WMO Training Material - Surface Velocity measurements using Image Velocimetry.

1 General description.

Surface velocity methods are based on measuring the water velocity at the surface, to calculate a stream discharge value. This process requires the tracking (timing) of surface structures, floats or natural tracers as they travel over a known distance. This allows a measured velocity to be calculated that is assumed to be representative of the actual water surface velocity at that measurement point. A common workflow for surface velocity methods to derive discharge include:

1. Surface velocities are measured at a single point or multiple points across the channel width.
2. Measured surface velocities are transformed to a mean velocity value representative for the full flow depth. This is achieved through formulas or through applying coefficients generally known as the 'surface alpha'.
3. Multiple mean velocities can be applied to a cross sectional area (in the same manner as a wading measurement) and discharge is calculated by either the mid or mean section method.
4. Requirements for surface velocity measurements are included under *ISO 748 Hydrometry – Measurement of liquid flow in open channels using current meters or floats.*

1.1 Advantages and disadvantages.

The resurgence of surface velocity methods is based on the practical advantages this method can provide over other discharge measuring techniques and the advancement of technologies such as drones. As with all measurement techniques there are usage criteria of which the user needs to be aware of to ensure confidence in the measured data.

1.2 Advantages.

1. Improved staff safety for high flow measurements.
2. Non-intrusive measurement technique.
3. Can be used to make velocity and/or discharge measurements.
4. No depth restrictions for velocity analysis. Suited to shallow flows where ADCP blanking distances are problematic.
5. Potential for remote applications where staff are not required on site during the measurement.
6. Inexpensive measuring equipment in the form of low cost cameras and drones.
7. Suited to high flow and high debris flood environments which present difficulties and dangers for ADCP measurements. This includes rapidly changing flows such as flash floods.
8. Comparable accuracy to currently accepted discharge measurement techniques, when applied correctly and tracer movement can be visualised.

9. Large volume of citizen science flood videos from social media sources that can be used.
10. Provides a visual record of flow events.

1.3 Disadvantages.

1. Surface tracers used to calculate velocity must be advected with the surface velocity.
2. Strong prevailing wind can potentially bias surface tracer movement (they become unrepresentative of the surface velocity).
3. Surface alpha values can be site and stage level specific.
4. As an area velocity method, cross sectional area needs to be measured, usually separately, and unless there are stable bed features the cross-sectional area may not be known with confidence.
5. A lack of surface tracers, or the inability to track surface tracers may compromise velocity data determination.

NOTE: As with any velocity/discharge measurement it is important that the analysis and results are checked for errors and that the data makes hydrological sense.

2 Surface velocity measurement methods.

The two most common methods currently using actively supported and stable software/hardware for calculating surface velocities and open channel discharge. These methods are:

- Image velocimetry – Predominantly using Large Scale Particle Image Velocimetry (LSPIV), and Space Time Image Velocimetry (STIV).
- Surface velocity radar – Fixed and mobile solutions.

2.1 Important considerations.

Surface velocity methods are not suitable for all measurement sites, and it is important that practitioners applying these methodologies understand where these methods will not provide accurate velocity/discharge data.

Important site conditions to avoid include:

1. strong prevailing wind at the water surface.
2. Clear water, no visible surface tracers, textures, or ripples that are advected with flow. Tracer material can be added by the user in the field if on site.
3. Tidally influenced flow, backwater effects (at/near hydraulic control), or any other site conditions that may prevent accurate quantification of a surface alpha coefficient (relates to discharge calculations only).

Important considerations when recording videos are:

1. Fixed camera sites need a secure camera mounting with a good view of the channel width including channel widths at peak flow heights.
2. Measurements undertaken using a drone require the drone to hover in a stable position during video collection. A 3-way gimbal assists in maintaining steady

video footage. Image stabilization methods also assist and are often built into the image velocimetry software.

3 Image Velocimetry Methods.

Image velocimetry is an increasingly popular surface velocity measurement technique that uses a recorded video of the water surface and moving tracers to calculate surface velocities. These velocities can be calculated at multiple points across a channel.

Image velocimetry relies on the accurate scaling of the pixels to metres, in relation to the camera sensor, channel width, and water level. This is achieved via an orthorectification process (Section 4).

Once the pixels are calibrated, surface tracers can be tracked over a precisely known distances via the pixels. The duration of the video provides the time reference required to calculate velocity.

There are currently two mature and supported desktop methods/algorithms available for image velocimetry processing:

- Large Scale Particle Image Velocimetry (LSPIV), which utilises a cross correlation algorithm. *Fujita et al 1997*
- Space Time Image Velocimetry (STIV), which uses a gradient tensor analysis. *Fujita et al 2004*

Additional methods being developed and applied to streamflow measurements such as optical flow.

Due to image velocimetry being a software-based velocity and discharge measurement solution, it is important that when deciding on which processing software to use that the software's results has been verified via concurrent measurements over a range of environmental conditions.

3.1 Large Scale Particle Image Velocimetry (LSPIV).

Since LSPIV was first developed (Fujita *et al*., 1998) the methodology has become further modified and can be known by many other abbreviations depending on the software application.

1. LSPIV is the application of particle image velocimetry (PIV) to a real world 3D environment.
2. The core processing algorithm to derive velocities is always a cross correlation analysis of surface tracer movement.
3. For this document the generic term of LSPIV is used to describe methods using a cross correlation, PIV based surface velocity analysis.
4. LSPIV can determine surface velocities in 2D (i.e., direction and magnitude).

3.1.1 LSPIV analysis.

All programs using cross correlation analyses require that the video frames be separated into individual images (frames). Separating each individual frame produces a series of time-lapse images. A video recorded at 30 FPS (frames per second) can therefore produce 30 separate images for each second of video recorded. The time difference between extracted images (frames) represents a time interval used in the velocity calculation.

When using LSPIV based image velocimetry software the following recommendations should be followed:

1. The time interval between successive images extracted from the video should be set long enough to allow the visualise the movement of tracers (typically over 15 to 25 pixels) and short enough to avoid tracer deformation (hence low correlation).
2. It is recommended that a minimum of 10 image pairs be extracted from a recorded video and used for velocity and discharge calculations.
3. Velocity magnitude and tracer availability should be considered when deciding the time interval of extracted images and video length.
4. Unsteady frame rates typically associated with Internet Protocol (IP) cameras, may provide incorrect time stamps to the extracted images. Incorrect time stamps can produce incorrect velocities (Detert, 2021).
5. The number of extracted images selected and analysed can impact on the computational time required to undertake the cross-correlation analysis and discharge calculation.
6. Due to natural turbulence in rivers a sufficient recording time is needed to obtain a stable time average.
7. It may be necessary to highlight stationary objects, such as trees, contained within the field of view to exclude and prevent negative bias of nearby velocity analysis (Figure 1).

LSPIV analysis may produce varying results depending on the analysis parameters selected by the user. It is important that users new to LSPIV are aware of the impacts of these choices which may require the optimum site settings to be determined by running multiple analysis at a site.

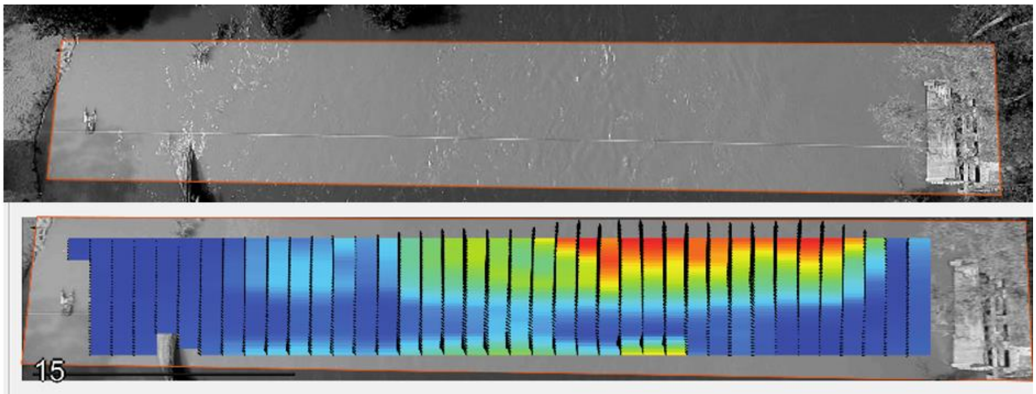


Figure 1. LSPIV velocity bias caused by including stationary objects in the analysis. The top image shows a stationary tagline across the channel. The bottom image shows how velocities have been biased low in the location of the tagline. Source: Mark Randall, RDMW, using RIVeR LSPIV software.

3.1.2 Interrogation area.

The Interrogation Area (IA) is a small area set in the images, where the analysis software will look to identify tracers and particle pattern displacement. The analysis looks to cross correlate (track) the movement of the same tracer between the sequential images.

Multiple interrogation areas are established across the Region of Interest (ROI), forming a grid where the velocity analysis is required.

The size of the IA needs to be large enough to contain tracer/particle patterns of movement, but small enough to be representative of the local flow and tracer movement. Velocity magnitude and tracer quality are determining factors when setting the size of the IA.

3.1.3 Search area.

The Search Area (SA) is a user-defined area containing the centres of IA in the second image that will be correlated with the IA in the first image, for each user designated node in the computational grid across the region of interest.

The size of the SA needs to be selected in relation to the magnitude of the tracer displacement between sequential images. Therefore, the velocity magnitude and tracer quality are determining factors when setting the size of the SA.

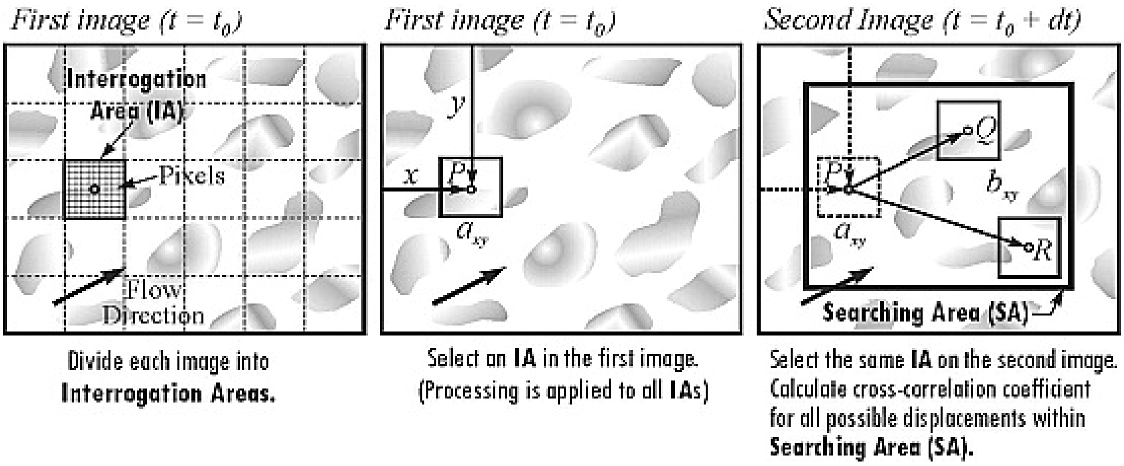


Figure 2. Cross correlation is computed between an interrogation area (IA) in the first image and IA areas located within a Search Area. Source: Muste *et al.,* 2008.

3.1.4 Processing filters.

Cross correlation analysis of tracer displacement requires post processing filters to be applied to minimise the impacts of erroneous data. Filters may include:

1. Correlation – strong correlations can be a result of fixed objects such as channel banks, rocks, and trees. A maximum correlation threshold is set to remove these returns from the velocity analysis. Correlation filters should be set between 0.4 and 0.98.
2. Velocity – maximum and minimum velocity thresholds can (software dependant) be set in both the x and y directions.
3. Filter thresholds applied should be set in accordance with the site, velocity and tracer conditions.
4. Different types of flow events may require different thresholds being set to prevent data being incorrectly excluded.
5. Following the application of filters, the initial raw velocity results are then averaged over all extracted image pairs to provide an average surface velocity and direction for each interrogation area contained within the section of the river under analysis.

6. Once LSPIV analysis has been completed the magnitude and distribution of velocities should be checked visually to ensure that they appear realistic, accurate, and correctly distributed across the channel.
7. Any significant errors should be corrected for by adjusting the analysis parameters and/or post processing filters.

LSPIV software generally requires clearly identifiable tracer material distributed across the width of the channel. If there are insufficient tracers available, LSPIV software may be unable to differentiate between water ripples/turbulence, which are representative of surface velocities, and wave noise that is not representative of surface velocities.

A measurement video containing few physical tracers passing through the analysis location therefore may cause analysis bias, usually a negative bias, in velocity and discharge.

These errors cannot be easily identified or corrected for in post processing procedures.

3.2 Space Time Image Velocimetry (STIV).

STIV combines the principles of image velocimetry with the concept of space-time tracking, which involves measuring the motion of fluid particles over a period of time along a known distance.

Unlike LSPIV techniques, which requires a series of images extracted at fixed intervals, STIV uses the entire video allowing for the measurement of fluid velocity over a continuous period of time. Velocities are calculated and averaged along individual search lines set by the user in the direction of flow, Fujita *et al*, 2007.

Additionally, STIV:

1. Only produces 1D velocities along user-defined search lines, usually set perpendicular to the cross-section and in the main flow direction.
2. Search lines are of a known length and, together with the known time duration of the video, provides a basis for an average surface velocity to be calculated.
3. Not suitable for defining circulating or unsteady flow that significantly varies its direction with time e.g., vortices.
4. Utilises all video frames for analysis. It does not require image extraction rates to be defined by the user.
5. Does not require user defined processing filters.
6. Velocities can be manually checked for possible calculation errors, and post processing corrections applied if required.

3.2.1 STIV velocity measurement.

To determine velocity each pixel located along the known length of a search line are stacked for every frame of the video. As tracers/surface structures travel along each search line they naturally create a visible line from the variation in brightness which is angled down from top left to bottom right creating what is termed a Space Time Image (STI). A STI is created for each line location as determined by the user providing a calculated surface velocity at multiple points across the channel.

A coherency analysis of the STI identifies the mean angle and therefore the mean surface velocity for each Search Line.

STIV assumes that the velocity is constant along the length of a velocity search line but can be used to measure velocity pulsing and wave speeds if velocities are not constant. Strong wind gusts can also be identified and corrected for.

STIV provides a robust analysis method for more challenging site conditions such as low tracer environments.

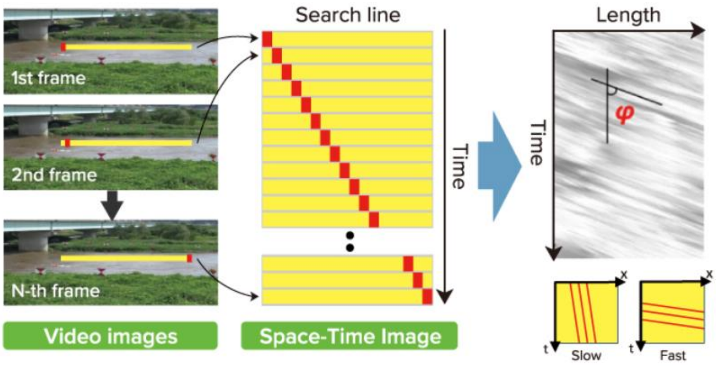


Figure 3. STIV analysis, pixels located along a Search Line are stacked below each other for every frame. Tracer movement along the Search Line produces an angled line representing the surface velocity.

Source*:* https://hydrosoken.co.jp/en/service/hydrostiv.php *viewed 20/06/2020*

As with LSPIV factors such as gravity waves, environmental noise, or few physical tracers can potentially produce bias in the STIV velocity analysis (generally negative bias) if uncorrected. Any significant velocity errors identified should be manually corrected for using post processing procedures, Section 3.2.3.

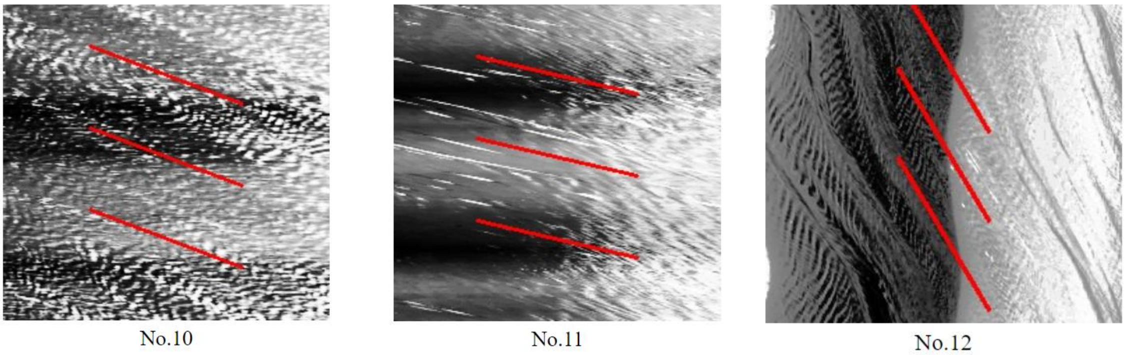


Figure 4. Automated STIV velocity analysis (red lines) using deep learning filters. No.10 contains gravity wave noise with no clear tracer movement. No.11 contains visible tracers on moving into an area containing gravity wave noise. No.12 contains additional drone camera movement creating wavey lines Source: Mark Randall, RDMW, using HydroSTIV software.

3.2.2 Length of STIV velocity analysis search lines.

STIV analysis calculates a single average velocity over the distance covered by the length of each search line. Correct length and placing of search lines will improve automated analysis and is determined by the nature of the site.

1. Length of search lines should be set to avoid longitudinal variations of velocity caused by varying channel slope, depth, and roughness from occurring along the search line.
2. Length can be site dependant on the available field of view ideally avoiding being placed over fixed structures such as trees, buildings, bridges.
3. Length for each search line can be individually set to avoid largely covering stationary objects.

4. A length of 5 to 10 metres is acceptable for most site requirements to correctly average out surface velocity pulsing. The longer the search line the greater the averaging distance of downstream velocities.
5. Multiple search lines can be placed along a channel reach contained within the video, Figure 5.

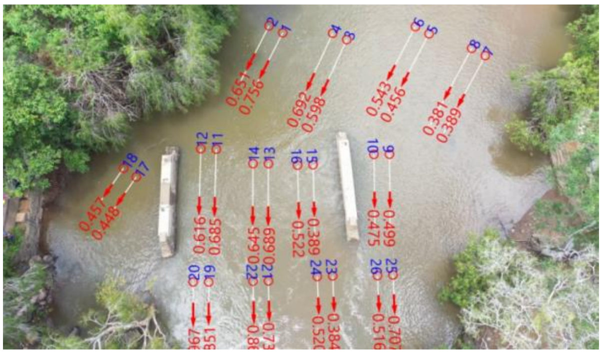


Figure 5. Multiple STIV search lines undertaking velocity analyses along a short channel reach. Source: Mark Randall, RDMW, using HydroSTIV software.

3.2.3 Post processing checks and validation.

After STIV analysis has been completed the magnitude and distribution of velocities should be checked visually to ensure that they appear realistic, accurate, and correctly distributed across the channel.

If post processing of a STIV measurement is required, then it is recommended that the user check:

1. All STI generated in a measurement should be examined to ensure that the mean orientation angle has been correctly identified.
2. STI analysis along each search line should be manually corrected if velocities have been incorrectly identified during automated processing (Sections **** and *****)
3. When manually correcting biased velocities, the user needs to consider the velocity magnitude and distribution across the cross section and consider removing erroneous velocities.
4. If an incorrect velocity for a search line cannot manually be corrected or interpolated between two measured velocities, then the search line should be removed from a discharge calculation.

3.2.3.1 STI visual analysis.

The user can check the automated analysis ability to correctly identify the mean angle of tracer movement and therefore velocity. If incorrect it is possible to visually identify the correct mean angle within the STI, Figure 6.

In Figure 6 the STI velocity was biased low due to the strong sun glare on the water which creates a stronger, more dominant signal intensity than the tracers representing the actual velocities. Due to the sun glare being stationary, it created a bias in the automated analysis to 0 m/s. Using a visual check, the user can identify tracer movement in the STI and has manually defined three tracer's particle movement with velocities of 1.96, 2.02, and 1.9 m/s. These three velocities are averaged for a mean surface velocity equalling 1.96 m/s.

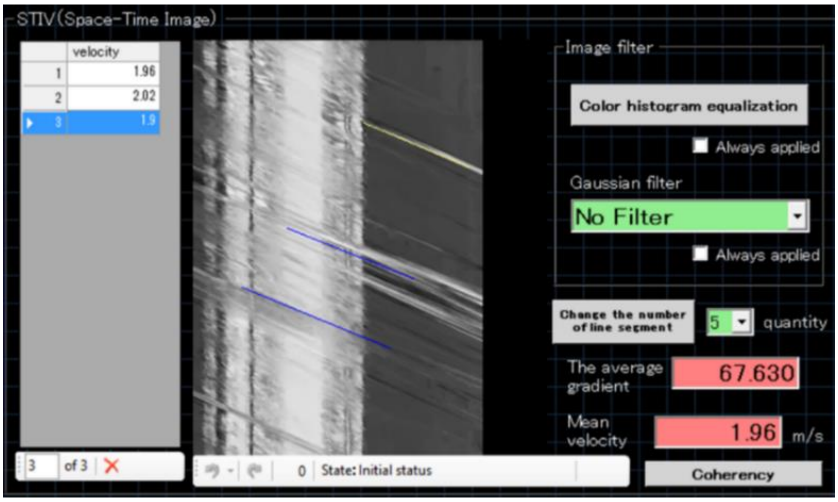


Figure 6. STIV velocity bias caused by sun glare on the water gives a more dominant signal than the tracers representing the actual velocities, biasing incorrectly the automated analysis to 0 m/s. Source: Mark Randall, RDMW, using KU-STIV software.

3.3 Site Selection, Installation, and Video Collection.

Hydraulically, the site selection criteria and management should be the same as with any other site used for velocity area discharge calculations.

Key points of note include:

1. The channel reach should provide a uniform depth and roughness over the measurement length.
2. The reach should be stable over the range of targeted flows to be measured.
3. Long term fixed installations should have the cross section and channel reach surveyed annually for three years for long term.
4. Cross sections and channel reach should be surveyed after any flow event that could have resulted in changes to depth and/or roughness.
5. Measured changes shall be assessed for impacts on velocity and discharge calculations against targeted measured flows.
6. Water level datum is required in relation to ground control point datum at the time of the recorded imagery.

Inability to comply with these recommendations may result in the collection of lesser quality velocity data and subsequent stage/discharge relationships. The user should take additional measures to validate the surface velocity discharge measurements with independent check measurements.

3.3.1 Site selection criteria for installing fixed cameras.

A fixed installation of a camera at a measurement site allows videos to be automatically recorded and stored for discharge processing, eliminating the need for staff to be onsite.

This provides a remote area monitoring solution along with the ability to undertake multiple discharge measurements at multiple sites during widespread or significant flood events.

Onsite cameras provide a visual record of flow events.

Depending on the target flow to be measured the following considerations should be applied when installing a fixed camera for image velocimetry.

1. A site containing visible surface movement that is advected with flow occurring for the range of target flows to be measured.
2. Stage measurements required for video processing should be located at the camera installation location to minimise impacts of stage and surface slope. If stage measurements are undertaken at a separate location, then surface slopes and stage transit times should be determined between the two locations. Additional sources of flow input should not exist between the two sites.
3. Sites where excessive shadows and sun glare are present may hide the movement of surface tracers in the video and therefore should be avoided. This is of particular importance at low flow sites that may not contain strong tracer signals.
4. Clear water where the riverbed may be visualised require a smaller positioning angle closer to the critical value. This may improve automated analysis if tracer materials aren't present.
5. The camera requires a clear Field of View (FOV) of the water's surface. Some minor obstructions can be accommodated in the FOV, but the user needs to consider that these could impact velocity analysis and may require manual corrections.
6. The ROI for the analysis needs to be visible to the camera through the full expected stage range at the site. Points of flow disturbance in either an upstream or downstream location should also be avoided for automated analysis.
7. The camera needs be fastened to a secure structure that will eliminate camera movement by wind/vibrations. Camera shake prevents accurate determination of tracer movement.
8. Night measurements will require a suitable infrared camera or illumination system including white light. A far-infrared camera provides an additional option.
9. Camera mounting elevation should be at a height that allows the critical angle between the camera and the water plane to remain above the minimum specified angle. This angle is dependent on the channel width and water level (Figure 7).
    - For LSPIV installations, the minimum recommended angle at the furthest analysis point of the camera is 15 degrees.
    - For STIV applications, the minimum angle is 2 degrees.
    - Angles above these minimums will improve tracer and velocity determination. Lower angles can increase potential for velocity bias and/or tracer resolving issues for these analysis methods.

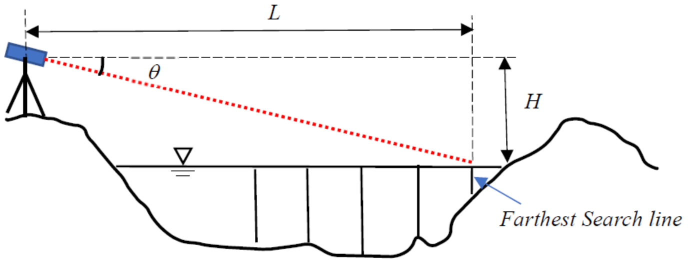


Figure 7. A fixed camera installation for STIV showing minimum critical angle measurement θ. The distance to the furthest analysis point is represented by L and the camera height above the water level plane equals H. As water level changes so will the value of θ. This value should not go below the minimum critical value depending on LSPIV or STIV analysis. (Source: Professor Ichiro Fujita, email correspondence July 2020).

3.3.2 Fixed camera setup and video recording guidelines.

The following criteria should be considered for a fixed camera setup and recording settings when establishing a fixed camera image velocimetry site:

1. Camera image shall not include lens distortion. Any identified lens distortion would need to be corrected with a lens correction process prior to analysis.
2. Image resolution in the stream wise direction should be set in relation to the furthest analysis point from the camera location (water level) and either the size of the ROI where the velocity analysis is taking place or the length of STIV measurement line being used.
3. The video resolution should be selected based on the channel width. In most instances a high-definition resolution (1920x1080) is suitable.
4. IP camera frame rate sampling should be stable. LSPIV software, due to the subsampling of frames used, are incapable of accommodating frame interval variability and instability, resulting in velocity errors (Detert, 2021).
5. It is recommended that a minimum frame rate of 24 frames per second be used.

When deciding on a camera model for a fixed site it is important to consider its video scheduling capabilities and data storage availability.

3.4 Image velocimetry using Remotely Piloted Aircraft Systems (RPAS).

The use of RPAS, commonly referred to as drones (the term drone will be used for the purpose of this document), provide a mobile solution for image velocimetry measurements, and only requires pixel scaling to calibrate pixel size when the camera is in a nadir position.

Drones can be used to quickly and safely measure discharge in flow conditions unsuitable or too dangerous for deployment of an Acoustic Doppler Current Profiler (ADCP) on a manned boat.

3.4.1 Drone video recording guidelines.

When using a drone to collect videos for image velocimetry analysis and discharge calculations the following collection procedures are required to ensure image velocimetry analysis can be applied correctly:

1. The camera is required to be in a nadir viewpoint when using pixel scaling. If filming from an oblique viewpoint, then an alternative orthorectification process will be required involving the camera properties and gimbal angle.
2. The entire channel width should be contained within the image if processing for discharge (Figure 8)
3. The drone is required to be hovering and stable to reduce any camera shake. Any significant movement of the drone could impact the velocity analyses results. Image stabilisation can be undertaken prior to analysis if camara shake is evident.
4. There needs to be at least one easily identifiable feature within the recorded video that has a known measured distance for scaling the pixels.
5. A cross section at the video location is required for discharge calculations. A cross section can be surveyed after the video collection if required.

6. Consider environmental elements such as sun glare, shadows, and wind affect. These may impact the drone's ability to visualise surface movement accurately, especially in lower flow environments.

Figure 8. An image from a drone flood video in Norway. Tracer particles that are advected with the flow are clearly visible across most of the channel width. This video is very good for image velocimetry analysis. Source: Kristoffer Florag-Dybvik, Norwegian Water Resources and Energy Directorate (NVE).

4 Image Orthorectification and Geometric Correction.

All image velocimetry methods require an orthorectification to be undertaken and is typically done during a camera installation.

Image orthorectification and geometric correction relate to the transformation process used to project 3D "real world" ground features onto a 2D image plane. Orthorectification corrects for distortion created by site topography, camera sensor angle, lens, and elevation creating a 2D image that is a measurable, mapped image (Figure 10).

This process is important to implement correctly as it forms the base data source for the velocity calculations and cross section placement.

Orthorectification is necessary to account for the reduction of displacement with an increasing distance to the image optical centre, lens distortion (Figure 9) can be a significant factor particularly in lens with wide field of view. Lens distorted images need to be treated with a lens correction prior to analysis.

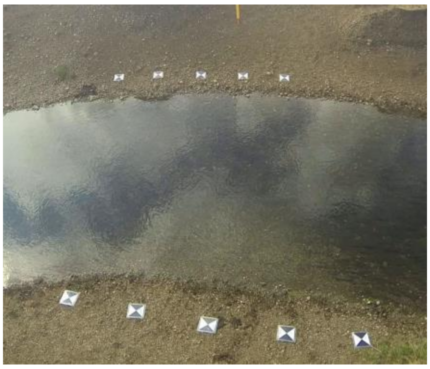


Figure 9. Uncorrected barrel distortion which creates curvature in what are actually straight lines. Typically occurs in wide angled lens (Source: Sophie Pearce, Newcastle University, UK).

Orthorectification is predominantly achieved using forms of the mathematical relationship described by the pin-hole camera model,

The choice of the orthorectification process to be applied is determined by the relationship of the camera sensor angle to the water level plane. A camera sensor looking vertically (nadir) to the water plane only requires a scaling factor/distance, whereas a camera mounted at an oblique angle requires a 3D or 2D orthorectification due to the distortion of the pixel shape as distance from the sensor increases.

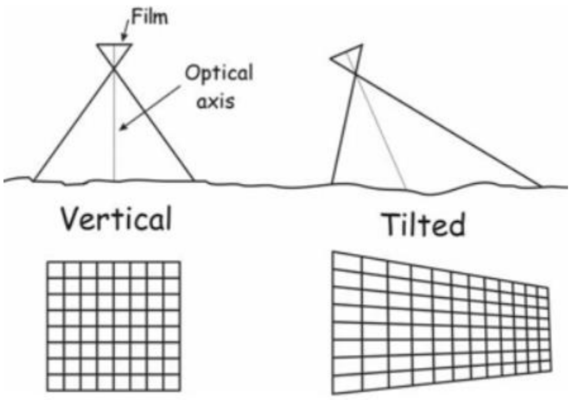


Figure 10. Shows how camera angle creates distortion in the pixels (Right). The left image shows a vertically positioned camera (nadir) from a drone. Source: https://www.esri.com/arcgis-blog/products/arcgis-pro/imagery/ortho-mapping-workspace/ viewed 20/05/2020.

Orthorectification requires a number of GCP located within the Field of View (FOV). Each GCP requires real world coordinates specific to its location and in relation to the position of the camera.

A 3D or 2D orthorectification requires GCP with known coordinate data in XYZ or XY format.

1. GCP survey data should be checked for relative accuracy before attempting orthorectification. Survey errors will complicate the orthorectification process. Large errors will cause the process to fail. The use of an RTK is recommended.
2. Once completed, the camera calibration is only valid for that camera mounting position, image resolution, zoom, and focal length. Any changes to these shall require a new calibration to be developed in the processing/measurement software. If not, velocity data and discharge will be inaccurate.
3. Depending on the orthorectification process and software used it may be necessary to use known information about the camera intrinsic and extrinsic parameters to improve the accuracy of the orthorectification. This information can include:
    - Camera mounting position and elevation (XYZ).
    - Focal length.
    - Pitch, Roll, and Yaw.

If the camera intrinsic and extrinsic parameters are not known, then these are estimated from the GCP data. Typically, this is done within the software.

This process is required to provide a ground surface distance (GSD) i.e. a pixel size in metres. The GSD value is used in image velocimetry to scale the distance travelled by the surface tracers used in the surface velocity calculation.

4.1.1 3D Orthorectification.

Required if a single camera installation will be recording multiple videos for image velocimetry analysis over an entire hydrograph, i.e. changing water level values.

1. Requires real world coordinates in the XYZ plane with Z representing elevation. Typically, this consists of Eastings (X) Northings (Y) and elevation (Z)

2. Shall be undertaken if a camera system is mounted obliquely and used to collect videos at multiple changing water levels.
3. GCP points should cover the range of water levels expected to be recorded and measured with image velocimetry.
4. A minimum of 6 GCP are required be to complete the orthorectification process.
    - It is best practice that a minimum of 8 GCP should be located and surveyed within the camera FOV (placed in a zigzag manner, both horizontally and vertically). Collecting a minimum of 8 GCP allows redundancy of 2 GCP if survey errors have occurred.
    - GCPs should be distributed across both channel banks.
5. GCPs can be placed and surveyed after a flood event has taken place so long as the camera image, zoom, focal length has not been changed. This allows a camera to be quickly deployed before major flood events.
6. GCPs do not have to remain visible in all videos collected so long as any GCPs used cover the range of water levels expected.
7. GCPs are used to calibrate the camera imagery which is applied to all videos collected during that particular installation. If the camera view is changed, then a new GCP calibration shall need to be undertaken within the analysis software.

Figure 11. An orthorectified image (Left) based on the real-world coordinates of each ground control point and the original camera image (Right). Source: Mark Randall, RDMW, using HydroSTIV software.

4.1.2 2D Orthorectification.

A 2D orthorectification (homography conversion) uses real world coordinates in the XY plane only. These coordinates are projected directly onto the plane of the camera sensor i.e., there is a homography between the real world and camera sensor planes. Water level height at the time of measurement constitutes the only elevation (Z) data required.

This method is best suited for single flow measurements where water level does not change. This method cannot be used to undertake multiple flow measurements across a hydrograph

If employing 2D orthorectification:

1. Only four GCP are required at water level and should not be aligned.
2. GCPs need to be set on the same horizontal plane as the water level.
3. XY grid coordinates or distances between each GCP are required to complete the orthorectification process. Some software requires distances between GCP rather than XY data.

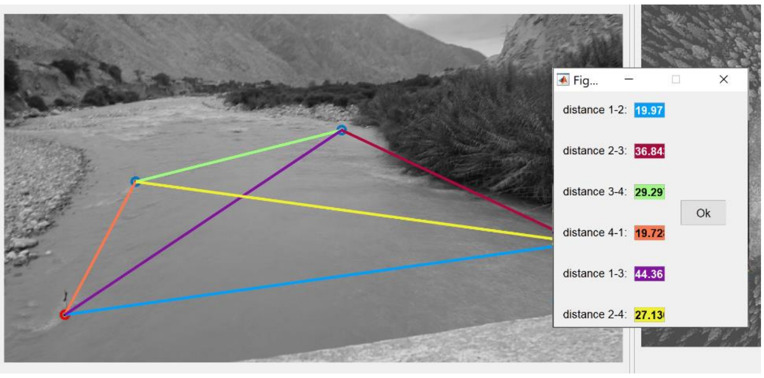


Figure 12 A 2D orthorectification process. In this LSPIV software the distances between each of four GCP are entered. The six coloured lines represent the six distances required. All four GCP are at water level. Source: RIVeR LSPIV software manual.

4.1.3 Scaling.

Scaling can be used when a camera is mounted vertically (nadir view) to the water surface so that the camera sensor and water surface are parallel with each other. This is typically the case with drone collected videos. To scale the pixels directly, a known distance between two points close to the water level, shall be visible within the video. As an example, the user could place two traffic cones within the video image at a separated distance determined by the user. Channel width also provides a useful distance reference which can be used. Scaling pixels in this manner reduces potential errors introduced by 3D and 2D orthorectification.

4.1.4 Orthorectification errors.

Errors in the orthorectification of the video imagery need to be considered and quantified as these will translate into errors with the pixel scaling used within the velocity calculation, and therefore ultimately the discharge calculation.

Enable	Point Name	X(m)	Y(m)	Height(m)	X(pixel)	Y(pixel)	Error:dX(m)	Error:dY(m)
☑	WQ pit top U/s corner	50.197	60.859	7.293	262.830	941.896	-0.012	-0.031
☑	Top 5-6m board	53.447	57.522	7.009	762.862	771.131	0.045	0.033
☑	HADCP high	55.948	55.920	5.570	942.288	772.447	-0.028	0.002
☑	HADCP low	60.056	57.397	3.636	844.399	713.188	0.014	-0.027
☑	Cone 1	105.224	72.172	7.073	618.521	82.574	-0.068	-0.017
☑	Cone 2	104.459	68.046	5.994	706.321	110.413	0.298	0.073
☑	Cone 3	109.218	67.964	7.876	727.833	55.565	-0.203	-0.040
☑	Cone 4	108.234	63.147	6.811	828.915	83.044	-0.025	-0.009
☑	Cone 5	113.863	53.069	7.463	1055.072	57.234	-0.071	0.000
☑	7m Board	51.216	59.603	8.012	455.878	800.959	-0.017	0.013

Figure 13. Ground control points used in an orthorectification. Orthorectification errors relate to the software's ability to map the pixel coordinates to the real-world co-ordinates. In this example the largest error is 0.298m. Source: Mark Randall, RDMW, using HydroSTIV software.

The orthorectification errors represent the software's ability to map the pixel coordinates to the real-world coordinates of the GCPs (reprojection errors). These errors are not an evaluation of the accuracy of the actual survey data. Erroneous survey errors will however adversely affect the accuracy of the orthorectification.

Orthorectification/reprojection errors should be quantified for each GCP (Figure 13)

To assess the magnitude of GCP error on pixel scaling and ultimately discharge it is recommended that the following evaluation process be undertaken. The process is the same used in photogrammetry and other forms of image mapping.

4.1.5 Assessing and quantifying horizontal accuracy for Ground Control Points.

The recognised geospatial standards to evaluate the horizontal accuracy of the GCP recommend the following process be undertaken:

1. Horizontal accuracy be assessed by calculating the root mean square error ($RMSE_r$) of the GCP in both the X and Y directions.
2. $RMSE_r$ values are then assessed against the calculated pixel size (GSD) from the orthorectification process undertaken.
3. Spatial accuracy should not exceed +/- three pixels or three times the reported GSD at the 68% confidence (1 Sigma). Figure 14 highlights the current international recommendations.
4. GCP that are used in the orthorectification process should be selected to provide the lowest positional uncertainty to prevent errors in the scaled pixel values. (See Figures 16, 18 and 19).
5. Any GCPs with large errors should be excluded from the process (Figure 15).

The $RMSE_r$ represents an averaged horizontal (XY) error in the rectified imagery between the pixel coordinates and GCP (real world) coordinates.

It is assumed that systematic errors have been eliminated, and that error is normally distributed.

$$RMSE_x = \sqrt{\frac{\sum_i (x_{image,i} - x_{GCP,i})^2}{n}} \qquad (1)$$

$$RMSE_y = \sqrt{\frac{\sum_i (y_{image,i} - y_{GCP,i})^2}{n}} \qquad (2)$$

$$RMSE_r = \sqrt{{RMSE_x}^2 + {RMSE_y}^2} \qquad (3)$$

Where: $x_{image,i}$, $y_{image,i}$ are the coordinates in the rectified image for the i^{th} GCP

$y_{GCP,i}$, $x_{GCP,i}$ are the surveyed coordinates of the i^{th} GCP.

i is an integer ranging from 1 to n.

n is the number of GCP used in the orthorectification.

RMSE errors are reported in the same units entered for the GCP coordinates. The positional uncertainty represented by $RMSE_r$ is a radial error around the GCP.

Common Orthoimagery Pixel Sizes	Recommended Horizontal Accuracy Class $RMSE_x$ and $RMSE_y$ (cm)	Orthoimage $RMSE_x$ and $RMSE_y$ in terms of pixels	Recommended use[7]
1.25 cm	≤1.3	≤1-pixel	Highest accuracy work
	2.5	2-pixels	Standard Mapping and GIS work
	≥3.8	≥3-pixels	Visualization and less accurate work
2.5 cm	≤2.5	≤1-pixel	Highest accuracy work
	5.0	2-pixels	Standard Mapping and GIS work
	≥7.5	≥3-pixels	Visualization and less accurate work
5 cm	≤5.0	≤1-pixel	Highest accuracy work
	10.0	2-pixels	Standard Mapping and GIS work
	≥15.0	≥3-pixels	Visualization and less accurate work

Figure 14. Positional accuracy assessment. Source: ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014).

Ground Control Points

Enable	Point Name	X(m)	Y(m)	Height(m)	X(pixel)	Y(pixel)	Error:dX(m)	Error:d
☑	#1	435340.569	415042.038	138.930	1771.456	692.102	0.000	0.001
☐	#2	435335.399	415038.089	138.920	1563.315	734.313	4.043	2.144
☑	#3	435338.962	415033.534	140.550	1027.682	862.399	0.001	-0.002
☐	#4	435341.209	415034.145	141.490	992.749	709.569	-2.183	-0.981
☑	#5	435308.596	415066.634	141.300	845.682	149.630	0.133	-0.134
☑	#6	435308.945	415055.396	139.210	568.848	259.309	-0.201	0.167
☑	#7	435308.462	415051.734	138.190	439.949	319.040	0.065	-0.072
☑	#8	435305.198	415050.076	139.960	298.176	247.032	0.095	-0.025
☑	#9	435303.512	415058.216	142.730	513.377	114.700	-0.124	0.073

Figure 15. GCP orthorectification results showing errors larger than ± 2m for GCP #2 and #4. Source: Mark Randall, RDMW, using HydroSTIV software.

Figure 16 (below) highlights the importance of identifying and eliminating GCP errors in the orthorectification process. The left image has GCP errors from Figure 15 excluded from the final orthorectification pixel scaling equals 0.033 m/pixel and discharge of 38.951 cumecs. The right image has the GCP errors included, and the pixel scaling is now 0.058 m/pixel.

Although the velocity distribution is identical between each analysis, due to the larger pixel size the velocities are now faster, increasing the discharge result to 40.714 cumecs. The 2.5 cm difference in scaling equates to 4.5% difference in calculated discharges.

The reference ADCP measurement conducted at the same time was 38.578 cumecs.

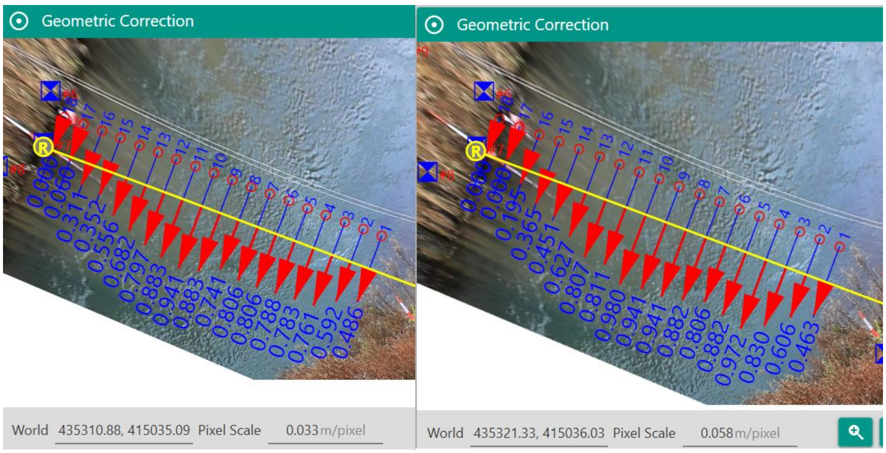


Figure 16. The impacts of the orthorectification errors on pixel scaling, velocity and discharge. The left image has GCP errors from figure 18 excluded from the final orthorectification. The right image has included the GCP errors which are transferred to the velocity analysis. Source: Mark Randall, RDMW, using HydroSTIV software.

4.1.6 Geometric correction.

Following the orthorectification process a geometric correction is applied to the imagery which is used in the surface velocity determination.

The geometric correction compensates for image distortions producing a corrected image with a high level of geometric integrity. An image that is not corrected for geometric distortion in the XY direction will contain pixels that are incorrectly located geographically. For oblique imagery the geometrically corrected image appears to get wider as distance increases from the camera location (Figure 17).

This appearance is due to the pixel sizes being corrected geometrically as the geographic distance from the camera increases. A geometrically corrected pixel will therefore contain a larger ground size in the background than a geometrically corrected pixel in the foreground of the oblique image.

The number of pixels contained in the image remain the same only the ground size for each pixel changes.

Figure 17. Oblique camera image (left), and the rectified image adjusted for increasing pixel ground size as distance from the camera increases. Source: Mark Randall, RDMW, using HydroSTIV software.

5 Image Velocimetry Discharge Calculation.

Image velocimetry uses a velocity area method of calculation (typically mean or mid-section methods) therefore much of the recommended guidance for undertaking surface velocity and discharge calculations are outlined in ISO748:2007 and are the same as applied to wading and ADCP measurements.

The term exposure time is used in a hydrometric sense and refers to the actual length of time used to calculate a representative surface velocity with minimal uncertainty. It is not a reference to camera shutter speed. Exposure time is therefore the actual length of video analysed in seconds to calculate surface velocities and discharge.

5.1.1 Exposure time.

1. The minimum recommended exposure time for surface velocity used in discharge calculations (ISO748:2007 Section 7.2.2 on surface velocities) is 20 seconds with a recommendation of 30 seconds.

   NOTE: some analysis methods use shorter measurement (video) lengths to improve computation times. If using shorter measurement times, it is important to verify that these shorter times are suitable for the site.

2. Increasing exposure time will improve spatial-temporal averaging of the velocity analysis and can help reduce measurement uncertainty caused by environmental, flow, and local site conditions.
3. When the minimum exposure time criteria cannot be met due to a single recorded video length being too short or due to site conditions, repeated measurements can instead be undertaken, and results averaged providing a single measurement that meets or exceeds the minimum recommended exposure time.
4. Image velocimetry measurements undertaken using a cross correlation method for velocity and discharge calculations should also consider using a minimum of 10 extracted image pairs for all velocity and discharge calculations. (Le Boursicaud *et al*. 2016).

5.1.2 Sampling interval.

Sampling interval is the separation time between velocity/discharge measurements (excluding subsample measurements).

Sampling intervals are dependent on expected stage changes during the measurement, and thus the appropriate interval depends on factors based on catchment shape, reach length, reach slope, land use, soil type, vegetation and precipitation.

These factors can all impact the shape of the flow hydrograph significantly and for this reason it is important to adjust the sampling interval of the image velocimetry measurements to ensure an accurate representation of the hydrograph (Figure 18).

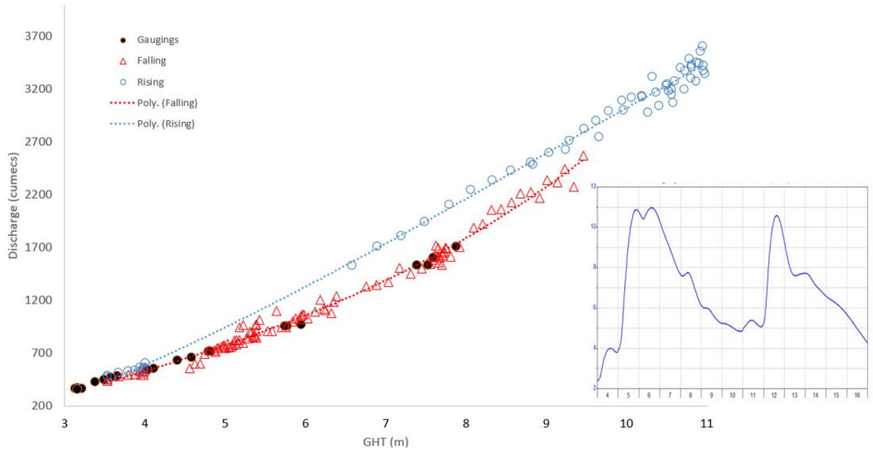


Figure 18. Loop rating identified by automated onsite STIV discharge measurements from fixed camera videos undertaken every 1 hour during daylight hours over two flood events during 12 days of flooding. Black circles indicate all ADCP measurements undertaken over the previous 10 years. Source: Mark Randall, RDMW, using HydroSTIV software.

If possible, site hydrographs should be reviewed when determining the sampling interval of a fixed camera.

5.1.3 Number of verticals.

Discharge is predominantly calculated via the velocity area method using either the mid or mean section method. ISO748 contains guidance on the recommended minimum number of verticals (surface velocity discharge calculation points) required and the maximum percentage of flow that should be contained within each vertical (typically 10%), Figure 19. Once again, these recommendations are the same as when undertaking a current meter wading or ADCP stationary measurement.

As with all measurement techniques and technologies it is important that velocities used in the discharge calculation are measured across the entire channel width rather than interpolated or extrapolated into large areas of the channel as this increases the uncertainty of the discharge data.

When considering the quality of a surface velocity measurement the same considerations applied to wading and/or ADCP discharge measurements when sections of the channel width are also not measured.

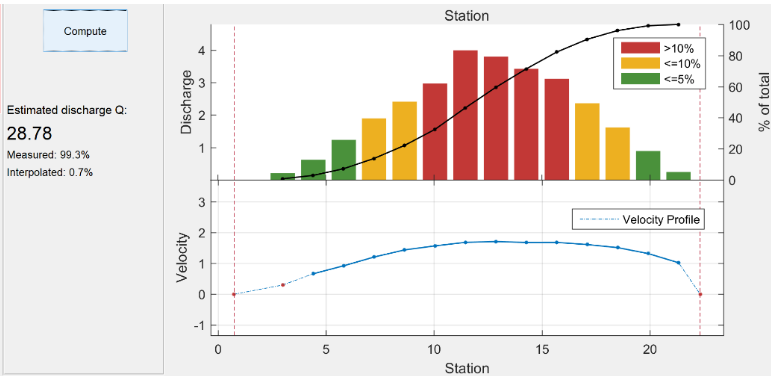


Figure 19. LSPIV discharge measurement report showing velocity and discharge information including percentage values for interpolated discharge data (0.7%). Source: RIVeR LSPIV software manual released 12/08/2020.

Once surface velocities have been calculated the user should identify the nature of the surface velocities and consider the following options when calculating discharge:

1. When several cross-sections can be measured, or when the position of a single cross-section is uncertain relative to observed surface velocity variations. Discharge should be computed through several cross-sections and consideration given to the average and the scatter of the results (Figure 20).
2. If the water slope across the cross-sections is significant, an accurate estimate of stage at each cross-section should be available.
3. The selection of a single cross-section location in the software should match the location where the cross-section data was obtained, unless secondary information is available which indicates that the reach is uniform in nature.
4. For all surface velocimetry methods, the resolution of the surface velocity profile should enable the capture of streamwise variations, with uniform or nonuniform spacing of the measurement points/verticals.
5. Depth variations should be also considered, ensuring coherence between bathymetric and velocity profile discretization.

#	Total discharge (m^3/s)	Gap (%)	Wetted area (m^2)	Gap (%)	Mean velocity (m/s)	Gap (%)	Measured discharge (m^3/s)	Meas. disch. / Tot. disch. (%)
1	762.186	-9.2	968.378	+0.0	0.787	-9.2	756.567	+99.3
2	854.659	+1.8	968.375	-0.0	0.883	+1.8	848.275	+99.3
3	901.799	+7.4	968.375	-0.0	0.931	+7.4	897.534	+99.5
Average	839.548	+0.0	968.376	+0.0	0.867	+0.0	834.125	+99.4

Figure 20. LSPIV analysis showing velocity analysis. Three cross section locations have been used to capture variance and provide an average discharge result. Source: Jerome Le Coz, IRSTEA, Fudaa LSPIV software.

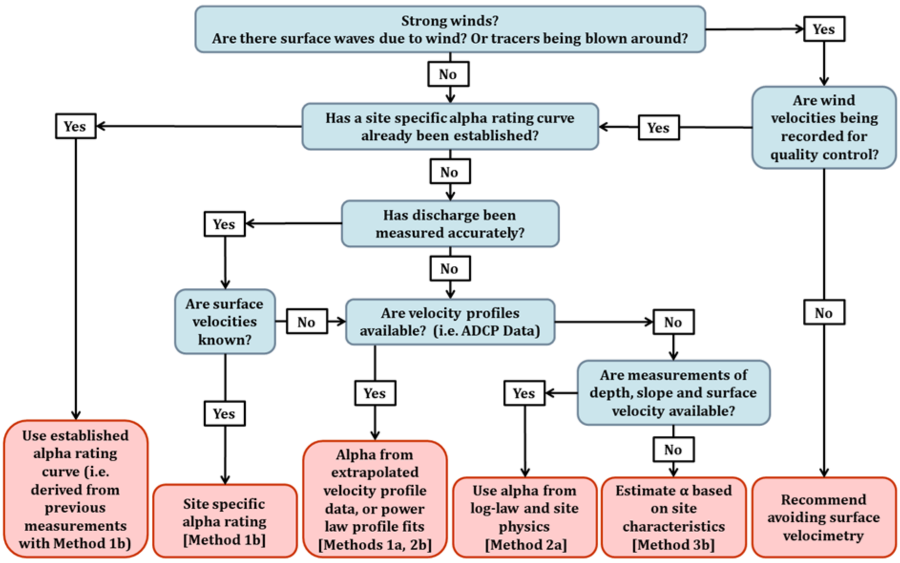
6 Surface velocity coefficients.

Methods that measure surface velocities for the purpose of calculating discharge albeit floats, image velocimetry, or surface velocity radar require the use of what's termed a velocity coefficient/factor, commonly referred to as the "surface alpha". Each measured surface velocity is multiplied by the surface alpha value to provide a depth averaged velocity used in the velocity area discharge calculation. Surface alpha values can represent a significant source of uncertainty and wherever possible a site-specific alpha value should be determined using all available site data including any ADCP data that may be available. It should be noted that most analysis software allows a surface alpha value to be simply amended later if/when a site-specific alpha value has been determined.

The default value for surface alpha is considered to be 0.857 which represents a typical 1/6th power law velocity profile, Rantz 1982. Surface alpha values are associated with channel roughness and therefore can vary considerably based on roughness and water depth. ISO 748:2007 section 7.1.5 provides some guidance on surface alpha values associated with roughness.

	normal	smooth	rough	very rough	extreme cases
m	6~7	10	4	2~3	
α	0.86 ~ 0.87	0.91	0.80	0.67 ~ 0.75	0.60 ~ 1.2

A comprehensive explanation on surface alpha calculation methods is found in Biggs et al 2023 including the field guide below.



Method 1a: Site alpha from extrapolated ADCP velocity data.
Method 1b: Site alpha from ADCP discharge and discharge from surface velocimetry.
Method 2a: Alpha from log law profiles .
Method 2b: Alpha from power law profiles.
Method 3a: Default alpha value.

Method 3b: Alpha estimation from site characteristics.

Source: Biggs *et al*., 2021 River discharge from surface velocity measurements – A field guide for selecting alpha

The calculation of surface velocity alpha coefficients follows established velocity profile theories.

6.1 Log law velocity profile.

With no flow acceleration, secondary flow or surface wind drag, a logarithmic velocity profile (Keulegan, 1938) can be assumed to extend to the surface. The depth averaged velocity is then related to the mean surface velocity ($\overline{u_s}$ equation 1):

$$\alpha = \frac{U}{\overline{u_s}} = 1 - \frac{\sqrt{gHS}}{k\overline{u_s}} \qquad (1)$$

U is the depth average velocity, k is the Von Kármán constant, H is flow depth above the log law origin, g is gravitational acceleration, S is slope, and α is the surface velocity coefficient.

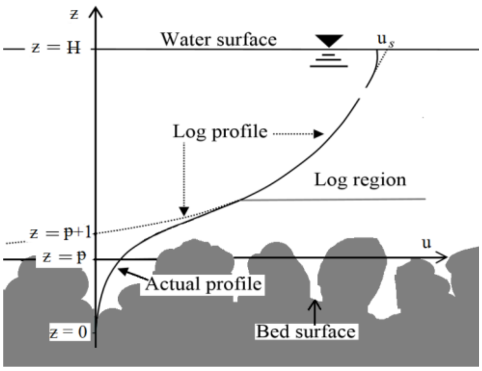


Figure 21*.* Typical vertical profile of downstream velocity over a gravel bed demonstrating an augmented logarithmic profile. Source: Smart and Biggs, 2020.

6.2 Power law velocity profile.

The velocity coefficient can also be estimated from the power law velocity profile as follows:

$$\alpha = \frac{U}{\overline{u_s}} = \left(\frac{1}{m+1}\right) \qquad (2)$$

Where m is the power law exponent describing the channel roughness.

- A 1/6th power law therefore = 6/7 = 0.857 surface alpha value.

6.3 Using a measured surface velocity and/or velocity profile data.

Surface Alpha coefficients may be determined from ADCP measurements containing velocity profile data and/or current meter/FlowTracker measurements that measure actual or near surface velocities and the mean velocity profiles. Velocity and depth data should be normalised. The surface alpha value is the ratio between the surface and mean values on the velocity profile as shown in Figure 22.

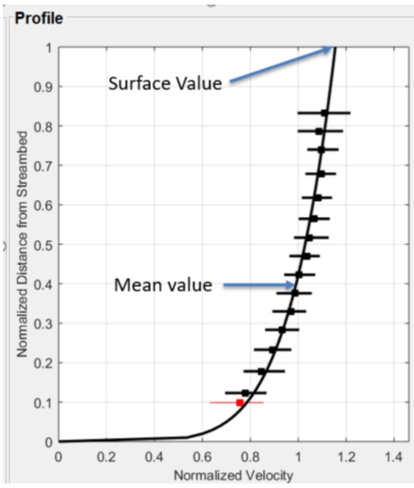


Figure 22. Normalised velocity profile from ADCP data showing surface and mean velocity profile locations. Source: Mark Randall, RDMW, using Qrev ADCP software.

Surface alpha is calculated by dividing the normalised velocity value for the mean (Value = 1), by the extrapolated value for the surface velocity location.

In Figure 32 this value is approximately 1.15 therefore 1 divided by 1.15 provides a calculated surface alpha value of 0.87 which is essentially the value for a 1/6th Power Law profile.

6.4 Probability concept method for calculating surface alpha.

If the velocity profile is non-standard, e.g., where the maximum velocity occurs below the water surface, then an alternative method of computing surface alpha may be used. The probability concept method (Chiu 1989; Chiu and Tung, 2002) is one such example, focussing on defining the velocity profile at a single location where the maximum velocity is located within the cross section and does not change location across the across the range of water levels measured. It is assumed that this location is constant over all flow regimes. Refer to the following papers for further information, Chiu *et al*., 2001; Fulton and Ostrowski, 2008.

An additional advantage of using the probability concept is that the surface coefficient factor used (entropy value) remains constant throughout the range of flows encountered on site.

6.5 Stage to Alpha Rating curves velocity index rating development.

To define how surface alpha values may change as the interactions between bed roughness and water levels change it may be beneficial to develop a site-specific alpha to stage rating curve. As with a stage discharge rating curve, this will allow alpha values to be determined.

Site α values can be recorded at multiple flows and plotted against stage (Figure 5) to generate a site-specific ‘stage-alpha rating curve’ (the first known use of stage–alpha rating curves was in early 1900s French hydrometry reports). An extrapolation of this curve can then be used to estimate site-specific α values for extreme flow conditions, including floods. Stage–alpha rating curves can also be used for interpolation to estimate alpha at water levels between those where measurements occurred.

Theoretical expressions of surface alpha vs flow depth/roughness may be used to extrapolate surface alpha to higher or lower flows as discussed by Le Coz *et al.*,2010 and Smart and Biggs, 2020.

6.6 Site specific velocity profile analysis.

A site-specific surface alpha should be calculated whenever possible using the methods described. Analysis of old ADCP or current meter data may assist.

Figure 23. Measuring velocity profiles at multiple verticals across a channel. Verticals near the banks are removed to avoid incorporating velocity profiles that are not representative of the main flow. Source: Hauet *et al.,* 2018.

When site velocity profile analysis is undertaken, it should be determined whether a single surface alpha is representative or whether different sections of the channel require their own surface alpha value. Large floodplains may have a very different surface alpha than the main channel as shown in Figure 24.

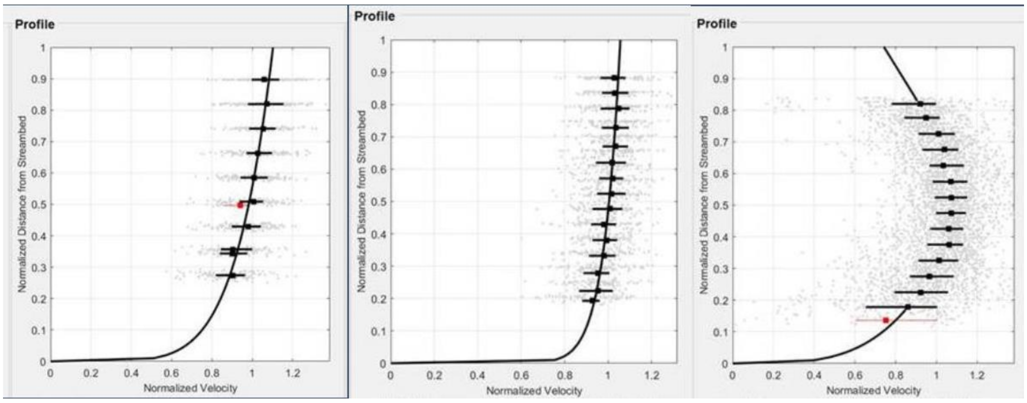


Figure 24. Measuring velocity profiles at three verticals across a channel. The left profile is the main channel, centre profile is at midway depth location between channel and flood plain, right profile is in the flood plain. Source: Mark Randall, RDMW, using Qrev ADCP software.

In Figure 24 the floodplain consisted of many small trees whose canopy vegetation slowed down the surface velocities while velocities below the surface, at the tree bases, have not caused the same flow resistance resulting in a very different velocity profile than the main channel. Surface alpha values calculated from the ADCP data in Figure 34 equated to 0.86, 0.91, and 1.4 respectively.

6.7 Channel characteristics impact on alpha.

The channel characteristics and hydraulic conditions at a monitoring site can have an impact on alpha.

1. Channel aspect ratio $(\frac{\text{width}}{\text{Depth}})$
2. Changes in water depth.
3. Channel bed roughness.
4. Unsteady flow or backwater conditions.
5. Hydraulic structures.
6. Vegetation.
7. Wind impacts.
8. Any suspected site characteristic impacts on the surface coefficients should be investigated and documented when determining the velocity profile.

Several observations published by Huet *et al*., 2018, based on the surface alpha coefficient analysis of 3611 gauging's from 176 French hydrometric stations suggests that:

1. Surface alpha coefficients increase with water depth (D).
2. For shallow water (less than 1 metre) alpha was close to 0.8
3. Alpha increased up to 0.9 for D of 9 metre in single channels.
4. Compound channels may be lower alpha.
5. Deep water holes could cause a higher alpha compared to more planar beds.

6. Link between alpha and the relative roughness is not as clear from the gauging analysis.

7. A mean alpha value of 0.8 occurred for relatively rough natural rivers (sandy, pebbly, boulder rivers)

8. A mean alpha value of 0.9 occurred for artificial concrete channels.

This document makes reference to the following documents:

ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)

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ISO 748:2007 Hydrometry – Measurement of liquid flow in open channels using current meters or floats.

ISO 15769:2010 Hydrometry — Guidelines for the application of acoustic velocity meters using the Doppler and echo correlation methods

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