Space-time velocimetry to estimate discharge during the 2022 River Murray flood

M.S. Gibbs [a], **J. Hughes** [b] **and Cuan Petheram** [c]

[a] *Environment, CSIRO, Waite, South Australia*
[b] *Environment, CSIRO, Black Mountain, Australian Capital Territory*
[c] *Environment, CSIRO, Sandy Bay, Tasmania*
Email: matt.gibbs@csiro.au

Abstract: Streamflow discharge measurement underpins a range of assessments, policy, and management related to resource management. The standard methods to measure discharge can be costly due to the time consuming and labour-intensive manual measurements required by highly specialized staff, particularly in remote and difficult to access sites. Surface velocity measurements achieved through video image analysis are becoming increasingly popular methods to estimate velocity and discharge, driven by remote pilot aircraft (RPA, or drone) and camera technology. These methods have the advantage of being non-intrusive and hence improved safety during high flow measurements, are suited to low flows and depths and inexpensive measuring equipment can be deployed remotely not requiring staff to be present. This paper demonstrates the application of video-based surface velocity methods during the peak of a high flow event in the River Murray in late 2022, peaking at approximately 200 GL/d (an annual exceedance probability of approximately 1 in 50).

Six videos were recorded with an RPA and a mobile phone camera at five locations between the townships of Renmark and Berri. The Space Time Image Velocimetry (STIV) method was used to compute surface velocities and available survey information was used to derive coordinates to orthorectify the video as well as river cross section bathymetry. The STIV method uses changes in brightness of the river surface in the direction of flow (a distance in space in the image) over time (between video frames) to produce diagonal lines on a combined image, with the slope of the line representing the surface velocity.

Three methods to estimate surface velocity were tested in combination with two methods to convert the surface velocity to the mean channel velocity. The deep learning method with a log-law relationship to derive mean channel velocity was found to perform the best for the videos recorded when compared to more traditional Acoustic Doppler Current Profiler discharge measurements recorded at the same time. The results demonstrate that relatively accurate discharge estimates can be achieved with minimal equipment, just a phone camera on the riverbank. The other data requirements, survey of points to orthorectify the video into real-world distances and survey of the river cross section to compute discharge, and the water level relative to these points, become the more significant data requirements to estimate discharge.

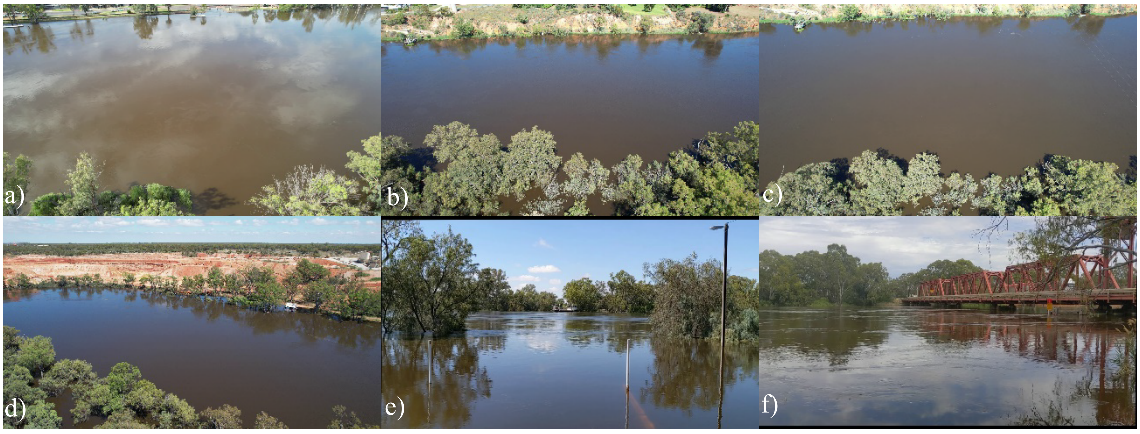

Figure 1. Still images from videos of the River Murray in South Australia used for surface velocimetry, a) Berri foreshore, b) Berri Road Low, c) Berri Road High, d) Berri Quarry, e) Lyrup and f) Paringa

Keywords: *Space-time velocimetry, surface velocity, discharge, hydrology, hydrography*

1. INTRODUCTION

Streamflow discharge measurement underpins a range of assessments, policy, and management related to water resource management (Petheram et al., 2022), flood risk and forecasting (Teng et al., 2022), environmental monitoring and responses (Bice et al., 2017) and water quality (Gibbs et al., 2022). Acoustic Doppler Current Profiler (ADCP) is the standard method to measure discharge; however, this can be costly due to the time consuming and labour-intensive manual measurements required by highly specialized staff (Acharya et al., 2021) often in remote and difficult to access sites. Contact with the water is also required, which increases human and equipment safety risks during high flows.

Surface velocity measurements achieved through video image analysis are becoming increasingly popular methods to estimate velocity and discharge, driven by remote pilot aircraft (RPA, or drone) and camera technology (Bureau of Meteorology, 2021). Compared to ADCPs these approaches have the advantage of being non-intrusive and hence improved safety during high flow measurements, suited to low flows and depths where other techniques may struggle (e.g. blanking distances) and the inexpensive measuring equipment can be deployed remotely not requiring staff to be present (Bureau of Meteorology, 2021). Surface velocimetry approaches are becoming accepted as a standard operational practice by authorities with hydrography responsibilities, such as the Australian Government and United States Geological Survey (Acharya et al., 2021; Bureau of Meteorology, 2021). This paper demonstrates the application of video-based surface velocity methods during the peak of a high flow event with an annual exceedance probability of approximately 1 in 50.

2. BACKGROUND

There are two common methods for calculating surface velocities from imagery. The first and most common in available software tools (e.g. RIVeR (Patalano et al., 2017) and Fudaa-LSPIV (Le Coz et al., 2014)) is the Large-Scale Particle Image Velocimetry (LSPIV) method which relies on the cross correlation between images to identify surface tracer movement. The second method is the Space Time Image Velocimetry (STIV) method (Hydro-STIV (Fujita et al., 2020)) that uses search lines parallel to a river cross section to create space-time images (STI) that identify changes in brightness. Changes in the river surface along the search line (a distance in space in the image) over time (between video frames) produce diagonal lines in the STI, with the slope of the line representing the surface velocity (Hydro Technology Institute, 2022).

Bureau of Meteorology (2021) notes several benefits of STIV over LSPIV, the approach supports the identification and correction of velocity errors, is far more computationally efficient and is capable of analysing video recorded at lower camera angles. However, STIV only produces 1D velocities along the search lines, compared to 2D surface velocities from LSPIV, which may be of interest for some applications or needed for sites with circulating or unsteady flow. Comparative studies typically find minimal differences between the methods (e.g. Pearce et al., 2020).

Based on a stationary video recording river flow, image velocimetry relies on the accurate scaling of the pixels to distance, in relation to the camera sensor, channel width and water level (Bureau of Meteorology, 2021). Typically, a video is recorded at an oblique angle to the river as opposed to directly above (nadir); however, this is possible using RPAs for smaller rivers. Geometric correction scales the image to account for the smaller distance represented by pixels further from the camera lens. This correction requires ground control points (GCPs) to convert the image pixels into real world coordinates. With a geometrically corrected video a velocimetry technique, such as LSPIV or STIV, can be applied to compute surface velocity.

To compute discharge the surface velocity must be translated to mean channel velocity for each section of river width used to compute discharge. Approaches to translate the velocity include assuming a log-law relationship with site specific parameter, α, or the maximum entropy method (Chiu, 1991). Finally, information on the river cross-section bathymetry is required to multiply the mean channel velocity by the area to result in discharge.

3. METHODS

3.1. Case study and sites

The case study involved opportunistic monitoring of the high flow event in the South Australian River Murray, peaking at approximately 200 GL/d on 22 December 2022 at the SA-Victoria border. This was the highest flow event since 1956, which was the largest event in the instrumental record. Five locations were selected (Figure 1), with two videos from the same location at different heights above the water, resulting in six videos for analysis. Videos captured the main channel of the river, expected to convey the majority of flow along the river; however, due to the high flow event there were substantial areas of floodplains not in the view of the camera.

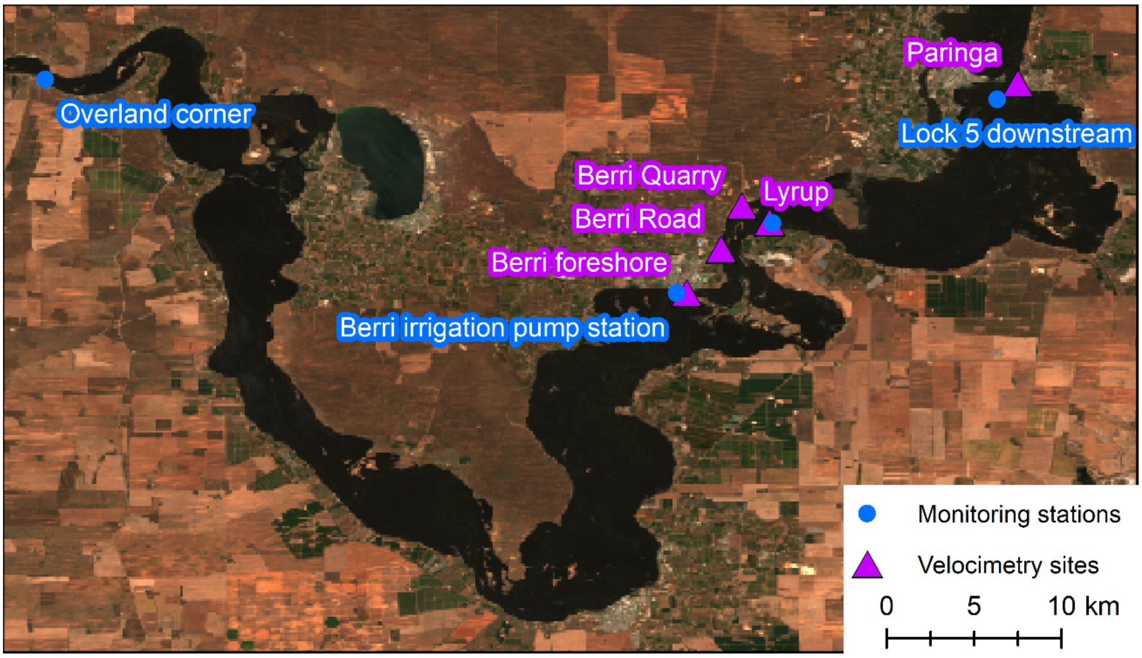

Figure 2. Map of case study location showing velocimetry sites to record video and monitoring stations used for water level and ADCP measurements. Background imagery represents floodplain inundation during the sampling period, based on surface reflectance from Sentinel-2A MSI on 17/12/22 sourced from Digital Earth Australia

3.2. Video capture

The videos around Berri were recorded using a Remote Pilot Aircraft (RPA, or drone), specifically a DJI Air 2S. Lyrup and Paringa videos were recorded from the bank using a phone camera, Pixel 4. Details of the videos recorded are provided in Table 1. All videos were recorded with a fixed frame rate of 30 frames per second. The two sites recorded from the bank, Lyrup and Paringa, had low critical angles, the angle between the camera and furthest search line, of 0.5 and 1.5 degrees respectively. Bureau of Meteorology (2021) recommends a minimum angle of 2 degrees. Lower angles can increase potential for velocity bias and/or tracer resolving issues for these analysis methods. Nadir video (looking directly down) capturing the full river width could not be recorded from the RPA within standard operating conditions (below 400 feet height), and hence oblique video was recorded. The lowest critical angle from the RPA at Berri Road Low was 11.6 degrees. Pixel scaling values ranged between 1 cm/pixel to 20 cm/pixel and were typically less than 10 cm/pixel. For comparison, Bureau of Meteorology (2021) recommends approximately 5 cm/pixel. Even with 4K video resolution the resulting pixel scaling of 5 cm/pixel could not be achieved for the furthest search lines, typically 170-200 m from the RPA.

The length of all videos exceeds the minimum accepted exposure time for determining the velocity at each vertical used in a discharge calculation i.e., a minimum exposure time of 20 seconds, with four of the six in line with the recommended exposure time for determining the velocity used in a discharge calculation i.e., a minimum exposure time of 30 seconds (Bureau of Meteorology, 2021).

Table 1. Site video details

Site	Date and time	Duration	Resolution	Water level (m AHD)	Height (m)
Berri foreshore	20/12/2022 17:08	0:00:31	1920 × 1080	16.35	52
Berri Quarry	22/12/2022 11:10	0:00:20	3840 × 2160	17.4	19.6
Berri Road High	22/12/2022 10:04	0:00:31	3840 × 2160	16.9	73
Berri Road Low	22/12/2022 10:05	0:00:30	3840 × 2160	16.9	36
Lyrup	22/12/2022 10:28	0:00:30	1920 × 1080	17.4	1.8
Paringa	20/12/2022 11:40	0:00:20	1920 × 1080	18.4	4

3.3. Velocity and discharge calculation

Initial testing found LSPIV algorithms and software could not to produce valid results for this location, due to limited visible tracers and issues with environmental variables such as reflections on the water surface. The STIV algorithm in Hydro-STIV (Fujita et al., 2020) was ultimately selected, as it is more suited to analysing changes in brightness (as opposed to tracking visible tracers) and for processing video recorded at low critical angles. Image stabilization was applied in Hydro-STIV prior to processing.

Ground control points (GCPs) are required to map the pixel space to real-world distances and geometrically correct the oblique videos recorded. Orthorectification using the 2D homography transformation was used, as it is well suited to single opportune flow measurements such as this (Bureau of Meteorology, 2021). This approach requires four or more control points at the same elevation as the water surface. GCPs were derived using visual analysis of natural markers in the video frames (e.g., tallest trees or structures) and LiDAR point clouds to derive the corresponding real-world coordinates. The LiDAR point clouds were collected by SA Department for Environment and Water (DEW) in 2021 with a nominal average point spacings 15 - 21 points/m^2, available on ELVIS. The water surface elevation is also required for orthorectification, which was estimated using available monitoring stations, at Berri Irrigation Pump Station (A4260537), Lyrup Pumping Station (A4260663) and Lock 5 Downstream (A4260513). Approximate river distance was used to interpolate the water level from adjacent stations to the video sites.

River bathymetry is required to determine discharge from the STIV surface velocity. Bathymetric surveys were undertaken for this section of river by SA Water in 2014, and the surveyed cross sections every 100 m were interpolated to bathymetric surface with 2 m resolution by DEW. 20 search lines across each cross section were used to derive the STIs, which gave less than 10% of the total discharge in each search line for all sites except for Lyrup (where 90% of search lines contained less than 10% of the discharge).

Three methods are available to estimate surface velocity from the STIs for each search line in Hydro-STIV, a deep learning algorithm (DL), the Luminance Gradient Tensor (LGT) method, and the Fourier Maximum Angle (FMA) method. Details of the methods are provided in Hydro Technology Institute (2022). The software includes two methods to convert the surface velocity to the mean channel velocity, a Velocity-Area method, with the default parameter of α=0.85 adopted, and the maximum entropy method (MEM). The three surface velocity methods and two depth conversion methods were tested, resulting in 6 discharge estimates from each video. DEW measured discharge using ADCP at the Overland Corner monitoring site (A4260528) during the event, which were used for comparison to the STIV estimates. The ADCP monitoring location is approximately 100 km downstream from the video recording sites. Comparing time to peak water level between Berri Pump Station and Overland Corner the travel time between sites was approximately 6 days, and the ADCP velocities have been shifted 6 days earlier for comparison. Review and correction of the velocity estimated at each STI for each site was undertaken for the most accurate combination of surface velocity and depth conversion method, for a final comparison to the ADCP discharge.

4. RESULTS

Figure 2 provides an example result for the Berri foreshore site. Each of the 20 search lines (blue) across the cross section (yellow) are used to compute a STI (three example images in the bottom panel). The STIs presented are for search lines 4, 5 and 6 with the changes in brightness along the search line are seen along the x axis (15 m), with the brightness from each frame 'copied' below one another along the y axis, with one row every 1/30 = 0.033s for a total of 31 seconds. The slope of the red diagonal lines on the STIs represent the estimated velocity of 1.216, 1.169 and 1.313 m/s, respectively.

The discharge results across the six different methods for each site were highly variable (Figure 3). There was also high variability across the sites, where in reality small changes in discharge occurred over the two days that the videos were recorded. The FMA method tended to produce the highest discharge values, with the LGT algorithm the most variable across the sites. In comparison, the DL method produced the most consistent results across the sites, and closer to the ADCP discharge measurements. The differences between the two methods to determine mean channel velocity were smaller than the difference between the surface velocity methods, particularly for the DL method. At the Berri Quarry site the MEM method resulted in a higher-than-expected discharge compared to the ADCP, and as such DL with Depth Area method was selected as the most suitable method for further review.

Manual corrections were applied to some search lines using the FMA method as a guide. This resulted in corrections being applied to 3 of the six estimates, with one search line corrected at Berri foreshore, two at Lyrup and four at Berri Road Low. The resulting discharge estimate compare well to the ADCP values

(Figure 4). The exception is at the Berri Road site, where the estimate from videos recorded at different heights (High and Low) are in relative agreement (4.8% difference), but the discharge is lower than that calculated at other sites from STIV and ADCP. Review of RPA video taken at the site suggests a substantial flow path across the floodplain behind the camera and as such it is expected that this site does not capture all the flow occurring through his section of river.

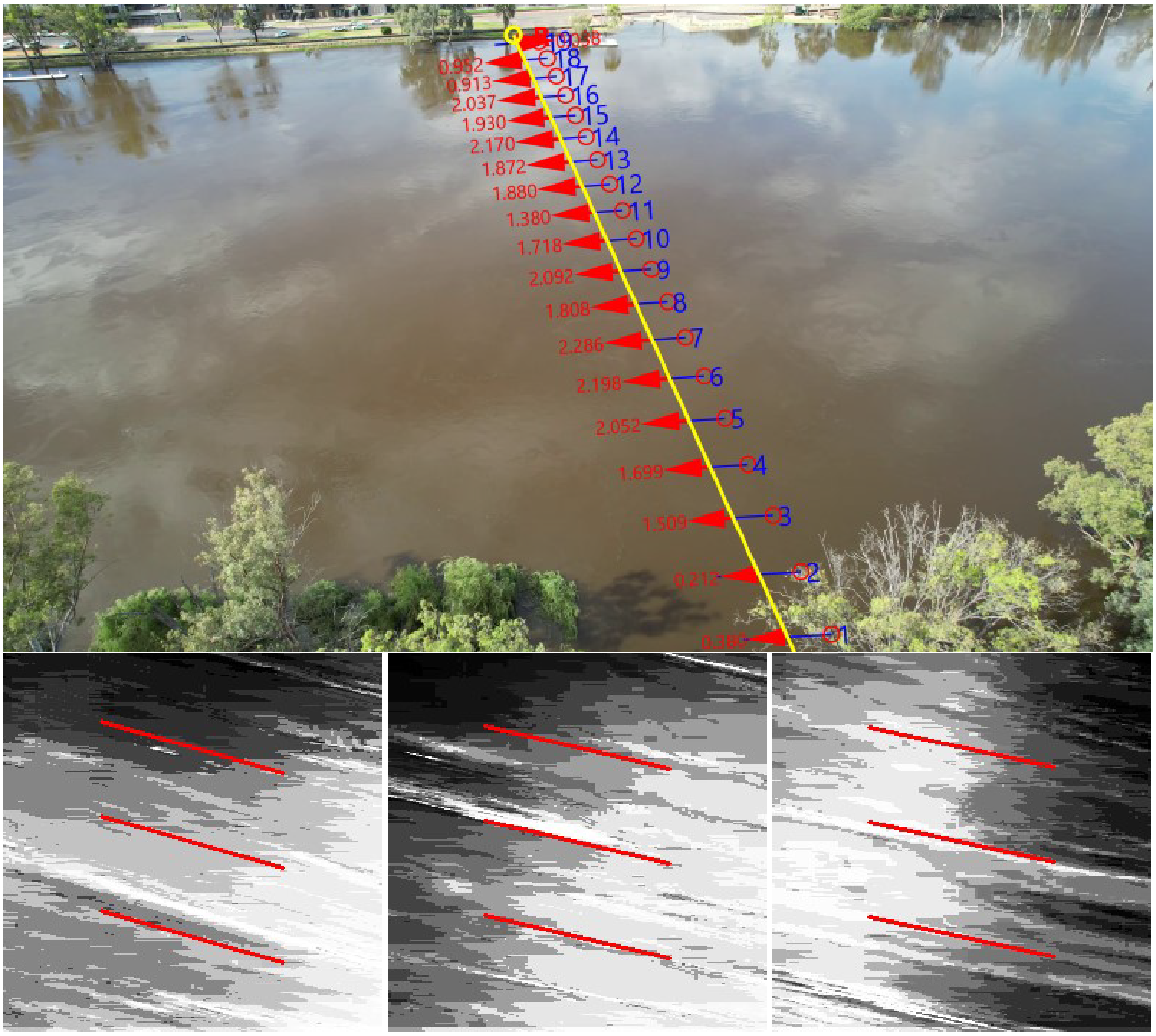

Figure 3. Example STIV result for the Berri foreshore site, based on the Deep Learning algorithm. for DL and depth area. Example STIs at search lines 4, 5 and 6, with the x axis representing the 15 m search line, and the pixels along that search line stacked for each video frame, at a rate of 30 frames per second for a total of 31 seconds. The angle of the stripe pattern indicates the calculated surface velocity in metres/second.

5. DISCUSSION AND CONCLUSIONS

The results indicate that accurate discharge estimates can be derived from STIV in comparison to more traditional and resource intensive methods, such as ADCP. Even from very low angle video (0.5 degree) the discharge estimate agreed with the STIV result from video recorded at a higher angle from a RPA, and with more traditional ADCP measurements. While critical angles this low are not recommended (Bureau of Meteorology (2021) recommends greater than 2 degrees for STIV), this result does demonstrate that relatively accurate discharge estimates can be achieved with minimal equipment, just a phone camera on the riverbank. The other data requirements, survey of GCPs to orthorectify the video to compute the STIs, survey of the river cross section to compute discharge, and the water level relative to these points, become the more significant data requirements to estimate discharge. Technological developments and RPAs can also support this data requirement, for example photogrammetry can be used to collect cross section data provided this imagery can be collected at a time when the riverbed is dry and there is a clear view of the bank (not obscured by vegetation, for example), or be used to undertake sonar survey. Once a site survey is configured video can be regularly recorded to monitor changes in discharge or develop stage-discharge rating curves.

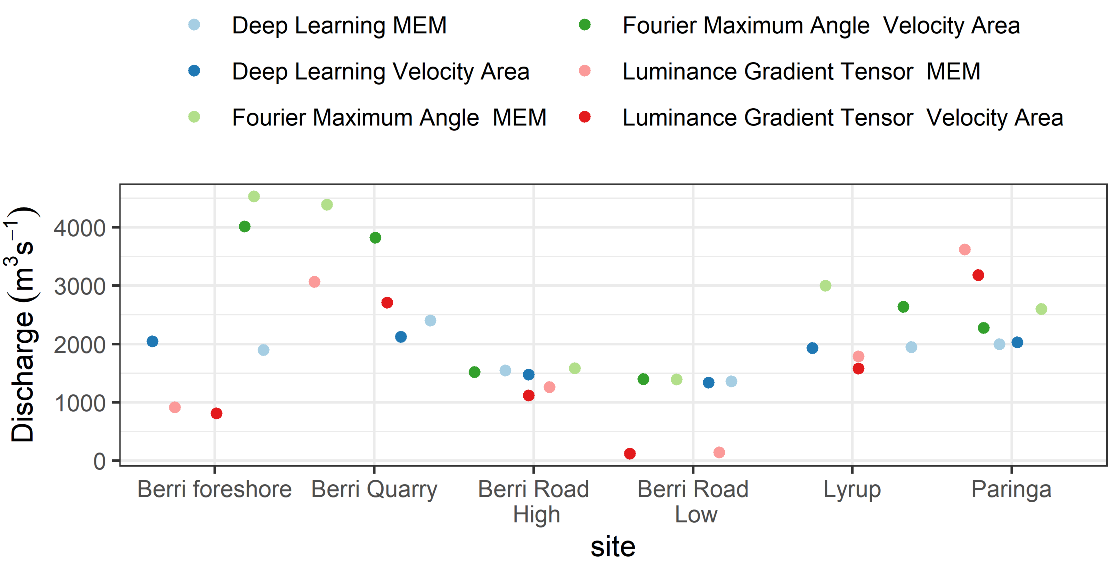

Figure 4. Comparison of algorithms for identifying surface velocity from STI (deep learning, Fourier maximum angle and Luminance gradient tensor) and methods to convert surface velocity to depth averaged velocity (velocity area method with 0.85 parameter, and MEM)

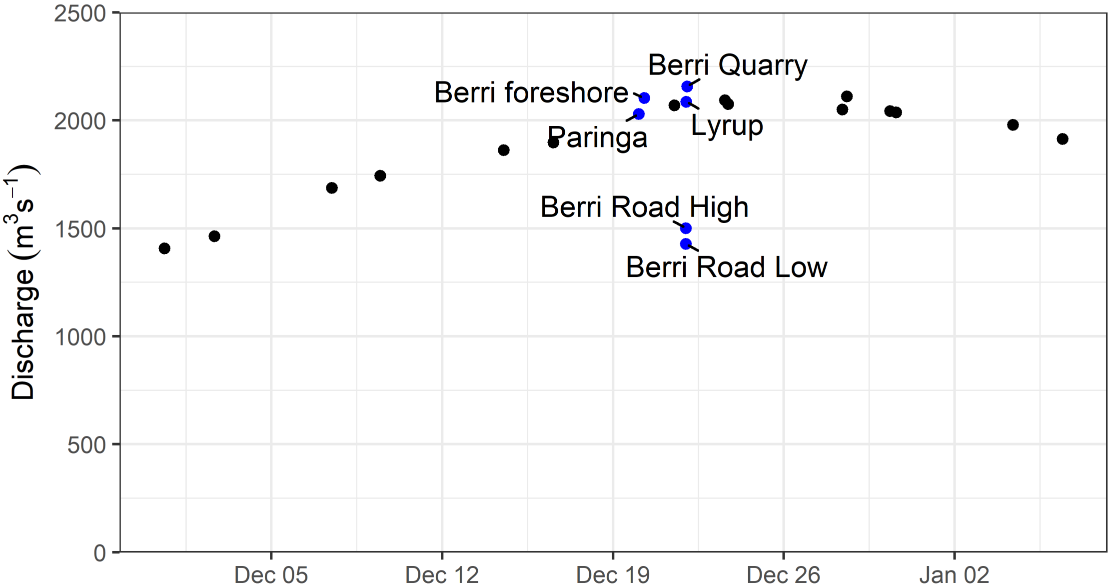

Figure 5. Comparison of STIV using deep learning and velocity area (blue) to ADCP (black). The measurement dates of ADCP discharge values were modified to six days earlier to account for the travel time, based on comparing the time to peak water level at Overland Corner and Berri Pump Station monitoring stations.

As with many off-the-shelf software tools, without critical application and interrogation the results from the different options in Hydro-STIV were highly variable (Figure 3). Through review of the results against other sources of information (ADCP measurements) the most accurate method for the sites considered could be identified. Even without ADCP measurements for comparison there are other indications of the quality of the estimates to guide the user, if highly unrealistic velocities are computed (>8 m/s was computed by the FMA algorithm), or large variations in calculated surface velocity from adjacent search lines that is not expected (e.g., due to changes in bathymetry) are all indications of erroneous calculations, along with manual review of the STIs for each search line. One, or a small number, of ADCP measurements at a site is useful to calibrate the Depth Area α parameter for converting surface velocity to mean channel velocity.

In conclusion, Space-Time Image Velocimetry was used to estimate discharge during the highest flow in the South Australian River Murray for over 60 years. Six videos were recorded from the riverbank using an RPA and a mobile phone camera between Berri and Renmark in South Australia over a two-day period. The most accurate surface velocities were derived from the deep learning algorithm available in Hydro-STIV software, and there was a relatively small difference between the two different methods to compute the depth averaged velocity from the surface velocity. The resulting discharge aligned well to ADCP measurements taken downstream. One site recorded lower discharge values than other sites and the ADCP, which could be attributed to a substantial floodplain flow path not included in the analysis. This work has demonstrated the potential for this technology to estimate discharge rates with minimal equipment requirements, and further work will continue to test and apply this technology using other approaches in other conditions.

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