



Evaluation of aDcp processing options for secondary flow identification at river junctions

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8 3 **Evaluation of aDcp processing options for secondary flow**
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11 4 **identification at river junctions**
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28
29 11 **Abstract**

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32 12 Secondary circulation in river confluences results in a spatial and temporal variation of
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34 13 fluid motion and a relatively high level of morphodynamic change. Acoustic Doppler
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36 14 current profiler (aDcp) vessel-mounted flow measurements are now commonly used to
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38 15 quantify such circulation in shallow water fluvial environments. It is well established that
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40 16 such quantification using vessel-mounted aDcps requires repeated survey of the same
41
42 17 cross-section. However, less attention has been given to how to process these data. Most
43
44 18 aDcp data processing techniques make the assumption of homogeneity between the
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46 19 measured radial components of velocity. As acoustic beams diverge with distance from
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48 20 the aDcp probe, the volume of the flow that must be assumed to be homogeneous
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50 21 between the beams increases. In the presence of secondary circulation cells, and where
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52 22 there are strong rates of shear in the flow, the homogeneity assumption may not apply,
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3 23 especially deeper in the water column and close to the bed. To reduce dependence on
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5 24 this assumption, we apply a newly-established method to aDcp data obtained for two
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7 25 medium-sized (~60-80 m wide) gravel-bed river confluences and compare the results with
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9 26 those from more conventional data processing approaches. The comparison confirms that
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11 27 in the presence of strong shear our method produces different results to more
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13 28 conventional approaches. In the absence of a third set of fully independent data, we
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15 29 cannot demonstrate conclusively which method is best, but our method involves less
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17 30 averaging and so in the presence of strong shear is likely to be more reliable. We conclude
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19 31 that it is wise to apply both our method and more conventional methods to identify where
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21 32 data analysis might be impacted upon by strong shear and where inferences of secondary
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23 33 circulation may need to be made more cautiously.
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36 **Keywords**

37 Acoustic Doppler current profiler

38 Secondary circulation

39 River confluences

40 River junctions

41 **Introduction**

42 Acoustic Doppler current profilers (aDcps) are now used widely to measure river flow in
43 three-dimensions, notably for the quantification of secondary flows. Applications have

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3 44 been made to river bedforms (e.g., Parsons et al., 2005; Kostaschuk et al., 2009; Shugar
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5 45 et al., 2010), bends (e.g., Dinehart and Burau, 2005; Kasvi et al., 2013; Vermeulen et al.,
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7 46 2014a, 2015; Engel and Rhoads, 2016; Knox and Latrubesse, 2016; Kasvi et al., 2017;
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9 47 Lotsari et al., 2017; Parsapour-Moghaddam and Rennie, 2018), junctions (e.g., Parsons
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11 48 et al., 2007; Lane et al., 2008; Szupiany et al., 2009; Riley and Rhoads, 2012; Riley et al.,
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13 49 2015; Gualtieri et al., 2017), bifurcations (e.g., Parsons et al., 2007; Szupiany et al.,
14
15 50 2012), canyons (e.g., Alvarez et al., 2017; Tomas et al., 2018; Venditti et al., 2014), deltas
16
17 51 (e.g., Czuba et al., 2011) and gravity currents (e.g., Garcia et al., 2007; Garcia et al.,
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19 52 2012). Research has also shown the need to make repeat section measurements (e.g.,
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21 53 Szupiany et al., 2007; Jackson et al., 2008) and also to process these data carefully,
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23 54 (Muste et al., 2004; Rennie and Church 2010; Tsubaki et al., 2012; Parsons et al., 2013;
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25 55 Petrie et al., 2013). Such processing must take into account positioning (Rennie and
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27 56 Rainville, 2006) and orientation (Zhao et al., 2014) errors, and the treatment of repeat
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29 57 section measurements (e.g., Szupiany et al., 2007; Jackson et al., 2008).

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36 58 This paper is concerned with recent observations regarding the inference of secondary
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38 59 flows from aDcp data and concerns regarding the assumption that flow is homogenous in
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40 60 the fluid volumes defined by the acoustic beams emitted from an aDcp and used to
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42 61 calculate any one point estimate (Vermeulen et al., 2014b). Acoustic beams are reflected
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44 62 by suspended particles, which, if moving, cause a Doppler shift in beam frequency, which
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46 63 is then detected at the sensor. This shift is directional so each beam measures the radial
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48 64 velocity, which is the velocity of particle motion parallel to the acoustic path. This can be
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50 65 assumed to be the flow velocity if the particle motion is identical to fluid motion. In order
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52 66 to resolve flow in more than one direction, aDcps require at least three acoustic beams to
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3 67 estimate three Cartesian components of velocity. The radial velocities originating from the
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5 68 beams are traditionally analyzed for a single measurement cycle at a single depth at a
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7 69 time (Vermeulen et al., 2014b). The velocity then applies to the volume of fluid defined by
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9 70 the beams at each depth. Flow within this volume is assumed to be homogeneous.
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11 71 However, as the beams spread from the sensor, depth bins increase in horizontal size
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13 72 (Rennie et al., 2002). This means that: (1) bins further from the sensor are likely to produce
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15 73 less reliable velocities because the bin size is greater and the flow within bins is more
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17 74 likely to be heterogeneous (Gunawan et al., 2011); and (2), even in smaller bins, velocities
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19 75 may be less reliable in zones of strong shear where also the within-bin flow is less likely
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21 76 to be homogeneous. In a river where measurements are made throughout the flow depth,
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23 77 the maximum shear may be close to the bed, where the beam divergence may also be
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25 78 greatest.

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31 79 One solution to this problem accounts for first order shear within the flow volume (e.g.
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33 80 Marsden and Ingram, 2004) through a Taylor expansion of the coordinate transform used
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35 81 to determine the Cartesian velocity components. Under this solution, flow is allowed to
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37 82 vary linearly within the bin, but the bin's volume becomes potentially larger with distance
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39 83 from the sensor. Vermeulen et al. (2014b) developed and tested a second solution. As
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41 84 explained in detail below, multiple radial (beam) velocity measurements within a single bin
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43 85 are put through a Cartesian transform to obtain a localized within-bin three-dimensional
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45 86 velocity. This method strongly reduces the volume over which homogeneity should be
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47 87 assumed and Vermeulen et al. (2014b) found that this significantly impacted
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49 88 interpretations of secondary velocities in the presence of strong shear. In this paper, we
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51 89 seek to quantify the effects of this method for the measurement of secondary flow in two
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3 90 medium-sized river junctions (c. 60-80 m post-junction channel width). River junctions are
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5 91 associated with very strong shear (e.g. Best and Roy, 1991; Biron et al., 1993, 1996a,
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7 92 1996b; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004, 2008; Konsoer
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9 93 and Rhoads, 2014; Sukhodolov et al., 2017), as well as well-developed secondary
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11 94 circulation (e.g. Ashmore et al., 1992; Rhoads and Kenworthy, 1995, 1998; Rhoads and
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13 95 Sukhodolov et al., 2001; Lane et al., 2008; Riley and Rhoads, 2012; Riley et al., 2015).
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17 96 Thus, understanding how to process effectively the aDcp data used to describe them is of
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19 97 paramount importance.

22 98 **Methods for estimating Cartesian velocity components from aDcp data**

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26 99 In this section, we describe the two different methodological approaches used in this study
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28 100 to estimate Cartesian velocity components: (1) Method A, the Vermeulen et al., (2014b)
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30 101 method; and (2) Method B, the conventional method. Common to all methods is the
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32 102 assumption that data are available from repeat measurement of the same cross-section,
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34 103 as has been shown to be critical for obtaining reliable estimates of secondary circulation
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36 104 from aDcp data (Szupiany et al., 2007), particularly when single transect measurements
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38 105 are not close enough together.
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42 106 ***Method A: based on Vermeulen et al., (2014b)***

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45 107 Application of the Vermeulen et al. (2014b) method requires mapping of radial beam
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47 108 velocity data onto a predefined mesh. This mesh requires both a bottom topography or
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49 109 bathymetric model, and an upper limit just below the water surface. As the measurements
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51 110 were made using several repeat transects for each cross section, the first step is to define
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54 111 a mean cross section for each set of individual transects (boat tracks). The second step

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3 112 is to define a grid mesh for this mean cross section. Third, all measured beam velocities
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5 113 are projected on to this cross section mesh. Finally, the beam velocities within each mesh
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7 114 cell are then used to resolve a Cartesian velocity for the mesh cell. Errors that influence
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9 115 these steps can be estimated.

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13 116 The first step is estimation of the mesh extremes, both the lower boundary or bathymetry
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15 117 model and the upper boundary near the water surface. To generate the bathymetry model
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17 118 we use depth soundings collected with the aDcp. We recognize that each beam may
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19 119 register a different distance of the stream bed from the sounder, especially as we are
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21 120 dealing with bathymetrically irregular cross-sections. Specifically, for each bottom track
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23 121 sounding within each transect, we use the UTM coordinates obtained with a coupled
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25 122 differential GPS (dGPS), the range of each bottom track beam return, and the instrument
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27 123 tilt to estimate the bed elevation and horizontal position of each beam impingement point
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29 124 on the bed. These bed positions are combined together to identify an initial mean transect.
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31 125 Provided a point is within a certain distance from the initial mean cross-section, LOWESS
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33 126 interpolation (Appendix A) is applied, which has the effect of defining a bathymetric model
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35 127 that gives most weight to points that appear to be closer to the cross-section. It is important
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37 128 to note that this mean transect is not necessarily orthogonal to the primary flow direction
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39 129 and so will not yield true primary and secondary flow estimates without further correction.
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41 130 We address this below.

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45 131 Once the initial bathymetric model is defined, we estimate a unique vector using the initial
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47 132 mean transect; that is the principal direction of the scatter cloud of all x and y UTM
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49 133 positions at the bed. This unique vector points in the direction of the largest eigenvector
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51 134 of the covariance matrix of all UTM positions (t). We then calculate the mean UTM position
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3 135 (ρ_{mean}) for each set of individual transects and the difference between each measured
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5 136 beam position (ρ_b) and the mean position. The dot product of these obtained values and
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7 137 the unique vector is then used to define the projection of each UTM position in the direction
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10 138 of the unique vector. To identify the final mean cross section, we sum up all individual
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12 139 projected vectors and obtain the best fit to all available data (Figure 1).
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15 140 To define the upper boundary of the mesh, we estimate the elevation of the water surface.
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17 141 As there is a blanking distance at the surface of the water during the measurement, we
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19 142 then remove this blanking distance, taken as 0.30 m. Thus, the mesh has also a blanking
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21 143 distance and the upper part of the cross-section is, strictly, the upper limit of available
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23 144 data, not the water surface.
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27 145 "Figure1"
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30 146 The second step uses the defined bathymetric model and available velocity bins within
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32 147 the measured area (not influenced by side lobes, and below the blanking distance) to
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34 148 define a cross-section mesh. The side-lobe interference is caused by the striking of the
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36 149 channel bed by side-lobe energy from each of the acoustic beams. This side-lobe energy
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38 150 has strong reflections from the bed, which result in echoes that overwhelm the signal from
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40 151 scatters near the bed. The thickness of the side-lobe layer is typically 6-7% of the
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42 152 measured depth (Morlock, 1996).
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47 153 To generate the mesh, the cross section is initially subdivided into vertical slices with equal
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49 154 widths (Δn). For each slice, the simplest definition of mesh cell thicknesses (Δz) divides
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51 155 each vertical equally. These verticals are converted to non-dimensional σ coordinates
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53 156 using following equation:
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$$\sigma = 1 - \left(\frac{p_v \cdot k \cdot \eta}{p_b \cdot k \cdot \eta} \right) \quad (\text{Vermeulen et al. 2014b}) \quad (1)$$

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7 158 where p_v stands for velocity measurement positions (m), p_b is the corresponding bed
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9 159 position (m) that is found using velocity measurement horizontal positions and applying
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11 160 the bathymetric model, k is the upward pointing unit vector and η are the water surface
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13 161 fluctuations around the mean water level at which $z=0$.
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17 162 However, because of beam spreading and differences in the distance of the sounder from
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19 163 the bed, which varies with position of the sounder, this tends to produce a highly
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21 164 heterogeneous number of measurements in each cell within the mesh. The alternative,
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23 165 adopted here, is to allow mesh cell thickness to vary through the water column such that
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25 166 there is a roughly equal number of beam velocities contributing to each mesh cell (see
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27 167 Figure 2 for a typical distribution).
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31 168 As the river bed form is varying, to follow its shape, each mesh cell is considered to be a
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33 169 cuboid with 6 edges, two on the left side, two in the middle and two on the right side. To
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35 170 define these edges, the first step is to define the middle point of each mesh cell. Once
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37 171 defined, by calculating the slope for each half part of the mesh cell, edges can be obtained.
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39 172 The mesh cell faces are then calculated on the basis of adjacent verticals and the mesh
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41 173 cell upper and lower boundaries.
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46 174 To identify the beams that contribute to each mesh cell, an index for each beam velocity
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48 175 is defined, which shows its associated mesh cell, using the projection of each radial
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50 176 velocity onto the estimated mean cross section (Figure 2).
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53 177 "Figure 2"
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3 178 In the third step, the radial velocities for each beam (**b**) that contribute to each mesh cell
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5 179 (the N beam velocities) have to be transformed into Cartesian velocities (v_x , v_y and v_z)
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8 180 using:

$$11 \quad \begin{pmatrix} b_1 \\ \vdots \\ b_N \end{pmatrix} = \begin{pmatrix} q_1 \\ \vdots \\ q_N \end{pmatrix} \cdot \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \leftrightarrow \mathbf{b} = \mathbf{Q} \cdot \mathbf{u} \quad (2)$$

15
16 182 where **q** is a unit vector which describes the direction of the acoustic beam.

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19 183 To obtain the raw beam velocities, we use matrix transformations obtained from the raw
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21 184 data to transform measured velocities in XYZ coordinates into beam velocities. The
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23 185 Vermeulen et al., (2014b) method includes in the transformations an explicit treatment of
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25 186 the random errors due to internal and external factors and the bias (systematic errors)
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27 187 caused by the measurement system and the nature of river flow (Tsubaki et al., 2012).
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29 188 Random errors include those that come from sampling a time-varying flow in the presence
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31 189 of strong gradients and represent a form of aliasing. By adding a combined term of errors
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33 190 ε , (2) becomes:

$$34 \quad \mathbf{b} = \mathbf{Q}\mathbf{u} + \varepsilon \quad (3)$$

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38 192 A least squares solution is fitted to (3) that minimizes the sum of the square of the errors.

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41 193 The optimal estimation ($\hat{\mathbf{u}}$) for (**u**) is then given by the normal equation:

$$42 \quad \hat{\mathbf{u}} = \mathbf{Q}^+ \mathbf{b} + \varepsilon \quad (4)$$

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45 195 where \mathbf{Q}^+ can be defined as:

$$46 \quad \mathbf{Q}^+ = (\mathbf{Q}^T \mathbf{Q})^{-1} \mathbf{Q}^T \quad (5)$$

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3 197 To solve three Cartesian velocity components, we need at least three equations. Each
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5 198 beam measurement in a mesh cell adds an equation. Where enough beam velocities are
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7 199 collected in a mesh cell and the equations are different from each other (beam velocities
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9 200 are measured from different directions), the velocity can be estimated. To check whether
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11 201 this is the case, the matrix describing the system of equations can be analyzed. In the
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13 202 processing we use the rank which indicates how many unknowns can be solved from the
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15 203 system of equations. When the rank is three, the three Cartesian velocities can be solved.
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17 204 Where the rank of the matrix is one or two, the system cannot be solved. Where the
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19 205 system of equations is overdetermined, the obtained solution is a matrix with more
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21 206 equations (rows) than unknowns (columns). The velocity can be solved using the
22
23 207 generalized inverse of the matrix and in such a way that the sum of squared errors is
24
25 208 minimized. As this combined term of errors also contains information about the turbulence
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27 209 and accuracy of the measurements, we can obtain the covariance matrix of the velocity
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29 210 components:

$$211 \quad \hat{\boldsymbol{\varepsilon}} = \mathbf{b} - \mathbf{Q}\hat{\mathbf{u}} \quad (6)$$

$$212 \quad \text{var}(\hat{\mathbf{u}}) = \frac{\hat{\boldsymbol{\varepsilon}}^T \hat{\boldsymbol{\varepsilon}} (\mathbf{Q}^T \mathbf{Q})^{-1}}{N-3} \quad (7)$$

213 and the variance of the velocity across the section can be then estimated as:

$$214 \quad \text{var}(\mathbf{u}) = \frac{\text{var}(\hat{\mathbf{u}})}{N} \quad (8)$$

215 **Method B: the standard aDcp method**

216 As the Doppler shift is directional, it can only measure radial velocities. With the standard
217 method, to determine Cartesian velocity components, radial velocities then have to be

218 resolved into three orthogonal velocity vectors. To do so, at least three beam velocities
 219 pointed in known directions are required. Also, because the beams are measuring
 220 different water profiles along their individual slant ranges, the assumption of horizontal
 221 homogeneity must be taken into account. Hence, in the standard method, the three
 222 dimensional velocity for each depth bin for each ping can be solved for a typical four-beam
 223 system using the following equations (Mueller and Wagner, 2009):

$$224 \quad V_x = \frac{(b_3 - b_1)}{\sqrt{2} \sin \theta} \quad (9)$$

$$225 \quad V_y = \frac{(b_4 - b_2)}{\sqrt{2} \sin \theta} \quad (10)$$

$$226 \quad V_z = \frac{-(b_1 + b_3)}{(2 \cos \theta)} = \frac{-(b_2 + b_4)}{(2 \cos \theta)} \quad (11)$$

227 where V_y is the cross stream velocity assuming beam 3 is pointed upstream, V_x is the
 228 streamwise velocity, V_z is the vertical velocity, b_1 , b_2 , b_3 and b_4 are the radial velocities
 229 measured in beams 1,2,3 and 4 respectively and θ is the tilt angle of the beams referenced
 230 to vertical. These data should then be corrected for pitch and roll angles, obtained from
 231 the internal inclinometer and the heading angle from the internal compass. Velocity
 232 outputs are already corrected for ship velocities.

233 To compare results obtained using Method B with those of Method A, we use the same
 234 mean cross section built for Method A, as well as the same bathymetric model and the
 235 same mesh. Each measured velocity vector is assigned to the appropriate mesh cell by
 236 projecting its 3D position (horizontal position and depth) onto the mean cross section
 237 mesh. We then average x, y, and z components of all velocities measured within a mesh
 238 cell to obtain the mean velocity vector for the mesh cell.

239 **Methodology**

240 This paper is motivated by the need to acquire three-dimensional data from junctions of
241 tributaries with a main river stem, here the River Rhône, western Switzerland, and so the
242 need to identify methods for reliably obtaining Cartesian velocities from aDcp data. The
243 Rhône tributaries typically have very high bedload transport rates for short periods of time,
244 leading to the formation of very large tributary mouth bars downstream of their junctions
245 with the main river. These bars are maintained for weeks or months such that at lower
246 tributary flow, with negligible sediment supply, there is a legacy effect of previous high
247 momentum tributary events upon junction morphology and secondary flow formation.

248 For this paper, we used a specially-designed rope and pulley system to collect aDcp data
249 from the junction of two tributaries with the Rhône (Figure 3).

250 “Figure 3”

251 The Lizerne is a Rhône tributary of almost 20 km length that flows south-westward from
252 the western slopes of the Tête Noire (2451m) or La Fava (2612m), in the Bernese Alps.
253 This river is heavily regulated for hydropower with sediment extracted upstream of the
254 junction. As a result, there is negligible sediment supply and no evidence of point bar
255 formation. It reaches the Rhône between Ardon and Vétroz, forming a 90° junction angle
256 and it has a bed that is nearly concordant with the Rhône.

257 The Grande Eau is a second tributary of the Rhône River which has a length of 26 km and
258 takes its source on the Vaud side of the Les Diablerets and flows into the Rhône River
259 with a 70° confluence angle, near Aigle. The Grande Eau bed is 1.5 m higher than the
260 Rhône such that it is markedly discordant.

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3 261 In this section, we: (1) describe the aDcp used to collect data; (2) describe how the aDcp
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5 262 was deployed; and (3) outline the analytical approaches used to interpret the results from
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7 263 the different methods. Although the method is valid for any aDcp that has an onboard
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10 264 compass and potential for differential GPS positioning, as is standard with most aDcps,
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12 265 we use a Sontek M9 aDcp in this study.

15 266 ***The Sontek M9 aDcp***

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18 267 The SonTek M9 aDcp is a nine-transducer system with three acoustic frequencies,
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20 268 configured as two sets of four profiling beams (3 MHz and 1 MHz transducers in Janus
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22 269 configurations) and one vertical beam (0.5 MHz Echo sounder) for depth measurements
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25 270 (SonTek YSI, 2010). It uses these two sets of four beams to provide raw radial velocity
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27 271 samples. These beams are equally spaced at 90° azimuth angles and are projected at an
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29 272 angle θ of 25 ° off the vertical axis (SonTek YSI, 2000). For the standard configuration,
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32 273 the four beams encompass a sampling diameter of 93% of the distance from the aDcp
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34 274 (7% of side-lobe) (SonTek YSI, 2000).

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37 275 The output velocities from the SonTek M9 Riversurveyor are either in Cartesian
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39 276 coordinates (XYZ) that are relative to sensor orientation or in Earth coordinates (ENU) for
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41
42 277 a SonTek system with compass and tilt sensors. These raw velocity data in Earth
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44 278 coordinates or XYZ coordinates are already corrected for the ship motion. To apply
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46 279 Method A to Sontek output data, as this method is based on radial velocities, it is
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48 280 necessary to transform these output velocities to radial velocities. To do so, we add ship
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51 281 velocities to these output velocities and then apply the inverses of the instrument's matrix
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53 282 coordinate transformations (obtained from MATLAB files output by the SonTek data
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55 283 collection software RiverSurveyor). As the survey is being undertaken using a moving
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3 284 vessel, these radial velocities then have to be corrected again for the boat velocity. There
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5 285 are two key methods for doing this. The first uses the bottom tracking to measure the boat
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7 286 velocity relative to the river bed, under the assumption that the latter is stationary (i.e.
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9 287 there is no bedload transport). The second tracks the boat position using differential GPS
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11 288 (dGPS, e.g. Zhao et al., 2014). In this study, we corrected all raw beam velocities for ship
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13 289 velocities, using dGPS as we could not exclude the possibility of there being bedload
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15 290 transport.

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17 291 To apply Method B in this study, we use the raw velocity data in Earth coordinates and
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19 292 we correct it for pitch and roll angles, obtained from internal inclinometer and heading
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21 293 angle data for the internal compass. For SonTek M9 aDcps, pitch is a y-axis rotation and
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23 294 roll an x-axis rotation.

24
25 295 Depending on the water depth and velocity, the Sontek M9 firmware changes the acoustic
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27 296 operating frequency and the water profiling mode on-the-fly, thus the number of sampled
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29 297 points in the vertical varies automatically from one profile to the next. Specifically, when
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31 298 the water is shallower than 0.75 m and the maximum velocity is less than 0.4 ms^{-1} , the
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33 299 M9 reports data acquired with a 3 MHz frequency using the pulse coherent mode to obtain
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35 300 a 2cm depth measurement resolution. For deeper situations, this frequency changes to 1
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37 301 MHz pulse coherent pings using a 6cm aDcp cell size. If the maximum velocity is greater
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39 302 than 0.4 ms^{-1} then SmartPulse (i.e., broadband) mode is utilized, with the 3 MHz beams
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41 303 if depth is less than 5 m and the 1MHz beams if depth is greater than 5m, with the aDcp
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43 304 cell size optimized based on the current water depth. As a result of these on-the-fly
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45 305 changes, each measured profile has a different number of aDcp cells and different aDcp
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47 306 cell sizes. Hence, to correct the aDcp cell size variability, for both methods A and B there
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49 307 is the need to define a cross-sectional mesh and to project the measured velocities to this
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3 308 mesh. For Method A we use the beam velocity vertical positions in a non-dimensionalized
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5 309 coordinate system using equation 1, within the predefined mesh explained in section 2.1.
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8 310 ***Deployment of the Sontek M9 in the river junctions***

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11 311 The survey work was undertaken in two junctions of the Swiss River Rhône, the Lizerne-
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13 312 Rhône confluence in August 2017 and the Grande Eau-Rhône confluence in May 2018,
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15 313 using a Sontek M9 vessel mounted aDcp and a specially-designed rope-pulley system
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17 314 (Figure 3c). The survey was spatial, monitoring 11 cross-sections from upstream of the
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19 315 junction to its downstream at the Lizerne-Rhône confluence with a Momentum ratio (M_r)
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21 316 of 0.018 (Figure 3a) and 11 cross-sections at the Grande Eau-Rhône confluence with a
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23 317 M_r of 0.022 (Figure 3b). Table 1 shows the general characteristics of these two
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25 318 confluences on the date of the measurements.
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30 319 “Table 1”
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33 320 As proposed previously by Dinehart and Burau (2005), Szupiany et al. (2007), Gunawan
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35 321 et al. (2011) and Vermeulen et al., (2014b) at least five repeats are required to have a
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37 322 robust estimation of secondary velocities. Hence, in this paper, data are processed for
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39 323 cross-section 6 at the Lizerne-Rhône confluence (Figure 3a), and for cross section 3 at
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41 324 the Grande Eau-Rhône confluence (Figure 3b). Identification of the minimum number of
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43 325 repeat transects necessary per cross-section was undertaken using cross-section 9 at the
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45 326 Lizerne-Rhône confluence (Figure 3a), which involves 16 repetitions. We noted that after
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47 327 application of Method A, the standard deviation of velocity stabilized with six repetitions,
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49 328 which is the number we adopt for this study.
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3 329 ***Bin position error determination***
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6 330 Application of Method A requires estimation of the error terms in (2). The size of the
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8 331 sampling volume in each beam is determined by the size of the bin used. As the SonTek
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10 332 M9 aDcp uses different bin sizes depending on the water track frequency (section 2.1.3),
11
12 333 these volumes could vary. Applying Method A might improve the velocity estimation for
13
14 334 large measurement volumes at depth, as it does not rely on the homogeneity assumption.
15
16 335 But as bins with a small number of velocity measurements will have greater error, this
17
18 336 method can estimate velocities with error. Also, if the beam velocity distribution within
19
20 337 each mesh cell is not linear, as averaging is made in the middle of each mesh cell, it can
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22 338 introduce error in velocity estimation. Thus, it is necessary to calculate a minimum
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24 339 necessary mesh cell size when applying Method A.
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29 340 Method B is inherently limited by spatial averaging due to the potential use of divergent
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31 341 beams and the associated homogeneity assumption. In other words, one must assume
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33 342 that the velocity is homogeneous over the horizontal domain defined by beam divergence
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35 343 (Eq.12). Method A has the advantage that velocities are recorded within an individual
36
37 344 beam depth bin, thus no spatial averaging between beams is required. However, in order
38
39 345 for Method A to overcome the uncertainty induced by spatial averaging inherent to Method
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41 346 B, it is essential that the bin location is known explicitly. Error in bin location can be induced
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43 347 by dGPS position and or tilt sensor (pitch and roll) errors. We therefore compare possible
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45 348 bin position errors using Method A to beam divergence obtained from Method B to indicate
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47 349 when Method A should be advantageous over Method B.
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52
53 350 Beam divergence is the spatial separation of the beams due to the Janus configuration of
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55 351 the beams with beam angles of 25° . This divergence determines the sampling volume that
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3 352 must be considered homogeneous for Method B and can be calculated using equation
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5 353 12:

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7
8 354 $x_b = 2d \tan \theta$ (12)
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10
11 355 where d is the depth in m and θ is the beam angle which for a SonTek aDcp is 25° . The
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13 356 aDcp dGPS is used to reference the velocity measurements in space and to estimate the
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15 357 ship velocity. If dGPS is used for ship velocity, this introduces errors in measurement of
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17 358 the absolute water velocity (because ship velocity is subtracted from the water velocity
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19 359 measured in the reference frame of the aDcp). This uncertainty introduces error in velocity
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21 360 calculations.
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25 361 To estimate the errors due to dGPS and the tilt sensors, in this study we assume normally
26
27 362 distributed random errors with a standard deviation of $\pm 1^\circ$ for tilt sensors, based on
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29 363 manufacturer specifications, and a normally distributed displacement error measured by
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31 364 the dGPS for the dGPS positions (as a function of satellite configuration during
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33 365 measurement), and we apply a Monte Carlo approach which we run 100 times sampling
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35 366 under these uncertainties. Each time we calculate the estimated secondary velocity
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37 367 differences as compared with the original secondary velocities.
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42 368 To be able to reduce the uncertainty due to velocity estimation using Method A compared
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44 369 to Method B, the errors induced in Method A related to GPS uncertainty and tilt sensors
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46 370 must be less than the errors in Method B due to beam divergence and the homogeneity
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48 371 assumption. Hence, Method A can be used if the error associated with a minimum aDcp
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50 372 cell size is in between the error due to beam divergence and the maximum estimated error
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52 373 due to the GPS and tilt sensors. Otherwise using this method introduces more error in
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54 374 velocity estimations than using Method B.
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3 **375 Data interpretation**
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6 376 Methods A and B, described above, were applied to the Sontek M9 data, to determine
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8 377 Cartesian velocities (v_x , v_y and v_z). As our interest is in process estimation, here we
9
10 378 describe the methods we apply to the Cartesian velocities to estimate processes relevant
11
12 379 to junction dynamics. In order to distinguish between primary and secondary components
13
14 380 of flow, we need to rotate the initial mean transect. Options for doing this are reviewed in
15
16 381 Lane et al. (2000) and we do not assess them here, but rather apply the zero net cross
17
18 382 stream discharge definition (Lane et al., 2000). By calculating the mean values of the x
19
20 383 and y velocity components (U and V), we then calculate the velocity magnitude (v). By
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22 384 rotating these velocity components to the direction of the cross-stream velocity, using the
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24 385 unique vector (σ), primary velocity vectors (\mathbf{v}_p) and secondary velocity vectors (\mathbf{v}_s) then
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26 386 can be estimated.
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32 387
$$v = \sqrt{U^2 + V^2} \quad (13)$$

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36 388
$$\begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} U \\ V \end{pmatrix} / v \quad (14)$$

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39 389 where σ_x and σ_y are sin and cos of the angle between the section angle and east.
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42 390
$$\mathbf{v}_p = \sigma_x \mathbf{v}_x + \sigma_y \mathbf{v}_y \quad (15)$$

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45 391
$$\mathbf{v}_s = -\sigma_y \mathbf{v}_x + \sigma_x \mathbf{v}_y \quad (16)$$

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49 392 However, secondary circulation is all flow that is orthogonal to the primary flow and not
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51 393 just horizontal flow; there should be not net secondary flux in a section; and so correction
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53 394 should also consider vertical velocities. Thus, we extend these relationships to include
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55 395 vertical velocities:
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$$396 \quad \begin{pmatrix} \sigma_{x,1} & \sigma_{x,2} & \sigma_{x,3} \\ \sigma_{y,1} & \sigma_{y,2} & \sigma_{y,3} \\ \sigma_{z,1} & \sigma_{z,2} & \sigma_{z,3} \end{pmatrix} = \begin{pmatrix} U \\ V \\ W \end{pmatrix} / v \quad (17)$$

397 where: U , V and W are the mean velocities of x , y and z velocity components, respectively

398 and v is the magnitude of the velocity which can be obtained using:

$$399 \quad v = \sqrt{U^2 + V^2 + W^2} \quad (18)$$

$$400 \quad \mathbf{v}_p = \sigma_{x,1} \mathbf{v}_x + \sigma_{x,2} \mathbf{v}_y + \sigma_{x,3} \mathbf{v}_z \quad (19)$$

$$401 \quad \mathbf{v}_s = \sigma_{y,1} \mathbf{v}_x + \sigma_{y,2} \mathbf{v}_y + \sigma_{y,3} \mathbf{v}_z \quad (20)$$

$$402 \quad \mathbf{v}_v = \sigma_{z,1} \mathbf{v}_x + \sigma_{z,2} \mathbf{v}_y + \sigma_{z,3} \mathbf{v}_z \quad (21)$$

403 To estimate velocity gradients, and to correct for weak curvature with the survey method

404 at the edges of each transect line (e.g. Figure 3), all data have been transformed into row

405 and column coordinates (η and ζ) using the following transformation:

$$406 \quad \begin{pmatrix} \frac{\partial}{\partial n} \\ \frac{\partial}{\partial z} \end{pmatrix} = \begin{pmatrix} \frac{\partial \eta}{\partial n} & \frac{\partial \zeta}{\partial n} \\ \frac{\partial \eta}{\partial z} & \frac{\partial \zeta}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial \eta} \\ \frac{\partial}{\partial \zeta} \end{pmatrix} \quad (22)$$

407 where n and z are horizontal and vertical coordinates on the section plane, respectively

408 (Vermeulen et al., 2014b).

409 Results

410 *Primary and secondary velocities*

411 Primary and secondary velocities estimated using methods A and B for the Lizerne-Rhône

412 confluence appear to be similar at cross-section 6 (Figures 4a and 4b) and the differences

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3 413 in estimated secondary flows are minor. The differences are most pronounced between -
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5 414 10 and 5 m, in the middle of the main channel.
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8 415 These primary and secondary velocity patterns show higher differences at cross-section
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10 416 3 of the confluence of Grande Eau-Rhône (Figures 4c and 4d) despite it having a similar
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12 417 momentum ratio to the Lizerne during measurement. Primary velocities differ significantly
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14 418 between methods A and B: (1) at greater distance from the aDcp because the bins contain
15
16 419 larger volumes of water assumed to be homogenous; and (2) at the edges of the cross-
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18 420 section where there are more beam velocity measurements (contours in Figures 4c and
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20 421 4d). Secondary velocity vectors estimated using Method A indicate flow convergence at
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22 422 the surface and flow descending towards the riverbed throughout the centre of the channel
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24 423 (Figure 4c). This is due to a high degree of bed discordance between the Grande Eau and
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26 424 the Rhône, which increases the penetration of the tributary flow into the main channel over
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28 425 the junction, and which forms a zone of high lateral and vertical shear, on the one hand,
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30 426 and main channel narrowing because of penetration of the tributary mouth bar on the other
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32 427 hand. The secondary velocity vectors estimated by Method B show a weaker penetration
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34 428 of the tributary flow into the main channel, which results in a reverse flow towards the bank
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36 429 on the tributary side of the channel at the surface of the mixing interface (Figure 4d). In
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38 430 this case, the core of the secondary circulation is located in the middle of the main channel
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40 431 and closer to the inner bank.
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48 432 “Figure 4”
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51 433 Figure 5 and Figure 6 quantify the differences in primary and secondary velocity patterns
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53 434 estimated using methods A and B, for the Lizerne-Rhône confluence. Figures 5a and 5c
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55 435 and Figures 6a show that almost 4% of mesh cells have a relative difference in primary
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3 436 velocities between methods A and B of more than 10%. These differences can exceed
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5 437 0.2 ms^{-1} and so they are relatively small. Velocity differences are more pronounced in
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7 438 estimated secondary velocities, with almost 82% of mesh cells having a difference of more
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10 439 than 10%, and almost 37% of mesh cells having a difference of more than 50% (Figure
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12 440 5b, 5d and 6b).

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15 441 “Figure 5”

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18 442 “Figure 6”

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21 443 At the Grande Eau-Rhône confluence, these differences are greater as compared with
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23 444 those of the Lizerne-Rhône confluence. Figures 7a, 7c and 8a show that these differences
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25 445 for primary velocities exceed 0.4 ms^{-1} in the zone of high vertical and lateral shear and
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27 446 near the inner bank. Almost 20% of the mesh cells have a relative difference in primary
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29 447 velocities between methods A and B of more than 10%. The secondary velocity
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31 448 differences are more pronounced between these two methods. Figures 7b and 7d show
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33 449 differences with a magnitude of 0.4 ms^{-1} near the edges and near the bed. Almost all the
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35 450 mesh cells have a difference in estimated secondary velocities between two methods.
36
37 451 Figure 8b shows that almost 93% of the mesh cells have a relative difference of 10%
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39 452 between methods A and B. although this value decreases to 55% for a relative difference
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41 453 of 90% between these two methods.
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47 454 “Figure 7”

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50 455 “Figure 8”
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3 456 ***Velocity gradients***
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6 457 As Figure 9 shows, there is a strong relationship between lateral gradient in secondary
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8 458 velocities and differences between the secondary velocities estimated using methods A
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10 459 and B for both the Lizerne-Rhône and the Grande Eau-Rhône confluences. This is
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12 460 because a stronger velocity gradient increases the probability that the assumption of flow
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14 461 homogeneity within a bin is likely to fail. Indeed, the marked differences between methods
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16 462 A and B at the Grande Eau confluence (Figure 7) are also in a zone of strong lateral shear.
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20 463 “Figure 9”
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23 464 ***Number of repeat transects***
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26 465 One way to reduce data fluctuations due to random errors and turbulence, during the
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28 466 measurement using moving vessel aDcps, is to average by using several repeat transects
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30 467 together in one cross section. As each estimated velocity measurement is a single sample
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32 468 in time, adding in a repeat section adds in an additional estimated velocity measurement.
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34 469 Under [8], this should cause the variance to increase, despite the number of
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36 470 measurements used in its estimation increasing, until the point at which there are enough
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38 471 repeats to capture the effects the range of scales of variation in turbulence impacting the
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40 472 measurement. Then, this variance will become stable. At this stage we can consider the
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42 473 number of repeats as the minimum number required to have a robust estimation of
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44 474 secondary velocity vectors that is to have reached estimates of velocity that are
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46 475 asymptotic on this stable state.
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51 476 Here we apply both methods A and B to the survey of 16 repeats at cross-section 9 in
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53 477 Figure 3a at the Lizerne-Rhône confluence. To allow a reasonable comparison, three
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55 478 mesh cells in the middle of the cross section, and at three different depths (near the
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3 479 surface, middle depth and near the bed) have been chosen (Figure 11). Results show
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5 480 that by using Method A, after six repeats, a stable variance of the velocity estimator is
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7 481 obtained at the Lizerne-Rhône confluence (Figure 11a). Many more repeats are needed
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9 482 using Method B (Figure 11b) and this is likely because Method B uses fewer
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11 483 measurements per mesh cell. These results also show a higher standard deviation of the
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13 484 velocity estimation near the surface, using Method A and before achieving the stable
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15 485 situation. This can be explained by the fact that near the surface Method A is more
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17 486 sensitive to errors caused by positioning, while near the bed, hence with distance from
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19 487 the sounder, as the beam spread increases, the improvement obtained using Method A
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21 488 is more pronounced (Figure 11a).

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26 489 “Figure 10”

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28 490 “Figure 11”

29 30 31 491 ***DGPS and tilt sensor uncertainty analysis***

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34 492 As explained above a normally distributed random error has been applied 100 times to
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36 493 both dGPS positioning (by adding a random offset) and tilt sensors (by changing pitch and
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38 494 roll angles randomly) and the secondary velocities have been estimated using Method A
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40 495 for each perturbed dataset. As Figure 12 shows, the magnitude of errors related to dGPS
41
42 496 accuracy are higher than those related to tilt sensor accuracy, for both confluences. These
43
44 497 values can reach $\pm 0.03 \text{ ms}^{-1}$ and confirms the earlier finding of Rennie and Rainville
45
46 498 (2006) which showed that GPS corrections can have average errors of about $\pm 0.03 \text{ ms}^{-1}$
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48 499 (Figures 12a and 12c). These magnitudes are also higher near the surface and near the
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50 500 bed for the Lizerne-Rhône confluence (Figure 12a). Near the surface, as there fewer
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52 501 measurements that can contribute to the estimation of aDcp position and tilt, uncertainties
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3 502 in dGPS data will have a greater effect. Near the bed, as the velocity gradient is higher,
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5 503 errors will be greater as well. Figure 12c shows higher magnitudes near the surface at
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7 504 cross-section 3 in Figure 3b for the Grande Eau-Rhône confluence.

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10 505 Errors related to tilt sensor uncertainty are higher where there is a higher velocity gradient.
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12 506 This is related to the fact that within the mesh cells with higher velocity gradients, as the
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14 507 velocity distribution is not linear, and as averaging is made in the middle of the mesh cell,
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16 508 it is more probable that the velocity will be affected by sensor inaccuracies of bin
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18 509 positioning, and so be in error (Figures 12b and 12d).
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23 510 “Figure 12”
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26 511 ***Homogeneity assumption analysis***

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28 512 Figure 13 shows the maximum inhomogeneity allowance, using Method B for both case
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30 513 studies. These results are obtained by dividing the velocity gradient obtained from
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32 514 equation 22 by the divergence of the beams from equation 12. They confirm that, for the
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34 515 homogeneity assumption to be valid and thus error to be minimized using Method B, the
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36 516 maximum mesh cell size, which can be used is as small as 5cm near the bed. Clearly,
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38 517 this is impossible as the configuration of the beams using aDcps always results in beam
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40 518 divergence greater than 5cm.
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45 519 “Figure 13”
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48 520 ***Primary and secondary flow patterns***

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51 521 In this section, we compared estimated primary and secondary velocities using methods
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53 522 A and B for other cross sections in Figure 3 for both river confluences.
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3 523 Figure 14 shows the results for cross sections 4, 5 and 7 (in Figure 3a) at the Lizerne-
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5 524 Rhône confluence. These cross sections also show similar results in primary and
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7 525 secondary velocity patterns for both methods A and B. Figure 15 shows different patterns
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9 526 in primary and secondary velocities estimation using Method A and B for cross sections
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11 527 4, 6 and 8 in Figure 3b at the Grande Eau-Rhône confluence. Method A leads to the
12
13 528 identification of a stronger and more coherent tributary penetration at cross-section 4 and
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15 529 weaker upwelling mid-channel, giving the impression of less intense secondary circulation
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17 530 (Figure 15). At section 6, flow towards the true left across the shallow top of the tributary
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19 531 mouth bar is identified and is coherent with Method A. At the channel-scale there is
20
21 532 general flow convergence reflecting channel narrowing (Figure 15). When using Method
22
23 533 B, these patterns are less coherent and flow is towards the true right in the vicinity of the
24
25 534 tributary mouth bar. These patterns are repeated for section 8 (Figure 15).

31 535 "Figure 14"

34 536 "Figure 15"

37 537 **Discussion**

41 538 In this paper we used data collected with boat-mounted aDcp technology at two
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43 539 confluences of the Swiss river Rhône, both with similar and very low momentum ratios
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45 540 (0.018, 0.022) and analysed these using two different methods, A and B, to estimate
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47 541 Cartesian velocity components. Method A is based on a methodological approach
48
49 542 developed by Vermeulen et al. (2014b). It differs by treating explicitly each individual beam
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51 543 velocity based on its position within a predefined mesh. Results show that this method
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53 544 reduces the volume over which the flow must be assumed to be homogenous (Fig 13). It
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3 545 can, but not necessarily does, result in differences in estimated primary and secondary
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5 546 velocities as compared with the more traditional method (B in this study), that involves
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7 547 determining velocities by averaging data from the spreading beams. Our results show that
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9 548 these differences are more pronounced in estimated secondary velocities than primary
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11 549 velocities and are higher where there is a greater lateral velocity gradient (Figure 9). The
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13 550 comparison between the two case studies shows that even though both confluences have
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15 551 a very low momentum ratio, as the confluence of the Grande Eau-Rhône has a more
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17 552 complex shear zone, likely due to the effects of bed discordance, and there are more
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19 553 significant differences in the estimation of primary and secondary velocities. This is related
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21 554 to the extent to which spreading of the aDcp measurement beams influences the
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23 555 secondary velocities, particularly in relation to lateral gradients in flow conditions. More
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25 556 standard methods (Method B in this study) are valid if the flow is completely homogenous
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27 557 over the diameter of the fluid column that the beams spread. This diameter varies over
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29 558 depth and is largest near the bed. In the case of the Grande Eau-Rhône confluence where
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31 559 stronger lateral velocity gradients exist in the flow, individual beams will not be measuring
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33 560 homogenous conditions, particularly near the bed and in the zone of high shear near the
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35 561 inner bank, because the spread of the beams may be greater in diameter than the width
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37 562 of the zone of lateral velocity variation. In this case, as Method A involves less spatial-
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39 563 averaging than Method B, it may provide more accurate information on the flow behavior,
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41 564 but such a conclusion really needs a third and independent method to confirm it. At the
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43 565 Lizerne-Rhône confluence, even though the momentum ratio is similar to Grande Eau-
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45 566 Rhône confluence, there is only more localized shear in the flow and a simplified shear
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47 567 zone (Figure 9). In such a situation, using Method B to detect the large scale patterns of
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49 568 secondary flow may be more advantageous, because it involves more spatial averaging.
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3 569 The above discussion suggests that whether or not high rates of lateral shear influence the
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5 570 potential importance of Method A depends on distance from the aDcp: with more
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7 571 divergence at greater depths, lower levels of lateral shear are likely to be acceptable.
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10 572 Figures 16a and 16b quantifies the relationship between lateral velocity gradient, depth
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12 573 and the magnitude of the relative differences in secondary velocities estimated using
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14 574 methods A and B for the cross-section 6 of the Lizerne-Rhône and cross-section 3 of the
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16
17 575 Grande Eau-Rhône confluences, respectively. At the Lizerne-Rhône confluence, as the
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19 576 zone of high lateral shear is absent, even though there is a strong relationship between
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21 577 the magnitude of the relative differences in secondary velocities estimated using methods
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23 578 A and B and the depth (Figure 16a), their relationship with the lateral velocity gradients is
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25
26 579 poor. In contrast, for the case of the Grande Eau-Rhône confluence (Figure 16b), where
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28 580 increasing the lateral velocity gradient and depth results in higher relative differences in
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31 581 secondary velocities. Thus, the need to use Method A will depend on the case being used
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33 582 and the extent to which there is lateral shear at greater distances from the aDcp. This is
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35 583 why whilst it may be tempting to introduce some kind of shear or velocity gradient
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37 584 threshold to identify when Method A might be preferable, to do so would be misleading as
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40 585 the threshold will also depend on the distance of the shear from the aDcp.

41
42 586 “Figure 16”
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45 587 Results also confirm that several repeat transects are indispensable to provide a robust
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47 588 estimation of secondary circulation and to reduce the effect of spatial inhomogeneity and
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49 589 temporal variations. Although Method A reduces the minimum number of repeat transects
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52 590 needed to estimate the secondary velocities, a larger number of these minimum repeat
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54 591 transects (6 or more repeats for Lizerne-Rhône confluence) appeared to be required. This
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3 592 is higher than in the earlier findings of Szupiany et al. (2007) and Vermeulen et al., (2014b)
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5 593 who argue that 5 repeats are enough to have a robust estimation of the turbulence
6
7 594 averaged velocity. We also note that an even number of repeats may be important to
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9 595 avoid directional bias in dGPS positions.
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13 596 Since Method A is based on the position of beams, if the bin position errors related to
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15 597 dGPS accuracy as well as sensor tilt are greater than homogeneity errors associated with
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17 598 beam divergence, standard Method B is more reliable. This is likely to be the case
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19 599 particularly in rivers shallower than those studied here and where high resolution is
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21 600 required due to large velocity gradients. In rivers of the scale studied here, and deeper,
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23 601 by increasing the mesh cell size, we can still have sufficient data to estimate velocity
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25 602 vectors, and the effects dGPS and tilt sensor errors have a minor effect. This confirms the
26
27 603 earlier findings by Vermeulen et al., (2014b), which showed that Method A provides the
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29 604 greatest improvement where the aDcp cell size is much smaller than the beam spread.
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31 605 We are not yet in a position to identify the depth at which Method A becomes preferable
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33 606 to Method B, and again this will depend on other parameters such as the intensity of shear
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35 607 and so may not be readily generalizable between confluences.
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40 608 The difficulty of identifying the depths of rivers and intensities of shear that make one
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42 609 method preferable over another precludes adoption of simple quantitative guidance on
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44 610 which method to use when. As both methods have some disadvantages, we argue that
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46 611 both methods should be applied. If they give similar results, then there should be
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48 612 confidence in both. If and where they differ, analysis should be undertaken to identify why,
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50 613 and hence which method is likely to be preferable. Association of the differences in
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52 614 primary and secondary velocities inferred between the two methods with estimates of
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3 615 shear intensity and with estimated tilt and positioning errors should then help decide
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5 616 whether Method A or Method B is preferable in a particular case. This preference may
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7 617 vary between confluences but also through time at a confluence, if shear or flow depth
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9 618 changes significantly between survey dates.

10 619 Finally, we wish to emphasise that the impact of averaging is only one element that must
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12 620 be considered in obtaining reliable primary and secondary flow estimates in river
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14 621 confluences. Other issues, such as the rotation method needed to distinguish primary and
15
16 622 secondary circulation, remain important and should be considered routinely.

623 **Conclusions**

624 This paper shows the advantage of working with the radial (beam) velocity measurements
625 of an aDcp within each bin prior to averaging them across a given volume of fluid (Method
626 A) as opposed to identify volumes of fluid and assuming bend homogeneity within them
627 (Method B). Such a treatment is important where there are strong velocity gradients in the
628 flow as with river channel confluences. In the first of our case-study confluences, the
629 Lizerne-Rhône, a very small tributary joined the main river, and the pattern of primary and
630 secondary velocities obtained with methods A and B were relatively similar, more so for
631 primary velocities. But for a second confluence, the Grande Eau-Rhône, with a similar
632 momentum ratio, there were much larger differences. We attributed this to the formation
633 of much stronger shear at this confluence. Method A also appeared to reduce the number
634 of repeat transects needed to estimate secondary velocities reliably. The main downside
635 is that Method A is more sensitive to errors related to positioning. Thus, good dGPS
636 accuracy and precision are required to perform a robust estimation of velocity.

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3 637 In smaller/shallower rivers, Method B may be acceptable indeed preferable as it is less
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5 638 sensitive to GPS errors. In larger rivers, Method A may be necessary, especially in the
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7 639 presence of strong shear at the confluence. Choice between these methods should be
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10 640 based upon an initial screening of the extent to which there is strong shear in the flow as
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12 641 well as the extent to which bins further from the aDcp are influenced by beam divergence.
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15 642 **Appendix A**

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18 643 The LOWESS model is a locally weighted polynomial regression, which at each point and
19
20 644 in the range of dataset, a low degree polynomial is fitted to a subset of the data, using
21
22 645 weighted least squares. This polynomial fit gives more weight to points closer to the point
23
24 646 whose response is being estimated. The value of the regression function for the point is
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26 647 then obtained by evaluating the local polynomial using the explanatory variable values for
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28 648 that data point. The LOWESS fit is complete after regression function values have been
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30 649 computed for each of the n data points. Many of the details of this method, such as the
31
32 650 degree of the polynomial model and the weights, are flexible ("Local regression," n.d.).
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39
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47 655 Gelare Moradi.
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3 1 “For the ESPL special issue: Measuring and numerical modelling of hydro-
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5 2 morphological processes in open-water”
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8 3 **Evaluation of aDcp processing options for secondary flow**
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11 4 **identification at river junctions**
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29 11 **Abstract**

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32 12 Secondary circulation in river confluences results in a spatial and temporal variation of
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34 13 fluid motion and a relatively high level of morphodynamic change. Acoustic Doppler
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36 14 current profiler (aDcp) vessel-mounted flow measurements are now commonly used to
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38 15 quantify such circulation in shallow water fluvial environments. It is well established that
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40 16 such quantification using vessel-mounted aDcps requires repeated survey of the same
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42 17 cross-section. However, less attention has been given to how to process these data. Most
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44 18 aDcp data processing techniques make the assumption of homogeneity between the
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46 19 measured radial components of velocity. As acoustic beams diverge with distance from
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48 20 the aDcp probe, the volume of the flow that must be assumed to be homogeneous
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50 21 between the beams increases. In the presence of secondary circulation cells, and where
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52 22 there are strong rates of shear in the flow, the homogeneity assumption may not apply,
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3 23 especially deeper in the water column and close to the bed. To reduce dependence on
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5 24 this assumption, we apply a newly-established method to aDcp data obtained for two
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7 25 medium-sized (~60-80 m wide) gravel-bed river confluences and compare the results with
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10 26 those from more conventional data processing approaches. The comparison confirms that
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12 27 in the presence of strong shear our method produces different results to more
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14 28 conventional approaches. In the absence of a third set of fully independent data, we
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16 29 cannot demonstrate conclusively which method is best, but our method involves less
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18 30 averaging and so in the presence of strong shear is likely to be more reliable. We conclude
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20 31 that it is wise to apply both our method and more conventional methods to identify where
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22 32 data analysis might be impacted upon by strong shear and where inferences of secondary
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24 33 circulation may need to be made more cautiously.
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35 ~~suggests an improvement in secondary flow representation compared to more~~
36 ~~conventional methods whilst also confirming that repeated transects are required to obtain~~
37 ~~reliable secondary flow and turbulence measurement. Use of the method resolves two~~
38 ~~counter-rotating cells in the confluence zone more clearly, with downward velocity in the~~
39 ~~channel centre. This pattern helps to explain development of confluence scour holes in~~
40 ~~such streams.~~

41 **Keywords**

42 Acoustic Doppler current profiler

43 Secondary circulation

44 River confluences

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6 46 **Introduction**
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10 47 Acoustic Doppler current profilers (aDcps) are now used widely to measure river flow in
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12 48 three-dimensions, notably for the quantification of secondary flows. Applications have
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14 49 been made to river bedforms (e.g., Parsons et al., 2005; Kostaschuk et al., 2009; Shugar
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16 50 et al., 2010), bends (e.g., Dinehart and Burau, 2005; Kasvi et al., 2013; Vermeulen et al.,
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18 51 2014a, 2015; Engel and Rhoads, 2016; Knox and Latrubesse, 2016; Kasvi et al., 2017;
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20 52 Lotsari et al., 2017; Parsapour-Moghaddam and Rennie, 2018), junctions (e.g., Parsons
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22 53 et al., 2007; Lane et al., 2008; Szupiany et al., 2009; Riley and Rhoads, 2012; Riley et al.,
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24 54 2015; Gualtieri et al., 2017), bifurcations (e.g., Parsons et al., 2007; Szupiany et al.,
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26 55 2012), canyons (e.g., Alvarez et al., 2017; Tomas et al., 2018; Venditti et al., 2014), deltas
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28 56 (e.g., Czuba et al., 2011) and gravity currents (e.g., Garcia et al., 2007; Garcia et al.,
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30 57 2012). Research has also shown the need to make repeat section measurements (e.g.,
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32 58 Szupiany et al., 2007; Jackson et al., 2008) and also to process these data carefully,
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34 59 (Muste et al., 2004; Rennie and Church 2010; Tsubaki et al., 2012; Parsons et al., 2013;
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36 60 Petrie et al., 2013). Such processing must take into account positioning (Rennie and
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38 61 Rainville, 2006) and orientation (Zhao et al., 2014) errors, and the treatment of repeat
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40 62 section measurements (e.g., Szupiany et al., 2007; Jackson et al., 2008).
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47 63 This paper is concerned with recent observations regarding the inference of secondary
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49 64 flows from aDcp data and concerns regarding the assumption that flow is homogenous in
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51 65 the fluid volumes defined by the acoustic beams emitted from an aDcp and used to
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53 66 calculate any one point estimate (Vermeulen et al., 2014b). Acoustic beams are reflected
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3 67 by suspended particles, which, if moving, cause a Doppler shift in beam frequency, which
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5 68 is then detected at the sensor. This shift is directional so each beam measures the radial
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7 69 velocity, which is the velocity of particle motion parallel to the acoustic path. This can be
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9 70 assumed to be the flow velocity if the particle motion is identical to fluid motion. In order
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11 71 to resolve flow in more than one direction, aDcps require at least three acoustic beams to
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13 72 estimate three Cartesian components of velocity. The radial velocities originating from the
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15 73 beams are traditionally analyzed for a single measurement cycle at a single depth at a
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17 74 time (Vermeulen et al., 2014b). The velocity then applies to the volume of fluid defined by
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19 75 the beams at each depth. Flow within this volume is assumed to be homogeneous.
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21 76 However, as the beams spread from the sensor, depth bins increase in horizontal size
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23 77 (Rennie et al., 2002). This means that: (1) bins further from the sensor are likely to produce
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25 78 less reliable velocities because the bin size is greater and the flow within bins is more
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27 79 likely to be heterogeneous (Gunawan et al., 2011); and (2), even in smaller bins, velocities
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29 80 may be less reliable in zones of strong shear where also the within-bin flow is less likely
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31 81 to be homogeneous. In a river where measurements are made throughout the flow depth,
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33 82 the maximum shear may be close to the bed, where the beam divergence may also be
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35 83 greatest.
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43 84 One solution to this problem accounts for first order shear within the flow volume (e.g.
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45 85 Marsden and Ingram, 2004) through a Taylor expansion of the coordinate transform used
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47 86 to determine the Cartesian velocity components. Under this solution, flow is allowed to
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49 87 vary linearly within the bin, but the bin's volume becomes potentially larger with distance
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51 88 from the sensor. Vermeulen et al. (2014b) developed and tested a second solution. As
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53 89 explained in detail below, multiple radial (beam) velocity measurements within a single bin
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3 90 are put through a Cartesian transform to obtain a localized within-bin three-dimensional
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5 91 velocity. This method strongly reduces the volume over which homogeneity should be
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7 92 assumed and Vermeulen et al. (2014b) found that this significantly impacted
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10 93 interpretations of secondary velocities in the presence of strong shear. In this paper, we
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12 94 seek to quantify the effects of this method for the measurement of secondary flow in two
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14 95 medium-sized river junctions (c. 60-80 m post-junction channel width). River junctions are
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17 96 associated with very strong shear (e.g. Best and Roy, 1991; Biron et al., 1993, 1996a,
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19 97 1996b; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004, 2008; Konsoer
20
21 98 and Rhoads, 2014; Sukhodolov et al., 2017), as well as well-developed secondary
22
23 99 circulation (e.g. Ashmore et al., 1992; Rhoads and Kenworthy, 1995, 1998; Rhoads and
24
25
26 100 Sukhodolov et al., 2001; Lane et al., 2008; Riley and Rhoads, 2012; Riley et al., 2015).
27
28 101 Thus, understanding how to process effectively the aDcp data used to describe them is of
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30
31 102 paramount importance.

103 **Methods for estimating Cartesian velocity components from aDcp data**

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37 104 In this section, we describe the two different methodological approaches used in this study
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40 105 to estimate Cartesian velocity components: (1) Method A, the Vermeulen et al., (2014b)
41
42 106 method; and (2) Method B, the conventional method. Common to all methods is the
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44
45 107 assumption that data are available from repeat measurement of the same cross-section,
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47 108 as has been shown to be critical for obtaining reliable estimates of secondary circulation
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49 109 from aDcp data (Szupiany et al., 2007), particularly when single transect measurements
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51 110 are not close enough together.
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3 111 **Method A: based on Vermeulen et al., (2014b)**
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6 112 Application of the Vermeulen et al. (2014b) method requires mapping of radial beam
7
8 113 velocity data onto a predefined mesh. This mesh requires both a bottom topography or
9
10 114 bathymetric model, and an upper limit just below the water surface. As the measurements
11
12 115 were made using several repeat transects for each cross section, the first step is to define
13
14 116 a mean cross section for each set of individual transects (boat tracks). The second step
15
16 117 is to define a grid mesh for this mean cross section. Third, all measured beam velocities
17
18 118 are projected on to this cross section mesh. Finally, the beam velocities within each mesh
19
20 119 ~~grid~~-cell are then used to resolve a Cartesian velocity for the meshgrid cell. Errors that
21
22 120 influence these steps can be estimated.
23
24
25

26
27 121 The first step is estimation of the mesh extremes, both the lower boundary or bathymetry
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29 122 model and the upper boundary near the water surface. To generate the bathymetry model
30
31 123 we use depth soundings collected with the aDcp. We recognize that each beam may
32
33 124 register a different distance of the stream bed from the sounder, especially as we are
34
35 125 dealing with bathymetrically~~largely~~ irregular cross-sections. Specifically, for each bottom
36
37 126 track sounding within each transect, we use the UTM coordinates obtained with a coupled
38
39 127 differential GPS (dGPS), the range of each bottom track beam return, and the instrument
40
41 128 tilt to estimate the bed elevation and horizontal position of each beam impingement point
42
43 129 on the bed. These bed positions are combined together to identify an initial mean transect.
44
45 130 Provided a point is within a certain distance from the initial mean cross-section, LOWESS
46
47 131 interpolation (Appendix A) is applied, which has the effect of defining a bathymetric model
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49 132 that gives most weight to points that appear to be closer to the cross-section. It is important
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51 133 to note that this mean transect is not necessarily orthogonal to the primary flow direction
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3 134 and so will not yield true primary and secondary flow estimates without further correction.

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5 135 We address this below.

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7
8 136 Once the initial bathymetric model is defined, we estimate a unique vector using the initial

9
10 137 mean transect; that is the principal direction of the scatter cloud of all x and y UTM

11
12 138 positions at the bed. This unique vector points in the direction of the largest eigenvector

13
14 139 of the covariance matrix of all UTM positions (t). We then calculate the mean UTM position

15
16 140 (p_{mean}) for each set of individual transects and the difference between each measured

17
18 141 beam position (p_b) and the mean position. The dot product of these obtained values and

19
20 142 the unique vector is then used to define the projection of each UTM position in the direction

21
22 143 of the unique vector. To identify the final mean cross section, we sum up all individual

23
24 144 projected vectors and obtain the best fit to all available data (Figure 1).

25
26
27 145 To define the upper boundary of the mesh, we estimate the elevation of the water surface.

28
29 146 As there is a blanking distance at the surface of the water during the measurement, we

30
31 147 then remove this blanking distance, taken as 0.30 m. Thus, the mesh has also a blanking

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33 148 distance and the upper part of the cross-section is, strictly, the upper limit of available

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35 149 data, not the water surface.

36
37
38 150 “Figure1”

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41 151 The second step uses the defined bathymetric model and available velocity bins within

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43 152 the measured area (not influenced by side lobes, and below the blanking distance) to

44
45 153 define a cross-section mesh. The side-lobe interference is caused by the striking of the

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47 154 channel bed by side-lobe energy from each of the acoustic beams. This side-lobe energy

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49 155 has strong reflections from the bed, which result in echoes that overwhelm the signal from

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3 156 scatters near the bed. The thickness of the side-lobe layer is typically 6-7% of the
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5 157 measured depth (Morlock, 1996).
6
7

8 158 To generate the mesh, the cross section is initially subdivided into vertical slices with equal
9
10 159 widths (Δn). For each slice, the simplest definition of mesh cell thicknesses (Δz) divides
11
12 160 each vertical equally. These verticals are converted to non-dimensional σ coordinates
13
14 161 using following equation:
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16

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18 162
$$\sigma = 1 - \left(\frac{\rho_v \cdot \mathbf{k} - \eta}{\rho_b \cdot \mathbf{k} - \eta} \right) \quad (\text{Vermeulen et al. 2014b}) \quad (1)$$

19
20
21

22 163 where ρ_v stands for velocity measurement positions (m), ρ_b is the corresponding bed
23
24 164 position (m) that is found using velocity measurement horizontal positions and applying
25
26 165 the bathymetric model, \mathbf{k} is the upward pointing unit vector and η are the water surface
27
28 166 fluctuations around the mean water level at which $z=0$.
29
30
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32 167 However, because of beam spreading and differences in the distance of the sounder from
33
34 168 the bed, which varies with position of the sounder, this tends to produce a highly
35
36 169 heterogeneous number of measurements in each cell within the mesh. The alternative,
37
38 170 adopted here, is to allow mesh cell thickness to vary through the water column such that
39
40 171 there is a roughly equal number of beam velocities contributing to each mesh cell (see
41
42 172 Figure 2 for a typical distribution).
43
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45

46 173 As the river bed form is varying, to follow its shape, each mesh cell is considered to be a
47
48 174 cuboid with 6 edges, two on the left side, two in the middle and two on the right side. To
49
50 175 define these edges, the first step is to define the middle point of each mesh cell. Once
51
52 176 defined, by calculating the slope for each half part of the mesh cell, edges can be obtained.
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177 The mesh cell faces are then calculated on the basis of adjacent verticals and the mesh
 178 cell upper and lower boundaries.

179 To identify the beams that contribute to each mesh cell, an index for each beam velocity
 180 is defined, which shows its associated mesh cell, using the projection of each radial
 181 velocity onto the estimated mean cross section (Figure 2).

182 “Figure 2”

183 In the third step, the radial velocities for each beam (**b**) that contribute to each mesh cell
 184 (the N beam velocities) have to be transformed into Cartesian velocities (v_x , v_y and v_z)
 185 using:

$$186 \begin{pmatrix} b_1 \\ \vdots \\ b_N \end{pmatrix} = \begin{pmatrix} q_1 \\ \vdots \\ q_N \end{pmatrix} \cdot \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \leftrightarrow \mathbf{b} = \mathbf{Q} \cdot \mathbf{u} \quad (2)$$

187 where **q** is a unit vector which describes the direction of the acoustic beam.

188 To obtain the raw beam velocities, we use matrix transformations obtained from the raw
 189 data to transform measured velocities in XYZ coordinates into beam velocities. The
 190 Vermeulen et al., (2014b) method includes in the transformations an explicit treatment of
 191 the random errors due to internal and external factors and the bias (systematic errors)
 192 caused by the measurement system and the nature of river flow (Tsubaki et al., 2012).
 193 Random errors include those that come from sampling a time-varying flow in the presence
 194 of strong gradients and represent a form of aliasing. By adding a combined term of errors
 195 ε , (2) becomes:

$$196 \mathbf{b} = \mathbf{Q} \mathbf{u} + \varepsilon \quad (3)$$

197 A least squares solution is fitted to (3) that minimizes the sum of the square of the errors.

198 The optimal estimation ($\hat{\mathbf{u}}$) for (\mathbf{u}) is then given by the normal equation:

$$199 \quad \hat{\mathbf{u}} = \mathbf{Q}^+ \mathbf{b} + \varepsilon \quad (4)$$

200 where \mathbf{Q}^+ can be defined as:

$$201 \quad \mathbf{Q}^+ = (\mathbf{Q}^T \mathbf{Q})^{-1} \mathbf{Q}^T \quad (5)$$

202 To solve three Cartesian velocity components, we need at least three equations. Each
 203 beam measurement in a mesh cell adds an equation. Where enough beam velocities are
 204 collected in a mesh cell and the equations are different from each other (beam velocities
 205 are measured from different directions), the velocity can be estimated. To check whether
 206 this is the case, the matrix describing the system of equations can be analyzed. In the
 207 processing we use the rank which indicates how many unknowns can be solved from the
 208 system of equations. When the rank is three, the three Cartesian velocities can be solved.
 209 Where the rank of the matrix is one or two, the system cannot be solved. Where the
 210 system of equations is overdetermined, the obtained solution is a matrix with more
 211 equations (rows) than unknowns (columns). The velocity can be solved using the
 212 generalized inverse of the matrix and in such a way that the sum of squared errors is
 213 minimized. As this combined term of errors also contains information about the turbulence
 214 and accuracy of the measurements, we can obtain the covariance matrix of the velocity
 215 components:

$$216 \quad \hat{\varepsilon} = \mathbf{b} - \mathbf{Q}\hat{\mathbf{u}} \quad (6)$$

$$217 \quad \text{var}(\hat{\mathbf{u}}) = \frac{\hat{\varepsilon}^T \hat{\varepsilon} (\mathbf{Q}^T \mathbf{Q})^{-1}}{N - 3} \quad (7)$$

218 and the variance of the velocity across the section can be then estimated as:

$$219 \quad \text{var}(\mathbf{u}) = \frac{\text{var}(\hat{\mathbf{u}})}{N}$$

220 (8)

221 **Method B: the standard aDcp method**

222 As the Doppler shift is directional, it can only measure radial velocities. With the standard
 223 method, to determine Cartesian velocity components, radial velocities then have to be
 224 resolved into three orthogonal velocity vectors. To do so, at least three beam velocities
 225 pointed in known directions are required. Also, because the beams are measuring
 226 different water profiles along their individual slant ranges, the assumption of horizontal
 227 homogeneity must be taken into account. Hence, in the standard method, the three
 228 dimensional velocity for each depth bin for each ping can be solved for a typical four-beam
 229 system using the following equations (Mueller and Wagner, 2009):

$$230 \quad V_x = \frac{(b_3 - b_1)}{\sqrt{2} \sin \theta} \quad (9)$$

$$231 \quad V_y = \frac{(b_4 - b_2)}{\sqrt{2} \sin \theta} \quad (10)$$

$$232 \quad V_z = \frac{-(b_1 + b_3)}{(2 \cos \theta)} = \frac{-(b_2 + b_4)}{(2 \cos \theta)}$$

233 (11)

234 where V_y is the cross stream velocity assuming beam 3 is pointed upstream, V_x is the
 235 streamwise velocity, V_z is the vertical velocity, b_1 , b_2 , b_3 and b_4 are the radial velocities
 236 measured in beams 1,2,3 and 4 respectively and θ is the tilt angle of the beams referenced
 237 to vertical. These data should then be corrected for pitch and roll angles, obtained from

1
2
3 238 the internal inclinometer and the heading angle from the internal compass. Velocity
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5 239 outputs are already corrected for ship velocities.
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8 240 To compare results obtained using Method B with those of Method A, we use the same
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10 241 mean cross section built for Method A, as well as the same bathymetric model and the
11
12 242 same mesh. Each measured velocity vector is assigned to the appropriate mesh cell by
13
14 243 projecting its 3D position (horizontal position and depth) onto the mean cross section
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16 244 mesh. We then average x, y, and z components of all velocities measured within a mesh
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18 245 cell to obtain the mean velocity vector for the mesh cell.
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23 246 **Methodology**

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26 247 This paper is motivated by the need to acquire three-dimensional data from junctions of
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28 248 tributaries with a main river stem, here the River Rhône, western Switzerland, and so the
29
30 249 need to identify methods for reliably obtaining Cartesian velocities from aDcp data. The
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32 250 Rhône tributaries typically have very high bedload transport rates for short periods of time,
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34 251 leading to the formation of very large tributary mouth bars downstream of their junctions
35
36 252 with the main river. These bars are maintained for weeks or months such that at lower
37
38 253 tributary flow, with negligible sediment supply, there is a legacy effect of previous high
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40 254 momentum tributary events upon junction morphology and secondary flow formation.
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42
43 255 For this paper, we used a specially-designed rope and pulley system to collect aDcp data
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45 256 from the junction of two tributaries with the Rhône (Figure 3).
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51 257 “Figure 3”
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3 258 The Lizerne is a Rhône tributary of almost 20 km length that flows south-westward from
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5 259 the western slopes of the Tête Noire (2451m) or La Fava (2612m), in the Bernese Alps.
6
7 260 This river is heavily regulated for hydropower with sediment extracted upstream of the
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9
10 261 junction. As a result, there is negligible sediment supply and no evidence of point bar
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12 262 formation. It reaches the Rhône between Ardon and Vétroz, forming a 90° junction angle
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14
15 263 and it has a bed that is nearly concordant with the Rhône.-

16
17 264 The Grande Eau is a second tributary of the Rhône River which has a length of 26 km and
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19
20 265 takes its source on the Vaud side of the Les Diablerets and flows into the Rhône River
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22 266 with a 70° confluence angle, near Aigle. The Grande Eau bed is 1.5 m higher than the
23
24 267 Rhône such that it is markedly discordant. It has a catchment area of 132 km² and the
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26
27 268 maximum monthly runoff occurs in May with an average of 52.5% of total annual runoff
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29 269 occurring during snowmelt in the four months April–July.

30
31
32 270 In this section, we: (1) describe the aDcp used to collect data; (2) describe how the aDcp
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34 271 was deployed; and (3) outline the analytical approaches used to interpret the results from
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36 272 the different methods. Although the method is valid for any aDcp that has an onboard
37
38 273 compass and potential for differential GPS positioning, as is standard with most aDcps,
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40
41 274 we use a Sontek M9 aDcp in this study.

275 ***The Sontek M9 aDcp***

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46
47 276 The SonTek M9 aDcp is a nine-transducer system with three acoustic frequencies,
48
49 277 configured as two sets of four profiling beams (3 MHz and 1 MHz transducers in Janus
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51 278 configurations) and one vertical beam (0.5 MHz Echo sounder) for depth measurements
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54 279 (SonTek YSI, 2010). It uses these two sets of four beams to provide raw radial velocity

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3 280 samples. These beams are equally spaced at 90° azimuth angles and are projected at an
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5 281 angle θ of 25° off the vertical axis (SonTek YSI, 2000). For the standard configuration,
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7 282 the four beams encompass a sampling diameter of 93% of the distance from the aDcp
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9
10 283 (7% of side-lobe) (SonTek YSI, 2000).

11
12
13 284 The output velocities from the SonTek M9 Riversurveyor are either in Cartesian
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15 285 coordinates (XYZ) that are relative to sensor orientation or in Earth coordinates (ENU) for
16
17 286 a SonTek system with compass and tilt sensors. These raw velocity data in Earth
18
19
20 287 coordinates or XYZ coordinates are already corrected for the ship motion. To apply
21
22 288 Method A to Sontek output data, as this method is based on radial velocities, it is
23
24 289 necessary to transform these output velocities to radial velocities. To do so, we add ship
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26
27 290 velocities to these output velocities and then apply the inverses of the instrument's matrix
28
29
30 291 coordinate transformations (obtained from MATLAB files output by the SonTek data
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32 292 collection software RiverSurveyor). As the survey is being undertaken using a moving
33
34 293 vessel, these radial velocities then have to be corrected again for the boat velocity. There
35
36 294 are two key methods for doing this. The first uses the bottom tracking to measure the boat
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38 295 velocity relative to the river bed, under the assumption that the latter is stationary (i.e.
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40 296 there is no bedload transport). The second tracks the boat position using differential GPS
41
42 297 (dGPS, e.g. Zhao et al., 2014). In this study, we corrected all raw beam velocities for ship
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44 298 velocities, using dGPS as we could not exclude the possibility of there being bedload
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46
47 299 transport.

48
49
50 300 To apply Method B in this study, we use the raw velocity data in Earth coordinates and
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52 301 we correct it for pitch and roll angles, obtained from internal inclinometer and heading
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1
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3 302 angle data for the internal compass. For SonTek M9 aDcps, pitch is a y-axis rotation and
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5 303 roll an x-axis rotation.

6
7 304 Depending on the water depth and velocity, the Sontek M9 firmware changes the acoustic
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9
10 305 operating frequency and the water profiling mode on-the-fly, thus the number of **measured**
11
12 306 **cellssampled points** in the vertical varies automatically from one profile to the next.
13
14 307 Specifically, when the water is shallower than 0.75 m and the maximum velocity is less
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16
17 308 than 0.4 ms^{-1} , the M9 reports data acquired with a 3 MHz frequency using the pulse
18
19 309 coherent mode to obtain a 2cm depth measurement resolution. For deeper situations, this
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21 310 frequency changes to 1 MHz pulse coherent pings using a 6cm **aDcp** cell size. If the
22
23 311 maximum velocity is greater than 0.4 ms^{-1} then SmartPulse (i.e., broadband) mode is
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25
26 312 utilized, with the 3 MHz beams if depth is less than 5 m and the 1MHz beams if depth is
27
28 313 greater than 5m, with the **aDcp** cell size optimized based on the current water depth. As
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30
31 314 a result of these on-the-fly changes, each measured profile has a different number of **aDcp**
32
33 315 cells and different **aDcp** cell sizes. Hence, to correct the **aDcp** cell size variability, for both
34
35 316 **m**Methods A and B there is the need to define a cross-sectional mesh and to project the
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37 317 measured velocities to this mesh. For Method A we use the beam velocity vertical
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39
40 318 positions in a non-dimensionalized coordinate system using equation 1, within the
41
42 319 predefined mesh explained in section 2.1.

43 44 45 320 ***Deployment of the Sontek M9 in the river junctions***

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47
48 321 The survey work was undertaken in two junctions of the Swiss River Rhône, the Lizerne-
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50 322 Rhône confluence in August 2017 and the Grande Eau-Rhône confluence in May 2018,
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52 323 using a Sontek M9 vessel mounted aDcp and a specially-designed rope-pulley system
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55 324 (Figure 3c). The survey was spatial, monitoring 11 cross-sections from upstream of the
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3 325 junction to its downstream at the Lizerne-Rhône confluence with a Momentum ratio (Mr)
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5 326 of 0.018 (Figure 3a) and 11 cross-sections at the Grande Eau-Rhône confluence with a
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7 327 Mr of 0.022 (Figure 3b). Table 1 shows the general characteristics of these two
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9 328 confluences on the date of the measurements.

10
11
12
13 329 “Table 1”

14
15
16 330 As proposed previously by Dinehart and Burau (2005), Szupiany et al. (2007), Gunawan
17
18 331 et al. (2011) and Vermeulen et al., (2014b) at least five repeats are required to have a
19
20 332 robust estimation of secondary velocities. Hence, in this paper, data are processed for
21
22 333 cross-section 6 at the Lizerne-Rhône confluence (Figure 3a), and for cross section 3 at
23
24 334 the Grande Eau-Rhône confluence (Figure 3b). Identification of the minimum number of
25
26 335 repeat transects necessary per cross-section was undertaken using cross-section 9 at the
27
28 336 Lizerne-Rhône confluence (Figure 3a), which involves 16 repetitions. We noted that after
29
30 337 application of Method A, the standard deviation of velocity stabilized with six repetitions,
31
32 338 which is the number we adopt for this study. Hence, in this paper, data are processed for
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34 339 cross-section 9, which involves 16 repeat transect surveys (Figure 3a) at the Lizerne-
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36 340 Rhône confluence and for cross section 3, which involves 6 repeat transect surveys
37
38 341 (Figure 3b) at the Grande Eau-Rhône confluence. The decision to use fewer repeat
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40 342 transects at the Grande Eau-Rhône was based upon the identification of the minimum
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42 343 number of cross-sections needed from the Lizerne-Rhône study.
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49 344 ***Bin position error determination***

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51 345 Application of Method A requires estimation of the error terms in (2). The size of the
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53 346 sampling volume in each beam is determined by the size of the bin used. As the SonTek

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3 347 M9 aDcp uses different bin sizes depending on the water track frequency (section 2.1.3),
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5 348 these volumes could vary. Applying Mmethod A might improve the velocity estimation for
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8 349 large measurement volumes at depth, as it does not rely on the homogeneity assumption.
9
10 350 But as bins with a small number of velocity measurements will have greater error, this
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12 351 method can estimate velocities with error. Also, if the beam velocity distribution within
13
14 352 each mesh cell is not linear, as averaging is made in the middle of each mesh cell, it can
15
16
17 353 introduce error in velocity estimation. Thus, it is necessary to calculate a minimum
18
19 354 necessary mesh cell size when applying Mmethod A.

20
21
22 355 Method B is inherently limited by spatial averaging due to the potential use of divergent
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24 356 beams and the associated homogeneity assumption. In other words, one must assume
25
26
27 357 that the velocity is homogeneous over the horizontal domain defined by beam divergence
28
29 358 (Eq.12). Method A has the advantage that velocities are recorded within an individual
30
31 359 beam depth bin, thus no spatial averaging between beams is required. However, in order
32
33 360 for Mmethod A to overcome the uncertainty induced by spatial averaging inherent to
34
35
36 361 Mmethod B, it is essential that the bin location is known explicitly. Error in bin location can
37
38 362 be induced by dGPS position and or tilt sensor (pitch and roll) errors. We therefore
39
40
41 363 compare possible bin position errors using Mmethod A to beam divergence obtained from
42
43 364 Mmethod B to indicate when Mmethod A should be advantageous over Mmethod B.

44
45
46 365 Beam divergence is the spatial separation of the beams due to the Janus configuration of
47
48 366 the beams with beam angles of 25°. This divergence determines the sampling volume that
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50
51 367 must be considered homogeneous for Method B and can be calculated using equation
52
53 368 12:

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56 369 $x_b = 2d \tan \theta$ (12)

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3 370 where d is the depth in m and θ is the beam angle which for a SonTek aDcp is 25° . The
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5 371 aDcp dGPS is used to reference the velocity measurements in space and to estimate the
6
7 372 ship velocity. If dGPS is used for ship velocity, this introduces errors in measurement of
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9
10 373 the absolute water velocity (because ship velocity is subtracted from the water velocity
11
12 374 measured in the reference frame of the aDcp). This uncertainty introduces error in velocity
13
14 375 calculations.

16
17 376 To estimate the errors due to dGPS and the tilt sensors, in this study we assume normally
18
19 377 distributed random errors with a standard deviation of $\pm 1^\circ$ for tilt sensors, based on
20
21 378 manufacturer specifications, and a normally distributed displacement error for measured
22
23 379 by the dGPS for the dGPS positions (as a function of satellite configuration during
24
25 380 measurement), and we apply a Monte Carlo approach which we run 100 times sampling
26
27 381 under these uncertainties. Each time we calculate the estimated secondary velocity
28
29 382 differences as compared with the original secondary velocities.

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33 383 To be able to reduce the uncertainty due to velocity estimation using Mmethod A
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35 384 compared to Mmethod B, the errors induced in Mmethod A related to GPS uncertainty
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37 385 and tilt sensors must be less than the errors in Mmethod B due to beam divergence and
38
39 386 the homogeneity assumption. Hence, Mmethod A can be used if the error associated with
40
41 387 a minimum aDcp cell size is in between the error due to beam divergence and the
42
43 388 maximum estimated error due to the GPS and tilt sensors. Otherwise using this method
44
45 389 introduces more error in velocity estimations than using Mmethod B.

390 ***Data interpretation***

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52
53 391 Methods A and B, described above, were applied to the Sontek M9 data, to determine
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55 392 Cartesian velocities (v_x , v_y and v_z). As our interest is in process estimation, here we

393 describe the methods we apply to the Cartesian velocities to estimate processes relevant
 394 to junction dynamics. In order to distinguish between primary and secondary components
 395 of flow, we need to rotate the initial mean transect. Options for doing this are reviewed in
 396 Lane et al. (2000) and we do not assess them here, but rather apply the zero net
 397 cross stream discharge definition (Lane et al., 2000). By calculating the mean values of
 398 the x and y velocity components (U and V), we then calculate the velocity magnitude (v).
 399 By rotating these velocity components to the direction of the cross-stream velocity, using
 400 the unique vector (σ), primary velocity vectors (\mathbf{v}_p) and secondary velocity vectors (\mathbf{v}_s)
 401 then can be estimated.

$$402 \quad v = \sqrt{U^2 + V^2}$$

403 (13)

$$404 \quad \begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} U \\ V \end{pmatrix} / v \quad (14)$$

405 where σ_x and σ_y are sin and cos of the angle between the section angle and east.

$$406 \quad \mathbf{v}_p = \sigma_x \mathbf{v}_x + \sigma_y \mathbf{v}_y \quad (15)$$

$$407 \quad \mathbf{v}_s = -\sigma_y \mathbf{v}_x + \sigma_x \mathbf{v}_y \quad (16)$$

408 However, secondary circulation is all flow that is orthogonal to the primary flow and not
 409 just horizontal flow; there should be not net secondary flux in a section; and so correction
 410 should also consider vertical velocities. ~~this rotation does not account for the possibility~~
 411 ~~that there is net vertical motion in a section, which is also a component of secondary~~
 412 ~~circulation.~~ Thus, we extend these relationships to include vertical velocities:

$$413 \quad \begin{pmatrix} \sigma_{x,1} & \sigma_{x,2} & \sigma_{x,3} \\ \sigma_{y,1} & \sigma_{y,2} & \sigma_{y,3} \\ \sigma_{z,1} & \sigma_{z,2} & \sigma_{z,3} \end{pmatrix} = \begin{pmatrix} U \\ V \\ W \end{pmatrix} / v \quad (17)$$

414 where: U , V and W are the mean velocities of x , y and z velocity components, respectively

415 and v is the magnitude of the velocity which can be obtained using:

$$416 \quad v = \sqrt{U^2 + V^2 + W^2} \quad (18)$$

$$417 \quad \mathbf{v}_p = \sigma_{x,1}\mathbf{v}_x + \sigma_{x,2}\mathbf{v}_y + \sigma_{x,3}\mathbf{v}_z$$

418 (19)

$$419 \quad \mathbf{v}_s = \sigma_{y,1}\mathbf{v}_x + \sigma_{y,2}\mathbf{v}_y + \sigma_{y,3}\mathbf{v}_z$$

420 (20)

$$421 \quad \mathbf{v}_v = \sigma_{z,1}\mathbf{v}_x + \sigma_{z,2}\mathbf{v}_y + \sigma_{z,3}\mathbf{v}_z$$

422 (21)

423 To estimate velocity gradients, and to correct for weak curvature with the survey method

424 at the edges of each transect line (e.g. Figure 3), solve the curvature of cross sections, all

425 data have been transformed into row and column coordinates (η and ζ) using the following

426 transformation:

$$427 \quad \begin{pmatrix} \frac{\partial}{\partial n} \\ \frac{\partial}{\partial z} \end{pmatrix} = \begin{pmatrix} \frac{\partial \eta}{\partial n} & \frac{\partial \zeta}{\partial n} \\ \frac{\partial \eta}{\partial z} & \frac{\partial \zeta}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial \eta} \\ \frac{\partial}{\partial \zeta} \end{pmatrix} \quad (22)$$

428 where n and z are horizontal and vertical coordinates on the section plane, respectively

429 (Vermeulen et al., 2014b).

430 Results

431 *Primary and secondary velocities*

432 Primary and secondary velocities estimated using mmethods A and B for the Lizerne-
433 Rhône confluence appear to be similar at cross-section 6 (Figures 4a and 4b) and the
434 differences in estimated secondary flows are minor. The differences are most pronounced
435 between --10 and -5 m, in the middle of the main channel, ,the differences in secondary
436 velocity vectors are more pronounced.

437 These primary and secondary velocity patterns show higher differences at cross-section
438 3 of the confluence of Grande Eau-Rhône (Figures 4c and 4d) despite it having a similar
439 momentum ratio to the Lizerne during measurement. Primary velocities differ significantly
440 between mmethods A and B: (1) at greater distance from the aDcp because the bins
441 contain larger volumes of water assumed to be homogenous; and (2) at the edges of the
442 cross-section where there are more beam velocity measurements (contours in Figures 4c
443 and 4d). Secondary velocity vectors estimated using Mmethod A indicate flow
444 convergence at the surface and flow descending towards the riverbed throughout the
445 centre of the channel (Figure 4c). This is due to a high degree of bed discordance between
446 the Grande Eau and the Rhône, which increases the penetration of the tributary flow into
447 the main channel above over the junction, which and which forms a zone of high lateral
448 and vertical shear, on the one hand, and main channel narrowing because of penetration
449 of the tributary point-mouth bar on the other hand. The secondary velocity vectors
450 estimated by Mmethod B show a weaker penetration of the tributary flow into the main
451 channel, which results in a reverse flow towards the bank on the inner-tributary bank-side
452 of the channel at the surface of the mixing interface (Figure 4d). In this case, the core of

1
2
3 453 the secondary circulation is located in the middle of the main channel and closer to the
4
5 454 inner bank.
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7

8 455 "Figure 4"
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10
11 456 Figure 5 and Figure 6 quantify the differences in primary and secondary velocity patterns
12
13 457 estimated using mm methods A and B, for the Lizerne-Rhône confluence. Figures 5a and
14
15 458 5c and Figures 6a show that almost 4% of mesh cells have a relative difference in primary
16
17 459 velocities between mm methods A and B of more than 10%. These differences can exceed
18
19 460 0.2 ms⁻¹ and so they are relatively small. Velocity differences are more pronounced in
20
21 461 estimated secondary velocities, with almost 82% of mesh cells having a difference of more
22
23 462 than 10%, and almost 37% of mesh cells having a difference of more than 50% (Figure
24
25 463 5b, 5d and 6b).
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30 464 "Figure 5"
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32
33 465 "Figure 6"
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36 466 At the Grande Eau-Rhône confluence, these differences are greater as compared with
37
38 467 those of the Lizerne-Rhône confluence. Figures 7a, 7c and 8a show that these differences
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40 468 for primary velocities exceed 0.4 ms⁻¹ in the zone of high vertical and lateral shear and
41
42 469 near the inner bank. Almost 20% of the mesh cells have a relative difference in primary
43
44 470 velocities between mm methods A and B of more than 10%. The secondary velocity
45
46 471 differences are more pronounced between these two methods. Figures 7b and 7d show
47
48 472 differences with a magnitude of 0.4 ms⁻¹ near the edges and near the bed. Almost all the
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50 473 mesh cells have a difference in estimated secondary velocities between two methods.
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52
53 474 Figure 8b shows that almost 93% of the mesh cells have a relative difference of 10%
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3 475 between ~~m~~methods A and B. although this value decreases to 55% for a relative
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5 476 difference of 90% between these two methods.
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8 477 "Figure 7"
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11 478 "Figure 8"
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14 479 ***Velocity gradients*** 15

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17 480 As Figure 9 shows, there is a strong relationship between lateral gradient in secondary
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19 481 velocities and differences between the secondary velocities estimated using methods A
20
21 482 and B for both the Lizerne-Rhône and the Grande Eau-Rhône confluences. This is
22
23 483 because a stronger velocity gradient increases the probability that the assumption of flow
24
25 484 homogeneity within a bin is likely to fail. Indeed, the marked differences between methods
26
27 485 A and B at the Grande Eau confluence (Figure 7) in the true right secondary circulation
28
29 486 cell describe above are also in a zone of strong lateral shear.
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33

34 487 "Figure 9"
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37 488 ***Number of repeat transects*** 38

39 489 One way to reduce data fluctuations due to random errors and turbulence, during the
40
41 490 measurement using moving vessel aDcps, is to average by using several repeat transects
42
43 491 together in one cross section. As each estimated velocity measurement is a single sample
44
45 492 in time, adding in a repeat section adds in an additional estimated velocity measurement.
46
47 493 Under [8], this should cause the variance to increase, despite the number of
48
49 494 measurements used in its estimation increasing, until the point at which there are enough
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51 495 repeats to capture the effects the range of scales of variation in turbulence impacting the
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53 496 measurement. Then, this variance will become stable. At this stage we can consider the
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2
3 497 number of repeats as the minimum number required to have a robust estimation of
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5 498 secondary velocity vectors that is to have reached estimates of velocity that are
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7
8 499 asymptotic on this stable state.

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10 500 Here we apply both methods A and B to the survey of 16 repeats at cross-section 9 in
11
12 501 Figure 3a at the Lizerne-Rhône confluence. To allow a reasonable comparison, three
13
14 502 mesh cells in the middle of the cross section, and at three different depths (near the
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16
17 503 surface, middle depth and near the bed) have been chosen (Figure 11). Results show
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19 504 that by using Mmethod A, after six repeats, a stable variance of the velocity estimator is
20
21 505 obtained at the Lizerne-Rhône confluence (Figure 11a). Many more repeats are needed
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23 506 using Mmethod B (Figure 11b) and this is likely because Method B uses fewer
24
25 507 measurements per mesh cell. These results also show a higher standard deviation of the
26
27 508 velocity estimation near the surface, using Mmethod A and before achieving the stable
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29 509 situation. This can be explained by the fact that near the surface Mmethod A is more
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31 510 sensitive to errors caused by positioning, while near the bed, hence with distance from
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33 511 the sounder, as the beam spread increases, the improvement obtained using Mmethod A
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35 512 is more pronounced (Figure 11a).

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39 513 “Figure 10”

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41
42 514 “Figure 11”

43 44 45 515 ***DGPS and tilt sensor uncertainty analysis***

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48 516 As explained above a normally distributed random error has been applied 100 times to
49
50 517 both dGPS positioning (by adding a random offset) and tilt sensors (by changing pitch and
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52 518 roll angles randomly) and the secondary velocities have been estimated using Mmethod
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54 519 A for each perturbed dataset. As Figure 12 shows, the magnitude of errors related to
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3 520 dGPS accuracy are higher than those related to tilt sensor accuracy, for both confluences.
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5 521 These values can reach $\pm 0.03 \text{ ms}^{-1}$ and confirms the earlier finding of Rennie and Rainville
6
7 522 (2006) which showed that GPS corrections can have average errors of about $\pm 0.03 \text{ ms}^{-1}$
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9
10 523 (Figures 12a and 12c). These magnitudes are also higher near the surface and near the
11
12 524 bed for the Lizerne-Rhône confluence (Figure 12a). Near the surface, as there ~~is a greater~~
13
14 525 ~~random error due to ship movements~~ fewer measurements that can contribute to the
15
16 526 estimation of aDcp position and tilt, uncertainties in dGPS data will have a ~~larger~~ greater
17
18 527 ~~effect on a bad velocity estimation~~. Near the bed, as the velocity gradient is higher, errors
19
20 528 will be greater as well. Figure 12c shows higher magnitudes near the surface at cross-
21
22 529 section 3 in Figure 3b for the Grande Eau-Rhône confluence.
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26 530 Errors related to tilt sensor uncertainty are higher where there is a higher velocity gradient.
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28 531 This is related to the fact that within the mesh cells with higher velocity gradients, as the
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30 532 velocity distribution is not linear, and as averaging is made in the middle of the mesh cell,
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32 533 it is more probable that the velocity will be affected by sensor inaccuracies of bin
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34 534 positioning, and so be in error (Figures 12b and 12d).
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39 535 “Figure 12”
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42 536 ***Homogeneity assumption analysis***

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45 537 Figure 13 shows the maximum inhomogeneity allowance, using Mmethod B for both case
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47 538 studies. These results are obtained by dividing the velocity gradient obtained from
48
49 539 equation 22 by the divergence of the beams from equation 12. They confirm that, for the
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51 540 homogeneity assumption to be valid and thus error to be minimized using Mmethod B, the
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53 541 maximum emesh cell size, which can be used is as small as 5cm near the bed. Clearly,
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3 542 this is impossible as the configuration of the beams using aDcps always results in beam
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5 543 divergence greater than 5cm.
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8 544 "Figure 13"
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11 545 ***Primary and secondary flow patterns***
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14 546 In this section, we compared estimated primary and secondary velocities using methods
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16 547 A and B for other cross sections in Figure 3 for both river confluences.
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18

19 548 Figure 14 shows the results for cross sections 4, 5 and 7 (in Figure 3a) at the Lizerne-
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21 549 Rhône confluence. These cross sections also show similar results in primary and
22
23 550 secondary velocity patterns for both methods A and B. Figure 15 shows different patterns
24
25 551 in primary and secondary velocities estimation using Mmethod A and B for cross sections
26
27 552 4,6 and 8 in Figure 3b at the Grande Eau-Rhône confluence. Method A ~~produces leads~~
28
29 ~~to the identification of a~~ stronger and more coherent tributary penetration at cross-section
30
31 553 4 and weaker upwelling mid-channel, giving the impression of less intense secondary
32
33 554 circulation (Figure 15). At section 6, flow towards the true left across the shallow ~~top of~~
34
35 555 ~~the tributary point-mouth~~ bar ~~top~~ is ~~maintained-identified~~ and is coherent with Mmethod A.
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37 556
38 557 At the channel-scale there is general flow convergence reflecting channel narrowing
39
40 558 (Figure 15). ~~When using~~ Mmethod B, these patterns are less coherent and flow is
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42 559 towards the true right in the vicinity of the ~~point-tributary mouth~~ bar. These patterns are
43
44 560 repeated for section 8 (Figure 15).
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50 561 "Figure 14"
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53 562 "Figure 15"
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563 Discussion

564 In this paper we used data collected with boat-mounted aDcp technology at two
565 confluences of the Swiss river Rhône, both with similar and very low momentum ratios
566 (0.018, 0.022) and analysed these using two different methods, A and B, to estimate
567 Cartesian velocity components. Method A is based on a methodological approach
568 developed by Vermeulen et al. (2014b). It differs by treating explicitly each individual beam
569 velocity based on its position within a predefined mesh. Results show that this method
570 reduces the volume over which the flow must be assumed to be homogenous (Fig 13). It
571 can, but not necessarily does, result in differences in estimated primary and secondary
572 velocities as compared with the more traditional method (B in this study), that involves
573 determining velocities by averaging data from the spreading beams. Our results show that
574 these differences are more pronounced in estimated secondary velocities than primary
575 velocities and are higher where there is a greater lateral velocity gradient (Figure 9). The
576 comparison between the two case studies shows that even though both confluences have
577 a very low momentum ratio, as the confluence of the Grande Eau-Rhône has a more
578 intense complex lateral-shear zone, likely due to the effects of bed discordance, and there
579 are more significant differences in the estimation of primary and secondary velocities. This
580 is related to the extent to which spreading of the aDcp measurement beams influences
581 the secondary velocities, particularly in relation to lateral gradients in flow conditions. More
582 standard methods (~~M~~method B in this study) are valid if the flow is completely
583 homogenous over the diameter of the fluid column that the beams spread. This diameter
584 varies over depth and is largest near the bed. In the case of the Grande Eau-Rhône
585 confluence where stronger lateral velocity gradients exist in the flow, individual beams will

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3 586 not be measuring homogenous conditions, particularly near the bed and in the zone of
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5 587 high shear near the inner bank, because the spread of the beams may be greater in
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8 588 diameter than the width of the zone of lateral velocity variation. In this case, as Mmethod
9
10 589 A involves less spatial-averaging than Mmethod B, it may can provide more accurate
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12 590 information on the flow behavior, but such a conclusion really needs a third and
13
14 591 independent method to confirm it. At the Lizerne-Rhône confluence, even though the
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16
17 592 momentum ratio is similar to Grande Eau-Rhône confluence, there is only more localized
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19 593 lateral shear in the flow and a simplified shear zone, (Figure 9). In such a situation, and
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21 594 using Mmethod B to detect the large scale patterns of secondary flow may be more
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23
24 595 advantageous, because it involves more spatial averaging.

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26
27 596 The above discussion suggests that whether or not high rates of lateral shear influence the
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29 597 need to adopt potential importance of Method A depends on distance from the aDcp: with
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31 598 more divergence at greater depths, lower levels of lateral shear are likely to be acceptable.
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33
34 599 Figures 16a and 16b quantifies the relationship between lateral velocity gradient, depth
35
36 600 and the magnitude of the relative differences in secondary velocities estimated using
37
38 601 methods A and B for the cross-section 6 of the Lizerne-Rhône and cross-section 3 of the
39
40 602 Grande Eau-Rhône confluences, respectively. At the Lizerne-Rhône confluence, as the
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42
43 603 zone of high lateral shear is absent, even though there is a strong relationship between
44
45 604 the magnitude of the relative differences in secondary velocities estimated using methods
46
47 605 A and B and the depth (Figure 16a), their relationship with the lateral velocity gradients is
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49
50 606 poor. In contrast, not as clear as for the case of the Grande Eau-Rhône confluence (Figure
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52 607 16b), where increasing the lateral velocity gradient and depth results in higher relative
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55 608 differences in secondary velocities. Thus, the need to use Mmethod A will depend on the

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3 609 case being used and the extent to which there is lateral shear at greater distances from
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5 610 the aDcp. This is why whilst it may be tempting to introduce some kind of shear or velocity
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7 611 gradient threshold to identify when Method A might be preferable, to do so would be
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9 612 misleading as the threshold will also depend on the distance of the shear from the aDcp.
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11
12 613 “Figure 16”
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15 614 Results also confirm that several repeat transects are indispensable to provide a robust
16
17 615 estimation of secondary circulation and to reduce the effect of spatial inhomogeneity and
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19 616 temporal variations. Although ~~M~~method A reduces the minimum number of repeat
20
21 617 transects needed to estimate the secondary velocities, a larger number of these minimum
22
23 618 repeat transects (6 or more repeats for Lizerne-Rhône confluence) appeared to be
24
25 619 required. This is higher than in the, compared to earlier findings of Szupiany et al. (2007)
26
27 620 and Vermeulen et al., (2014b) who argue that 5 repeats are enough to have a robust
28
29 621 estimation of the turbulence averaged velocity. We also note that an even number of
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31 622 repeats may be important to avoid directional bias in dGPS positions.
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36 623 ~~As aDcp data obtained from multiple transects are notoriously noisy, another approach to~~
37
38 624 ~~averaging involves post-processing that takes binned data estimated from multiple~~
39
40 625 ~~transects, and averaging these data through spatial smoothing. This is adopted in the~~
41
42 626 ~~Velocity Mapping Toolbox (VMT) (Parsons et al., 2013). The VMT maps ensembles onto~~
43
44 627 ~~the mean straight cross-section and interpolates each one of these grid nodes using linear~~
45
46 628 ~~interpolation. The bed profile is estimated using the mean of the four beams. These~~
47
48 629 ~~projected and interpolated velocity data from each set of transects are averaged using a~~
49
50 630 ~~simple arithmetic averaging, at every grid node, to provide a composite representation of~~
51
52 631 ~~the velocity field. Once the averaging is complete for all the nodes, a coordinate~~
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3 632 transformation is applied to transform Earth velocity components into velocity components
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5 633 in the plane of the cross section (U, V and W) (Parsons et al., 2013). The VMT can also
6
7 634 use a smoothing window which is a moving average and it averages every velocity vector
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9
10 635 with its nearest neighbor. The user can define the horizontal and vertical smoothing
11
12 636 window size.

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14
15 637 It was not the aim of this paper to evaluate the specific VMT method, but to put our
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17 638 comparison of Methods A and B into context, Figure 17a shows results obtained for
18
19 639 primary and secondary velocities for the VMT, at cross section 6 in Figure 3a at the
20
21 640 Lizerne-Rhône confluence, that is comparable with Figures 4a and 4b for our Methods A
22
23 641 and B. The pattern of primary and secondary velocities are similar to each other for all
24
25 642 three methods (Figures 17a, 4a and 4b). Although the VMT results have been obtained
26
27 643 using a horizontal and vertical smoothing window sizes of 2, they are not as coherent as
28
29 644 the results obtained using methods A and B, suggesting that using the VMT requires more
30
31 645 repeat transects or more repeat stationary measurements.

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36 646 Figure 17b shows primary and secondary velocities estimated using the VMT for cross-
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38 647 section 3 in Figure 3b at the Grande Eau-Rhône confluence. Again, as the VMT uses a
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40 648 straight mean cross section, estimated velocities are not as coherent as those of method
41
42 649 A and B (Figures 4c and 4d).

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46 650 “Figure 17”

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49 651 Since Mmethod A is based on the position of beams, if the bin position errors related to
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51 652 dDGPS accuracy as well as sensor tilt are greater than homogeneity errors associated
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53 653 with beam divergence, standard Mmethod B is more reliable. This is likely to be the case

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2
3 654 particularly ~~the case~~ in rivers smaller shallower than those studied here rivers and where
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5 655 high resolution is required due to large velocity gradients. In ~~big rivers~~ of the scale studied
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7 656 here, and deeper, by increasing the mesh cell size, we can still have sufficient data to
8
9 657 estimate velocity vectors, and the ~~errors related to effects~~ dGPS and tilt sensor errors have
10
11 658 a minor effect. –This confirms the earlier findings by Vermeulen et al., (2014b), which
12
13 659 showed that Method A provides the greatest improvement where the aDcp cell size is
14
15 660 much smaller than the beam spread. We are not yet in a position to identify the depth at
16
17 661 which Method A becomes preferable to Method B, and again this will depend on other
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19 662 parameters such as the intensity of shear and so may not be readily generalizable
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21 663 between confluences.

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23
24 664 The difficulty of identifying the depths of rivers and intensities of shear that make one
25
26 665 method preferable over another precludes adoption of simple quantitative guidance on
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28 666 which method to use when. As both methods have some disadvantages, we argue that
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30 667 both methods should be applied. If they give similar results, then there should be
31
32 668 confidence in both. If and where they differ, analysis should be undertaken to identify why,
33
34 669 and hence which method is likely to be preferable. Association of the differences in
35
36 670 primary and secondary velocities inferred between the two methods with estimates of
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38 671 shear intensity and with estimated tilt and positioning errors should then help decide
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40 672 whether Method A or Method B is preferable in a particular case. This preference may
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42 673 vary between confluences but also through time at a confluence, if shear or flow depth
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44 674 changes significantly between survey dates.

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47 675 Finally, we wish to emphasise that the impact of averaging is only one element that must
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49 676 be considered in obtaining reliable primary and secondary flow estimates in river
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3 677 confluences. Other issues, such as the rotation method needed to distinguish primary and
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5 678 secondary circulation, remain important and should be considered routinely.
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8 9 679 **Conclusions**

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12 680 This paper shows the advantage of working with the radial (beam) velocity measurements
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14 681 of an aDcp within each bin prior to averaging them across a given volume of fluid
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16 682 (Mmethod A) as opposed to identify volumes of fluid and assuming bend homogeneity
17
18 683 within them (mmethod B). Such a treatment is important where there are strong velocity
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20 684 gradients in the flow as with river channel confluences. In the first of our case-study
21
22 685 confluences, the Lizerne-Rhône, a very small tributary joined the main river, and the
23
24 686 pattern of primary and secondary velocities obtained with methods A and B were relatively
25
26 687 similar, more so for primary velocities. But for a second confluence, the Grande Eau-
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28 688 Rhône, with a similar momentum ratio, there were much larger differences. We attributed
29
30 689 this to the formation of much stronger shear at this confluence. Method A also appeared
31
32 690 to reduce the number of repeat transects needed to estimate secondary velocities reliably.
33
34 691 The main downside is that Mmethod A is more sensitive to errors related to positioning.
35
36 692 Thus, good dGPS accuracy and precision are required to perform a robust estimation of
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38 693 velocity.
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45 694 In smaller/shallower rivers, Method B may be acceptable indeed preferable as it is less
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47 695 sensitive to GPS errors. In larger rivers, Method A may be necessary, especially in the
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49 696 presence of strong shear at the confluence. Choice between these mMethods should be
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51 697 based upon an initial screening of the extent to which there is strong shear in the flow as
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53 698 well as the extent to which bins further from the aDcp are influenced by beam divergence.
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699 **Appendix A**

700 The LOWESS model is a locally weighted polynomial regression, which at each point and
701 in the range of dataset, a low degree polynomial is fitted to a subset of the data, using
702 weighted least squares. This polynomial fit gives more weight to points closer to the point
703 whose response is being estimated. The value of the regression function for the point is
704 then obtained by evaluating the local polynomial using the explanatory variable values for
705 that data point. The LOWESS fit is complete after regression function values have been
706 computed for each of the n data points. Many of the details of this method, such as the
707 degree of the polynomial model and the weights, are flexible (“Local regression,” n.d.).

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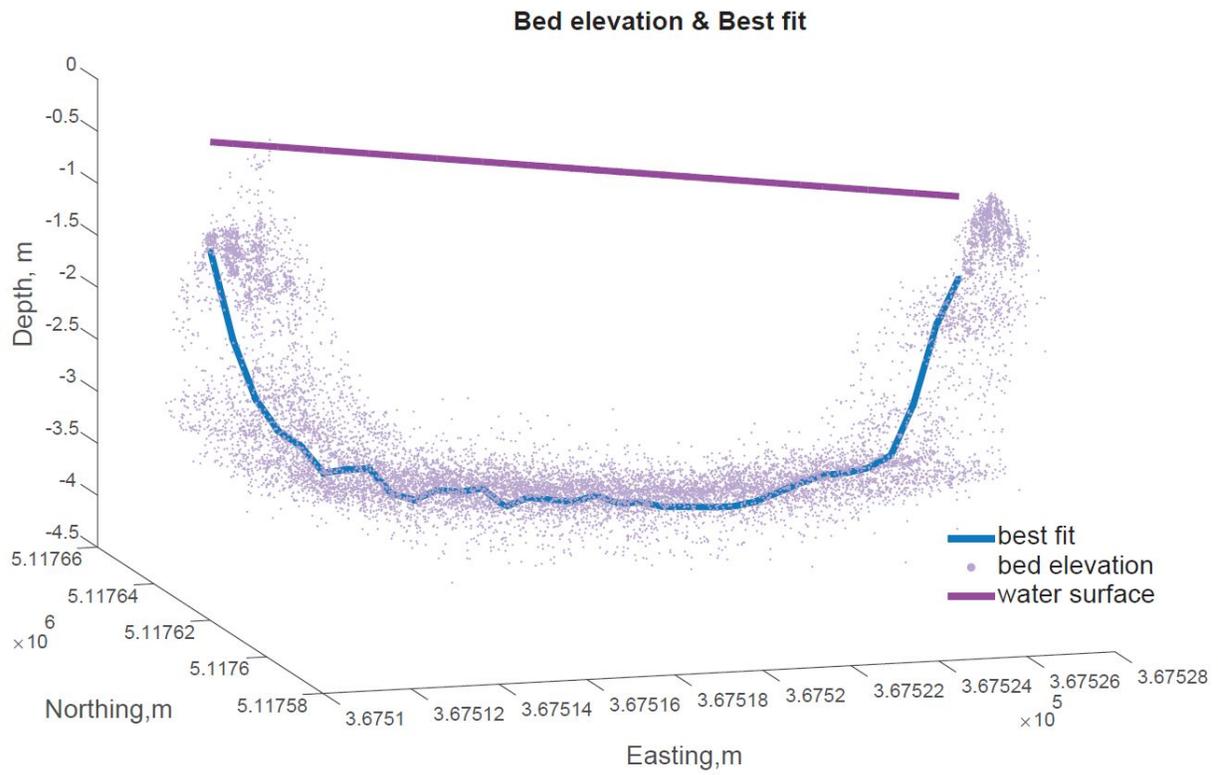
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Sites	Lizerne	Grande eau
Tributary upslope contributing area (km ²)	64.8	132
Main stem upslope contributing area (km ²)	3401	5088
Basin area ratio	1.89%	2.59%
Tributary width (m)	6.5	16.5
Main stem width upstream of junction (m)	46	58
Width ratio	0.15	0.28
Junction angle (°)	80	70
Tributary Froude number	0.32	0.05
Bed slope of the tributaries upstream of the confluence (%)	~0.5	0.5-1
Main stem slope upstream of the confluence (%)	2	2.2
Tributary slope (°)	33.1	26.6
<u>Rhône discharge during measurement (m³s⁻¹)</u>	<u>182</u>	<u>300</u>
<u>Tributary discharge during measurement (m³s⁻¹)</u>	<u>4</u>	<u>8.13</u>
Discharge ratio during measurement	0.022	0.027
Momentum ratio (Mr) during measurement	0.018	0.022

Table 1: Selected upper Rhône tributaries with their typical characteristics

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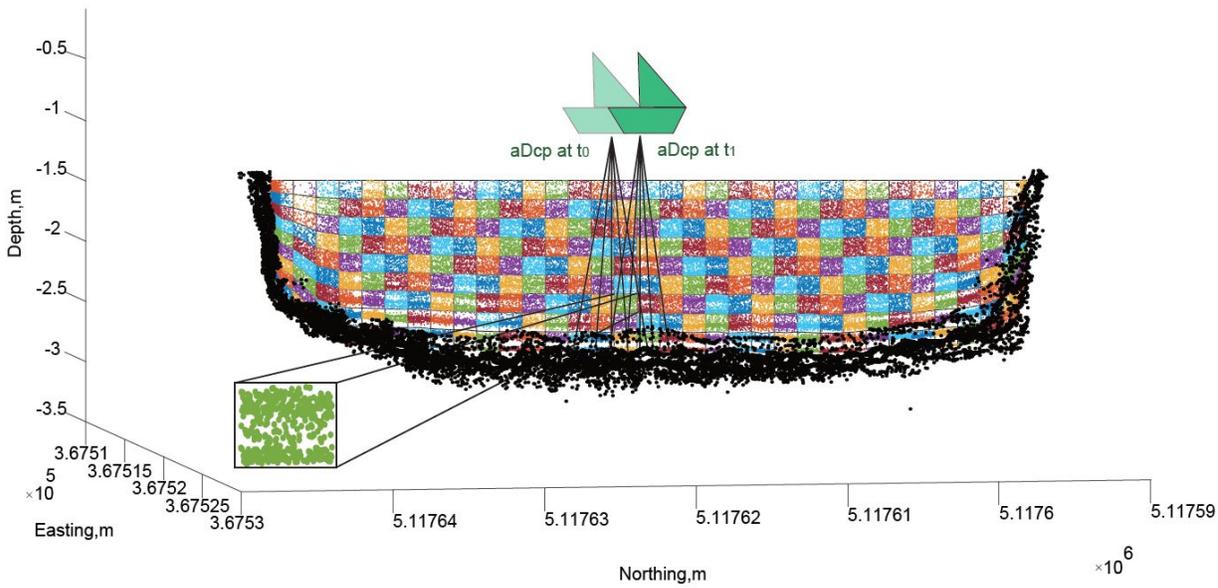


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Figure 1: Bed elevations, the best fit to those elevations and the water level representation

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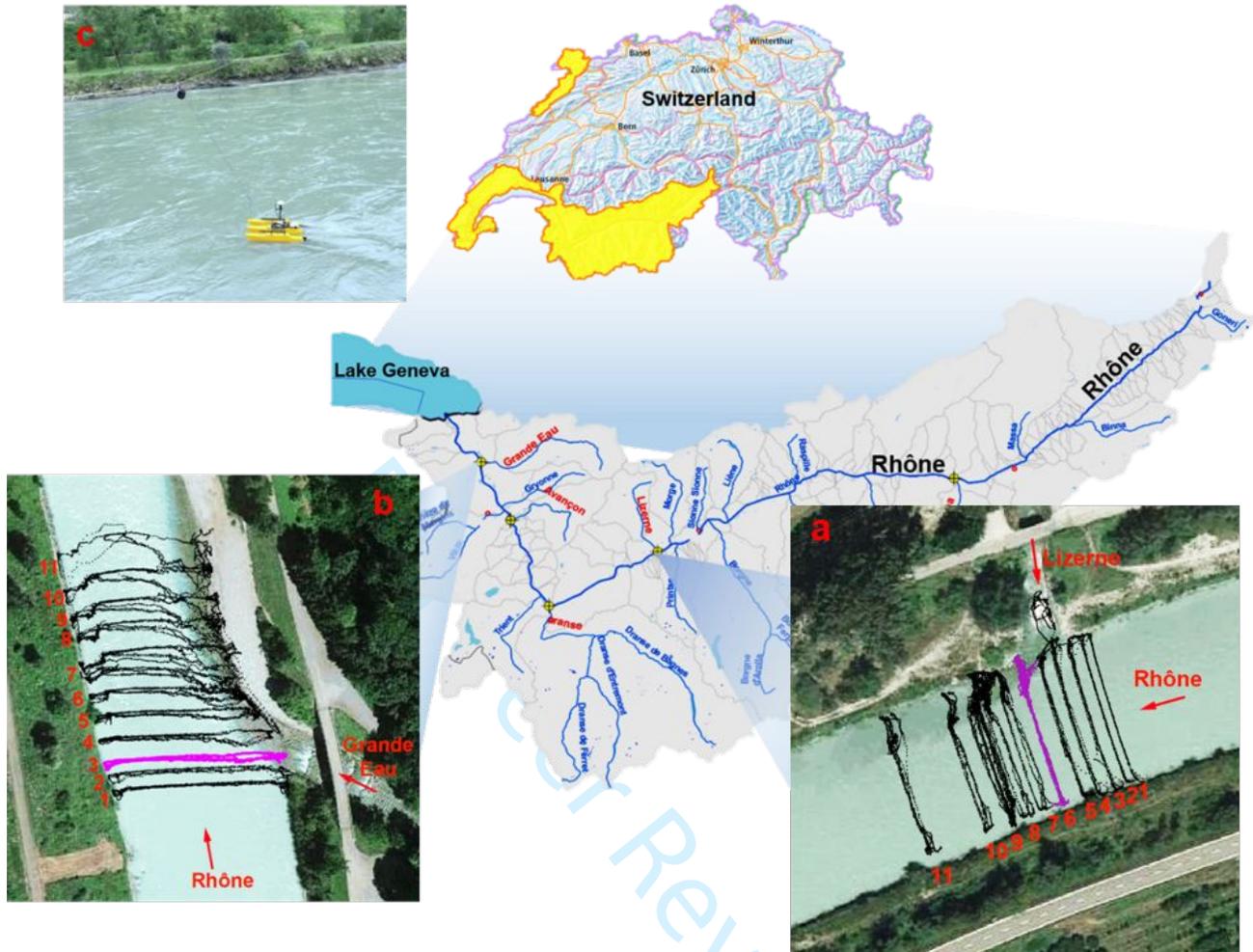


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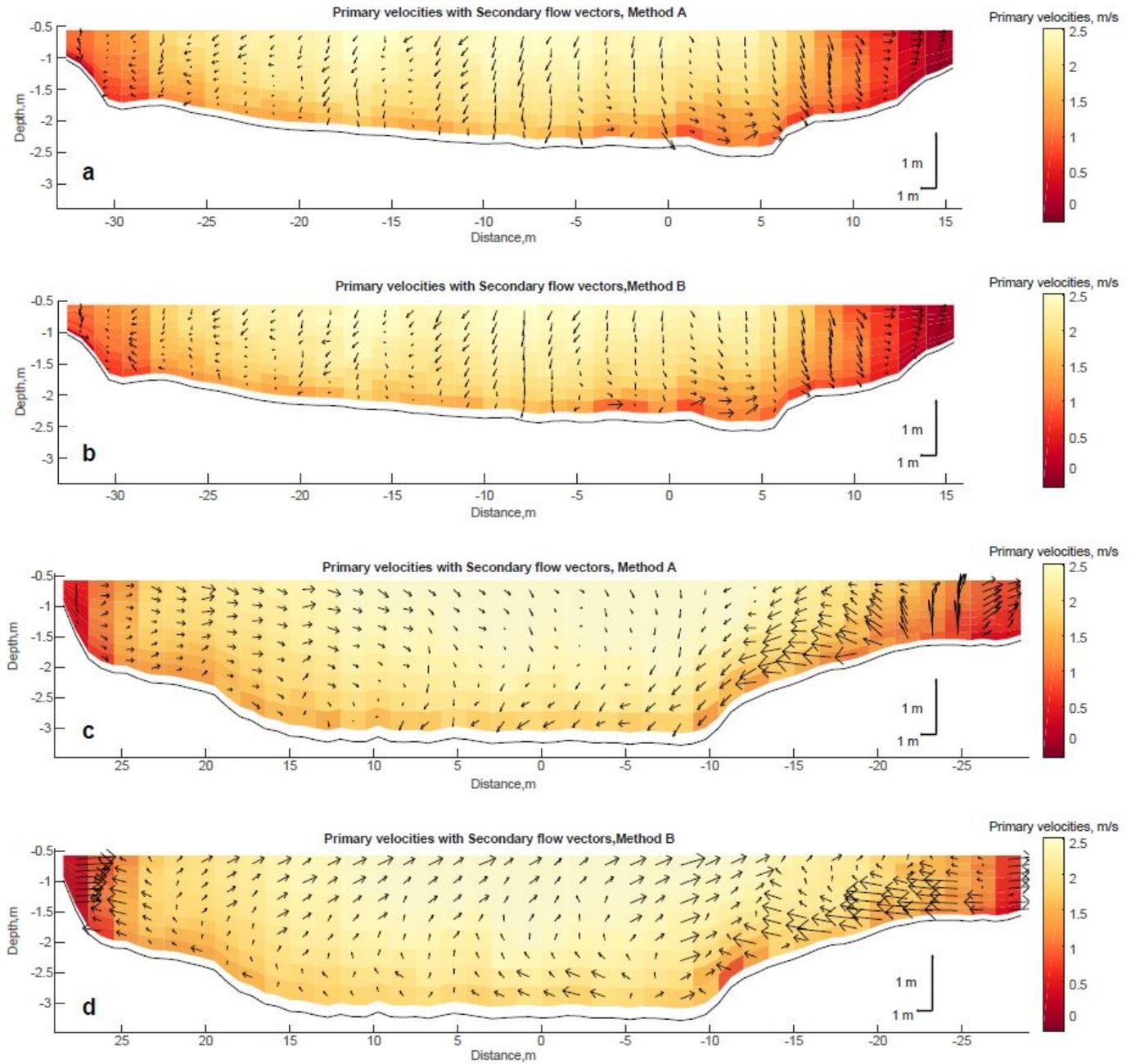
Figure 2: An example of beam velocity positioning within each mesh cell, using *Mmethod A*, dots show beam velocities and color is an automatic Matlab function to distinguish between different *mesh* cells

Peer Review



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873 *Figure 3: Tracks navigated by SonTek aDcp moving boat system at a) Lizerne-Rhône confluence near Vétroz, at*
 874 *07/07/2017 and b) Grande Eau-Rhône confluence near Aigle at 23/05/2018. The repeated transect data assessed in*
 875 *this paper are from cross-section 6 at the Lizerne-Rhône confluence a and cross-section 3 at the Grande Eau-Rhône*
 876 *confluence and c) Rope-Pulley system*



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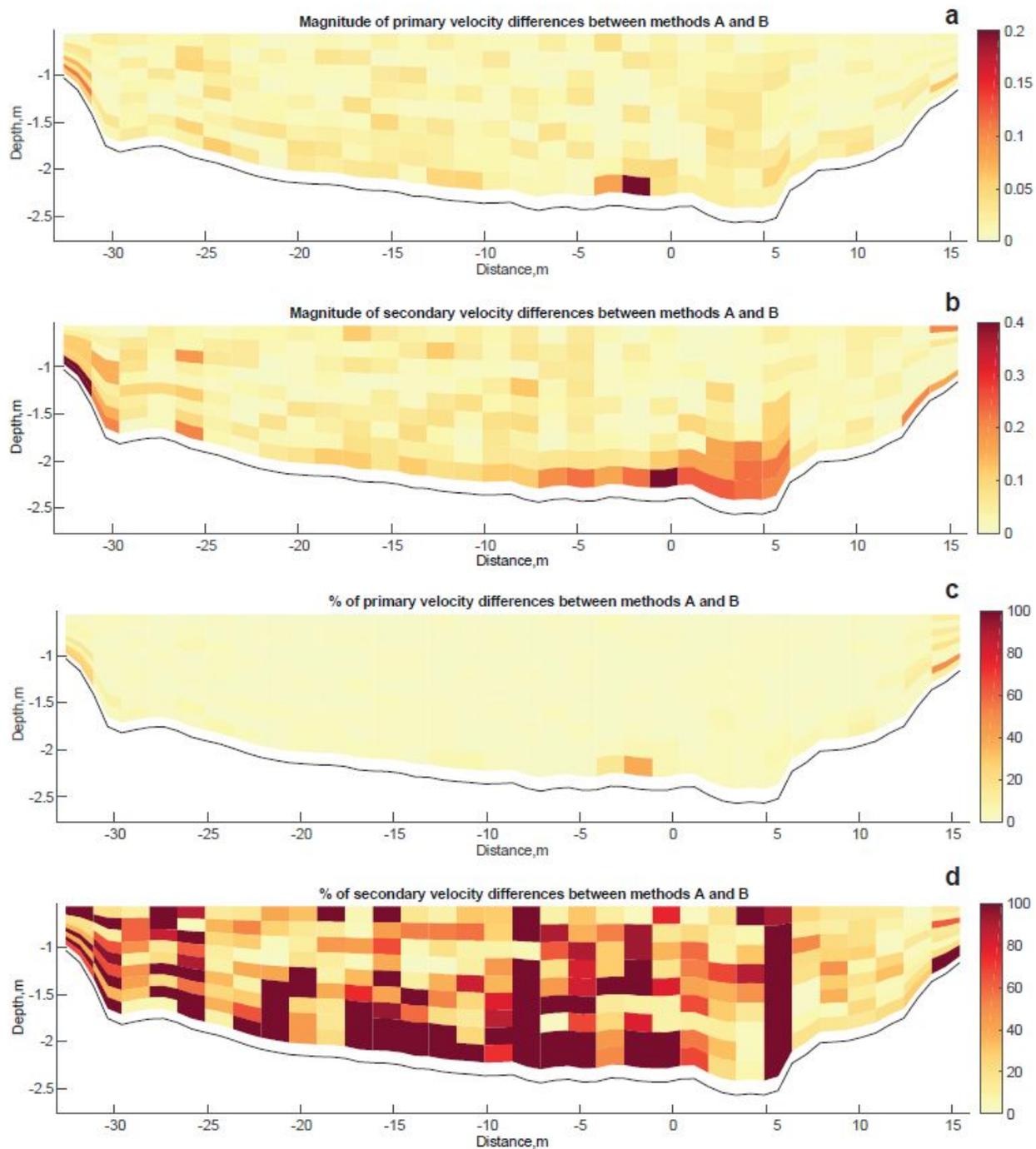
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Figure 4: Primary and secondary velocities estimated with method A at a) for the Lizerne-Rhône Method A (a) and Method B (b) and the ,-cross-section 9 and b) Grande Eau-Rhône, -cross-section 3, confluences and method B at c) Lizerne-Rhône, -cross-section 9, and d) Grande Eau-Rhône Method A (c) and Method B (d); view is looking downstream, -cross-section 3, confluences



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Figure 5: Differences between magnitude of primary and secondary velocities (m/s) between methods A and B (a and b) and the percentages of their difference (m/s) (c and d), at the Lizerne-Rhône confluence, for cross-section 9; [view is looking downstream.](#)

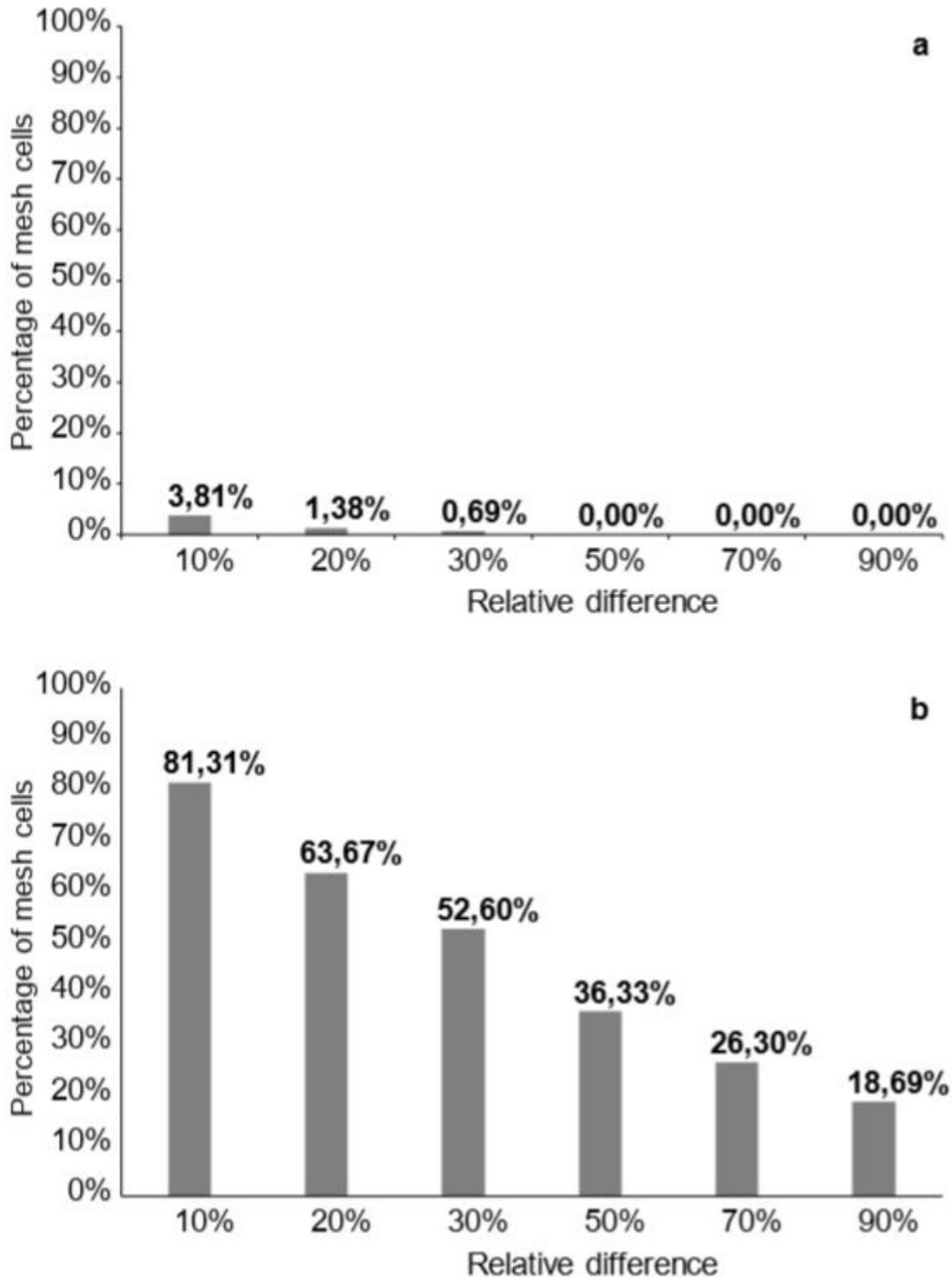


Figure 6: Relative differences in a) primary velocity magnitudes and b) secondary velocity magnitudes, between methods A and B, at the Lizerne-Rhône confluence, for corss-section 9

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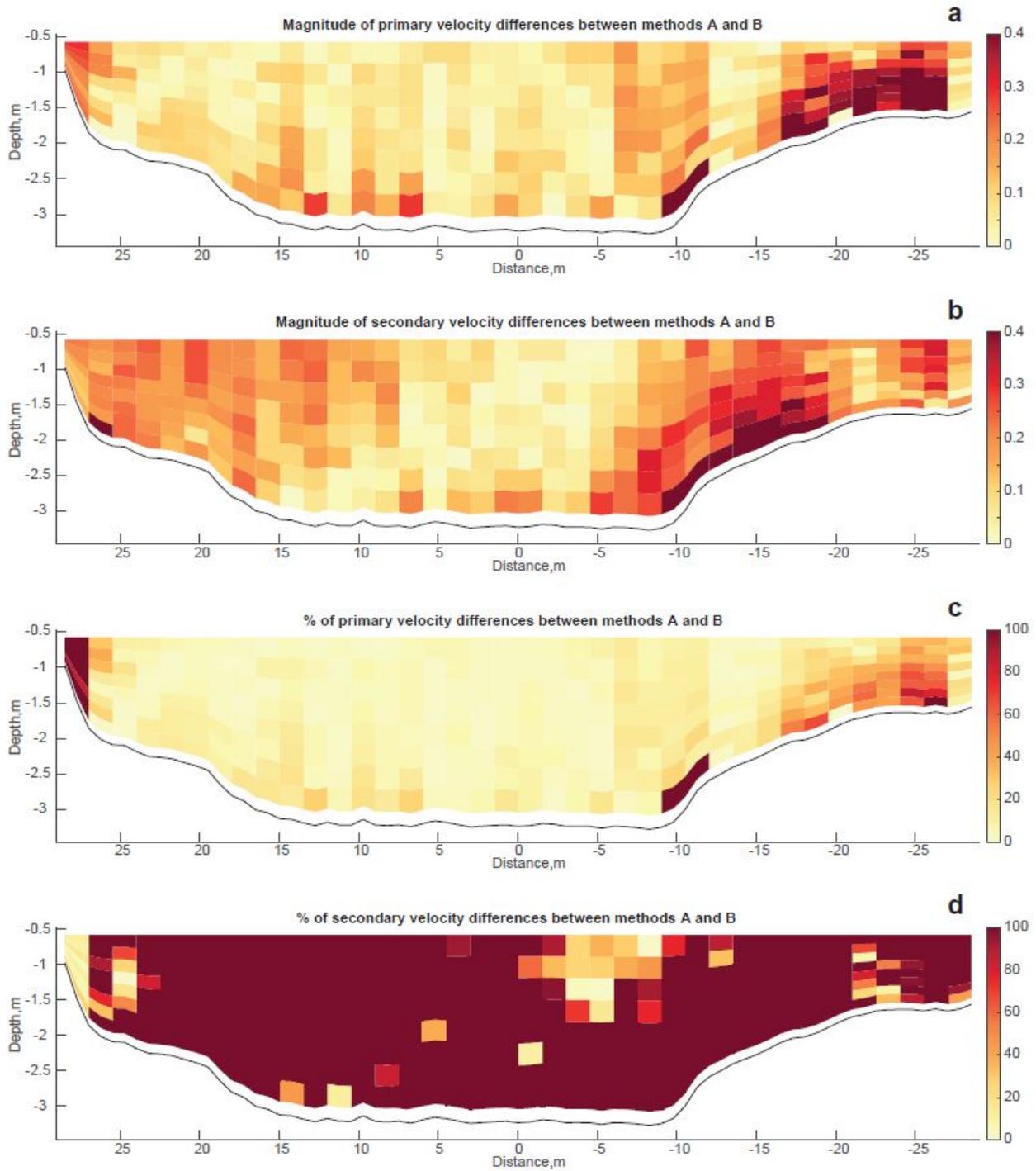
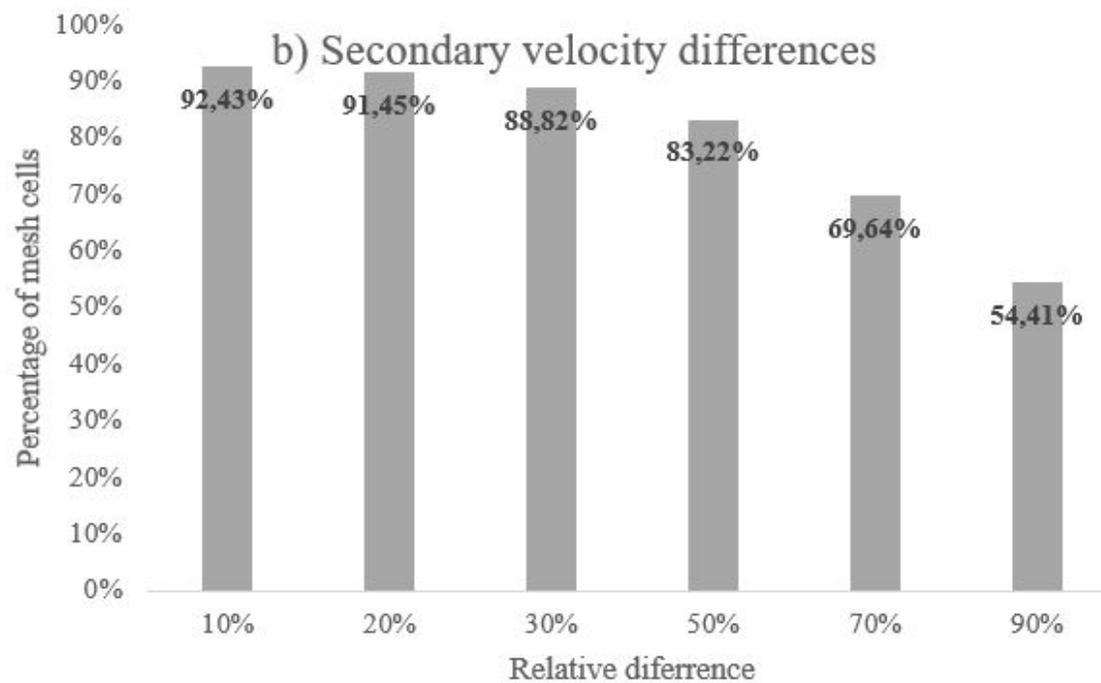
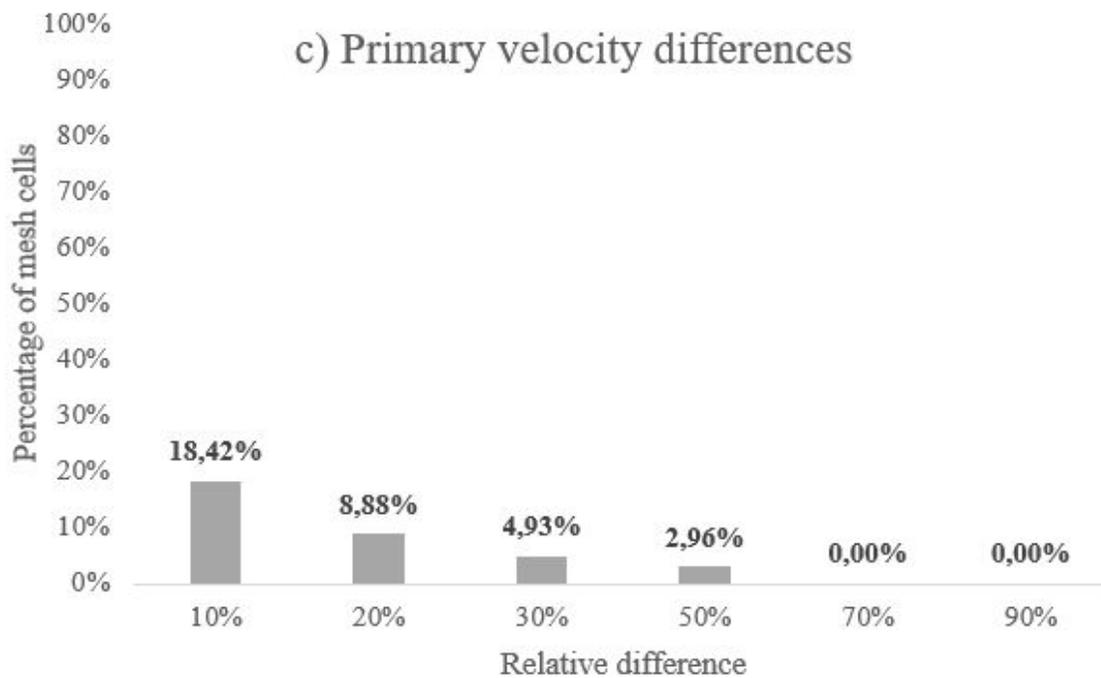


Figure 7: Differences between magnitude of primary and secondary velocities (m/s) between methods A and B (a and b) and the percentages of their difference (m/s) (c and d), at the Grande Eau-Rhône confluence, for cross-section 3; view is looking downstream.



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Figure 8: Relative differences in a) primary velocity magnitudes and b) secondary velocity magnitudes, between methods A and B, at the Grande Eau-Rhône confluence, for cross-section 3; [view is looking downstream.](#)

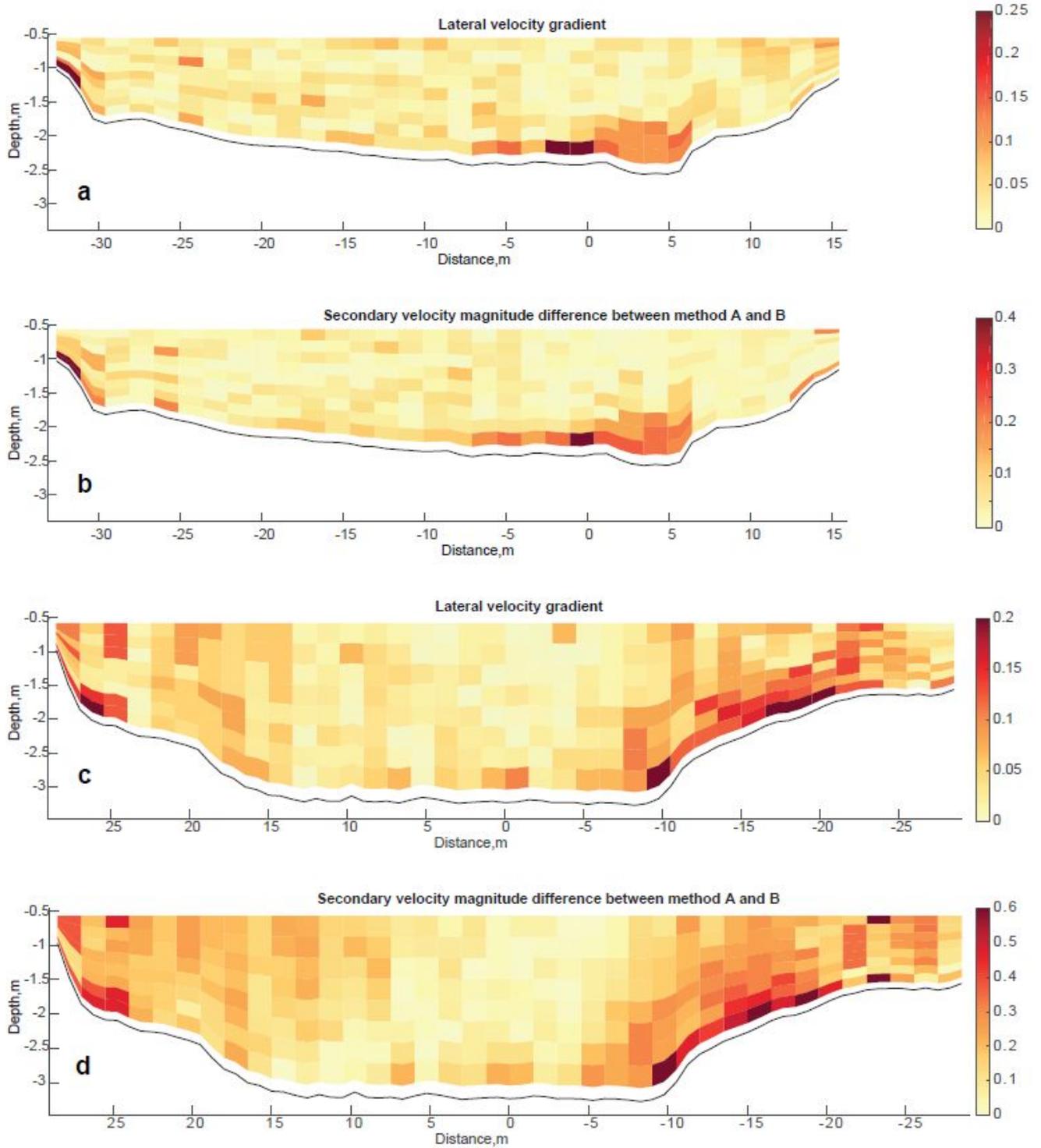
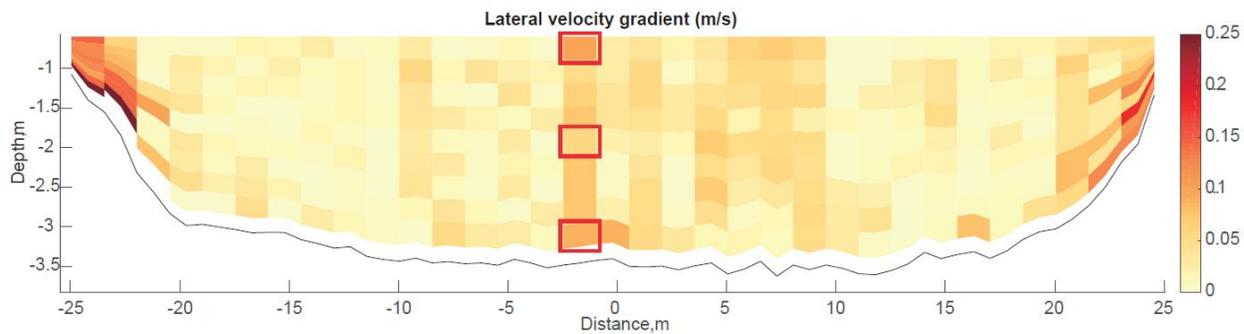


Figure 9: Lateral velocity gradients (a, c) and differences in the secondary velocity magnitudes (b, d) at the Lizerne-Rhône cross-section 9 (a,b) and the Grande Eau-Rhône cross-section 3 (c,d) confluences; *view is looking downstream.*

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Figure 10: Water column and mesh cells for cross section 9 in Figure 3a at the Lizerne-Rhône confluence, in which standard deviation of the estimated velocities have been calculated; view is looking downstream.

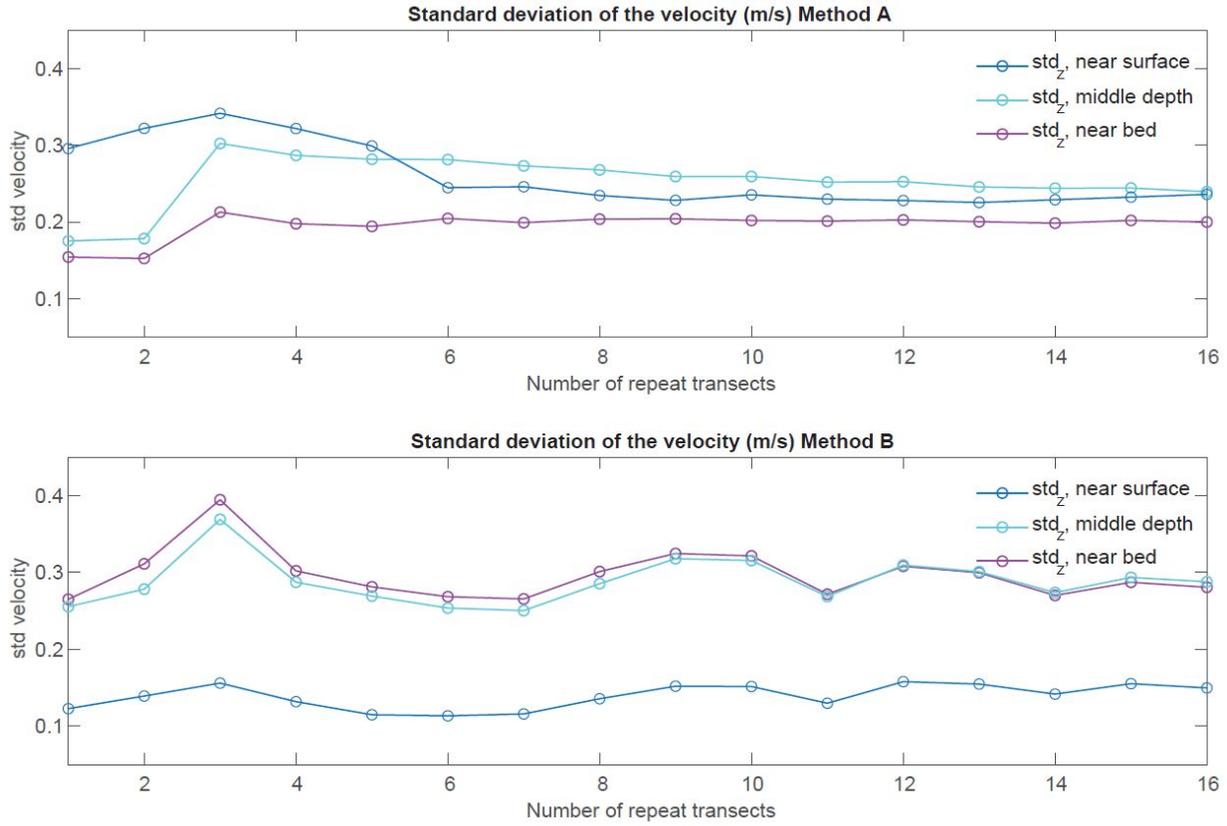
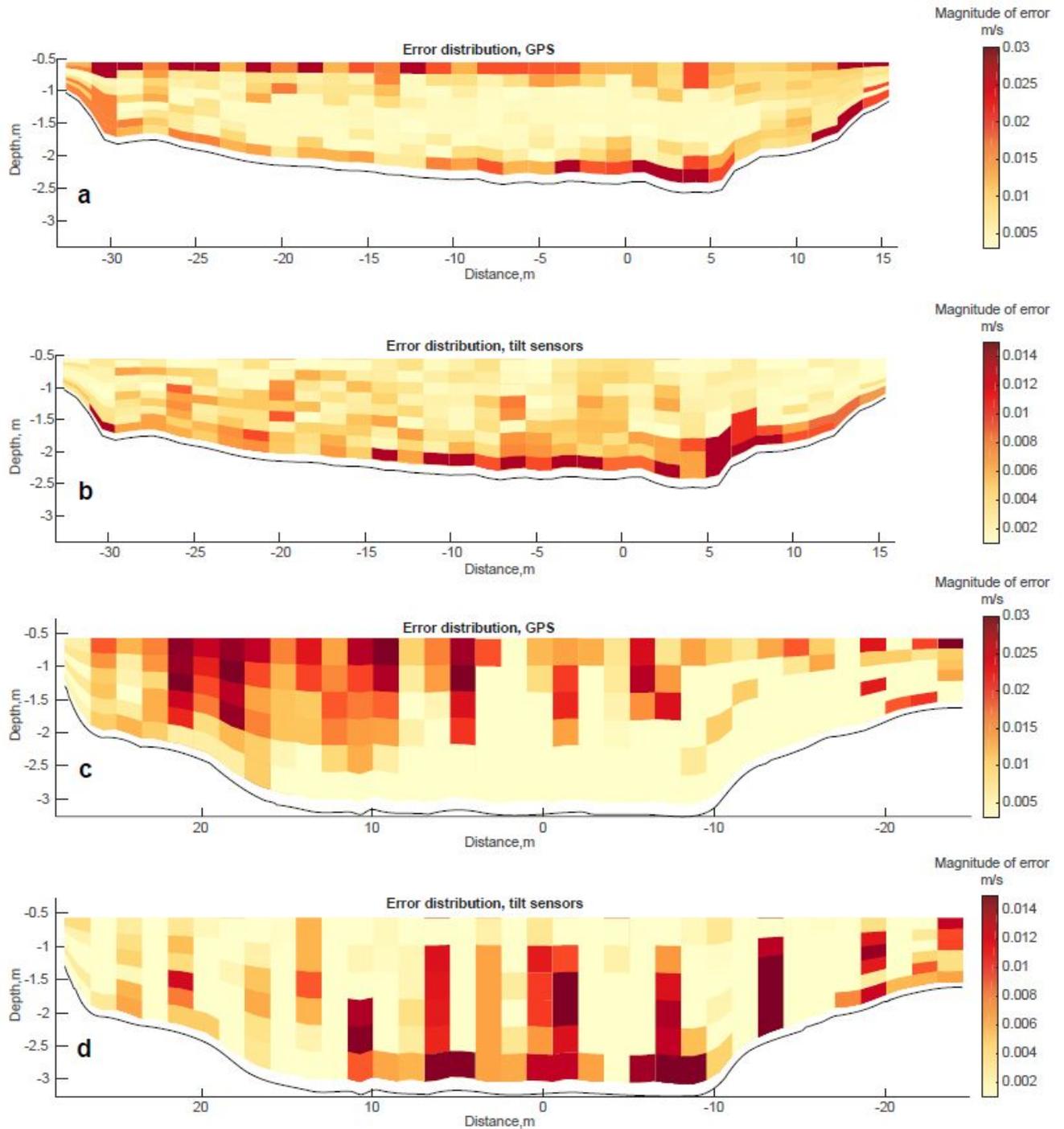


Figure 11: Standard deviation of the velocity estimated using methods A and B for 16 repeats at the Lizerne-Rhône confluence cross-section 9

Review



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907 Figure 12: Error distributions related to GPS for a) Lizerne-Rhône confluence and c) Grande Eau- Rhône confluence,
 908 and sensors accuracies for b) Lizerne-Rhône confluence and d) Grande Eau-Rhône confluence, in estimating the
 909 secondary velocities using *M*method A; view is looking downstream.

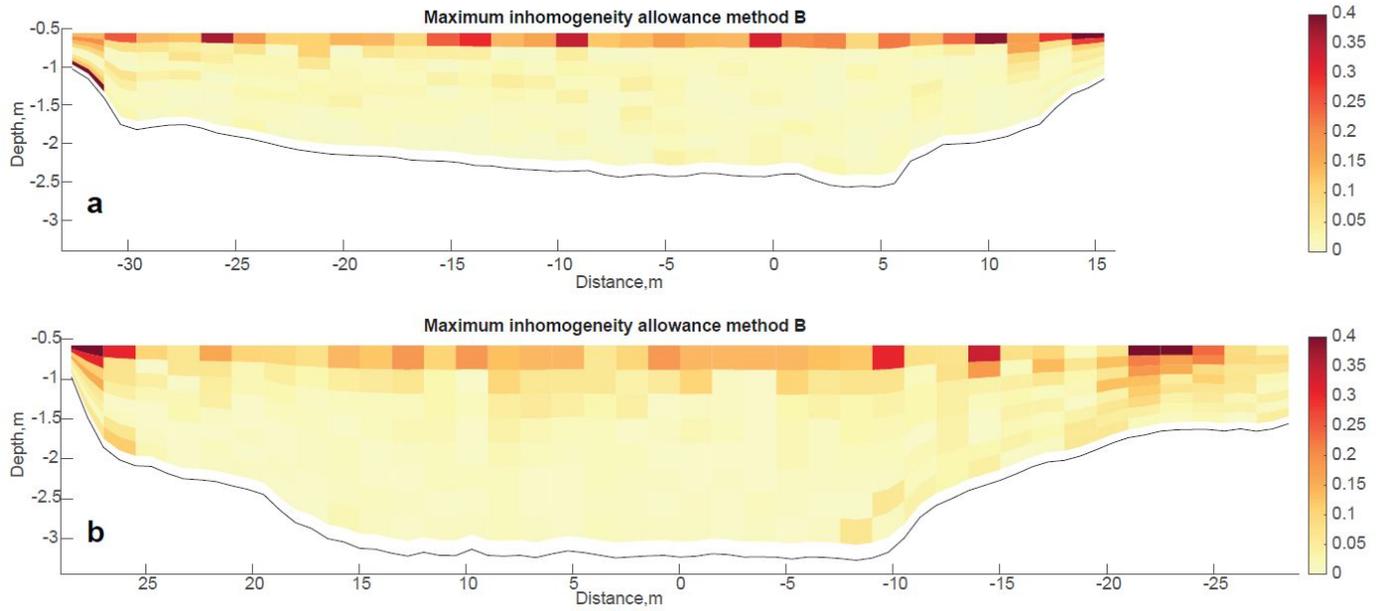
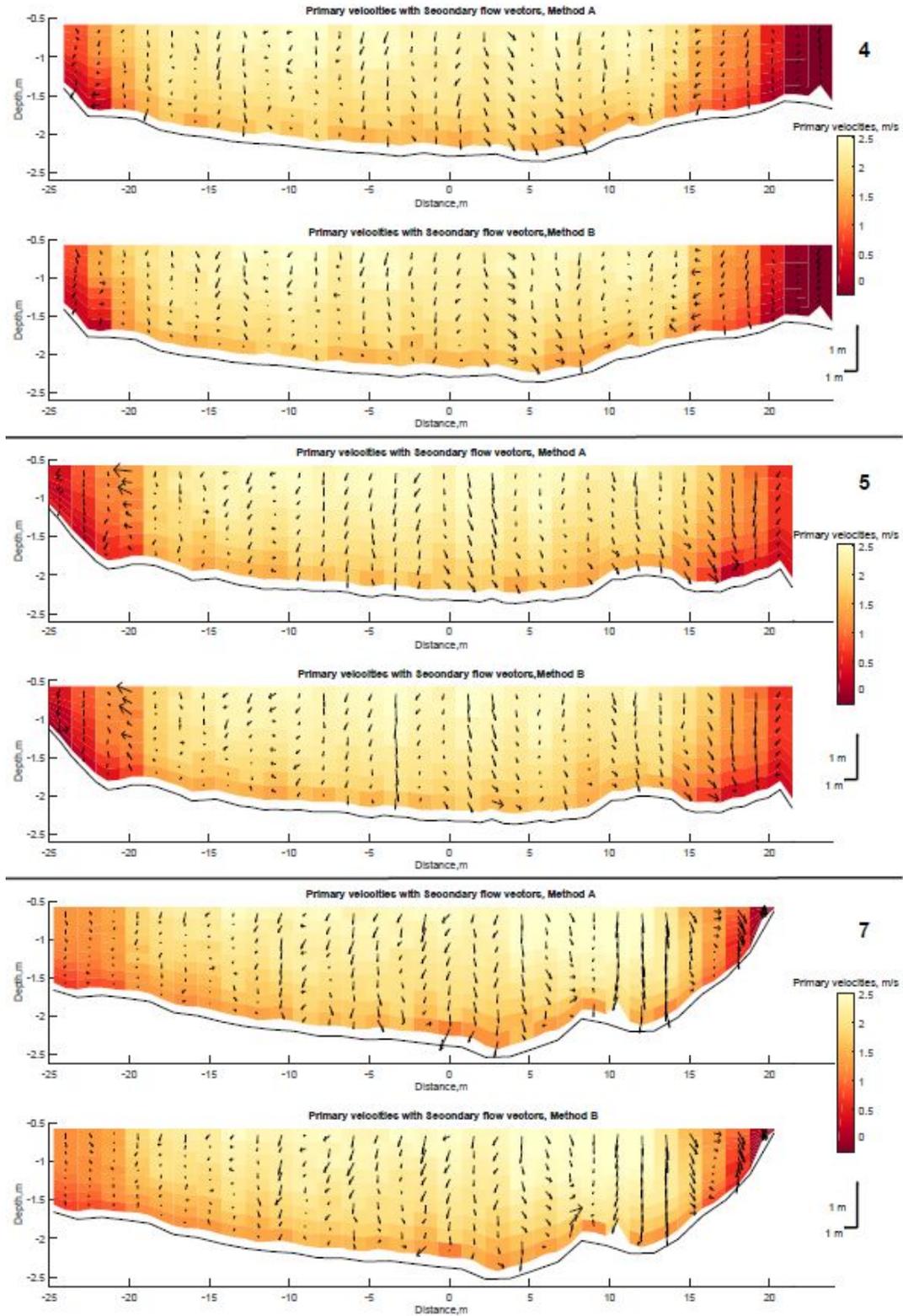


Figure 13: Maximum inhomogeneity allowance (m) using *M*method B for a) Lizerne-Rhône and b) Grande Eau-Rhône confluences; *view is looking downstream.*

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Figure 14: Primary velocities (contours) with secondary velocity vectors estimated using methods A and B at cross sections 4, 5 and 7 in Figure 3a at the Lizerne-Rhône confluence; *view is looking downstream.*

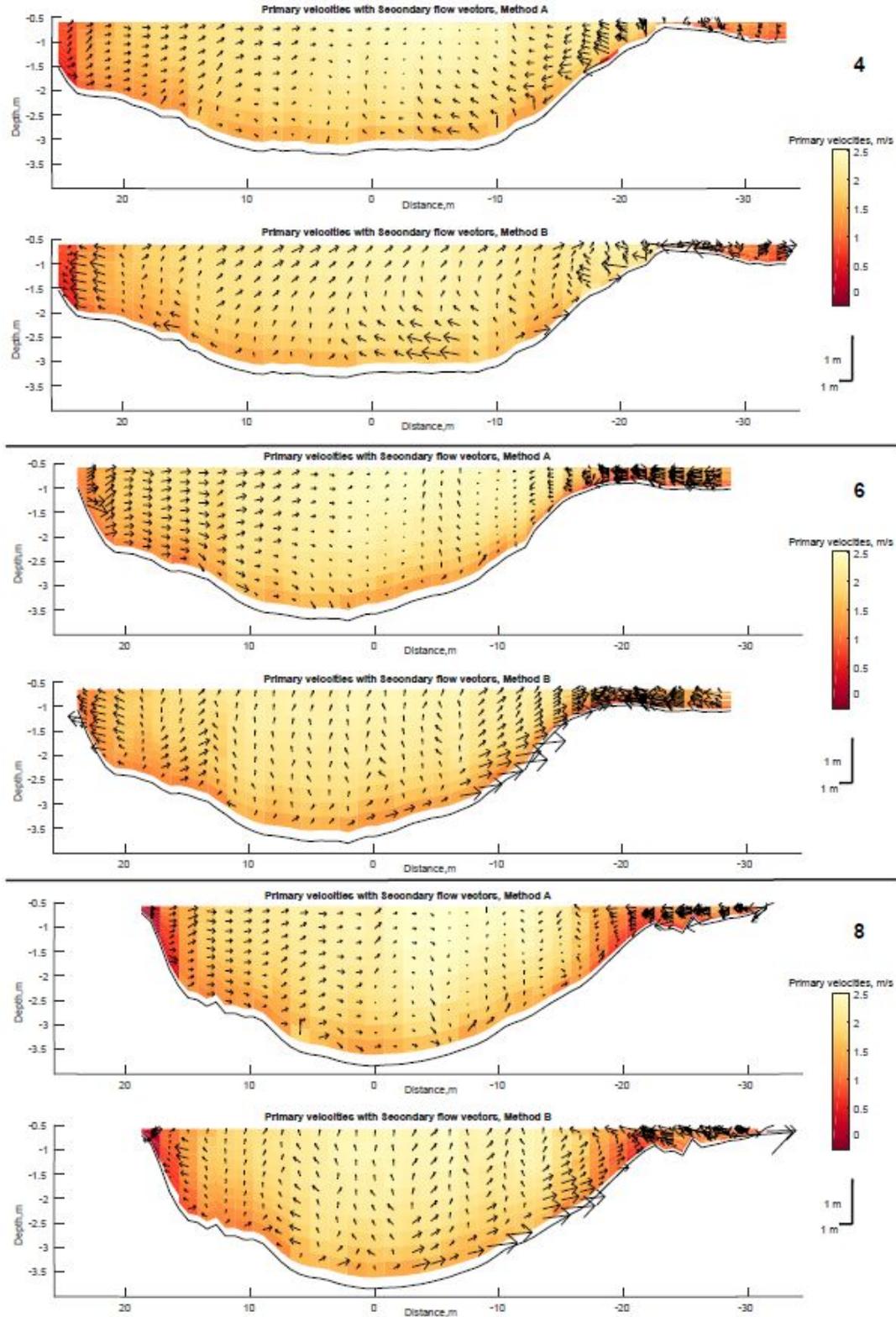


Figure 15: Primary velocities (contours) with secondary velocity vectors estimated using methods A and B at cross sections 4, 6 and 8 in Figure 3b at the Grande Eau-Rhône confluence; *view is looking downstream.*

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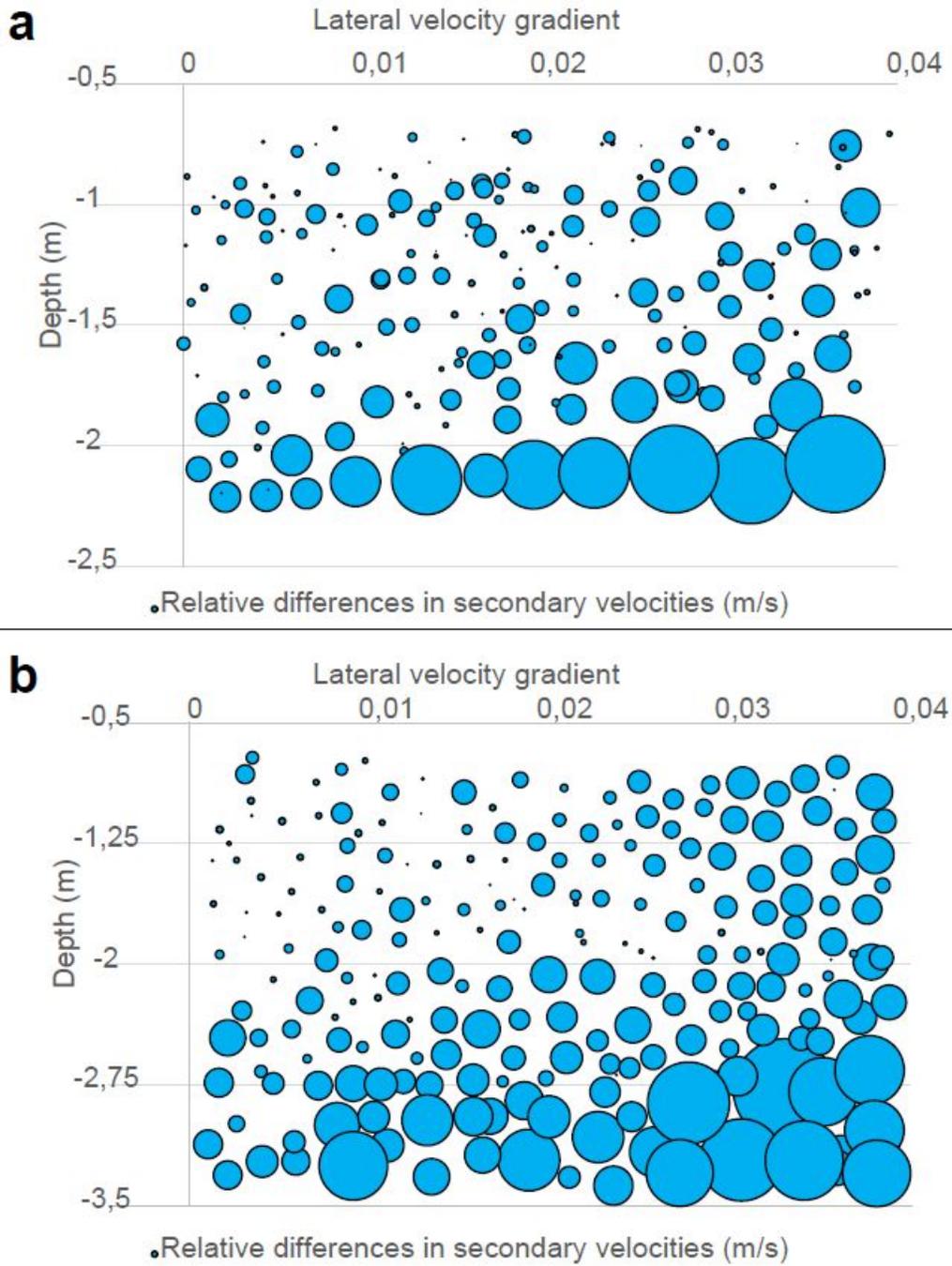
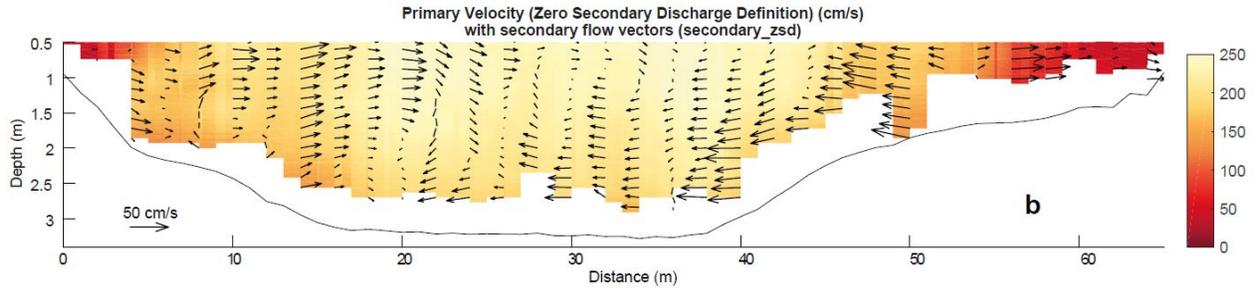
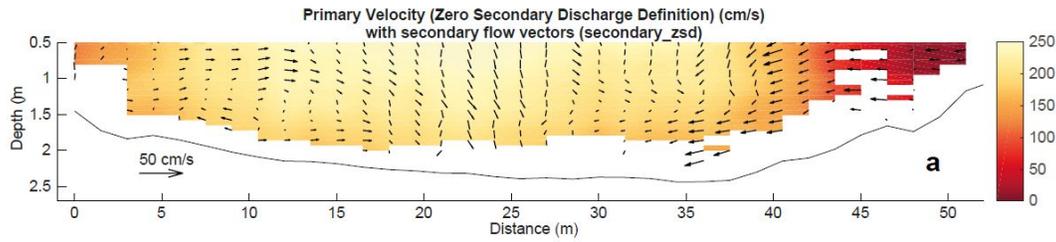


Figure 16: Relationship between lateral velocity gradient, depth and relative differences in secondary velocities for a) the Lizerne-Rhône confluence and b) the Grande Eau-Rhône confluence

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924 ~~Figure 17: Primary velocities (contours) with secondary velocity vectors estimated using~~
 925 ~~the VMT at cross section 6 in Figure 3a at the Lizerne-Rhône confluence and at cross~~
 926 ~~section 3 in Figure 3b at the Grande Eau-Rhône confluence. These are comparable with~~
 927 ~~results in Figure 4a/4b for the Lizerne-Rhône and 4c/4d for the Grande Eau-Rhône~~
 928 ~~confluences~~

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2
3 Dear Professor Kirkby,
4

5 Thank you for the decision of moderate revision on our paper ESP-19-0030.R1. We
6 have now been able to undertake the requested changes (marked below in black).
7 We detail our response below (marked below in blue) and we have also supplied a
8 manuscript with changes tracked.
9

10
11 With best wishes
12 Gelare Moradi for the authors
13
14

15 ASSOCIATE EDITORS COMMENTS 16

17
18 Thank you for your careful revision which has greatly improved the manuscript.
19 However reviewers have identified a number of points that require some further
20 revision or clarification before acceptance.

21 *Thank you for this positive assessment. We explain our response to these revision*
22 *requests below.*
23
24

25 Reviewer: 1
26

27 The revised version of this paper is much improved and the modified analysis
28 presented in the paper focusing on flow within two confluences, rather than
29 downstream of a single confluence, provides a refined basis for comparison of the
30 two different methods (A and B) for evaluating flow structure at confluences using
31 ADCP data. The authors are to be commended for undertaking this substantial
32 revision and addressing most of the issues raised in my previous review.

33 *We thank the reviewer for this positive assessment.*
34
35

36 The paper now represents an important contribution, but still needs moderate
37 revision to be of publishable quality.

38 *We explain the changes made below.*
39
40

41 1) Abstract lines 26-29 The blanket statement here that method A is an improvement
42 over Method B (implied) is somewhat at odds with the conclusion that the two
43 methods have advantages and disadvantages and that both can in the absence of
44 strong shear produce similar results. Also, the extent to which Method A is more
45 accurate than Method B cannot be determined conclusively from a comparison using
46 the two different methods to process the same ADCP data. Some independent
47 measure of the flow using information that is known to accurately represent local
48 flow conditions (such as a dense array of ADV measurements) would be needed to
49 determine whether ADCP data from either method are accurately capturing the flow
50 structure. What seems most appropriate is to indicate that the two methods can, in
51 the presence of strong shear, produce different results, and, given the averaging
52 inherent to method B, it is reasonable to assume that Method A should provide more
53 accurate results under these conditions than Method B. In other words, a more
54 tempered statement would seem appropriate given what is accomplished in the
55 study.
56

57 *This is a very fair point. We have now replaced the end of the abstract with “The*
58 *comparison confirms that in the presence of strong shear our method produces*
59
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2
3 *different results to more conventional approaches. In the absence of a third set of*
4 *fully independent data, we cannot demonstrate conclusively which method is best,*
5 *but our method involves less averaging and so in the presence of strong shear is*
6 *likely to be more reliable.”*
7

8
9 2) Abstract lines 29-32 This statement about counter-rotating cells and scour is not
10 consistent with results presented in the paper. No clear identification of counter-
11 rotating cells using method A is presented in the results, nor is a comparison made
12 between counter-rotating cells by methods A versus B. These cells also are not
13 related to scour. This statement should be dropped from the abstract and perhaps
14 replaced with a statement that the use of both methods, along with consideration of
15 the factors that influence each method, is valuable for evaluating flow structure
16 at confluences (see point 30 below).

17
18 *We agree. This has been removed and replaced with “We conclude that it is wise to*
19 *apply both our method and more conventional methods to identify where data*
20 *analysis might be impacted upon by strong shear and where inferences of secondary*
21 *circulation may need to be made more cautiously.”*
22

23
24 3) Line 118 – irregular cross-sections. I assume this is referring to the irregularity of
25 the bathymetry at cross sections, rather than an irregular alignment of the cross
26 section. This should be made clear.

27 *Agreed – we have inserted “bathymetrically” before “irregular”*
28

29
30 4) Lines 126 to 134 If I understand it correctly, given the way the processing
31 calculates the mean cross section, the orientation of any cross section relative to the
32 alignment of the river channel can vary from cross section to cross section along the
33 river. In many fluvial applications the desire is to have cross sections perpendicular to
34 the local channel alignment. For a relatively straight channel, such as the Rhone in
35 this study, that would also imply that cross sections are parallel to one another. The
36 extent to which this condition is achieved seems to depend on the boat tracks and
37 the clouds of bathymetric points produced by these tracks. To what extent did the
38 resulting cross sections for analysis differ from one another and from the alignment of
39 the river?
40

41 To some extent this issue is rendered moot by the use of the zero net secondary
42 discharge to analyze the flow structure, but that method also involves rotation of the
43 cross sections. It might be good to show the alignment of the cross sections derived
44 from the processing method and the alignment of the zero net secondary discharge
45 cross sections on figure 3. Cross section alignment can influence the interpretation of
46 secondary flow (see point 7 below).
47

48 *The reviewer is right to note here that there are two controls on the analysis relating*
49 *to cross-section orientation: the first is the orientation of data collection which defines*
50 *the initial mean transect, and this is easier when the main channel is straighter; but*
51 *this does not necessarily lead to the correct identification of secondary circulation, for*
52 *which rotation is then needed. To respond to this revision request, we have made*
53 *two changes.*
54

- 55 1. *We have added the following at before former line 126 “It is important to note*
56 *that this mean transect is not necessarily orthogonal to the primary flow*
57 *direction and so will not yield true primary and secondary flow estimates*
58 *without further correction. We address this below.”; and just after reminded the*
59 *reader that the initial bathymetric model is the initial mean transect. This*
60

1
2
3 makes the relationship between the transect definition during data collection
4 and the identification of primary/secondary circulation clearer.

- 5
6 2. In response to point 7 below, we mention more clearly the importance of
7 secondary flow correction, and that we do not assess this in this study.

8
9 5) Lines 326-329 The decision to use six cross sections seems to be based on the
10 analysis of standard deviation of the velocity data. Although this is presented in the
11 results, this basis should at least be mentioned here.

12 Agreed – we have added “*Hence, in this paper, data are processed for cross-section*
13 *6 at the Lizerne-Rhône confluence (Figure 3a), and for cross section 3 at the Grande*
14 *Eau-Rhône confluence (Figure 3b). Identification of the minimum number of repeat*
15 *transects necessary per cross-section was undertaken using cross-section 9 at the*
16 *Lizerne-Rhône confluence (Figure 3a), which involves 16 repetitions. We noted that*
17 *after application of Method A, the standard deviation of velocity stabilized with six*
18 *repetitions, which is the number we adopt for this study.*”

19
20
21 6) Lines 363-368 why was a standard deviation of plus or minus 1 degree chosen as
22 a reasonable value for tilt sensor error? Also what was the standard deviation of the
23 displacement error distribution? How was this determined?

24 We have added “*based on manufacturer specifications*” for the tilt error; and
25 “*measured by the dGPS for the dGPS positions (as a function of satellite*
26 *configuration during measurement)*” for the positions.

27
28
29 7) Lines 380-381 The zero net secondary discharge method was used to determine
30 secondary flow. This choice can have an influence on the depiction of secondary flow
31 compared to other secondary-flow depiction methods (e.g. cross-stream
32 perpendicular to the local channel alignment, Rozovskii method, maintenance of flow
33 continuity of between cross sections). This issue should at least be mentioned in the
34 discussion or conclusion (i.e. that this aspect of data processing, not just the ADCP
35 operation, is a relevant one for producing differences in secondary flow patterns, but
36 is not considered in this study).

37 This is correct. We use the zero net secondary discharge method as work two
38 decades (Lane et al., 2000) showed that other methods (e.g. Rozovskii) are not
39 correct (Rozovskii, for example, means that the primary flow direction changes within
40 an individual cross-section). To make this clear, we have made two changes

- 41
42 1. In the methods section we now write “*In order to distinguish between primary*
43 *and secondary components of flow, we need to rotate the initial mean*
44 *transect. Options for doing this are reviewed in Lane et al. (2000) and we do*
45 *not assess them here, but rather apply the zero net cross stream discharge*
46 *definition (Lane et al., 2000).*”
47
48 2. We have added at the end of the Discussion “*Finally, we wish to emphasise*
49 *that the impact of averaging is only one element that must be considered in*
50 *obtaining reliable primary and secondary flow estimates in river confluences.*
51 *Other issues, such as the rotation method needed to distinguish primary and*
52 *secondary circulation, remain important and should be considered routinely.*”
53
54
55

56 8) Lines 391 to 400 It is not clear why angular rotations are needed for vertical
57 velocities. A rotation should not be necessary if the cross section is a plane aligned
58 from the flow surface to the bed.
59
60

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3 No – we disagree here. Secondary velocity is defined as that component of velocity
4 that is orthogonal to the primary flow direction and this includes components that will
5 be both predominantly lateral and vertical. The next flux associated with both lateral
6 and vertical fluxes should be zero for true definition of the primary velocity, which is
7 why this rotation is needed. We have made this clear by adding “*secondary
8 circulation is all flow that is orthogonal to the primary flow and not just horizontal flow;
9 there should be not net secondary flux in a section; and so correction should also
10 consider vertical velocities*”.

11
12
13 9) Line 401 What does curvature of cross-sections refer to here?? How are the
14 cross-sections curved?

15 We have clarified this by adding “*correct for weak curvature with the survey method
16 at the edges of each transect line (e.g. Figure 3)*”.

17
18
19 10) Lines 410-411 this statement about differences is not put into any context and
20 seems to contradict the previous sentence that the velocities are similar for the two
21 methods

22 Agreed – modified to “*and the differences in estimated secondary flows are minor.
23 The differences are most pronounced between -10 and 5 m, in the middle of the main
24 channel*”.

25
26
27 11) Figure 4 - the caption for this figure appears to be incorrect. The top two frames
28 (a and b) are for one confluence and the bottom two (c and d) are for the other. The
29 caption is confusing as written.

30 Corrected to “*Figure 4: Primary and secondary velocities estimated for the Lizerne-
31 Rhône Method A (a) and Method B (b) and the Grande Eau-Rhône Method A (c) and
32 Method B (d)*”

33
34
35 12) Table 1 It would be good to include the velocity ratio (ratio of mean velocities) in
36 this table as this should provide the most direct information on the difference in the
37 magnitude of lateral fluid shear between the two flows. Based on the arguments in
38 the text this ratio should be much larger for Grand Eau than for Lizerne.

39 This may be correct if the two tributaries had beds at the same altitudes, but there is
40 also a very marked difference in tributary elevations and hence depth ratios. This
41 means that the velocity ratio is not a useful parameter to report. This was not clear in
42 our previous version of the paper and so we have now made this clear through the
43 following changes:
44

- 45 1. Where we introduce the Lizerne, we have modified the description of the
46 junction angle to: “*It reaches the Rhône between Ardon and Vétroz, forming a
47 90° junction angle and it has a bed that is nearly concordant with the Rhône.*”
48 – and where we introduce the Grande Eau, we now write: “*The Grande Eau
49 bed is c. 1.5 m higher than the Rhône such that it is markedly discordant*”.
- 50 2. In the results, we now mention the importance of bed discordance with the
51 relevant sentence modified to: “*This is due to a high degree of bed
52 discordance between the Grande Eau and the Rhône, which increases the
53 penetration of the tributary flow into the main channel over the junction, and
54 which forms a zone of high lateral and vertical shear, on the one hand, and
55 main channel narrowing because of penetration of the tributary point bar on
56 the other hand.*”
57
58
59
60

3. When we now discuss Figure 7 we have added in reference to vertical and lateral shear.

13) Line 415 reference figures 4 c and d here
Added

14) Line 421 and 422 above the junction? Flow enters at the junction. This phrase can be deleted.
Clarified – it was meant to be vertical. We now use “over” rather than “above”.

15) Line 423 tributary point bar should be change to tributary mouth bar. Point bars occur in meandering rivers
Changed

16) Line 427 inner bank? Not clear which bank this is. Assume the left bank but it should be specified as there is no clear inner and outer bank
Changed to “bank on the tributary side of the channel”.

17) Line 456 to to 459 It is not entirely clear what cell is being referred to here as the “described above” is disconnected by many lines of intervening text. Recommend it be explicitly reidentified here.

We have rewritten the sentence as “Indeed, the marked differences between methods A and B at the Grande Eau confluence (Figure 7) are also in a zone of strong lateral shear.” to make reference back to Figure 7.

Also the use of the term cell for secondary flow and cell for the mesh can be confusing at places. May want to consider using mesh cell and secondary cell rather than just the term cell.

This is an excellent point – there are actually 3 cells: the aDcp, the mesh (numerical, that we use for the analysis) and secondary circulation. For all mentions of cell we now distinguish between these.

18) Line 475 -478 the stabilization of the variance is likely a product of the number of measurements contained within the each mesh cell. Do methods A and B produce different numbers of measurement points within each mesh cell? It seems likely they would given that method A should produce many more individual velocity readings than method B. This might be an important factor in stabilizing variance.

This is right and we have clarified it – adding, “and this is likely because method B uses fewer measurements per mesh cell.”

19) Line 527 mouth bar
Modified

20) Line 521-523 careful with language here. Method A cannot produce stronger penetration or weaker upwelling of the flow. It indicates that secondary velocity components differ from those depicted by Method B, which has implications for the strength of penetration and upwelling.

Yes – and so we have modified the text in 6 places to make sure we mean identification rather than production.

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3 21) Line 546 would be good to present velocity ratio in table 1 to confirm this. Also
4 information from the primary velocity data on the maximum lateral shear gradients for
5 the shear layers in each confluence would also be useful.

6 This is a useful point and did need some clarification. As noted above, the issue is
7 more that the GE-R has a more complex shear zone (with lateral and vertical shear)
8 rather than necessarily a more intense lateral shear zone. To capture this point, we
9 have rewritten the section as "*the Grande Eau-Rhône has a more complex shear
10 zone, likely due to the effects of bed discordance, and there are more significant
11 differences in the estimation of primary and secondary velocities*"
12
13

14
15 22) Line 557 As mentioned with the abstract, this statement should be qualified. One
16 can reasonably assume it should provide more accurate information on the
17 secondary velocities, but this cannot be conclusively confirmed without independent
18 corroborating evidence.

19 Yes – this is a very fair point and to follow our changes to the abstract, ee have
20 modified the sentence to: "*In this case, as method A involves less spatial-averaging
21 than method B, it may provide more accurate information on the flow behavior, but
22 such a conclusion really needs a third and independent method to confirm this
23 conclusion.*"
24
25

26 23) Line 564 low levels of lateral shear acceptable for using method B??

27 Given our response to point 21, we have modified this sentence to: "*At the Lizerne-
28 Rhône confluence, even though the momentum ratio is similar to Grande Eau-Rhône
29 confluence, there is only more localized shear in the flow and a simplified shear zone
30 (Figure 9). In such a situation, using method B to detect the large scale patterns of
31 secondary flow may be more advantageous, because it involves more spatial
32 averaging.*"
33
34
35

36 24) Line 569 velocity ratio and max values of lateral velocity would help confirm the
37 absence of lateral shear.

38 See above – lateral shear is not, in our view, the only issue (it is already shown also
39 in Figure 9 – it is more the complexity of the shear zone arising from both lateral and
40 vertical shear. We hesitate in adding more quantitative data because it might lead to
41 others applying an overly simplified rule when the magnitude of shear likely to lead to
42 method A being needed also varies with the distance of the shear zone from the
43 sensor. We now make this point explicitly by adding "*It may be tempting to introduce
44 some kind of shear or velocity gradient threshold to identify when Method A might be
45 preferable. To do so could be misleading as this value will also depend on the
46 distance of the shear from the aDcp.*"
47
48
49

50 25) Line 568-573 run-on sentence need to revise this by at least splitting it into two
51 sentences.

52 Sentence split into two
53
54

55 26) Line 579-584 Again a rather long sentence. Also it is best to use an even number
56 of transects to avoid potential directional bias in GPS signals

57 The sentence is now split and we have added "*We also note that an even number of
58 repeats may be important to avoid directional bias in dGPS positions.*"
59
60

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3 27) Line 599-611 This section on VMT is underdeveloped and gives the impression
4 of material that has been inserted into the paper as an afterthought. The comparison
5 is only for a single cross section and generalizations should not be drawn on the
6 basis of this comparison, even suggestively, especially given that VMT has provided
7 high-quality depictions of secondary flow at confluences in many instances. It is also
8 not clear why the results of the VMT analysis include larger areas near the bed
9 without data. Moreover, the statement about VMT using a straight mean cross-
10 section is confusing. Don't methods A and B also use straight mean cross-sections?
11 It seems best that this rather superficial comparison with VMT be deleted from the
12 paper. Doing so will not detract from its main message of the paper. Generally VMT
13 results should be consistent with Method B, although the level of spatial detail may
14 be greater in VMT depending on the size of the cells in relation to bin size.

15
16
17 *We agree and so have removed completely this text, including Figure 17.*

18
19 28) Lines 615-618 can some indication be provided here about what constitutes a
20 small river versus a large river (would avoid the use of the term "big" since that term
21 is often associated with mega rivers such as the Amazon and Congo)? Use of small
22 versus large is rather subjective and it would be helpful to have at least some metrics
23 associated with these terms.

24
25 *This is a good point and needed three changes to be made. First, we are now explicit
26 that what we think matters here is depth (and hence shallower versus deeper).*

27 *Second, we don't have enough cases to specify what this depth is and so we simply
28 state relative to our studied confluences in the modified text.*

29
30 *These two changes are now included in this statement: "This is likely to be the case
31 particularly in rivers shallower than those studied here and where high resolution is
32 required due to large velocity gradients. In rivers of the scale studied here, and
33 deeper, by increasing the mesh cell size, we can still have sufficient data to estimate
34 velocity vectors, and the effects dGPS and tilt sensor errors have a minor effect."*

35
36 *The third change relates to the point that we don't have enough data either to identify
37 specifically what we mean by big and small but also to urge caution, following the
38 difficulty if identifying critical values of shear. What is big (so Method A) and small (so
39 method B) will also depend on shear. To capture this point we have added: "We are
40 not yet in a position to identify the depth at which Method A becomes preferable to
41 Method B, and again this will depend on other parameters such as the intensity of
42 shear and so may not be readily generalizable between confluences."*

43
44 29) Line 631 again velocity data would be useful for evaluating shear

45 *See arguments made above.*

46
47
48 30) It might be appropriate to recommend that it can be useful to use both methods
49 to analyze flow structure at confluences, as this paper has done, to see how they
50 differ. If they do not differ greatly this provides reinforcement that the depicted
51 patterns are probably accurate. If they differ, consideration should be given to the
52 factors that can produce differences between the two methods, and a preference for
53 one depiction over another weighted according to the prevalence of these factors.
54 This is an excellent suggestion and conforms with our Conclusion. Our response to
55 point 24 partly makes this conclusion.

56 We have added the following to capture this argument:
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59
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3 “We are not yet in a position to identify the depth at which Method A becomes
4 preferable to Method B, and again this will depend on other parameters such as the
5 intensity of shear and so may not be readily generalizable between confluences.
6 The difficulty of identifying the depths of rivers and intensities of shear that make one
7 method preferable over another precludes adoption of simple quantitative guidance on
8 which method to use when. As both methods have some disadvantages, we argue that
9 both methods should be applied. If they give similar results, then there should be
10 confidence in both. If and where they differ, analysis should be undertaken to identify
11 why, and hence which method is likely to be preferable. Association of the differences
12 in primary and secondary velocities inferred between the two methods with estimates
13 of shear intensity and with estimated tilt and positioning errors should then help decide
14 whether Method A or Method B is preferable in a particular case. This preference may
15 vary between confluences but also through time at a confluence, if shear or flow depth
16 changes significantly between survey dates.”
17
18
19

20 Reviewer: 2

21
22
23 Comments to the Author
24 General comments

25
26 The reviewer appreciates all the answers and effort made by the authors to address
27 all suggestions and comments made by reviewers in the new manuscript submission,
28 which has significantly improved the manuscript.

29 We thank the reviewer for this positive assessment.

30
31
32 Before publication, I suggest the authors clarify some specific questions detailed
33 below.

34
35 Note: As a suggestion, in order to the proposed methodology is easily apply by
36 ADCP users, I strongly recommend the development of an open source code. To
37 include these methods into the widely used VMT software will be an excellent tool for
38 ADCP users interested on flow structures estimation at complex hydrodynamics zone
39 such as confluence, bifurcation, bends, etc...

40 We think the best way to achieve this is to integrate the method into the VMT and we
41 are currently in discussion with the VMT developers to do this. We can also make our
42 own code available upon request and have added this to the acknowledgements.
43
44

45 Specific Comments:

46
47
48 Table 1: discharge from Rhone and tributary rivers are not provided.

49 Added

50
51 Figure 4: caption references do not agree with figures and text.

52 Corrected in response to Reviewer 1.

53
54 Figure 4: I suppose sections are looking downstream. Clarify in caption.

55 Clarified, and in all other captions

56
57
58 Line 411-412: there are other verticals with similar differences. Could the authors
59 justified in more details?
60

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3 Typo: -5m should be 5 m – corrected; this then deals with this concern
4

5 Line 416-417: It was confuse to me that this affirmation is valid for primary velocities
6 but secondary component look opposite (i.e. at shorter distance from ADCP). Could
7 you clarify?
8

9 We don't make this affirmation for secondary velocities. This difference, though, is
10 partly explained because it depends on the magnitude of primary velocity relative to
11 secondary velocity. We don't think this needs to be explained as we don't discuss
12 secondary velocities in this way.
13

14 Line 421-428: the sentence is very confused. Could the authors rewrite this
15 sentence?
16

17 Clarified in response to the request from reviewer 1 (point 14)

18 Moreover, Grande Eau-Rhône streams have difference densities that could explain
19 the penetration of Grande Eau river into Rhone near bed? It will be useful for reader
20 to have this information to understand the non-common secondary pattern processes
21 presented at this confluence.
22

23 We don't believe this is an issue as the differences in suspended sediment load and
24 temperature were negligible during measurement. We prefer not to get into this issue
25 as it would detract from the paper.
26

27 Figure 4 and 7: I cannot see an agreement between Figure 4c,d and Figure 7b,d. For
28 example, a clear differences in secondary velocities intensity is presented near water
29 surface at distance between 0 to -10 and lower discrepancy between distance 20 to
30 10. However, Figure 7 shows the opposite behavior.
31

32 This is simply a color scale effect – Figure 7 plots magnitudes of difference whereas
33 Figure 4 c/d show absolute values. The zone described above suggests differences
34 of around 0.1 m/s in Figure 7 which scales with the differences shown in the same
35 zone by comparing vector lengths Figures 4c and 4d. No changes made.
36

37 Figure 6: add legend in figure 6a.

38 We have deleted the figure 6b legend
39

40
41 Line 495-497: This sentence is not clear to me. Why the relation between ship
42 movements and uncertainties in dGPS data produce a large error near surface and
43 not in all water columns?
44

45 This was unclear – and so we have rewritten it as “*Near the surface, as there fewer*
46 *measurements that can contribute to the estimation of aDcp position and tilt,*
47 *uncertainties in dGPS data will have a greater effect.*”
48

49 Line 608-612: it is surprising to me the big difference between Method A and B with
50 VMT (similar that is doing by methods B). How many transects were used to obtain
51 figure 17b using VMT? In order to compare the methods should be the same amount
52 than Figure 4. Clarify.
53

54 The VMT comparison has been removed.
55
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Table 1: Selected upper Rhône tributaries with their typical characteristics

Sites	Lizerne	Grande eau
Tributary upslope contributing area (km ²)	64.8	132
Main stem upslope contributing area (km ²)	3401	5088
Basin area ratio	1.89%	2.59%
Tributary width (m)	6.5	16.5
Main stem width upstream of junction (m)	46	58
Width ratio	0.15	0.28
Junction angle (°)	80	70
Tributary Froude number	0.32	0.05
Bed slope of the tributaries upstream of the confluence (%)	~0.5	0.5-1
Main stem slope upstream of the confluence (%)	2	2.2
Tributary slope (°)	33.1	26.6
Rhône discharge during measurement (m ³ s ⁻¹)	182	300
Tributary discharge during measurement (m ³ s ⁻¹)	4	8.13
Discharge ratio during measurement	0.022	0.027
Momentum ratio (Mr) during measurement	0.018	0.022

Figure 1: Bed elevations, the best fit to those elevations and the water level representation

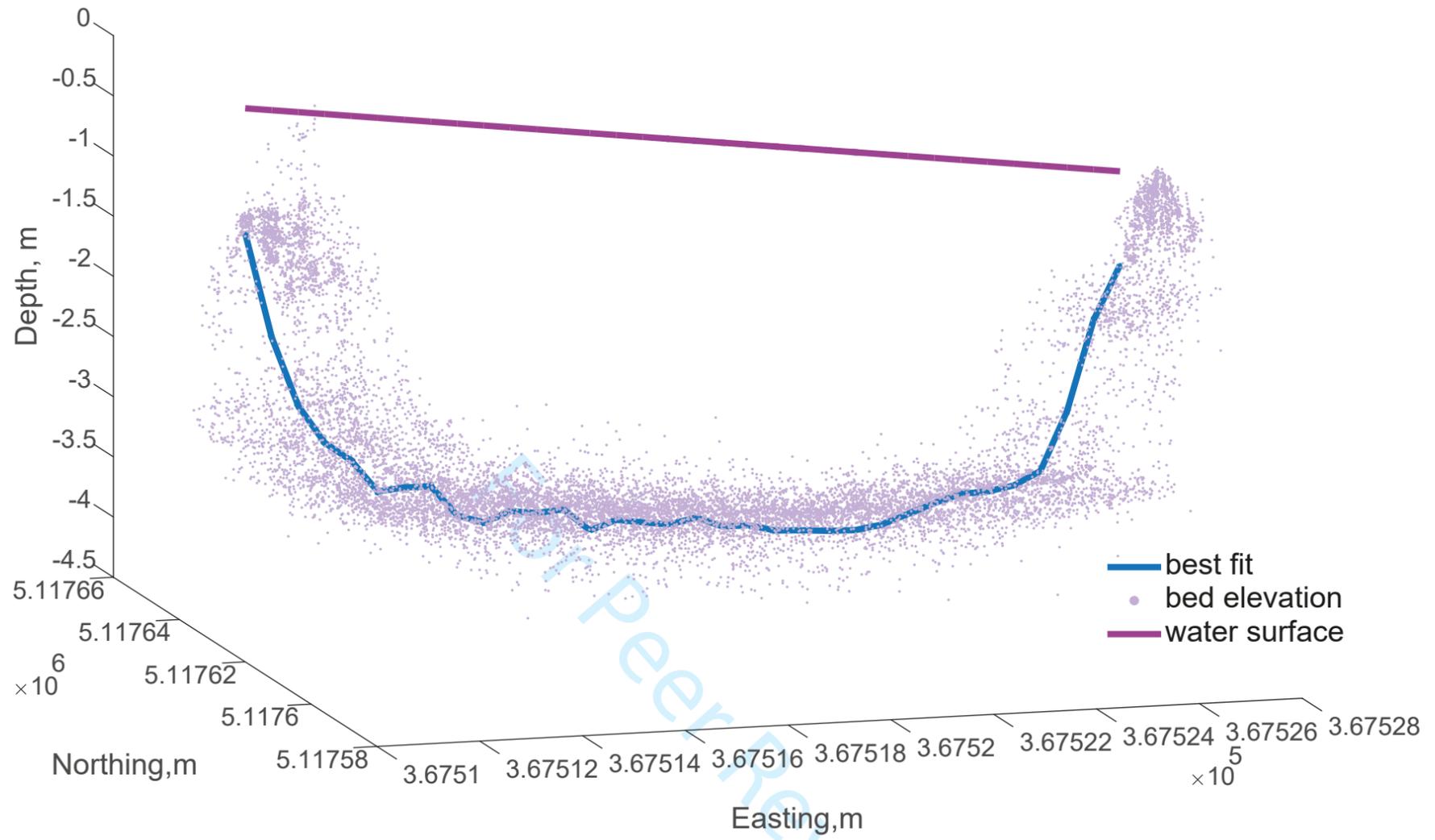
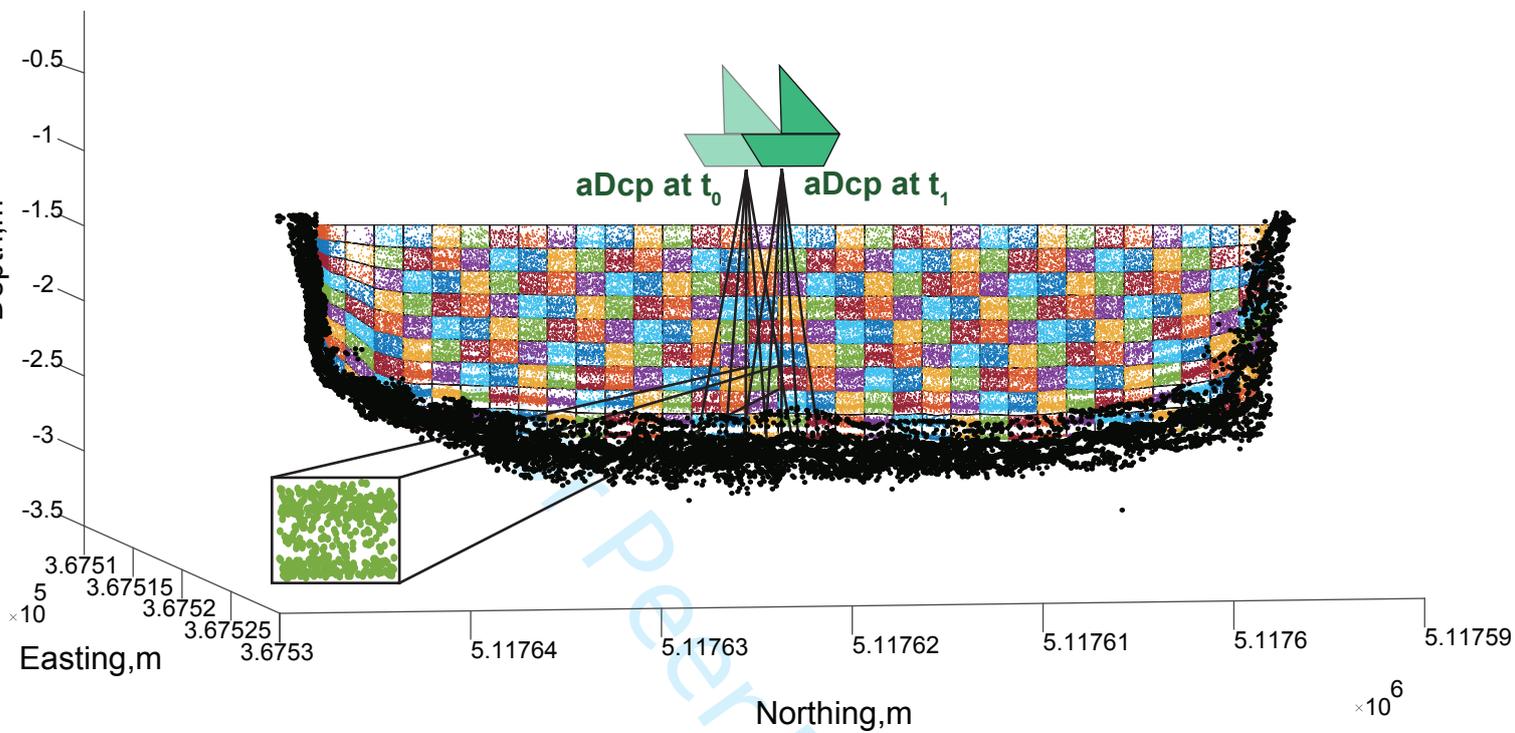


Figure 2: An example of beam velocity positioning within each mesh cell, using method A, Dots show beam velocities and color is an automatic Matlab function to distinguish between different cells



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Figure 3: Tracks navigated by SonTek aDcp moving boat system at a) Lizerne-Rhône confluence near Vétroz, at 07/07/2017 and b) Grande Eau-Rhône confluence near Aigle at 23/05/2018. The repeated transect data assessed in this paper are from cross-section 6 at the Lizerne-Rhône confluence and cross-section 3 at the Grande Eau-Rhône confluence and c) Rope-Pulley system

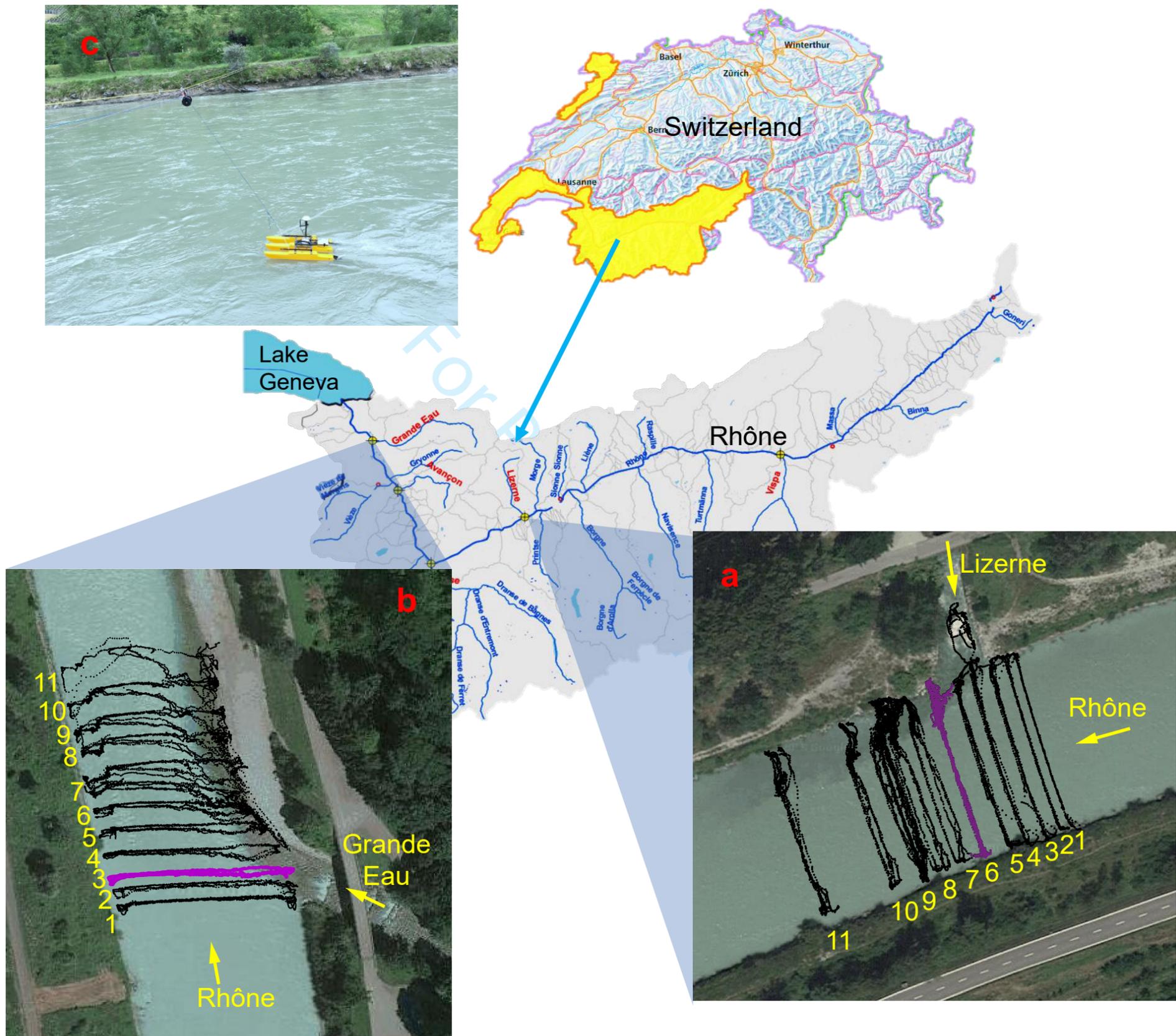


Figure 4: Primary and secondary velocities estimated for the Lizerne-Rhône Method A (a) and Method B (b) and the Grande Eau-Rhône Method A (c) and Method B (d); view is looking downstream.

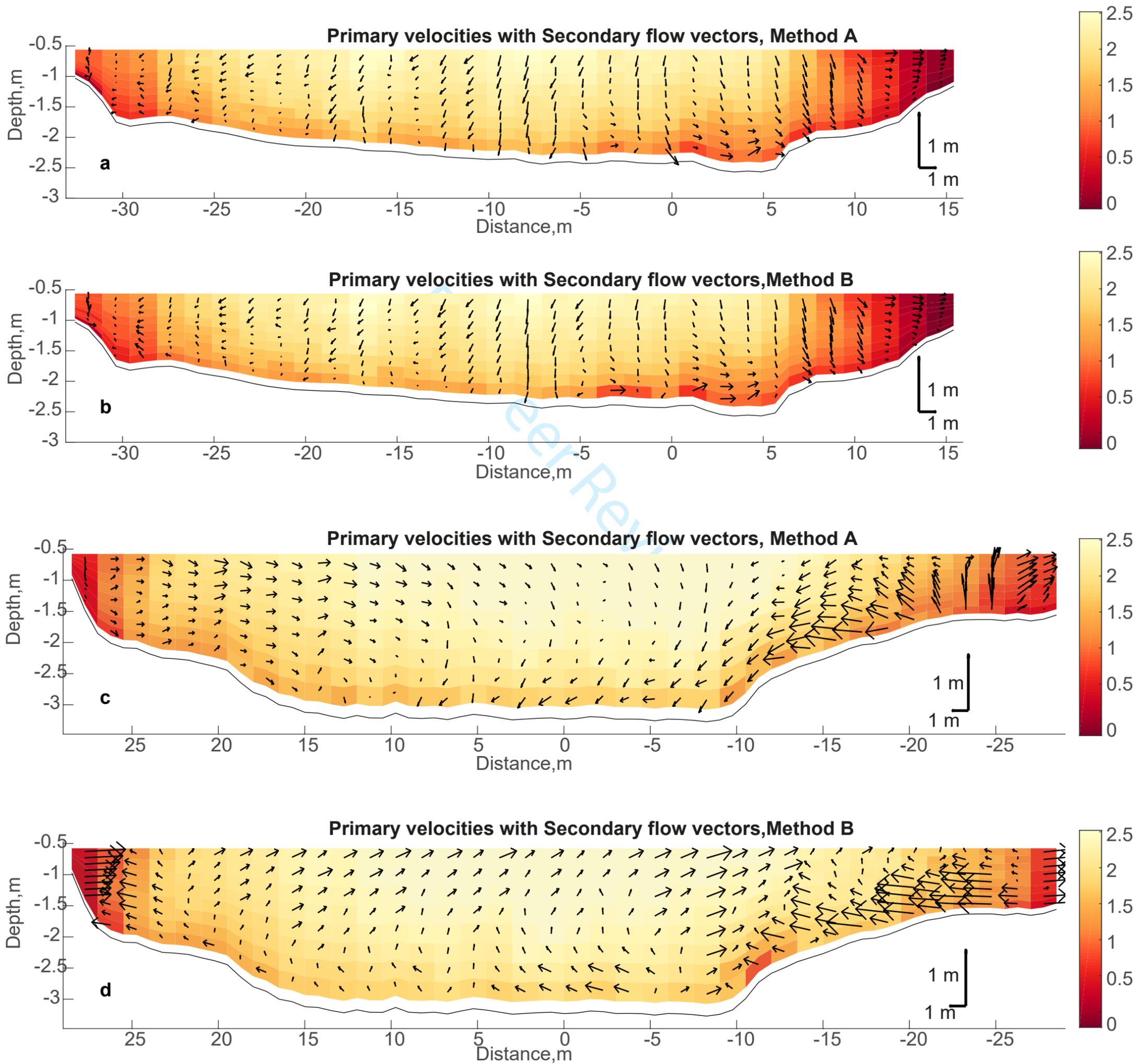


Figure 5: Differences between magnitude of primary and secondary velocities (m/s) between methods A and B (a and b) and the percentages of their difference (m/s) (c and d), at the Lizerne-Rhône confluence, for cross-section 9; view is looking downstream.

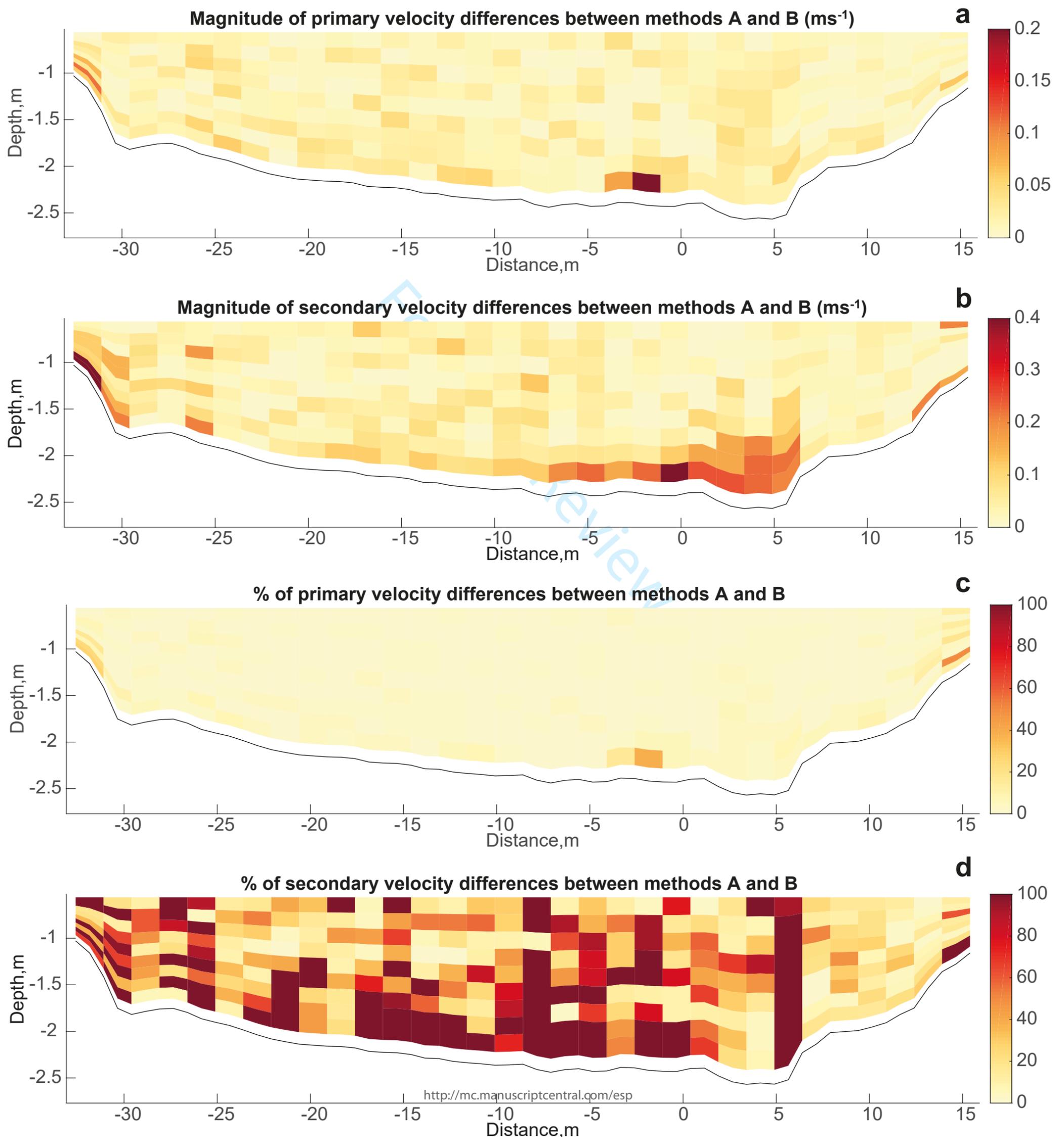


Figure 6: Relative differences in a) primary velocity magnitudes and b) secondary velocity magnitudes, between methods A and B, at the Lizerne-Rhône confluence, for cross-section 6

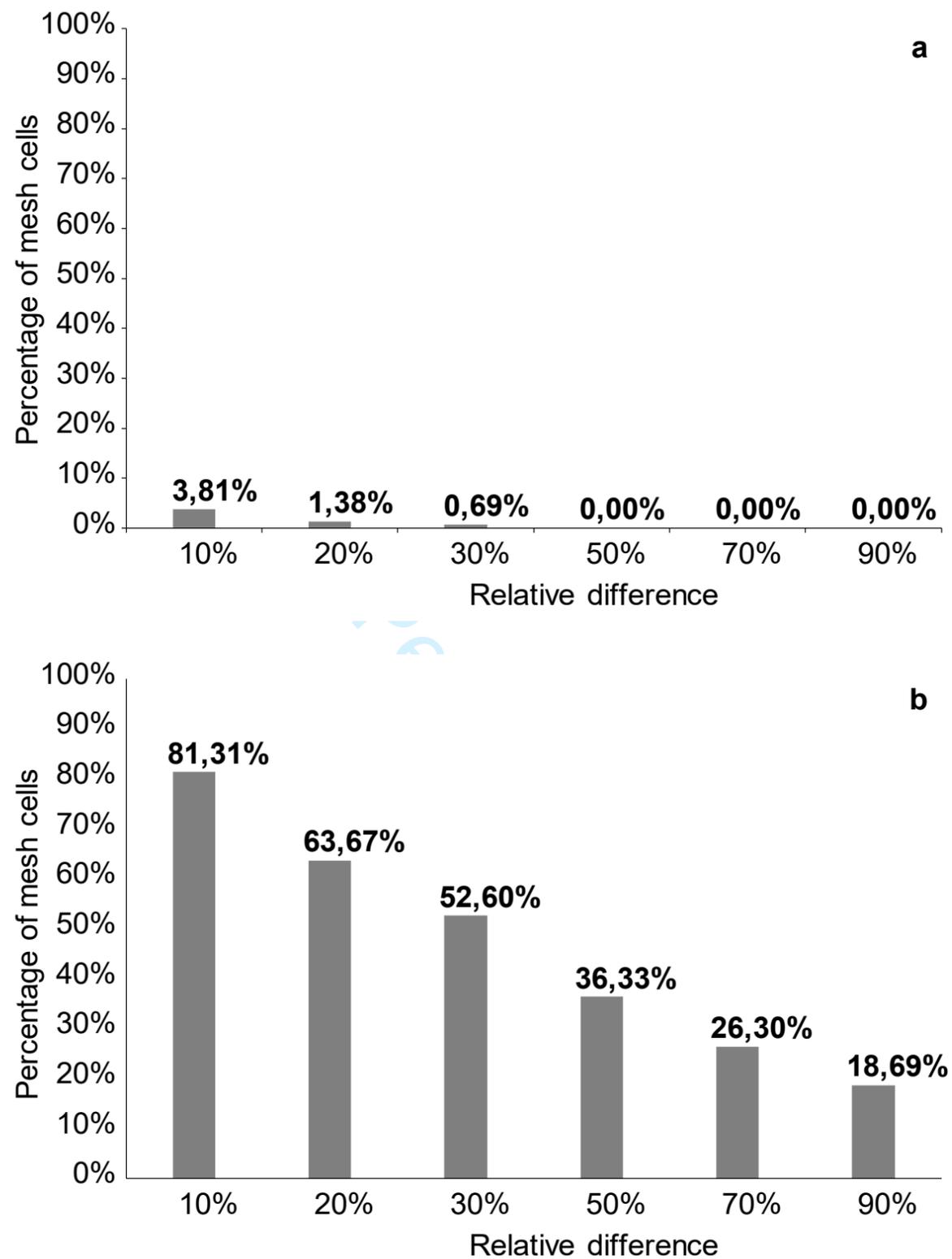


Figure 7: Differences between magnitude of primary and secondary velocities (ms^{-1}) between methods A and B (a and b) and the percentages of their difference (c and d), at the Grande Eau-Rhône confluence, for cross-section 3. view is looking downstream.

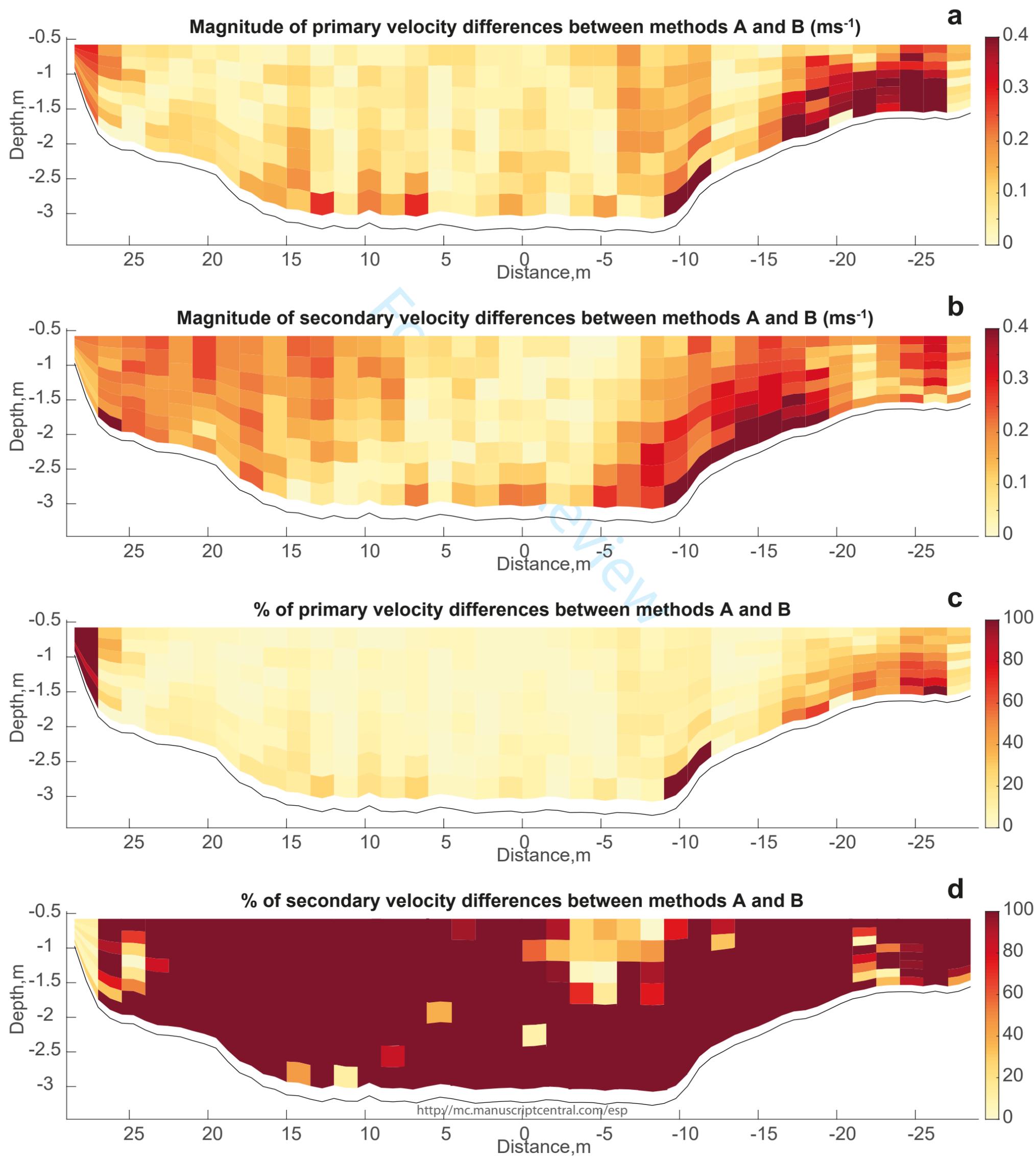


Figure 8: Relative differences in a) primary velocity magnitudes and b) secondary velocity magnitudes, between methods A and B, at the Grande Eau-Rhône confluence, for cross-section 3, view is looking downstream.

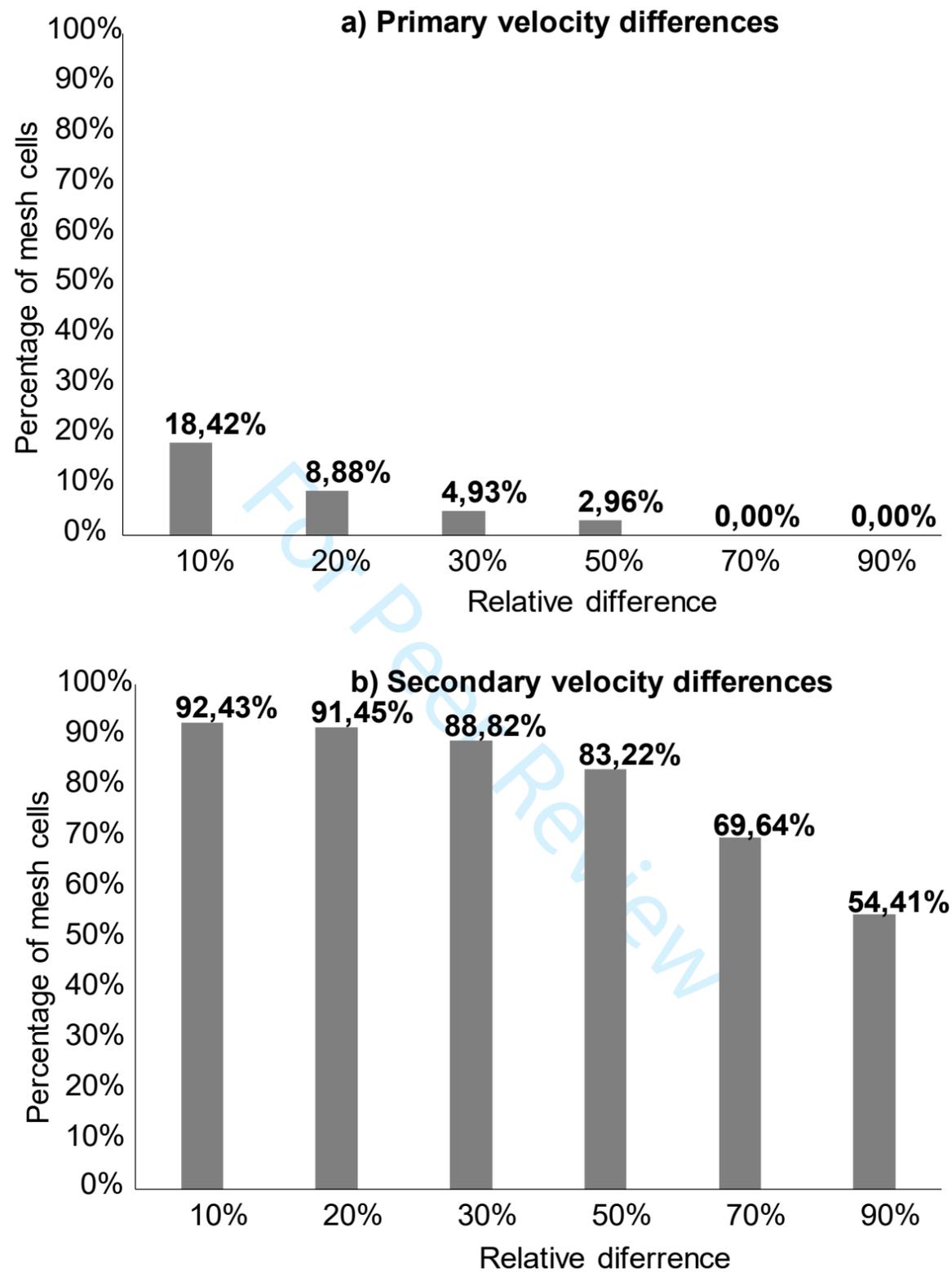


Figure 9: Lateral velocity gradients (s^{-1}) (a, c) and differences in the secondary velocity magnitudes (ms^{-1}) (b, d) at the Lizerne-Rhône cross-section 6 (a,b) and the Grande Eau-Rhône cross-section 3 (c,d) confluences. view is looking downstream.

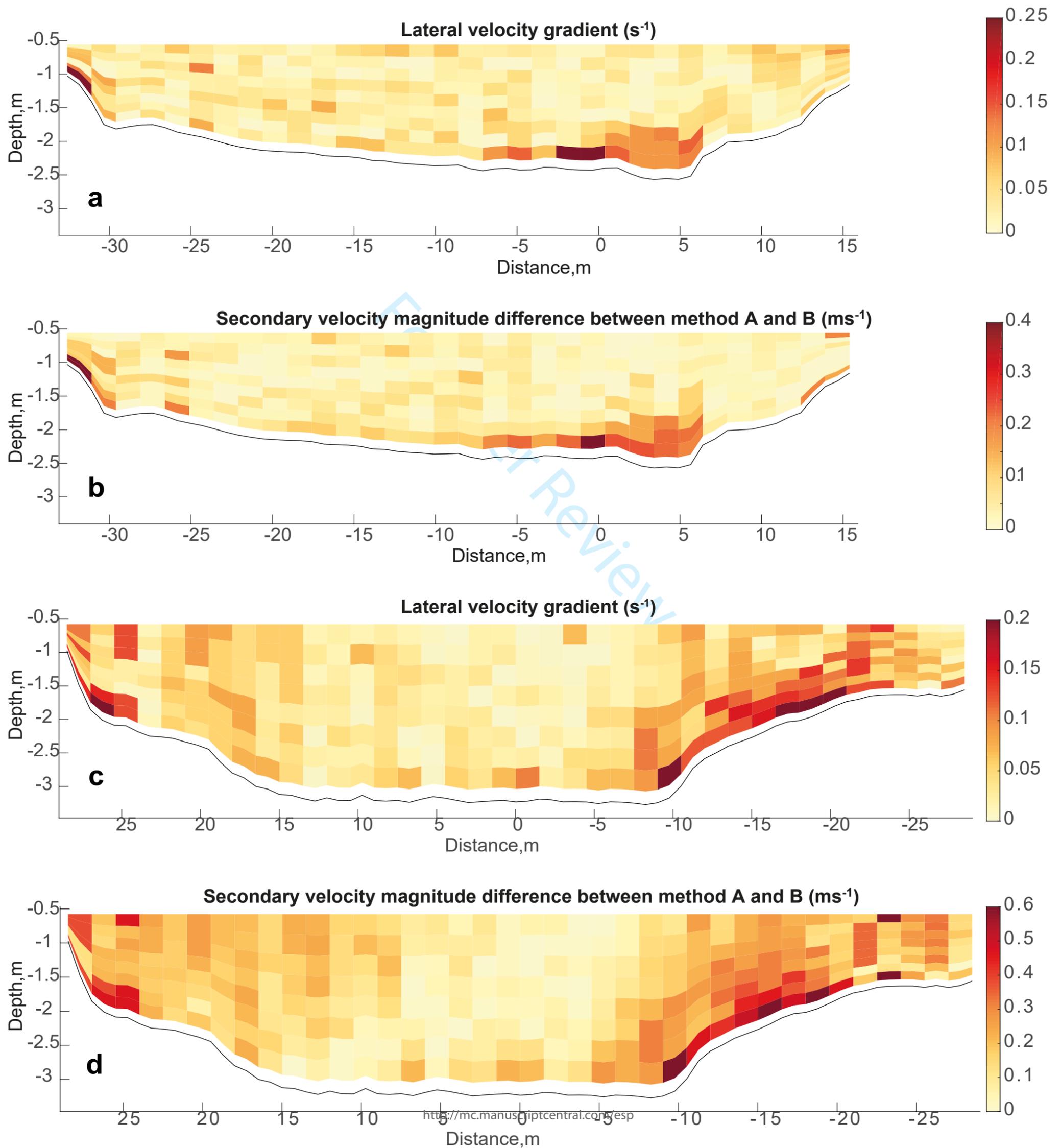


Figure 10: Water column and mesh cells for cross section 9 in Figure 3a at the Lizerne-Rhône confluence, in which standard deviation of the estimated velocities have been calculated. view is looking downstream.

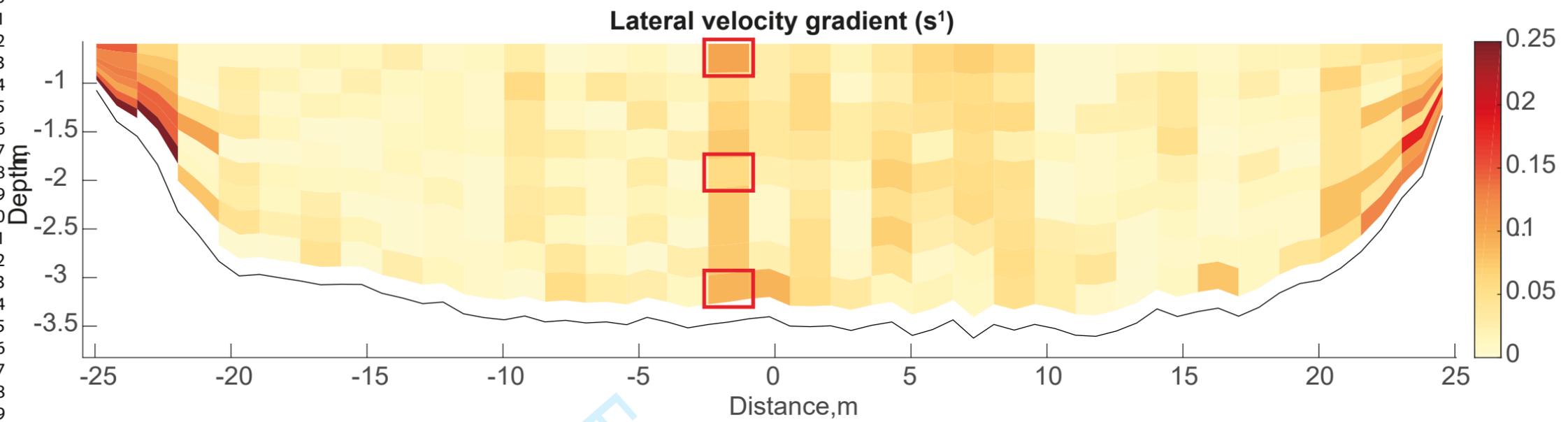


Figure 11: Standard deviation of the velocity estimated using methods A and B for 16 repeats at the Lizerne-Rhône confluence cross-section 9

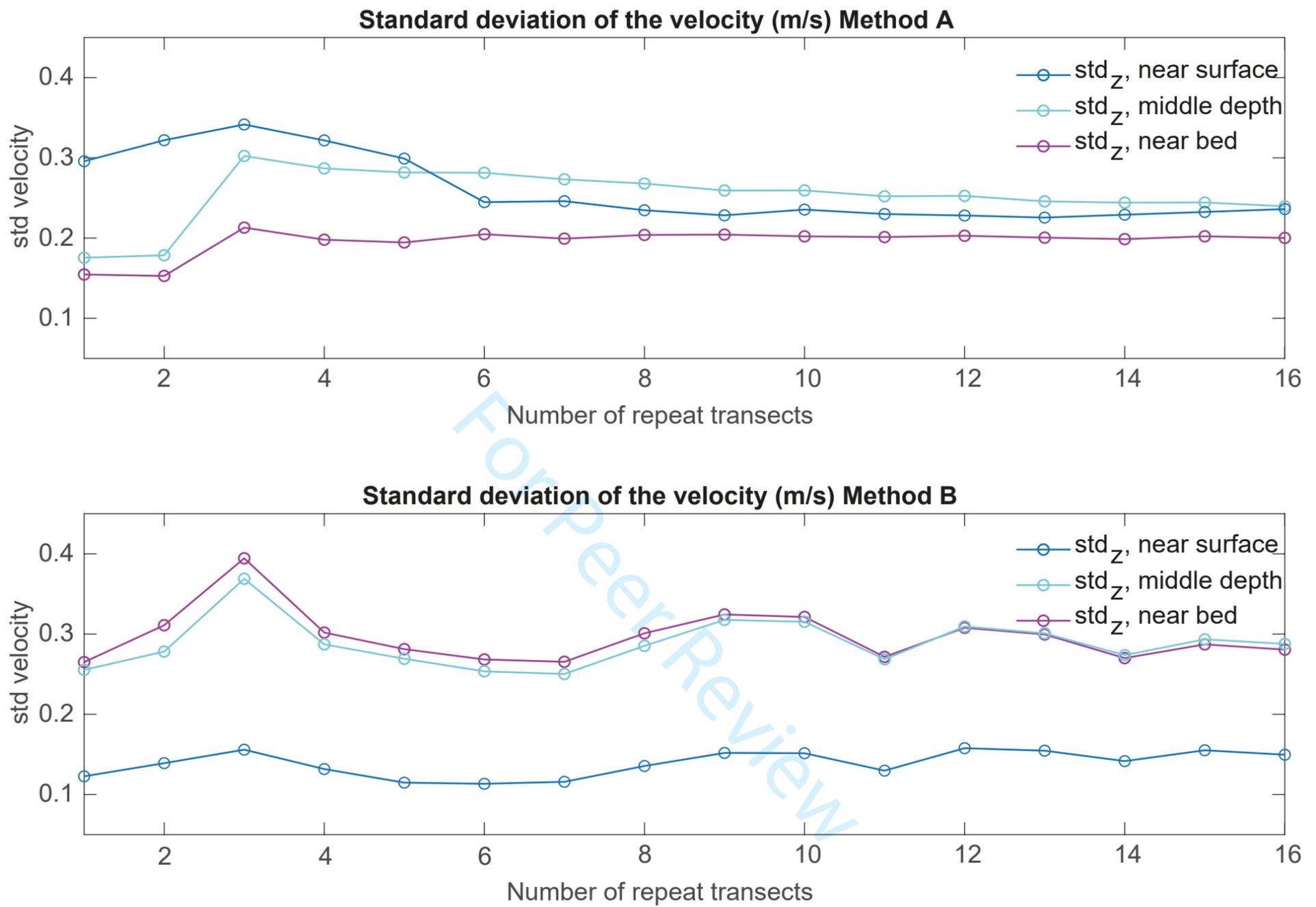


Figure 12: Error distributions related to GPS for a) Lizerne-Rhône confluence (cross-section 6) and c) Grande Eau- Rhône confluence (cross-section 3), and sensors accuracies for b) Lizerne-Rhône confluence (cross-section 6) and d) Grande Eau-Rhône confluence (cross-section 3), in estimating the secondary velocities using method A. view is looking downstream.

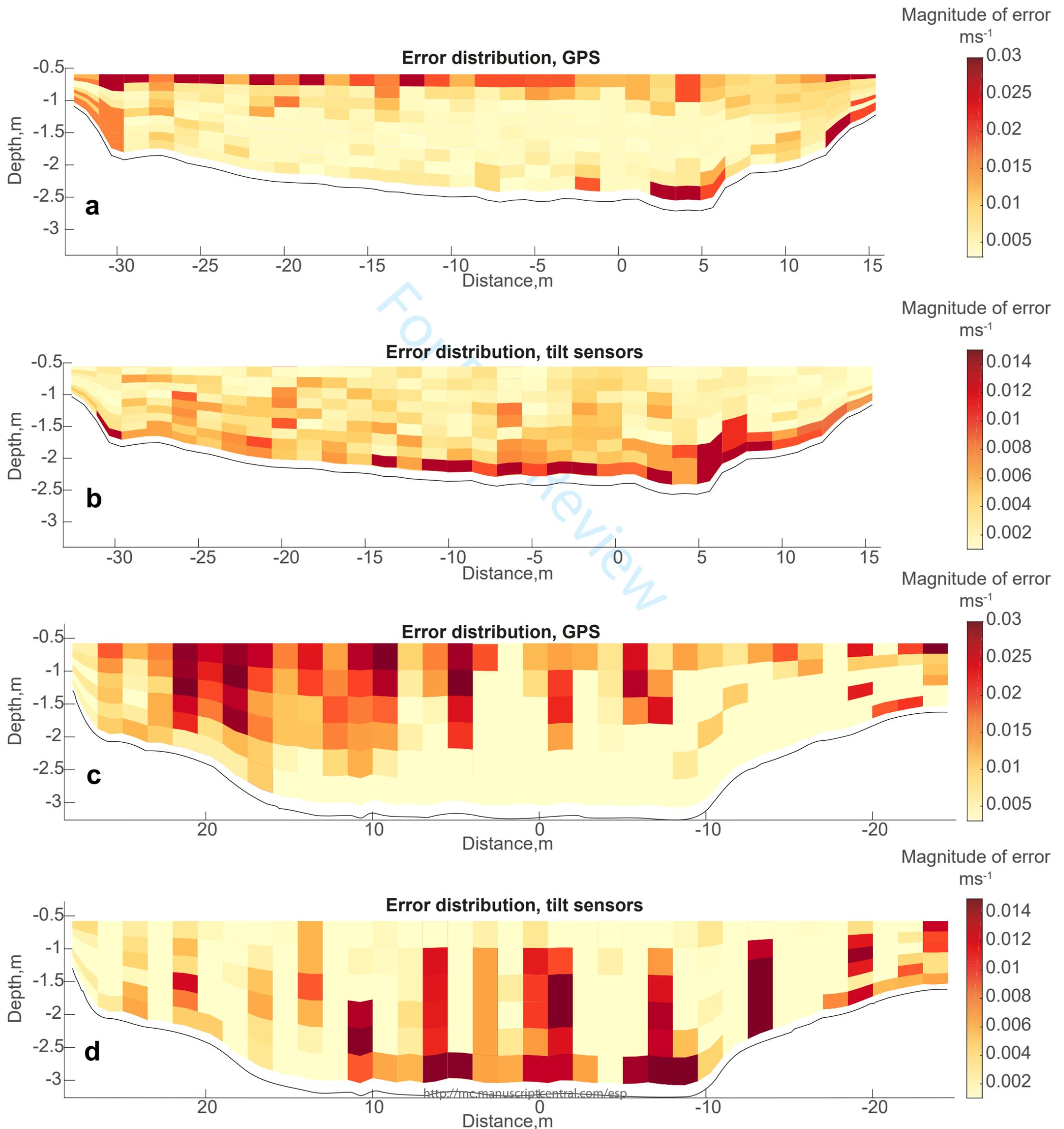


Figure 13: Maximum inhomogeneity allowance (m) using method B for a) Lizerne-Rhône confluence at cross-section 6 and b) Grande Eau-Rhône confluence at cross-section 3. view is looking downstream.

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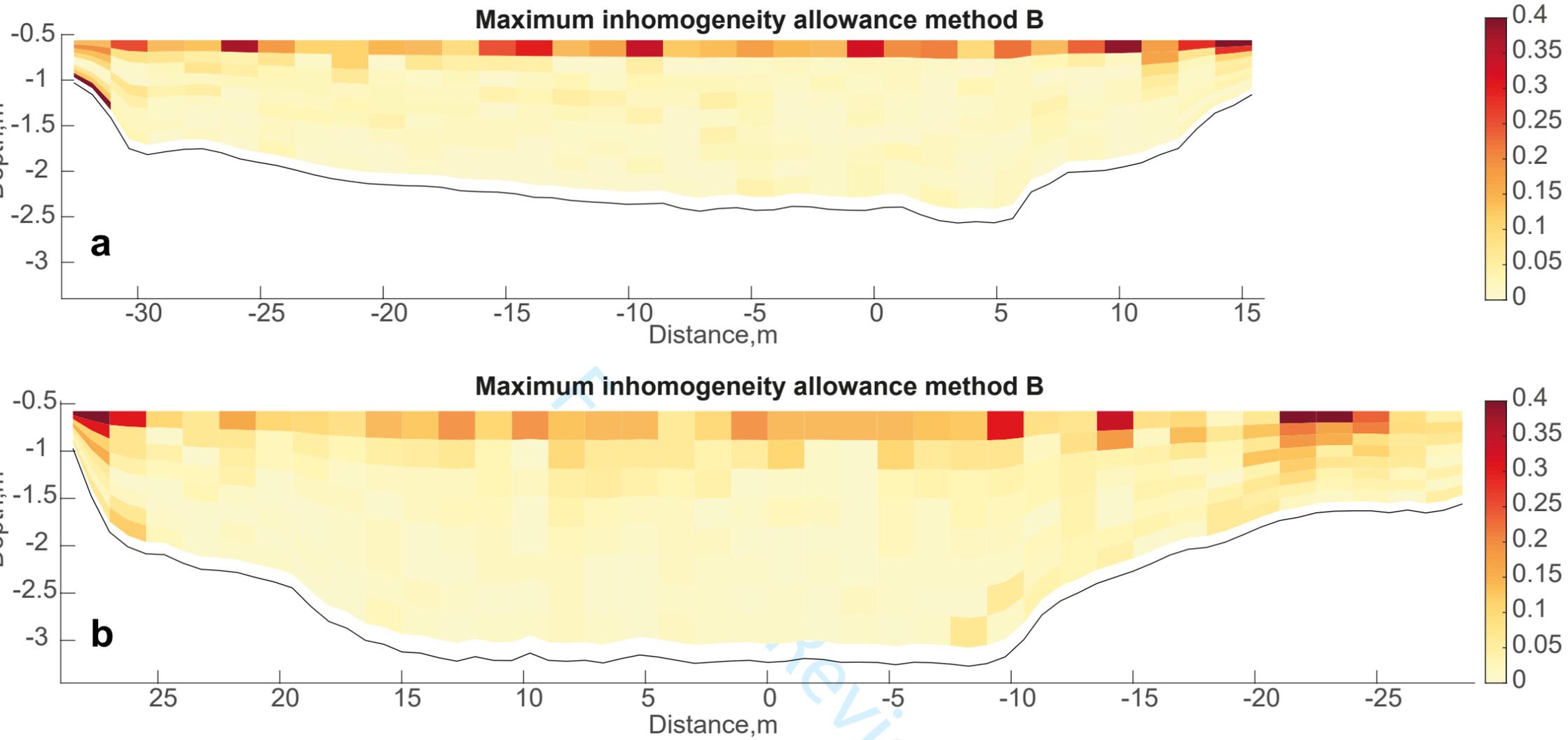


Figure 14: Primary velocities (contours) with secondary velocity vectors estimated using method A and B at cross sections 4,5 and 7 in Figure 3a at the Lizerne-Rhône confluence. view is looking downstream.

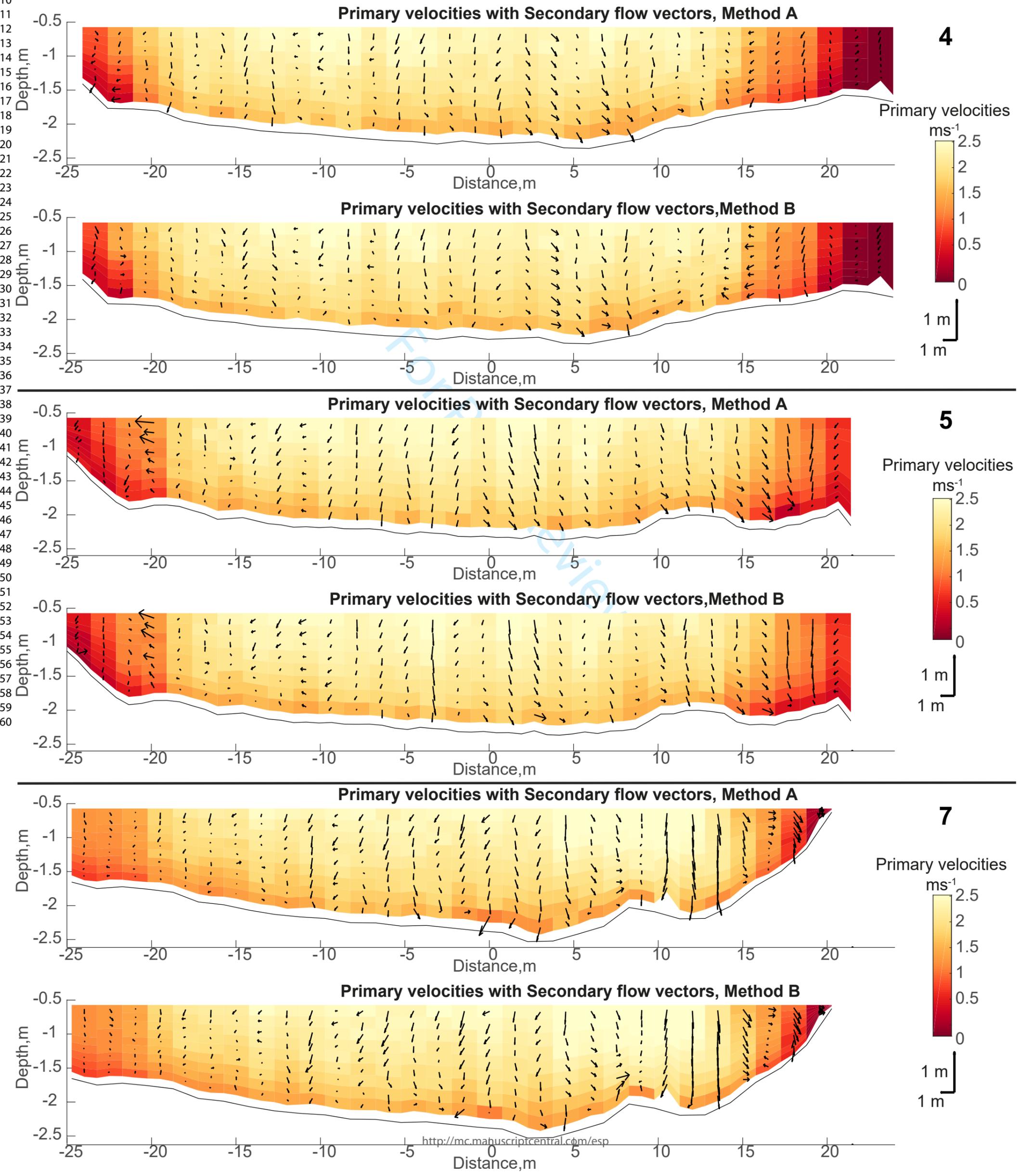


Figure 15: Primary velocities (contours) with secondary velocity vectors estimated using method A and B at cross sections 4,6 and 8 in Figure 3b at the Grande Eau-Rhône confluence. view is looking downstream.

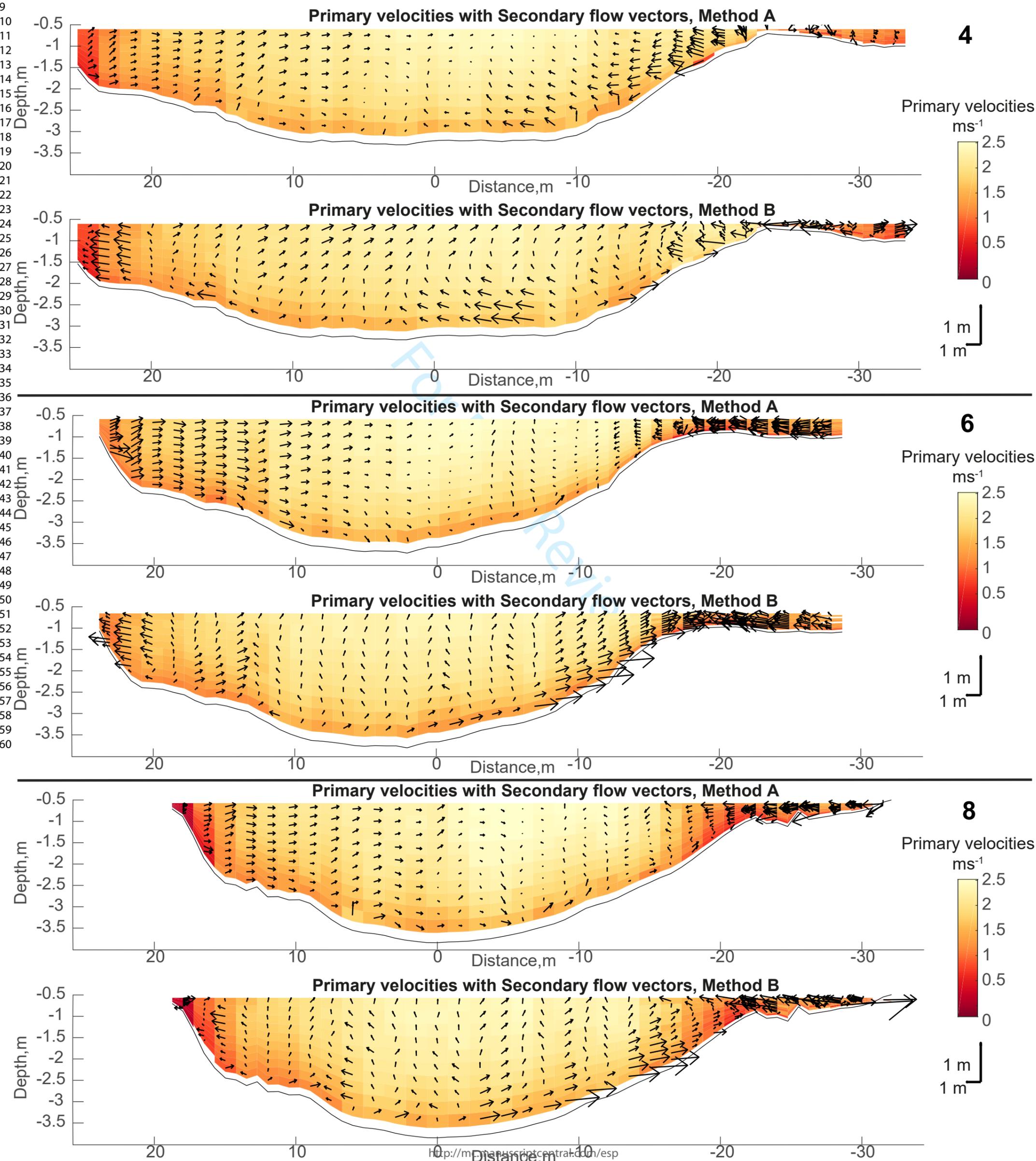
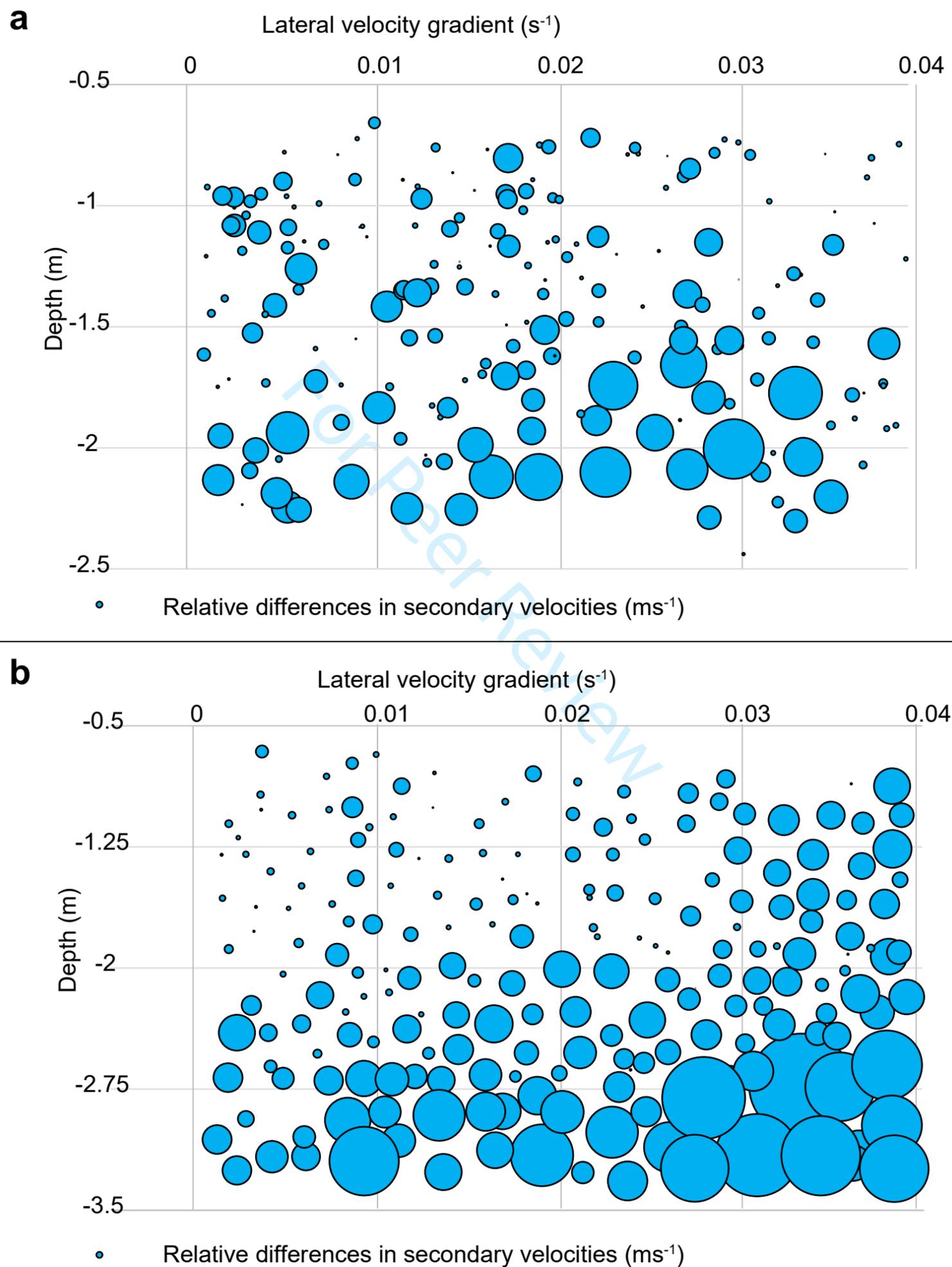


Figure 16: Relationship between lateral velocity gradient, depth and relative differences in secondary velocities for a) the Lizerne-Rhône confluence at cross-section 6 and b) the Grande Eau-Rhône confluence at cross-section 3



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3 1 “For the ESPL special issue: Measuring and numerical modelling of hydro-
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5 2 morphological processes in open-water”
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8 3 **Evaluation of aDcp processing options for secondary flow**
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10 4 **identification at river junctions**
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23
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28
29 11 **Abstract**

30
31 12 Secondary circulation in river confluences results in a spatial and temporal variation of
32
33 13 fluid motion and a relatively high level of morphodynamic change. Acoustic Doppler
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35 14 current profiler (aDcp) vessel-mounted flow measurements are now commonly used to
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37 15 quantify such circulation in shallow water fluvial environments. It is well established that
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39 16 such quantification using vessel-mounted aDcps requires repeated survey of the same
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41 17 cross-section. However, less attention has been given to how to process these data. Most
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43 18 aDcp data processing techniques make the assumption of homogeneity between the
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45 19 measured radial components of velocity. As acoustic beams diverge with distance from
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47 20 the aDcp probe, the volume of the flow that must be assumed to be homogeneous
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49 21 between the beams increases. In the presence of secondary circulation cells, and where
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51 22 there are strong rates of shear in the flow, the homogeneity assumption may not apply,
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3 23 especially deeper in the water column and close to the bed. To reduce dependence on
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5 24 this assumption, we apply a newly-established method to aDcp data obtained for two
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7 25 medium-sized (~60-80 m wide) gravel-bed river confluences and compare the results with
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9 26 those from more conventional data processing approaches. The comparison confirms that
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11 27 in the presence of strong shear our method produces different results to more
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13 28 conventional approaches. In the absence of a third set of fully independent data, we
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15 29 cannot demonstrate conclusively which method is best, but our method involves less
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17 30 averaging and so in the presence of strong shear is likely to be more reliable. We conclude
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19 31 that it is wise to apply both our method and more conventional methods to identify where
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21 32 data analysis might be impacted upon by strong shear and where inferences of secondary
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23 33 circulation may need to be made more cautiously.
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36 **Keywords**

37 Acoustic Doppler current profiler

38 Secondary circulation

39 River confluences

40 River junctions

41 **Introduction**

42 Acoustic Doppler current profilers (aDcps) are now used widely to measure river flow in
43 three-dimensions, notably for the quantification of secondary flows. Applications have

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3 44 been made to river bedforms (e.g., Parsons et al., 2005; Kostaschuk et al., 2009; Shugar
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5 45 et al., 2010), bends (e.g., Dinehart and Burau, 2005; Kasvi et al., 2013; Vermeulen et al.,
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7 46 2014a, 2015; Engel and Rhoads, 2016; Knox and Latrubesse, 2016; Kasvi et al., 2017;
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9 47 Lotsari et al., 2017; Parsapour-Moghaddam and Rennie, 2018), junctions (e.g., Parsons
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11 48 et al., 2007; Lane et al., 2008; Szupiany et al., 2009; Riley and Rhoads, 2012; Riley et al.,
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13 49 2015; Gualtieri et al., 2017), bifurcations (e.g., Parsons et al., 2007; Szupiany et al.,
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15 50 2012), canyons (e.g., Alvarez et al., 2017; Tomas et al., 2018; Venditti et al., 2014), deltas
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17 51 (e.g., Czuba et al., 2011) and gravity currents (e.g., Garcia et al., 2007; Garcia et al.,
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19 52 2012). Research has also shown the need to make repeat section measurements (e.g.,
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21 53 Szupiany et al., 2007; Jackson et al., 2008) and also to process these data carefully,
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23 54 (Muste et al., 2004; Rennie and Church 2010; Tsubaki et al., 2012; Parsons et al., 2013;
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25 55 Petrie et al., 2013). Such processing must take into account positioning (Rennie and
26
27 56 Rainville, 2006) and orientation (Zhao et al., 2014) errors, and the treatment of repeat
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29 57 section measurements (e.g., Szupiany et al., 2007; Jackson et al., 2008).

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31 58 This paper is concerned with recent observations regarding the inference of secondary
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33 59 flows from aDcp data and concerns regarding the assumption that flow is homogenous in
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35 60 the fluid volumes defined by the acoustic beams emitted from an aDcp and used to
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37 61 calculate any one point estimate (Vermeulen et al., 2014b). Acoustic beams are reflected
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39 62 by suspended particles, which, if moving, cause a Doppler shift in beam frequency, which
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41 63 is then detected at the sensor. This shift is directional so each beam measures the radial
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43 64 velocity, which is the velocity of particle motion parallel to the acoustic path. This can be
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45 65 assumed to be the flow velocity if the particle motion is identical to fluid motion. In order
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47 66 to resolve flow in more than one direction, aDcps require at least three acoustic beams to
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3 67 estimate three Cartesian components of velocity. The radial velocities originating from the
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5 68 beams are traditionally analyzed for a single measurement cycle at a single depth at a
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7 69 time (Vermeulen et al., 2014b). The velocity then applies to the volume of fluid defined by
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9 70 the beams at each depth. Flow within this volume is assumed to be homogeneous.
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11 71 However, as the beams spread from the sensor, depth bins increase in horizontal size
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13 72 (Rennie et al., 2002). This means that: (1) bins further from the sensor are likely to produce
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15 73 less reliable velocities because the bin size is greater and the flow within bins is more
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17 74 likely to be heterogeneous (Gunawan et al., 2011); and (2), even in smaller bins, velocities
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19 75 may be less reliable in zones of strong shear where also the within-bin flow is less likely
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21 76 to be homogeneous. In a river where measurements are made throughout the flow depth,
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23 77 the maximum shear may be close to the bed, where the beam divergence may also be
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25 78 greatest.

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31 79 One solution to this problem accounts for first order shear within the flow volume (e.g.
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33 80 Marsden and Ingram, 2004) through a Taylor expansion of the coordinate transform used
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35 81 to determine the Cartesian velocity components. Under this solution, flow is allowed to
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37 82 vary linearly within the bin, but the bin's volume becomes potentially larger with distance
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39 83 from the sensor. Vermeulen et al. (2014b) developed and tested a second solution. As
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41 84 explained in detail below, multiple radial (beam) velocity measurements within a single bin
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43 85 are put through a Cartesian transform to obtain a localized within-bin three-dimensional
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45 86 velocity. This method strongly reduces the volume over which homogeneity should be
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47 87 assumed and Vermeulen et al. (2014b) found that this significantly impacted
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49 88 interpretations of secondary velocities in the presence of strong shear. In this paper, we
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51 89 seek to quantify the effects of this method for the measurement of secondary flow in two
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3 90 medium-sized river junctions (c. 60-80 m post-junction channel width). River junctions are
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5 91 associated with very strong shear (e.g. Best and Roy, 1991; Biron et al., 1993, 1996a,
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7 92 1996b; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004, 2008; Konsoer
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9 93 and Rhoads, 2014; Sukhodolov et al., 2017), as well as well-developed secondary
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11 94 circulation (e.g. Ashmore et al., 1992; Rhoads and Kenworthy, 1995, 1998; Rhoads and
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13 95 Sukhodolov et al., 2001; Lane et al., 2008; Riley and Rhoads, 2012; Riley et al., 2015).
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17 96 Thus, understanding how to process effectively the aDcp data used to describe them is of
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19 97 paramount importance.

22 98 **Methods for estimating Cartesian velocity components from aDcp data**

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26 99 In this section, we describe the two different methodological approaches used in this study
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28 100 to estimate Cartesian velocity components: (1) Method A, the Vermeulen et al., (2014b)
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30 101 method; and (2) Method B, the conventional method. Common to all methods is the
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32 102 assumption that data are available from repeat measurement of the same cross-section,
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34 103 as has been shown to be critical for obtaining reliable estimates of secondary circulation
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36 104 from aDcp data (Szupiany et al., 2007), particularly when single transect measurements
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38 105 are not close enough together.
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42 106 ***Method A: based on Vermeulen et al., (2014b)***

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45 107 Application of the Vermeulen et al. (2014b) method requires mapping of radial beam
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47 108 velocity data onto a predefined mesh. This mesh requires both a bottom topography or
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49 109 bathymetric model, and an upper limit just below the water surface. As the measurements
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51 110 were made using several repeat transects for each cross section, the first step is to define
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54 111 a mean cross section for each set of individual transects (boat tracks). The second step

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3 112 is to define a grid mesh for this mean cross section. Third, all measured beam velocities
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5 113 are projected on to this cross section mesh. Finally, the beam velocities within each mesh
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7 114 cell are then used to resolve a Cartesian velocity for the mesh cell. Errors that influence
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9 115 these steps can be estimated.

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13 116 The first step is estimation of the mesh extremes, both the lower boundary or bathymetry
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15 117 model and the upper boundary near the water surface. To generate the bathymetry model
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17 118 we use depth soundings collected with the aDcp. We recognize that each beam may
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19 119 register a different distance of the stream bed from the sounder, especially as we are
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21 120 dealing with bathymetrically irregular cross-sections. Specifically, for each bottom track
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23 121 sounding within each transect, we use the UTM coordinates obtained with a coupled
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25 122 differential GPS (dGPS), the range of each bottom track beam return, and the instrument
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27 123 tilt to estimate the bed elevation and horizontal position of each beam impingement point
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29 124 on the bed. These bed positions are combined together to identify an initial mean transect.
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31 125 Provided a point is within a certain distance from the initial mean cross-section, LOWESS
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33 126 interpolation (Appendix A) is applied, which has the effect of defining a bathymetric model
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35 127 that gives most weight to points that appear to be closer to the cross-section. It is important
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37 128 to note that this mean transect is not necessarily orthogonal to the primary flow direction
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39 129 and so will not yield true primary and secondary flow estimates without further correction.
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41 130 We address this below.
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48 131 Once the initial bathymetric model is defined, we estimate a unique vector using the initial
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50 132 mean transect; that is the principal direction of the scatter cloud of all x and y UTM
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52 133 positions at the bed. This unique vector points in the direction of the largest eigenvector
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54 134 of the covariance matrix of all UTM positions (t). We then calculate the mean UTM position
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3 135 (ρ_{mean}) for each set of individual transects and the difference between each measured
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5 136 beam position (ρ_b) and the mean position. The dot product of these obtained values and
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7 137 the unique vector is then used to define the projection of each UTM position in the direction
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10 138 of the unique vector. To identify the final mean cross section, we sum up all individual
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12 139 projected vectors and obtain the best fit to all available data (Figure 1).

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15 140 To define the upper boundary of the mesh, we estimate the elevation of the water surface.
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17 141 As there is a blanking distance at the surface of the water during the measurement, we
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19 142 then remove this blanking distance, taken as 0.30 m. Thus, the mesh has also a blanking
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21 143 distance and the upper part of the cross-section is, strictly, the upper limit of available
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23 144 data, not the water surface.

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27 145 "Figure1"

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30 146 The second step uses the defined bathymetric model and available velocity bins within
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32 147 the measured area (not influenced by side lobes, and below the blanking distance) to
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34 148 define a cross-section mesh. The side-lobe interference is caused by the striking of the
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36 149 channel bed by side-lobe energy from each of the acoustic beams. This side-lobe energy
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38 150 has strong reflections from the bed, which result in echoes that overwhelm the signal from
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40 151 scatters near the bed. The thickness of the side-lobe layer is typically 6-7% of the
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42 152 measured depth (Morlock, 1996).

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47 153 To generate the mesh, the cross section is initially subdivided into vertical slices with equal
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49 154 widths (Δn). For each slice, the simplest definition of mesh cell thicknesses (Δz) divides
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51 155 each vertical equally. These verticals are converted to non-dimensional σ coordinates
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53 156 using following equation:

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$$\sigma = 1 - \left(\frac{\rho_v \cdot \mathbf{k} - \eta}{\rho_b \cdot \mathbf{k} - \eta} \right) \quad (\text{Vermeulen et al. 2014b}) \quad (1)$$

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7 158 where p_v stands for velocity measurement positions (m), p_b is the corresponding bed
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9 159 position (m) that is found using velocity measurement horizontal positions and applying
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11 160 the bathymetric model, \mathbf{k} is the upward pointing unit vector and η are the water surface
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14 161 fluctuations around the mean water level at which $z=0$.

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17 162 However, because of beam spreading and differences in the distance of the sounder from
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19 163 the bed, which varies with position of the sounder, this tends to produce a highly
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21 164 heterogeneous number of measurements in each cell within the mesh. The alternative,
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23 165 adopted here, is to allow mesh cell thickness to vary through the water column such that
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26 166 there is a roughly equal number of beam velocities contributing to each mesh cell (see
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28 167 Figure 2 for a typical distribution).

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31 168 As the river bed form is varying, to follow its shape, each mesh cell is considered to be a
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33 169 cuboid with 6 edges, two on the left side, two in the middle and two on the right side. To
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35 170 define these edges, the first step is to define the middle point of each mesh cell. Once
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37 171 defined, by calculating the slope for each half part of the mesh cell, edges can be obtained.
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40 172 The mesh cell faces are then calculated on the basis of adjacent verticals and the mesh
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43 173 cell upper and lower boundaries.

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46 174 To identify the beams that contribute to each mesh cell, an index for each beam velocity
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48 175 is defined, which shows its associated mesh cell, using the projection of each radial
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50 176 velocity onto the estimated mean cross section (Figure 2).

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53 177 “Figure 2”
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3 178 In the third step, the radial velocities for each beam (**b**) that contribute to each mesh cell
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5 179 (the N beam velocities) have to be transformed into Cartesian velocities (v_x , v_y and v_z)
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8 180 using:

$$11 \quad \begin{pmatrix} b_1 \\ \vdots \\ b_N \end{pmatrix} = \begin{pmatrix} q_1 \\ \vdots \\ q_N \end{pmatrix} \cdot \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \leftrightarrow \mathbf{b} = \mathbf{Q} \cdot \mathbf{u} \quad (2)$$

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16 182 where **q** is a unit vector which describes the direction of the acoustic beam.

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19 183 To obtain the raw beam velocities, we use matrix transformations obtained from the raw
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21 184 data to transform measured velocities in XYZ coordinates into beam velocities. The
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23 185 Vermeulen et al., (2014b) method includes in the transformations an explicit treatment of
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25 186 the random errors due to internal and external factors and the bias (systematic errors)
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27 187 caused by the measurement system and the nature of river flow (Tsubaki et al., 2012).
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29 188 Random errors include those that come from sampling a time-varying flow in the presence
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31 189 of strong gradients and represent a form of aliasing. By adding a combined term of errors
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35 190 ε , (2) becomes:

$$36 \quad \mathbf{b} = \mathbf{Q}\mathbf{u} + \varepsilon \quad (3)$$

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41 192 A least squares solution is fitted to (3) that minimizes the sum of the square of the errors.

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43 193 The optimal estimation ($\hat{\mathbf{u}}$) for (**u**) is then given by the normal equation:

$$44 \quad \hat{\mathbf{u}} = \mathbf{Q}^+ \mathbf{b} + \varepsilon \quad (4)$$

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49 195 where \mathbf{Q}^+ can be defined as:

$$50 \quad \mathbf{Q}^+ = (\mathbf{Q}^T \mathbf{Q})^{-1} \mathbf{Q}^T \quad (5)$$

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3 197 To solve three Cartesian velocity components, we need at least three equations. Each
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5 198 beam measurement in a mesh cell adds an equation. Where enough beam velocities are
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7 199 collected in a mesh cell and the equations are different from each other (beam velocities
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9 200 are measured from different directions), the velocity can be estimated. To check whether
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11 201 this is the case, the matrix describing the system of equations can be analyzed. In the
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13 202 processing we use the rank which indicates how many unknowns can be solved from the
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15 203 system of equations. When the rank is three, the three Cartesian velocities can be solved.
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17 204 Where the rank of the matrix is one or two, the system cannot be solved. Where the
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19 205 system of equations is overdetermined, the obtained solution is a matrix with more
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21 206 equations (rows) than unknowns (columns). The velocity can be solved using the
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23 207 generalized inverse of the matrix and in such a way that the sum of squared errors is
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25 208 minimized. As this combined term of errors also contains information about the turbulence
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27 209 and accuracy of the measurements, we can obtain the covariance matrix of the velocity
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29 210 components:

$$211 \quad \hat{\boldsymbol{\varepsilon}} = \mathbf{b} - \mathbf{Q}\hat{\mathbf{u}} \quad (6)$$

$$212 \quad \text{var}(\hat{\mathbf{u}}) = \frac{\hat{\boldsymbol{\varepsilon}}^T \hat{\boldsymbol{\varepsilon}} (\mathbf{Q}^T \mathbf{Q})^{-1}}{N - 3} \quad (7)$$

213 and the variance of the velocity across the section can be then estimated as:

$$214 \quad \text{var}(\mathbf{u}) = \frac{\text{var}(\hat{\mathbf{u}})}{N}$$

215 (8)

216 ***Method B: the standard aDcp method***

217 As the Doppler shift is directional, it can only measure radial velocities. With the standard
218 method, to determine Cartesian velocity components, radial velocities then have to be

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3 219 resolved into three orthogonal velocity vectors. To do so, at least three beam velocities
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5 220 pointed in known directions are required. Also, because the beams are measuring
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7 221 different water profiles along their individual slant ranges, the assumption of horizontal
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9 222 homogeneity must be taken into account. Hence, in the standard method, the three
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11 223 dimensional velocity for each depth bin for each ping can be solved for a typical four-beam
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14 224 system using the following equations (Mueller and Wagner, 2009):

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$$V_x = \frac{(b_3 - b_1)}{\sqrt{2} \sin \theta} \quad (9)$$

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$$V_y = \frac{(b_4 - b_2)}{\sqrt{2} \sin \theta} \quad (10)$$

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$$V_z = \frac{-(b_1 + b_3)}{(2 \cos \theta)} = \frac{-(b_2 + b_4)}{(2 \cos \theta)}$$

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28 228 (11)

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31 229 where V_y is the cross stream velocity assuming beam 3 is pointed upstream, V_x is the
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33 230 streamwise velocity, V_z is the vertical velocity, b_1 , b_2 , b_3 and b_4 are the radial velocities
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35 231 measured in beams 1,2,3 and 4 respectively and θ is the tilt angle of the beams referenced
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37 232 to vertical. These data should then be corrected for pitch and roll angles, obtained from
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39 233 the internal inclinometer and the heading angle from the internal compass. Velocity
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41 234 outputs are already corrected for ship velocities.

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45 235 To compare results obtained using Method B with those of Method A, we use the same
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47 236 mean cross section built for Method A, as well as the same bathymetric model and the
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49 237 same mesh. Each measured velocity vector is assigned to the appropriate mesh cell by
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51 238 projecting its 3D position (horizontal position and depth) onto the mean cross section

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3 239 mesh. We then average x, y, and z components of all velocities measured within a mesh
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5 240 cell to obtain the mean velocity vector for the mesh cell.
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8 9 241 **Methodology**

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12 242 This paper is motivated by the need to acquire three-dimensional data from junctions of
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14 243 tributaries with a main river stem, here the River Rhône, western Switzerland, and so the
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16
17 244 need to identify methods for reliably obtaining Cartesian velocities from aDcp data. The
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19 245 Rhône tributaries typically have very high bedload transport rates for short periods of time,
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21 246 leading to the formation of very large tributary mouth bars downstream of their junctions
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24 247 with the main river. These bars are maintained for weeks or months such that at lower
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26 248 tributary flow, with negligible sediment supply, there is a legacy effect of previous high
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28 249 momentum tributary events upon junction morphology and secondary flow formation.
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31 250 For this paper, we used a specially-designed rope and pulley system to collect aDcp data
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33 251 from the junction of two tributaries with the Rhône (Figure 3).
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35
36 252 “Figure 3”
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39 253 The Lizerne is a Rhône tributary of almost 20 km length that flows south-westward from
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41 254 the western slopes of the Tête Noire (2451m) or La Fava (2612m), in the Bernese Alps.
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44 255 This river is heavily regulated for hydropower with sediment extracted upstream of the
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46 256 junction. As a result, there is negligible sediment supply and no evidence of point bar
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48 257 formation. It reaches the Rhône between Ardon and Vétroz, forming a 90° junction angle
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50 258 and it has a bed that is nearly concordant with the Rhône.
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3 259 The Grande Eau is a second tributary of the Rhône River which has a length of 26 km and
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5 260 takes its source on the Vaud side of the Les Diablerets and flows into the Rhône River
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7 261 with a 70° confluence angle, near Aigle. The Grande Eau bed is 1.5 m higher than the
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10 262 Rhône such that it is markedly discordant.

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13 263 In this section, we: (1) describe the aDcp used to collect data; (2) describe how the aDcp
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15 264 was deployed; and (3) outline the analytical approaches used to interpret the results from
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17 265 the different methods. Although the method is valid for any aDcp that has an onboard
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20 266 compass and potential for differential GPS positioning, as is standard with most aDcps,
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22 267 we use a Sontek M9 aDcp in this study.

25 268 ***The Sontek M9 aDcp***

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28 269 The SonTek M9 aDcp is a nine-transducer system with three acoustic frequencies,
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30 270 configured as two sets of four profiling beams (3 MHz and 1 MHz transducers in Janus
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32 271 configurations) and one vertical beam (0.5 MHz Echo sounder) for depth measurements
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35 272 (SonTek YSI, 2010). It uses these two sets of four beams to provide raw radial velocity
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37 273 samples. These beams are equally spaced at 90° azimuth angles and are projected at an
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39 274 angle θ of 25 ° off the vertical axis (SonTek YSI, 2000). For the standard configuration,
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42 275 the four beams encompass a sampling diameter of 93% of the distance from the aDcp
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44 276 (7% of side-lobe) (SonTek YSI, 2000).

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46
47 277 The output velocities from the SonTek M9 Riversurveyor are either in Cartesian
48
49 278 coordinates (XYZ) that are relative to sensor orientation or in Earth coordinates (ENU) for
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51 279 a SonTek system with compass and tilt sensors. These raw velocity data in Earth
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53
54 280 coordinates or XYZ coordinates are already corrected for the ship motion. To apply

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2
3 281 Method A to Sontek output data, as this method is based on radial velocities, it is
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5 282 necessary to transform these output velocities to radial velocities. To do so, we add ship
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7 283 velocities to these output velocities and then apply the inverses of the instrument's matrix
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9
10 284 coordinate transformations (obtained from MATLAB files output by the SonTek data
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12 285 collection software RiverSurveyor). As the survey is being undertaken using a moving
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14 286 vessel, these radial velocities then have to be corrected again for the boat velocity. There
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16
17 287 are two key methods for doing this. The first uses the bottom tracking to measure the boat
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19 288 velocity relative to the river bed, under the assumption that the latter is stationary (i.e.
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21 289 there is no bedload transport). The second tracks the boat position using differential GPS
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23
24 290 (dGPS, e.g. Zhao et al., 2014). In this study, we corrected all raw beam velocities for ship
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26 291 velocities, using dGPS as we could not exclude the possibility of there being bedload
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28 292 transport.

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31 293 To apply Method B in this study, we use the raw velocity data in Earth coordinates and
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33 294 we correct it for pitch and roll angles, obtained from internal inclinometer and heading
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35 295 angle data for the internal compass. For SonTek M9 aDcps, pitch is a y-axis rotation and
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37 296 roll an x-axis rotation.

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40 297 Depending on the water depth and velocity, the Sontek M9 firmware changes the acoustic
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42 298 operating frequency and the water profiling mode on-the-fly, thus the number of sampled
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44 299 points in the vertical varies automatically from one profile to the next. Specifically, when
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46
47 300 the water is shallower than 0.75 m and the maximum velocity is less than 0.4 ms^{-1} , the
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49 301 M9 reports data acquired with a 3 MHz frequency using the pulse coherent mode to obtain
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51 302 a 2cm depth measurement resolution. For deeper situations, this frequency changes to 1
52
53
54 303 MHz pulse coherent pings using a 6cm aDcp cell size. If the maximum velocity is greater
55
56 304 than 0.4 ms^{-1} then SmartPulse (i.e., broadband) mode is utilized, with the 3 MHz beams
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3 305 if depth is less than 5 m and the 1MHz beams if depth is greater than 5m, with the aDcp
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5 306 cell size optimized based on the current water depth. As a result of these on-the-fly
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7 307 changes, each measured profile has a different number of aDcp cells and different aDcp
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9 308 cell sizes. Hence, to correct the aDcp cell size variability, for both methods A and B there
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11 309 is the need to define a cross-sectional mesh and to project the measured velocities to this
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13 310 mesh. For Method A we use the beam velocity vertical positions in a non-dimensionalized
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15 311 coordinate system using equation 1, within the predefined mesh explained in section 2.1.

19 20 312 ***Deployment of the Sontek M9 in the river junctions***

21
22 313 The survey work was undertaken in two junctions of the Swiss River Rhône, the Lizerne-
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24 314 Rhône confluence in August 2017 and the Grande Eau-Rhône confluence in May 2018,
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26 315 using a Sontek M9 vessel mounted aDcp and a specially-designed rope-pulley system
27
28 316 (Figure 3c). The survey was spatial, monitoring 11 cross-sections from upstream of the
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30 317 junction to its downstream at the Lizerne-Rhône confluence with a Momentum ratio (Mr)
31
32 318 of 0.018 (Figure 3a) and 11 cross-sections at the Grande Eau-Rhône confluence with a
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34 319 Mr of 0.022 (Figure 3b). Table 1 shows the general characteristics of these two
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36 320 confluences on the date of the measurements.

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40
41 321 “Table 1”

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44 322 As proposed previously by Dinehart and Burau (2005), Szupiany et al. (2007), Gunawan
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46 323 et al. (2011) and Vermeulen et al., (2014b) at least five repeats are required to have a
47
48 324 robust estimation of secondary velocities. Hence, in this paper, data are processed for
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50 325 cross-section 6 at the Lizerne-Rhône confluence (Figure 3a), and for cross section 3 at
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52 326 the Grande Eau-Rhône confluence (Figure 3b). Identification of the minimum number of
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3 327 repeat transects necessary per cross-section was undertaken using cross-section 9 at the
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5 328 Lizerne-Rhône confluence (Figure 3a), which involves 16 repetitions. We noted that after
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7 329 application of Method A, the standard deviation of velocity stabilized with six repetitions,
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9 330 which is the number we adopt for this study.
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12 13 331 ***Bin position error determination*** 14

15 332 Application of Method A requires estimation of the error terms in (2). The size of the
16
17 333 sampling volume in each beam is determined by the size of the bin used. As the SonTek
18
19 334 M9 aDcp uses different bin sizes depending on the water track frequency (section 2.1.3),
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21 335 these volumes could vary. Applying Method A might improve the velocity estimation for
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23 336 large measurement volumes at depth, as it does not rely on the homogeneity assumption.
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25 337 But as bins with a small number of velocity measurements will have greater error, this
26
27 338 method can estimate velocities with error. Also, if the beam velocity distribution within
28
29 339 each mesh cell is not linear, as averaging is made in the middle of each mesh cell, it can
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31 340 introduce error in velocity estimation. Thus, it is necessary to calculate a minimum
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33 341 necessary mesh cell size when applying Method A.
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39 342 Method B is inherently limited by spatial averaging due to the potential use of divergent
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41 343 beams and the associated homogeneity assumption. In other words, one must assume
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43 344 that the velocity is homogeneous over the horizontal domain defined by beam divergence
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45 345 (Eq.12). Method A has the advantage that velocities are recorded within an individual
46
47 346 beam depth bin, thus no spatial averaging between beams is required. However, in order
48
49 347 for Method A to overcome the uncertainty induced by spatial averaging inherent to Method
50
51 348 B, it is essential that the bin location is known explicitly. Error in bin location can be induced
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53 349 by dGPS position and or tilt sensor (pitch and roll) errors. We therefore compare possible
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3 350 bin position errors using Method A to beam divergence obtained from Method B to indicate
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5 351 when Method A should be advantageous over Method B.
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8 352 Beam divergence is the spatial separation of the beams due to the Janus configuration of
9
10 353 the beams with beam angles of 25° . This divergence determines the sampling volume that
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12 354 must be considered homogeneous for Method B and can be calculated using equation
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14 355 12:
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17
18 356 $x_b = 2d \tan \theta$ (12)
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20

21 357 where d is the depth in m and θ is the beam angle which for a SonTek aDcp is 25° . The
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23 358 aDcp dGPS is used to reference the velocity measurements in space and to estimate the
24
25 359 ship velocity. If dGPS is used for ship velocity, this introduces errors in measurement of
26
27 360 the absolute water velocity (because ship velocity is subtracted from the water velocity
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29 361 measured in the reference frame of the aDcp). This uncertainty introduces error in velocity
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31 362 calculations.
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35 363 To estimate the errors due to dGPS and the tilt sensors, in this study we assume normally
36
37 364 distributed random errors with a standard deviation of $\pm 1^\circ$ for tilt sensors, based on
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39 365 manufacturer specifications, and a normally distributed displacement error measured by
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41 366 the dGPS for the dGPS positions (as a function of satellite configuration during
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43 367 measurement), and we apply a Monte Carlo approach which we run 100 times sampling
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45 368 under these uncertainties. Each time we calculate the estimated secondary velocity
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47 369 differences as compared with the original secondary velocities.
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52 370 To be able to reduce the uncertainty due to velocity estimation using Method A compared
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54 371 to Method B, the errors induced in Method A related to GPS uncertainty and tilt sensors
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3 372 must be less than the errors in Method B due to beam divergence and the homogeneity
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5 373 assumption. Hence, Method A can be used if the error associated with a minimum aDcp
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7 374 cell size is in between the error due to beam divergence and the maximum estimated error
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10 375 due to the GPS and tilt sensors. Otherwise using this method introduces more error in
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12 376 velocity estimations than using Method B.

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15 377 ***Data interpretation***

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18 378 Methods A and B, described above, were applied to the Sontek M9 data, to determine
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20 379 Cartesian velocities (v_x , v_y and v_z). As our interest is in process estimation, here we
21
22 380 describe the methods we apply to the Cartesian velocities to estimate processes relevant
23
24 381 to junction dynamics. In order to distinguish between primary and secondary components
25
26 382 of flow, we need to rotate the initial mean transect. Options for doing this are reviewed in
27
28 383 Lane et al. (2000) and we do not assess them here, but rather apply the zero net cross
29
30 384 stream discharge definition (Lane et al., 2000). By calculating the mean values of the x
31
32 385 and y velocity components (U and V), we then calculate the velocity magnitude (v). By
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34 386 rotating these velocity components to the direction of the cross-stream velocity, using the
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36 387 unique vector (σ), primary velocity vectors (\mathbf{v}_p) and secondary velocity vectors (\mathbf{v}_s) then
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39 388 can be estimated.

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44 389
$$v = \sqrt{U^2 + V^2}$$

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46 390 (13)

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49 391
$$\begin{pmatrix} \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} U \\ V \end{pmatrix} / v \quad (14)$$

50
51
52
53 392 where σ_x and σ_y are sin and cos of the angle between the section angle and east.

$$393 \quad \mathbf{v}_p = \sigma_x \mathbf{v}_x + \sigma_y \mathbf{v}_y \quad (15)$$

$$394 \quad \mathbf{v}_s = -\sigma_y \mathbf{v}_x + \sigma_x \mathbf{v}_y \quad (16)$$

395 However, secondary circulation is all flow that is orthogonal to the primary flow and not
 396 just horizontal flow; there should be not net secondary flux in a section; and so correction
 397 should also consider vertical velocities. Thus, we extend these relationships to include
 398 vertical velocities:

$$399 \quad \begin{pmatrix} \sigma_{x,1} & \sigma_{x,2} & \sigma_{x,3} \\ \sigma_{y,1} & \sigma_{y,2} & \sigma_{y,3} \\ \sigma_{z,1} & \sigma_{z,2} & \sigma_{z,3} \end{pmatrix} = \begin{pmatrix} U \\ V \\ W \end{pmatrix} / v \quad (17)$$

400 where: U , V and W are the mean velocities of x , y and z velocity components, respectively
 401 and v is the magnitude of the velocity which can be obtained using:

$$402 \quad v = \sqrt{U^2 + V^2 + W^2} \quad (18)$$

$$403 \quad \mathbf{v}_p = \sigma_{x,1} \mathbf{v}_x + \sigma_{x,2} \mathbf{v}_y + \sigma_{x,3} \mathbf{v}_z$$

404 (19)

$$405 \quad \mathbf{v}_s = \sigma_{y,1} \mathbf{v}_x + \sigma_{y,2} \mathbf{v}_y + \sigma_{y,3} \mathbf{v}_z$$

406 (20)

$$407 \quad \mathbf{v}_v = \sigma_{z,1} \mathbf{v}_x + \sigma_{z,2} \mathbf{v}_y + \sigma_{z,3} \mathbf{v}_z$$

408 (21)

409 To estimate velocity gradients, and to correct for weak curvature with the survey method
 410 at the edges of each transect line (e.g. Figure 3), all data have been transformed into row
 411 and column coordinates (η and ζ) using the following transformation:

$$\left(\frac{\partial}{\partial z}\right) = \begin{pmatrix} \frac{\partial \eta}{\partial z} & \frac{\partial \zeta}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial \eta} \\ \frac{\partial}{\partial \zeta} \end{pmatrix} \quad (22)$$

where n and z are horizontal and vertical coordinates on the section plane, respectively (Vermeulen et al., 2014b).

Results

Primary and secondary velocities

Primary and secondary velocities estimated using methods A and B for the Lizerne-Rhône confluence appear to be similar at cross-section 6 (Figures 4a and 4b) and the differences in estimated secondary flows are minor. The differences are most pronounced between 10 and 5 m, in the middle of the main channel.

These primary and secondary velocity patterns show higher differences at cross-section 3 of the confluence of Grande Eau-Rhône (Figures 4c and 4d) despite it having a similar momentum ratio to the Lizerne during measurement. Primary velocities differ significantly between methods A and B: (1) at greater distance from the aDcp because the bins contain larger volumes of water assumed to be homogenous; and (2) at the edges of the cross-section where there are more beam velocity measurements (contours in Figures 4c and 4d). Secondary velocity vectors estimated using Method A indicate flow convergence at the surface and flow descending towards the riverbed throughout the centre of the channel (Figure 4c). This is due to a high degree of bed discordance between the Grande Eau and the Rhône, which increases the penetration of the tributary flow into the main channel over the junction, and which forms a zone of high lateral and vertical shear, on the one hand, and main channel narrowing because of penetration of the tributary mouth bar on the other

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3 433 hand. The secondary velocity vectors estimated by Method B show a weaker penetration
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5 434 of the tributary flow into the main channel, which results in a reverse flow towards the bank
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7 435 on the tributary side of the channel at the surface of the mixing interface (Figure 4d). In
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10 436 this case, the core of the secondary circulation is located in the middle of the main channel
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12 437 and closer to the inner bank.

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14
15 438 “Figure 4”

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17
18 439 Figure 5 and Figure 6 quantify the differences in primary and secondary velocity patterns
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20 440 estimated using methods A and B, for the Lizerne-Rhône confluence. Figures 5a and 5c
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22 441 and Figures 6a show that almost 4% of mesh cells have a relative difference in primary
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24 442 velocities between methods A and B of more than 10%. These differences can exceed
25
26 443 0.2 ms^{-1} and so they are relatively small. Velocity differences are more pronounced in
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28 444 estimated secondary velocities, with almost 82% of mesh cells having a difference of more
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30 445 than 10%, and almost 37% of mesh cells having a difference of more than 50% (Figure
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32 446 5b, 5d and 6b).

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37 447 “Figure 5”

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40 448 “Figure 6”

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43 449 At the Grande Eau-Rhône confluence, these differences are greater as compared with
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45 450 those of the Lizerne-Rhône confluence. Figures 7a, 7c and 8a show that these differences
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47 451 for primary velocities exceed 0.4 ms^{-1} in the zone of high vertical and lateral shear and
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49 452 near the inner bank. Almost 20% of the mesh cells have a relative difference in primary
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51 453 velocities between methods A and B of more than 10%. The secondary velocity
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53 454 differences are more pronounced between these two methods. Figures 7b and 7d show
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3 455 differences with a magnitude of 0.4 ms^{-1} near the edges and near the bed. Almost all the
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5 456 mesh cells have a difference in estimated secondary velocities between two methods.
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7 457 Figure 8b shows that almost 93% of the mesh cells have a relative difference of 10%
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10 458 between methods A and B. although this value decreases to 55% for a relative difference
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12 459 of 90% between these two methods.
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15 460 "Figure 7"
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18 461 "Figure 8"
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20 21 462 ***Velocity gradients*** 22

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24 463 As Figure 9 shows, there is a strong relationship between lateral gradient in secondary
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26 464 velocities and differences between the secondary velocities estimated using methods A
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28 465 and B for both the Lizerne-Rhône and the Grande Eau-Rhône confluences. This is
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30 466 because a stronger velocity gradient increases the probability that the assumption of flow
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32 467 homogeneity within a bin is likely to fail. Indeed, the marked differences between methods
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34 468 A and B at the Grande Eau confluence (Figure 7) are also in a zone of strong lateral shear.
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38 469 "Figure 9"
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40 41 470 ***Number of repeat transects*** 42

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44 471 One way to reduce data fluctuations due to random errors and turbulence, during the
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46 472 measurement using moving vessel aDcps, is to average by using several repeat transects
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48 473 together in one cross section. As each estimated velocity measurement is a single sample
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50 474 in time, adding in a repeat section adds in an additional estimated velocity measurement.
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52 475 Under [8], this should cause the variance to increase, despite the number of
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54 476 measurements used in its estimation increasing, until the point at which there are enough
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3 477 repeats to capture the effects the range of scales of variation in turbulence impacting the
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5 478 measurement. Then, this variance will become stable. At this stage we can consider the
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7 479 number of repeats as the minimum number required to have a robust estimation of
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9 480 secondary velocity vectors that is to have reached estimates of velocity that are
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11 481 asymptotic on this stable state.
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14 482 Here we apply both methods A and B to the survey of 16 repeats at cross-section 9 in
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16 483 Figure 3a at the Lizerne-Rhône confluence. To allow a reasonable comparison, three
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18 484 mesh cells in the middle of the cross section, and at three different depths (near the
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20 485 surface, middle depth and near the bed) have been chosen (Figure 11). Results show
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22 486 that by using Method A, after six repeats, a stable variance of the velocity estimator is
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24 487 obtained at the Lizerne-Rhône confluence (Figure 11a). Many more repeats are needed
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26 488 using Method B (Figure 11b) and this is likely because Method B uses fewer
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28 489 measurements per mesh cell. These results also show a higher standard deviation of the
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30 490 velocity estimation near the surface, using Method A and before achieving the stable
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32 491 situation. This can be explained by the fact that near the surface Method A is more
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34 492 sensitive to errors caused by positioning, while near the bed, hence with distance from
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36 493 the sounder, as the beam spread increases, the improvement obtained using Method A
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38 494 is more pronounced (Figure 11a).
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44 495 "Figure 10"

46 496 "Figure 11"

49 497 ***DGPS and tilt sensor uncertainty analysis***

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52 498 As explained above a normally distributed random error has been applied 100 times to
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54 499 both dGPS positioning (by adding a random offset) and tilt sensors (by changing pitch and
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3 500 roll angles randomly) and the secondary velocities have been estimated using Method A
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5 501 for each perturbed dataset. As Figure 12 shows, the magnitude of errors related to dGPS
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7 502 accuracy are higher than those related to tilt sensor accuracy, for both confluences. These
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10 503 values can reach $\pm 0.03 \text{ ms}^{-1}$ and confirms the earlier finding of Rennie and Rainville
11
12 504 (2006) which showed that GPS corrections can have average errors of about $\pm 0.03 \text{ ms}^{-1}$
13
14 505 (Figures 12a and 12c). These magnitudes are also higher near the surface and near the
15
16 506 bed for the Lizerne-Rhône confluence (Figure 12a). Near the surface, as there fewer
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18 507 measurements that can contribute to the estimation of aDcp position and tilt, uncertainties
19
20 508 in dGPS data will have a greater effect. Near the bed, as the velocity gradient is higher,
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22 509 errors will be greater as well. Figure 12c shows higher magnitudes near the surface at
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24 510 cross-section 3 in Figure 3b for the Grande Eau-Rhône confluence.
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29 511 Errors related to tilt sensor uncertainty are higher where there is a higher velocity gradient.
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31 512 This is related to the fact that within the mesh cells with higher velocity gradients, as the
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33 513 velocity distribution is not linear, and as averaging is made in the middle of the mesh cell,
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35 514 it is more probable that the velocity will be affected by sensor inaccuracies of bin
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37 515 positioning, and so be in error (Figures 12b and 12d).
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41 516 "Figure 12"
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44 517 ***Homogeneity assumption analysis***

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47 518 Figure 13 shows the maximum inhomogeneity allowance, using Method B for both case
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49 519 studies. These results are obtained by dividing the velocity gradient obtained from
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51 520 equation 22 by the divergence of the beams from equation 12. They confirm that, for the
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53 521 homogeneity assumption to be valid and thus error to be minimized using Method B, the
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3 522 maximum mesh cell size, which can be used is as small as 5cm near the bed. Clearly,
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5 523 this is impossible as the configuration of the beams using aDcps always results in beam
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7 524 divergence greater than 5cm.
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10 525 "Figure 13"
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13 526 ***Primary and secondary flow patterns*** 14 15

16 527 In this section, we compared estimated primary and secondary velocities using methods
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18 528 A and B for other cross sections in Figure 3 for both river confluences.
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21 529 Figure 14 shows the results for cross sections 4, 5 and 7 (in Figure 3a) at the Lizerne-
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23 Rhône confluence. These cross sections also show similar results in primary and
24 530 secondary velocity patterns for both methods A and B. Figure 15 shows different patterns
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26 531 in primary and secondary velocities estimation using Method A and B for cross sections
27
28 532 4,6 and 8 in Figure 3b at the Grande Eau-Rhône confluence. Method A leads to the
29
30 533 identification of a stronger and more coherent tributary penetration at cross-section 4 and
31
32 534 weaker upwelling mid-channel, giving the impression of less intense secondary circulation
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34 535 (Figure 15). At section 6, flow towards the true left across the shallow top of the tributary
35
36 536 mouth bar is identified and is coherent with Method A. At the channel-scale there is
37
38 537 general flow convergence reflecting channel narrowing (Figure 15). When using Method
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40 538 B, these patterns are less coherent and flow is towards the true right in the vicinity of the
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42 539 tributary mouth bar. These patterns are repeated for section 8 (Figure 15).
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50 541 "Figure 14"
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53 542 "Figure 15"
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543 Discussion

544 In this paper we used data collected with boat-mounted aDcp technology at two
545 confluences of the Swiss river Rhône, both with similar and very low momentum ratios
546 (0.018, 0.022) and analysed these using two different methods, A and B, to estimate
547 Cartesian velocity components. Method A is based on a methodological approach
548 developed by Vermeulen et al. (2014b). It differs by treating explicitly each individual beam
549 velocity based on its position within a predefined mesh. Results show that this method
550 reduces the volume over which the flow must be assumed to be homogenous (Fig 13). It
551 can, but not necessarily does, result in differences in estimated primary and secondary
552 velocities as compared with the more traditional method (B in this study), that involves
553 determining velocities by averaging data from the spreading beams. Our results show that
554 these differences are more pronounced in estimated secondary velocities than primary
555 velocities and are higher where there is a greater lateral velocity gradient (Figure 9). The
556 comparison between the two case studies shows that even though both confluences have
557 a very low momentum ratio, as the confluence of the Grande Eau-Rhône has a more
558 complex shear zone, likely due to the effects of bed discordance, and there are more
559 significant differences in the estimation of primary and secondary velocities. This is related
560 to the extent to which spreading of the aDcp measurement beams influences the
561 secondary velocities, particularly in relation to lateral gradients in flow conditions. More
562 standard methods (Method B in this study) are valid if the flow is completely homogenous
563 over the diameter of the fluid column that the beams spread. This diameter varies over
564 depth and is largest near the bed. In the case of the Grande Eau-Rhône confluence where
565 stronger lateral velocity gradients exist in the flow, individual beams will not be measuring

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3 566 homogenous conditions, particularly near the bed and in the zone of high shear near the
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5 567 inner bank, because the spread of the beams may be greater in diameter than the width
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7 568 of the zone of lateral velocity variation. In this case, as Method A involves less spatial-
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10 569 averaging than Method B, it may provide more accurate information on the flow behavior,
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12 570 but such a conclusion really needs a third and independent method to confirm it. At the
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14 571 Lizerne-Rhône confluence, even though the momentum ratio is similar to Grande Eau-
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16 572 Rhône confluence, there is only more localized shear in the flow and a simplified shear
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18 573 zone (Figure 9). In such a situation, using Method B to detect the large scale patterns of
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20 574 secondary flow may be more advantageous, because it involves more spatial averaging.
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24 575 The above discussion suggests that whether or not high rates of lateral shear influence the
25
26 576 potential importance of Method A depends on distance from the aDcp: with more
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28 577 divergence at greater depths, lower levels of lateral shear are likely to be acceptable.
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31 578 Figures 16a and 16b quantifies the relationship between lateral velocity gradient, depth
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33 579 and the magnitude of the relative differences in secondary velocities estimated using
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35 580 methods A and B for the cross-section 6 of the Lizerne-Rhône and cross-section 3 of the
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37 581 Grande Eau-Rhône confluences, respectively. At the Lizerne-Rhône confluence, as the
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39 582 zone of high lateral shear is absent, even though there is a strong relationship between
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41 583 the magnitude of the relative differences in secondary velocities estimated using methods
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43 584 A and B and the depth (Figure 16a), their relationship with the lateral velocity gradients is
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45 585 poor. In contrast, for the case of the Grande Eau-Rhône confluence (Figure 16b), where
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47 586 increasing the lateral velocity gradient and depth results in higher relative differences in
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49 587 secondary velocities. Thus, the need to use Method A will depend on the case being used
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51 588 and the extent to which there is lateral shear at greater distances from the aDcp. This is
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3 589 why whilst it may be tempting to introduce some kind of shear or velocity gradient
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5 590 threshold to identify when Method A might be preferable, to do so would be misleading as
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7 591 the threshold will also depend on the distance of the shear from the aDcp.
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10 592 "Figure 16"
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13 593 Results also confirm that several repeat transects are indispensable to provide a robust
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15 594 estimation of secondary circulation and to reduce the effect of spatial inhomogeneity and
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17 595 temporal variations. Although Method A reduces the minimum number of repeat transects
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19 596 needed to estimate the secondary velocities, a larger number of these minimum repeat
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21 597 transects (6 or more repeats for Lizerne-Rhône confluence) appeared to be required. This
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23 598 is higher than in the earlier findings of Szupiany et al. (2007) and Vermeulen et al., (2014b)
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25 599 who argue that 5 repeats are enough to have a robust estimation of the turbulence
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27 600 averaged velocity. We also note that an even number of repeats may be important to
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29 601 avoid directional bias in dGPS positions.
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34 602 Since Method A is based on the position of beams, if the bin position errors related to
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36 603 dGPS accuracy as well as sensor tilt are greater than homogeneity errors associated with
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38 604 beam divergence, standard Method B is more reliable. This is likely to be the case
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40 605 particularly in rivers shallower than those studied here and where high resolution is
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42 606 required due to large velocity gradients. In rivers of the scale studied here, and deeper,
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44 607 by increasing the mesh cell size, we can still have sufficient data to estimate velocity
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46 608 vectors, and the effects dGPS and tilt sensor errors have a minor effect. This confirms the
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48 609 earlier findings by Vermeulen et al., (2014b), which showed that Method A provides the
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50 610 greatest improvement where the aDcp cell size is much smaller than the beam spread.
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53 611 We are not yet in a position to identify the depth at which Method A becomes preferable
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3 612 to Method B, and again this will depend on other parameters such as the intensity of shear
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5 613 and so may not be readily generalizable between confluences.

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7 614 The difficulty of identifying the depths of rivers and intensities of shear that make one
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10 615 method preferable over another precludes adoption of simple quantitative guidance on
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12 616 which method to use when. As both methods have some disadvantages, we argue that
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14 617 both methods should be applied. If they give similar results, then there should be
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17 618 confidence in both. If and where they differ, analysis should be undertaken to identify why,
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19 619 and hence which method is likely to be preferable. Association of the differences in
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21 620 primary and secondary velocities inferred between the two methods with estimates of
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23 621 shear intensity and with estimated tilt and positioning errors should then help decide
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26 622 whether Method A or Method B is preferable in a particular case. This preference may
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28 623 vary between confluences but also through time at a confluence, if shear or flow depth
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31 624 changes significantly between survey dates.

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33 625 Finally, we wish to emphasise that the impact of averaging is only one element that must
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35 626 be considered in obtaining reliable primary and secondary flow estimates in river
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37 627 confluences. Other issues, such as the rotation method needed to distinguish primary and
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40 628 secondary circulation, remain important and should be considered routinely.

41 42 43 629 **Conclusions**

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46 630 This paper shows the advantage of working with the radial (beam) velocity measurements
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48 631 of an aDcp within each bin prior to averaging them across a given volume of fluid (Method
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51 632 A) as opposed to identify volumes of fluid and assuming bend homogeneity within them
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53 633 (Method B). Such a treatment is important where there are strong velocity gradients in the
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56 634 flow as with river channel confluences. In the first of our case-study confluences, the

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3 635 Lizerne-Rhône, a very small tributary joined the main river, and the pattern of primary and
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5 636 secondary velocities obtained with methods A and B were relatively similar, more so for
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7 637 primary velocities. But for a second confluence, the Grande Eau-Rhône, with a similar
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9 638 momentum ratio, there were much larger differences. We attributed this to the formation
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11 639 of much stronger shear at this confluence. Method A also appeared to reduce the number
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13 640 of repeat transects needed to estimate secondary velocities reliably. The main downside
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15 641 is that Method A is more sensitive to errors related to positioning. Thus, good dGPS
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17 642 accuracy and precision are required to perform a robust estimation of velocity.
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22 643 In smaller/shallower rivers, Method B may be acceptable indeed preferable as it is less
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24 644 sensitive to GPS errors. In larger rivers, Method A may be necessary, especially in the
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26 645 presence of strong shear at the confluence. Choice between these methods should be
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28 646 based upon an initial screening of the extent to which there is strong shear in the flow as
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30 647 well as the extent to which bins further from the aDcp are influenced by beam divergence.
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34 648 **Appendix A**

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37 649 The LOWESS model is a locally weighted polynomial regression, which at each point and
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39 650 in the range of dataset, a low degree polynomial is fitted to a subset of the data, using
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41 651 weighted least squares. This polynomial fit gives more weight to points closer to the point
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43 652 whose response is being estimated. The value of the regression function for the point is
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45 653 then obtained by evaluating the local polynomial using the explanatory variable values for
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47 654 that data point. The LOWESS fit is complete after regression function values have been
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49 655 computed for each of the n data points. Many of the details of this method, such as the
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51 656 degree of the polynomial model and the weights, are flexible (“Local regression,” n.d.).
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13 661 Gelare Moradi.
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