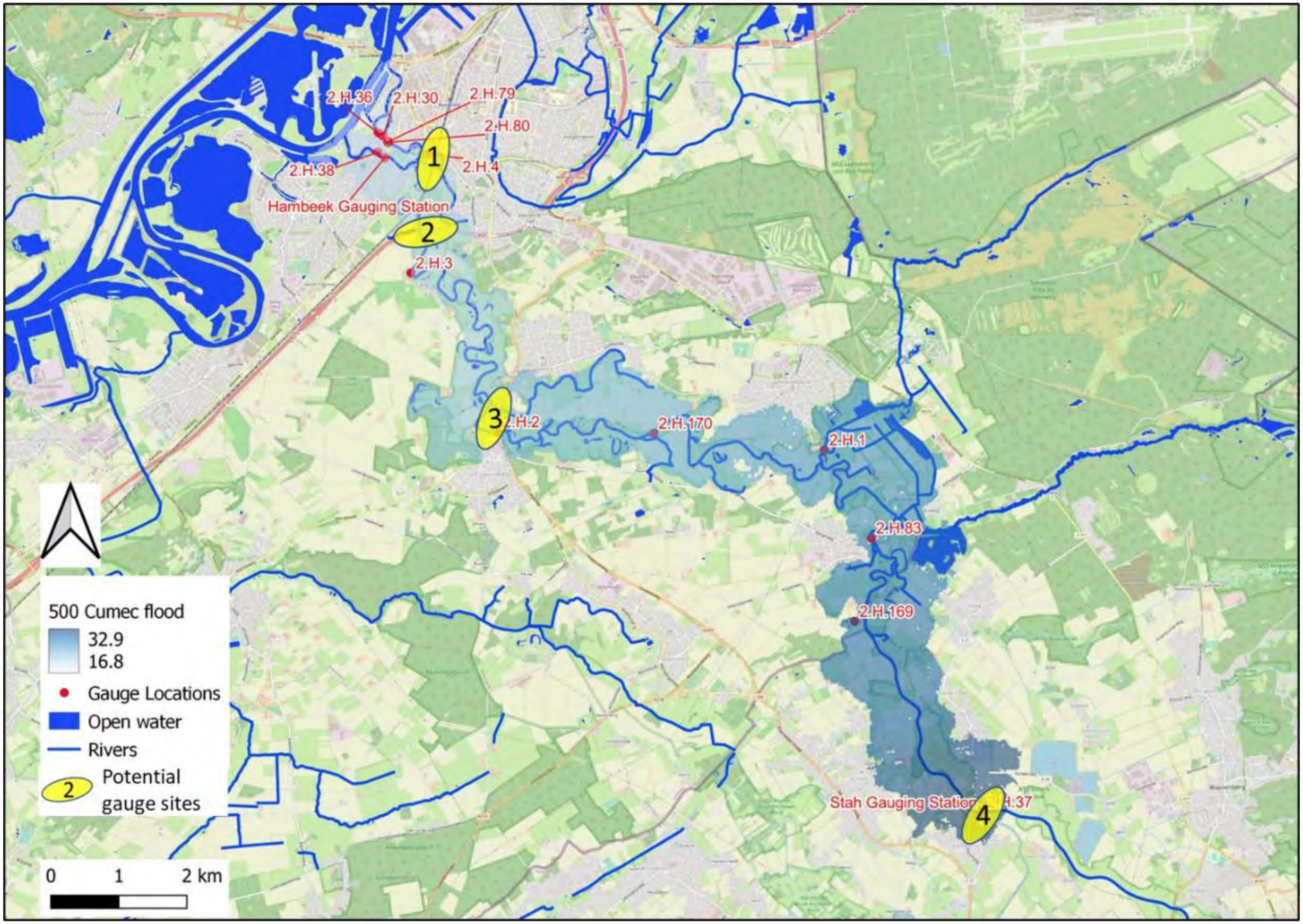


Figure 6. *Lower Roer catchment showing the modeled 500 m^3s^{-1} flood flow inundation extent with associated water surface elevation plus the location of the four potential sites for new/improved discharge monitoring.*

Table 2. Locations on the lower Roer which may be suitable for the measurement of discharge over an extended range.

Site	Description	River centre-line coordinates
1	Railway bridge crossing of the Roer and side channel (Groene Overlaat) on the south-eastern side of Roermond.	51.18545143°N, 5.99101103°E
2	Cycle/foot bridge located at the point where the A73 road passes in a tunnel beneath the Roer approximately 1 km south of Site 1.	51.17534308°N, 5.98756243°E
3	N293 road bridge crossing the Roer located between Sint Odilienberg and Melick.	51.14876144°N, 6.00349374°E
4	The Stah gauging station located in Germany on the K21 road between Kempen and Ophoven.	51.09770467°N, 6.10475772°E

3.2. Site 1: Railway bridge in Roermond (51.18545143°N, 5.99101103°E)

This, the most downstream site, is located on the outskirts of Roermond at a point where the river is actually divided between the main channel and a bypass, the Groene Overlaat (Plate's 1 and 2), which is designed as a fish ladder to enable fish to pass from the Hambeek overflow channel upstream into the Roer mainstem bypassing the large weir located downstream of the railway bridge (refer to Figure 7). At this point the railway sits on an embankment, and this is likely to confine all but the highest flood flows meaning that the flow has to pass between the abutments and bridge pier that act as the supports to the rail bridge crossing the Roer main channel (see Plate 3) or between the abutments and two bridge piers that support the railway crossing over the subsidiary bypass channel (Plate 4). To the right of the bridge (facing downstream) there is high ground which will never become inundated (Plate 5). Channel cross-sections here appear, in both channels, to be roughly trapezoidal in form although the exact geometry could not be determined on the field visit and, unfortunately, the digital surface model data available does not include the complete channel bathymetry.

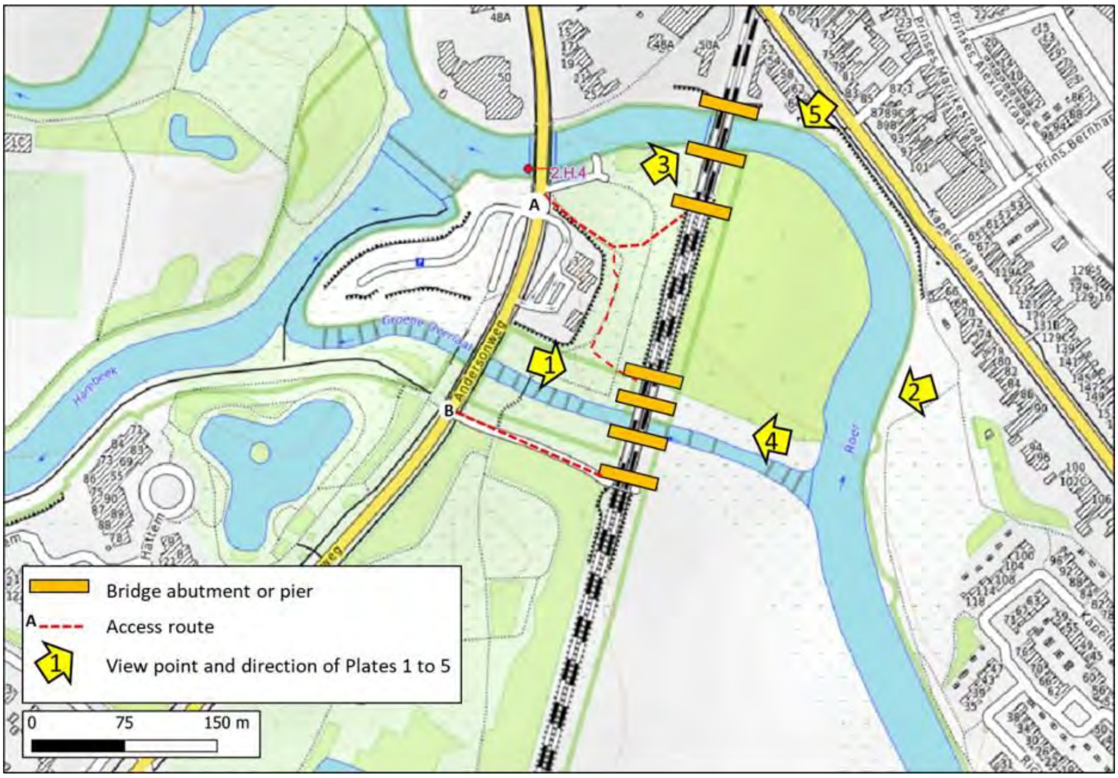


Figure 7. Map of Site 1 showing access routes and the viewpoint and orientation of Plates 1 to 5.

Plate 1. *Looking upstream along the Groene Overlaat channel to the railway bridge. The bridge has concrete abutments and two offset piers, one on either channel bank.*

Plate 2. *Upstream inlet to the bypass channel which has poles and a boom to prevent floating debris from entering.*

Plate 3. *View looking upstream beneath the railway bridge crossing the main channel of the Roer.*

Plate 4. *View downstream along the Groene Overlaat channel to the railway bridge.*

Plate 5. *View from the main channel right bank downstream to the railway bridge.*

The flow at this site can be affected by both backwater from the River Meuse and by the operation of floodgates which are located near stage gauges 2.H.79 and 2.H.80 (refer to Figure 3). Also, the channel approaching the bridge forms a tight bend. Due to both these factors this location would not be suitable for the application of a simple Q-H rating type relationship and rather the mean flow velocity distribution would have to be continuously measured here or an index velocity approach employing fixed side-looking ADCP used in order to determine discharge. Note that there is currently an active stage gauge (gauge 2.H.4) located just downstream of the rail bridge in the main channel here (see Figure 7). The bridge abutments and piers at each crossing are of concrete construction and could act as anchor points if, for example, camera-based surface velocimetry was to be employed. Similarly, an array of surface velocity radar could be mounted on the underside of the rail bridge relatively easily.

Access can be gained to either set of bridge abutments via the small footpath located beside a petrol station located on Andersonweg (marked 'A' in Figure 7) and alternatively the abutment on the left bank of the bypass channel can be accessed via the small road leading off Andersonweg (marked 'B' on Figure 7). The issue of access to, and fitting of equipment on, railway infrastructure was discussed briefly with Waterschap Limburg staff when the site was visited, and the impression given was that the land and infrastructure owner (ProRail) might be resistant to the water authority using railway infrastructure for mounting monitoring equipment. Figure 8a displays the 0.5 m digital terrain model and ground cover overlayed with the inundation extent of the 500 m^3s^{-1} modelled flood extent.

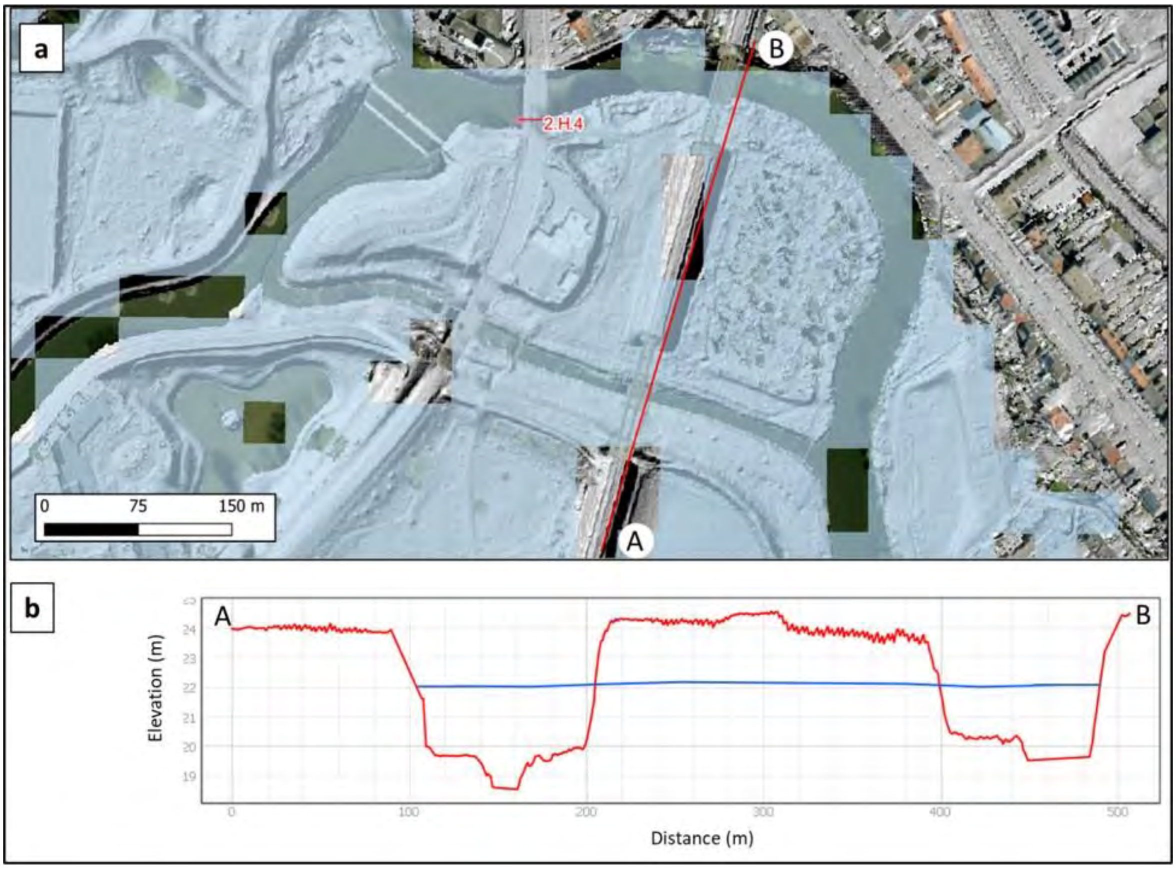


Figure 8. *a) Digital terrain model for the area surrounding the railway bridge crossing the Roer in Roermond with the location of the terrain transect (line 'A-B') defined, and; b) Terrain profile along 'A-B' with water-surface elevation (blue line) for the 500 m^3s^{-1} modeled flow. Note that the full river channel cross-sectional areas are not shown as the digital surface model used does not include independently surveyed bathymetry.*

Line 'A-B' in this figure represents the location of a transect through the terrain, which is displayed in Figure 8b. In the lower figure the two bridge openings can be seen along with the water surface elevation of the 500 m^3s^{-1} flow (blue line) which lies at approximately 22 m NAP elevation. The bridge openings have a span of approximately 95 m between the abutments on the left-hand, bypass channel, and 85 m between the abutments on the right-hand, main river, and these represent the spans that would have to be monitoring in order to capture flows over the range desired. It should be noted that, while the majority of flow is modelled to pass through the two bridge spans for the 500 m^3s^{-1} flow event, some flow is predicted to pass overland to the south of the bridge. The full extent of flood coverage at this location in the catchment is shown in Figure 9. From Figure 9a it appears, upon first inspection, that flow passes over the railway embankment along the transect line 'A-B'. However, Figure 9b shows that, while flow approaches the crest elevation of the embankment and may pass over it in a limited number of places, the majority of the area to the North of the embankment that has been modelled as inundated, on the left-hand floodplain, has probably been fed by flow that has passed out of bank on the downstream side of the railway bridge. Thus, it can be concluded that even at this peak flow if the two railway bridge openings were monitored almost the entire flow of the Roer would in fact be accounted for.

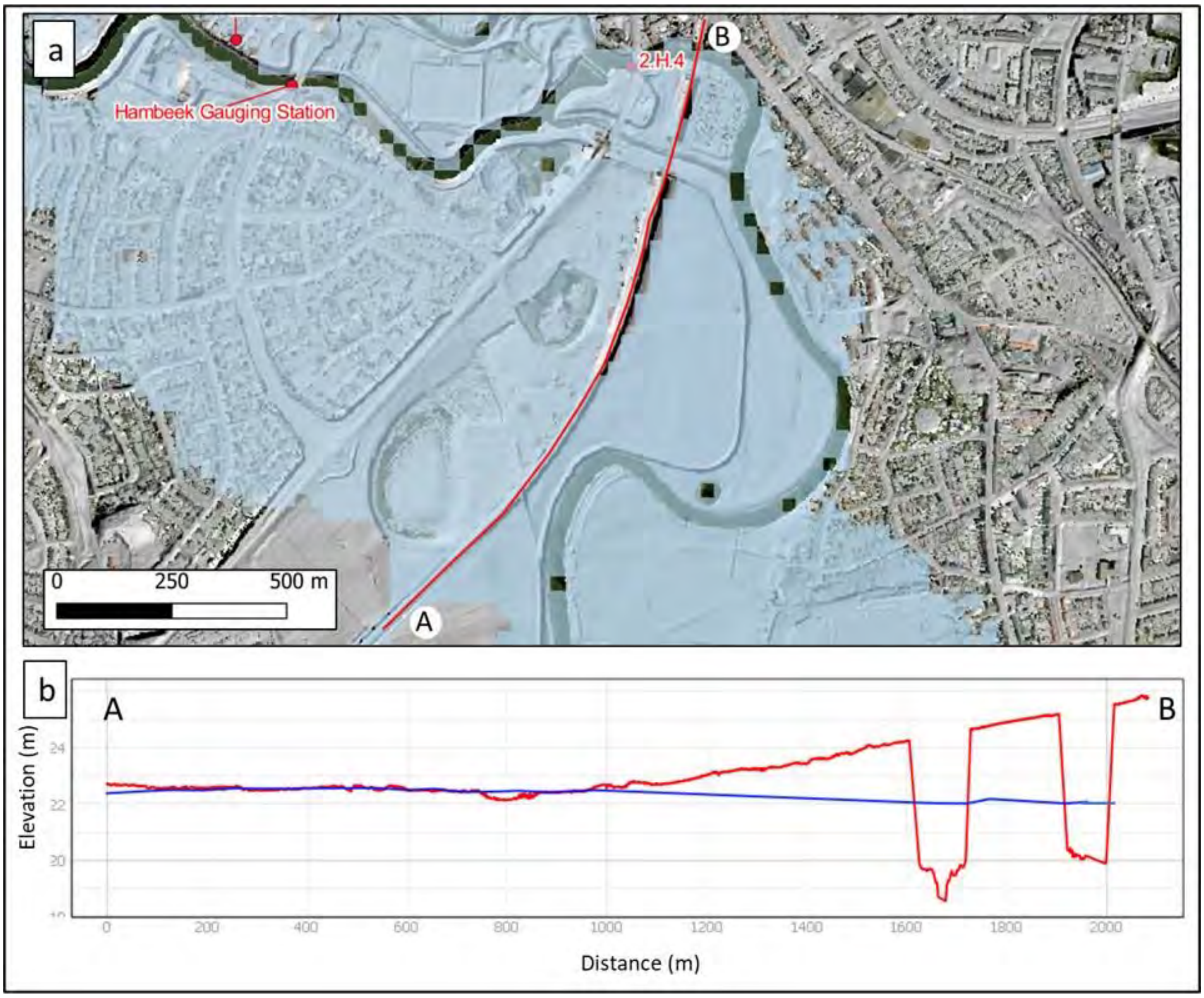


Figure 9. a) Digital terrain model with full extent of flood inundation associated with the 500 m^3s^{-1} flow (dark blue cover) at Site 1, and; b) The terrain (red line) and flow elevation (blue line) profile through transect 'A-B'.

3.3. Site 2: Cycle/foot bridge parallel to the A73 road tunnel (51.17534308°N, 5.98756243°E)

This site is located approximately one-kilometre due south of Site 1 at a point where the A73 road passes under the river in a tunnel (see Figure 10). The site was selected because there is a cycle/foot bridge that passes over the river at this point spanning from the left bank, which is formed of high ground that will remain above flood levels, across to a lower elevation on the right bank (Plates 6, 7 and 8) where the cycle path continues perpendicular to the floodplain for about 400 m on a slight rise in the land (Plate 9). Vehicle access to the site can be made from a small road (Leroperweg) on the left-hand side of the river which passes over the entrance to the A73 tunnel (refer to point 'A' in Figure 10). The line-of-site from the bridge, perpendicular to the floodplain on either side is almost completely unobstructed by structures or vegetation making this location attractive for camera-based river monitoring. The river cross section is semi-trapezoidal at this point and appears relatively free of obstruction on both the upstream approach to the bridge and downstream sides. The channel here follows a slightly sinuous course for approximately 200 m downstream and 100 m upstream of the bridge beyond which it is highly sinuous in nature.

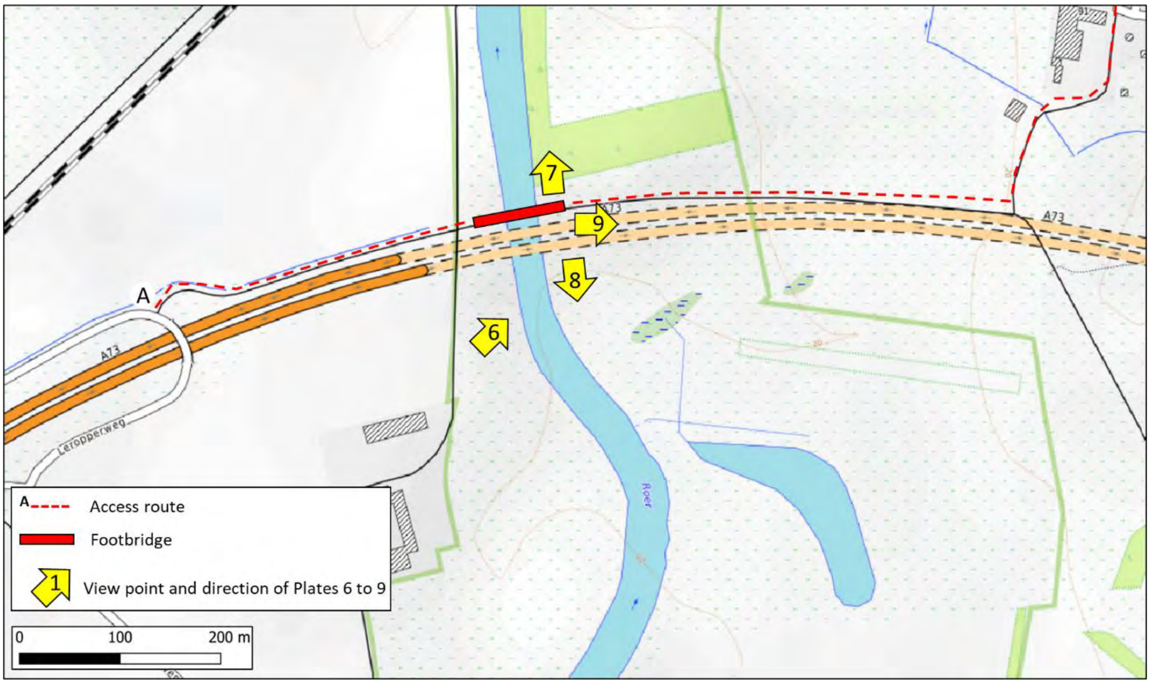


Figure 10. Site 2 location schematic showing the foot/cycle bridge, the point for vehicle access (A) and viewpoint and orientation of Plates 6 to 9.

Flow at this location can be affected by backwater from the Meuse and the operation of flood gates in Roermond so a simple Q-H rating relationship could not be applied. Therefore, an index velocity method using side-looking ADCP, or continuous measurement of velocity using camera-based velocimetry or surface radar in conjunction with bathymetry tied to stage gauges would be required for continuous discharge monitoring. On the floodplain measurement of velocity could be undertaken using camera-based velocimetry. The attractiveness of this site for measuring out-of-bank flows lies in the fact that there is the possibility of access from high ground on the left bank to the cycle path, which runs perpendicular to the channel on the right floodplain. A transect along this cycleway could be monitored using surface velocity measurement through camera-based velocimetry, although the lateral extend that would have to be covered is considerable, almost 1.1 km in the case of a 500 m^3s^{-1} flood. Therefore, multiple cameras would have to be used to cover this extent making discharge calculation more complex, and costly. The terrain profile and predicted elevation of the 500 m^3s^{-1} flood is shown in Figure 11a. Figure 11b shows a profile cut-line along transect 'A-B' (marked in Figure 11a) which follows the cycle/footpath for the first 400 m beyond the right-hand end of the bridge and then a further 700 m across open terrain to a point where the ground level rises above the predicted 500 m^3s^{-1} flood extent. Flow water surface elevation is predicted to a lie at approximately 22.6 m NAP at this location. The benefit of a having a hard-surfaced cycleway, across at least part of the floodplain, is that infrastructure could be mounted on poles along this line and accessed easily. Also, given that there is a concrete/asphalt surface on the cycle path if surface flow velocity were monitoring along this line the bed roughness would be quite low and invariant, compared to say an agricultural field, which would make the conversion of surface velocity values to mean velocities, as required to calculate discharge, much easier. Note that currently there is not a stage gauge located at this site, the nearest being gauge 2.H.3 which is located approximately 700 m upstream (refer to Figure 3).

Plate 6. *Looking downstream from the left riverbank towards the cycle/foot bridge at Site 2.*

Plate 7. *View from the cycle/foot bridge at Site 2 looking downstream.*

Plate 8. *View from cycle/foot bridge at Site 2 looking upstream.*

Plate 9. *View at Site 2 from the right-hand end of the cycle/foot bridge looking along the cycle path.*

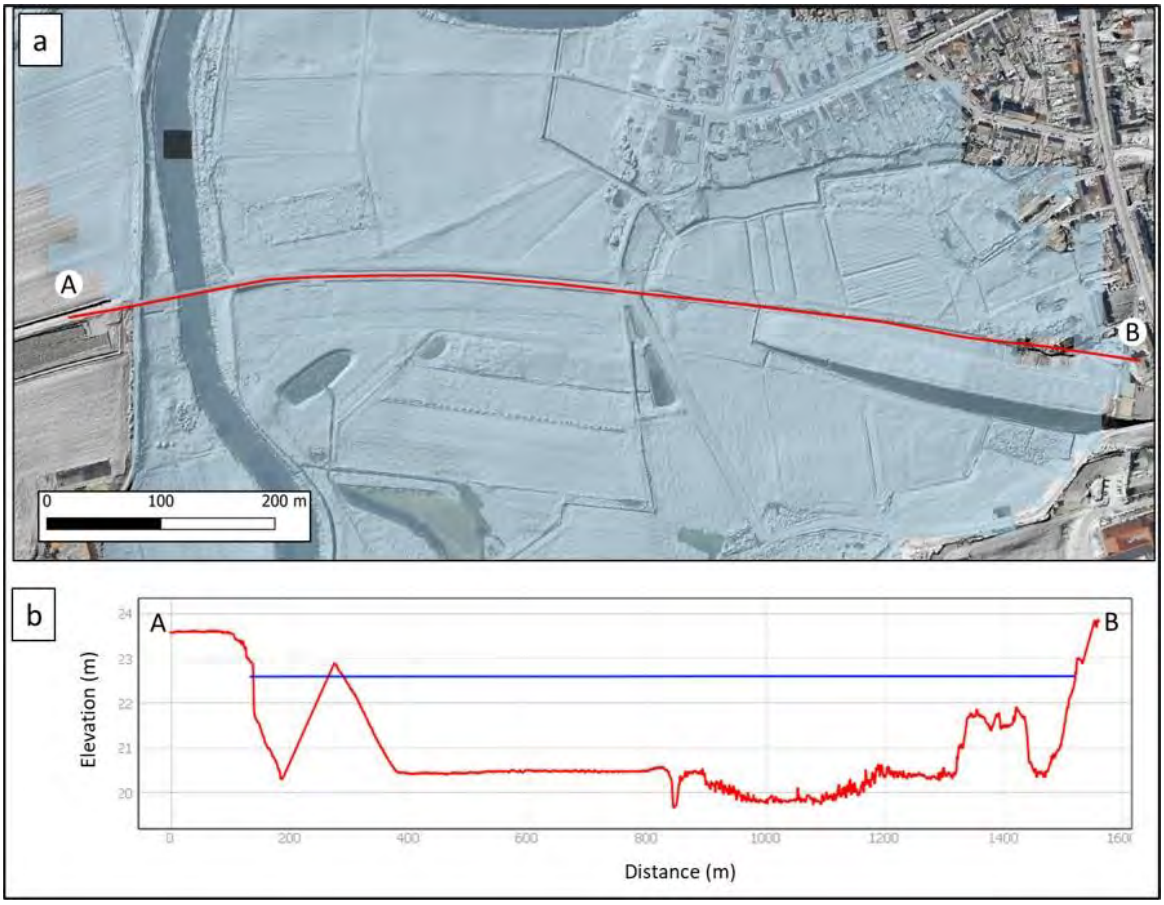


Figure 11. a) Digital terrain model for the area around Site 2 showing the extent of flood inundation associated with the modeled 500 m^3s^{-1} flow (dark blue cover), and; b) The terrain (red line) and flow elevation (blue line) profile through transect 'A-B'.

3.4. Site 3: Road bridge between Sint Odilienberg and Melick (51.14876144°N, 6.00349374°E)

Site 3 is located approximately 2.5 km southeast of Site 2 at the point where a bridge carries the N293 road across the Roer between the villages of Sint Odilienberg and Melick (see Figure 12). The river lies against the left-hand side of the floodplain here and the left end of the bridge span sits well above the predicted 500 m^3s^{-1} flood level so could be accessed during flood flows from the south through Sint Odilienberg. The bridge itself is of concrete construction with supporting piers on both riverbanks. Stage gauge 2.H.2 is located at this bridge and can be seen in Plate 10. A view of the right-bank underside of this bridge is shown in Plate 11. The river at this location appears to have a semi-trapezoidal cross-section although the geometry below the water surface is unknown. The channel is reasonably straight in planform for a distance of approximately 100 m in the upstream, and 250 m in the downstream, direction beyond which it meanders. There are some trees and undergrowth along the upstream side of the bridge, but the downstream side is free of any vegetation and cameras could readily be mounted to the bridge deck here for monitoring or a cableway mounted across the channel to carry ADCP measurement equipment.

Figure 12. Location of Site 3 at the bridge carrying the N293 road across the Roer between Sint Odilienberg and Melick. Also shown are the viewpoint and orientation of Plates 10 to 12.

The attractiveness of this location lies in the fact that the channel should be accessible, at least from the south, in flood flows and the majority of flow is likely to pass through the main bridge opening. Beyond the right-hand (northern) end of the bridge the road dips down towards floodplain level and crosses a small tributary stream, the Melicker Leigraaf on a single span concrete bridge (see Plate 12).
The digital terrain model with extent of the modelled 500 m^3s^{-1} flood is show in Figure 13a. Figure 13b shows a cut through this terrain along line 'A- B' from which it can be seen that the modelled flow will pass over the top of the raised roadway in the vicinity of the tributary channel although beyond this the ground rises again towards the village of Melick. If flow through this secondary channel could be monitored continuously then it is likely that measurement of both it and flow through the main bridge span would capture the majority of discharges likely to be encountered at this location. Note however, that the water-surface elevation of the modelled 500 m^3s^{-1} flow is predicted to lie at approximately 25 m NAP here and that such a flow will sit above the level of the secondary channel bridge deck along a length of approximately 130 m parallel to the road. Consequently, this out-of-bank flow would have to be monitored too, in order to capture a flood of such a magnitude. It is possible that a stage-discharge rating relationship could be developed for the main channel here as this location lies just upstream of the influence of back-water from the Meuse (Helena Pavelkova, personal communication, 13th September 2023) and the channel is reasonably regular and free of obstruction. However, discharge under the secondary bridge over the tributary stream is unlikely to form a simple linear relationship with stage as backwater from the main stem of the Roer itself may come into effect here. Consequently, a different approach would have to be adopted, perhaps using camera-based velocimetry. Also, it was noted at the time of the field trip on 5th July 2023 that a new, possibly unlicensed, crossing had been made over this tributary approximately 25 m downstream of the secondary road bridge which appeared to have significantly undersized flow capacity and this is likely to cause the backing up of flows at this point increasing the likelihood of flood flows in this side channel overtopping the bridge here.

Plate 10. *View looking upstream from the bridge carrying the N293 road across the Roer near the village of Sint Odilienberg. The green pole on the riverbank, centre-left, contains the 2.H.2 stage gauge.*

Plate 11. *View of the underside of the road bridge at Site 3 from the right bank looking downstream. The river channel itself is out of view at the top left-hand-side of this photograph.*

Plate 12. *View looking downstream along the small tributary stream, the Melicker Leigraaf, which crosses the floodplain parallel to the Roer at Site 3.*

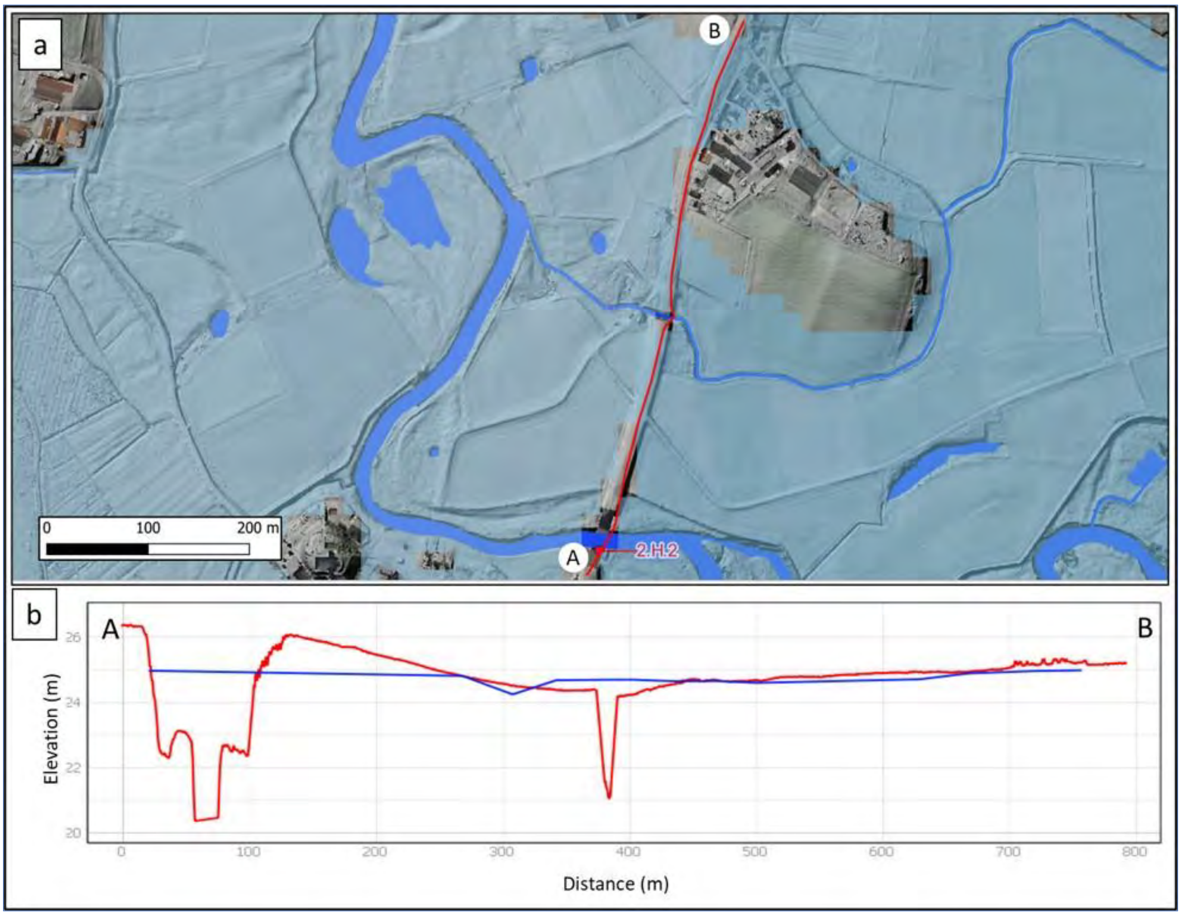


Figure 13. *a) Digital terrain model with extent of inundation associated with the modeled 500 m^3s^{-1} flood (dark blue cover) at Site 3, and; b) The terrain (red line) and flow elevation (blue line) profile through transect 'A-B'.*

3.5. Site 4: Stah gauging station (51.09770467°N, 6.10475772°E)

Site 4 is situated at the Stah gauging station which is located within Germany about 9 km southeast of Site 3 at the point where a bridge carries the K21 road over the Roer between Kempen, to the south, and Ophoven, to the north (see Figure 14). The bridge at this location has vertical concrete abutments and a pair of streamlined piers that rest on the channel banks either side of the main channel. The bridge deck is of pre-stressed concrete construction and runs from high ground on the left bank of the river to land at a slightly lower elevation on the right-hand floodplain (Plate 13). A tributary of the Roer, the Wurm, confluences with the Roer about 100 m upstream of the road bridge (Plate 14). At this location the river appears to have a regular semi-trapezoidal cross-section, is obstruction free and has a relatively straight planform over an extent of approximately 350 m in the upstream direction and follows a gentle right-hand bend downstream of the bridge. At this point along its course the Roer is not affected by backwater from the Meuse or flood control structures that lie within Roermond making it a suitable location for creating a stage-discharge rating relationship, as has indeed been developed for the site.

Figure 14. Location of Site 4 at the Stah gauging station. Also shown are the location of two bypass culverts and the viewpoint and orientation of Plates 13 to 16.

Figure 15a displays the 0.5 m digital terrain model for this location with the modelled 500 m^3s^{-1} flood flow inundation extent overlayed. A cross-terrain profile line has been selected perpendicular to the channel and cut across the floodplain following high ground along the K21 road to the north (Plate 15) into the village of Ophoven and, on the left-hand floodplain through the village of Kempen, south along the same road to the furthest extent of the predicted inundation. The water surface elevation varies between 33 m NAP at the left-hand end of this cut-line to 32.4 m NAP at the right-hand end. It can be seen from Figure 15b that, for this flow event, there are a number of locations beyond the main channel itself that would have to be monitored to capture flood flow, one over a range of approximately 150 m to the south of Kempen and at three locations on the right-hand floodplain. The first of these, located beyond the main channel at approximately 600 m along the terrain transect line in Figure 15b, is sited at a pair of box-culverts which pass beneath the road, and it is thought that this location would represent a preferential flow path for water on the floodplain. If this site were to be selected for high-flow discharge monitoring these structures should be monitored as a significant proportion of flood flow is likely to pass through them. It is unlikely that a stage-discharge rating relationship could be developed for these culverts however for two reasons. First, because flow through the structures is impeded at the downstream end as the culvert inverts (bases) are actually set below the ground surface elevation immediately downstream of the culvert exits (see Plate 16) meaning that a backwater will develop within the culverts themselves. Second, because flow coming out-of-bank in the main channel, downstream of the gauge itself onto the right-hand floodplain, may well cause an irregular backwater effect for flow passing through these two structures. Therefore, if these culverts were to be used to monitor flood flow, direct measurement of velocity would be required here using camera-based velocimetry or perhaps surface velocity radar. It is unlikely that pressure transducers could be used to accurately monitor the water surface slope along the length of the culvert as inlet, or outlet control may prevail meaning that under certain conditions, there may in fact be a hydraulic jump inside the culverts themselves.

Plate 13. *View from the Stah gauging station looking upstream towards the bridge carrying the road over the Roer between the village of Kempen, to the south, and Ophoven, to the north.*

Plate 14. *View looking upstream along the Roer to its confluence with the Wurm on the left bank.*

Plate 15. *View from the right bank of the Roer looking north parallel to the road embankment.*

Plate 16. *Exit point of the sunken box culverts which pass beneath the road north of the Roer at the Stah gauge.*

Unfortunately, peak flows at this site are also predicted to pass over the road high ground further north along the k21 road at a point between 675 m and 725 m along the terrain profile line shown in Figure 15b and again, over an extended length, with potentially some significant depth (over 0.5 m), between 1150 m and 1650 m along the terrain profile towards the town of Ophoven. Consequently, these locations would also have to be continuously monitored if flows of 500 m^3s^{-1} were to be captured. Overall then, while Stah represents a suitable location for determining in-bank flows using the current stage-discharge rating relationship, if the ambition is to be met that flows up to 500 m^3s^{-1} should be measured, then monitoring apparatus would have to be installed at the pair of box culverts and also over a range of approximately 550 m towards Ophoven on the right-hand floodplain, and over a range of approximately 150 m south of the town of Kempen on the left-hand floodplain. Thus, monitoring the complete range of expected flows here, including floodplain flows, is likely to call for an extensive network of infrastructure.

While on a field site visit on 5th July 2023, Waterschap Limburg staff mentioned that a site inspection team had attempted to access the Stah gauge from the south during the July 2021 flood event with the intention of measuring out of bank flows but were in fact turned back by emergency services staff who had blocked the roadway. Thus, it was speculated, that in-person high flow monitoring may not be an option at this site especially given that it falls within the jurisdiction of German, rather than Dutch, authorities. Plate 17 shows a photograph taken by inspection staff during the July 2021 flood which demonstrates the high volume of flow which can pass through the two box culverts.

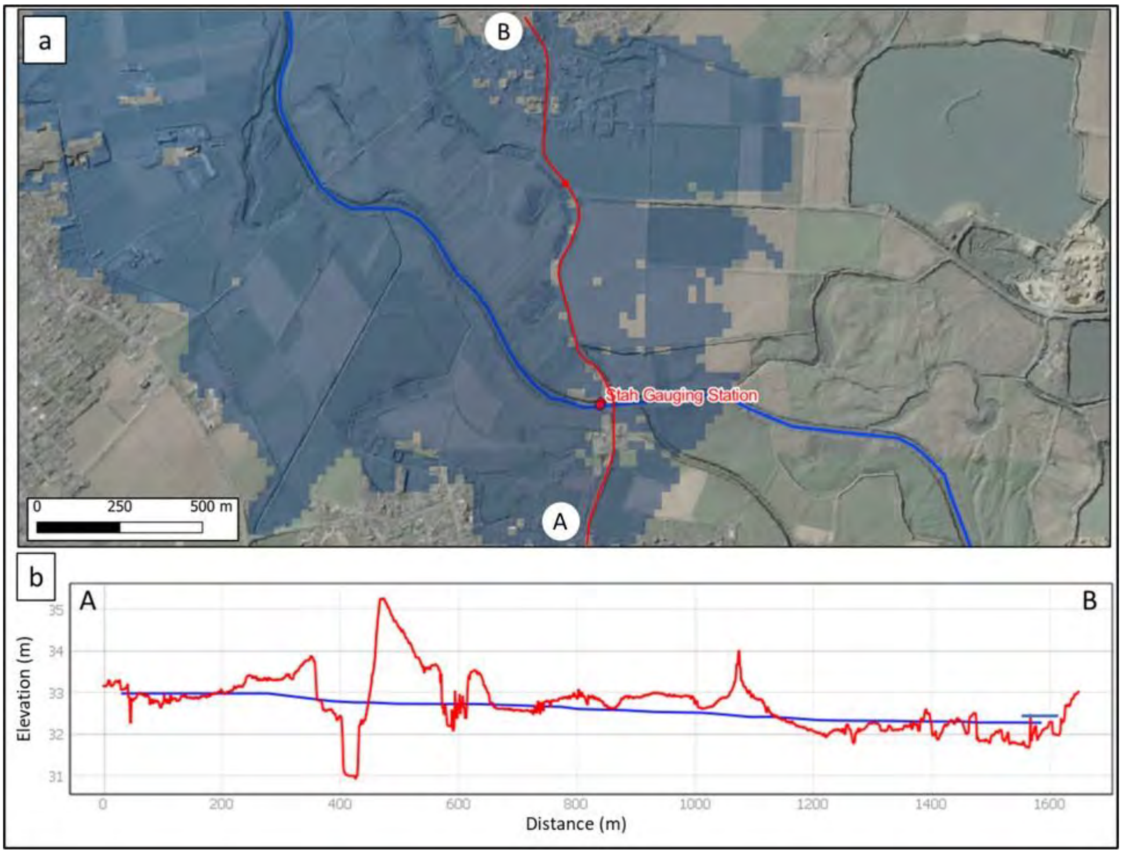


Figure 15. a) Digital terrain model with extent of inundation associated with the modeled 500 m^3s^{-1} flood flow (dark blue cover) at Site 4, and; b) The terrain (red line) and flow elevation (blue line) profile through transect 'A-B'.

Plate 17. Floodplain flow passing out of the downstream end of the two box culverts located approximately 100 m north of the main Roer channel at the Stah gauge during the July 2021 flood event (image courtesy of Waterschap Limburg).

4. Discharge measurement techniques under investigation

4.1. Introduction

River discharge is a function of flow geometry and velocity, and its measurement can be broken down into the following two categories (Muste and Hoitink, 2017):

Discrete: The measurement of flow at a given point in time. Such information is usually quite easy to gather during normal flow conditions, but difficult, dangerous, or impossible during high flow conditions. The means to acquire discrete data and protocols for data acquisition are given in guidelines such as World Meteorological Association (2010).

Continuous: These are typically made in conjunction with some form of rating curve which are formed from a pre-measured relationship between stage and discharge or more complex variables including channel slope and the rate of change of stage. Rating curves are developed by obtaining field measurements of discharge along with the chosen indicator variable over as wide a range of flow conditions as possible to build up a set of paired data from which a predictive relationship can be derived.

Given that Waterschap Limburg wish to predict discharge over a wide range of flows on a permanent basis it is the continuous form of discharge measurement that shall be focused upon here although, of course, discrete measurements will have to be undertaken if a new rating-type discharge predictor is to be developed as the means to capture the range of flows desired. There follows a brief summary of continuous discharge measurement methods that are derived from the rating-type approach as this forms one of the techniques that could potentially be adopted for improved flow monitoring on the lower Roer. The discussion of rating curve approaches is followed by assessment of the use of tomographic technology (Fluvial Acoustic Tomography) to determine cross-section averaged channel velocity and then remote methods for determining surface flow velocities via particle/disturbance tracking using cameras (Large Scale Particle Image Velocimetry and associated tracking technologies) and through the use of surface velocity radar technology. The latter two technologies rely on the use of coefficients to convert the measured surface velocities into depth averaged values from which discharge can then be derived via continuity when the associated bathymetry is also known.

4.2. Rating Curves

By indexing in situ measurement of discharge to a known stage (the elevation of the water surface above a fixed datum) at a chosen measurement site recorded stage measurements can be related to discharge through a rating curve. The actual relationship represents a fit to the spread of paired stage-discharge measurements and is typically defined by a power-type function of the form $Q(H) = a(H - H_o)^b$, where Q = discharge, H = stage, H_o = stage at which Q = 0, and a and b are a constant and coefficient respectively. Field measurement of velocities, required to determine discharge values, was traditionally done using velocity meters but is more typically undertaken nowadays using Acoustic Doppler Current Profilers (ADCP’s) or Acoustic Doppler Velocimeters (ADV’s). In order to construct a robust consistent rating relationship a gauging site must adhere to a number of basic rules, as detailed by Rantz (1982a), including the necessity for there to be minimal change over time in the local channel morphology and structure of the flow in the gauged reach. Rating curves typically have a 4 % - 12 % error as compared with in situ measurements (Horner et al., 2018) but extrapolation of rating curves to very low or high flows, beyond which the original relationship was developed can produce errors of up to 200 % (Kiang et al., 2018).

The disadvantage of this approach is that the development of stage-discharge relationships can be expensive in terms of the human effort required to collect the calibration data and also that changes in channel morphology over time mean that the relationship must be periodically checked and adjusted using new field-measured data. Also, crucially, obtaining discharge measurements at high out-of-bank flows is often difficult and the chance to do so occurs infrequently, so rating curves can rarely be applied beyond bank-full flow, a situation that currently applies to the Stah gauge on the Roer where the highest reliable discharge that can be determined is 135 m^3s^{-1} because field measurement of flows higher than this, at the point where floodplain inundation occurs, has not been attempted as yet.

One option for improving the range of discharge measurement at the Stah gauge itself is therefore to initiate a policy whereby the site is visited when out-of-bank flows occur by developing a written protocol for such events that ensures safe and efficient field practices are achieved by a site team who are specifically tasked with such measurement as and when the opportunity arises. There are, however, a number of obstacles involved when trying to measure out-of-bank flows. First, it may not be possible to travel to the gauge site in flood flows because access to the site is physically blocked by the flood itself and/or there may be restrictions to access imposed by emergency services, as indeed occurred at the Stah gauge when an attempt was made to take measurements during the July 2021 flood event (Bart van der Aa, personal communication, 5th July 2023). Second, high velocities may pose a threat to manned access to the gauge cross-section via boat if ADCP is the preferred method of determining discharge, both in terms of the risk of personnel potentially being swept away and because of the risk that floating debris may pose to boats and instrumentation. Third, manoeuvring on the floodplain in a manned vessel during out of bank flows is risky due to the unpredictable nature of the terrain beneath the boat and because of fixed obstructions such as walls, trees and power supply infrastructure.

4.2.1. Limitation of standard rating curves

The standard rating curve approach is strictly only applicable to uniform and steady flow, neither of which are likely to exist during the passage of a flood wave where large variations of flow in time and/or space tend to occur. In the case of flow non-uniformity, local irregularities in river geometry such as weirs, river confluences and local channel high points caused by riffles may cause a backwater or conversely drawdown in the channel, which cannot be accounted for in a simple stage-discharge relationship. Under these conditions discharge is a function of stage and river slope for which a stage-fall-discharge rating relationship must be developed, as detailed by Rantz (1982b).

Flow unsteadiness, caused by the passage of a flood-wave causes a non-unique relationship between stage and mean channel flow velocity because, typically, the rising limb of a flood wave is much shorter than the falling limb and the associated acceleration rates are consequently different for either portion of the hydrograph. Analysis has shown that velocities on the rising limb tend to be greater than on the falling limb of the hydrograph and as a consequence depth-average velocity for a given stage will vary accordingly (Song and Graf, 1996). The consequence of this is that there is hysteresis in any given stage-discharge relationship with one relationship that applies to rising flows and a second to falling flows. It has been found that such hysteresis is particularly significant in channels that have shallow slopes which are also subject to large flow unsteadiness (Hidayat et al., 2011). The potential for such an inconsistency must therefore be explored when any new stage-discharge relationship is being constructed and it is not known to what degree either of these factors may influence the standard rating relationships used on the lower Roer at the Stah and Hambeek gauges although the few calibration measurements that have been made at these sites have shown good agreement with the equations that are currently applied.

4.2.2. Methods for extending the rating curve I: Slope-area method

In this method high, out-of-rating, flows are determined by entering field recorded data on water surface slope and the cross-sectional area of the flow along with a roughness coefficient estimate into Manning's equation from which the associated discharge can be derived. The means for determining water surface slope has traditionally been the use of high-water stage marks left by floods such as debris and fine sediment lines deposited on the floodplain surface. The cross-sectional area associated with high watermarks can be determined from pre-existing knowledge of the channel and floodplain bathymetry and an appropriate Manning's 'n' obtained from published reference values such as Barnes (1967). In order for the method to be applied effectively estimates should be made over three or more sequential channel cross-sections that are assumed to maintain uniform flow over a wide range of discharges. Site selection must also take into account: a) the capacity for high-water marks to form; b) the necessity for major changes in channel configuration not to occur during flood wave propagation; c) that there are not upstream or downstream flow controls, and; d) that the reach must be long enough to develop a fall in free-surface elevation that is greater than the range of uncertainty inherent in the high water marks (Dalrymple and Benson, 1968; ISO 1070, 1992). Of course, because river channels are invariably non-uniform the method must take account of factors that may affect the friction slope as this will depart from the water surface slope under such conditions. Dalrymple and Benson (1968) suggest that the slope-area method can replicate discharge within a 10% accuracy or better, but for the technique to be applied successfully a suitable channel reach must be found that follow the guidelines of Rantz (1982b) and ISO 1070 (1992).

If pressure transducers, linked to telemetry, are used to measure water surface slope along a channel then the slope area method can be used to continuously estimate discharge, rather than simply peak water levels. This approach has been called the Continuous Slope Area method (CSA) (Muste and Hoitink, 2017) and because it provides direct measurement of the flow free surface during the rising and falling limb of the hydrograph can capture the loop effect generated in the stage-discharge rating relationship (Stewart et al., 2012). This method has been found to replicate field measured discharges with uncertainties ranging from 12.3 % to 15.5 % (Stewart et al., 2012) but the technique has not been reported extensively as yet in the academic literature. A rationalised version of this technique, which can be applied to in-bank flows, called the Simplified Continuous Slope Area method (SCSA) was developed by Muste et al. (2016) which is based on continuous measurement of water surface elevation at just two locations rather than the three specified in CSA guidelines. In this technique the stage differential between two locations along the channel is used to provide a measure of the flow slope and this is combined with a one-time survey of the channel cross-section at the downstream gauge, from which flow area can be related to stage, and an estimate of Manning's 'n'. Together these provide the input variables required to solve for discharge from Manning's roughness equation. A schematic diagram of the SCSA is shown in Figure 16.

Because there are a number of telemetry-linked stage gauges in operation along the lower Roer the SCSA method could readily be applied here to determine in-bank flows at locations between the Stah gauge and gauge 2.H.4 on the outskirts of Roermond (refer to Figure 3). This approach has been adapted and tested by the authors using data obtained from the lower Roer and an example of its application is given in Appendix A.

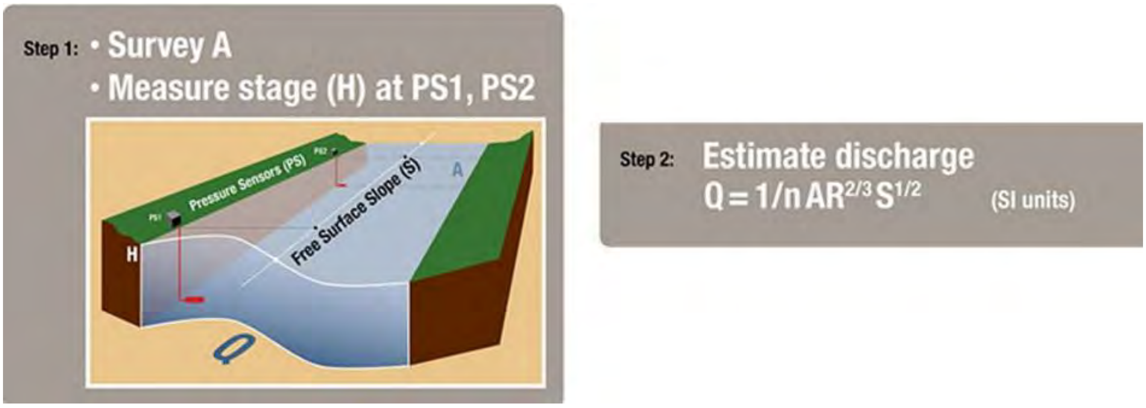


Figure 16. Schematic of variables used in the simplified continuous area method (adapted from Muste and Hoitink (2017)).

4.2.3. Methods for extending the rating curve II: Index-velocity method

This technique involves the inclusion of a continuously measured flow parameter which is used as an index to complement the standard stage-discharge relationship. Such an approach helps to overcome the ambiguity in the relationship between mean flow velocity and stage encountered where there is highly unsteady flow. The index velocity can be obtained in a number of ways including at a point (Chiu, 1987), along a line (Rantz, 1982b) or over the stream surface (Muste et al., 2008). The technique has become more widespread in recent years with the advent of horizontal ADCP (H-ADCP) which can be mounted at a fixed point in the cross-section where gauging is to be achieved and reference velocities sent in conjunction with stage information via telemetry to give real-time discharge estimates (Hoitink et al., 2009). In this approach repeated simultaneous measurements are made of stage, discharge and an index velocity and these are combined into two rating curves, one of channel cross-sectional area as a function of stage and the other of mean channel velocity as a function of the index velocity. The stage-area rating is constructed using a detailed bathymetric survey of the channel cross-section. The second rating curve is determined by dividing the channel discharge measured during calibration test by the cross-sectional area to give a mean velocity and pairing that value with a representative index velocity taken at the same time from a known fixed point in the channel. The relationship between mean and index velocities is commonly determined using a regression model. In practice index velocities are obtained by averaging velocities acquired in individual cells along the line of site of a horizontal ADCP. Once the two relationships have been established, continuous direct measurement of depth and index-velocity at the gauge site provide values of channel cross-sectional area and mean flow velocity which, when multiplied together give the channel discharge. Figure 17 shows a schematic diagram which outlines this procedure.

The accuracy of this procedure depends on the quality of the relationship developed between the mean and index velocity. For simple channel cross-sections this relationship is usually linear but more complex, compound, channels require more elaborate fits to the data in the form of a bimodal rating (Ruhl and Simpson, 2005). In flood conditions there may be hysteresis in the relationship between the mean and index velocity on the rising and falling stage of the hydrograph which must also be taken into account, and this has been explored by Ruhl and Simpson (2005) and Levesque and Oberg (2012).

The index-velocity method in of itself does not provide the means to measure high, out-of-bank flows, and the simple stage-discharge relationships used by Waterschap Limburg for the Stah and Hambeek gauges seem to be quite satisfactory at present, but this technique should be borne in mind when considering future development of gauging capabilities on the lower Roer.

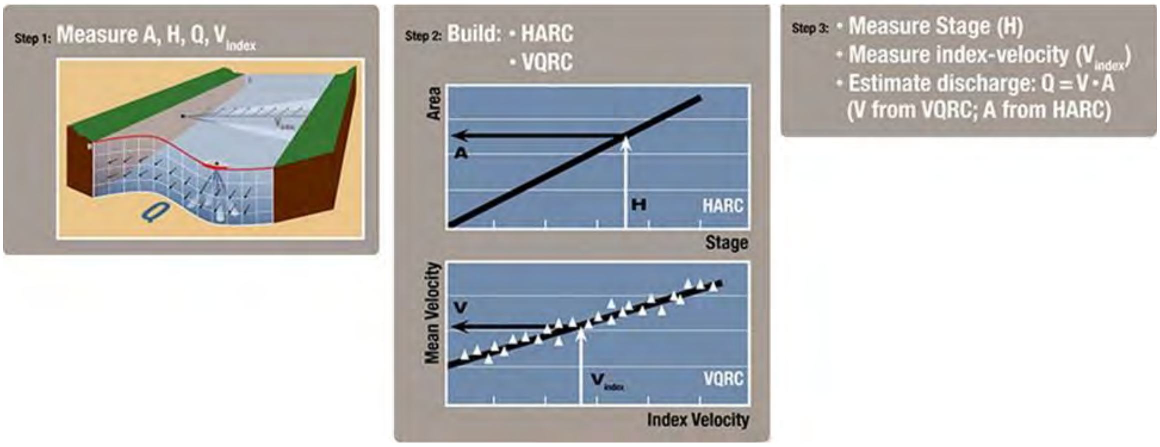


Figure 17. A summary of the process of developing a discharge rating curve using the index velocity method. Here H = channel stage, A = channel cross-sectional area, V_{index} = measured index velocity, HARC = stage-area rating curve and VQRC = index-mean velocity rating curve (adapted from Muste and Hoitink (2017)).

4.2.4. Methods for extending the rating curve III: Use of numerical models

The problems associated with direct measurement of flow velocities on floodplains has led to the use of numerical simulations for filling in data points beyond the bankfull level on standard stage-discharge rating curves. Relatively simple 1D models have been applied in practice such as the 1D version of HEC RAS (Kean and Smith, 2005; USACE, 2017) but also more complex 2D models that capture momentum exchange between the main channel and floodplain (Shiono and Muto, 1998; Lang et al., 2010; USACE, 2017). Numerical models can also be used in conjunction with velocity-based discharge estimation approaches such as the index-velocity method to better define flow dynamics. Nihei and Kimizu (2008) developed an approach which combines a simplified version of the streamwise momentum equation, to solve for a velocity profile across the channel, with input data obtained from a horizontal ADCP. The ADCP data is used to optimize a coefficient added to the momentum equation that accounts for flow unsteadiness and nonuniformity at the gauging site. This method was elaborated upon by Iwamota and Nihei (2009) to enable its application to compound channels. The use of numerical models in real time to improve upon the basic index-velocity approach is an emerging technique and is likely to become more prevalent in future as ever-increasing computation power reduces model run times.

The approach of using numerical model information to extend a rating curve could be undertaken in the lower Roer catchment as Waterschap Limburg do have a 1D SOBEK model for the river between the Stah gauging station and the rivers confluence with the Meuse (Helena Pavelkova, personal communication, 13th September 2023). However, if such an approach were to be adopted for the current, favoured, gauge location at Stah this model would have to be extended further upstream because this point currently represents the upstream boundary of the SOBEK model, where the flow boundary conditions are applied, and as such is not suitable for the extraction of reliable out-of-bank stage-discharge information. Helena Pavelkova (personal communication, 13th September 2023) also explained however that there is a 2D model, developed by the Wasserverband Eifel-Rur (WVER) who operate further upstream on the Roer in Germany, which extends from the upper catchment down as far as Vlodrop on the lower Roer, which is approximately 4.2 km downstream of the Stah gauge so if data could be obtained from this model there would be the possibility of constructing a synthetic extension to the rating curve at Stah. The basis for this technique is outlined below following the approach adopted by Lang et al. (2010) with reference to its application at the Stah gauging station:

1. Use paired values of H and Q (stage and discharge values used to create the original rating curve) to calibrate the numerical model at the precise location of the Stah gauge such that roughness coefficient values are adjusted in the model so that for a given Q obtained from the rating curve paired data the stage in the model matches that of the empirical rating curve value of H. This should be done for all separate paired discharge-stage values used in the rating curve independently. This will result in a set of roughness coefficient values for paired stage-discharge data between low flows and the stage up to which field derived discharge data could be obtained. If the model used only accepts one roughness coefficient for a given cell / cross-section, then an average of these coefficient values should be used in the model. If the model can accept stage-dependent roughness coefficients, then these should be applied according to the stage range for which they were derived when calibrating against the original rating curve. Low flow gauge values (a few centimetres of water) should be excluded from this analysis as a 1/2D Saint Venant type model will not be applicable for such shallow flows where the diameter of the bed material is large compared with water stage (Smart et al., 2002). It is noted however, that bed material grainsize in the lower Roer is sand/silt and therefore even quite low stage values could be used to calibrate the model.

2. This calibration of the model, locally for the gauge site, using the rating curve data will be based upon field readings that are subject to measurement error. Lang et al. (2010) dealt with this issue by applying an envelope to the primary rating curve. They assumed that water stage (H) could be affected by an additive error of ±5 cm, while discharge (Q) could be affected by a multiplicative error of ±10 % although they note that such an error range may be pessimistic, and an accuracy is usually sought when generating rating curves of ±1 cm for stage and ±5 % for discharge (Pelletier, 2011). An envelope curve for the Q(H) rating curve can then be generated be developing versions of the numerical model with roughness coefficients calibrated for H_i + 5 cm, $0.9Q_i$ rating values and H_i − 5 cm, $1.1Q_i$ rating values. See Figure 18.

   Once the model has been calibrated for the known in-bank rating values it can be run for a range of out-of-bank flows, where flow spills onto the floodplain and H-Q values extracted from these runs that are then used to augment the upper end of the rating curve for which no physical field data exists. This extension of the model to flood-flow conditions assumes of course that the roughness coefficient values applied to the floodplain are inherently accurate and that such hydraulic factors as momentum exchange are also factored into the coefficients, if not explicitly defined in the model. The envelope curve should also be extended to the model derived rating values, including an added error margin associated with inaccuracy in the estimated floodplain roughness coefficient, to give a range of possible discharges between [$Q^-(H)$; $Q^+(H)$].

3. Once the extended rating curve has been developed, an attempt should be made to validate the values generated via the model beyond the range of field data for which the original rating curve was developed using, for example, flood mark information collected from, and in the neighbourhood of, the gauge site (H_{flood}). It is then possible to compare the flood mark heights with water levels computed for a range of discharges in the envelope curve of the rating curve and calibration of the model is deemed acceptable when the observed flood marks lie within the envelope water line.

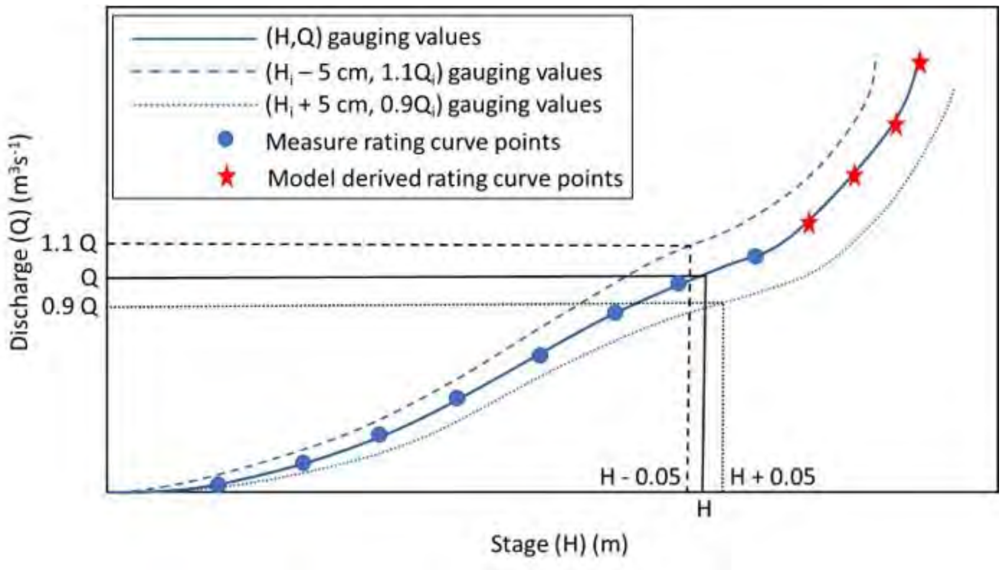


Figure 18. Stage-discharge rating curve with error envelope and extension via numerical model (adapted from Lang et al. (2010)).

4.3. Fluvial Acoustic Tomography (FAT)

4.3.1. Background

To avoid the issues caused by non-uniform and unsteady flow when using a simple stage-discharge rating relationship it is preferential to actually measure the flow field at a gauging site in order to obtain a known mean velocity from which discharge can then be calculated. One approach to address this issue, which was described above, is to install a horizontal ADCP from which a continuous measure of velocity along a path across the channel can be determined and used as a reference velocity in the index-velocity rating approach (see Section 4.2.3). An alternative approach used to determine a reference velocity that has been employed extensively in the past is the use of Acoustic Velocity Meters (AVM's) which work on the 'time-of-travel' principle (see for example Ruhl and DeRose (2004)). An AVM system comprises two transducers that are mounted diagonally across a channel linked to a central processing unit by cables. The system works on the basis that an acoustic signal that has a component travelling in-line with the water velocity (i.e. in the downstream direction) from transducer A to B will move faster than an acoustic signal that has a component travelling against the water flow from transducer B to A and the water velocity along the acoustic path is consequently proportional to the difference in time required for the signal to travel in each direction between the two transducers (see Figure 19). The flow velocity, determined along the acoustic path, is then converted using knowledge of the paired transducer geometry relative to the channel primary flow direction, to obtain the mean velocity of the channel flow in the downstream direction at the depth at which the pair of transducers are set within the water column, as shown in Figure 19.

A more recent, important, technological development that uses as its base the acoustic principles employed in AVM, is that of Fluvial Acoustic Tomography (FAT). This technique, first reported by Kawanisi et al. (2010), is capable of measuring a rivers cross-sectional average velocity, not simply velocity along a transect, by using multiple ray paths that cover the entire cross-section of the flow, as shown in Figure 20.

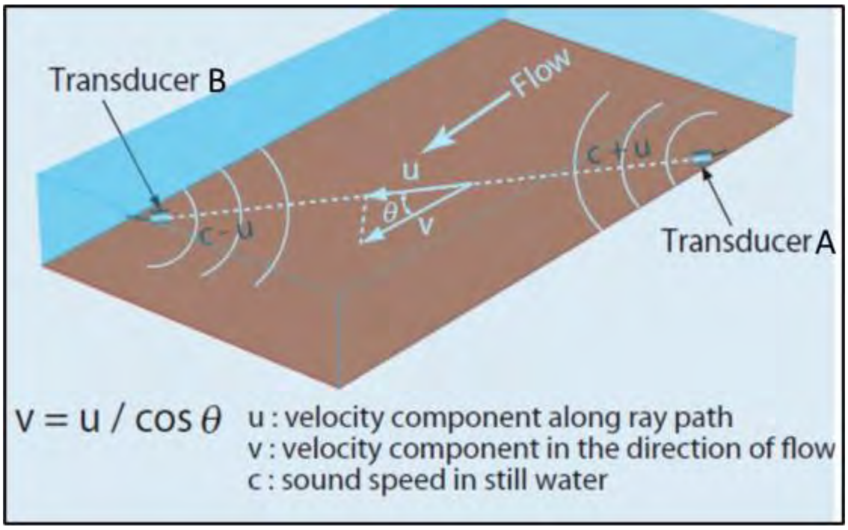


Figure 19. *Principle used to determine mean flow velocity using a pair of acoustic transducers (modified from Kawanisi et al. (2010)).*

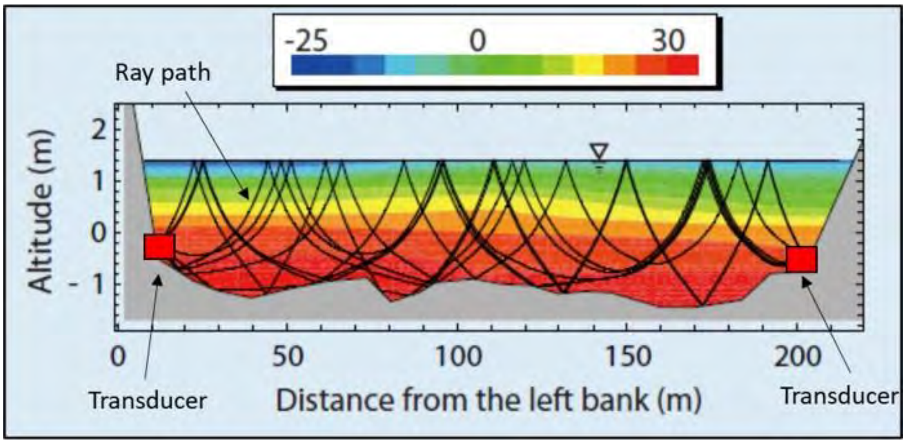


Figure 20. River cross-section showing an acoustic ray path within the water body transmitted and received by two transducers. The colour contours refer to deviations in sound travel speed caused by a salinity gradient in the flow (modified from Kawanisi et al. (2010)).

The theory behind determining mean flow velocity using this technique is as follows. Consider two acoustic stations set diagonally on either side of a river with a horizontal spacing L in a fluid medium moving with velocity v. The sound wave travel times in the forward and reverse directions between the transmitters, t_1 and t_2 are calculated by:

$$t_1 = \frac{L}{C + u_m} \tag{1}$$

and

$$t_2 = \frac{L}{C - u_m} \tag{2}$$

where c = speed of sound in the fluid and, u_m = flow velocity along the sound path.

From equations (1) and (2) the sound speed and water velocity averaged along the sound path are then given by:

$$c = \frac{L}{2}\left(\frac{1}{t_1} + \frac{1}{t_2}\right) \quad (3)$$

and

$$u_m = \frac{L}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \quad (4)$$

The velocity along the ray path is then converted to a downstream mean flow velocity ($\bar{v}_m$) by:

$$\bar{v}_m = \frac{u_m}{\cos\theta} \quad (5)$$

where θ = angle between the path of the ray transmission and the stream axis (refer to Figure 19). Finally, the streamflow is calculated as:

$$Q = A(H) \cdot \bar{v}_m \cdot \sin\theta \quad (6)$$

where A(H) = the oblique cross-sectional area along the transmission line and is a function of the water level (H).

The velocity resolution (u_r) of the FAT system can be expressed as:

$$u_r = \frac{c^2}{2L} \cdot \frac{1}{2f} \quad (7)$$

where f = central frequency of the broadband transducer. For example, given a speed of sound of c = 1436 ms^{-1}, a transmission length of L = 301.96 m and a transmitter frequency of 25 kHz the velocity resolution would be 0.068 ms^{-1}.

Note that if the downstream flow path in the channel is relatively linear a pair of transducers set in a diagonal pattern will suffice in order to obtain the mean flow velocity. However, if the flow pattern is more complex, such as in a meander bend then a three-station system is required set up in a triangular configuration (see Al Sawaf et al. (2023)).

4.3.2. Error structure in the use of FAT

The error structure inherent in the use of FAT contains the four variables given in equation (6). The first (A) and second (H) terms are independent of the FAT system itself while the third term (v_m) depends on the velocity resolution of the FAT system (δu) and the velocity magnitude (u) while the fourth term is the relative error of streamflow due to the stream direction which is function of the transmission line angle (θ) and fluctuations in the stream direction (δθ). The relative error terms are therefore given by (Kawanisi et al., 2016):

$$\frac{\delta Q}{Q} = \left\{\frac{\frac{\delta h_m}{h_m}}{1 - \frac{A}{L \cdot h_m}} + \frac{\frac{\delta A}{A}}{1 - \frac{L \cdot h_m}{A}}\right\} + \left\{\frac{\delta u}{u} + \frac{\delta\theta}{\cos\theta \cdot \sin\theta}\right\} \quad (8)$$

where δ = an error term and, h_m = mean water surface elevation.

To minimise error in the first two terms precise stage monitoring and an accurate bathymetric survey are required, while the error components related to the FAT system itself, the third and fourth terms, can be summarised as:

$$\frac{\frac{c^2}{2L} \cdot \frac{2}{2f} \cdot \frac{1}{\sqrt{S}}}{u} + \frac{\delta\theta}{\cos\theta \cdot \sin\theta} \qquad (9)$$

where the numerator of the first term is the velocity resolution of the FAT system in which S = number of samples used to determine a velocity estimate.

4.3.3. Application of FAT

This technology was applied by Kawanisi et al. (2010) to determine discharge in a tidal river system and the results compared favourably with those obtained at the same time and location using an array of ADCP's. Kawanisi et al. (2012) went on to demonstrate this technology in a shallow gravel-bed river in Japan, Bahreinimotlagh et al. (2019) at two sites in Iran and Danial et al. (2019) in a branched tidal network, again in Japan. More recently Al Sawaf et al. (2023) showed that the primary river flow direction can be determined, and the discharge calculated, using a triangular network of just three FAT transmitters rather than two pairs set with crossing transmission lines as is usually employed with AVM setups, a refinement that makes for cheaper and more practical deployment.

The main advantage of the FAT system over the use of AVM's and H-ADCP is that a cross-section average mean flow velocity is obtained enabling a direct calculation of discharge, the system is robust and can be used in flood flow conditions and is not impaired by high suspended sediment concentrations in the flow. The main disadvantage of the system is that the transducers must be submerged below the water surface in order that the sound path can travel through the waterbody, and they therefore have a minimum operating depth (which depends on their transmission frequency) thus precluding the measurement of very low flow conditions.

4.3.4. Commercial FAT system

The FAT system pioneered by Kawanisi et al. (2010) has been developed as a commercial product by Dr Kiyoshi Kawanisi who runs River and Coastal Instruments (RCI) LLC, based in Hiroshima, Japan. The hardware available for purchase has been developed such that it comprises a fully functioning FAT system in which transducers are time synchronized by a GPS-linked clock in order that acoustic travel times are precisely measured. The complete setup is designed for continuous monitoring use and runs off a DC12-18V (~300W) power supply which can be mains connected. The recorded data is transmitted via wireless LAN enabling real time output of discharge readings. A data sheet supplied by the manufacturer is shown in Appendix B. Transducers are available in a range of transmission frequencies (7, 10, 30 and 50 kHz) as transmission frequency will affect both the maximum ray path length that can be covered and the minimum depth in which it can operate (see specifications in Appendix B). A pricing sheet for the FAT components is shown in Appendix C.

4.4. Surface velocity methods I: Camera-based image velocimetry

4.4.1. Introduction

Camera based image velocimetry of open channel flows is achieved through Large Scale Particle Image Velocimetry (LSPIV). This represents a technique whereby cameras mounted at the side, or above a river, are used to detect and track particles or disturbances on the water surface of the flow to determine surface velocities. A range of adjustment techniques are then available to convert these surface velocities to a predicted mean velocity for the channel cross-section. The derived mean velocity is then used in conjunction with the known cross-sectional area of flow, determined from a pre-surveyed bathymetry, to determine discharge via the continuity equation. The use of LSPIV in rivers stems from Particle Image Velocimetry (PIV) which was originally developed for analysing flow conditions in the laboratory environment over quite small areas of flow (see for example Raffel et al. (1998) but was translated to field conditions, with sensing over large surface areas (hence the term Large Scale PIV), by the pioneering work of Fujita and Komura (1994) and Aya et al. (1995).

4.4.2. LSPIV principles

There are five components to LSPIV: flow visualisation; illumination; image recording; image orthorectification, which is necessary because cameras used in LSPIV are normally set at an oblique angle to the rivers surface, and; image processing. The sequence used in LSPIV measurement is shown in Figure 21.

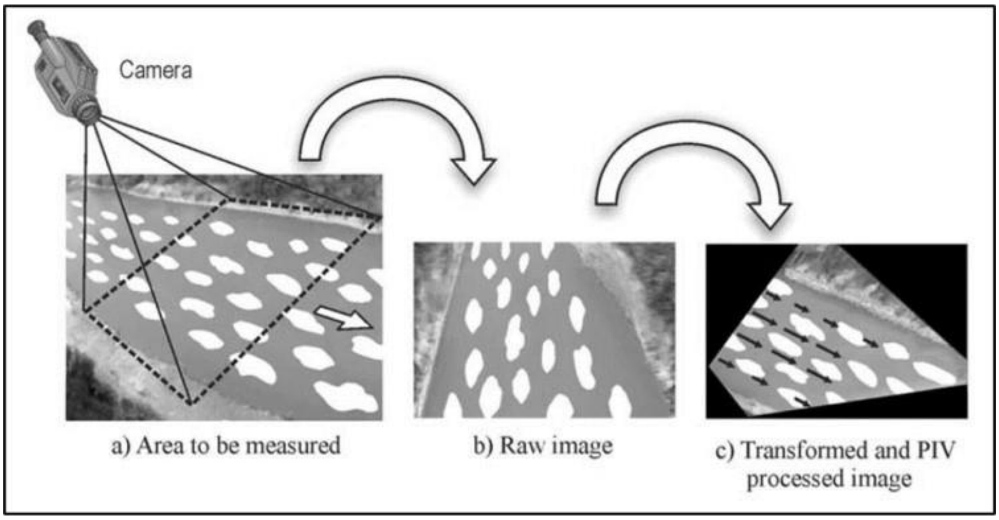


Figure 21. LSPIV measurement sequence: (a) imaging area to be measured (white areas depict natural features on water surface used for visualisation), (b) the distorted raw image, and (c) orthorectified image that has been processed with velocity vectors overlaid (after Muste et al. (2008)).

Flow visualisation, illumination and recording components of the system are interrelated and, in conventional PIV, are driven by a number of rules of thumb regarding concentration of particles, their size with respect to image processing parameters and the desirable maximum particle displacement in a sequence of images. Unfortunately, under field conditions sub-optimal image recording conditions may occur especially with respect to two light related factors: a) variable and under/over illuminated target areas, and; b) glare or shadow on the water surface. These issues mean that the correct siting of cameras in field conditions is crucial (Hauet et al., 2008). A further issue is that of insufficient flow seeding. Generally, movement of the free surface is visualized by tracers such as floating debris, foam or boils on the water surface created by turbulence but such tracers are not always present in sufficient quantities. However, another favourable condition occurs where specular reflection formed by incident light interacting with free-surface deformations, caused by wind or large-scale turbulence, can be used as a seeding surrogate.

The framing of flow during recording is decided by the availability of light and tracers at the free surface while the size of image used is commensurate with its resolution and the capacity to distinguish movement of the water body in consecutive pairs of images. With regards to sampling frequency a wide range of laboratory and field measurements in the past have indicated that a 30 Hz sample rate on a conventional video system is sufficient for capturing velocities encountered in most natural hydraulic conditions (Muste et al., 2008).

Images used for LSPIV are usually taken at an oblique angle to the water surface from a structure such as a bridge or high up on a riverbank and these images therefore have to be rectified using a transformation scheme in order to extract accurate data. In general, a conventional photogrammetric relation is applied to produce orthoimages using the known coordinates of Ground Control Points (GCPs) surveyed in the field in real X, Y, Z and the image coordinates in an x, y coordinate system. This is shown schematically in Figure 22, and the mapping relation between the two systems is given by Fujita et al. (1998):

$$x = \frac{A_1X+ A_2Y+ A_3Z+A_4}{C_1X+ C_2Y+ C_3Z+1},\ y = \frac{B_1X+ B_2Y+ B_3Z+ B_4}{C_1X+ C_2Y+ C_3Z+1} \quad (10)$$

where the eleven mapping coefficients A_1 to C_3 can be determined by the least square method using the known GCPs.

Generally, a minimum of 6 GCPs are needed for conducting the transformation which must be surveyed in the field and can take the form of know fixed objects such as trees, building corners, power line poles, etc., or known benchmarks if available. Note that the effects of radial lens distortion throughout an image must be corrected for before the above transformation is made. In addition to the geometrical transformation of the image a reconstruction of the pixel intensity distribution must also be made to obtain the non-distorted image which is achieved for a given pixel using a cubic convolution interpolation of the intensity in 16 neighbouring points of the original image.

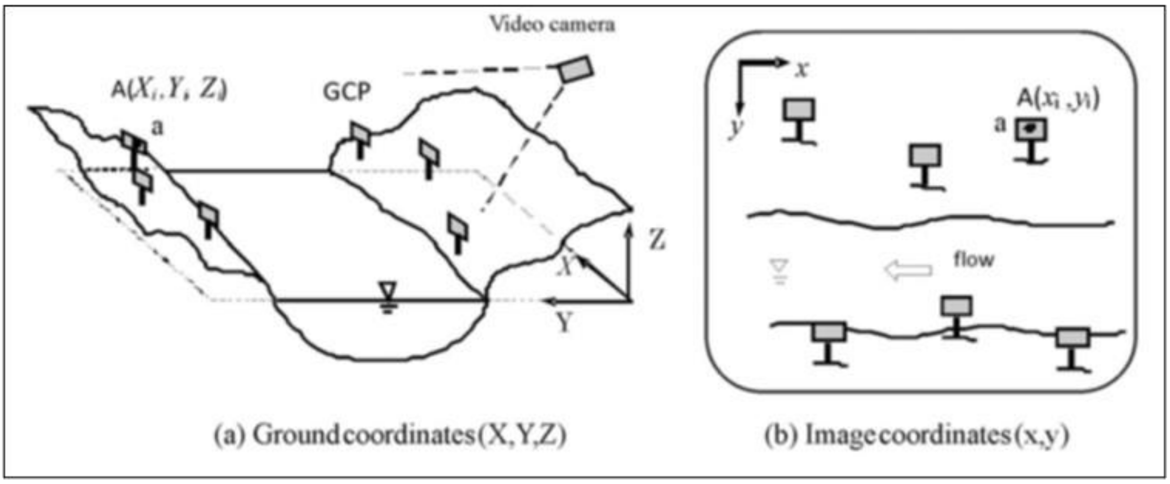


Figure 22. Relationship between camera and field coordinate system in LSPIV (after Muste et al. (2008)).

Once the image has been orthorectified it can be processed using standard PIV algorithms to estimate velocities whereby a pattern matching technique is applied. The principle works by obtaining the pattern of features in a small Interrogation Area (IA) (see Figure 23) of an initial image and comparing this with a window of the same area within a larger Search Area (SA) of the second image in the sequence using a similarity index. This is then repeated for all other window areas in the second image and the window in the second image having the closest similarity index when compared with the initial image is assumed to be the pattern's most probable displacement over the time interval between which the two images were taken. Once the distance between the centre of the IA and paired window in the second image is calculated the velocity can be obtained by dividing this by the time difference between which the pair of images were taken. This search process is applied to all IA's in the initial image to generate a set of velocity vectors covering the entire image area. A variety of similarity indices have been employed by researchers. Fujita et al. (1998), for example, use the cross-correlation coefficient as a similarity index in which the pair of particles showing the maximum cross-correlation coefficient, when comparing an IA with windows in a SA, is selected as the candidate vector. In this approach the cross-correlation coefficient, R_{ab}, is defined as:

$$R_{ab} = \frac{\sum_{x=1}^{MX}\sum_{y=1}^{MY}[(a_{xy} - \bar{a}_{xy})(b_{xy} - \bar{b}_{xy})]}{\left[\sum_{x=1}^{MX}\sum_{y=1}^{MY}(a_{xy} - \bar{a}_{xy})^2 \sum_{x=1}^{MX}\sum_{y=1}^{MY}(b_{xy} - \bar{b}_{xy})^2\right]^{1/2}} \quad (11)$$

where MX and MY = sizes of the interrogation areas in the two images separated by time differential dt, and a_{xy} and b_{xy} = distribution of grey-level intensities (ranging from 0 to 255 for an 8-bit image) in the two interrogation areas (see Figure 23). The overbar variables indicate mean values for the intensity of the entire interrogation area.

This algorithm, which is similar to that used by Fincham and Spedding (1997), uses a variance normalised correlation in which each pixel in the IA is equally weighted such that the background is given equal weighting to the particles in the image and this approach means that velocities can be determined from low-resolution images such as those captured by standard video cameras. It also allows the use of relatively small sampling areas which significantly increases the available spatial resolution and reduces the errors encountered when measuring high-vorticity flows.

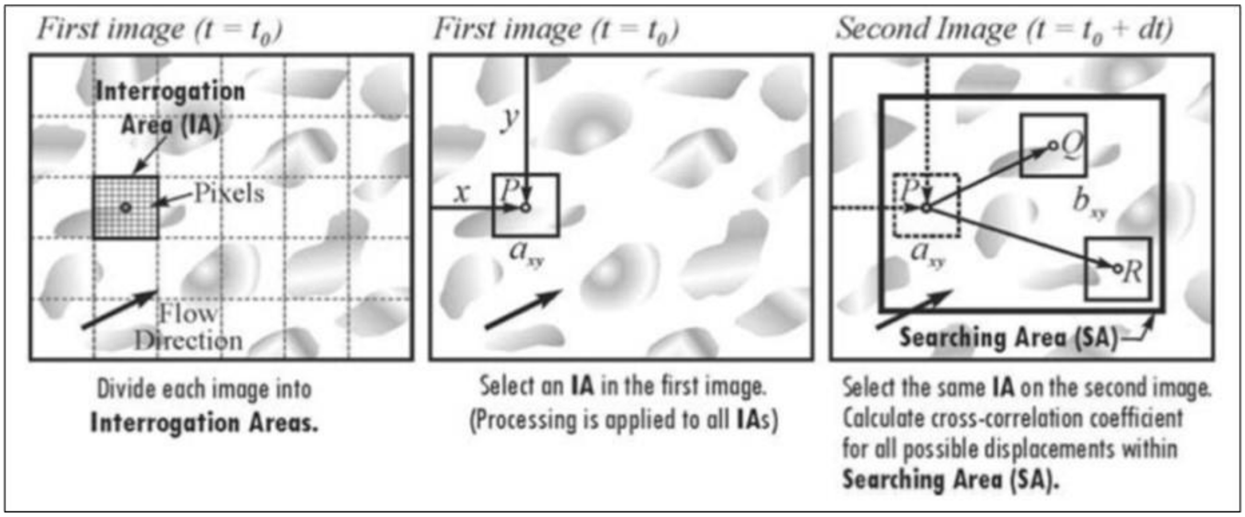


Figure 23. LSPIV image processing sequence using Interrogation Areas (IA's) in an initial image and multiple Search Areas (SA's) in the following image in the sequence over time differential dt (after Muste et al. (2008)).

The outcome of processing raw LSPIV measurements using the above technique is an instantaneous vector field from which it is possible to perform Lagrangian and Eulerian analysis for determining spatial and temporal flow pattern such as the mean velocity field, streamlines and vorticity. The LSPIV surface velocities, in conjunction with bathymetry information, taken from a pre-existing survey can be used to determine channel discharge. Surface velocities at a number of points along the path of the surveyed cross-section (v_i) (see Figure 24) are computed by linear interpolation from neighbouring grid points of the PIV-estimated surface velocity vector field (v_s) and assuming that the shape of the vertical velocity profile is the same at each point i the depth averaged velocity (v_{av}) is related to the surface velocity by a velocity index, which is typically known as the alpha coefficient (or sometime k coefficient). The discharge for each river subsection (i, i + 1) is computed following the standard Velocity Area Method (VAM) (see Rantz (1982b) for example).

The all-important alpha conversion coefficient value is dependent on the shape of the vertical velocity profile which is affected by the flow aspect ratio, Froude and Reynolds numbers, bed roughness and the relative submergence of large-scale roughness elements. Laboratory experiments have been conducted in an attempt to define the dependence between surface velocity and these variables by Polatel (2005). Under experimental conditions of both rough and smooth beds the velocity index was found to vary between 0.789 and 0.928 and it was shown that index values were higher for smooth beds and larger flow depths. Overall, in that research, it was concluded that the range of index values was in fact quite small given the variety of roughness conditions tested, but the index represents an area of ongoing research as this variable is crucial for the translation of surface velocities to depth average values and thence to channel discharge.

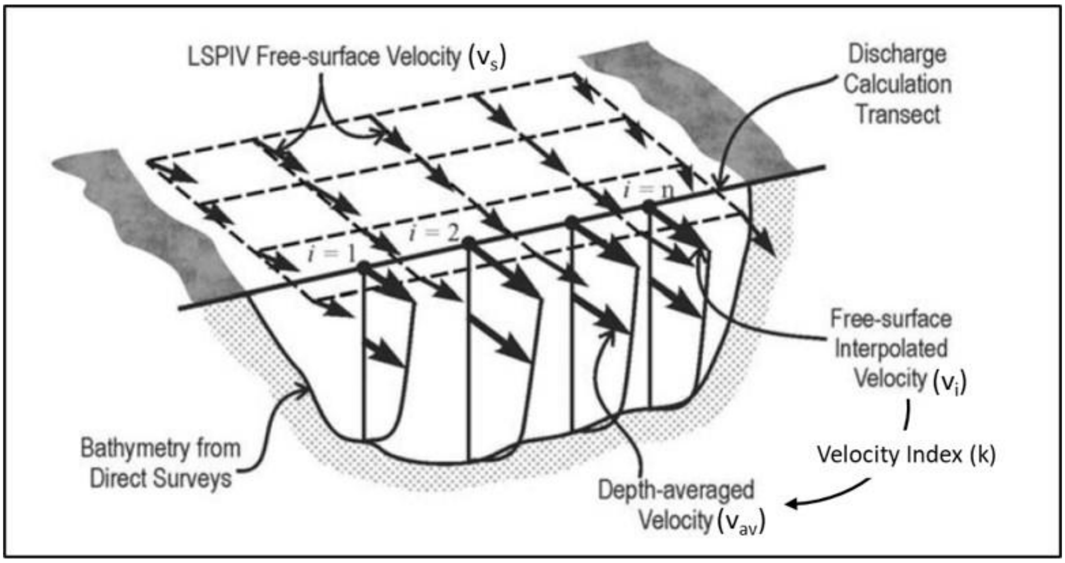


Figure 24. *Procedure for converting LSPIV surface velocity vectors to depth-averaged velocities along a surveyed cross-section (modified from Muste et al. (2008)).*

The accuracy of LSPIV varies spatially and depends upon the obliqueness of the camera view as this impacts image perspective distortion, with objects nearer the camera being better resolved than those further away. Other important spatial factors include the non-uniformity of seeding material on the water surface and the quality of illumination. Indeed, Kim (2006) identified a total of 27 sources of error in the LSPIV process with estimated velocities being affected by (in order): seeding density; identification of the GCPs; accuracy of flow tracing by the seeding material, and; sampling time. By taking into account all measurable sources of error when undertaking LSPIV measurements in adverse conditions (low visibility) Kim (2006) obtained an average total error in velocity of 10 % and a maximum error of 35 %. Direct comparison of velocities obtained via LSPIV with those measured by a second, calibrated device, under laboratory conditions gave an average different of 3.5 % (Muste et al., 1999) while comparison between LSPIV velocities measured under field conditions with those obtained by ADCP showed differences of up to 10 % (Muste et al., 2004b). Interestingly, it has been found that the accuracy of discharge measurements determined using LSPIV are slightly better than those of the surface velocities from which discharge is derived because of the spatial averaging inherent in estimation of discharge using the velocity area method. Muste et al. (2004a) found that discharges measured using LSPIV in a small stream (12 m wide) in the USA were only 2 % greater than those measured simultaneously using an ADCP based device, while measurements in a larger river (70 m wide) generated LSPIV derived discharge values that were 5.6 % lower than those determined by a gauging station at the measurement site and 1.4 % higher than those determined using an ADCP.

LSPIV technology has been built upon since its inception and applied by, for example, Hauet et al. (2008) using stationary surveillance cameras, and by Jodeau et al. (2008) and Dramais et al. (2011) who used mobile systems. Later, Le Boursicaud et al. (2016) demonstrated the use of social media data to gauge rivers while surface velocity and discharge measurements have also been made from unmanned aerial vehicles (Detert and Weitbrecht, 2015; Tauro et al., 2016) and through the use of smart phones (Luthi et al., 2014; Carrel et al., 2019). The application of this technology in flood flow conditions has been demonstrated by Jodeau et al. (2008), Le Coz et al. (2010) and Fujita and Kunita (2011). The technique has also seen use in a variety of flow environments including large river estuaries (Bechle and Wu, 2011; Pena-Haro et al., 2021b), mountain environments (Young et al., 2015), urban areas (Leitão et al., 2018) and in shallow surface flows (Muste et al., 2014).

The development of this technique has led to the generation of a number of different data acquisition and processing methods such as Large Scale Particle Tracking Velocimetry (LSPTV), Kanade-Lucas Tomasi Image Velocimetry (KLTIV), Optical Tracking Velocimetry (OTV) and Surface Structure Image Velocimetry (SSIV) otherwise known as Space Time Image Velocimetry (STIV) (see Fujita et al. (2007)). In recent years collaborative initiatives have been launched in order to develop systematic, transparent comparisons of these different techniques (Pearce et al., 2020) which may ultimately lead to a homogenization of methods (Perks et al., 2020). STIV actually offers a slightly different approach to calculation of surface velocity as it does not use a cross-correlation method to quantify surface tracer movement, instead using a gradient tensor method first described by Fujita et al. (2007). The method uses video analysis, rather than camera stills and there is no frame extraction, or the use of interrogation and search areas. Instead, the method uses Search Lines in the direction of flow, which are set by the user. Each line is of a known length and, together with the know time duration of the video, provides a basis for an average surface velocity to be calculated. The analysis process then takes each pixel in turn along a Search Line and stacks it for every frame of the video. As tracers/surface structures travel along each pixel of the Search Line they naturally create a visible line angled down from top left to bottom right of the space-time image (see Figure 25). A coherency analysis of the Space Time Image (STI) then identifies the mean angle and therefore the mean surface velocity for each Search Line.

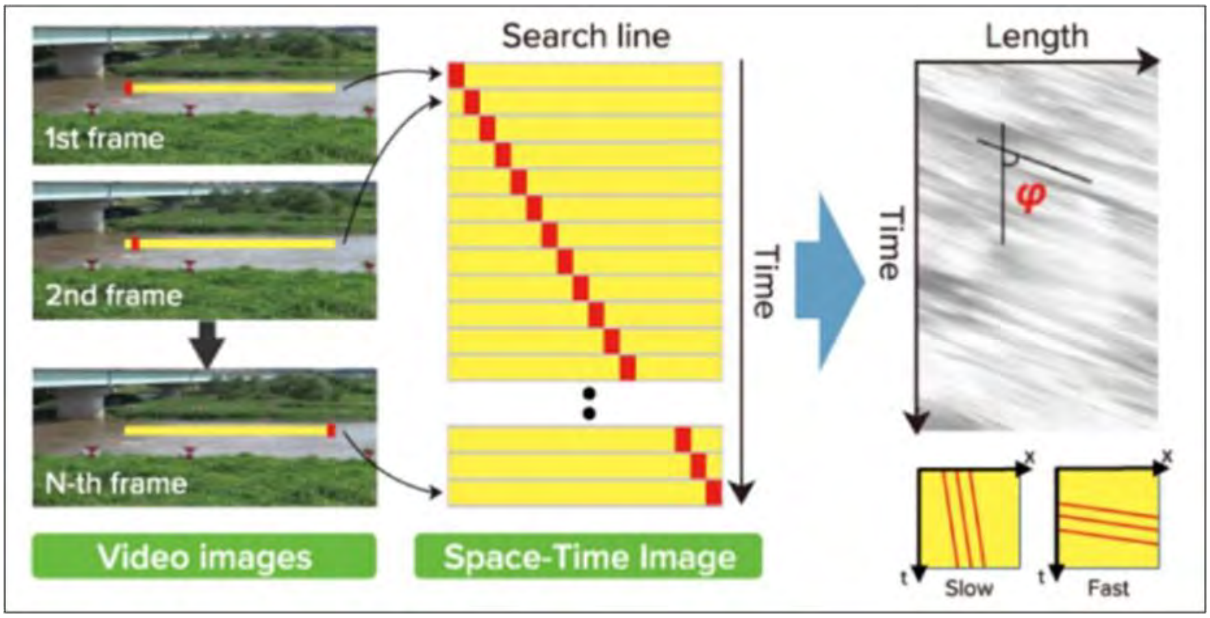


Figure 25. STIV analysis using the gradient tensor whereby all pixels along a Search Line are stacked below each other for every time frame. Tracer movement along the Search Line produces an angled line pattern which represents the surface velocity (after Australian Government Bureau of Meteorology (2020)).

Discharge is calculated in LSPIV using the velocity area method so surface velocity values must be determined for a number of pre-defined discrete 'bins' along the channel cross-section where the bathymetry is known. These values are then converted to mean velocities usually using a velocity index, and this mean velocity multiple by the area of the bin that it is associated with to give a sub-section discharge. This calculation is performed for all bins, the total sum of which gives the channel discharge.

4.4.3. Considerations regarding camera setup

With regards to reducing error in LSPIV, properly aiming the camera at the target flow area is critical. Cameras should be placed at a relatively high vantage point with the optical axis perpendicular to the flow direction (a titling angle of 10 degrees was found by to be an acceptable limit by Kim et al. (2007)). Glare and shadow on the water surface will impact image processing so diffuse light or midday recordings are advised (Muste et al., 2008) although this is of course not possible when continuous measurement is required. Camera installation should ensure that there is no vibration caused by, for example, the wind and of crucial important is the accuracy of GCP survey. Finally, the quality of the camera image is all-important. Data indicates that the quality of recordings are directly related to the size of the imaging sensor in the camera.

4.4.4. Commercially available LSPIV/STIV systems

Consultation was undertaken with Hessel Winsemuis (winsemius@rainbowsensing.com) (27th September 2023), who has expertise in LSPIV development, to obtain further information regarding the practical implementation of this technology for flood flow measurement on the lower Roer catchment. Hessel has developed free open-source software for conducting LSPIV (www.openrivercam.org) and has considerable experience in the practical deployment of LSPIV systems. His company offers a consultation service for installation of LSPIV and he is in fact currently collaborating with Waterschap Limburg on a pilot project which is testing the use of LSPIV in conjunction with his software on the Geul River. Hessel indicated during discussion that he would be willing to offer his services if a LSPIV setup were to be considered for the Roer also. Through discussion with Hessel and also through a search of the literature it was found that there is currently a European company, SEBA Hydrometrie GmbH & Co (www.seba-hydrometrie.com), who offer a commercially available image-based velocimetry system known as the DischargeKeeper (DK). The technology behind this system was originally developed by Photrack (www.photrack.ch) a Swiss company and has been documented in the academic literature by Peña-Haro et al. (2021a). The system uses the Surface Structure Image Velocimetry (SSIV) approach to determine movement on the water surface (Fujita et al., 2007). This system has reached Technology Readiness Level (TRL) 9 (European Commission, 2014) and has been installed at more than 50 sites to date in channels ranging between 40 cm and 100 m wide. As far as the authors are aware this system represents the only commercially available camera imaging system for determining surface velocities and discharge that has been evaluated in the academic literature and which has had broad uptake by commercial clients. The system is presented by SEBA on their website as having the following characteristics:

- Easy to install and configure.
- Continuous real time processing with the system able to process consecutive videos, for example, every 2 minutes.
- Day and night time measurements.
- Algorithm capable of working under low and high flow conditions and is able to work under conditions where there are few traceable particles or structures on the surface.
- Is capable of use in different types of rivers.
- Has the ability to continuously monitor river stage.
- Can transfer the outputs in digital or analog form.

- May be solar powered.

A summary of the technical specifications of the DischargeKeeper camera and system are given in Appendix D. The package offered by SEBA associated with the DischargeKeeper technology includes initial consultation regarding site selection and optimization and then, if purchased, full on-site installation and implementation of the equipment and software, making this a relatively hands-free option for the client.

4.5. Surface velocity methods II: Use of surface velocity radar (SVR)

4.5.1. Background

Surface Velocity Radar (SVR) represent a second non-contact method for estimating water surface flow velocities. Such radar fall into a number of categories: 1) continuous wave microwave systems (Yamaguchi and Niizato, 1994); 2) monostatic UHF doppler radar (Teague et al., 2003), and; 3) pulsed doppler microwave radar (Plant et al., 2005). Both UHF and microwave doppler radar work on the principle that the system receives scattered return signals from the water surface produced through what is known as Bragg scattering in which the transmitted electromagnetic wave is reflected by a roughened water surface. These returned short waves produce a doppler shift which can be used to determine water surface flow velocity. Bragg scattering is a resonant phenomenon in which the short waves that cause backscatter can be characterized by the Bragg condition (Costa et al., 2006):

$$\lambda_b = \frac{\lambda}{2\sin\theta} \qquad (12)$$

where λ_b = wavelength of the resonant water wave (Bragg wave), λ = the electromagnetic wavelength, and θ = incidence angle.

It is important to note that for this technique to work the flow must have some surface roughness and neither UHF nor microwave will work in the absence of short waves that have a wavelength of about 0.5 m on the flow surface. In the case of UHF at a frequency of 350 MHz, the wavelength ~ 86 cm so λ_b is approximately 0.5 m. SVR are directed at an angle to the water surface, and a small area illuminated (decimetres to a few metres in size) from which the wave returns are sampled. The flow velocity (u) can be determined from:

$$u = \frac{\lambda}{2\cos\theta} f_d \qquad (13)$$

where f_d = doppler frequency shift.

Short surface waves are produced directly by the wind and indirectly by longer waves, by turbulence on the water surface, and by rainfall. The water surface motion is thus complex and a broad doppler spectrum may be generated from which the centre must be identified in order to determine river velocity. Note that a possible source of error in this system is encountered if wind adds to the surface wave velocity although this effect is generally small and can be corrected for if the wind vector is measured in conjunction with the SVR measurements (Alimenti et al., 2020). It was report by Tamari et al. (2014) that adequate measurements could be obtained using SVR where the incidence angle was less than 50 degrees, while Lee and Julien (2006) reported optimal results for an incidence angle of 30 degrees. Further, it was found by Son et al. (2023) that directing SVR in an upstream direction produced less error in velocity estimates, as compared with placement looking downstream, when measurements were validated using velocities obtained from an acoustic doppler velocimetry probe.

SVR are relatively easy to install and use as compared with LSPIV and are not affected by light intensity (although recently the use of infra-red light in LSPIV has overcome this limitation). Both LSPIV and SVR are limited though by heavy rain and where poor surface textures are encountered, especially under very low flow conditions.

4.5.2. Radar types

There are important differences to be considered in the manner of deployment and type of data obtained from different SVR systems which are outlined below:

1) Continuous microwave systems represent the simplest and least expensive method for monitoring river surface velocity. Such systems, for example the RiverScat (which operates at 24 GHz (K band)) developed by the University of Washington (Costa et al., 2006) use a single antenna mounted vertically above the water surface on a structure or cableway and sample a small area of the flow surface below. This therefore effectively gives a point measurement of surface velocity in the channel cross-section. Therefore, as a cross-section surface velocity profile of a river is required in order to obtain mean velocities in a series of bins from which total discharge can be determined, multiple radar units are required to accomplish this, set across the river cross-section, or the radar needs to be towed into a number of predetermine sampling points across the river on a cableway. Also, in low-turbulence rivers, continuous wave microwave sensors will not yield a measurement unless rain is falling or wind blowing. This problem can be reduced by operating the radar closer to the water surface. Continuous microwave radar systems have to be placed in line with the channel flow and above the water surface. Researchers have mounted them on bridges or fixed platforms (Kim et al., 2015), along taglines (Costa et al., 2006), aboard unmanned aerial vehicles (Fulton et al., 2020) and on hand-held mobile tripods (Welber et al., 2016).

2) Pulsed doppler microwave radar can sample velocity across the entire river cross-section in a number of predefined bins whose locations are determined by a time gate and whose size increase with distance from the antenna unit. Such as system, the RiverRad (which operates at 9.36 GHz), developed by the University of Washington, operates using a pair of antennae mounted on either side of the river, facing each other at an angle to the main flow direction. The range achievable with the RiverRad system is 480 m. The optimal location of such radar system is in a straight channel with steady, uniform flow and limited variation in bed roughness and river slope (Costa et al., 2006). Uncertainties associated with variation is stage when using such systems have been found to be negligible.

3) UHF radar, such as RiverSonde, developed by CODAR Ocean Sensors Ltd. (Teague et al., 2003) were originally developed for measuring ocean surface currents but have been adapted for use in rivers by modifying them to operate at a higher frequency consistent with shorter Bragg wavelengths found in open channel flow. These radars make measurements of the doppler frequency, the distance or range to the scattering patch, and the direction of arrival of radar echoes. From this information, and assuming flow is predominantly unidirectional, the total surface flow velocity across the channel can be estimated as per pulsed doppler radar systems. These systems use a monostatic approach with both transmitting and receiving antenna mounted on the same riverbank. For example, RiverSonde which operates at 350 MHz uses three antennae set at one half of the radar wavelength apart with the outer two antenna set at

30 degrees from the direction of the centre antenna. The maximum range of this system is 140 m.

In terms of operational use, the main limitation of continuous radar systems is the fact that they have to be moved across the river in order to sample surface velocity in a series of bins, while issues associated with UHF and pulsed radar include the fact that they can struggle to sample velocities close to the river's edge, where interference from the riverbank can disrupt or block the signal. UHF and pulsed radar systems also involve more hardware and require greater care in terms of sitting and configuring when being installed as compared with continuous radar systems.

4.5.3. SVR Application

Costa et al. (2006) tested the three different types of SVR described above and found very good agreement amongst all three in terms of surface velocities measured at the same location (the continuous radar type was mounted on a cableway and drawn across the river to a number of sample points in order to obtain the cross-section velocity profile). These surface velocity profiles were then converted to mean values using a coefficient obtained through a simple law-of-the-wall type assumption. Discharge was then determined by combining these mean velocities with the channel geometry which was determined using Ground Penetrating Radar (GPR) that was drawn across the river on a cableway. Discharges determined in this way compared very favourably with those obtained by a nearby rating curve, lying within 1 – 3 % of the rating curve values for all three radar systems. The assumption of a law-of-the-wall velocity distribution was applicable to the channels in question, having as they did, regular cross-sections and relatively low roughness heights. Son et al. (2023) examined the impact of antenna tilt and yaw angle upon surface velocity estimated using a portable commercially available continuous microwave system but did not make an attempt to determine depth-averaged velocities, and thence discharge, from their measurements. Similarly, Hong et al. (2016) used a continuous microwave system mounted on a bridge to measure surface velocities, but rather than determining a depth averaged value from these, used the surface velocities as index values that were then related to mean channel velocities to give discharges by both the index-velocity and velocity-area methods. This approach was used to demonstrate the use of surface velocity radar as a substitute for H-ADCP, which is commonly used in practice when applying the index-velocity method, but which has the disadvantage of being in contact with the flow and can therefore be damaged by floating debris. Lee et al. (2002) used an X-band pulsed radar to measure the velocity distribution across a river section during a typhoon on a river in Taiwan and compared the derived results with discharge from a nearby rating curve. The novelty of their approach was that both depth averaged velocity and flow depth (and consequently channel cross-sectional area) were determined from the surface velocity distribution measured over the entire channel cross-section using the pulsed radar system, in combination with measured water surface slope and a bed roughness estimate. Comparison with nearby rating curve-based discharges gave a strong correlation, and also identified hysteresis in the flood discharge associated with the typhoon event which could not be determined from the simple rating curve relationship. Fulton et al. (2020) tested the use of a continuous microwave doppler radar borne on a small UAV to determine river discharge, the intent being to show its application to hard-to-access river environments. They used a different approach to determine depth averaged velocity using an algorithm based upon the Principle Of Maximum Entropy (POME) (Chiu, 1987). The authors conclude by stating that UAV borne radar represents a useful alternative to the use of static radar when sites are hard to access but cautioned that surface velocities can be impacted by prop-wash from the UAV rotors and by large-scale secondary flow and eddying, especially close to structures that disturb the surface wave pattern which is relied upon to detect flow velocities. The combination of UAV-borne continuous microwave radar measurement to obtain surface velocity and the use of the POME principle were also employed by to determine discharge in two rivers in Italy by Alimenti et al. (2020). In this work the 2D Entropy-based Velocity Model (EVM) developed by Moramarco and Singh Vijay (2010) from Chiu's (1987) original work was applied to determined mean velocity. Discharges calculated using this approach compared favourably with those obtained via a rating curve for one site but were 18 % different at another although the authors note that the latter measurements were taken during low flows where secondary currents may have affected both the radar measurement of surface velocities and the computation of the depth averaged value.

4.5.4. Limitations of SVR

Australian Government Bureau of Meteorology (2020) identified the following limitations associated with the use of commercially available SVR systems:

- A lack of strong and consistent surface water movement will impair the generation of a doppler shift. This is particularly a problem in slow moving deep streams.
- Some manufacturers define a minimum of 3 mm water surface disturbance for good SVR signal definition to be returned.
- Wind impacts, especially in slow rivers, may generate biased SVR measurements.
- As water level rises, so the SVR measurement zone reduces relative to a fixed camera position, and thus a smaller portion of the stream surface is analysed. This can cause accuracy issues, particularly in rivers with a large stage range.
- Inclination of sensors past the manufacturers recommended operation parameters will result in erroneous or no velocity data.

4.5.5. Commercially available surface velocity radar

An online search has revealed that there are a number of continuous surface velocity radar available commercially. However, pulsed doppler and UHF systems do not appear as readily available, based upon an internet search, although such systems are known to exist. The consequence of this is that the products that are readily available for purchase sample a fixed area on a river surface and cannot therefore be used to reveal the cross-channel surface velocity profile automatically. Options for applying continuous radar types to sample the full surface velocity profile across a river include drawing the radar across the flow section on a cableway or mounting multiple radar at fixed points across the channel on the underside of a structure such as a bridge (Costa et al., 2006). One other alternative, not found in the literature, is to have a radar sensor mounted on a horizontally rotatable platform so that it can sample different sections of the flow surface from a fixed point. The drawback of this is that the sampled water-surface footprint will change as the radar angle is adjusted so that the sample area will not be consistent, and this will lead to inconsistency in velocity estimates. In the case of the Roer river, fixed, downward looking, radar could be used in practice at all four selected field sites for sampling velocities of the main channel flow by mounting multiple sensors across the channel under the bridges at each location. This would simply act to measure in-channel flows however and would not tackle the issue of the difficult to measure floodplain flow events. The two box culverts at Site 4 could have a radar sensor mounted above each to sample surface velocity however, in order at least to capture the surface velocities of these flows. If mounted here they would have to be placed on poles looking upstream at each culvert site to avoid being inundated at high flow, because flood flow conditions can indeed fill and possibly overtop the culverts, as shown in Plate 17 (Section 3.5).

The main providers of surface velocity radar, that are available in Europe include OTT (https://www.otthydromet.com/en/), Geolux (https://www.geolux-radars.com/rss2300w), and Viatronics (https://www.viatronics.fi/). The OTT SVR 100 surface velocity radar (https://www.ott.com/products/water-flow-3/ott-svr-100-2406/), which operates in the K band (24 GHz) is claimed to have a velocity acquisition range of 0.08 to 15 ms^{-1} and can be solar powered. This system has some beneficial features including an internal vibration sensor that accounts for such disturbances and an inclination sensor to give the precise tilt angle. A specification sheet for this sensor is given in Appendix E. The Geolux RSS-2-300W radar (www.geolux-radars.com/rss2300w) also operates in the K-band (24,075 GHz) and can measure in the same velocity range as the OTT SVR 100 (see Appendix F). It too has an internal inclination and vibration sensor and can be configured remotely over the internet. Geolux also offer the RSS-2-200WL (https://www.geolux-radars.com/rss2300wl) flow meter which combines the standard K-band radar with a water level sensor and has the capacity to convert the measured surface velocity to a mean velocity and discharge if the user enters alpha coefficient (which they call a K-coefficient) and cross-sectional area geometry data (see Appendix G). This sensor therefore operates in the same manner as the DischargeKeeper by measuring surface velocity and then converting the output to a discharge which makes it a very attractive option. Viatronics offer a number of SVR, one that can be fixed to a structure, the SVR-1 Pro (https://www.viatronics.fi/en/products/security-solutions/basic-model-surface-velocity-radar-hand-held-svr-radar-for-water-flow-measurement/) and two that are designed for handheld use, the SVR-3 pro (https://www.viatronics.fi/en/products/security-solutions/onsite-checkpoint/) and SRV-2 Basic (https://www.viatronics.fi/en/products/security-solutions/surface-velocity-radar-hand-held-svr-radar-for-water-flow-measurement/). A product sheet for the SVR-1 is shown in Appendix H. This unit could be mounted and used as a permanent surface velocity measurement station as per the OTT SVR 100. The other two units are handheld and are designed for spot measurement of water surface velocities. A product information sheet for the SVR-3 is given in Appendix I. Although the primary interest in this report is in continuous monitoring of discharge such hand-help spot devices could be used by field operatives during flood flow conditions to obtain surface velocity estimates from structures such as bridges when conditions are too dangerous to enter the water with a boat or to deploy floating ADCP devices.

4.6. Comparison of surface velocity methods with an ADCP

Australian Government Bureau of Meteorology (2020) offers an excellent set of guidelines for the application of image-based and surface radar velocimetry to discharge measurement. The characteristics of LSPIV as compared with acoustic techniques (ADCP) and Surface Velocity Radar are shown in Table 3.

Table 3. Comparison of selected characteristics of ADCP, Radar and image-based velocimetry for measurement of river flow (from *Australian Government Bureau of Meteorology (2020)).*

Technique or Characteristics	Acoustic	Radar	Image
Measurement type	Profile: along the acoustic beam path (verticals); three-component velocity.	Point: at the intersection of the beam with the free surface; one-component velocity.	Surface: instantaneous vector field at the free surface; two-component velocity.
Flow tracers	Small particles usually naturally suspended in the water column.	Small surface waves created by wind or by flow turbulence at the free surface.	Foams, debris, ice floes, and specular reflections on the free surface deformations (waves, boils, kolks). Added seeding.
Operating constraints	Instrument probe in contact with the flow. The flow assumed horizontally homogeneous.	The ratio between the Incident electromagnetic and water wave wavelengths within specified range. Instrument aligned with the dominant velocity.	Survey of minimum six points within the imaged area. Occasionally, additional seeding and illumination.
Output quality	Good spatial and temporal resolution. Inaccurate for very slow flows.	Limited spatial and temporal resolution. No reverse flows. Inaccurate for very slow flows.	Good spatial and temporal resolution.

Note that LSPIV is a relatively low-cost technology as compared with ADCP and because the components involved are already in the digital domain this facilitates data management and makes its use particularly applicable to real-time system implementation. Both Radar and LSPIV, combined with drone technology, make an attractive alternative to field measurement of velocities in flood flows when data collection is desired to extend stage-discharge relationships, as such conditions pose a hazard to staff operating ADCP from small boats or where, in fact, the field site cannot be accessed by operatives at all.

The main advantages and disadvantages of surface velocity techniques are as follows:

Advantages

- Improved safety for high flow measurement.
- Non-intrusive measurement technique.
- No depth restrictions for velocity analysis.
- Potential for remote application where staff are not required on site during the measurement.
- Suited to high flow and high debris environments.
- Comparable accuracy to current accepted discharge measurement techniques, when applied correctly.
- Provide a visual record of flow events.

Disadvantages

- Surface tracers used to calculate velocity must be advected at the surface velocity.
- Wind can potentially bias surface tracer/disturbance movement.
- The conversion of surface to mean velocities requires site-dependent parameters.
- As a velocity-area method, changes in cross-section need to be accounted for.
- A lack of surface tracers will compromise velocity determination.

4.7. Summary of methods to determine mean velocity from surface-measured velocities

Both image-based velocimetry and surface velocity radar obtain velocities from the water surface when in fact it is depth-averaged velocity that is required to determine discharge. Two techniques have been developed to obtain what is, in effect, a multiplication factor that is applied to measured surface velocity values to convert them to mean values:

1. Use of an alpha value which is based upon: a) direct surface-velocity to mean velocity ratio; b) the log-law (law-of-the-wall), or; c) a power law. In this case a coefficient is applied to each surface velocity in the designated cross section to obtain mean velocities that are used in the velocity-area method for calculating discharge.
2. Principle of Maximum Entropy (POME) probability-based method derived from the work of Chiu (1987). This method uses a single surface velocity value from the channel cross-section at the point where surface flow velocities are at their maximum range.

4.7.1. Alpha coefficient determination

The manner in which alpha values can be determined are outlined in detail by Biggs et al. (2021) and are summarised below.

4.7.1.1. Alpha from site calibration data

The alpha coefficient can simply be defined as the ratio of depth-averaged velocity to surface velocity:

$$\alpha = \frac{\bar{u}}{u_s} \tag{14}$$

where α = alpha coefficient, $\bar{u}$ = depth-averaged velocity, u_s = measured time-averaged surface velocity.

The standard value applied to alpha is 0.85 or 0.86 (Rantz, 1982b) which originates from velocity profiles that follow a 1/6th power law (Smart and Biggs, 2020a). This value is reasonable for rectangular channels which have a relatively large width to depth ratio and where the flow depth to roughness height ratio is also large but in practice there is significant natural variation in α due to variations in channel geometry and flow conditions, etc. The best way to determine an alpha coefficient for a channel is to make field measurements of the vertical velocity profile at the site where the surface velocity is to be sampled by camera or radar so that the ratio, given in equation (14) can be determined empirically. It is preferable to sample the location on a number of different occasions, with the flow at a range of stages from low to high, in order to check whether this velocity ratio is in fact influenced by depth. Alpha values can then be plotted against stage to give a site-specific stage-alpha rating curve. Alpha values for extreme floods can then be determined by extrapolation of this curve. Note that if an ADCP is used to determine the velocity profile, surface velocities will not actually be measured and they will have to be determined through some form of extrapolation of a fit to the recorded velocity data, which may actually introduce bias into the results as the true surface velocities may not simple be a function of the extension of the velocity profile at lower depths due, for example, to factors such a wind shear and secondary currents. However, to avoid the issue of profile extrapolation that is required when using an ACDP, an electromagnetic or propeller current meter could be used to measure near surface velocities directly.

A second method for determining a site average alpha value is to use the ratio of a reference discharge (Q_{Ref}) obtained from velocity measurements using an ADCP or a current meter and measured cross-sectional area, to that calculated from the surface velocimetry (Q_s) using an initial alpha value of 1 (Biggs et al., 2021):

$$\alpha = \frac{Q_{Ref}}{Q_{s,\alpha=1}} \tag{15}$$

Q_{Ref} could also be obtained through other means however, such as from a stage-discharge rating curve if the surface velocity measurement site is located close to a gauging station.

4.7.1.2. Alpha from log law profiles

For logarithmic velocity profiles alpha can be defined as (Smart and Biggs, 2020a):

$$\alpha = \frac{H}{H - z_0} - \left[\ln\left(\frac{H}{z_0}\right)\right]^{-1} \tag{16}$$

where H = flow depth and z_0 = roughness height from the log law velocity profile.

Under the assumption that $H >> z_0$ and $u_* = \sqrt{gHS}$, where u_* = shear velocity, g = acceleration due to gravity, and S = energy slope, this equation simplifies to:

$$\alpha = 1 - \frac{\sqrt{gHS}}{\kappa u_s} \tag{17}$$

where κ = von Karman constant (~ 0.42).

To estimate alpha at a gauging site, parameters that are averaged in both space and time are needed. First cross-sectional mean depth can be determined by H = A / b (where A = flow cross-sectional area and b = channel top width). Second u_s must be determined from the surface velocity measurement technique used. If this is a standard surface velocity radar, then a single surface velocity value is given for any reading which is then used as the value of u_s. If surface-imagery is used however, then there will be a range of velocity values generated across the image from which an average must be taken. A simple average is not representative however as it will not account for changes in channel cross-sectional area (i.e., more flow in the centre of the channel where it is deeper and faster). To account for this difference, it is recommended to compute an area weighted cross-section averaged surface velocity (Smart and Biggs, 2020a):

$$u_s = \frac{1}{A}\sum_{n=1}^{N} u_{s,n} \cdot dA_n \quad (18)$$

where $u_{s,n}$ = time averaged surface velocity at section n, and dA_n = area of section n.

This equation can be further simplified for convenience, since the area weighted surface velocity summation $\sum_{n=1}^{N} u_{s,n} \cdot dA_n$ is simply discharge with α = 1 ($Q_{s,\alpha=1}$), i.e., the discharge calculated from the surface velocity using an alpha coefficient of 1):

$$Q_{s,\alpha=1} = \sum_{n=1}^{N} 1 \cdot u_{s,n} \cdot dA_n \quad (19)$$

Thus, u_s becomes:

$$u_s = \frac{Q_{s,\alpha=1}}{A} \quad (20)$$

And the equation for alpha simplifies to:

$$\alpha = 1 - \frac{A\sqrt{gHS}}{\kappa Q_{s,\alpha=1}} \quad (21)$$

For cases where flow depth is not significantly greater than the boundary roughness height more complex formulations of equation (17) may be required, and these are outlined in Smart and Biggs (2020b). A measure of the energy slope is also required to solve for alpha in (17) or (21) and this should be obtained from field measurements of water surface slope or, if water surface slope cannot be obtained, by simply assuming that the local channel bedslope, which could be obtained from digital terrain model data, is a reasonable approximation for the energy slope (an assumption of uniform flow).

This approach provides a practical means to determine the alpha coefficient where no velocity profile data is available but where flow depth and cross-sectional area can be obtained from field measurements and slope can be obtained from digital terrain model data. The approach does have limitations though in that it assumes that $u_* = \sqrt{gHS}$ which may not be the case for narrow cross-sections and assumes that the log profile extends to the water's surface which may in fact not be the case either due to surface dip caused by factors such as the wind and secondary currents.

4.7.1.3. Alpha from power law profiles

For velocity profiles that can be parameterised by a power law, alpha can be estimated from the power law exponent (M) as follows, according to the derivation of Smart and Biggs (2020a):

$$\alpha = \frac{1}{M+1} \quad (22)$$

The practical method for determining the power law exponent, M, is discussed by Biggs et al. (2021) in the context of processing ADCP data using commercially available software. The approach can be followed, however, using any velocity profile data that has been gathered in the field. The data should be plotted with normalised velocity on the x-axis: ($u_z/\bar{u}$), where u_z = velocity reading taken at height z from the channel bed and $\bar{u}$ = depth-averaged velocity, and normalised depth on the y-axis: (z/H). A power function should then be fitted to the data, and the exponent from this equation used as the value of M in equation (22). This approach is useful when field data can readily be obtained from, for example, ADCP profiles, but the fitting of a power function to the data has the same limitation as the log-law approach in that it assumes the velocity data will fit a well-defined theoretical function.

4.7.1.4. Alpha estimates without input data

The default alpha value that can be applied if no measured data is available is 0.85 − 0.86, as defined by Rantz (1982b), but as mentioned before this really only applies to relatively wide channels in which boundary roughness is not a significant proportion of flow depth. A slight improvement on this default can be based upon visual assessment of site characteristics. For example, Turnipseed and Sauer (2010) recommend selecting alpha values of between 0.84 and 0.90, where the lower values are assigned to irregular streambeds and higher values used for smooth beds such as concrete-lined channels. Hauet et al. (2018) examined empirical data from 3611 gauging's over 176 sites and found that alpha generally increased with flow depth but could not find a clear relationship between alpha and bed roughness or relative roughness. Biggs et al. (2021) present the data shown in Table 4 based upon information obtained from Le Coz et al. (2011) and Fujita (2018), where alpha is determined as a function of site roughness and the expected power law profile exponent (M).

Table 4. Estimates of α based upon site roughness and the expected power law profile exponent (M) (modified from Smart et al. (2021)).

	normal	smooth	rough	very rough	extreme cases
M	0.143 − 0.167	0.1	0.25	0.333 − 0.5	
α	0.86 − 0.87	0.91	0.8	0.67 − 0.75	0.6 − 1.2

4.7.2. Principle Of Maximum Entropy (POME) probability based method

The Principle Of Maximum Entropy (POME) is linked to information theory (Shannon, 1948) and was first applied to open channels by Chiu (1987) and Chiu et al. (1995) who predicted the two-dimensional velocity distribution in a channel as a function of the maximum velocity in the flow cross-section. The advantage of this method is that it provides a mathematical basis for translating a single surface velocity to a mean value and can resolve non-standard velocity profiles (a log-law distribution) in cases where the maximum velocity occurs below the water surface. Under this approach the location of maximum surface velocity must first be identified across the channel cross-section, this being define as the y-axis location as, according to the theory, this point contains the most information content (velocity = 0 to velocity = maximum). This surface velocity is then translated to a mean velocity using the following equations, presented by Fulton et al. (2020). First, the velocity distribution along the y-axis in probability space is represented by:

$$u = \frac{u_{max}}{M} \ln\left[1 + \left(e^{M} - 1\right)F(u)\right] \tag{23}$$

where u = velocity as a function of depth at the y-axis, u_{max} = maximum velocity at the y-axis, M = probability distribution used to describe the velocity distribution and $F(u) = \int_{o}^{u} f(u)du$ represents the cumulative distribution function, or the probability of a randomly sampled point velocity less than or equal to u. For cross-sections where u_{max} is known to occur below the water surface, the velocity distribution can be characterized by:

$$u = \frac{u_{max}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{y}{D-h} \exp\left(1 - \frac{y}{D-h}\right)\right] \tag{24}$$

where D = total distance from the channel bottom to the water surface at the y-axis, y = incremental distance from the channel bottom to the water surface, and h = vertical distance from the water surface to u_{max}. In those cases where u_{max} occurs at the water surface, the velocity distribution is defined by:

$$u = \frac{u_{max}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{y}{D} \exp\left(1 - \frac{y}{D}\right)\right] \tag{25}$$

A curvilinear coordinate system (Chiu et al., 1986) is used to translate the velocity distribution from probability space to physical space and is used to describe the variables h, D and y. The probability distribution function *F*(u) is invariant with time and water level and hence M and h/D are constant for a given channel cross-section (Chiu, 1995; Moramarco and Dingman, 2017). Equations (24) and (25) are solved using a Gauss-Newton nonlinear least squares method. In order to determine M, the parameter ϕ is also required and can be computed in two ways. The first relies on velocity and depth pairs being obtained in the field. Values for u_{max}, M(ϕ) and h/D are then computed using a nonlinear estimator. The second method, used by Fulton et al. (2020) relies on historical pairs of mean and maximum velocity being obtained in the field along with the function:

$$\phi = \frac{u_{mean}}{u_{max}} = \frac{e^M}{(e^M - 1)} - \frac{1}{M} \tag{26}$$

where $\phi = u_{mean}/u_{max}$ = function of M, and u_{mean} = mean flow velocity.

Discharge is then computed using u_{max}, along with the parameter ϕ and the channel cross-sectional area:

$$Q = \phi \cdot u_{max} \cdot A \tag{27}$$

where A = cross-sectional flow area.

In practice Fulton et al. (2020) derived M by using nonlinear curve fitting of the vertical velocity distribution in the channel based upon data obtained from ADCP measurements prior to collection of surface velocities using UAV-borne radar. They applied equation (25) as the vertical velocity distribution was found to conform to the log-law principle with no near-surface velocity dip. The authors quoted values of M range from 1.12 to 4.06 over the five channels studied. Values of ϕ, computed using equation (26), were quoted as ranging from 0.591 to 0.771. Fulton et al. (2020) note that efforts should be made to establish ϕ, M and h/D from easily measurable metrics such as channel top width and slope to enable their establishment a priori without having to resort to stream gauging.

5. Lower Roer discharge measurement options

5.1. Introduction

A series of eight discharge measurement options, spread amongst the four potential gauging sites identified in Chapter 3, are presented here that enable extending discharge measurement capability on the lower Roer. These options vary in cost, robustness, uncertainty and discharge / stage measurement range and demonstrate what can be done with the technologies and techniques explored in Chapter 4.

A key factor involved in implementation of any new measurement system, identified by Waterschap Limburg staff, is the need to gain accurate, continuous, discharge readings from a distance as far upstream of Roermond as possible in order to give reasonable lead-in times for flood risk mitigation measures to be implemented in the town and surrounding area. Given this requirement, it has become evident that operational staff would like to obtain improved discharge data from the Stah gauging station which provides a lead-in time between flood detection and its arrival in Roermond of approximately 8 to 15 hours. In the course of undertaking field investigations on the lower Roer, between the confluence of the river with the Meuse upstream as far as the Stah gauge itself, four potential discharge measurement sites were identified, one being at the Stah gauge itself, the others however, lying downstream of this, much closer to Roermond. When considering a site that provides optimal conditions for capturing discharges up to the specified maximum of 500 m^3s^{-1}, the Stah gauging site (Site 4, refer to Section 3.5) is in fact not the most suitable for measuring out-of-channel flows. This is because the modelled inundation extent for a 500 m^3s^{-1} flood event is predicted to spread over a distance of approximately 1.6 km across the Roer floodplain (see Figure 15a) at this location. The ground transect along the right-hand floodplain, drawn in Figure 15b was traced along the path of high ground formed by a road leading from the bridge at the Stah gauging site north to the village of Ophoven and while this road embankment acts as a structure that holds back flow at some locations, the road is shown to overtop along considerable lengths. Floodplain flows are also predicted to occur on the southern floodplain, south of the village of Kempen. The location where flows will likely be most contained (laterally) during flood events is in fact at Site 1 (51.18545143°N, 5.99101103°E) (refer to Section 3.2) and this location therefore provides the opportunity to most accurately measure the range of flows specified in the project remit. This finding therefore poses a dilemma as the optimal discharge measure site with regards to capturing flood flows is close to Roermond town centre and is therefore least suitable with regards to providing early warning. However, the original scope of research requested by Waterschap Limburg did not specify that the Stah gauge location was the only target site to consider, this fact only became apparent later after consultation with staff. Therefore, we present four sets of options here. First, we shall outline four options for discharge measurement at the Stah gauging site as this location is optimal in terms of flood-risk hazard warning. Second, we shall present discharge measurement options at Site 1 as this location is optimal in terms of flow confinement and therefore the potential for measuring the greatest range of flows. Third, we shall outline an option for flow measurement at Site 3 as this represents a compromise location, which is both reasonable to equip for floodplain flow measurement and lies 8 km from where the Roer enters Roermond city limits. Finally, for completeness, we outline an option for in-channel flow measurement at Site 2 as this location is easy to access and relatively easy to equip although measurement of floodplain flows is not considered here as the lateral extent of such flows may spread over 1 km across the floodplain making out-of-bank flow detection both complex and expensive.

5.2. Options for discharge measurement at the Stah gauging station (51.09770467°N, 6.10475772°E)

5.2.1. Option 1: Extension of the Stah gauge rating curve using field measurements and numerical model data

The most reliable means to obtain accurate measurement of discharge at the Stah gauging station is considered to be extension of the rating curve using field measured discharge data obtained during out-of-bank flows. Currently the rating curve for the Stah gauge is considered reliable up to a stage of 135 m^3s^{-1}, which is approximately at the peak of in channel flows. Field measured data of discharge, combined with stage during out-of-bank flows should be used to add further points to the present rating curve for a range of flood flows. If this option is undertaken application of the 2D model for the Roer (operated by Wasserverband Eifel-Rur (WVER)), that includes the Stah gauge site should also be sought to derive stage-discharge points for a range of flood flow conditions at the gauge. The campaign of flood flow field measurements can then be used to calibrate the model locally so that the semi-theoretical rating curve points can be validated and adjusted if necessary.

5.2.1.1. Option 1: Actions

1) Within the management structure of Waterschap Limburg develop a responsive field team that is capable of accessing the Stah gauge site as and when required to measure floodplain flows. For floodplain discharge measurement manned boat access is not safe and the use of an ADCP borne on a towable or mortorised platform is recommended. Such devices include the StreamPro ADCP produced by Teledyne Marine (https://www.teledynemarine.com/brands/rdi/streampro). The StreamPro has been identified as a suitable tool because it is claimed to have a minimum operating depth for data collection of 10 cm, the minimum that the authors could find from manufacturer information on boat borne ADCP. A data sheet for the StreamPro is shown in Appendix J. The more expensive Teledyne Marine RiverPro 1200 (https://www.teledynemarine.com/brands/rdi/riverpro-adcp) is also an option as this can be mounted on a trimaran boat configuration which would be more stable in rough floodplain-flows and also has an internal GPS, which unfortunately the StreamPro does not have. The minimum operating depth for the RiverPro ADCP is greater though (minimum quoted in the specification documentation is 20 cm) so it could not be used in as shallow surface flows as the StreamPro. A data sheet for the RiverPro 1200 ADCP and associated boat (https://www.teledynemarine.com/en-us/products/Pages/high-speed-riverboat.aspx) is shown in Appendix K. There is also the option of using a handheld surface velocity radar to obtain spot values of water surface velocities from locations where it is safe to stand above the flow, such as on the road bridge at the Stah gauge, or at the two bypass culverts located approximately 100 m beyond the northern end of the bridge. One such device is the Viatronics SVR-3 Pro (https://www.viatronics.fi/en/products/security-solutions/onsite-checkpoint/). Refer to Appendix G for the specification information sheet for this product. The team that is designated to undertaken field measurements should be briefed on the reason for making such measurements and the data required and have a stringent safety protocol in place. Floodplain discharge data can then be used, in conjunction with associated stage data from the Stah gauge to derive further data points for the rating relationship above the stage to which they are currently applicable.

2) Model an extension of the Stah rating curve. Waterschap Limburg currently have a 1-D SOBEK model of the lower Roer but the upstream boundary of this lies at the Stah gauge itself meaning that it is not suitable for modeling flood flow stage-discharge data at this location. However,

communication with Waterschap Limburg staff has revealed that Wasserverband Eifel-Rur (WVER) who operate in the upstream catchment have a 2D numerical model of the Roer which runs past the Stah gauge, downstream as far as Vlodrop. There is therefore the possibility, if cooperation from this water authority can be achieved, of using this model to derive stage-discharge points to add to the Stah rating curve data, as long as any uncertainties associated with the downstream boundary conditions of this model do not extend as far upstream as the Stah gauge (such as the use of a non-calibrated normal depth). This exercise would involve calibrating the model locally, based upon the stage-discharge relationship given in the Waterschap Limburg rating curve, and then performing flood flow simulations to add stage values to the rating curve for simulated flood discharge events. The main benefits of doing so are that fact that this method is both cheap and quick to implement. The modelled rating curve results can then be verified using measured discharge data gathered from flood events obtained through the targeted field campaign. More details on model extension of rating curves are given in Section 4.2.4 and the process described there should be followed to obtain the model rating curve values along with a measure of uncertainty.

5.2.1.2. Option 1: Site considerations

No fixed infrastructure would be required under this option. However, for the field measurement campaign there must be, on constant standby, the means to access the site by vehicle and the means to measure floodplain discharges safety. The ideal hardware solution would be a towable or remotely powered ADCP such as the StreamPro. Access to the Stah gauge site can be undertaken by road from the north or south during high flow conditions. It is likely that the bridge at the Stah gauge will always remain above the flood flow level and can therefore be traversed. The road leading north from the bridge is likely to not become inundated in all but the highest flows and can therefore, theoretically, be traversed to access locations where floodplain flows can be measured such as the two box culverts the lie approximately 100 m north of the right-hand-end of the bridge. It is important that field crews understand that, where discharge measurements are taken during flood flows, the ADCP survey transect should lie at 90 degrees to the primary flow path across the flood plain and that the same transect location should be used each time measurements are made during flood events.

5.2.1.3. Option 1: Discharge measurement range

The current effective range of the Q-H rating curve at Stah is from 29.95 m NAP where the discharge is 0 m^3s^{-1} to approximately 32.5 m NAP where the discharge is 135 m^3s^{-1}. The channel cross-section at the Stah gauge is shown in Figure 26, indicating the water surface elevation for the current maximum reliable gauge reading and the water surface elevation predicted by modeling a 500 m^3s^{-1} flow. Note that the channel bathymetry is truncated in this plot as elevation data is not available in the channel itself below approximately 31 m NAP. Modeling results show that the elevation of a 500 m^3s^{-1} flood (see Figure 26) lies between 32.9 m (at the channel left bank) and 32.8 m (at the channel right bank). For the purpose of using the 2D model to extend the rating curve at this site a number of simulations should therefore be run for discharges ranging between 135 m^3s^{-1} and 500 m^3s^{-1} to generate new, higher, Q-H rating points, the stages of which ought to lie between 32.5 m NAP and 32.8 m – 32.9 m NAP respectively. The maximum measurement range that could be achieved under this option is dependent therefore upon the flood flows which can be measured by field teams that lie above 32.5 NAP on the floodplain on either side of the main channel at the Stah gauge which can be used to validate the new modelled Q-H rating values.

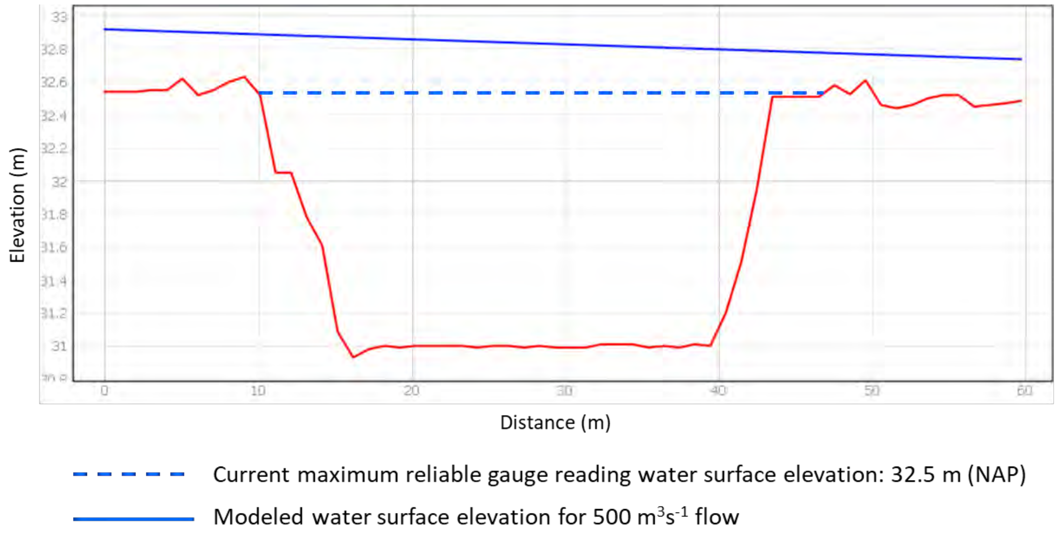


Figure 26. Channel cross-section at the Stah gauging station extracted from 0.5 m DEM data showing the elevation of the current maximum reliable gauge reading and the modelled elevation of a 500 m^3s^{-1} flood. Note that the channel bathymetry is truncated below 31 m NAP.

5.2.1.4. Option 1: Cost

Costs involved in this Option include the budget required to organise and train a team of field staff who are on call 24 hours per day to perform reactive measurement at the Stah gauging site. It is recommended that for safety reasons, three team members should be present during any field survey. The cost associated with the staffing of this operation cannot readily be quantified without closer consultation with Waterschap Limburg and it is left to this organization to draw up a cost plan for the setting up and management of this activity. Costing will have to include the following:

1) Man-hours for field measurement and data processing.
2) Vehicle use and fuel costs to drive to the site.
3) Safety equipment including life jackets, waterproof mobile phone, possible hand-held VHF radios for local communication.

Man-hours will also be required to combine new discharge measurements with stage information and compare this with model results for the purpose of verification / calibration of new high-flow rating curve data points.

Cost associated with equipment can be quantified to a degree. For example, if Waterschap Limburg do not currently have a towable ADCP, the cost of the Teledyne Instruments StreamPro model is €18,295.00 (excluding VAT and 15% shipping cost for import by Teledyne from the U.S., plus local shipping) The RiverPro 1200 ADCP costs €28,230.00, while the High Speed Boat required to carry this costs €5,676.00 (all costs exclude VAT and 15% shipping cost from the U.S. plus local shipping). This quote was obtained from Aqua Vision (www.aquavision.nl) on 6th October 2023, and is based upon a Dollar/Euro exchange rate of USD/EUR (1/0.95). Also note that the StreamPro can be rented from Aqua Vision for €91.00 per day and the High Speed River Boat with RiverPro 1200 ADCP mounted aboard for €250.00 per day plus a €250.00 handling fee (quote also obtained 6th October 2023). The cost of the Viatronics SVR-3 Pro handheld surface velocity radar is €4,495.00 and an add-on GPS module for this costs €495.00 (both excluding VAT and shipping cost). This quote was obtained from Viatronics (www.Viatronics.fi) on 6th October 2023.

Costs associated with accessing the numerical model and its operation cannot be quantified directly but factors to consider are costings for communication and meeting with the WVER, time taken to run and process model results, and time required to modify the rating curve itself.

5.2.1.5. Option 1: Limitations

With regards to a field campaign the main limitations are associated with risk to the field crew performing flood flow discharge measurement. A stringent risk assessment should therefore be put in place to ensure that unsafe practices do not occur. Similarly, a protocol would have to be drawn up regarding the data collection practices. Another key limitation is that associated with access to the site as, for example, a field team who went to the Stah gauge during the July 2021 flood were turned back by German authorities close to the Stah gauge. This limitation may not be easily overcome as it would involve active collaboration with German emergency service in advance to negotiate safe access to the Stah gauge site during flood flow conditions. There are also a number of issues specific to the use of ADCP for flow measurement that have to be taken into account:

1. Boat-mounted ADCP's require a minimum submergence of approximately 0.1 m to ensure that the sensor head remains below the water when a boat tilts due to wind or wave action (Muste and Hoitink, 2017);
2. ADCP's in general cannot measure the lower 6% of the water column (Muste and Hoitink, 2017);
3. Bottom irregularities on the floodplain can cause complexities (Vermeulen et al., 2014), and;
4. A high sediment concentration in the flow may preclude ADCP readings from being taken at all.

Limitations associated with the modeling exercise are much fewer, but collaboration would be required with WVER who own the 2D model.

5.2.1.6. Option 1: Uncertainty estimate

Uncertainties in this Option include those associated with collection of flood flow discharge measurements using ADCP as mentioned in the limitations above. The StreamPro is quoted as having an accuracy of ±1% of the water velocity relative to the ADCP. Rating curves typically have a 4 % - 12 % error as compared with in situ measurements (Horner et al., 2018) and Rantz (1982b) states that if a stage-discharge curve is developed correctly the error between rating curve discharges and those determined in the field should be no more that 5 %.

Uncertainties associated with the initial model estimates of stage-discharge points are largely bound up in the quality of roughness coefficient estimation for flows that are beyond the initial calibrated operating range of the model, i.e., floodplain roughness coefficients. Inherent computation capabilities in the model itself including the manner of solution will also add to this uncertainty to a greater or lesser degree. This uncertainty must initially be quantified using error estimates around the stage discharge relationship. The method for doing this is presented in Section 4.2.4. Initial uncertainty in model estimates is estimated to lie in the range 10 % to 20 % deviation in terms of the difference between predicted and actual (measured) discharges. Ultimately the uncertainty in the modeled stage discharge relationship can only be reduced through the introduction of field-measured flood-flow calibration data, undertaken through the on ongoing site measurement campaign.

There is also the potential for uncertainty associated with the current rating curve relationship for the Stah gauge because of future morphological instability in the channel, and the quality of the relationship should be checked periodically using discharge data measured using ADCP and compared against the rating curve, as has been undertaken in the past. Note that it is recommended by Rantz (1982b) that a rating relationship should be adjusted if field measured discharges vary by more than 5 % from those predicted by the rating curve.

5.2.1.7. Option 1: Robustness of approach

Overall, this approach is practically robust and there are no risks regarding the purchase of new technology that might fail or not perform as expected. It represents a low-risk strategy which could be implemented easily by Waterschap Limburg. The main weakness lies in the fact that reliance is placed upon collection of flow data during flood events to calibrate the extended rating curve that has initially been extended using numerical model simulations. This means that the time for completion of this option, to a level where it is satisfactory for robust extended gauging purposes, could be many years and depends entirely on future hydrological conditions.

5.2.2. Option 2: Use of camera-based image velocimetry to capture floodplain flows passing through box culverts located near the Stah gauging station

This option would involve the permanent installation of camera-based surface velocimetry monitoring equipment at the two box culverts which lie approximately 100 m north of the end of the road bridge located at the Stah gauging site (51.09902638°N, 6.10389827°E). The location of these two culverts is shown in Figure 27. When considering methods to capture floodplain flows at the Stah gauge for the target maximum discharge of 500 m^3s^{-1} it is evident that the full lateral extent that would have to be monitored is significant on both the left and right-hand floodplain (refer to Section 3.5 and Figure 15). It is considered that the cost and effort required to permanently, actively monitor the full distance involved is prohibitive and likely to involve unacceptable levels of error when it comes to the uncertainties associated with discharge measurement at each section of floodplain where flood flows may occur. However, there is one location at this site where flood plain flows are known to coalesce and to pass through controlled, measurable cross-sections, those being the site of two box culverts located just north of the Stah gauge at 51.09902638°N, 6.10389827°E. Attempts have been made to measure flow through these culverts during the July 2021 flood event (refer to Plate 17).

In theory discharge through a culvert can be determined by measuring flow stage at a number of key points along the culvert length. The physical features associated with culvert flow are shown in Figure 27. There are five locations of importance along a culvert section: a) the approach channel cross-section, at a distance equivalent to one opening width upstream from the entrance (Section 1); b) the culvert entrance (Section 2); c) the culvert barrel; d) the culvert outlet (Section 3), and e) the tailwater (Section 4).

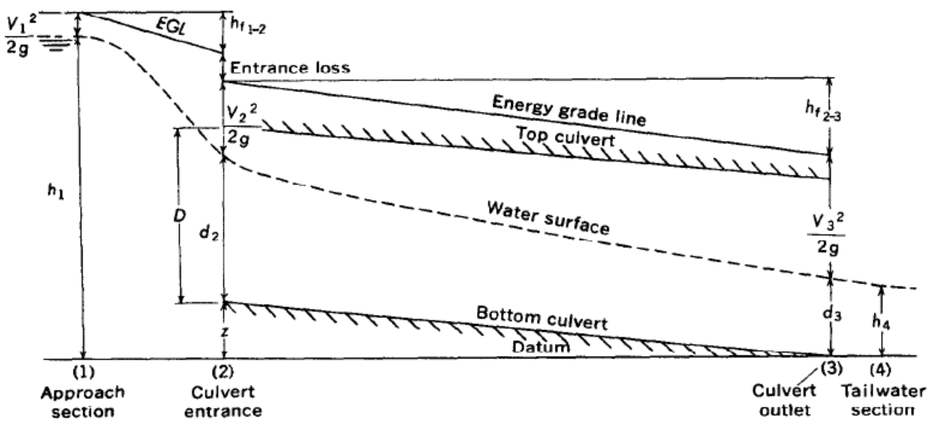


Figure 27. *Representation of flow properties and through a culvert section.*

Culverts are classified according to which of their ends controls the discharge capacity: inlet control or outlet control. If water can flow through and out of the culvert faster than it can enter, the culvert is under inlet control. If water can flow into the culvert faster than it can flow through and out, the culvert is under outlet control. Culverts under inlet control will always flow partially full. Culverts under outlet control can flow either partially full or full. A simplified method for defining culvert flow classifies it into six different types on the basis of the type of control, the steepness of the barrel, the relative tailwater and headwater heights, and in some cases, the relationship between critical depth and culvert size. These parameters are quantified through the use of the ratios given in Table 5 and the flow types are defined schematically in Figure 28.

Table 5. Characteristics of types of culvert flow (modified from Bodhaine, 1968).

Flow type	*Barrel flow*	*Location of terminal section*	*Kind of control*	*Culvert slope*	$h_1 - z/D$	h_4/h_c	h_4/D
I	Partly full	Inlet	Critical depth	Steep	< 1.5	< 1.0	≤ 1.0
II	Partly full	Outlet	Critical depth	Mild	< 1.5	< 1.0	≤ 1.0
III	Partly full	Outlet	Backwater	Mild	< 1.5	> 1.0	≤ 1.0
IV	Full	Outlet	Backwater	Any	> 1.0	–	> 1.0
V	Partly full	Inlet	Entrance geometry	Any	≥ 1.5	–	≤ 1.0
VI	Full	Outlet	Entrance and barrel geometry	Any	≥ 1.5	–	≤ 1.0

Note: D = maximum vertical height of the barrel and diameter of circular culverts, z is defined in Figure 27 and h_c = critical flow depth.

The discharge through a culvert is determined by application of the continuity equation and the energy equation between Section 1 and a section within the culvert barrel. The location of the downstream section depends on the type of flow condition experienced in the culvert and there are consequently six different equations for determining discharge through a culvert, which are shown in Figure 28. In order to apply these equations for continuous monitoring of discharge through the culverts at the Stah gauge the flow regimes that exist through the culvert would have to first be modeled to determine where monitoring stage gauges should be placed along the culvert profile in order to solve the appropriate discharge equation. It is likely that flow at these culverts will fall into a number of different regimes depending on local conditions as they may be affected by backwater from downstream (especially because the culverts are partially sunken below ground level at the downstream end). Unfortunately, as flow occurs very rarely through these culverts the setup of permanent stage gauge monitoring equipment would have to be based upon the results of detailed hydraulic modeling alone which would introduce a very high degree of uncertainty in prediction initially before actual field data could be used to verify the range of flow conditions present. Consequently, the use of gauges to continuously measure flow at these culverts has been discarded as an option here in favour of methods whereby flow velocity and cross-section area are measured directly.

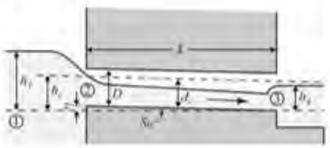
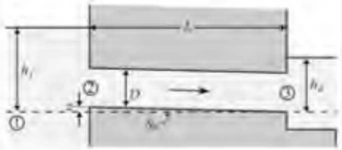
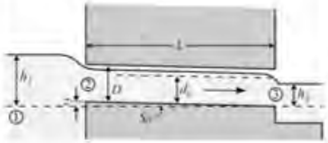
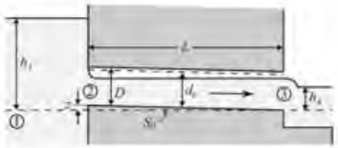
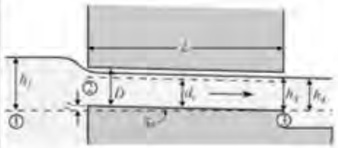
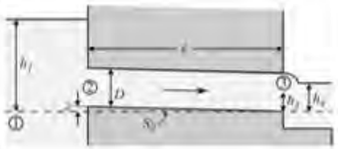
Type	Example	Equation	Type	Example	Equation
1 Critical depth at inlet $\frac{h_1 - z}{D} < 1.5$ $\frac{h_4}{h_c} < 1.0$ $S_0 > S_c$		$Q = C_d A_c \sqrt{2g\left(h_1 - z + \frac{\alpha v_1^2}{2g} - d_c - h_{f,1\text{-}2}\right)}$ where Q = discharge from the culvert (m3/s, ft3/s) Cd = discharge coefficient v1 = average velocity of the water approaching the culvert entrance α = [illegible] coefficient ([illegible] assumed as 1.0) dc = the critical depth Ac = flow area at the critical section of the culvert [illegible]	**4** Submerged outlet $\frac{h_1 - z}{D} > 1.0$ $\frac{h_4}{D} > 1.0$		$Q = C_d A_o \sqrt{2g\left(\frac{h_1 - h_4}{1 + \frac{29 C_d^2 n^2 L}{R^{4/3}}}\right)}$ where Ao is the culvert area. The complicated term in the denominator corrects for friction. For [illegible] and for culverts less than 50 ft long, the friction loss can be ignored. $Q = C_d A_o \sqrt{2g(h_1 - h_4)}$
2 Critical depth at outlet $\frac{h_1 - z}{D} < 1.5$ $\frac{h_4}{h_c} < 1.0$ $S_0 < S_c$		$Q = C_d A_c \sqrt{2g\left(h_1 + \frac{\alpha v_1^2}{2g} - d_c - h_{f,1\text{-}2} - h_{f,2\text{-}3}\right)}$	**5** Rapid flow at inlet $\frac{h_1 - z}{D} \geq 1.5$ $\frac{h_4}{D} \leq 1.0$		$Q = C_d A_o \sqrt{2g(h_1 - z)}$
3 Tranquil flow throughout $\frac{h_1 - z}{D} < 1.5$ $\frac{h_4}{D} \leq 1.0$ $\frac{h_4}{h_c} > 1.0$		$Q = C_d A_3 \sqrt{2g\left(h_1 + \frac{\alpha v_1^2}{2g} - h_3 - h_{f,1\text{-}2} - h_{f,2\text{-}3}\right)}$ where A3 is the flow area at section 3 [illegible]	**6** Full flow, free outfall $\frac{h_1 - z}{D} \geq 1.5$ $\frac{h_4}{D} \leq 1.0$		$Q = C_d A_c \sqrt{2g(h_1 - h_3 - h_{f,2\text{-}3})}$ Note that distance h3 is undefined. For conservative first approximations, h3 can be taken as the barrel diameter

Figure 28. Classification of culvert flow with equations for estimating discharge (adapted from Bodhaine, 1968).

The only reliable option is therefore to permanently measure velocity and combine this with known cross-sectional areas to calculate discharge. Camera-based velocimetry is identified as a reliable method for achieving this. The time and financial cost of developing and calibrating a system in-house would be high but the authors have identified a manufactured who has developed a camera-based velocimetry system that includes calculation of discharge in an integrated package that is installed and calibrated on site by the manufacturer, thus providing an off-the-shelf solution for camera-based velocimetry. This system, the DischargeKeeper (DK) produced by SEBA Hydrometrie, is described in Section 4.4.4. and the recommendation is that this system should be purchase for application at the culvert site. Consultation has been sought with Dr Issa Hansen (hansen@seba.de) who works for this company and who was one of the developers of the system. The authors of this report sent the information available regarding the culvert site to Dr Hansen who confirmed that the DischargeKeeper might be employable here as a discharge measurement solution. Details obtained from consultation with SEBA on the installation of the DischargeKeeper are included in the following sections for this Option. Note that the DischargeKeeper system also measures water level from the camera-imaging and therefore bathymetry is tied to each set of velocity measurements enabling discharge to be calculated. In instances where this automatic detection is not possible a pressure transducer can be installed locally and integrated with the DischargeKeeper system which uses this data to derive the bathymetry. It is also important to note that the camera systems operate in the infra-red range so can perform measurements round the clock, including during hours of darkness. Installation of the DischargeKeeper system is normally undertaken by SEBA staff, although the customer can install it themselves if they wish. Configuration of the system is performed remotely, once all required parameters are available (cross-section, reference measurements, coordinates of two reference points on both channel banks and the camera position).

5.2.2.1. Option 2: Actions

Contact Dr Hansen of SEBA Hydrometrie (hansen@seba.de) to further investigate installation of the DischargeKeeper camera-based velocimetry system at the two box culverts located at 51.09902638°N, 6.10389827°E. If suitable, commission installation of this system by the manufacturer who, as part of the service, will come on site to optimize siting the camera and setting up the system for the particular conditions present.

5.2.2.2. Option 2: Site considerations

The siting of the camera’s used in the DischargeKeeper system would be undertaken by the company themselves but the process would involve consideration of factors including:

- Primary flow direction.
- Degree of light/shadow and water surface glare (note that there are trees in the vicinity of the culvert site which might impact these factors).
- Consideration of the degree of surface roughness of the flow.

SEBA ask prospective users of the DischargeKeeper system to initially send site information to them using a standard form, from which they can make initial decisions regarding the potential utility of the device (see Appendix L). Much of this information could not be provided by the authors of this report and site suitability was considered from photographs and descriptions given to Dr Hansen of SEBA. The company survey and upload the total cross-section where measurements are to be made considering the highest water level under flood events which enables the DK to measure under low (as long as the roughness of the water surface is good enough for image processing) and high-water levels. Different types of cameras are used depending on the river/stream width and in this case, based upon the site photographs supplied, a PTZ camera was recommended which can cover flow widths of between 2 m and 160 m. Successful application of the system includes the requirement that: 1) there must be some visible movement on the water surface for the flow to be captured (wave heights > 3 mm), and: 2) sites are recommended to have flow velocities > 0.2 ms^{-1} (although they note that the system has been able to measure speeds as low as 0.1 ms^{-1} depending upon site conditions). Dr Hansen cautioned that strong wind and low flow velocities can increase uncertainty in surface velocity measurements. With regards to the DischargeKeeper method for converting surface velocities to mean values this is achieved using an alpha coefficient multiplication factor (refer to Section 4.7.). In order to obtain this value SEBA ask for video footage of flow at the site to be sent to them in advance and, if possible, reference data obtained with ADCP from which this coefficient value can be determined. Obviously, the limitation associated with the culvert site proposed is that currently there are no reference flow measurements available and such flows will occur infrequently during flood events, but Dr Hansen stated that, 'Reference measurements are recommended for the calibration, but we could install the DischargeKeeper and once a reference measurement is available, we would update the calibration'. Therefore, initially mean velocity values may be somewhat inaccurate, but would be improved over time with acquisition of calibration data.

It must be recognised that flow at this culvert site is likely to be highly non-uniform and affected by backwater from downstream so there will be considerable uncertainty associated with the conversion of surface to mean velocities. Also, it is expected that discharge estimates would be highly suspect when the culvert is fully submerged, and flow is pressurised so the operating range of the DischargeKeeper system is expected to be from shallow flows of say 10 cm up to a depth just below the point where flow is influenced by the soffit (roof) of the culvert at the inlet or outlet. A possible location for the DischargeKeeper camera at this site is shown in Figure 29.

Another factor to consider regarding conversion of surface velocity to mean values here is that both approach and exit flows at this culvert are in arable fields where vegetation length, and therefore surface roughness, varies with time of year. Consequently, the alpha conversion coefficient would be time-variable if the ground surface in the vicinity of the measurement location is not managed. Therefore, it is recommended that, whether the camera is placed at the upstream or downstream end of the culvert, the ground surface in the vicinity should be restricted from agricultural practices and made a consistent surface roughness, perhaps by covering with a tarmac surface in the area where velocities are to be sensed in order that roughness is consistent. This may involve purchase of an area of ground from the farmer who owns the land in the vicinity of the culvert. The actual siting of the camera, and associated housing for processing, power supply and telemetry equipment would also have to be considered as the camera will be placed looking 90 degrees to the primary flow direction near the culvert entrance or exit, preferably on high ground, or on a purpose-built structure, to avoid inundation. This land would have to be permanently acquired and fenced off to avoid intrusion by people or livestock.

5.2.2.3. Option 2: Discharge measurement range

It is not possible to provide a precise discharge at which discharge through the two box culverts will become active due to flow across the floodplain without employing detailed hydraulic modeling, but an approximate stage value can be given. Figure 30 shows a cross section through the digital terrain model located at the culvert entrance. This terrain profile transect is located along the same path as that shown on the inset diagram in Figure 29. Unfortunately, because the precise details of the culvert openings are not known this terrain plot, located at the culvert entrances will have to suffice to derive stage ranges over which flow measurements using the DischargeKeeper could be taken. It appears from the terrain profile that the minimum elevation of the culvert inlets is approximately 31.8 m NAP. However, discharge cannot be determined for the lowest of flows as surface roughness elements such as vegetation are likely to protrude above the water surface unless the target area covered by the DischargeKeeper is made permanently smooth. Therefore, an approximate minimum stage from which discharges could be estimated is suggested as being 32 m NAP. The modeled elevation of the a 500 m^3s^{-1} flow is shown in Figure 30 as lying at a stage of approximately 32.75 m NAP and it is known that this elevation will likely lie above the roof of the culvert inlets as video footage from this site taken in July 2021 shows that the culvert exit, at least, was in fact submerged for a flood flow that was well below the modeled 500 m^3s^{-1} value (refer to Plate 17). As the DischargeKeeper system relies on the conversion of surface velocities to a depth averaged value using an alpha coefficient, which is generally based upon the assumption that there is a free surface to the flow, it is considered that the system should not be used to determine discharge for flow depths that impinge on the culvert roof. Therefore, the maximum operable stage of the system must be set lower than 32.75 m NAP. The elevation of the culvert roof cannot be ascertained from the terrain profile shown in Figure 30, so an approximate estimate has been made that the culvert roof lies at 32.65 m NAP. Therefore, to give a little leeway to ensure that flows which might impinge on the culvert roof are not measured we recommend that flows at the culvert inlet could be successfully measured over a stage range of between 32 m NAP and 32.6 m NAP by the DischargeKeeper system under this option.

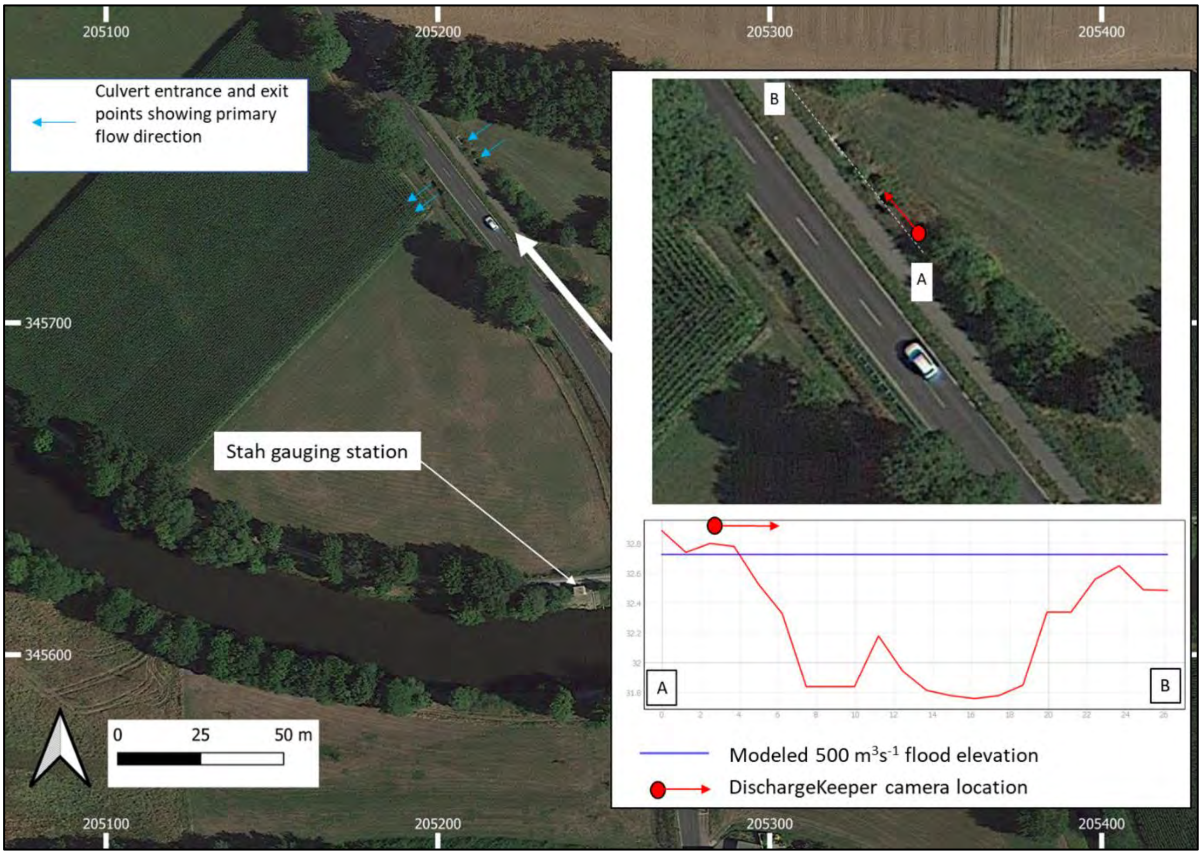


Figure 29. Location of two box culverts near to the Stah gauging station identified for monitoring via surface velocity methods and prospective placement of DischargeKeeper camera.

5.2.2.4. Option 2: Cost

The cost quoted for one DischargeKeeper system for a river width of up to 50 m is €37,000.00 (excluding VAT). This cost includes installation on site plus inclusion of an external water level sensor for redundancy (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made include:

1) Pole mounting for the camera.
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.

3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing.

4) As it is likely that field-based velocity measurements will not have been obtained at the camera location prior to installation a measurement protocol and field team will also have to be assembled to ensure that ADCP measurements are made at the point where the camera images the water surface during flood-flow events in order to provide calibration information for the DischargeKeeper. This would not be a permanent exercise as, once sufficient calibration information is obtained, the system will calculate discharges adequately.

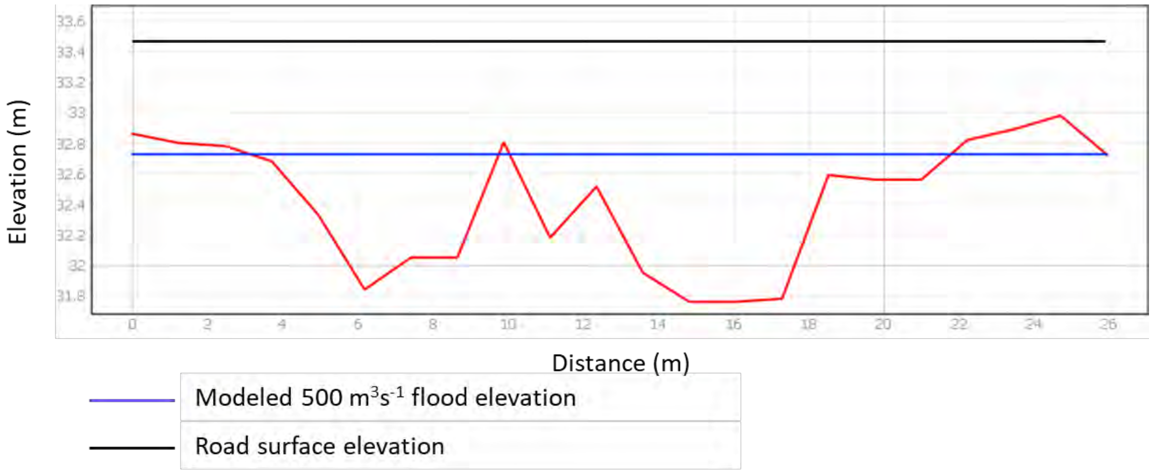


Figure 30. Cross-section terrain profile taken through the two box culvert entrances showing the elevation of the road surface and the modeled 500 m^3s^{-1} flood event.

5.2.2.5. Option 2: Limitations

The main limitation associated with use of this system is whether satisfactory mean velocities can be obtained from surface velocities given the complexity of flow approach and exit from the culverts, the variable nature of the ground surface roughness beyond the culverts, and the fact that the velocity estimates are likely to be made just beyond the culvert openings themselves where the cross-section expands suddenly. The geometry of the culvert openings can be used for the bathymetry required in the discharge estimate, but velocities will have to be imaged slightly outside the culvert at a location where flow acceleration/deceleration will be considerable. This site therefore represents a challenge for converting surface velocity estimates to discharge and whether it is indeed truly feasible using the DischargeKeeper system would have to be determined through further consultation with SEBA staff.

5.2.2.6. Option 2: Uncertainty estimate

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. Also, night vision of the camera is quoted as being good up to 50 m distance which should be adequate for this site. The measurable velocity range is quoted as being 0.2 to 15 ms^{-1} which is more than adequate for the site in question.

The main uncertainty associated with the system application at this specific site is whether conditions are suitable for the DischargeKeeper and that would have to be determined independently by SEBA staff. If installed the initial discharge estimates are likely to have a significant degree of uncertainty because there may not be field data available to calibrate the coefficient used to convert surface velocity values to mean values. A concerted effort would therefore have to be made to measure velocity profiles using an ADCP at the point where the camera images the water surface during any flood flow event.

5.2.2.7. Option 2: Robustness of approach

The attractiveness of this option lies in the fact that it would be sited, installed and calibrated by staff from the company who have designed the system and would require limited technical input from Waterschap Limburg personnel. The baseline hardware cost involved is significant however, the DischargeKeeper system for this site costing €37,000.00 (excluding VAT), with there being the risk that it might not function in a manner that is consistently accurate enough for robust discharge estimates to be made. However, SEBA staff would give extensive advice on the viability of using this system at the site in question if this option were pursued further. The ability for this approach to deliver depends very much upon whether the system can predict discharge accurately, which is a function of two factors:

1) As the system relies on light as the sensing medium factors such as the presence of shadow and glare and the degree to which the infrared system can pick up the surface flow at night will all influence the accuracy of the surface velocity measurement.
2) The degree to which the surface velocity conversion coefficient (alpha coefficient) can accurately represent the adjustment of the maximum surface flow velocity to the depth-averaged velocity. This conversion factor will depend upon the depth of flow being sensed meaning that the associated uncertainty will also vary with stage unless the alpha coefficient can be made stage dependent in the DischargeKeeper.

5.2.3. Option 3: Use of surface radar velocimetry to capture floodplain flows passing through the box culverts located near the Stah gauging station

The basis for this option is the same as that outlined in Option 2 above, that of using surface velocity estimates to determine discharge, but in this case by employing surface velocity radar mounted above the entrance to each culvert opening. The use of such a system would be cheaper than that, in terms of hardware cost, of employing the DischargeKeeper but the software required for conversion of surface velocity to mean velocity and for combining this with bathymetry to give discharge would have to developed in-house by Waterschap Limburg our outsourced to another company (Note: One system, the Geolux RSS-2-300WL radar flow meter performs these calculations internally so no further software would be required). Two surface velocity radar would be required, one above the entrance to each culvert and telemetry equipment provided to transmit surface velocity and stage levels at the culvert entrances to a central computer. It would be necessary to check and calibrate the alpha coefficient values used with field data obtained from an on-site team during flood flows, as outlined under Option 2.

5.2.3.1. Option 3: Actions

The Geolux RSS-2-300WL radar flow meter would provide the ideal solution for this approach (see Appendix G). One radar would have to be mounted above the entrance to each culvert opening. In combination with the installation of hardware the culvert cross-sectional areas would have to be surveyed and entered into the radar software along with an appropriate surface velocity conversion coefficient.

5.2.3.2. Option 3: Site considerations

The surface velocity radar should be mounted on poles above the culvert entrances to avoid their becoming damaged during extreme flood flows. The main considerations when siting the OTT SVR 100 radar, as given in their instruction manual, which are also likely to be applicable to Geolux radar are:

- Minimum surface disturbance height for accurate velocity measurement is a 1 mm surface wave.
- Optimal tilt angle is 30 degrees and at this angle the sensor should be no higher than 10 m above the water surface.
- The sensor should be placed looking upstream to reduce the impact of raindrop interference or placed underneath a structure such as a bridge which shields the water surface from raindrops.
- There must be no stationary objects in the radar footprint (such as bridge piers, rocks, etc.) as these will generate erroneous returns.
- The unit should be used to sample uniform flow conditions with parallel streamlines, i.e., in a straight section of channel where there are not contractions or expansions.

5.2.3.3. Option 3. Discharge measurement range

The discharge measurement range for this option will be the same as that which applies to Option 2, for the measurement of flow at the culverts using the DischargeKeeper system (refer to Figure 30). Therefore, we recommend that flows at the culvert inlet could be successfully measured over a stage range of between 32 m NAP and 32.6 m NAP by the radar system used under this option.

5.2.3.4. Option 3. Cost

The cost of a single OTT SVR 100 unit is €5,268.31 and two of these would be required. Also required with this setup is a data logger (4G (LTE-M) AD data logger with SLA-cover) which has internet data transmission capability costing €810.00. The total cost would therefore be €11,346.62. An optional solar panel with backup battery is also available which would cost €670.00. All prices exclude VAT and delivery cost from within the Netherlands (quote was obtained from RMA Hydromet (https://rmahydromet.nl) on 7th October 2023). RMA Hydromet also offer the Geolux RSS-2-300W as an alternative to the OTT radar and this is much cheaper, €2,480.00 (excluding VAT) and seems to have a similar specification to the OTT design. The data logger (€810.00) would also be required with this option (quote obtained 7th October 2023). However, the most attractive option for the surface radar-based method is likely to be the Geolux RSS-2-300WL flow meter however as this also contains a water level sensor and has the capacity to determine discharge if the user enters an alpha coefficient conversion factor and the channel cross-sectional area, in a manner similar to that performed by the DischargeKeeper. The cost of this device for a single unit is €4,800.00 (excluding VAT and delivery) (quote obtained from RMA Hydromet on 6th October 2023). Two would be required, so the total cost would come to €9,600.00. This hardware cost is considerably cheaper than the DischargeKeeper system and therefore presents an attractive option but be aware that a surface radar only produces a point value for velocity and assumes that flow conditions are semi-uniform and, as mentioned in the limitation for this option (Section 5.2.3.4.), this is unlikely to be the case at the entrance to these culverts.

Additional costs for which estimates have not been made include:

- Mounting of radar units on poles.
- Cost of cable connection and housing for data transmission via internet to a receiving station.
- A field team will have to be assembled to ensure that ADCP measurements are made, at the point where the radar footprint lies, during flood-flow events in order to provide calibration information for determining the alpha coefficient. This would not be a permanent exercise as

once sufficient calibration information is obtained the system will calculate discharges adequately.

5.2.3.5. Option 3: Limitations

The main limitation associated with the use of surface velocity radar is related to the fact that flow is unlikely to be uniform and streamlines parallel at the culvert entrances. The streamline pattern will also vary with flow depth which means that the error associated with velocity estimates may also vary with stage. A second limitation is that stationary objects should not appear in the radar measurement footprint. This is an issue because the ground surface near to the culvert entrances lies in arable fields where vegetation of varying lengths may be present, depending on the time of year. Therefore, for practical application of the radar, the radar footprint area upstream of the culverts would have to be excluded from farming practices and either permanently surfaced with a stone/asphalt cover or regularly mown if left covered by vegetation as any vegetation emerging above the water surface could seriously bias velocity estimates. Limitations are also present because these surface velocity estimates must be converted to mean values using an alpha coefficient that, initially, is likely to be uncalibrated due to lack of measured flow data in the vicinity of the radar footprint. Field measurement of flood flows at this location would have to be undertaken to validate and adjust the coefficient if necessary.

5.2.3.6. Option 3: Uncertainty estimate

If the Geolux RSS-2-300WL flow radar were purchased this is documented as having a 1 % surface velocity accuracy and ±2 mm water level accuracy. The detection distance for the device is quoted as being 15 to 30 m and the velocity measurement range as being 0.02 to 15 ms^{-1} which will be adequate for the conditions that will prevail at this site. Uncertainties will also be incurred in the selection of an appropriate alpha surface velocity conversion coefficient and the quality of the cross-section bathymetry survey, although if the culvert mouth opening area is used this will be both accurate and stable over time. The uncertainty associated with the selection of an alpha coefficient will reduce once field measurement of the ratio of mean to maximum velocity is achieved using ADCP surveys during flood flow conditions. Note that a major source of error will occur due to the fact that a surface velocity radar obtains a point measurement of velocity and not a cross-section surface velocity distribution as is performed by the DischargeKeeper. Also, this type of radar really assumes that streamlines across the surface section are parallel which will not be the case at the culvert entrances. We assume therefore that the initial discharge uncertainty could be up to 20% reducing to 10% with adequate alpha coefficient calibration data.

5.2.3.7. Option 3: Robustness of approach

This option is considered somewhat more robust than that of using image-based velocimetry especially if the Geolux RSS-2-300WL flow meter were to be used. Radar uses radio waves as the medium for sensing the water surface velocity which is not dependent upon factors such a light intensity. The radar units can also be easily sited directly above the entrance to each culvert without the need to acquire land adjoining the culvert entrance itself. The use of a continuous K-band radar system does have limitations though in that a point velocity is estimated by the system rather than a surface velocity distribution and that velocity is then used as the sole value when converting to a depth-averaged value, rather than apportioning flow into smaller cross-section segments in which individual discharges are calculated and summed to give the total (the velocity area method). Associated with this issue is the assumption that the flow in the radar footprint has parallel streamlines, a requirement for determination of a representative average velocity from the returned radio wave, and this assumption is likely to be violated to some degree at the culvert entrances. There is also the issue of applying a representative alpha surface velocity conversion factor which is common to the image-based velocimetry approach. However, this sensing technology is much cheaper than, specifically, the DischargeKeeper image-based system, costing €9,600.00 (excluding VAT) to equip the two culvert entrances and is physically more robust in terms of the sensing technology in that a return signal will be obtained, and a velocity estimated, as long as there is some disturbance of the flow surface. It therefore represents a lower risk option than installation of the DischargeKeeper system. One other factor to be aware of regarding the application of radar technology is that certain frequencies may be banned or restricted depending upon the region or country because they interfere with other technologies, especially military applications. The authors sought advice from staff at RMA Hydromet, the company that sells the OTT and Geolux radar systems, regarding the use of the K-band radar in the Netherlands and they confirmed that systems in this frequency range are legal for use and that they had in fact already installed such radar at a number of locations in the past for Rijkswaterstaat (Rob ter Brake, personal communication, 13th October 2023).

5.2.4. Option 4: Use of DischargeKeeper to measure flow passing through the road bridge opening at the Stah gauge

The bridge located at the Stah gauge site carries the K21 road over the Roer between the village of Kempen to the south, located on the left-hand floodplain, and Ophoven to the north, located on the right-hand floodplain. This road, beyond the extents of the bridge itself, lies on a raised embankment which is approximately 1.5 – 2 m heigh and which extends, on the right-hand floodplain, as far as the village of Ophoven which lies approximately 700 m north of the river itself. This embankment, through which the two box culverts mentioned in Options 2 and 3 pass, acts to hold back high, out-of-bank, flood flows upstream of the bridge forcing flow to either pass through the box culverts or to pond upstream of the road and be diverted through back through the bridge opening between the bridge abutments and pair of bridge piers. Thus, while very high floodplain flows are shown in the hydraulic modeling exercise to overtop the road embankment (refer to Figure 15) flows lower than the embankment top, but which are still travelling on the floodplain, out-of-bank, are likely to be directed to pass either through the bridge opening itself, or if high enough through the culvert openings. Flood flows in the vicinity of the bridge will therefore pond upstream, against the road embankment, be contracted and accelerate through the bridge opening itself and then expand once again and spill out onto the floodplain on the downstream side.

It can be argued therefore that the bridge opening itself presents an ideal location to measure high flood flows as all but the highest floods will in fact be directed off the flood plain through this opening, being block and steered towards this by the K21 road embankment. The bridge itself has vertical concrete abutments and a pair of narrow, streamlined piers that rest on the channel banks either side of the main channel itself and this opening therefore represents a well-defined, fixed, geometry that extends well above maximum flood levels. Therefore, the measurement of flow through a section of the bridge itself would likely capture discharges greater than could be achieved by measurement of flow downstream of the bridge at the present location of the gauging station building and cableway, where it is presumed that calibration discharge measurements have been made in the past. This is because here, beyond the confines of the bridge abutments, the flow spills out onto the floodplain once again and is not contained within the in-bank channel cross-section.

Because flood flows will accelerate through the bridge opening, and then decelerate immediately downstream, this location is not suitable for the development of a Q-H rating curve as flow through the bridge section will be far from uniform. Therefore, flow velocities must be measured directly here and combined with the flow cross-section within the bridge opening to determine discharge. This site therefore lends itself well to the use of the DischargeKeeper system as one camera could be used at this cross-section to determine surface velocities across the entire width of the bridge opening for stages ranging from very low to peak flow conditions. Radar could also be deployed here, but because these only provides a point measurement of surface velocity a series of radar would have to be mounted on the underside of the bridge deck across the opening to give the velocity distribution across the full width. The combining of multiple velocity readings from a series of radar and the computation of depth averaged values from these is likely to be a more complex task than using the complete surface velocity distribution derived by the DischargeKeeper system, so the latter is favoured at this site.

5.2.4.1. Option 4: Actions

Contact Dr Hansen of SEBA Hydrometrie (hansen@seba.de) to further investigate installation of the DischargeKeeper camera-based velocimetry system on either the left or right side of the main Roer channel at the upstream side of the bridge opening. If suitable, commission installation of this system by the manufacturer who, as part of the service, will come on site to optimize siting the camera and setting up the system for the particular conditions present.

5.2.4.2. Option 4: Site considerations

It is proposed that that a DischargeKeeper camera be mounted at the upstream side of the bridge opening at the Stah gauge such that the surface velocity distribution is measured across the channel where it is confined at either side by the solid bridge abutments. Measurement here will mean that surface velocities can be measured up to peak flood flows (which are predicted from hydraulic modeling not to reach the bridge deck itself) within a cross section that has a maximum top width of approximately 37.5 m between the left and right bridge abutments. It is possible that the DischargeKeeper camera could actually be mounted on the side of the bridge deck itself, as long as the camera is set at an angle such that the maximum potential flow width can be captured across the upstream side of the bridge. Figure 31 shows a close up of the bridge site at the Stah gauging station with a prospective location for mounting the DischargeKeeper camera. Note that some vegetation clearance may be necessary to give the DischargeKeeper camera an unrestricted view across the opening at the upstream side of the bridge opening. The site consideration factors outlined in Section 5.2.2.2. regarding DischargeKeeper setup would also have to be taken into account for this location. An advantage of using the DischargeKeeper here is that the flow is contained within a reasonably regular channel cross-section and ADCP measurements can readily be taken of the flow field where surface velocity readings are to be taken meaning that the development of truly representative alpha conversion value will be relatively straightforward at this location.

5.2.4.3. Option 4: Discharge measurement range

A wide range of discharge should be measurable using the DischargeKeeper at this site from very low flows of only a few cumecs up to and above that which can be accurately captured by the Stah rating curve itself. One advantage of setting up the DischargeKeeper to measure flow at this bridge site is that discharge estimates made by this system can be checked and calibrated against discharge estimates made by the current Stah Q-H rating curve up to the stage elevation for which this rating curve is reliable at approximately 32.5 m NAP where the discharge is 135 m^3s^{-1} (assuming of course that the Stah rating curve is accurate). Beyond this elevation flows upstream and downstream of the bridge will spill out onto the floodplain but will be contained within the bridge abutments at the bridge crossing itself meaning that, as long the DischargeKeeper surface velocity measurement conversion to mean velocities is accurate, flows significantly greater than 135 m^3s^{-1} should be measurable using this Option. Figure 32 shows a cross-section transect through the bridge itself (red line) which is marked as by line 'A–B' in Figure 31. The modeled elevation of a 500 m^3s^{-1} flow is also shown in Figure 30 and it can be seen that this predicted water surface elevation lies well below the elevation of the bridge deck, between the bridge abutments. The second cross-section plotted in Figure 32 represents the ground terrain approximately 10 m downstream of the section through the bridge, close to location of the Stah gauge housing. This is marked as line 'C – D' in Figure 31. It can be seen that the highest point of this cross-section lies below the elevation of the 500 m^3s^{-1} modelled flood demonstrating that flows greater than

32.5 m NAP go out-of-bank at the gauge itself but are contained upstream between the bridge abutments.

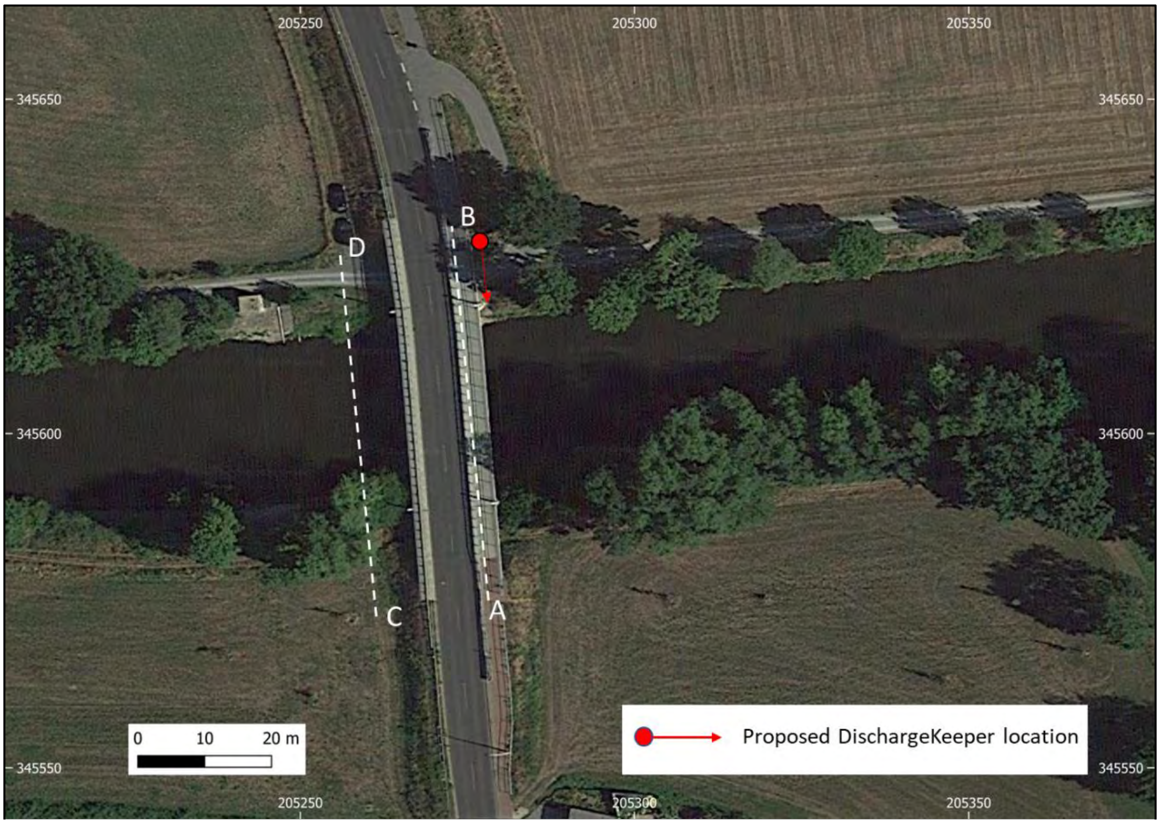


Figure 31. *Road bridge crossing located at the Stah gauging station with proposed approximate location of DischargeKeeper camera. Transects 'A-B' and 'C-D' are plotted in Figure 32.*

5.2.4.4. Option 4: Cost

The cost quoted for one DischargeKeeper system for a river width of up to 50 m is €37,000.00 (excluding VAT). This cost includes installation on site plus inclusion of an external water level sensor for redundancy (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made include:

1) Pole mounting for the camera (mounting on the bridge side may be a possibility).
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.
3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing although it is suggested that camera could be mounted to the bridge structure itself.
4) ADCP readings across the channel width will be required at the location where the DischargeKeeper is to measure the surface velocity distribution in order that an appropriate alpha correction factor can be derived to convert the measured surface velocities to mean velocities. This will incur costs associated with sending out a field team on a number of occasions to measure velocity distributions for a range of flow stages including, if possible, during flood flow conditions.

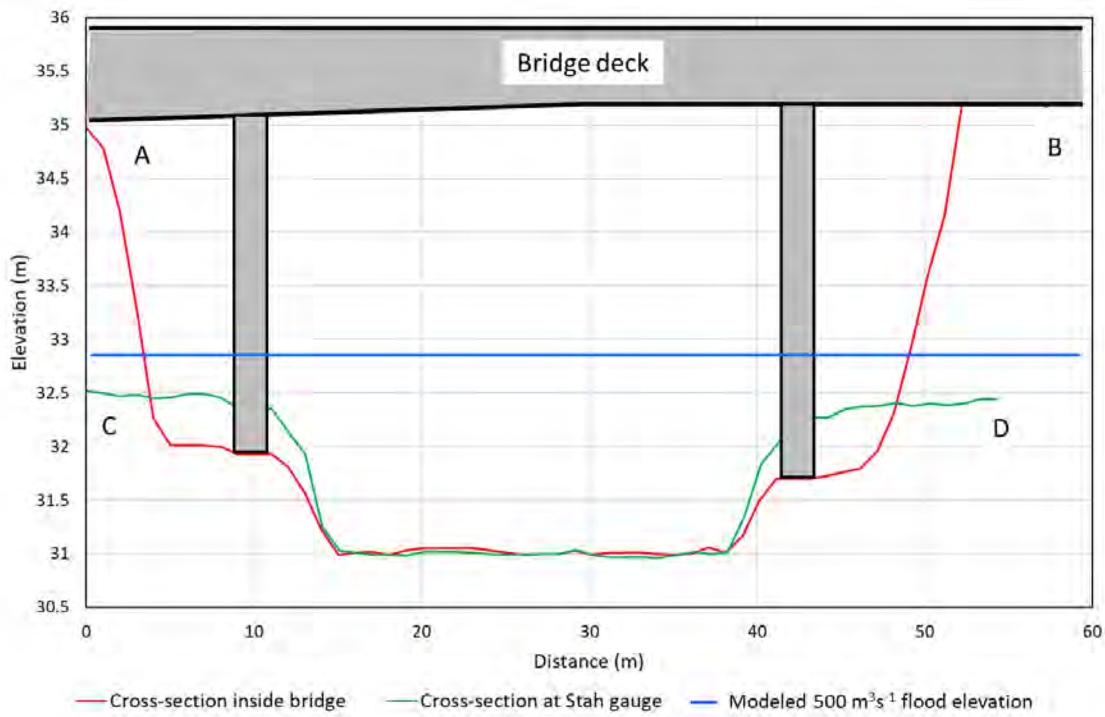


Figure 32. *Cross sections through the Roer channel at the Stah road bridge (transect A–B) and at the Stah gauge itself (transect C–D) which lies approximately 30 m downstream, along with the water surface elevation of a 500 m^3s^{-1} flood event. The location of these two cross-sections transects are marked in Figure 31. Note that the channel bathymetry is truncated at 31 m NAP due to no-return from the LiDAR data used to generate the digital elevation model.*

5.2.4.5. Option 4: Limitations

It is important to understand that this option, by itself, will not ensure measurement of the full range of flows expected at the site, especially floodplain flows, an unknown component of which will pond on the floodplain upstream of the bridge at the Stah gauge and may pass through the two bypass culverts to the north of the bridge or pass over or round the raised road embankment elsewhere across the width of the floodplain at this site. Regarding the measurement infrastructure itself, the accuracy of discharge estimates obtained using the DischargeKeeper will depend primarily upon how well the surface velocities are converted to depth-averaged values using the alpha conversion factor. It should also be recognised that the channel cross-section geometry at the bridge itself may vary over time due to geomorphological adjustment, especially under high flow conditions, so periodic re-surveys of the cross-section associated with the DischargeKeeper measurement location will be required in order to check, and to account for, any significant changes.

One further factor that needs to be considered is that the DischargeKeeper velocity readings must be made in line with the opening area of the bridge cross-section itself between the two bridge abutments. This is because the water surface elevation of the flow may vary significantly locally at a bridge section especially during flood flow events. Under such conditions, when flow is likely to travel laterally from both the left and right-hand floodplain to the bridge opening, the water will, under subcritical flow conditions (which are thought likely to be present at this site at all stages), back up and increase in depth immediately upstream of the bridge opening but then over a short distance at the mouth of the bridge and through bridge-section itself will accelerate and decrease in depth (refer to Figure 33).

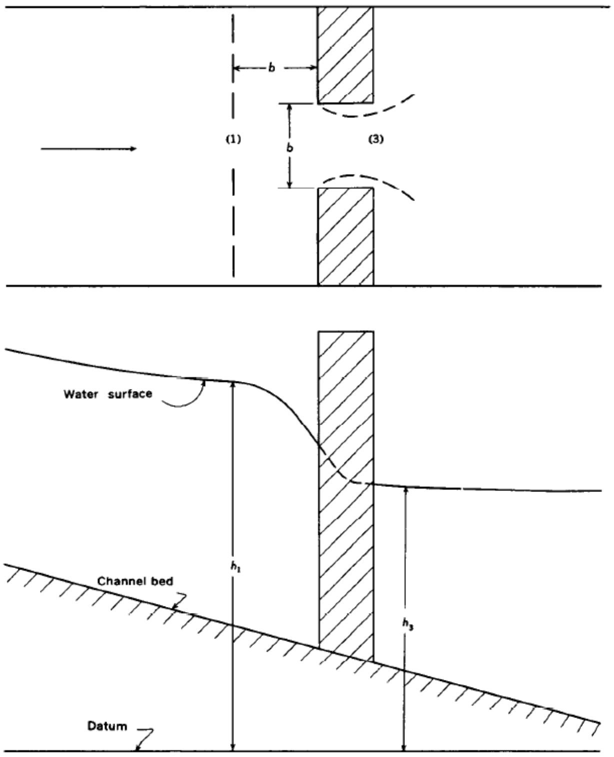


Figure 33. *Definition sketch of an open channel contraction through a bridge showing local variation in the water surface profile under subcritical flow conditions (after Rantz (1982a)).*

This effect will become more pronounced the greater the degree of contraction of the flow, provided flows remain subcritical. Therefore, it can be seen that flow cross-sectional area and velocity will vary significantly over a short length of channel and as the bridge opening itself will act as the cross-sectional area used in this discharge measurement method it is crucial that velocity measurements be extracted from the camera-images exactly in line with the cross-sectional area used in the calculations otherwise significant errors may occur in the estimates of discharge.

5.2.4.6. Option 4: Uncertainty estimate

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. Also, night vision of the camera is quoted as being good up to 50 m distance which should be adequate for this site. The measurable velocity range is quoted as being 0.2 to 15 ms^{-1} which is more than adequate for the site in question.

5.2.4.7. Option 4: Robustness of approach

The attractiveness of this option lies in the fact that it would be sited, installed and calibrated by staff from the company who have designed the system and would require limited technical input from Waterschap Limburg personnel. The DischargeKeeper system is considered to be well-suited to this particular site and once set up is likely to operate both affectively and accurately. This particular option is likely to improve the discharge measurement range in the Roer river channel itself above that which is currently reliably capable using the Stah rating curve as flow passing through the bridge section itself is contained between the solid bridge abutments which act as a boundary to the lateral spread of flow up to any flood depth likely to be experienced at the site.

5.3. Options for discharge measurement at Site 1 (51.18545143°N, 5.99101103°E)

Site one, located at the two railway bridges which cross the Roer and the Groene Overlaat side channel, has been identified as the location in the lower catchment where flood flows are most contained and therefore offers the best opportunity to measure out-of-bank flood discharge conditions. This site is affected by backwater from the Meuse however, so a standard stage-discharge rating curve would not be appropriate here. Therefore, an index-velocity based approach would have to be applied, or direct measurement of velocity and cross-sectional area. It was considered by that authors that this location would perhaps be suitable for the use of Fluvial Acoustic Tomography (FAT) which is discussed in Section 4.3. The authors corresponded with the inventor and distributor of the FAT system, Dr Kiyoshi Kawanisi of Hiroshima University, to discuss suitability of the system for use at the four prospective gauge sites selected on the lower Roer. Given the fact that the tomography transducers require a minimum flow depth of approximately 0.3 m in which to function and the units must be placed near to the banks of the channel it was considered by Dr Kawanisi that Site 1 was one location where the FAT system could be used to measure both low and flood flows given that the entire range of discharges experienced here are likely to be contained between the bridge abutments of the two railway bridge crossings.

The second option suggested for use at this site is the Discharge Keeper system. Here two cameras would be required, one for the main channel and a second to cover the Groene Overlaat bypass channel.

5.3.1. Option 1: Use of Fluvial Acoustic Tomography (FAT) system

The recommendation for use of FAT at this site was based upon the presentation of site photographs and maps to Dr Kawanisi, and a detailed site inspection has not been undertaken to precisely determine the location of the transducer units. However, Dr Kawanisi presented the authors of this report with a conceptual plan of how he thought the system could best be deployed at this location.

5.3.1.1. Option 1: Actions

Purchase FAT system through Dr Kawanisi's company, River and Coastal Instruments (RCI) LLC. Installation would have to be accomplished by a local company according to the siting recommendations given by the supplier. In order to use this system, the bathymetry along the path of each pair of transducers would need to be surveyed in the field accurately also, and each surveyed transect equipped with a stage gauge from which flow cross-section bathymetry can be retrieved for each set of transducer velocity predictions.

5.3.1.2. Option 1: Site considerations

The setup recommended by Dr Kawanisi is shown in Figure 34. Basically, two sets of transducers will be required at each opening to cover both low-flow, in-channel, conditions and high-flow, out-of-bank, conditions. For both low and high flow conditions in the bypass channel pairs of transducers are adequate. However, in the main channel under high flow conditions the primary downstream velocity direction may be variable as the flow is travelling round a bend so three transducers are required in order to triangulate on the primary flow path (refer to Al Sawaf et al. (2023)).

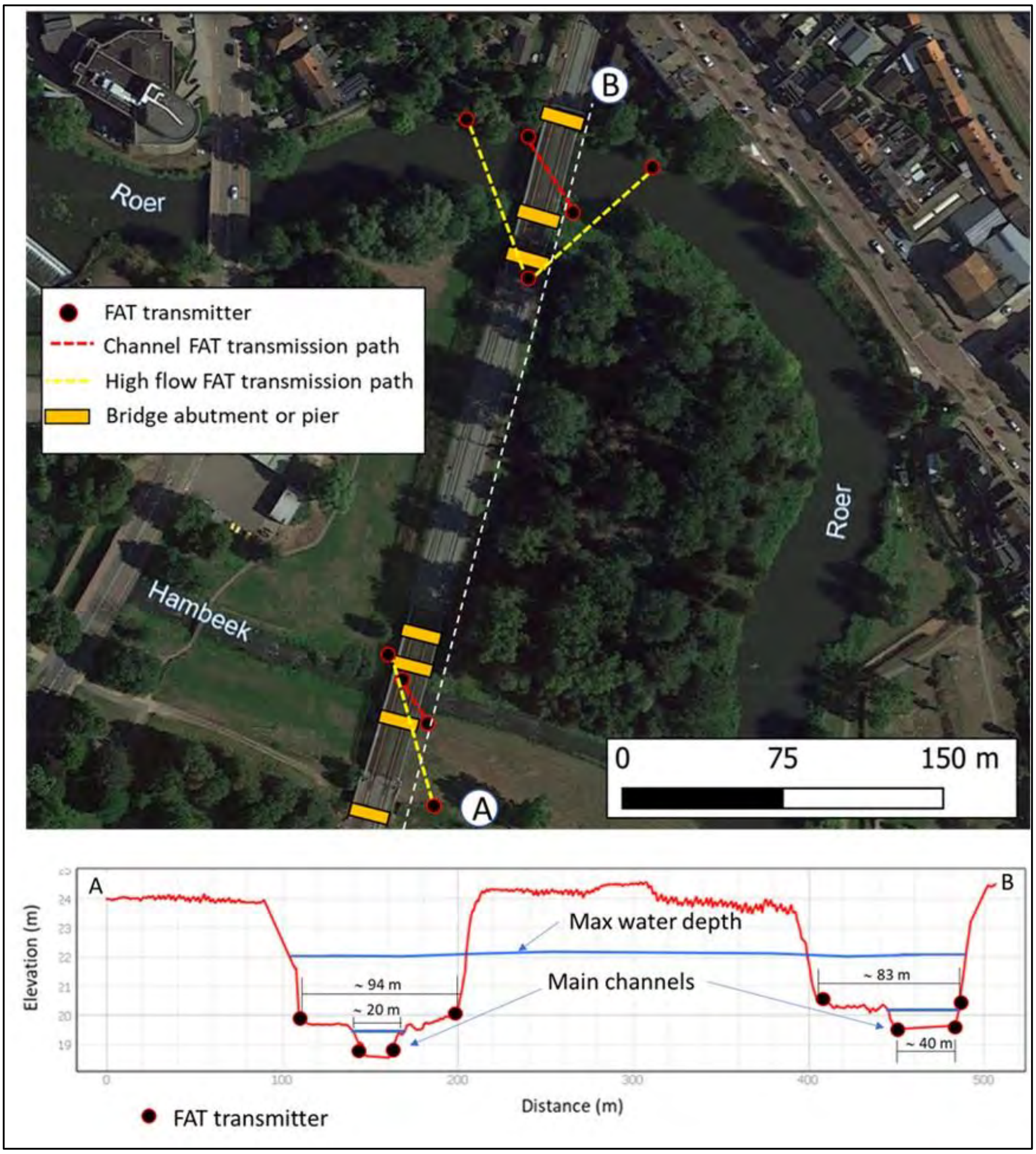


Figure 34. *Recommended arrangement of Fluvial Acoustic Tomography transmitters for measurement of flow at Site 1. Upper diagram shows planform arrangement while the lower diagram shows a transect through path 'A-B'.*

FAT units are available in a range of transmission frequencies, which affect both the path length and the minimum depth that can be measured. Dr Kawanisi indicated that FAT units with a frequency of 53 kHz would be optimal for the path lengths estimated at this site. Note that the system can be run off direct mains power that is compatible with Dutch domestic electrical supply and does not require batteries in order to run in continuous operation. This system is internet-enabled meaning that real-time data acquisition is possible. In order to set up the system bathymetric surveys would have to be completed along the line of each pair of FAT transducers up to the highest elevation from which flow data would be collected. Pressure-transducers would have to be purchased additionally, one for each FAT pair transect so that for any given reading of depth, the cross-sectional area of flow can be retrieved and multiplied by the cross-section averaged velocity determined by the FAT transducers in order to determine discharge. The data loggers for the FAT units are capable of receiving digital input from pressure transducers and can transmit that data also. Each transducer requires its own data logger unit which would need to be placed in a secure housing above flood flow levels. These use automatic GPS connection in order to achieve transmission synchronization. In the configuration recommended there would be 9 FAT units and therefore 9 data loggers that would require their own housing. These 9 units would require a power supply. Data transmission from each logger is via W-LAN and this would need to be received locally and transmitted via the internet to a computer where this data is combined to determine discharge. Alternatively, the computation could be undertaken by a processing unit based on-site and the results transmitted via the internet.

5.3.1.3. Option 1: Discharge measurement range

Because the FAT system has a minimum operating depth of 0.3 m of water, very low discharges may not be measurable under this option, especially in the Groene Overlaat bypass channel. However, because it is likely that all flows above this minimum level, including the highest flood flows, will pass through the two monitored bridge openings it is expected that this system will be capable of successfully measuring all flood flow conditions that are likely to occur on the Roer. For example, referring to Figure 34 it can be seen that a modeled flood flow of 500 m^3s^{-1} is predicted to lie at a stage elevation of approximately 22 m NAP at the two bridge openings which is well below the elevation of the bridge decks meaning that such a flow would pass unrestricted through the bridges and would be measurable by the FAT system.

5.3.1.4. Option 1: Cost

A costing has been provided by Dr Kawanisi for the complete setup of this system which is shown in Table 6. The total cost of hardware to order from River and Coastal Instruments (RCI) LLC is €93,516.00 (excluding VAT and shipping). Quote obtained from River and Coastal Instruments (RCI) LLC on 20th September 2023. Further costs that will be incurred, but not priced here include:

- Installation of the FAT units such that they are securely fixed in place using solid, support structures on a concrete base. The alignment of the units is crucial, and they must not be dislodged or subject to vibration once in place. Cabling running from each unit to data loggers would also have to be secured and preferably buried to avoid disturbance by river flow or human interference.
- Installation of pressure transducers for each cross section in secure housing with wired connection to the FAT data loggers. Five would ideally be required, one for each FAT path.
- Housing for the nine data logger units with power connection. These must be secure and protected from interference by the public.
- A computer with W-LAN capability to receive the data from the loggers locally and transmit computed discharges over the internet.
- Costs associated with detailed survey of the cross-section along the path of each FAT pair. Five such cross-sections would be required for this configuration.
- Development of software that converts pressure transducer readings to an associated cross-sectional area and combines this with mean velocities derived from the FAT pairs to give discharge. The software would need to be able to choose when to switch between making discharge predictions using the low sets of transmitters or the high sets and calculate the correct primary velocity vector from the triangular configuration used for high flow calculation on the main Roer channel.

Table 6. Quotation (in euros) for FAT system that would be required to equip Site 1 for tomographic discharge measurement. Note that prices are not inclusive of VAT.

Quote for FAT_53 kHz				September 20, 2023
Item	**Quantity**	**Description**	**Unit Price (CNY)**	**Total Price (CNY)**
1	9	FAT logger 53 KHz	€ 6,667.00	€ 60,003.00
2	9	Transducer Unit (T266, Preamp, POM housing with Bulkhead connector)	€ 1,627.00	€ 14,643.00
3	6	Transducer cable (55 m)	€ 1,550.00	€ 9,300.00
4	3	Transducer cable (100 m)	€ 1,800.00	€ 5,400.00
5	9	12VDC power unit	€ 135.00	€ 1,215.00
6	1	Remote communication devices	€ 350.00	€ 350.00
7	1	Firmware	€ 105.00	€ 105.00
			Sub-Total (EUR):	€ 91,016.00
			Shipping Charges (EUR):	€ 2,500.00
			Final Total (EUR):	€ 93,516.00

5.3.1.5. Option 1: Limitations

A key limitation with the FAT system is that the transducers must be submerged to a certain depth before transmission can be achieved. For the 53 KHz units suggested this minimum is 0.3 m depth of water. Therefore, any flows shallower than this cannot be detected. This is unlikely to be an issue in the main Roer channel but could cause issues in the bypass channel. The consequence of this is that low discharges in this channel may not be recorded.

A second limitation associated with deployment of this setup is the need for there to be a clear line of sight between each pair of transmitters so that sound waves are not obstructed. One potential siting difficulty lies with the positioning of the high flow pair of transmitters on the Groene Overlaat side channel as the path between the transmitters cannot be blocked by obstructions and there is a bridge pier located on the channel left bank here which the transmitter path would have to pass diagonally, while at the same time the cross-section bounding the transmitter pair would need to be formed by the railway embankments that would contain high flows. The precise siting of this transmitter pair would have to be investigated further to ensure effective placement.

A third limitation is that fact that on-site support for setup and installation cannot be provided because, while Dr Kawanisi is happy to consult regarding installation remotely, on-the-ground services are not provided. There may therefore be a considerable effort required to become familiar with the devices and installation may involve an initial trial-and-error process.

5.3.1.6. Option 1: Uncertainty estimate

Installed correctly the FAT system offers robust discharge calculation and does not require a calibration exercise, other than initial trials to confirm that the units are performing correctly. The main uncertainties are associated with precision of the FAT units, the quality of bathymetric survey and the reliability of pressure transducer readings from which the cross-sectional area is derived. The error structure that must be accounted for when using the FAT system is presented in Section 4.3.2. Bahreinimotlagh et al. (2019) determined that the uncertainty associated with using this approach had a maximum possible value of 15 %. The accuracy of mean velocity measurement along the transmission path is quoted in the specification information (Appendix B) as being ± 0.1 cms^{-1}, along a ray-path length of 500m. The velocity range that can be detected is -20 to +20 ms^{-1} which is more than adequate for this location.

5.3.1.7. Option 1: Robustness of approach

This system is highly robust with regards to estimation of mean flow velocity as compared with surface-velocity detection systems. It does have limitations though in that flow depths shallower than 0.3 m cannot be sampled to obtain velocity readings, meaning that this system will not be able to capture the lower end of the discharge range specified in the research scoping requirements (a requirement to capture discharges range from 5 to 500 m^3s^{-1}). The main risk associated with purchase of this system is that, while advice can be given on siting and setup remotely, the actual installation would have to be undertaken by a local contractor who will not have had experience with this equipment before. There are also some physical limitations in that the system requires nine transducer and data logger installations which must be securely mounted, and alignment geometry maintained, for the technology to work properly. The degree of uncertainty associated with the system is also potentially slightly larger than that of image-based surface velocimetry (a maximum of 15 % error in discharge accuracy estimates quoted in the literature, as compared with 10 % quoted for the DischargeKeeper, although the latter quote for the DischargeKeeper assumes optimal site conditions).

5.3.2. Option 2: Use of the SEBA Hydrometrie DischargeKeeper system

This Option involves the installation of the DischargeKeeper system at Site 1. Two camera setups would be required, one for the main channel and one for the bypass channel.

5.3.2.1. Option 2: Actions

Contact Dr Hansen of SEBA Hydrometrie (hansen@seba.de) to investigate installation of the DischargeKeeper camera-based velocimetry system at Site 1. Consultation was not undertaken between the authors of this report and SEBA staff regarding siting this system at the two railway bridge openings, but the authors consider that this location could be successfully equipped with DischargeKeeper cameras. It is proposed that a camera is mounted high up on the railway embankment at the bypass channel (the Groene Overlaat), and a camera should also be installed on the right bank of the main channel on high ground, or possibly on the bridge structure itself, to observe the full width of the water surface at this location.

5.3.2.2. Option 2: Site considerations

It is thought that the DischargeKeeper system could employ PTZ infrared cameras at this site, as recommended by SEBA for the box culvert locations at the Stah gauging station. These have a range of 5 m to 160 m which it is believed would adequately cover the full potential width of flow during flood conditions. The camera would have to be mounted relatively high up at the bypass channel in order that it could view both low flow conditions in the narrow bypass channel itself and high, flood flow conditions. The same factors regarding siting of the camera would have to be considered as outlined in Section 5.2.2.2. Final recommendations regarding applicability of the system would need to be made by SEBA staff prior to purchase, and staff from that company would be involved in the physical installation of the system on site thus making the setup relatively hands-free for Waterschap Limburg staff. Figure 35 shows prospective locations for the cameras at the two bridge openings. Note that some vegetation clearance might be necessary at both locations in order that the camera view of the flow cross-section is not obstructed.

Video of flow conditions and measurement of flow at prospective DischargeKeeper sites is required for calibrating the coefficient used to convert surface velocity readings to mean velocities, and here that could be achieved on both channels, at least during in-bank flow conditions, prior to purchase of the system. Further readings should be taken however during flood flow conditions when discharge passes out of bank from the channels themselves onto the small floodplain areas present between the two sets of bridge openings as flow characteristics here will be different, being subject to more surface roughness and interference from bridge piers than flow in the main channels.

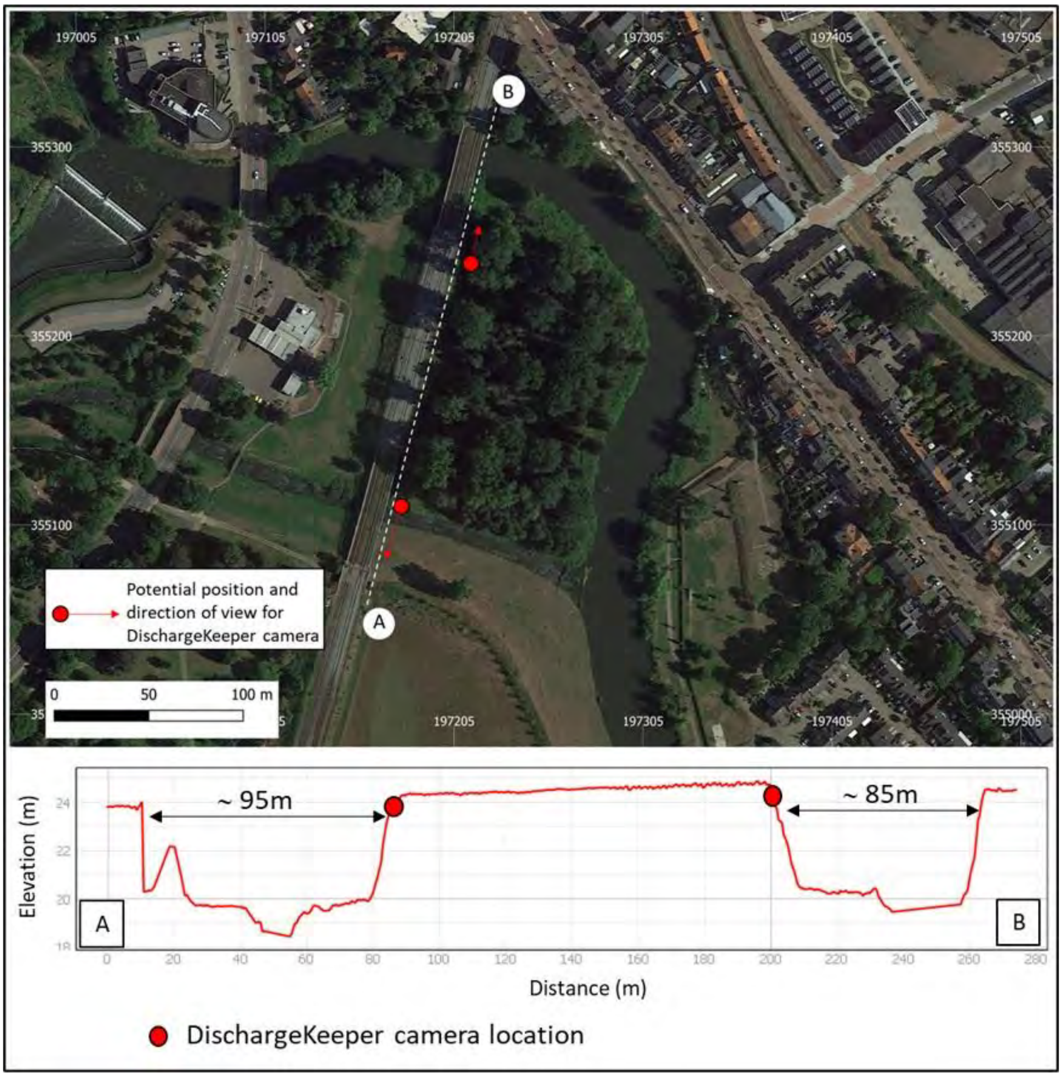


Figure 35. Possible siting locations for DischargeKeeper cameras at Site 1. Transect image below shows vertical placement of cameras and approximate maximum distance over which images would have to be obtained.

5.3.2.3. Option 2: Discharge measurement range

The DischargeKeeper system should be capable of measuring the full range of flows that are likely to be encountered in the lower Roer at this site from low base flows, up to any expected peak flow condition. For example, referring to Figure 34, it can be seen that a modeled flood flow of 500 m^3s^{-1} is predicted to lie at a stage elevation of approximately 22 m NAP at the two bridge openings which is well below the elevation of the bridge decks meaning that such a flow would pass unrestricted through the bridges and would be measurable by the two DischargeKeeper cameras.

5.3.2.4. Option 2: Cost

The cost of the DischargeKeeper system for sites where camera-based data is required over a distance of between 50 m and 250 m, as would be the case at this site, is €45,000.00 (excluding VAT) per camera setup including installation. Therefore, the total cost for this site would be €90,000.00 (excluding VAT) in total for the hardware, assuming that only two cameras are required (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made include:

1) Pole mounting for the two cameras.
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.
3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing.
4) Costing for Waterschap Limburg staff to collect data on flow conditions at the site, preferably using ADCP, prior to installation of the system. As it is likely that field measurement will not initially be available for flow that pass out-of-bank onto the floodplain areas at each site a management strategy and funding would have to be put in place to make sure that such data is collected, on an opportunistic basis, as and when such conditions do occur.

5.3.2.5. Option 2: Limitations

One limitation with use of the system at this site lies with the fact that permission would have to be sought from ProRail who own the railway infrastructure to mount the cameras on the railway embankments or bridges themselves. However, if this were not possible, the cameras could be mounted on tall poles set in ground near to, but not on, land owned by ProRail.

A second limitation lies in the fact that, while flow calibration data could be obtained for the site under in-bank flow conditions, such data may not be available for out-of-bank conditions prior to installation of the system. However, the system can be configured and adjusted remotely by SEBA staff so once ADCP based flow data had been obtained during flood-flow conditions, results from this could be used to adjust the surface velocity conversion parameter.

A third limitation of the setup here lies in the fact that the night vision of the DischargeKeeper cameras is quoted as being good up to 50 m distance which is not quite adequate for the full potential range required during flood conditions at both bridge openings. It may therefore be necessary to actually employ two cameras at each opening, one on either side to cover the full potential flow width during hours of darkness. Consultation should be sought with SEBA staff to discuss whether this limitation can be overcome during the scoping phase if the system is actively considered for use at this location.

5.3.2.6. Option 2: Uncertainty estimate

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. The measurable velocity range is quoted as being 0.2 to 15 ms^{-1} which is more than adequate for the site in question. Uncertainty will be associated with the conversion of surface velocity values to mean values in the case of out-of-bank flow conditions as calibration data is unlikely to be available at the time of system installation. Therefore, initially, it is considered that the uncertainty in discharge estimates will be greater than the 10 % value quoted in specification for the system and could be as high as 20 % prior to the acquisition of calibration data during high-flow conditions.

5.3.2.7. Option 2: Robustness of approach

The use of image-based surface velocimetry at this site will be subject to the factors outlined in Section 5.2.2.2. for the application of the DischargeKeeper at Site 4 (the Stah gauge location). However, because there are continuous flow conditions at this site, as compared with the culverts at Site 4, calibration data for determining the surface velocity to depth-averaged velocity conversion coefficient can be collected prior to installation, at least for in-bank flows, providing some initial data from which the accuracy of the system can be assessed, and performance optimised. There are potential limitations though in that it is not known, at this time, whether the system could be set up to image the entire potential flood-flow width at night, the maximum night-time range of the infra-red cameras quoted as being 50 m in the DischargeKeeper technical specifications. This issue would have to be resolved through discussion with SEBA staff if Waterschap Limburg were to pursue this option further. In terms of cost the estimate for installing a two DischargeKeeper cameras at this site (one for each channel) would be €90,000.00 (excluding VAT) which is similar to the hardware cost quoted for the fluvial acoustic tomography option at this site (€93,516.00 (excluding VAT and shipping)) but is considered a lower risk option in terms of implementation as the DischargeKeeper is sited, installed and managed by staff from SEBA, the company that makes the system.

5.4. Option for discharge measurement at Site 3 (51.14876144°N, 6.00349374°E)

Site 3 has been selected as an option for discharge measurement because there is the potential to measure a large proportion of out-of-bank flow at this location, as most floodplain flows are likely to pass the site through the small side stream, the Melicker Leigraaf which runs under a road approximately 325 m north of the end of the main road bridge over the Roer (refer to Figure 12). The proposed approach here is to develop a standard stage-discharge rating curve for the main channel at this point and to separately monitor the Melicker Leigraaf subsidiary channel using the DischargeKeeper system or possibly the Geolux RSS-2-300WL flow meter radar system, as direct velocity measurements will be required at this site for accurate discharge measurement due to flow contraction through the bridge structure and due to obstruction of the flow downstream and backwater effects from the Roer itself.

5.4.1. Actions

Develop a stage-discharge rating curve for the Roer main channel at Site 3 using repeat ACDP transects to obtain accurate discharge measurements in combination with local stage readings. This site is suitable for a stage-discharge rating curve in that backwater effects from the River Meuse do not extend this far up the Roer. However, the suitability of the site must be investigated in more detail to make sure that it is suitable according to the stage-discharge siting characteristics defined by Rantz (1982a). There is currently a stage gauge located slightly upstream of the bridge at Site 3 that may be suitable for use as the stage reader for the proposed stage-discharge relationship here, but the siting of the gauge should be checked, especially with regard to its ability to read flow levels from zero flow up to the peak flow elevation within the channel.

Dr Hansen of SEBA Hydrometrie (hansen@seba.de) should be contacted to investigate installation of the DischargeKeeper camera-based velocimetry system on the right-bank of the Melicker Leigraaf stream immediately upstream of the road bridge that crosses this channel in order to capture as large a range of flows as possible that will pass beneath the roadway at this location. Use of the Geolux RSS-2-300WL flow meter radar system should also be considered as an alternative.

5.4.2. Site considerations

There is currently a stage gauge located just upstream of the bridge at Site 3 (gauge 2.H.2) that could possibly be used for development of a stage-discharge rating curve although its position means that it may not be ideal if any backwater conditions are created by the bridge piers during high flow. Suitability of this gauge must be investigated in more detail to make sure that it is able to measure stages from zero flow up to the peak flow elevation within the channel. If this gauge proves not to be suitable it is recommended that a new gauge be sited downstream of the bridge structure itself, away from flow disturbance caused by the bridge itself. A programme of discharge measurements will need to be activated in order to develop the stage-discharge relationship with measurements taken on a semi-regular basis over the course of possibly several years in order to develop enough points to define the rating curve. With regards to discharge measurement location, it is recommended that this be undertaken downstream of the bridge beyond the point where morphological adjustment of the channel, which may be caused by the bridge itself, occurs. Gauging transects could be aided by the setting up of a cableway across the channel along which a boat mounted ADCP such as the StreamPro (https://www.teledynemarine.com/brands/rdi/streampro) can be towed (also see Appendix J). A potential location for a discharge measurement transect that could be equipped with a cableway is shown in Figure 36. The potential location for a discharge measurement transect is denoted by the transect 'A-B'. Note, if morphological adjustment associated with the bridge itself is considered insignificant the downstream side of the bridge itself could be used for the discharge measurement transect and a cableway mounted to this structure. It is acknowledged that there is currently vegetation such as small trees growing beside the low flow channel at this location downstream of the bridge which may have to be managed and cut back for the site to perform better for stage-discharge measurements. The advantage of this Site is that the channel is slightly incised into the floodplain here meaning that flows up to 500 m^3s^{-1} appear to be contained in the channel itself at this point (see Figure 36). Note that the elevation data is truncated in Figure 36 and does not show the full bathymetry below the elevation where the LiDAR could penetrate.

With regards to the suitability of the DischargeKeeper system for use at the Melicker Leigraaf bridge crossing, advice was sought from Dr Issa Hansen of SEBA, who thought that it could be used here, based upon the site information provided. Information on specific siting of the camera for the DischargeKeeper system at this location was not provided by Dr Hansen, but the authors of this report considered placing the camera as shown in Figure 36. The cross-sectional area that could be monitored by the system is shown in transect 'C-D' in this figure. This location is likely to be suitable because both low flows which occur in the stream here during normal conditions, and high flood-flow conditions, can be monitored from the same vantage point. The surface velocity would be measured across the upstream opening area of the bridge that passes over the Melicker Leigraaf. Flows could be measured up to, but not including the point where they are impeded by the underside of the bridge deck itself as this would severely distort the velocity profile and make conversion of surface velocity measurements to depth averaged values highly suspect.

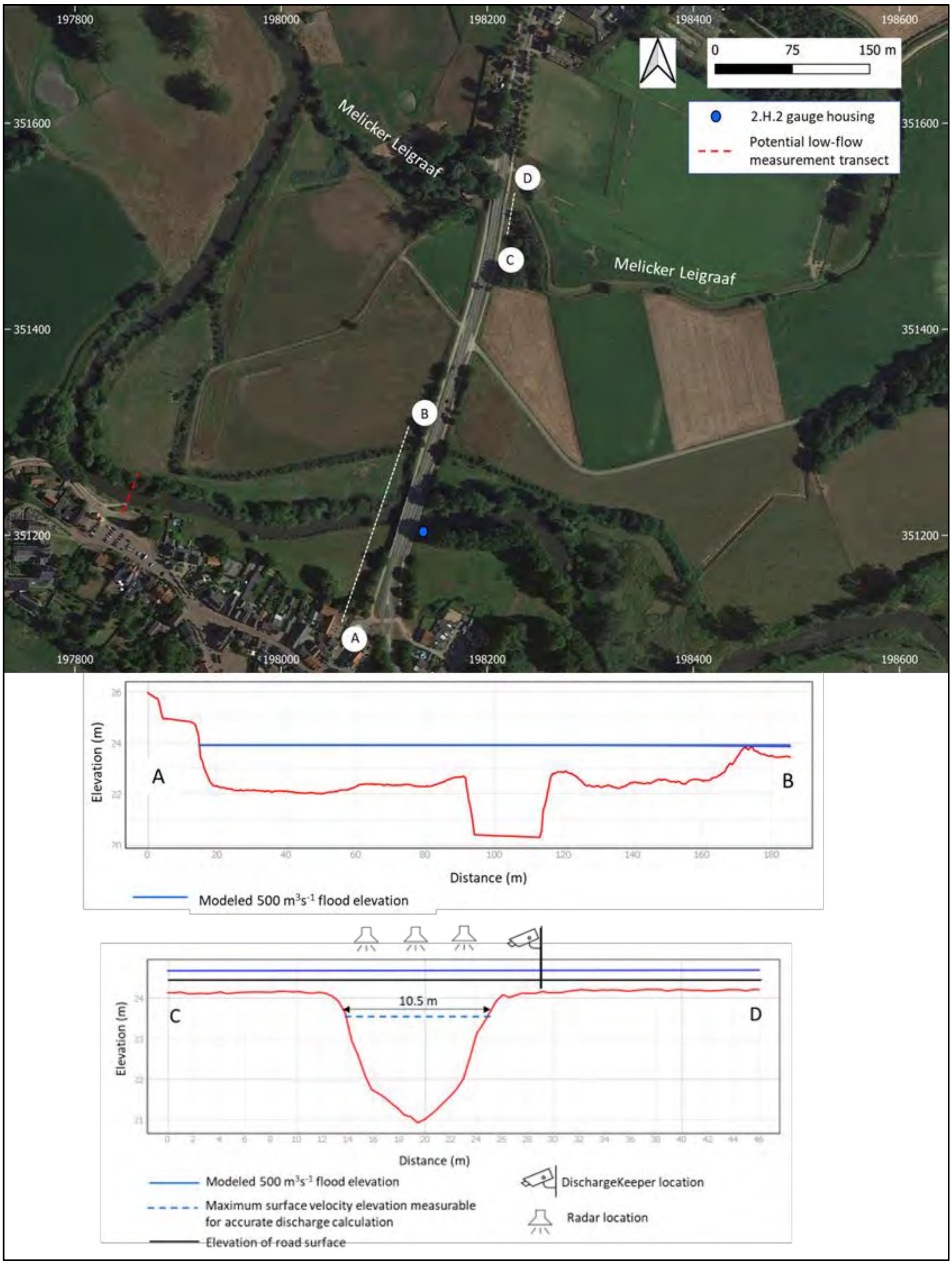


Figure 36. *Possible position for discharge measurement transects at Site 3 for the purpose of developing stage-discharge rating curve and proposed location for a DischargeKeeper camera or surface velocity radar to measure flow in the Melicker Leigraaf side channel.*

5.4.3. Discharge measurement range

As discussed in Section 5.4.2. it appears likely that the rating curve developed for the main Roer channel will be capable of measuring a discharge range from minimum base flows up to a discharge lying at an elevation of 24 m NAP (refer to Figure 36, transect 'A-B'). The modeled discharge for this high-flow elevation is 500 m^3s^{-1}, but the rating curve will not be capable of capturing this entire discharge as a proportion of the flow is likely to go out-of-bank in flood conditions on the right-hand floodplain and will pass downstream through the Melicker Leigraaf channel. It is proposed that this channel is monitored using a DischargeKeeper system which would be capable of measuring discharge from base-flows to flows that are augmented by flood flow from the Roer itself up to stage elevation of approximately 23.5 m NAP a height that is estimated to lie just below the lowest elevation of the bridge deck (refer to Figure 36, transect 'C-D'). Note that flows up to 500 m^3s^{-1} cannot be monitored though as they will not be contained within the cross-section available at this point and will in fact pass over the road surface on top of the bridge here rising to an elevation of 25 m NAP. The discharge that would be captured at the peak measurable stage in the Melicker Leigraaf is unknown but the combination of the rating curve in the main Roer channel and discharge measurement using the DischargeKeeper system in the Melicker Leigraaf is, combined, likely to measure almost all flows expected to be experienced at this point on the Roer.

5.4.4. Cost

The cost of developing a stage-discharge rating curve for the site is not quantified here but the costs to consider are:

- Possible installation of a cableway used to guide a boat mounted ADCP.
- Possible installation of a new stage gauge downstream of the bridge location if the current gauge proves not to be suitable.
- The man-hours and hardware cost for obtaining the data required to develop the rating curve, collected by repeat transect survey of the flow cross-section using ADCP.
- Man-hours for processing ADCP data and developing the rating curve.

The cost quoted for one DischargeKeeper system for a river width of up to 50 m (which will be adequate for the Melicker Leigraaf bridge site) is €37,000.00 (excluding VAT) (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made when installing this system include:

1) Pole mounting for the camera.
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.
3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing.
4) Costing for Waterschap Limburg staff to collect data on flow conditions in the Melicker Leigraaf, preferably using ADCP, prior to installation of the system. As it is likely that field measurement will not initially be available for high flows at this site and a strategy and funding would have to be put in place to make sure that such data is collected, on an opportunistic basis, as and when such conditions do occur.

5.4.5. Limitations

There may be limitations in developing a stage-discharge rating curve here that have not been accounted for. The assumptions for developing a good stage-discharge rating curve include the requirement that flow is relatively uniform, that there is not a backwater, induced from an obstruction downstream, created through the site over the full range of flows expected, and that the channel morphology is relatively stable. It is known that the influence of backwater from the Meuse does not extend this far upstream meaning that the site is not compromised in that manner, but further hydraulic analysis should be performed to see if other, more local factors may come into play here. It is known that the Roer is geomorphologically active in this reach so once the rating curve has been established it should be checked periodically for anomalies in the relationship caused by change in the local bed level and bank alignment due to geomorphological activity. One further issue to consider if developing a rating curve is the time necessary to do so, which will be over the course of several years, as data will be required for the full range of in-channel flows.

Limitations associated with the use of the DischargeKeeper system include the fact that flow measurements will be required in the Melicker Leigraaf channel in order to determine the alpha coefficient required to convert surface flow velocities to depth averaged values and these may only be possible for very low flows in this channel initially. A concerted effort needs to be made therefore to access this site and take readings in this channel using ADCP during higher flows in order that the DischargeKeeper can be accurately calibrated. It is likely that the velocity profile will be complicated at this site because during high flows discharge will contract and accelerate through the bridge opening causing the type of local depth and velocities changes shown in Figure 33, and because the surface roughness may be variable with time of year for out of bank flows as the riverbank here is composed of dense vegetation (see Plate 12).

5.4.6. Uncertainty estimate

Rating curves typically have a 4 % - 12 % error as compared with in situ measurements (Horner et al., 2018) and Rantz (1982b) states that if a stage-discharge curve is developed correctly the error between rating curve discharges and those determined in the field should be no more that 5 %.

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. There will also be uncertainty associated with the conversion of surface velocity values to mean values in the case of out-of-low-flow channel conditions in the Melicker Leigraaf as calibration data is unlikely to be available at the time of system installation. Therefore, initially, it is considered that the uncertainty in discharge estimates will be greater than the 10% value quoted in specification for the system and could be as high as 20% prior to acquisition of calibration data during high-flow conditions.

5.4.7. Robustness of approach

The development of a rating curve, based upon field-measured discharge data, at a site having appropriate conditions (Rantz, 1982a) is considered a highly robust method for determining discharge. Site 3 is considered reasonable for the application of a standard rating curve technique as the Roer, this far upstream from the Meuse, is not affected by backwater conditions created by that river. The local hydraulic conditions should be investigated further though using, for example, the 1D SOBEK model to check that there are no features local to this site that might influence a linear stage-discharge relationship. Standard caveats regarding channel stability should also be borne in mind and it is recognised that the rating curve would have to be checked periodically for drift in the relationship due to bed level changes. One limitation of developing a new rating curve is that field measurements will be required across a range of flows which will induce a cost and time expense.

With regards to capturing out of bank flows that are likely to be directed through the Melicker Leigraaf, the application of the DischargeKeeper system is recommended in order that the surface velocity distribution can be obtained across the full width of expected flows (refer to Section 5.4.2.) in this channel. The limitations associated with this system, including measurement of surface velocity and the conversion of that velocity to a depth-averaged value are outlined in Section 5.2.2.2. and would have to be considered further in consultation with SEBA staff. The cost of the DischargeKeeper system for use at Site 3 is projected to be €35,000.00 (excluding VAT), a considerable investment. However, one option that could also be explored is the installation of a k-band radar, such as the Geolux RSS-2-300WL flow meter, on the road bridge over the Melicker Leigraaf to determine discharge for flows that fall within this channel. This system could not be used for high out-of-channel flows here, as the radar provides a local estimate of velocity, but it would represent a much cheaper system to install, costing €4,800.00 (excluding VAT).

5.5. Option for discharge measurement at Site 2 (51.17534308°N, 5.98756243°E)

Site 2 was originally selected as a potential new discharge measurement location because the Roer river channel is set at this point against high ground on the left-bank meaning that all flood flows here will pass out of bank on the right floodplain and will pass over a well-maintained cycle path that runs at ninety degrees to the floodplain. Consequently, it was considered suitable as access to the site could be made during flood flows safety via the road infrastructure on the left-hand floodplain and the cycle path, when submerged would offer a stable transect, of fixed roughness, which could be monitored using, for example, a DischargeKeeper system. The draw-back of the site is the fact that the lateral extent of flood plain flows could be over 1.2 km, with a depth of up to 2 m on the floodplain itself for a 500 m^3s^{-1} flood event (refer to Figure 11). This site is therefore actually less suitable than Site's 1, 3 and 4 with regards to capturing a wide range of flows but is included here for completeness.

A second reason for developing a new rating curve here, or upstream at Site 3, is that through discussion with staff from Waterschap Limburg, it was understood that there were issues with predictions made by their 1-D SOBEK model of the lower Roer because it was thought that a certain percentage of the flows recorded at the Stah gauge (which are used as the upstream boundary conditions in the model) are in fact lost or augmented further downstream in the catchment due to groundwater inflow/outflow. Thus, having a second gauging station at this site would help determine the magnitude of these, as yet unrecorded, groundwater flows between Site 2 (or 3) and the Stah gauge upstream. The SOBEK model predictions could therefore be improved with data from this new gauge.

One other factor that makes this site attractive, at least for in-channel flow measurement, is that fact that bathymetric surveys are made on a regular basis in this reach to check that there is a sufficient depth of sediment cover between the channel bed and the A73 road tunnel which passes beneath the channel here (refer to Section 2.4). These repeat surveys can therefore also be used to check the stability of the bathymetry associated with the gauging station site and adjustments made to the cross-sectional geometry as necessary when detected.

5.5.1. Actions

As Site 2 is affected by backwater from the River Meuse downstream a Q-H rating curve cannot be developed here. Therefore, a direct velocity measurement system is required, and it is recommended to employ the DischargeKeeper system at this site. Dr Hansen of SEBA Hydrometrie (hansen@seba.de) should therefore be contacted to discuss installation of this system.

5.5.2. Site considerations

It is recommended to place the DischargeKeeper camera on high ground on the left-bank of the Roer at this site. The suggested location for the camera is shown in Figure 37.

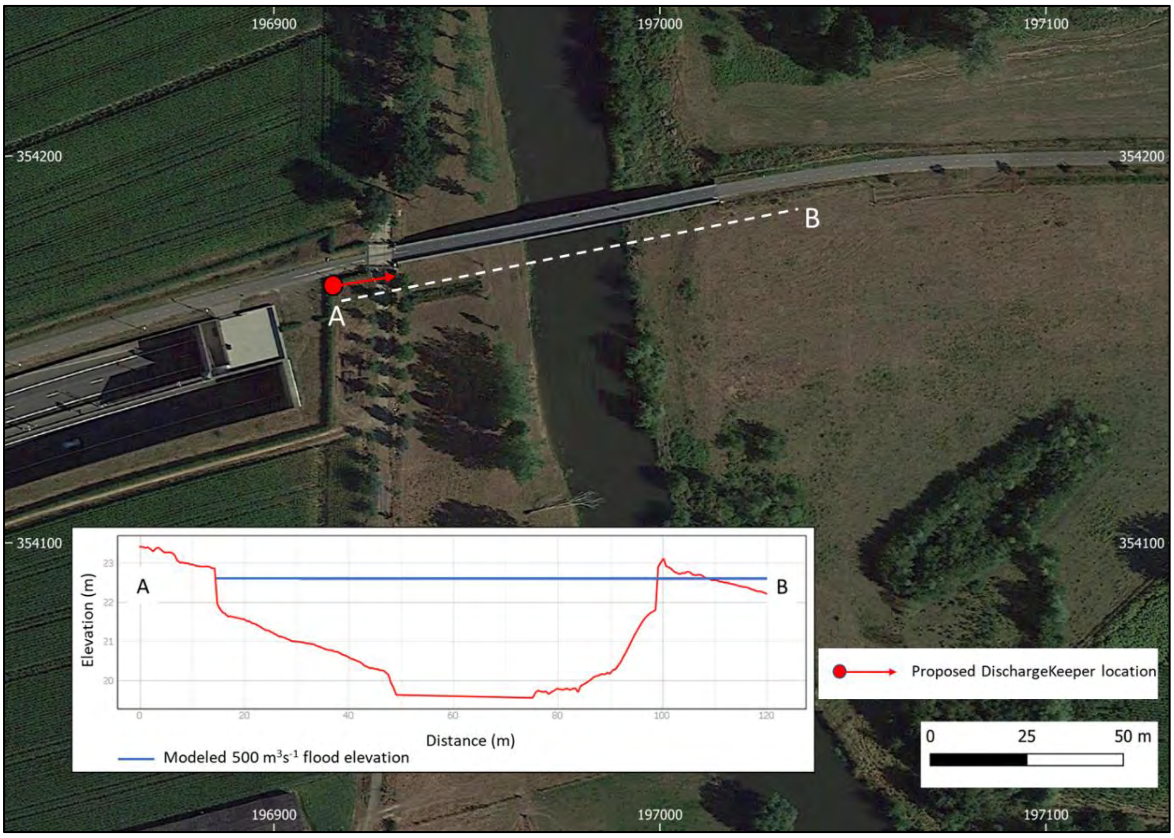


Figure 37. *Site 2 showing the suggested location for placement of a DischargeKeeper camera. Inset diagram shows a terrain cross-section profile along line 'A–B' with the modeled 500 m^3s^{-1} flood elevation marked. Note that the bathymetry is truncated in this cross-section at approximately 19.5 m due to no-return in the LiDAR data used to develop the digital terrain model.*

This point is accessible by vehicle and lies above even the highest likely flood flow elevation. It is suggested that a DischargeKeeper be used solely to monitor flows within the channel cross-section itself, and not across the full potential floodable width of the right-hand floodplain as this would in fact entail the use of multiple cameras along a transect, each of which would monitor a portion of the floodplain flow. The cost involved in doing this, and the uncertainty associated with attempting to sum readings from multiple cameras is considered too high to make the instrumentation of the total potentially floodable width feasible. For the DischargeKeeper camera used to monitor the channel cross-section the siting and operational factors outlined in Section 5.2.2.2. should be considered. This cross-section monitoring location is considered to be quite suitable for camera-based velocimetry as the channel boundary is free of vegetation and the channel cross-section is regular and relatively straight meaning that the conversion of measured surface velocities to depth-averaged values using an alpha coefficient should be relatively straight-forward once ADCP measurement of a range of flows has been undertaken to provide input data for this conversion factor.

5.5.3. Discharge measurement range

The DischargeKeeper installed at Site 2 will be able to measure a range of discharges from base-flows up to and including flows which reach a depth of approximately 23 m NAP. It can be seen in Figure 37 that that a modelled 500 m^3s^{-1} flood event water surface elevation lies 22.8 m NAP at this location, but this does not mean of course that the DischargeKeeper will be able to measure discharges of this magnitude as, upstream of the bridge cross-section itself, flow will pass out-of-bank at stages as low as 21.2 m NAP and will then bypass the river channel on the right-hand floodplain. It is not possible to ascertain the actual maximum discharge that may be captured by the DischargeKeeper within the channel itself without detailed hydraulic modeling.

5.5.4. Cost

The DischargeKeeper camera will need to be able to sense a maximum, flood-flow river width of approximately 85 m at this site. The cost of a single DischargeKeeper system that is capably of measuring across this lateral extent is €45,000.00 (excluding VAT) (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made when installing this system include:

1) Pole mounting for the camera.
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.
3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing.
4) Costs incurred for Waterschap Limburg staff to collect calibration flow data, preferably using ADCP, across the transect that will be imaged by the DischargeKeeper camera in order to determine the surface velocity alpha conversion coefficient. Collection of such data should be relatively straightforward at this site and can be undertaken using a boat or towed ADCP unit such as the StreamPro.

5.5.5. Limitations

There are two key limitations with this setup. First, the quoted night-time operating range of the DischargeKeeper camera is 50 m, while the possible maximum range that needs to be sensed at this location is up to 85 m in flood flows. This means that if flood flow conditions occur during the hours of darkness a certain portion of the flow width may not be picked up by the camera. The solution to this problem may be to mount two cameras at the site, one on either side of the channel to cover the full potential flow width but this issue has not been investigated in detail by the authors and it is recommended that SEBA Hydrometrie be contacted to discuss this particular problem. The second limitation is that only in-channel flows will be picked up by the use of a single DischargeKeeper system at this site and the extent, and volume of flow out-of-bank flows during floods may be significant.

5.5.6. Uncertainty estimate

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. Also, night vision of the camera is quoted as being good up to 50 m distance, as mentioned above, which is significantly less that the potential maximum width that may be found here during flood conditions. SEBA staff should be consulted to discuss options to increase the measurement range during hours of darkness. The measurable velocity range of the DischargeKeeper is quoted as being 0.2 to 15 ms^{-1} which is more than adequate for the site in question. There will also be uncertainty associated with the conversion of surface velocity values to mean values although it will be relatively easy to obtain ADCP transects at this site over a range of flow conditions in order to calibrate the surface velocity alpha conversion coefficient.

5.5.7. Robustness of approach

The installation of a DischargeKeeper system at this site to monitor in-bank flows is thought to be a relatively risk-free option as site conditions are favourable for the use of camera-based velocimetry and good surface velocity calibration data can be obtained with relative ease. The issue of sensing the full flow width during floods at night must be addressed however as the night-time effective range of the DischargeKeeper camera system is documented as being 50 m while the full flood width of flow in the channel section itself may be up to 85 m. Also, it is important to recognise that the option of measuring in-the channel flow at this site alone means that flood flows will not be picked up and the in-bank range of flows that will likely be contained by the channel at Site 2 appears to be considerably lower than say at Site 3, making the latter a preferential choice if only in-bank flows are to be gauged.

6. Recommendations

The scope of research presented to the authors of this report was to explore the possibilities for measuring discharge over a wide range of flows (between 5 and 500 m^3s^{-1}) on the lower Roer river from the Stah gauging station (51.09770467°N, 6.10475772°E) downstream as far as the river's confluence with the Meuse river in Roermond. A series of nine sub-questions or instructions were also posed to help focus the scope of work, which are as follows:

1. What does a measurement site need to meet to deliver good continuous flow measurement? This includes taking into account the infrastructure, accessibility and land ownership present.
2. Are there any other site conditions to consider?
3. Conduct a site survey to identify the best measurement location.
4. Is an existing measurement site suitable or adaptable for this flow measurement?
5. Which measurement system or combination of measurement systems can best be used?
6. What is technically required to adapt or set up a flow measurement system?
7. A cost estimate for setting up the measurement system.
8. What measurement range and measurement error can be expected and is realistic?
9. Advice on how to perform maintenance of the station to guarantee a good quality of the measurement.

In this Chapter these questions and instructions will be addressed in the above order and recommendations presented on which of the eight discharge measurement options presented in Chapter 5 the authors suggest should be pursued in order to best fulfil the overall remit of the project aim, that of measuring as wide a flow range as possible through a continuous gauging system. A summary of the eight discharge measurement options that were explored in Chapter 5 are given in Table 7. Recall that the discharge measurement techniques investigated in this research were the following:

1. Extension/development of a rating curve using numerical model and field data.
2. Camera-based surface image velocimetry.
3. Radar-based surface image velocimetry.
4. Fluvial Acoustic Tomography.

6.2. What does a measurement site need to meet to deliver good continuous flow measurement?

Prior to conducting a field survey, the authors of this report used maps, digital terrain data and a 500 m^3s^{-1} modeled flood extent map to determine where out-of-bank flows are likely to naturally spread across the floodplain on the lower Roer in order to help focus the field visit. The main factors considered when looking for a satisfactory continuous gauging site, which are applicable to all four discharge measurement methods explored, were as follows:

1) Containment of the lateral extent of flood flows: Regardless of the practical method used to determine discharge, if flood flows need to be included in the measurement range, then flow needs to be contained either naturally, or physically by structures, within as narrow a lateral extent as possible. This is because discharge, is compose of two variables which must both be measured: a) the cross-sectional area of the flow, and; b) the mean velocity of the flow within that area. Therefore, any continuous discharge measurement system must be capable of determining both

of these variables across the entire range of flows that are encountered, and it is therefore beneficial if both of these parameters are contained within a restricted fixed cross-section where area is known, and velocity can be measured with confidence. In the desk-based phase of this study the authors therefore looked for locations on the lower Roer where the flood flow extent, as predicted by the numerical modeling results, appeared to be constrained within as narrow a section as possible, such as between bridge abutments or by natural geographical features.

2) Accessibility: Regardless of the gauging method used the site must be accessible for four main reasons:

    1. Installation of required flow measurement equipment.
    2. Collection of initial data required to calibrate the discharge measurement system (this applies to most discharge measurement techniques including rating curves and the used of camera-based velocimetry or surface radar).
    3. Site maintenance and repair of the measurement infrastructure.
    4. Periodic re-survey of the site bathymetry to check whether the geometry used in the discharge measurement technique has adjusted due to morphological change in the channel. This requirement applies to any discharge measurement techniques employed as all require a known, pre-surveyed, bathymetry in order to determine discharge.

   The potential gauging sites considered by the authors are all accessible by vehicle and are located at or close to publicly accessible road bridge crossing of the Roer main channel.

3) Land ownership and river management policy restrictions: Any discharge measurement infrastructure will need to be placed on land, or attached to a structure, which is likely to be owned by a third-party organisation or individual. The installation of a gauging station will necessarily mean that, at the very least, access rights will have to be secured to the river channel section to be gauged and land possibly bought if permanent structures are to be installed. The specifics of land ownership were not investigated for the gauging sites chosen in this research but the necessity for land purchase or permission to install infrastructure is raised where appropriate in each of the options presented in Chapter 5. One important factor that had to be taken into account on the lower Roer was that of a current river management policy which stipulates that the Roer river channel must be free to naturally meander across its floodplain upstream of the Roermond urban area. This stipulation led the authors of this report to discount one important gauging measurement option, that of using a fixed weir of flume structure, as for such devices to work effectively the river channel would have to be locked in place on the floodplain so that the structure does not have the potential to be bypassed by natural migration of the channel.

6.3. Are there any other site conditions to consider?

The four different gauging techniques identified as potential candidates for extended discharge measurement each have their own specific set of requirements in terms of site condition. These are outlined in Chapter 4 in associated with each technique but are re-iterated in Section 6.7 of this Chapter in association with the specific option identified by the authors as likely to be most successful in terms of fulfilling the remit of the scope of work.

Site	Option	Measurement technique	Costs*	Measurement Range	Accuracy
1	1	Fluvial Acoustic Tomography (FAT).	1) FAT equipment: €93,516. 2) FAT unit installation and transmitter housing plus cable routing. 3) 9 × cross-section surveys. 4) 5 × pressure transducer installation.	Discharge: 0 – 500 m^3s^{-1}.	• Flow velocity: ± 0.1 cms^{-1} • Discharge < 15 %.
	2	DischargeKeeper.	1) 2 × DischargeKeeper units: €90,000. 2) Camera mounting and housing. 3) Cross-section survey and field discharge measurement campaign.	Discharge: 0 – 500 m^3s^{-1}.	• Flow velocity: < 5 % error. • Water level: < 1 cm error. • Discharge < 10 % with accurate calibration. Initial error max. ~ 20%.
2		DischargeKeeper.	1) DischargeKeeper unit: €45,000. 2) Camera mounting and housing. 3) Possible land purchase in vicinity of camera. 4) Cross-section survey and field discharge measurement campaign.	Discharge: 0 m^3s^{-1} to unknown maximum. Stages up to 23m NAP.	• Flow velocity: < 5 % error. • Water level: < 1 cm error. • Discharge < 10 % with accurate calibration. Initial error max. ~ 20%.
3		Main Roer channel: Rating curve. Melicker Leigraaf channel: DischargeKeeper.	1) Man-hours for discharge measurement and analysis of data. 2) Possible installation of new and/or secondary stage gauge. 3) DischargeKeeper unit: €37,000. 4) Camera mounting and housing. 5) Possible land purchase for siting camera. 6) Cross-section survey and field discharge measurement campaign.	Main Roer channel discharge 0 m^3s^{-1} to maximum stage of 24m NAP. Melicker Leigraaf side channel range 0 m^3s^{-1} to discharge at a stage of 23.5m NAP.	For DischargeKeeper in Melicker Leigraaf: • Flow velocity: < 5 % error. • Water level: < 1 cm error. • Discharge < 10 % with accurate calibration. Initial error max. ~ 20%. • Main channel rating curve should remain within 5% of true values if maintained correctly.
4	1	Extended rating curve via modeling (main channel and floodplain).	1) Towable ADCP (StreamPro): €18,295 (if required). 2) Man-hours for measurement of discharge. 3) Man-hours numerical modelling.	Discharge: 0 – 500 m^3s^{-1}. 0 – 135 m^3s^{-1} initially on current rating and 135 – 500 m^3s^{-1} via numerical model extension. Extend reliable gauge reading from 32.5m NAP to 32.9m NAP.	• Current rating curve should remain within 5% of true values if maintained correctly. • Initial modeled rating may deviate by approx. 10% - 20% prior to calibration.
	2	Floodplain bypass culverts: DischargeKeeper.	1) DischargeKeeper unit: €37,000. 2) Camera mounting and housing. 3) Possible land purchase for siting camera. 4) Cross-section survey and discharge measurement campaign.	Flow through two bypass culverts. Discharge unknown. Stage measurement range ~ 32 m NAP - 32.6 m NAP from culvert low flow to near-full capacity.	• Flow velocity: < 5 % error. • Water level: < 1 cm error. • Discharge < 10 % with accurate calibration. Initial error max. approx. 20%.
	3	Floodplain bypass culverts: Geolux surface velocity radar.	1) 2 × Geolux RSS-2-300WL flow meter: €9,600. 2) Radar mounting and housing. 3) Cross-section survey and field discharge measurement campaign.	Flow through two bypass culverts. Discharge unknown. Stage measurement range ~ 32 m NAP – 32.6 m NAP from culvert low flow to near-full capacity.	• Flow velocity: 1% accuracy. • Water level: ±2 mm. • Discharge < 10% with accurate calibration. Initial error max. ~ 20%.
	4	Main Roer channel: DischargeKeeper.	1) DischargeKeeper unit: €37,000. 2) Camera mounting and housing. 3) Possible land purchase fir siting camera. 4) Cross-section survey and discharge measurement campaign.	Discharge in main channel from 0 m^3s^{-1} to unknown peak. Assumed to be greater than measurable by the current rating (135 m^3s^{-1}). Entire range of flow depths measurable.	• Flow velocity: < 5 % error. • Water level: < 1 cm error. • Discharge < 10 % with accurate calibration. Initial error max. ~ 20%.

Prices do not include VAT and any additional shipping costs.

Table 7. Summary of discharge measurement options for Sites 1 to 4 on the lower Roer as detailed in Chapter 5.

One further site consideration, specific to this project, not identified in the initial research proposal was the fact that the Stah gauging station on the Roer is considered by Waterschap Limburg staff to be off primary importance. This is because it represents the furthest upstream point on the Roer that they actively monitor and therefore provides that greatest flood warning lead-in time for the town of Roermond, there being a delay of approximately 8 to 15 hours between a flood passing the Stah gauge and its arrival at the town. Therefore, the Stah gauge represents the site operated by the Waterschap Limburg from which they would primarily wish to receive improved discharge measurement capabilities if possible, with sites lying further downstream being considered less optimal due to shorter flood warning lead-in times. This operationally specific issue had therefore to be considered when selecting a gauging location for extended discharge measurement.

6.4. Conduct a site survey to identify the best measurement location.

A field site visit was undertaken on the 5th July 2023 and sites along the lower Roer visited based upon prior identification of suitable locations using map data and flood modeling results. From this combined desk and field exercise four potential gauging sites were identified on the lower Roer lying between the outskirt of Roermond and the Stah gauging station itself, which is located approximately 24 river kilometers upstream, close to the Dutch-German border. The details of these four sites, the specific reasons for selecting them, and their site characteristics are discussed in detail in Chapter 3. A summary of the site locations is presented here in Table 7 and are shown geographically in Figure 6 (Chapter 3).

Table 7. Locations on the lower Roer selected as potential discharge measurement stations.

Site	Description	River centre-line coordinates	River kilometre distance to Roermond city limits* (km)	Rank according to potential for measuring flow in the range 5 to 500 m^3s^{-1}
1	Railway bridge crossing of the Roer and side channel (Groene Overlaat) on the south-eastern side of Roermond.	51.18545143°N, 5.99101103°E	0	1
2	Cycle/foot bridge located at the point where the A73 road passes in a tunnel beneath the Roer approx. 1 km south of Site 1.	51.17534308°N, 5.98756243°E	1.7	4
3	N293 road bridge crossing the Roer located between Sint Odilienberg and Melick.	51.14876144°N, 6.00349374°E	8	2
4	The Stah gauging station located in Germany on the K21 road between Kempen and Ophoven.	51.09770467°N, 6.10475772°E	24	3

* *City limits defined as the railway bridge crossing the Roer at location 51.18545143°N, 5.99101103°E.*

These four sites are ranked in Table 7 with regard to the primary objective, that of their suitability for measuring a wide range of flows, between 5 and 500 m^3s^{-1} using one or more of the discharge measurement techniques identified in Section 6.2. Site 1 represents the best candidate because all flood flows are likely to pass through two fixed bridge openings here, both of which could be monitored using camera-based velocimetry or radar (refer to Section 3.2 for details). Site 3 represents the second ranked ideal candidate because the modeling results shown that all flood flows will pass either through the main channel section, or along a nearby secondary channel that could be separately monitored (refer to Section 3.4 for details). Site 4, the Stah gauge is ranked third as although the current gauging station located at this site performs well for in-bank flows the potential for floodplain flow to be distributed over a wide lateral extend on either floodplain means that it is less than ideal for measuring flood discharge conditions (refer to Section 3.5). Finally, Site 2 is ranked fourth because, while the main channel is suitable for gauging using camera or radar-based velocimetry it appears from modeling results that out-of-bank flows at this site are likely to spread laterally over a floodplain width of up to 1.2 km (refer to Section 3.3).

Based solely upon the criteria of discharge measurement range, Site 1 would be the logical choice to recommend overall. However, the authors recommend the discharge measurement option associated with Site 3 because it offers a compromise in that there is the potential to actively measure a large proportion of flood flows here (although not up to 500 m^3s^{-1} as might otherwise be achievable at Site 1) and the site is located 8 kilometres upstream of Roermond city limits (refer to Table 7) thus providing some lead-in time for flood warning. Also, in making recommendations associated with Site 3 the authors also believe that there is the possibility for increasing flood warning-lead in times further at this site using a technique which is outlined in Section 6.11.

A second reason for developing a new discharge measurement station downstream of the Stah gauge is that, through discussion with staff from Waterschap Limburg, it was understood that there were issues with predictions made by their 1-D SOBEK model for the lower Roer because it was thought that a certain percentage of the flows recorded at the Stah gauge (which are used as the upstream boundary conditions in the model) are in fact lost or augmented further downstream in the catchment due to groundwater inflow/outflow. Thus, having a second gauging station at a site downstream would help determine the magnitude of these, as yet unrecorded, groundwater flows. The SOBEK model predictions could therefore be improved with data from this new gauge.

6.5. Is an existing measurement site suitable or adaptable for this flow measurement?

The current gauging station operated on the lower Roer by Waterschap Limburg, the Stah gauge, is the preferred site for discharge measurement by this authority because of the flood warning lead-in time that measurement from this site affords. However, as discussed in Section 6.4, this site is not ideal for high, out-of-bank flow measurement. Four Options are discussed that could be applied at the Stah gauge which are detailed in Chapter 5, (Section 5.2) and these approaches could be taken forward by Waterschap Limburg, but they are considered less likely to meet the primary aim of measuring the discharge range set out in the project scope.

6.6. Which measurement system or combination of measurement systems can best be used?

The authors recommend that Site 3 be selected for extended discharge measurement on the lower Roer because there is the potential to measure a large proportion of out-of-bank flow at this location as most floodplain flows are likely to pass the site through the small side stream, the Melicker Leigraaf, which runs under the road approximately 325 m north of the end of the main road bridge over the Roer (refer to Figure 12 in Chapter 3). The proposed approach is to develop a standard stage-discharge rating curve for the main channel at this point and to separately monitor the Melicker Leigraaf subsidiary channel using either surface-velocity sensing technology or radar. For flows that pass during flood events through the bridge opening over the Melicker Leigraaf the authors of this report recommend the use of the DischargeKeeper system (refer to Chapter 4, Section 4.4.4) or possibly the Geolux RSS-2-300WL flow meter radar system (refer to Chapter 4, Section 4.5.5.) as direct velocity measurements will be required at this site for accurate discharge measurement due to flow contraction through the bridge structure and due to obstruction of the flow downstream and backwater effects from the Roer itself.

6.7. What is technically required to adapt or set up a flow measurement system?

6.7.1. Rating curve measurement technique requirements

It is recommended that a standard stage-discharge (Q-H) rating curve be developed for the Roer main channel at Site 3 using repeat ACDP transects to obtain accurate discharge measurements in combination with local stage readings. The rating relationship will represent a fit to the spread of paired stage-discharge measurements and is typically defined by a power-type function of the form $Q(H) = a(H - H_o)^b$, where Q = discharge, H = stage, H_o = stage at which Q = 0, and a and b are a constant and coefficient respectively. The development of a rating curve, based upon field-measured discharge data, at a site having appropriate conditions is considered a highly robust method for determining discharge. The key criteria recommended by Rantz (1982a) for selecting an effective rating curve gauging site are:

1) The river course is straight for at least 100m upstream and downstream of the gauge site.
2) The site should be located away from a source of variable backwater. If there is likely to be backwater effects a uniform reach for measurement of water surface slope should be sought along with a site for installation of an auxiliary gauge.
3) Flow is confined to one channel at all stages and there is no bypass or sub-surface flow.
4) The stream is not subject to significant morphological change through scour and fill and is free of aquatic vegetation.
5) Banks are high enough to contain flood flows and are free of brush (vegetation).
6) There is some form of low flow control, such as a weir of riffle, or rock outcrop downstream of the stage gauge such that there is always a pool of water which will enable the gauge to measure low flows and to avoid excessive velocities at the gauge water intakes at high flows which might distort the stage reading.
7) A reach suitable for direct measurement of discharge is available close to the gauge (note that it is not necessary for both low and high flows to be measured at exactly the same location). The measurement cross-section should be in proximity to the gauge but does not need to be precisely at the same point.
8) The site is readily accessible for ease of installing and operating the gauging station.
9) Ideally the measurement section should be of fairly uniform depth and flow-lines parallel and fairly uniform throughout the cross-section.

Rantz (1982a) notes that, 'Rarely will an ideal site be found, and judgement must be exercised in choosing (an) adequate site, each of which (will have) some shortcomings'.

Site three is considered reasonable for the application of a standard rating curve technique because it is relatively straight for a distance of at least 100 m both upstream and downstream of the bridge crossing (criteria 1) (refer to Figure 38) and because the Roer, this far upstream from the Meuse, is not affected by backwater conditions created by that river (criteria 2). The local hydraulic conditions should be investigated further though using, for example, the Waterschap Limburg 1D SOBEK model to check that there are no features local to this site that might influence a linear stage-discharge relationship.

Note that, as suggested by criteria 2, the local measurement of water surface slope in conjunction with stage can be used to improve a rating curve relationship if the relationship displays some form of hysteresis. It is recommended that gauge 2.H.2 which is located at Site 3 (Figure 38) be used for this purpose in conjunction with a new gauge sited within a few hundred metres of this, either upstream or downstream, in order to obtain local water surface slope.

The 2.H.2 stage gauge could possibly be used for developing the stage-discharge rating curve at this site although its position means that it may not be ideal if any unusual backwater conditions are created by the bridge piers located on either bank here during high flow. Suitability of this gauge must be investigated in more detail to make sure that it is able to measure stages from zero flow up to the peak flow elevation within the channel. If this gauge proves not to be suitable it is recommended that a new gauge be sited downstream of the bridge structure away from flow disturbance caused by the bridge itself. It is not known if a pool forms in this reach at low flow, associated with a local downstream control, such that stage gauge readings can be taken from close to zero discharge (criteria 6) but an artificial low flow control could be built downstream of the gauge to achieve this. Such a control would take the form of a low in-channel weir that backs flow up to the stage-gauge intakes such that even at zero discharge in the channel there is some depth of flow in the pool at the gauge. Rantz (1982a) recommends that the intakes for a stage recorder should be located upstream from a low-water control at a distance equal to at least three times the depth of water on the control structure at the maximum estimated stage that is possible at that location. The reason for this is that if gauge intakes are located any closer than that to the control they may lie in a region where the streamlines have vertical curvature, a condition which is undesirable for accurate stage measurement.

A programme of discharge measurements will need to be activated in order to develop the stage-discharge relationship with measurements taken on a semi-regular basis over the course of possibly several high discharge events in order to develop enough points to define the rating curve. With regards to a discharge measurement location, it is recommended that this be undertaken downstream of the bridge. A suitable gauging transect could be developed by the setting up of a cableway across the channel along which a boat mounted ADCP such as the StreamPro (https://www.teledynemarine.com/brands/rdi/streampro) can be towed (also see Appendix J). A potential location for a discharge measurement transect that could be equipped with a cableway is shown in Figure 38 denoted by the transect 'A-B'. The advantage of this location is that the channel is slightly incised into the floodplain here meaning that flows up to 500 m^3s^{-1} appear to be contained in the channel itself at this point, the predicted water surface elevation for that discharge lying at 24 m NAP (criteria 3 and 5). Note, if morphological adjustment associated with the bridge itself is considered insignificant (criteria 4) the downstream side of the bridge itself could be used for the discharge measurement transect and a cableway mounted to this structure. Note that low and high flow measurements do not necessarily have to be made at exactly the same point (criteria 7), and from site investigation it appears that a location further downstream of the bridge might be ideal for low flow discharge measurement where vehicle access can be gained right down to channel level (see Figure 38).

It is acknowledged that there is currently vegetation such as small trees growing beside the low flow channel downstream of the bridge, which may have to be managed and cut back for discharge measurements to be made (criteria 5). This vegetation takes the form of small trees and while these will shed their leaves in winter the overall structure of the vegetation is likely to remain in place throughout the year meaning that their impact on the stage-discharge relationship will be fairly invariant with season. Aquatic vegetation growth within the channel itself did not appear to be a significant issue at the proposed discharge measurement point (criteria 4).

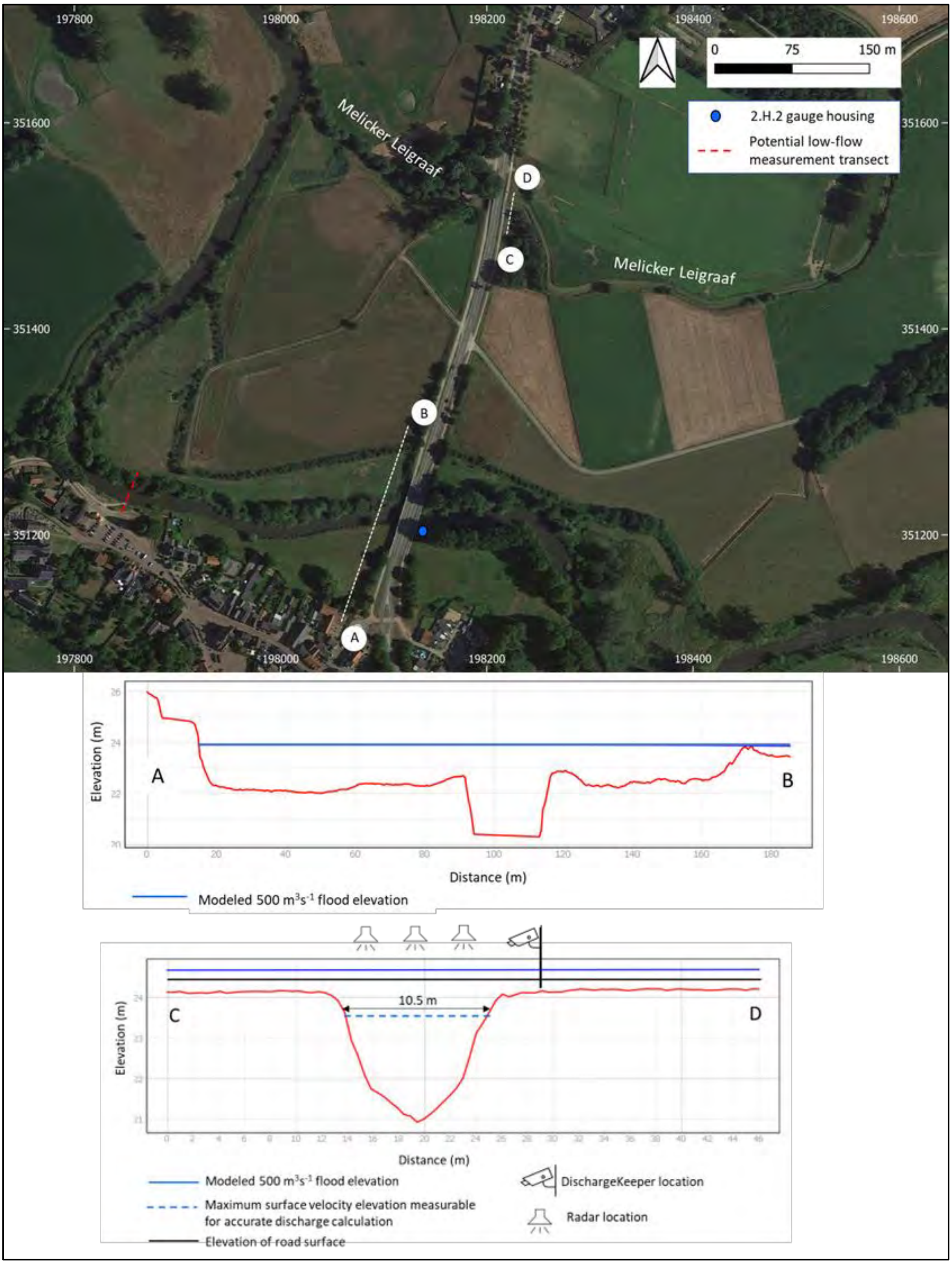


Figure 38. Possible position for location of discharge measurement transects at Site 3 for development of stage-discharge rating curve and siting location for surface velocity monitoring via camera or radar on the Melicker Leigraaf channel.

The degree to which the channel is morphologically active here is not known and will need to be investigated further, especially in the vicinity of the road bridge (criteria 4). It is known that the Roer is geomorphologically active in this reach so once the rating curve has been established it should be checked periodically for anomalies in the relationship cause by possible bed elevation and width changes.

With regards to criterion 9, there may be some departure from uniform, parallel flow lines during high flows at the proposed measurement location, because of the substantial bridge piers that support the road bridge which lie either side of the low flow channel but this limitation can be mitigated to some degree by setting the discharge measurement transect downstream of the bridge at a point where streamlines close up behind the bridge piers, as suggested by the placement of transect 'A-B'.

6.7.2. Melicker Leigraaf channel surface velocity-based discharge measurement technique requirements

The small tributary channel that lies to the north of the Roer at Site 3, the Melicker Leigraaf, is predicted to carry all out-of-bank flows that cannot be contained within the Roer main channel. A rating curve measurement approach cannot be used at this site due to likely backwater effects from the Roer itself and due obstruction downstream of the bridge that crosses this stream (refer to Section 3.4). The only reliable option available therefore here is to permanently measure velocity and combine this with known cross-sectional areas to calculate discharge. There are two options that are possible for performing this task that each have their advantages and disadvantage, either camera-based velocimetry or surface velocity radar either of which could be applied here. Camera-based velocimetry is discussed Chapter 4, Section 4.4, and surface velocity radar in Chapter 4, Section 4.5. The advantage of camera-based velocimetry is that the entire velocity distribution on the flow surface is determined whereas surface velocity radar simply give a point estimate. However, camera-based velocimetry relies on light as a sensing medium whereas surface velocity radar is not affected by light level. A disadvantage of both methods is that the measured surface velocity values must be converted to depth averaged values using a correction factor, the alpha coefficient, the value of which must be obtain with measured data from the site in question over a range of flow.

The camera-based velocimetry system that is recommended, the DischargeKeeper (DK), produced by SEBA Hydrometrie, is described in detail in Section 4.4.4. (also refer to Appendix D for a technical specification document on this system). Consultation has been sought with Dr Issa Hansen (hansen@seba.de) who works for SEBA, and who was one of the developers of the system, regarding its use at this location and Dr Hansen confirmed that the DischargeKeeper might be employable here as a discharge measurement solution. Information on specific siting of the camera for the DischargeKeeper system was not provided by Dr Hansen but the authors of this report considered placing the camera as shown in Figure 38, transect 'C–D'. This location is also shown in Plate 18. This location is likely to be suitable because both the low flows which occur in the stream here during normal conditions, and high flood-flow conditions, can be monitored from the same vantage point. Note that flows up to 500 m^3s^{-1} cannot be monitored though as they will not be contained within the cross-section available at this point and will in fact pass over the road surface on top of the bridge here. It appears then that, flows up to an elevation of 23.5 m NAP could be measured and converted to a discharge, but flows may rise above this level to 25 m NAP during a 500 m^3s^{-1} flood (Figure 38). Note that the maximum active flow width can be considered at this location as the cross-sectional area of flow within the bridge opening as all flows that have a water surface elevation below the maximum road height here must pass through the bridge cross-section. The active section that would have to be monitored therefore is that visible in Plate 20 and shown in Figure 38, transect 'C-D'.

The DischargeKeeper system also measures water level from the camera-imaging system and therefore bathymetry is tied to each set of velocity measurements enabling discharge to be calculated. Where this automatic detection is not possible, a pressure transducer can be installed locally and integrated with the DischargeKeeper system which uses this data to derive the bathymetry. It is also important to note that the camera systems operate in the infra-red range so can perform measurements round the clock, including during hours of darkness. The quoted night-time range of the camera system is 50 m. Installation of the DischargeKeeper system is normally undertaken by SEBA staff, although the customer can install it themselves if they wish. Configuration of the system is performed remotely, once all required parameters are available (cross-section, reference measurements, coordinates of two reference points on both channel banks and the camera position). In siting a DK camera SEBA staff consider the following factors:

- Primary flow direction.
- Degree of light/shadow and water surface glare.
- Consideration of the degree of surface roughness of the flow.

SEBA ask prospective users of the DischargeKeeper system to initially send site information to them using a standard form, from which they can make initial decisions regarding the potential utility of the device (see Appendix L). Much of this information could not be provided by the authors of this report and site suitability was considered from photographs and descriptions given to Dr Hansen of SEBA. The company survey and upload the total cross-section where measurements are to be made considering the highest water level under flood events which enables the DK to measure under low (as long as the roughness of the water surface is good enough for image processing) and high-water levels. Different types of cameras are used depending on the river/stream width and in this case, based upon the site photographs supplied, a PTZ camera was recommended which can cover flow widths of between 5 m and 160 m. Successful application of the system includes the requirement that: 1) there must be some visible movement on the water surface for the flow to be captured (wave heights > 3 mm), and: 2) sites are recommended to have flow velocities > 0.2 ms^{-1} (although they note that the system has been able to measure speeds as low as 0.1 ms^{-1} depending upon site conditions). Dr Hansen cautioned that strong wind and low flow velocities can increase uncertainty in surface velocity measurements.

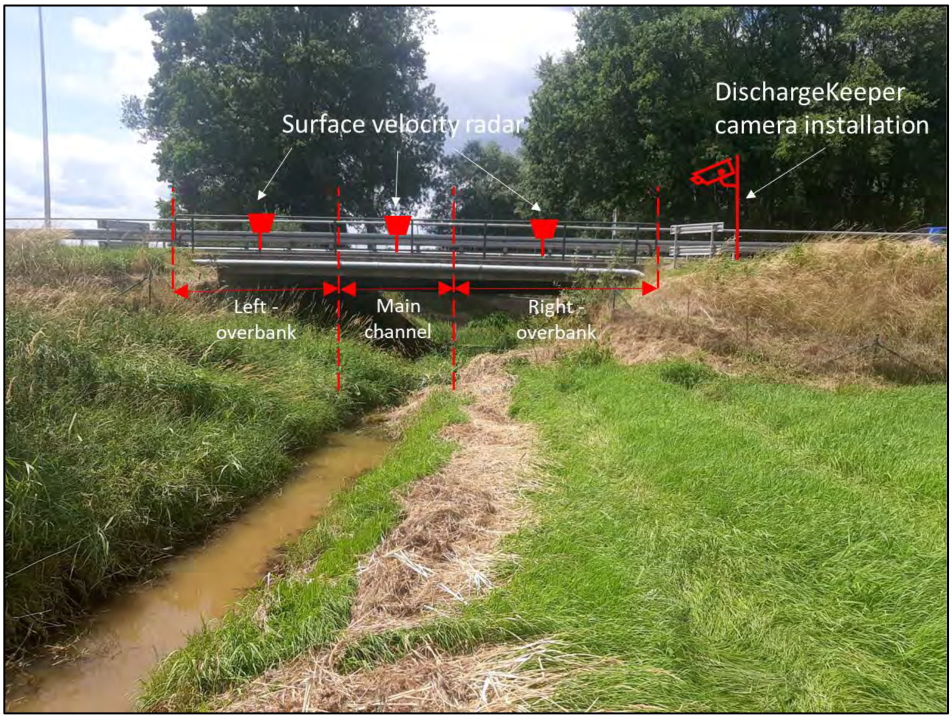


Plate 18. *Suggested locations for placement of DischargeKeeper camera or three Geolux surface velocity radar to monitor the Melicker Leigraaf stream at Site 3.*

With regards to the DischargeKeeper method for converting surface velocities to mean values this is achieved using an alpha coefficient multiplication factor (refer to Section 4.7.). In order to obtain this value SEBA ask for video footage of flow at the site to be sent to them in advance and, if possible, reference data obtained with ADCP from which this coefficient value can be determined. Obviously, the limitation associated with installing the DischargeKeeper at this site is that currently there are no reference flow measurements available and high flow events will be infrequent, but Dr Hansen stated that, 'Reference measurements are recommended for the calibration, but we could install the DischargeKeeper and once a reference measurement is available, we would update the calibration'. Therefore, initially mean velocity values may be somewhat inaccurate, but would be improved over time with acquisition of calibration data. A concerted effort needs to be made therefore to access this site and take readings in this channel using ADCP during a range of flows in order that the DischargeKeeper can be accurately calibrated.

Turning to the use of radar, it is suggested that the Geolux RSS-2-300WL radar flow meter could be used to measure surface flow velocity to determined discharge in the Melicker Leigraaf channel. The use of surface velocity radar is discussed in Chapter 4, Section 4.5 and specifications of the Geolux RSS-2-300WL radar are given in Appendix G. This radar system is considerably cheaper than the DischargeKeeper (refer to Section 6.8 for costing of these two options) but the disadvantage is that only a point measurement of velocity would be obtained if one radar were used at the bridge over the Melicker Leigraaf. The use of a single radar is likely to cause significant misrepresentation of the true velocity distribution through the bridge section therefore but one way to remedy this would be to use multiple radar across the bridge opening, perhaps one for the main channel, and one for each of the left and right out-of-bank zones. The proposed distribution of radar is shown in Plate 18. The surface velocity radar should be mounted on poles above the upstream side of the bridge to avoid them becoming damaged during extreme flood flows. The main considerations factors that should be considered when siting the radar are:

- Minimum surface disturbance height for accurate velocity measurement is a 1 mm surface wave.
- Optimal tilt angle for the radar is 30 degrees.
- The sensor should be placed looking upstream to reduce the impact of raindrop interference or placed underneath a structure such as a bridge which shields the water surface from raindrops.
- There must be no stationary objects in the radar footprint (such as bridge piers, rocks, etc.) as these will generate erroneous returns.
- The unit should be used to sample uniform flow conditions with parallel streamlines, i.e., in a straight section of channel where there are not contractions or expansions.

Note that, as with the DischargeKeeper system, surface velocity radar velocity readings must be converted to depth-averaged values for the purpose of calculating discharge using an alpha coefficient which must be determined through analysis of field measured flow velocity data along a cross-sectional transect of the channel where the radar will sense the water surface.

6.8. A cost estimate for setting up the measurement system.

The cost of developing a stage-discharge rating curve for the site is not quantified here but the costs to consider are:

1) Possible installation of a cableway used to guide a boat mounted ADCP.
2) Possible installation of a new stage gauge downstream of the bridge location if the current gauge proves not to be suitable.

3) Possible installation of a secondary stage gauge to measure local water surface slope if a simple stage-discharge rating is not sufficient to describe the full range of discharge.
4) The man-hours and hardware cost for obtaining the data required to develop the rating curve, collected by repeat transect survey of the flow cross-section using ADCP. Note that if a towable ADCP is required the Teledyne Instruments StreamPro would be adequate for this location. This costs €18,295.00 (excluding VAT and 15% shipping cost for import by Teledyne from the U.S., plus local shipping). Quote obtained from Aqua Vision (www.aquavision.nl) on 6th October 2023.
5) Man-hours cost for processing ADCP data and developing the rating curve.

The cost quoted for one DischargeKeeper system for a river width of up to 50 m (which will be adequate for the Melicker Leigraaf Bridge site) is €37,000 (excluding VAT) (quote obtained 3rd October 2023 from SEBA Hydrometrie). Additional costs for which estimates have not been made when installing this system include:

1) Pole mounting for the camera.
2) Waterproof housing for the associated processing, power supply and internet transmission equipment plus ground preparation for the housing and security measures to prevent interference from members of the public.
3) Possible need to purchase land in the vicinity of the camera system for both the camera mounting and the housing.
4) Cost involved in surveying the cross-sectional bathymetry at the measurement site which is required as input to the DischargeKeeper for calculation of discharge.
5) Costing for Waterschap Limburg staff to collect data on flow conditions in the Melicker Leigraaf, preferably using ADCP, prior to installation of the system. As it is likely that field measurement will not initially be available for high flows at this site and a strategy and funding would have to be put in place to make sure that such data is collected, on an opportunistic basis, as and when such conditions do occur.

Alternatively, if the Geolux RSS-2-300WL flow meter were employed the cost of this device for a single unit is €4,800 (excluding VAT and delivery) (quote obtained from RMA Hydromet on 6th October 2023). As three units are suggested for the Melicker Leigraaf bridge site, in order to obtain a representative lateral velocity distribution, the total cost would come to €14,400.00. Additional costs for which estimates have not been made include:

1) Mounting of radar units on poles.
2) Cost of cable connection and housing for data transmission via internet to a receiving station.
3) Cost involved in surveying the cross-sectional bathymetry at the measurement site which is required as input for calculation of discharge.
4) Costing for Waterschap Limburg staff to collect data on flow conditions in the Melicker Leigraaf, preferably using ADCP, prior to installation of the system. As it is likely that field measurement will not initially be available for high flows at this site and a strategy and funding would have to be put in place to make sure that such data is collected, on an opportunistic basis, as and when such conditions do occur.

6.9. What measurement range and measurement error can be expected and is realistic?

6.9.1. Discharge measurement range

As discussed in Section 6.7.1. it appears likely that the rating curve developed for the main Roer channel will be capable of measuring a discharge range from minimum base flows up a discharge which have a water surface elevation lying at an elevation of 24 m NAP (refer to Figure 38). The modelled discharge for this high-flow elevation is 500 m^3s^{-1}, but the rating curve will not be capable of capturing this entire discharge as a proportion is likely to go out-of-bank in flood conditions on the right-hand floodplain and will pass downstream through the Melicker Leigraaf channel. It is proposed that this channel is monitored using a DischargeKeeper system or multiple surface velocity radar which would be capable of measuring discharge from base-flows in the Melicker Leigraaf to flows that are augmented by flood flow from the Roer itself up to stage elevation of 23.5 m NAP a height that is estimated to lie just below the lowest elevation of the bridge deck (refer to Figure 38, transect 'B-C'). Note that flows up to 500 m^3s^{-1} cannot be monitored though as they will not be contained within the cross-section available at this point and will in fact pass over the road surface on top of the bridge here rising to an elevation of 25 m NAP. The discharge that would be captured at the peak measurable stage in the Melicker Leigraaf is unknown but the combination of the rating curve in the main Roer channel and discharge measurement using the DischargeKeeper system in the Melicker Leigraaf is, combined, likely to measure almost all flows expected to be experienced at this point on the Roer.

6.9.2. System measurement error

Rating curves typically have a 4 % - 12 % error as compared with in situ measurements (Horner et al., 2018) and Rantz (1982b) states that if a stage-discharge curve is developed correctly the error between rating curve discharges and those determined in the field should be no more that 5 %.

The DischargeKeeper system is quoted as having the following accuracy characteristics:

- Flow velocity: < 5 % error of the true (directly measured) value.
- Water level: < 1 cm error.
- Discharge < 10 % error of the true (directly measured) value.

Note that these values are all subject to site conditions. The measurable velocity range of the DischargeKeeper is quoted as being 0.2 to 15 ms^{-1} which is more than adequate for the site in question. There will also be uncertainty associated with the conversion of surface velocity values to mean values via the alpha coefficient in the case of out-of-low-flow channel conditions in the Melicker Leigraaf as calibration data is unlikely to be available at the time of system installation. Therefore, initially, it is considered that the uncertainty in discharge estimates will be greater than the 10% value quoted in specification for the system and could be as high as 20% prior to acquisition of calibration data during high-flow conditions.

If the Geolux RSS-2-300WL flow radar were purchased this is documented as having the following accuracy characteristics:

- Flow velocity: within 1 % of true (directly measured) value.
- Water level: ±2 mm error.

The detection distance for the device is quoted as being 15 to 30 m and the velocity measurement range as being 0.02 to 15 ms^{-1} which will be adequate for the conditions that will prevail at this site. Note that a source of error that will be inherent with using surface velocity radar is the fact that they determine a single surface velocity value and not a cross-section surface velocity distribution as is performed by the DischargeKeeper. This source of error can be reduced by using multiple radar across the full potential flow width as suggested here. Also, this type of radar really assumes that streamlines across the water surface are parallel which will not be the case for high flows at the approach to the bridge opening and this will introduce an unknown level of uncertainty to the velocity measurements.

Overall, while the cost of using even multiple radars is likely to be less than a single DischargeKeeper unit, the authors ultimately recommend the use of the latter because the complete velocity distribution is measured across the flow surface from which the DischargeKeeper then computes discharge using the velocity area method (Rantz, 1982a) for a number of sub-compartments of the flow cross-sectional area. If the Geolux RSS-2-300WL flow radar were to be used, it too can be given alpha coefficient information to calculate depth averaged velocity and can also detect stage from which the cross-sectional area of the flow can be determined but it would be up to the installer to determine how the cross-sectional area of the channel were partitioned between the three radars used, with the assumption that the mean velocity determined by each radar is applicable to the entire area of flow for the channel section it were sited to cover (low-flow channel, left-overbank, right-overbank, refer to Plate 20).

6.10. Advice on how to perform maintenance of the station to guarantee a good quality of the measurement

6.10.1. Maintenance of the rating curve

The development of a rating curve, based upon field-measured discharge data, at a site having appropriate conditions (Rantz, 1982a) is considered a highly robust method for determining discharge and given consideration of the relevant conditions at Site 3 it is expected that results obtained using a rating curve methodology here will be satisfactory from the perspective of measurement accuracy. Rating curves, once established, must be checked however to determine whether shifts have occurred between discharge and stage. The recommendation of Rantz (1982b) is that a minimum of 10 discharge measurement checks should be undertaken per year once a rating curve has been established unless it has been demonstrated that the relation is invariant with time. Based upon U.S. practice (Rantz, 1982b), it is recommended that, if a measured discharge-stage pair depart from an established rating curve by less than 5 %, the discharge is considered to be a verification of the rating curve. If, during a field measurement exercise a discharge-stage pair are found to depart by more than 5 % from the rating curve a second discharge measurement should be undertaken straight away to check whether this departure is due to measurement error or is indeed due to a shift in the relationship (note that this protocol means that the stage-discharge data should be processed in the field at the time of measurement, in order that a repeat survey can be made if the initial survey produces a deviation of more than 5 %). Factors that can cause a shift in the rating curve that are applicable to Site 3 are as follows:

1) Vegetation: An increase in growth of vegetation can both reduce the effective area of a channel and increase roughness. Both these factors will cause stage to increase for a given discharge. If vegetation is deciduous then there may be a seasonal change in roughness associated with the growth of leaves in Spring and their fall in Autumn. This seasonal effect is more likely to impact high flows than low as it is generally associated with trees growing beside the channel, the lower portion of which are likely to be relatively invariant with the time of year with regard to surface area and roughness, while the crown of the tree may vary significantly with regard to these parameters over the annual cycle. Aquatic weed, growing in the river channel itself may have the

same effect if its extent changes significantly although this will only effect flows in the low flow portion of the channel. At Site 3, downstream of the bridge, excessive weed growth was not observed at the time of the field visit (July). However, there are trees growing beside the low flow channel here along the right bank that may have a seasonal impact on the rating of high discharges (see Figure 38). This issue can be dealt with in two ways. First, river-side vegetation can be cut back in the reach that is likely to control the stage-discharge relationship at the gauge. At Site 3, this would involve the management of trees on the right riverbank downstream of the gauge. A second approach is to develop a rating curve that has two curves at the higher end of the flow range, one for summer and one for winter conditions, although this approach is only recommended if the differences are found to be marked and predictable. Note that some annual cycle of vegetation management may be necessary regardless of the impact on the rating curve at the location where a cableway is placed for undertaking discharge transects especially if that location is within the region of the channel downstream of the bridge where tree growth occurs as a clear cross-section path will be required in order that a boat borne ADCP can be towed across the channel.

2) Erosion / damage of a channel section control: Low flows at a gauge are normally controlled by what is known as a section control. Natural section controls include riffles and bedrock outcrops. If there is no natural section control at a gauge site and a pool is not present at low flows in the reach, a small weir is often built for this purpose. If such a control is eroded away or damaged this usually causes a downward shift in the low flow portion of the rating curve. This shift usually only occurs at the lower end of the rating curve because section controls tend to be drowned out and do not affect the stage-discharge relationship during higher flows that are controlled by the channel geometry itself. It is unknown if there is already any form of natural section control in place downstream of Site 3 at present, and it may be necessary to build a small weir to generate a low flow pool so that, even for the situation of zero discharge there is still a minimum reading on the stage gauge used for the rating.
3) Scour and fill: This is a local phenomenon with scour of the riverbed generally occurring on the rising limb of the hydrograph and fill occurring on the falling limb, the two phenomenon causing a corresponding downward and upward shift in the stage discharge relationship respectively. This shift may apply to the whole length of the rating curve or more usually will only apply to a portion, especially lower flows as at high flow the impact of scour and fill may be effectively drowned out by other controls in the channel gauging section (refer to Figure 39). As this phenomenon is cyclic and relates to the hydrograph detection, the rating can only be undertaken through repeat measurements of discharge and stage during different portions of a hydrograph. If the difference is found to be small, it can be ignored. If it is consistent and significant and can be directly corelated with the rising and falling limb of the hydrograph, then two branches can be developed to the rating, one for the rising limb and one for the falling. The degree to which scour and fill occurs will depend on the nature of the channel bed material. The grainsize of the bed material at Site 3 has not been quantified but visual inspection suggests that it is composed of silt and sand which may indeed be susceptible to scour and fill. One factor that may influence scour and fill at the site is the acceleration of flow past the two piers that support the bridge. These piers are located on the riverbanks, either side of the low flow channel but in higher flows that pass out of this channel they may induce flow acceleration that causes scour around their base and deposition of the scoured material downstream. The potential for this to occur can only be determined through further field investigation at the site.
4) Degradation and aggradation: these, like scour and fill represent erosion of the riverbed, and therefore a downward shift in the stage discharge relationship, or deposition on the riverbed, and therefore an upward shift in the stage discharge relationship, respectively. The difference between these two sets of processes is that aggradation and degradation are reach/system wide phenomenon caused by factors that disrupt the balance between the rivers erosive power (a combination of discharge and slope) and the capacity for sediment to be eroded (a combination of

the quantity supplied and its size). Factors causing such a shift include, for example, dredging of a reach, construction of a dam, and channel straightening and tend to cause a systematic change in channel base level that persists over many years. Such shifts may develop gradually over time due to progressive erosion or sedimentation of the channel bed or may occur suddenly in response to, for example, dredging.

5) Change in channel width: If the channel width changes due to bank erosion, or say the expansion of a point bar, then this will cause a change in the rating relationship, especially at higher flows. The river banks look, from visual inspection, to be quite stable downstream of the bridge at Site 3 (through a review of the timeline of available Google Earth images) but the Roer is known to be geomorphologically quite active in terms of both bed elevation change and actively meanders along its lower course, responding in part to human activities in the catchment over the past 200 years (Wolf et al., 2021; Wolf et al., 2022). The newly developed rating curve should therefore be regularly checked to identify whether there are systematic shifts in the rating associated with aggradation/degradation and adjustment of channel width.

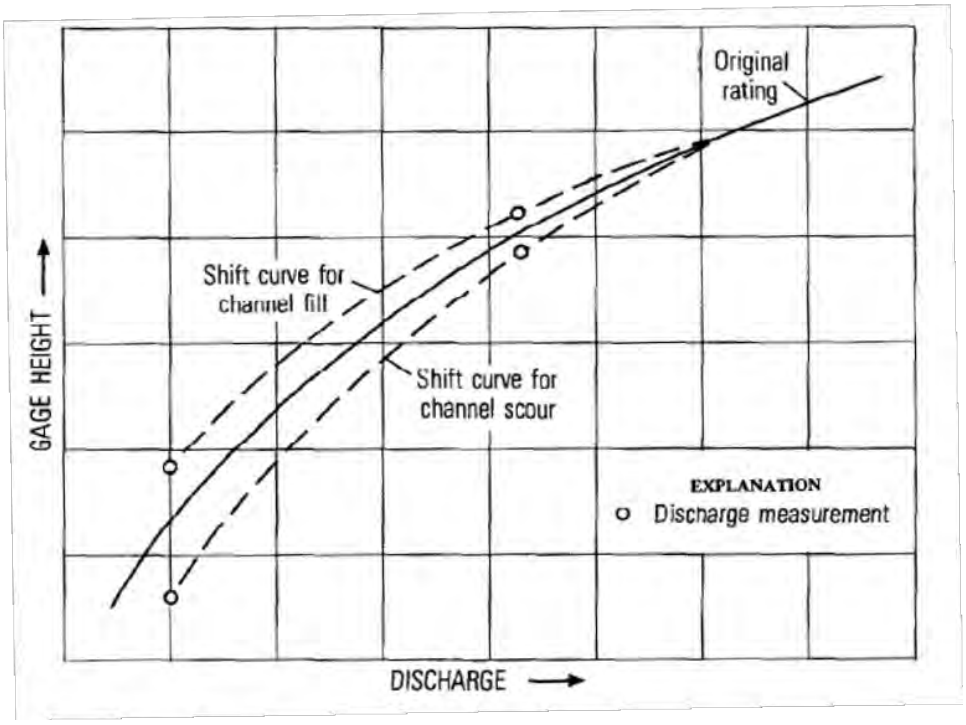


Figure 39. *Example of shifts in rating curve associated with scour and fill (adapted from Rantz (1982b)).*

6.10.2. Maintenance of the Melicker Leigraaf surface-velocity measurement gauge site

The main maintenance issue associated with the use of the DischargeKeeper system is that the camera's view of the water surface should not be obstructed by the growth of vegetation as this will prevent areas of the water surface from being analysed using the STIV methodology. Vegetation could also impact measurement obtained using surface velocity radar because, although vegetation does not act directly as an obstruction to the radar signal, if there is vegetation within the radar footprint area that is moving at a different frequency to that of the water surface waves, due to the wind for example, the radar will receive a doppler shift return from this that could bias the interpretation of the doppler spectrum from which the water surface velocity is determined (Australian Government Bureau of Meteorology, 2020)

At Site 3 this will mean that the area viewed by the camera or radar upstream of the road bridge must be periodically checked for vegetation growth that might obstruct the instruments' ability to image the water surface. Regular checks should therefore be performed throughout the Spring and Summer season but could be scaled back during winter months.

A major source of uncertainty associated with the use of surface flow velocity sensing technology to determine discharge is that surface velocity must be converted to depth-averaged values using an alpha conversion coefficient. This coefficient is determined through field measurement of velocity profiles at the location where the sensor is to detect surface velocity, in order to establish the ratio between surface velocities and depth averaged values. This ratio is controlled by a number of factors associated with the flow hydrodynamics one of which is the roughness of the channel boundary and if this roughness varies, then the shape of the velocity profile may also vary and with it the ratio of surface to depth-averaged values. Factors that may cause a variation in channel boundary roughness upstream of the road bridge over the Melicker Leigraaf at Site 3, where surface velocities are to be measured, include the annual cycle of aquatic weed growth in the small low-flow channel, and the growth of annual vegetation such as grasses and reeds either side of this channel up to the limits of the channel cross-section itself (see Plate 20). Such variable growth may therefore induce error in the conversion of the surface velocities to depth averaged values as the alpha coefficient ratio may vary with time of year according to density and height of vegetation. A second issue associated with this, and which comes into play if radar were used, is that stiff vegetation protruding through the water surface might create a local standing wave under high flow velocities and such stationary waves can cause errors in angle correction when the radar impulse is reflected from the stationary wave and not the plane water surface which could thus bias the velocity measurement (Australian Government Bureau of Meteorology, 2020).Therefore, it is recommended that vegetation upstream of the bridge be kept short, and a consistent length throughout the year to avoid measurement error and changes in the local hydrodynamics. The area that should be maintained is recommended as covering the full lateral width of the channel that may be inundated by flow at the bridge opening itself, upstream for at least 10 meters, to ensure that the flow within the area to be sensed by the camera or radar is fully adjusted to the local boundary conditions as determined by the managed ground cover.

6.11. Further research regarding discharge measurement on the lower Roer

It is recommended that, prior to implementation of any of the options outlined in Chapter 5 that employ radar technology, further research be carried out to investigate the effectiveness of continuous surface velocity radar systems, perhaps in collaboration with Rijkswaterstaat who already have experience with their use. The application of this technology specifically to measuring flow at culvert inlets and bridges should be investigated further as here conditions for their use are acknowledge as potentially being sub-optimal because streamlines may contract at a culvert entrance, rather than being parallel (a requirement that has been stipulated in best-practice guidance for surface radar technology), an effect that will become more pronounced as flow depths at the inlet increase.

The issue of providing effective flood warning lead-in times for the town of Roermond also needs to be explored further. The preference for use of readings from the Stah gauge site by Waterschap Limburg staff is recognised by the authors, as the measurement of discharge at this location offers approximately 8 to 15 hours of lead-in time for flood risk mitigation strategies to be put in place before the flood wave arrives at Roermond itself. This research has found that the Stah gauge site is not the best place to capture the full range of out-of-bank flows that were the target of this research (5 to 500 m^3s^{-1}) and that Site 3, located at the point where the N293 road bridge crosses the Roer between Sint Odilienberg and Melick (51.14876144°N, 6.00349374°E) naturally lends itself, for geographical reasons, to measurement of flood flows over a much more contained lateral extent. This site is, however, much closer to Roermond than the Stah gauge (it lies approximately 8 river kilometres from the town, whereas the Stah gauge lies approximately 24 river kilometres from the town) which means that flood warning times will be greatly reduced if readings are solely taken from this gauge. However, the authors can develop a solution to this issue. For a control volume bounded by Site 3 and the Stah station, where water levels are continuously monitored, the discharge at Stah can be computed in real time from the discharge at Site 3 based on a predeveloped discharge transfer function that uses a digital elevation model within the control volume. This real time translation of the discharge at Site 3 to the discharge at Stah station can be highly accurate especially with extra water level recordings at intermediate locations between the two sites, both in the channel and on the floodplain. Indeed, Waterschap Limburg already have a series of stage gauges in this reach, that currently monitor in-bank flow stage at least. One issue with the application of this approach is that continuity of mass is assumed between the two locations, and Waterschap Limburg staff voiced concerns about this assumption due to the unknown degree to which discharge is lost to, or gained from, groundwater flows in the lower Roer. This issue can be addressed however, in part, by installing a new gauge at Site 3, as this will provide information on the quantity of flow lost between the Stah gauge, which lies approximately 16 river kilometres upstream, and this point on the river, at least over the range for which the rating curves at the two locations are directly applicable. It is proposed therefore that this discharge translation exercise be explored further, specifically in the context of its application to discharge measurement and flood risk warning on the lower Roer.

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8. Appendices

Appendix A: The use of the current pressure transducer network to determine in-bank discharge

The fact that Waterschap Limburg currently has a network of actively monitored stage gauges along the lower Roer is advantageous as this data can in fact be used to determine discharge at a site where the channel cross-section bathymetry is known and can be related to stage. The technique uses the following information: a) data from each recording interval from pairs of stage gauges located over a known long-stream distance to determine water-surface slope; b) the stage recorded at the downstream gauge at each recording interval is used to derive flow cross-sectional area, wetted perimeter and channel top-width from a look-up table based upon the pre-determined channel cross-section geometry; c) a predetermined value for the channel bedslope over the distance between the two recording stage gauges, and; d) a known calibrated Manning's roughness coefficient for the cross-section where discharge is to be determined. These data are then applied to the equation for gradually varied flow to determine the unknown mean flow velocity and thence discharge at each stage recording interval. Using these data in combination with the equation for gradually varied flow means that accurate discharge estimates can be made on the basis that the flow is non-uniform between the pair of stage recorders, a necessity for any valid estimate of discharge in a natural river having, as they do, irregular geometry, slope and roughness. The approach of using pairs of stage gauges to determine water surface slope and thence discharge has been documented in the academic literature (Harlan et al., 2021) although they used a Bayesian technique in combination with Manning's equation to determine discharge for channels where the full bathymetry of the cross-section and channel roughness were unknown.

An example of how this approach can be achieved is now given for the hypothetical situation where Site 3 on the lower Roer is chosen as a new discharge gauging site. The basis for the calculation of discharge using this approach requires the following data:

1. Bathymetry of the channel cross-section up to the peak in-bank flow that can be automatically derived from associated stage readings, i.e., the development of an algorithm whereby, for any recorded stage at the location chosen, the associated flow cross-sectional area, wetted perimeter and hydraulic mean depth can be automatically recalled.
2. Continuous recording of stage at some point upstream of the chosen discharge calculation location in order that at any given recording point in time the water surface slope, between that point and the discharge measurement location, can be determined according to:

$$S_w = \frac{(H_2 - H_1)}{L} \quad (1)$$

   where S_w = water surface slope ($m m^{-1}$) of the flow upstream of the measurement cross-section, H_1 = stage (m) at the measurement station, H_2 = stage at the upstream measurement gauge (m), and L = channel length between the locations of H_1 and H_2 (m).
3. An estimate of a roughness coefficient for the channel at the downstream location where discharge is to be determined, for example a Manning's 'n' value. This can be a constant, fixed value, regardless of stage or preferentially a variable value that is stage dependent to account for changes in bank and bed roughness across a range of stages.
4. The slope of the channel bed between the two stage gauge locations.

This data is applied to the equation for gradually varied flow such that for each measurement recorded the associated mean flow velocity is determined and thence the associated discharge via the continuity equation. The gradually varied flow equation (Chadwick et al., 2021) is given as follows:

$$\frac{dd}{dx} = \frac{S_b - S_f}{1 - {F_r}^2} \tag{2}$$

where d = flow depth (m), x = upstream long-channel distance (m), S_b = slope of the channel bed (mm^{-1}) which in the practical case discussed here is determined over distance L between the two chosen gauge locations, S_f = friction slope (mm^{-1}) and F_r = Froude number.

From, for example, Manning's flow resistance equation S_f can be derived as:

$$S_f = \left(\frac{\bar{u}\cdot n}{R^{2/3}}\right)^2 \tag{3}$$

where $\bar{u}$ = channel mean flow velocity (ms^{-1}), n = Manning's roughness coefficient, and R = hydraulic radius (m) = A / P in which A = channel cross-sectional area (m^2) and P = wetted perimeter (m).

The Froude number, for the purpose of these calculations is defined as:

$$F_r = \frac{\bar{u}}{\sqrt{g\cdot d_h}} \tag{4}$$

where g = acceleration due to gravity (approx. = 9.81 ms^{-2}), and d_h = hydraulic mean depth (m) = A / w_T in which w_T = flow top width (m).

The left-hand side of equation (2) can, in practical terms, be determined from the bedslope and water-surface slope along the upstream length (L) over which these two parameters have been determined between the pair of stage gauges at H_1 and H_2. Substituting L for x on the left-hand-side of equation (2) we get:

$$\frac{dd}{dL} = S_w - S_b \tag{5}$$

Note that in the above equation if there is a backwater in the upstream reach, i.e. the water is getting shallower with distance upstream the bedslope will be greater than the water surface slope and dd/dL will have a negative value while if there is draw-down in the channel reach, with the flow depth being greater at the upstream as compared with the downstream gauge then dd/dL will have a positive value. Substituting equations (3), (4) and (5) into equation (2) and rearranging to determine the mean channel flow velocity we arrive at:

$$\bar{u} = \left[\frac{g\cdot d_h\cdot R^{4/3}\cdot[S_b - (S_W - S_b)]}{\left[-R^{4/3}\cdot(S_w - S_b)\right] + (g\cdot d_h\cdot n^2)}\right]^{0.5} \tag{6}$$

From this the discharge (Q) can then simply be determine via the continuity equation as Q = $\bar{u}$·A. There follows an example of this calculation using data obtained from analysis of the distance between the stage gauges in the lower Roer and stage data taken from the July 2021 flood event on the Roer. The chosen location for discharge calculation is Site 3 where gauge 2.H.2 is located.

The long-stream (thalweg) distances between gauges upstream of Roermond on the Roer have been determined using a GIS and are shown in Table A1. Refer to Figure 1 for these gauge locations. We shall determine the water surface slope, S_w using the difference in gauge readings at 2.H.2 (H_1) and the next upstream gauge 2.H.170 (H_2) over the intervening thalweg distance (L) which is 2996 m.

Table A1. Thalweg distances between consecutive pairs of stage gauges on the lower Roer.

Thalweg distance between gauges (m)					
2.H.4 - 2.H.3	2.H.3 - 2.H.2	2.H.2 - 2.H.170	2.H.170 - 2.H.1	2.H.1 - 2.H.83	2.H.83 - Stah
2603	5633	2996	3809	3156	5772

As an example of stage data from these gauges Figure A1 shows a plot of stages for each gauge taken at two different times: 16th July 2021 at 14:45 during the rising limb of the flood event and 27th July at 5:45am as the flood was receding (refer to Figure 2). Taking readings from the 27th of July 2021 at 5:45am the value for 2.H.170 (H_2) is 24.10 m and the value for 2.H.2 (H_1) is 22.44 m so the water surface slope, S_w = (24.10 − 22.44) / 2996 = 0.000553 mm^{-1}.

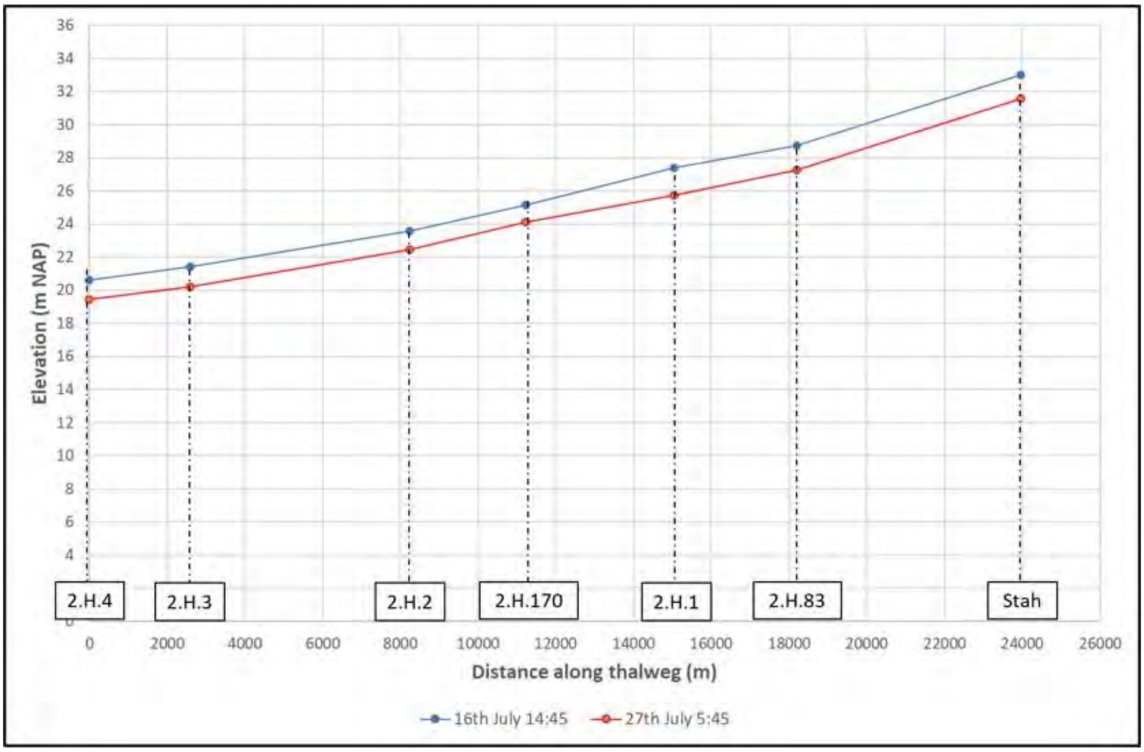


Figure A1. Plot of water surface elevation along the lower Roer between gauges 2.H.4 and the Stah gauging station for two different times during the July 2021 flood event.

In order to determine channel bedslope between gauges 2.H.2 and 2.H.170 we shall use the minimum channel bed elevations extracted from cross-sections used in the 1D SOBEK flow model (supplied by Waterschap Limburg) that lie close to each of these sites. The minimum channel bed elevation for the model cross-section located just upstream of gauge 2.H.2 is 19.08 m NAP, while the minimum elevation of the model cross-section closest to gauge 2.H.170 is 20.65 m NAP. Therefore, the channel bedslope, S_b, between the gauges is (20.65 - 19.08) / 2996 = 0.000524 mm^{-1}. Therefore, the gradient of change in water depth over this length (dd/dL) is equal to S_w - S_b = 0.000553 − 0.000524 = 0.000029 mm^{-1}.
We now need to know at gauge 2.H.2 what the geometry of the flow cross-section is for a stage height of 22.44 m and Figure A2 shows a cross section for this location based upon a combination of the digital surface model data obtained online from the PDOK digital data repository (www.pdok.nl) which is present down to an elevation of 20.3 m and data from the 1D SOBEK mode cross-section which is located nearest to gauge 2.H.2, below this height. Based upon this data the area of the flow cross-section for a water surface elevation of 22.4 m is, A = 58.73 m^2 and the wetted perimeter, P = 25.89 m. The cross-

sectional area and wetted perimeter were calculated using the HEC-RAS river flow modeling software package (https://www.hec.usace.army.mil/software/hec-ras/). Consequently, the hydraulic radius, R = 58.73 / 25.89 = 2.27 m. The other variable required from this cross-section data, the hydraulic depth is determined from the flow top width (W_T = 23.52 m) and is equal to, d_h = 58.73 / 23.52 = 2.50 m. The final variable we need is a value for is the channel roughness, and a representative Manning's n of 0.04 has been selected as this value is currently used in the SOBEK model in the vicinity of gauge 2.H.2.

Entering these data into equation (6) gives a mean flow velocity of 0.96 ms^{-1} and the discharge is therefore 0.96 × 58.73 = 56.47 m^3s^{-1}. The discharge recorded at the Stah gauge for that date and time (27th July at 5:45am) was 58.14 m^3s^{-1}, meaning that there is only a -2.9 % difference between the value determined using the method presented here and that determined from the Stah rating curve. Note that the selection of an accurate roughness coefficient is crucial when using this approach as, for example, if n is changed from 0.04 to a value of 0.035 the calculated discharge increases significantly to 64.56 m^3s^{-1} producing a percentage error difference with the gauge value of +10.5 %.

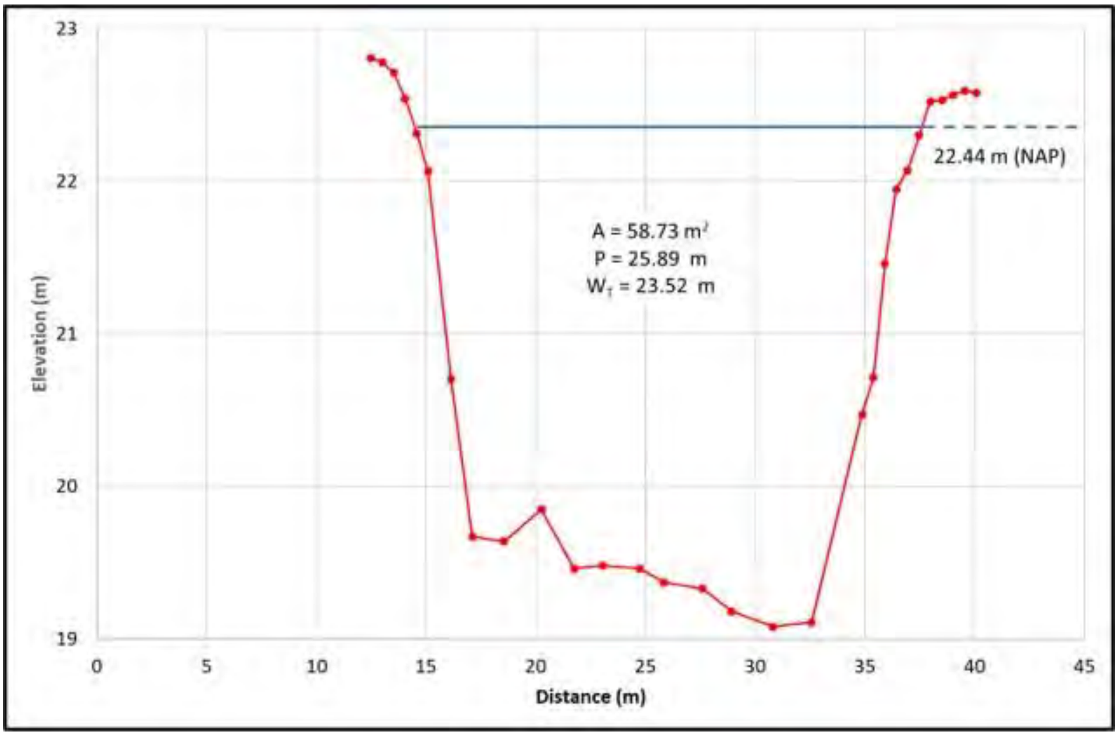
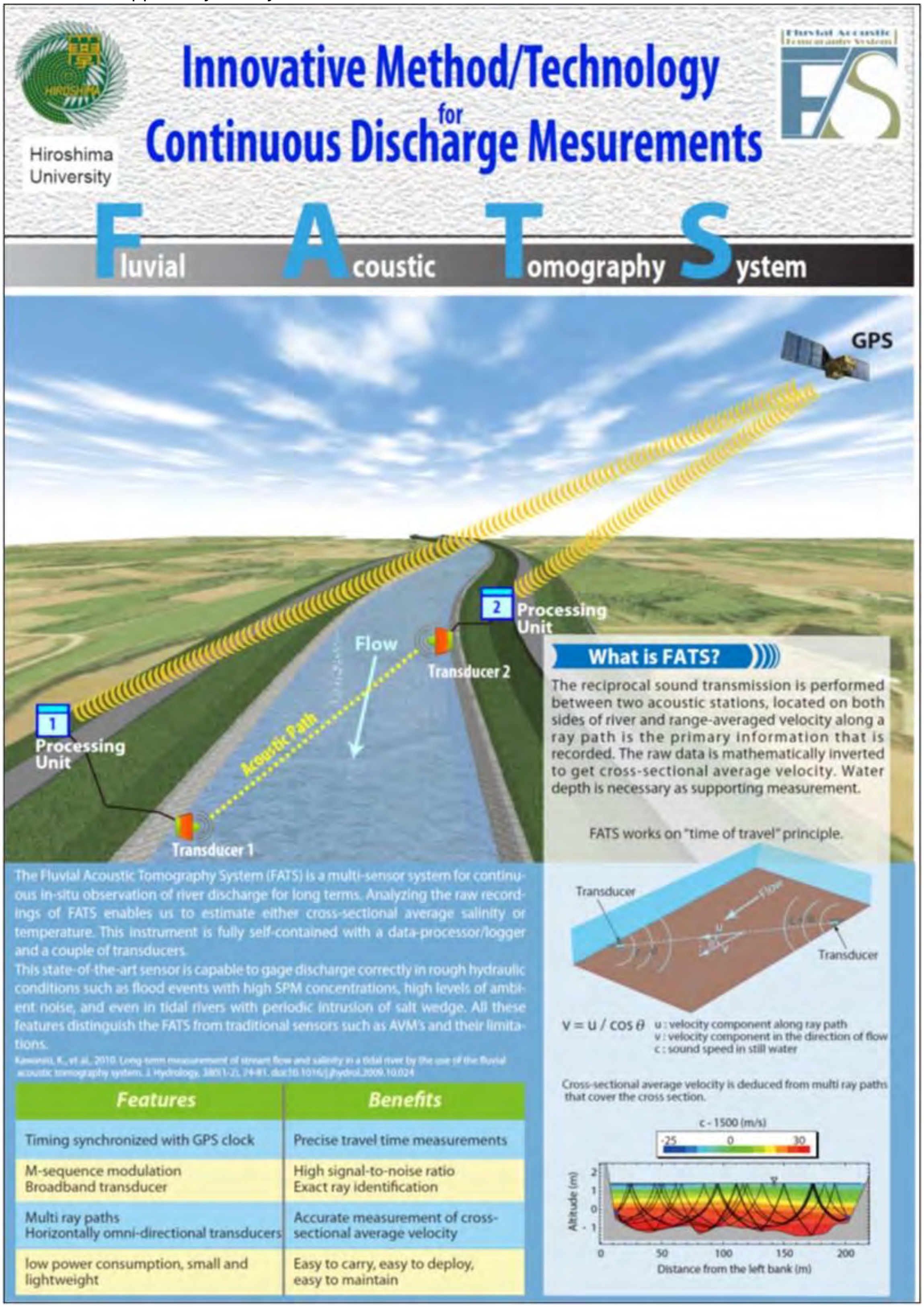


Figure A2. Cross-section of the Roer at gauge 2.H.2 with the estimated channel cross-sectional area, wetted perimeter and top width for a stage of 22.44 m.

Appendix B: Fluvial Acoustic Tomography (FAT) product specification

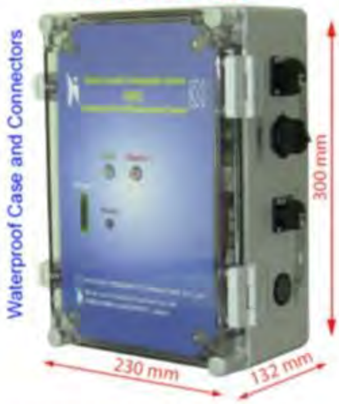
Information supplied by Dr Kiyoshi Kawanisi of River and Coastal Instruments, LLC.



SPECIFICATIONS

Central Frequency	7 kHz, 10 kHz, 30 kHz, 50 kHz
Ray Path Length	10 kHz: 0.3～20 km, 30 kHz: 0.1 ～2 km
Depth Range	> 1.5 m (10 kHz), > 0.5 m (30 kHz)
Velocity Range	-20 m/s to 20 m/s
Transmit Interval	30 seconds to 24 hours
Time Accuracy	< 0.5 μs
Velocity Accuracy	1 % ±0.1 cm/s (at ray path length 500 m)
Velocity Resolution	4 cm/s (at 30 kHz and ray length 500 m)
Power	12 v to 18 v DC; 5 W (at transmit 100 W)
Weight in Air	Processing unit: 3.5 kg, Transducer: 1 kg
Size	Processing unit: 30 cm × 23 cm × 13.2 cm Transducer housing: Φ10 cm × 25 cm

FATS Data Logger

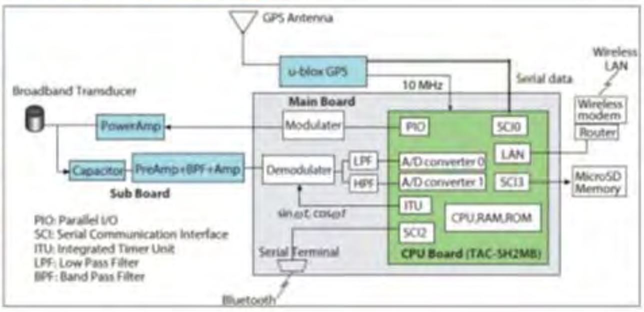


Transducer Unit

25 kHz Broadband Transducer

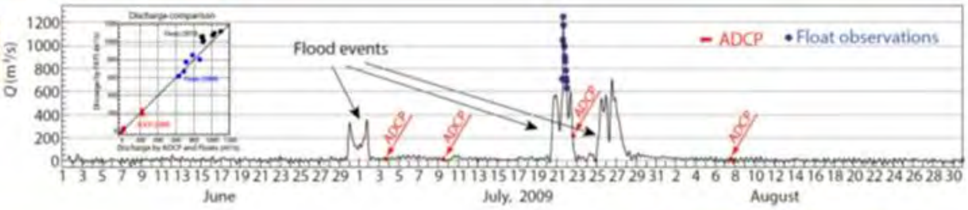
INSTALLATIONS

BLOCK DIAGRAM

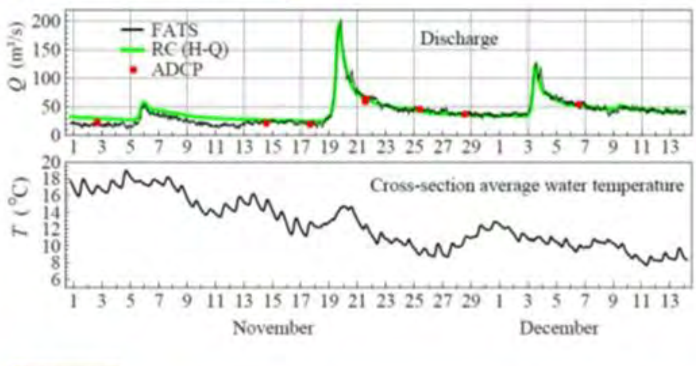


Examples of FATS Measurements

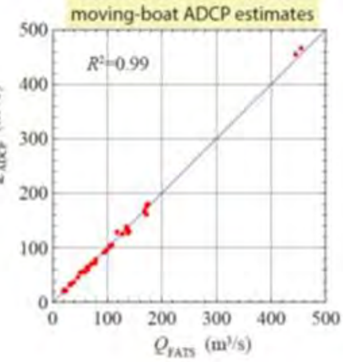
Discharge Q in a flood way with array of sluice gates.



Measurements in a mountain river



Relation between FATS and moving-boat ADCP estimates



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Appendix C: Fluvial Acoustic Tomography (FAT) component price guide

Information supplied by Dr Kiyoshi Kawanisi of River and Coastal Instruments, LLC.

Item	Quantity	Description	Unit Price ($USD)	Total Price ($USD)
1	2	FAT logger 53 kHz for T226 (Part No.: SN-F50-001, SN-F50-002)	$7,000.00	$14,000.00
2	2	FAT logger 53 kHz for T204 (Part No.: SN-F50-011, SN-F50-012)	$7,000.00	$14,000.00
3	2	FAT logger 30 kHz (Part No.: SN-F30-003, SN-F30-004)	$7,000.00	$14,000.00
4	2	FAT logger 17 kHz (Part No.: SN-F17-001, SN-F17-002)	$7,000.00	$14,000.00
5	2	FAT logger 10 kHz (Part No.: SN-F10-003, SN-F10-004)	$7,200.00	$14,400.00
6	2	Transducer Unit 58kHz (T226, preamp, POM housing with Bulkhead connector) (Part No.: SN-T58-001, SN-T58-002)	$1,250.00	$2,500.00
7	2	Transducer Unit 54kHz (T204, preamp, POM housing with Bulkhead connector) (Part No.: SN-T54-001, SN-T54-002)	$1,650.00	$3,300.00
8	2	Transducer Unit 25kHz (T257, preamp, POM housing with Bulkhead connector) (Part No.: SN-T25-001, SN-T25-002)	$1,650.00	$3,300.00
9	2	Transducer Unit 17kHz (T235, preamp, POM housing with Bulkhead connector) (Part No.: SN-T17-001, SN-T17-002)	$2,000.00	$4,000.00
10	2	Transducer Unit 10kHz (ITC2016, preamp, POM housing with Bulkhead connector) (Part No.: SN-T10-001, SN-T10-002)	$3,700.00	$7,400.00
11	2	Transducer underwater cable of 55 m	$961.00	$1,922.00
12	2	Transducer underwater cable of 100 m	$1,173.00	$2,346.00
13	2	Bruetooth adapter (Class 1)	$110.00	$220.00
14	1	W-LAN router	$50.00	$50.00
15	1	Industrial energy-saving computer	$2,000.00	$2,000.00
16	1	Firmware	$100.00	$100.00

Appendix D: Technical specifications for the DischargeKeeper monitoring system

Obtained from: www.seba-hydrometrie.com.

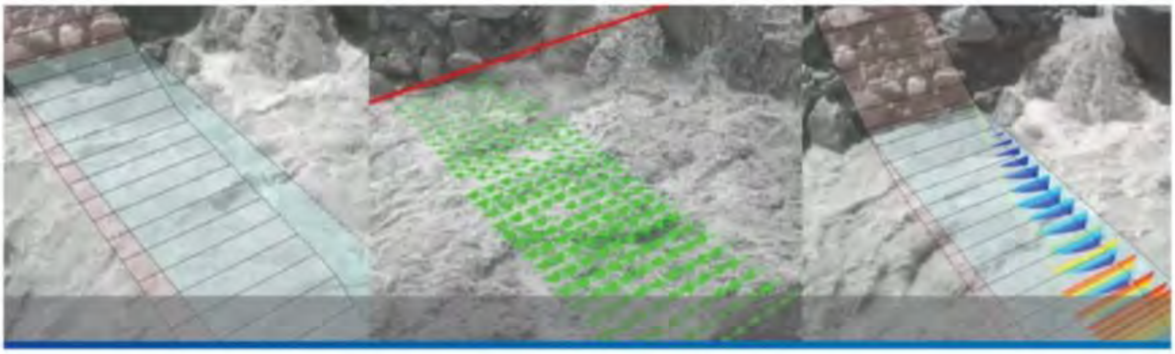
SEBA HYDROMETRIE

DischargeKeeper

Non-intrusive, optical flow measurement for rivers, irrigation and wastewater channels

- Camera-based measurement of water level, surface velocity and discharge
- Versatile camera mounting positions
- Non-intrusive system, reliably measuring during flood events
- Remote transmission of measurement data and proof images
- Real-time, in-situ discharge measurements and alarm

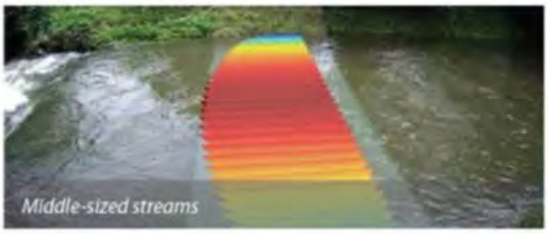
C13_DischargeKeeper_e 04.06.2020



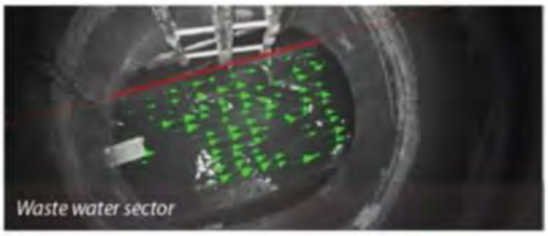
Product description and functionality

The DischargeKeeper is an innovative product for the continuous measurement and storage of water level, surface velocity and discharge in rivers, irrigation furrows and wastewater channels.

The DischargeKeeper consists of an IP-camera, an infrared beamer as well as processing and transmission units. This non-intrusive measurement system can be mounted on existing structures in a versatile way.



Middle-sized streams

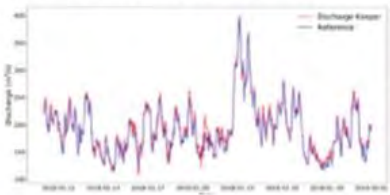


Waste water sector

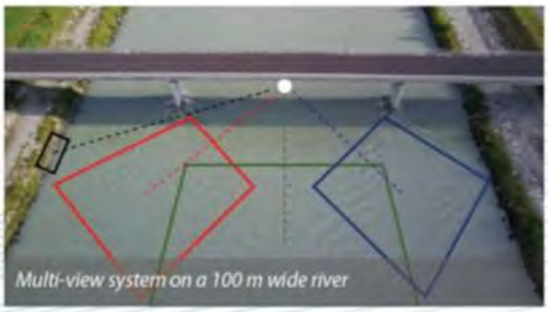
The surface velocity profile is measured optically using a patented cross correlation approach, SSIV. The water level detection is carried out simultaneously by an image processing technique. The vertical velocity profile is obtained following ISO standard EN ISO 748:2007. Integrating the velocity over the river width yields the discharge.

Wider rivers can be monitored in multi-view mode, using pan-tilt-zoom cameras for which several views are defined. The water level is measured optically in a dedicated level view and the surface velocity in dedicated velocity views. The information obtained in these different views is combined to compute the discharge.

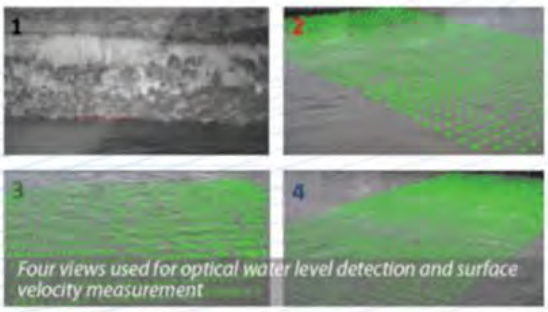
In less than a minute, the user receives the measurement results of the water level, average flow velocity and the discharge. In addition to the digitized measured values, proof images are stored on the customers FTP server and optionally, they may be uploaded to the SEBA server.



Discharge time series of DischageKeeper and of reference data



Multi-view system on a 100 m wide river

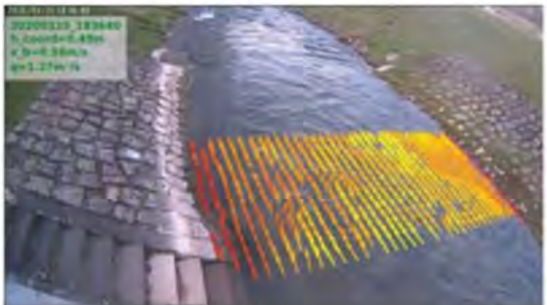


Four views used for optical water level detection and surface velocity measurement

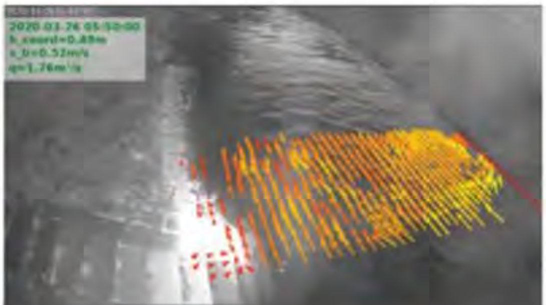
Special features and benefits

- **Simple installation:** The weatherproof IP-camera and the infrared beamer can be mounted easily on e.g. a gauge station, a mast, concrete constructions or a bridge. The process unit can be housed in a water gauge station or in a protective case. Elaborate and expensive installations in the water are no longer required.
- **No flow tracers required:** A special feature of the developed measuring system is that no flow tracers need to be added for flow velocity detection. The DischargeKeeper operates on visible moving surface structures. Nevertheless, naturally occurring floating objects on the water surface (e.g. leaves) enhance the measurement signal.
- **Representative measurement:** Unlike other non-intrusive sensor types (such as radar), the DischargeKeeper computes the volumetric flow rate with measurements of the entire surface velocity field, so that the discharge obtained is based on a robust and spatially resolved velocity measurement.
- **Non-intrusive:** The DischargeKeeper does not come into contact with the measured medium. A damage of the equipment as a result of siltation, vegetation growth etc. is excluded. Therefore the technology is practically maintenance-free.
- **On-site evaluation:** All DischargeKeeper measurement parameters (water level, surface velocity, and discharge) are collected and processed locally on site almost in real time.
- **Smart:** DischargeKeeper informs when critical system states are reached or when definable thresholds are exceeded/ fallen below.
- **Autonomy:** The DischargeKeeper may be operated with 12V batteries charged by solar power or fuel cells (on request).
- **Robust, weather insensitive, precise:** The Discharge-Keeper can also be used under a wide variety of environmental, weather, and lighting conditions.
- **More than just a sensor:** The DischargeKeeper provides both, the required measurement values and proof images from the measuring site in HD quality. In case of doubt, the parameters, such as the water level, can be verified using the present image information. Time-consuming service missions to the measuring site can be reduced or even avoided.
- **Redundancy:** The water level is measured optically, but existing external water level sensors can be combined with the optical system to provide redundant information.

Installation on a wide river



Proof image of a day measurement



Proof image of a night measurement

Technical Specifications

Non-intrusive, optical flow measuring system for processing and storing of videos, images and measured data of surface water. Inclusive remote access to DischargeKeeper and camera (on request).
Measurement results are available in real-time on a web portal. Mounted in a robust protection housing made of plastic with lock.

Camera:	**Single view**	**Multi-view**
Width:	< 50 m	< 250 m per camera (several cameras possible)
Resolution:	3 MP full HD 1080p PoE IR	
Protection class:	IP66	
Frame rate:	30 fps	
Night vision:	up to 50 m	
Operating system:	Linux	
Measuring range:	0.2 - 15 m/s	
Accuracy:		
Flow velocity:	< 5 % of measured value*	
Water level:	< 1 cm*	
Discharge:	< 10 % of measured value*	
	**) depending on site conditions.*	
External water level input:	4...20 mA or SHWP/RS485 or SHWP/RS232 or SDI-12 (on request)	
Data output:	ModBus or 4...20 mA or SHWP/RS485 or SDI-12	
Temperature:		
Operating temperature camera:	-10°C ...+50°C, -40°C... +50°C (on request)	
Operating temperature central unit:	0°C...+60 °C, -40°C...+70°C (on request)	
Storage temperature:	-20 ... +85 °C	
Power supply:	230 V / 12 V, grid or solar power or fuel cell (on request)	
Protection housing:		
Material:	fibre reinforced plastic	
Mounting:	at wall or on mast	
Mast clamping range: *Deviating clamping ranges cause extra costs!*	round Ø 40-190 mm square 50-150 mm	
Dimensions:	400 x 600 x 200 mm	

The right is reserved to change or amend the foregoing technical specification without prior notice

Contact:
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Appendix E: OTT SVR 100 product information

Obtained from: www.otthydromet.com/en/p-ott-svr-100-surface-velocity-radar/6315100490.

Technical Data
OTT SVR 100

Surface Velocity Radar for Measuring Open Channel Flow

- Usage Type
  Fixed installation
- Product Highlights
  Identify data influenced by sensor movement (e.g., wind, traffic) using meta data from integrated vibration and tilt sensors
- Application fields
  Non-contact surface velocity radar
- Internal data logger
  No
- Measurement range
  0.08 ... 15 m/s (0.26 ... 49 ft./s)

OTT SVR 100 is a simple, non-contact, compact surface water velocity radar sensor. Designed for measuring flow in open channels and rivers where reliable velocity data is required continuously, during floods or periods of high concentrations of suspended sediments.

The sensor is mounted above the water surface, away from floating debris using a flexible bracket for vertical or horizontal installation. Velocity measurements and sensor status information from the integrated vibration and tilt sensor is available via SDI-12 over RS-485 and Modbus. It is also compatible with OTT Prodis 2 software for system calibration.

1-2

Technical Data
OTT SVR 100

Measurement device for	**Contactless velocity measurement**
Measurement Range*	**0.08 ... 15 m/s (0.26 ... 49 ft./s)** *** Depending on flow conditions**
Resolution	**0,1 mm/s , (0.0001 ft)**
Accuracy	**± 2% of measured value**
Radar opening angle	12° Azimuth 24° Elevation
Detection distance	1 ... 50 m (3.3 ... 164 ft.)
Distance to water	**0.5 ... 25 m (1.64 ... 82 ft.)**
Radar frequency	**24 GHz (K-band)**
Interfaces	
Serial Interfaces	SDI-12, RS-232, RS-485
Protocols	SDI-12, MODBUS
Power supply	**9 ... 27 VDC**
Power/current consumption	
active	typ. < 112 mA at 12 VDC
Maximum Current	< 250 mA
Dimensions	
(LxWxH)	134,5 x 114,5 x 80 mm (5.3 x 4.5 x 3.2 in) (without mounting bracket)
Material	
Housing	ASA & Aluminium
Radom	TFM PTFE
Mounting	1.4301 (V2A)
Rotation range of swivel mount	**Lateral axis: ±90 °** **Longitudinal axis: ±15 °**
Cable length	**10 m (32.8 ft)**
Weight	
with mounting bracket	820 g (1.81 lbs.)
without mounting bracket	1530 g (3.37 lbs.)
Temperature, in operation	**-40° ... +85°C (-40° ... +185° F)**
Housing	**IP 68**

2-2

Appendix F: Geolux RSS-2-300W surface velocity radar product information

Information obtained from: www.geolux-radars.com/products.

RSS-2-300W Surface Velocity Radar

HIGH-PRECISION NON-CONTACT OPEN CHANNEL SURFACE VELOCITY METER

Highlights

- Contactless surface velocity measurement
- Accuracy tested at Swiss Federal Institute of Metrology METAS and Brodarski Institut Labs
- RS-232, RS-485 Modbus, analog 4-20 mA interfaces in all models
- Remote configuration of all instrument parameters through any digital communication interface
- Robust small size IP68 aluminum or stainless steel enclosure

Applications

- Early flood warning
- Monitoring of flow and irrigation channels
- Accurate discharge monitoring in rivers
- Flow tracking in salt and copper mine channels
- Sewage and waste water discharge measurement

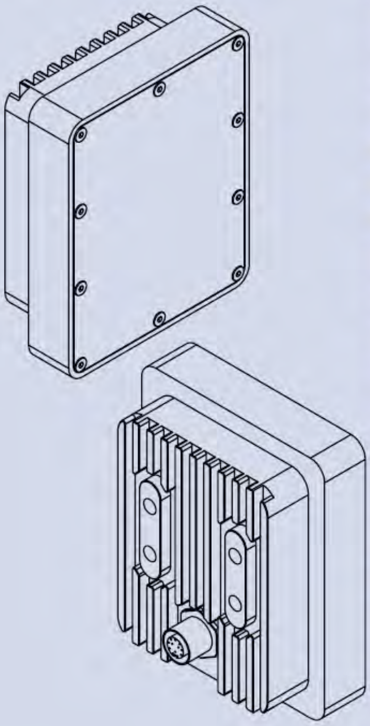
Product Description

The Geolux RSS-2-300W radar sensor uses radar technology for providing contactless measurement of surface flow velocity. Contactless radar technology enables quick and simple sensor installation above the water surface with minimum maintenance.

The radar operates in K-band (24.075 GHz to 24.175 GHz) and provides flow speed readings 10 times per second over serial RS-232, RS-485 Modbus, and analog 4-20 mA output.

The instrument is easily integrated with Geolux or third-party dataloggers and all of the settings can be remotely configured. An integrated MEMS sensor is used for automatic angle compensation. Internal vibration monitoring and SNR calculation can be used for measurement quality assessment.

Detailed Specifications



Radar Type	K-band 24.075 GHz to 24.175 GHz Doppler radar, 20 dBm EIRP
Beam Angle	12° Azimuth, 24° Elevation
Detection Distance	20 m above the water
Speed Range	0.02 m/s to 15 m/s
Resolution	0.001 m/s
Accuracy	1%
Sampling Frequency	10 sps
IP Rating	IP68
Serial Interface	1 x serial RS-485 half-duplex 1 x serial RS-232 (two wire interface)
Serial Baud Rate	9600 bps to 115200 bps
Serial Protocols	GLX-NMEA, Modbus
Analog Output	1 x 4-20 mA
SDI-12 Interface	Available with an optional add-on module
Connector	M12 circular 12-pin
Input Voltage	9 to 27 VDC
Power Consumption	950 mW operational 85 mW standby
Maximal Current	< 250 mA
Temperature Range	-40 °C to +85 °C (without heating or coolers)
Enclosure Dimensions	110 mm x 90 mm x 50 mm

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For more information, contact us:

Phone: +385 1 6701 241
E-mail: geolux@geolux.hr

Geolux
www.geolux-radars.com

Appendix G: Geolux RSS-2-300WL flow meter product information

Information obtained from: www.geolux-radars.com/products.

RSS-2-300WL Flow Meter

HIGH-PRECISION NON-CONTACT OPEN CHANNEL FLOW VELOCITY & LEVEL METER

Highlights

- Contactless flow measurement and surface velocity measurement
- Integrated discharge (flow) calculation
- RS-232, RS-485 Modbus, SDI-12, and analog 4-20 mA interfaces in all models
- Remote configuration of all instrument parameters through any digital communication interface
- Robust IP68 aluminum or stainless steel enclosure

Applications

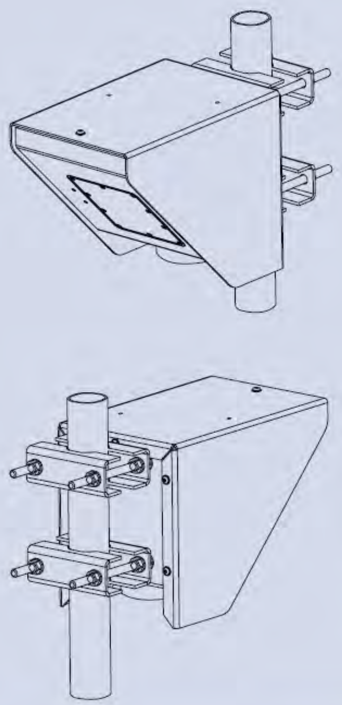
- Early flood warning
- Monitoring of flow and irrigation channels
- Accurate discharge monitoring in rivers
- Flow tracking in salt and copper mine channels
- Sewage and waste water discharge measurement

Product Description

The Geolux RSS-2-300WL has an integrated radar surface velocity and level meter for contactless measurements of surface flow velocity and water level. Contactless radar technology enables quick and simple sensor installation above the water surface with minimum maintenance.

Calculation of the total flow discharge is internally implemented within the instrument by combining surface velocity measurement, water level measurement, and a configured cross-section of the river or channel. Defining the measurement parameters such as profile cross-section, material of the edges, location of the sensor above the water, and all other instrument settings can be easily set with the Geolux configuration application using any available communication interface.

Detailed Specifications



Detection Distance	15 m / 30 m
Speed Range	0.02 m/s to 15 m/s
Speed Resolution	0.001 m/s
Speed Accuracy	1%
Level Resolution	0.5 mm
Level Accuracy	± 2 mm
Sampling Frequency	1 sps / 10 sps optional
IP Rating	IP68
Serial Interface	1 x serial RS-485 half-duplex 1 x serial RS-232 (two wire interface)
Serial Baud Rate	9600 bps to 115200 bps
Serial Protocols	GLX-NMEA, Modbus
Other Protocols	SDI-12
Analog Output	4-20 mA, programmable velocity, level or flow
Input Voltage	9 to 27 VDC
Power Consumption	1.3 W operational; 0.235 W standby
Maximal Current	< 750 mA
Temperature Range	-40 °C to +85 °C (without heating or coolers)
Enclosure Dimensions	150 mm x 200 mm x 250 mm

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For more information, contact us:

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Geolux
www.geolux-radars.com

Appendix H: Viatronics SVR-1 Pro product information

Information obtained from: www.viatronics.fi/en/products/security-solutions.

VIATRONICS SVR

Accurate Water Speed Measurement Designed specifically to measure streams and rivers, the SVR gives you precise speed measurement from a stationary position outside the body of water. The SVR is perfect tool for flood and wastewater management applications.

The SVR is extremely valuable for measuring water surface velocity during high velocity flows and flood conditions where a using contact measurement instrument poses a risk to safety.

FUNCTIONS

- Touchscreen controls
- Built in data logger with automatic date and time information.
- Allows scientists to determine the surface velocity of water
- Includes cosine error correction, allowing the unit to compensate for horizontal and vertical angles
- Wide velocity flow range (0.1 – 80 m/s)
- 12-30 VDC Power Interface
- Accepts tripod mounting
- User friendly measurement and reading
- Data port for computer.

TECHNICAL SPESIFICATIONS

Measurement Specifications	
Minimum Velocity	0.1 m/s
Maximum Velocity	80 m/s
Measurement Accuracy	± 0.3% - Speeds are rounded down to the nearest tenths of a unit
Mechanical specifications:	
Weight	1 kg
Dimensions	L 24 cm (9.45 in), H 10 cm (6.30 in), W 100 cm (4.76 in)
Case Material	Die Cast Aluminium
General specifications	
Units	MPS (meters per seconds), FPS (feet per second), KPH (kilometres per hour), MPH (miles per hour) and Knots
Horizontal Cosine Angle Correction	0 ° - 60 °
Sensitivity / range setting	0 - 8 / up to 100 meters away depending measurement conditions
Antenna Parameters	
Type / Nominal transmission frequency	Ka Band / 34.7 GHz
Polarization / Beam width	Circular / 12° (+/- 1°)
Nominal Microwave Power Output	15 mW nominal
Maximum Aperture Power Density	1 mW/cm²
Touchscreen Parameters	
Size / Type	2.4" / IPS LCD
Resolution (pixels) / Colors	320 x 240 / 65 000
Luminance / Contrast	800 cd/m² / 1000:1 **(SUNLIGHT READABLE)**
Viewing angle / Backlight	ALL (160°) / White LED backlight
Environment	
Ambient Temperatures	-22°F to +158°F, -30°C to +70°C
Maximum Humidity	90% relative humidity at 99°F (37 °C non-condensing)
Water resistance	IP65 or IP67 version, Meets International Robustness Standard according Europe an Community Standard BS EN 60529 1992 (IEC 529:1989)
Power	
Supply Voltage Range	12 - 30 VDC
Standby	0.200 amperes
Antenna ON	0.450 amperes

Appendix I: Viatronics SVR-3 Pro product information

Obtained from: www.viatronics.fi/en/products/security-solutions.

VIATRONICS SVR

Accurate Water -Speed Measurement Designed specifically to measure streams and rivers, the SVR gives you precise speed measurement from a stationary position outside the body of water. The SVR is perfect tool for flood and wastewater management applications.

The SVR is extremely valuable for measuring water surface velocity during high velocity flows and flood conditions where a using contact measurement instrument poses a risk to safety.

FUNCTIONS

- Touchscreen controls
- Built in data logger with automatic date and time information.
- Allows scientists to determine the surface velocity of water
- Includes cosine error correction, allowing the unit to compensate for horizontal and vertical angles
- Wide velocity flow range (0.1 – 80 m/s)
- Powered by Makita, Replaceable & rechargeable Li-ion batteries
- Accepts tripod mounting
- User friendly measurement and reading
- Data port for computer.
- Internal cosine error correction, allowing the unit to compensate vertical angles up to 60 degrees

TECHNICAL SPESIFICATIONS

Measurement Specifications	
Minimum - Maximum Velocity	0.1 - 80 m/s
Measurement Accuracy	± 0.3% - Speeds are rounded down to the nearest tenths of a unit
Mechanical specifications:	
Weight	1.5 kg (3.3 lb)
Dimensions	L 19 cm (7.5 in), H 26.4 cm (10.4 in), W 8.6 cm (3.4 in)
Case Material	Die Cast Aluminium & Composite (PVC)
General specifications	
Units	MPS (meters-per-second), CMPS (centimetres-per-second) FPS (feets-per-second), KPH (kilometres-per-hour), MPH (miles-per-hour) and Knots
Horizontal Cosine Angle Correction	0 °- 60 °
Sensitivity / range setting	0 - 8 / up to 100 meters away depending measurement conditions
Antenna Parameters	
Type / Nominal transmission frequency	Ka-Band / 34.7 GHz
Polarization / Beam width	Circular / 12° (+/- 1°)
Nominal Microwave Power Output	15 mW nominal
Maximum Aperture Power Density	1 mW/cm²
Touchscreen Parameters	
Size / Type	2.4" / IPS LCD
Resolution (pixels) / Colors	320 x 240 / 65 000
Luminance / Contrast	800 cd/m² / 1000:1 **(SUNLIGHT READABLE)**
Viewing angle / Backlight	ALL (160°) / White LED backlight
Environment	
Operating Temperatures	-22°F to +158°F, -30°C to +70°C
Maximum Humidity	90% relative humidity at 99°F (37°C non-condensing)
Water resistance	IP64, Meets International Robustness Standard according European Community Standard BS EN 60529:1992 (IEC 529:1989)
Voltages	
Supply Voltage Range	7.2VDC – 20VDC
Power Supply	replaceable Li-ion batteries, 18V / 1.3Ah
Power Consumption	
Standby / Antenna On	0.200 / 0.450 amperes

Appendix J. Teledyne Marine StreamPro ADCP product information

Obtained from: https://www.teledynemarine.com/brands/rdi/streampro.

TELEDYNE MARINE

PRODUCT DATASHEET

StreamPro ADCP

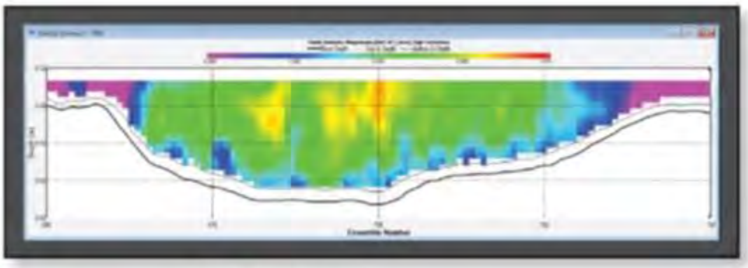
Shallow Streamflow Measurement System

Teledyne RD Instruments' **StreamPro ADCP** (Acoustic Doppler Current Profiler) is the industry standard in streamflow measurement. Built on years of Broadband experience, StreamPro enables a detailed measurement in a matter of minutes—a fraction of the time required using handheld point Doppler, electromagnetic, or mechanical devices. A discharge is obtained in real time and comes with QA/QC checks both during data collection and in post-processing to ensure compliance with organizational standards.

The StreamPro's transducer can be towed from the front or middle of the float, or can be removed and hand-held in the water for applications such as under-ice flow measurements.

PRODUCT FEATURES

- **Solid Acoustics:** 2 MHz operating frequency plus 20-degree beam angle ensures fullest velocity profile across the widest range of depth and sediment conditions.
- **Reduced Disturbance:** Smallest transducer head of any ADCP; reduced flow disturbance and easy use under ice.
- **Long-Range Bottom Tracking:** Reliable up to 7 m, profiling up to 6 m, standard on all systems.
- **Wireless Range:** 200 m long Bluetooth range ensures even short range communications resist dropouts.
- **Configurable:** Minimum cell size 1 cm with up to 30 cells.
- **Stable Floats:** Trimaran-style standard and high-speed options ensure consistent data under variable conditions.
- **GPS option available.**
- **Flexible Data Format:** Compatible with Teledyne RDI's WinRiver II software for data display and processing.
- **Low Power:** Full day of operation on AA batteries.
- **Affordable:** Surprisingly value-priced to suit your budget.



ADCP	IDEAL FIELD ENVIRONMENT
StreamPro ADCP	Shallow streams, 10 cm - 6 m
RiverPro ADCP	Deep streams to shallow rivers, 20 cm - 25 m
RiverRay ADCP	Shallow to deep rivers, 40 cm - 60 m

Above right: Sample data from StreamPro in high-precision mode in Cépet, France.

Above: Teledyne RDI's StreamPro ADCP can simply be pulled across the stream as you walk across a bridge, or attached to a tagline to collect real-time data.

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StreamPro ADCP Shallow Streamflow Measurement System

TECHNICAL SPECIFICATIONS

Water Velocity Profiling	Profiling range	0.1 m[1] to 6 m		
	Velocity range	±5 m/s[3]		
	Accuracy	±1% of water velocity relative to ADCP, ±2 mm/s		
	Resolution	1 mm/s		
	Number of cells	1–30		
	Cell size	1 cm to 20 cm		
	Blanking distance	3 cm		
	Data output rate	1 Hz		
Bottom Tracking	Depth range	0.1 m–7 m[2]		
	Accuracy	±1.0% of bottom velocity relative to ADCP, ±2 mm/s		
	Resolution	1 mm/s		
Depth Measurement	Range	0.1 m–7 m[2]		
	Accuracy	1%[4]		
	Resolution	1 mm		
Sensors		Temperature	Tilt (pitch and roll)	Compass (heading)
	Range	-4° to 45°C	±90°	0-360°
	Accuracy	±0.5°C	±0.3°	±1°
Operation Modes	Standard profiling (Broadband)			
	High-precison profiling (included, for depths 0.1 m to 1.0 m)			
Transducer	Frequency	2 MHz		
	Configuration	Janus 4 beams at 20° beam angle		
Software (included)	**WinRiver II** (standard) for moving-boat measurement			
Available Upgrades	• **SxS Pro Software** for stationary measurement • **Q-View Software** for quality assessment and reporting • **GPS** • **Riverboat SP** or **High-Speed Riverboat (HSRB)**			
Communications	Bluetooth wireless range 200 m[5]			
	Baud rates: 115,200 bps			
Construction	Cast polyurethane with stainless hardware			
Power	Voltage	10.5 – 18 VDC (8 AA batteries, alkaline or rechargeable NiMH)		
	Battery capacity	7.5 hours continuous with 8 AA alkaline batteries; 12.75 hours continuous with 8 AA NiMH rechargeable batteries		
Environmental	Operating temperature:	-5°C to 45°C		
	Storage temperature:	-20°C to 50°C		
Physical Properties	Weight in air	5.9 kg including electronics, transducer, float, and batteries		
	Dimensions	Electronics housing: 16 x 21 x 11 cm		
		Transducer: 3.5 cm diam. x 15 cm length; Float: 42 x 70 x 10 cm *(line drawings available upon request)*		

1 Assume one good cell (minimum cell size) with high precision profiling mode, range measured from the transducer surface.
2 Assume fresh water, actual range depends on temperature and suspended solids concentration.
3 2 m/s for standard float, 3.5 m/s for optional high-speed float.
4 Assume uniform water temperature and salinity profile.
5 Nominal range; actual may vary with environmental conditions.

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Appendix K: Teledyne Marine RiverPro 1200 ACDP and High Speed River Boat information

Obtained from: https://www.teledynemarine.com/brands/rdi/riverpro-adcp.

TELEDYNE MARINE

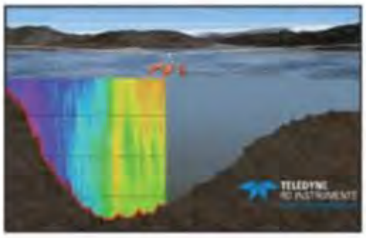
PRODUCT DATASHEET

RiverPro 1200 ADCP

Intelligent River Discharge Measurement System

Hits the sweet spot between accurate and easy to use

Unique in its class as a true broadband ADCP, the RiverPro 1200 delivers the very highest accuracy bottom track and water profiling on a second-by-second basis. This is a must for river measurements in which depth and velocity change constantly, often rapidly! RiverPro 1200 users worldwide know that with the right technology, variability between transects can be minimized, saving you time both in the field and back at the office.



We know there's lots to think about in the field!

Rest assured all the setup parameters to make a good measurement are expertly determined by RP1200's "adaptive sampling" algorithms. With the instrument handling data setup and optimization, you can focus on what matters most: field objectives, correct procedure, and skilled execution.

Because the environment matters

Extreme events – both floods and droughts – climate change, pollution, wildlife habitat, and river restoration projects have all increased the need for volumetric flow data. The multi-purpose RiverPro 1200 is the ideal tool to accurately collect the critical in-situ water column and riverbed details needed for actionable analysis.

All the right features you expect from a premium product

RiverPro 1200's option to integrate user-supplied GPS or echosounder, Bluetooth comms, manual configuration, powerful visualization and processing software, and unsurpassed years of expertise in service and support from an ISO-certified company culminate to deliver a best-in-class solution.

IDEAL FIELD ENVIRONMENTS

StreamPro	Shallow 10 cm - 6 m
RiverPro 1200	**Mid-Range 20 cm - 25 m**
RiverRay	Deep 40 cm - 60 m
RiverPro 600	Advanced Applications 54 cm - 100 m

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TELEDYNE MARINE

PRODUCT DATASHEET

RiverPro 1200 ADCP

Intelligent River Discharge Measurement System

TECHNICAL SPECIFICATIONS

Water Velocity Profiling	Operation mode	Broadband / pulse-coherent; automatic / manual			
	Velocity range	±5 m/s default, ±20 m/s maximum			
	Profiling range[1,2]	12 cm to 25 m			
	Accuracy	±0.25% of water velocity relative to ADCP, ±2 mm/s			
	Resolution	1 mm/s			
	Number of cells	15-30 typical, 200 maximum			
	Cell size	2 cm to 5 m			
	Data output rate	1-2 Hz (typical)			
Bottom Tracking	Operation mode	Broadband			
	Velocity range	±9 m/s			
	Depth range[2]	15 cm to 35 m			
	Accuracy	±0.25% of bottom velocity relative to ADCP, ±2 mm/s			
	Resolution	1 mm/s			
Slant Beams (Depth Measurement)	Range[2]	15 cm to 35 m			
	Accuracy[3,4]	±1%			
	Resolution	1 mm			
Vertical Beam (Depth Measurement)	Range[2]	20 cm to 120 m			
	Accuracy [4]	±1%			
	Resolution	1 mm			
Standard Sensors		Temperature	Tilt (pitch and roll)	Compass	GPS (embedded)
	Range	-5°C to 45°C	±90°	0-360°	
	Accuracy[5]	±0.5°C	±0.3°	±1°	3 m horizontal
Transducer and Hardware	System frequency	Slant beams: 1228.8 kHz / Vertical beam: 614.4 kHz			
	Configuration	4 piston transducers, Janus arrangement with 20° beam angle/ 1 vertically mounted piston transducer			
	Internal memory	16 MB			
Communications	Standard	RS-232, 1200 to 115,200 baud. Bluetooth, 115,200 baud, 200 m range.			
Software (included)	**WinRiver II** (standard) for moving-boat measurement, **Q-View** (optional), **SxS Pro** (optional)				
Power	Input voltage	10.5–18 VDC			
	Power consumption	1.5W typical			
	Battery (inside float)	12V, 7A-hr lead acid gel cell (rechargeable)			
	Battery capacity	>40 hrs continuous operation			
Float (optional)	Configuration	Three hulls (trimaran)			
	Material	Polyethylene			
	Dimensions	Length 120 cm, width 80 cm, height 20 cm			
	Weight	10 kg bare; 17 kg with instrument and battery			
GPS Integration (optional)	Integration with customer-supplied GPS, depth sounder, gyro compass via RS-232				
Environmental	Operating temperature	-5°C to 45°C			
	Storage temperature	-20°C to 50°C			
Available Upgrades	**SxS Pro** Software for Stationary Measurement • **QView** Software for quality assessment and reporting • **GPS** (position-only or vector) • **HSRB**				

1 Distance measured from the center of the first cell to the transducer surface.
2 Assumes fresh water, actual range depends on temperature and suspended solids concentration.
3 For beam-averaged depth data.
4 Assumes uniform water temperature and salinity profile.
5 For combined tilt <+/-70° and dip angle <70°.

TELEDYNE MARINE
RD INSTRUMENTS
Everywhereyoulook™

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Obtained from: https://www.teledynemarine.com/en-us/products/Pages/high-speed-riverboat.aspx.

Teledyne Oceanscience

High-Speed Riverboat™

Tethered Boat for Fast-Flowing Waters

The Right Choice for High Water Velocities

For the best data quality in the most challenging measurement conditions, the Teledyne Oceanscience High-Speed Riverboat (HSRB) is the new benchmark for acoustic Doppler current profiling for discharge measurements. The advanced hull design allows the boat to slice through standing waves and still maintain instrument position and data collection. Fast-flowing water, often problematic with conventional tethered boat designs, can be handled with relative ease with the High-Speed Riverboat.

The HSRB has gathered data at water velocities over 20 fps (6m/s). The state-of-the-art trimaran hull design cuts through surface waves, strongly resists overturning, and maintains instrument orientation in high flows. For sites where tethered boat measurements have been impossible, or data were too poor to be of value, the High-Speed Riverboat is the solution. The High-Speed Riverboat is strong and robust to cope with the worst deployment conditions.

PRODUCT FEATURES

- Advanced hull design to slice through standing waves
- Obtain measurements in velocities up to 20 fps
- Real-time data transmission to shore laptop
- Single or dual-person mobilization
- Made of high impact UV-resistant ABS
- Any instrument up to 8" in diameter may be accommodated
- Accommodates multiple instruments on one boat

A Teledyne Marine Company

TELEDYNE OCEANSCIENCE
Everywhereyoulook™

High-Speed Riverboat

Tethered Boat for Fast-Flowing Waters

TECHNICAL SPECIFICATIONS

Physical	Center Hull Length Overall Width Weight Hull Material Crossbar Material Hardware Fin Configuration	152.5 cm (60") 122 cm (48") 13.6 kg (30 lbs.) High-Impact, UV-Resistant ABS Anodized Aluminum with Quick-Release Clamp Stainless Steel Large, Foldable Kick-Up Fins
Perfomance	Typical Measurement Water Velocity Maximum Water Velocity	3-5 m/s (10-16 fps) 6.09 m/s (20 fps)
Instrumentation	Acoustic Doppler Current Profilers	Teledyne RD Instruments RiverRay Teledyne RD Instruments RiverPro Teledyne RD Instruments Rio Grande Teledyne RD Instruments StreamPro Teledyne RD Instruments Monitor Sontek RiverSurveyor M9 Linkquest Flowquest Rowe RiverPROFILER
	Depth Sounder	External Mount
	GPS	Hemisphere A101 Hemisphere S320

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Appendix L: DischargeKeeper installation checklist supplied by SEBA to potential customers

Checklist supplied to the authors by Dr Issa Hansen of SEBA Hydrometrie.

SEBA HYDROMETRIE

Checklist

Discharge measurement DischargeKeeper

Distributor:					Revision: 1.0	Date: 22.02.2022	created: ahe/lh	Release: et

Questionnaire for the DischargeKeeper

1. Address details:

Company:

End Customer:

Contact person:

Street:

Zip Code, City:

Tel. no.:

E-mail:

Project Name:

In order to provide you with an optimal solution for your application, we need to know the conditions and possible constraints of your site as well as possible. Therefore, we ask you to take a few minutes to answer the questions below. The more information you provide, the better we can find the right solution. Please send the sheet to: **info@seba.de** or by fax to: **(+49) 08341 964848.** Thank you.

2. Details of the measuring point:

Measuring point name / water body:

Geo-coordinates / locality:

Water width (approx.):

Water level (approx. medium):

Flow velocity (approx. medium):

Typical wind speed:

min/max air temperature:

Humidity often > 90%: Yes ☐ No ☐

Backwater situation: Yes ☐ No ☐

T:\Marketing\Formulare\Durchflussmessung\Formular\DischargeKeeper

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SEBA HYDROMETRIE

3. Measurement setup (hardware):

3.1. Camera and infrared beamer

Distance location camera to opposite bank (approx.): [m]

Mounting location:

Wall mounting:

Mast mounting: **circular:** **diameter:** [mm]

rectangular: **dimensions:** *(length x width)* [mm]

Bridge mounting*:
*(*Please provide sketch or photo.)*

Distance camera - protective housing (DK central unit): [cable length]

≤ 10 meters 10-15 meters 15-50 meters ≥ 50 meters

3.2 Remote data transmission/SIM card

Is internet access provided? Yes* No
**) Prerequisite: Provision of an Ethernet interface, min. 250 kbit/s*
Consultation with customer's IT department necessary

If no internet access: Mobile data signal available? UMTS/3G LTE/4G
Prerequisite: stable 3G/4G reception, min. 250 kbit/s

Note: Although SEBA performs a mobile frequency check for each country, we cannot guarantee that the corresponding frequencies are actually offered by the internet provider at the measuring point.

Is live access to camera stream required? Yes No

Note: For live images, addional fees apply (annual or data credits). In addition, a higher data volume is required for the SIM card for remote data transmission.

If no internet access:
SIM card details

Is a SIM card provided by the customer? Yes No
SIM card requirements:
M2M, UMTS/LTE tariff, card format: 2 FF, minimum volume: 10 GB

3.3. Measuring system protection

Where should the protective housing be mounted?
Dimension of the protective housing: 430 x 330 x 200 mm (width x height x depth)

Wall mounting:

Pole mounting: **circular:** **diameter:** [mm]

rectangular: **dimensions:** *(length x width)* [mm]

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3.4. Power supply

Is grid power available?

Yes ☐ — ☐ 230 VAC (single-phase, TN-S system, back-up fuse on site). ☐ 12 VDC (peak current and average consumption to be specified at time of bid) ☐ Other

No ☐

3.5. Data logger with remote data transmission (optional)

Is an external data logger available on site? Yes ☐ No ☐

Should h, v and Q data be transferred to an external logger? Yes ☐ No ☐

Details of the existing external data logger: *(only one option can be selected)*

Data transfer: Analog ☐ *(0…1/5 V or 0/4…20 mA)* SDI-12 ☐ Modbus ☐ SHWP ☐

3.6. Redundant water level measurement

Is redundant water level measurement available? Yes ☐ No ☐

Output signal of the existing water level sensor?

Analogue ☐ *(0…1/5 V or 0/4…20 mA)* SDI-12 ☐ SHWP/RS 485 ☐ Modbus ☐

Note: the provision of the output signal for the water level at the control cabinet (DK central unit) is done by the customer.

If there is no external water level measurement available yet:

Which sensor type is preferred?

Pressure probe ☐ Bubbler system ☐ Radar ☐ Angle encoder ☐

Should the water level sensor additionally be connected to a further data logger? Yes ☐ No ☐

4. Information on the measuring operation:

Required measuring interval *(water level, flow velocity, flow rate)* ______ [min]

Required transmission interval (measurement data & test images) ______ [min]
Note: Measurement data & test images are transferred to the SEBA web portal „www.seba-discharge.de" by default.

5. Data flow and data format details:

In addition to transferring data to the SEBA web portal „www.seba-discharge.de" (see item 4), should data, images and movies be transferred to an FTP server? *(only one option can be selected)*

- **SEBA FTP server** (data download, format: csv, zrxp or ARCON)
- **Customer FTP** (data upload, format: zrxp)
- **No**

6. Additional information/comments:

7. Pictures/films for site assessment:

- **Pictures of measuring point (different views, if possible also under low water level conditions)**
- **Video recording, e.g. with a smartphone**

Please note the following procedure:

- If possible, please record from the planned DischargeKeeper camera position.
- Please hold the camera still for the recording and do not pan back and forth.
- Supported hand position during video recording
- The view segment should include the water surface and parts of the opposite shore .
- Duration of the video recording approx. 5 seconds

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