COMMENTS TO EDITOR

Your manuscript has been reviewed by two referees. Both referees provided very positive feedback highlighting the value of your contribution, and both suggested that some minor revisions be made. One more “major” criticism, though, was that your manuscript may be “too positive about the results”, and that your optimism may be “related to other studies or results that are not included in the current paper” (I am quoting one referee, here). I do agree with the referee that the main conclusions of your manuscript regarding unseeded methods should be based on data/information reported in your manuscript. That being said, I can see from your responses to the referees that you have already identified where – in the Results and Discussion sections – you will need to make text changes to nuance some of your statements/conclusions.

Response:

This document contains the replies to the comments of the article hess-2020-136 titled "Assessing different imaging velocimetry techniques to measure shallow runoff velocities during rain events using an urban drainage physical model" by Juan Naves et al.

First, we want to thank the editor and the reviewers for their positive evaluation of our work and the very constructive suggestions to improve our manuscript. We sincerely believe that the comments and suggestions have significantly contributed to improve the quality of the manuscript. In this document, we provide detailed responses to each reviewer’s comment indicating all relevant changes made in the manuscript, and a marked-up version of the manuscript to facilitate a concise review process.

As reviewers and editor may note in the revised version of the manuscript, we have changed the nomenclature of the ‘SSIV technique’ by ‘LSPIVu technique’. This change is motivated by a request received by mail from Salvador Peña when the HESS discussion was closed. S. Peña works at the company that developed the SSIV method (Photrack AG - http://photrack.ch) appearing as author in Leitão et al. (2018), Lüthi et al. (2014) and Hansen et al. (2017), which were referenced in the present study. He stated that the SSIV methodology was not clearly explained in their collaboration in Leitão et al. (2018) because it is a proprietary software, but it slightly differs from our procedure and, although we have not transgressed any intellectual property, he kindly asked us to use other nomenclature for avoiding confusion to their potential customers, since photrack is economically exploiting the SSIV methodology. Therefore, as our intention of using ‘SSIV’ was to refer to the name given by the first application of LSPIV for obtaining surface velocities form urban catchments without using artificial particles and we do not want to cause prejudice, we have decided to change this nomenclature from SSIV to LSPIVu within the manuscript. In the following, we have included the mail received from S. Peña and the mail that we sent to the editor with which we confirmed that changing the nomenclature at this stage of the revision was within the procedures of the journal:

From: Salvador Peña <pena@photrack.ch>
Sent: sábado, 5 de septiembre de 2020 8:12
To: Juan Naves García-Rendueles <juan.naves@udc.es>
Cc: José Anta Álvarez <jose.anta@udc.es>; GARCÍA BERMEJO, JUAN TOMÁS <juan.gbermejo@upct.es>
Subject: Recent HESS publication using SSIV method

Dear Juan Naves,
My name is Salvador Peña-Haro and I work at photrack where we have developed the SSIV methodology.

Today I came across your publication at HESS "Assessing different imaging velocimetry techniques to measure shallow runoff velocities during rain events using an urban drainage physical model" and I was surprised to see the SSIV method mentioned.

The description of the SSIV method in your article is very different from our methodology, probably because you have based your application on the paper of Leitao et al., 2018 where the method is not fully explained since it is proprietary. Although in your paper you developed a correct methodology using LSPIV to determine surface runoff velocity and you have not transgressed any intellectual property, I like to kindly ask you to change the name of your method to avoid confusion with the SSIV method given the differences between both. I believe these changes are very easy to implement since they are only related to the name SSIV. Of course you can refer -and we will be happy if you do- to Leitao et al., 2018.

As the open discussion at HESS is closed, I'm not able to comment this issue on the journal website.
Kind regards,

Salvador Peña-Haro
CTO
photrack AG

From: Juan Naves García-Rendueles <juan.naves@udc.es>
Sent: September 8, 2020 10:03 AM
To: Genevieve Ali <gali@uoguelph.ca>
Cc: José Anta Álvarez <jose.anta@udc.es>; GARCÍA BERMEJO, JUAN TOMÁS <juan.gbermejo@upct.es>
Subject: Revision enquiry hess-2020-136

Dear Editor Genevieve Ali,

We are finishing the review of the HESS manuscript hess-2020-136 'Assessing different imaging velocimetry techniques to measure shallow runoff velocities during rain events using an urban drainage physical model' by Naves et al., and we will upload the requested files with the changes demanded as soon as possible.

Regarding the above manuscript, we would like to make an enquiry about a request that we have recently received from Salvador Peña (Photrack AG, Flow measurements), asking us to change the nomenclature used for one of the imaging techniques included within our article. Below is included the e-mail received from S. Peña.

Following S. Peña comments, in our HESS manuscript we are using 'SSIV' (Surface Structure Image Velocimetry) to name the application of LSPIV technique without artificial particles following the

> paper of Leitao et al. (2018) (https://doi.org/10.1016/j.jhydrol.2018.09.001). In response to this mail, we arranged a meeting with Salvador where he explained that they named SSIV to a specific imaging processing methodology that was developed by his company, is a patented method and is being economical exploited by photrack. SSIV methodology was not clearly explained in their collaboration in Leitão et al. (2018) because it is proprietary, but according to them it slightly differs from our procedure and, although we have not transgressed any intellectual property, they kindly ask us to use other nomenclature for avoiding confusion to their potential customers.
>
> The intention of using 'SSIV' was to refer to the name given by the first application of LSPIV for obtaining surface velocities form urban catchments without using artificial particles, and we do not wanted in any way to cause prejudice to anyone. Therefore, considering that the change of nomenclature within our manuscript is easy to implement and it does not affect to any scientific contribution, we are willing to change the name of the technique in the revised version of the manuscript and explaining the motivation.
>
> However, as the request has been formulated once the HESS discussion was closed, we would like to ensure that doing this is within the procedures of the journal and if additional data (like the mail received) will be specifically required in the Author's Response document
>
> Thanks for your time and consideration.
>
> Best regards,
>
> Juan

In addition, we have slightly modified the text to adapt the content to the new nomenclature and note that our LSPIVu technique is also a LSPIV-based method (like SSIV) to obtain runoff velocities without using artificial particles. Pg 2 Ln 55 and Pg 6 Ln 33:

> *"In addition, LSPIV-based methods can be applied to determine runoff velocities without the presence of particles such as in Leitão et al. (2018), where a method called Surface Structure Image Velocimetry (Lüthi et al., 2014; Hansen et al., 2017) introduces some improvements based on image pre-processing analysis to measure shallow flows in a flood experimental facility."*
>
> *"Then, a LSPIV-based method named as LSPIVu in this work and the BIV technique were used to obtain velocity fields from the unseeded and LED-illuminated experiments. LSPIVu is inspired in the non-open SSIV procedure employed in Leitao et al. (2018) and uses a SLB image pre-processing to remove the background from the analysis and satisfactorily trace the movement of air bubbles and surface water reflections generated by raindrops."*

COMMENTS TO REVIEWER 1

General comments

This study assesses four image based velocimetry techniques for measuring water velocity in shallow flows as would be observed in overland flows over paved surfaces during rainfall events. The problem is physically challenging, and the authors use a dedicated lab setup to assess these techniques with an eye to evaluating their potential for more difficult and varied conditions in the field. The work is derived from a larger project that has led to a number of significant publications over the last couple of years and is a direct extension of a 2019 paper that validated one of the approaches used (LSPIV). The validated approach is used as the reference condition for the current paper. The paper overall was well written and the methods appeared to be suitable for assessing the other velocimetry techniques.

Response:

We appreciate the reviewer for the time invested in reviewing our manuscript and for the positive evaluation of our work. We are grateful for the detailed review and believe that the constructive comments and suggestions will lead to a deeper and clearer analysis of the results presented in this article, contributing to significantly improve the quality of the manuscript. In this document, we present the responses to the reviewer's comments indicating how and where these were addressed in the revised version of the manuscript.

Despite the quality of the work, the authors in my opinion are too positive about the results. In looking at the results from my reviewer's perspective, it appears that the unseeded techniques are not suitable for measuring velocities in shallow flows. Even in relatively straight flows with low precipitation, there is an offset between the unseeded techniques and the LSPIV results that is not well explained. It is not clear to me how the magnitude of this offset could be predicted without controlled tests. As the precipitation intensity increases, the error in the unseeded techniques increases to the point where the results are no longer even correlated with the validated technique. In these conditions I would argue that the unseeded techniques are simply not suitable. Despite this, many of the statements in the discussion and conclusions are quite positive about the techniques. The optimism seems to be related to other studies or results that are not included in the current paper. Something needs to be adjusted, either by including those results (maybe cases without any precipitation at all?) or by drawing sharper lines about which techniques are reliable in different conditions.

Response:

Based on the comment of the reviewer, we have reread the manuscript and we agree that the discussion and conclusions appear too positive considering results presented for unseeded methods BIV and LSPIVu (as explained in the comment to the editor, we have changed the nomenclature of SSIV by LSPIVu). This may lead journal readers to confusion if a clear and contextualized interpretation of the results is not included. The positiveness showed is due to the great potential of unseeded techniques as a tool to obtain runoff velocity data from media sources commonly available in urban environments, such as surveillance cameras, traffic cameras, or even social media. From our point of view, this is a novel and powerful data source with a great potential to solve the current lack of surface runoff velocity data, which is key in the proper calibration of the increasingly more accurate 2D-1D dual urban drainage models that are currently being developed. The use of these data sources has been recently introduced in the field of urban drainage (Leitão et al. 2018, de Vitry et al. 2020). In addition, in contrast with the increasingly more common application of visualization techniques to rivers monitorization (Pearce et al. 2020, Tauro et al. 2016, Tauro et al. 2018), their use for urban runoff measurements is still limited to some initial applications on the analysis of the velocities in a stormwater storage facility (Zhu et al., 2019) and in simulated urban floods (Leitão et al. 2018), both without precipitation. Therefore, this is the first work where the influence of raindrop interference with the recorded images and their impact in the measurement of velocities is analyzed, and therefore is still much room for improvement in this novel implementation.

In this context, we consider as positive the results obtained from unseeded techniques for low rain intensities where the results correlate with LSPIV results, since two different techniques are being used. The different density and size of bubbles and artificial fluorescent particles explains the offset found for low rain intensities, since tracers are affected in different degrees by raindrop impacts and may be transported at different velocities. The gap obtained in this study between seeded and unseeded experiments may be thus interpreted as an indicator of the uncertainties that may appear when using visualization techniques in rainy conditions depending on the type of tracer. As commented by the reviewer, we think that the prediction of the magnitude of this offset is currently challenging, so further investigation on how rain impacts the transport of possible tracers appears as an interesting research line to reduce uncertainties in runoff velocity measurements. Finally, the different tracers analyzed also explain the different behavior of seeded and unseeded techniques when the rain intensity is increased. While raindrop impacts produce fast and random changes of position in bubbles, that are incremented with rain intensity, the higher density of fluorescent particles confers themselves inertia to avoid such sudden movements. We think that this great affection of raindrops in unseeded techniques, leading to erroneous results for high rain intensities, is an important result of the present work and we agree that this should have been clearer presented in the text.

We have thus revised the results and discussion and conclusions chapters to clarify these points by, as suggested by the reviewer, drawing sharper lines between the performance of each methods, explaining deeply the offset obtained between seeded and unseeded techniques, and discussing the potential and possible challenges of visualization techniques to measure urban runoff velocities. Among other little modifications, the following sentences have been added in the Results and discussion and Conclusions sections to clearly specify that unseeded methods are not working for high intensities (Pg 13, Ln 335; Pg 19, Ln 423; and Pg 22, Ln 497):

> *“However, the velocity fields obtained for rain intensities of 50 and 80 mm h^{-1} showed that both the LSPIVu as well as the BIV techniques resulted in erroneous velocity distributions, being more affected the areas where greater velocities are developed”*
>
> *“The use of bubbles as tracers gives unseeded techniques an opportunity to measure velocities in extremely shallow flows where particles tend to be deposited. However, LSPIVu and BIV are more affected by the impact of raindrops leading to erroneous results for high rain intensities, especially for high velocity flows”*
>
> *“Unseeded techniques are highly affected by raindrop impacts. First, the gap between seeded and unseeded techniques is reduced as the rain intensity is increased, so rain intensity should be also considered to determine the velocity index for estimating depth-average velocities. Then, raindrop impacts also produce fast and random changes of position of the bubbles used as tracers, leading to erroneous velocities for high rain intensities. However, the ability of measuring extremely shallow flows where particles tend to be deposited, and their easy implementation without the need of adding artificial particles, make unseeded techniques worthy of future investigations as new source of runoff velocity data in urban catchments.”*

The explanation of the offset between seeded and unseeded experiments has been completed in Section 3.2 (Pg 13, Ln 326) and stated in conclusions (Pg 22, Ln 487) as follows:

> *“All visualization techniques presented a similar velocity distribution for the lowest rain intensity (first row), although an offset of approximately 0.05 m s-1 was obtained for the unseeded techniques. This offset is produced because the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Considering the novel application of these techniques in presence of rain, it can be deduced that all techniques obtained a good performance for 30 mm h^{-1} rainfall and that lower velocity indexes are required in the case of unseeded techniques to convert the results to depth-averaged velocities, as observed in previous references (Leitão et al., 2018; Martins et al., 2018; Naves et al., 2019a)”*
>
> *“Both seeded and unseeded techniques provide suitable velocity distributions for lower rain intensities in case of unidirectional flows, observing an offset of approximately 0.05 m s-1 between them. This offset is a consequence of the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Lower velocity indexes are thus required in the case of unseeded techniques to convert the results to depth-averaged velocities. In case of more complex flows, unseeded techniques are not able to adequately measure since bubbles have difficulties to follow the runoff generated.”*

Questions and comments:

148 – Is the LSPIVb procedure significantly different than the LSPIV? In reading the methods I thought that the results might arrive at the same point as each requires a threshold, one applied to the difference, the other to the base images and then the difference is then

calculated. The results also show that they are nearly the same. The point of the LSPIVb analysis is not emphasized in the paper. What is the motivation for evaluating this technique? It is not really discussed in the results or appear in the conclusions to a significant extent. Does it ‘better remove background and shadows. . .”? Should other people use it instead of the regular LSPIV?

Response:

This is an interesting comment of the reviewer. It is true that preprocessing of both LSPIV and LSPIVb depends on only one threshold, but the different purpose of these thresholds leads to different preprocessed images. First, the sliding background preprocess was applied in the LSPIV technique to remove all elements that remain fixed between two consecutive frames, including the road surface, other elements of the physical model, and immobile particles. The threshold used in this case corresponds a percentage of the grey value to consider that an element does not move since, although the pixel correspond to a immobile element, this value may slightly vary because of variations on water surface or raindrops interferences. In contrast, the binarization performed for LSPIVb technique seeks mainly to isolate the brightest pixels, which in this case will correspond with the fluorescence particles used as tracers. Then, we also remove deposited and immobile particles with the sliding background filter, but the binarization makes the previous margin of gray value used in LSPIV unnecessary.

Binarization is used in PIV studies (e.g. Zhou et al. 2013) to remove the remaining noise in raw PIV images, resulting in images where all the particles have the same intensity and thus have equal contribution to the correlation function. However, this preprocessing technique would lead to increase measurement uncertainty if the threshold value is not properly addressed (Raffel et al. 2018). The motivation of including binarization in seeded experiments (LSPIVb technique) was firstly consistency with the unseeded techniques found in the literature. While LSPIVu seeks to remove immobile features from frames through sliding background and analyze the movement of all other elements, BIV seeks to analyze only the movement of bubbles, which are identified as the brightest elements in the images, removing the rest of features from the images. When we applied these preprocessing procedures to seeded experiments images, we observed that the processed images were slightly different and the binarization (in LSPIVb technique) reduced the number of particles to analyze in the images. For example, this can be observed in the following figure (Figure R1), where the same frame obtained from seeded videos was preprocessed following the procedures for LSPIV and LSPIVb respectively.

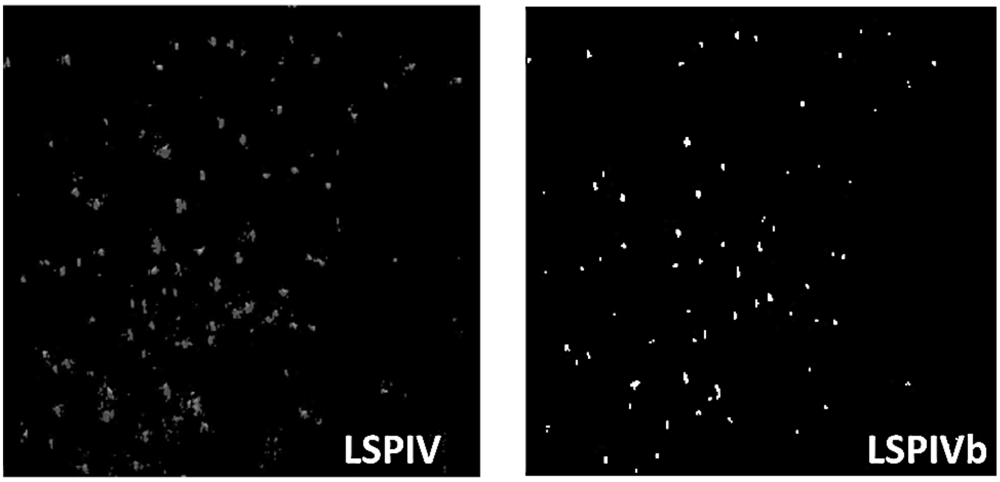

Figure R1. Preprocessed frame for LSPIV and LSPIVb imaging techniques.

In view of the differences between the images and the use of binarization in the literature, we decided to include LSPIVb technique to investigate the influence of binarization in the analysis of seeded experiments. As noted by the reviewer, the achieved results with both seeded techniques are very similar with slightly higher velocities obtained by techniques that use binarization. This similarity indicates that, except particles and bubbles, cameras did not record many other moving elements that disturb the results, so binarization does not include significant benefits in these experiments. Another interesting difference observed is that techniques including binarization resulted in noisier velocity results. This may be due to the fact that, if the binarization is applied, the sliding background filter may remove parts of tracers in motion that are overlapped in consecutive frames since no different grey values are considered, which also might explain the slightly higher velocities obtained. This indicates that binarization, which may be useful to isolate tracers if seeded experiments are performed with natural or regular artificial illumination, should be used with care in future applications and it is not recommended if the non-binarized images results in good correlations.

A detailed explanation of the motivation of evaluating LSPIVb and a more extended discussion about the similar results obtained using LSPIV and LSPIVb have been added to Methods and Results sections for a better comprehension of the achieved results. Specifically, the following text has been added to the methodology (Sections 2.2 and 2.2.1 respectively) to clarify the motivation of LSPIVb (Pg 6, Ln 138 and Pg 7, Ln 163):

> *“Finally, a slight variation of the LSPIV methodology named LSPIVb was implemented to investigate the influence of binarization pre-process also in the analysis of seeded UV experiments. This strategy seeks to isolate the brightest pixels, which in this case correspond with the fluorescence particles, to ensure that other elements such as bubbles or water reflections are not interfering in the PIV analysis.”*

> *"This filter ensures that only the fluorescent particles are being considering in the PIV cross-correlation, preventing possible small interferences that bubbles or water reflections may produce despite the special illumination* (Zhou et al. 2013).*"*

In addition, the similar results obtained by LSPIV and LSPIVb have been discussed in Results and discussion section as follows (Pg 18, Ln 407):

> *"Then, the velocity fields showed very similar results between LSPIV and LSPIVb and between LSPIVu and BIV with slightly higher velocities measured by methods using binarization pre-processing (LSPIVb and BIV). This similarity indicates that, except particles and bubbles, cameras did not record many other moving elements that disturb the results, so binarization does not includes significant benefits in these experiments. In addition, it has been observed that techniques that include binarization result in noisier velocity results (see velocity fields for 30 and 80 mm h-1 in the supplementary information). This may be due to the fact that, if binarization is applied, the sliding background filter may remove parts of tracers in motion that are overlapped in consecutive frames since no different grey values are considered, which also might explain the slightly higher velocities obtained. Therefore, this filter should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements."*

Finally, an additional point has been added to conclusions (Pg 23, Ln 504):

> *"The similarity found between LSPIV and LSPIVb and between LSPIVu and BIV indicates that binarization preprocessing has not significant benefits in these experiments since cameras did not record moving elements that significantly disturb the results. In addition, it has been found that this procedure lead to noisier results, so binarization should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements."*

Minor issues:

16 - complex sentence. should split into one about the natural tracers and the second about the raindrop impacts.

Response:

The sentence has been split and slightly modified to simplify the text (Pg 1, Ln 17):

> *"First, the use of naturally-generated bubbles and water shadows and glares as tracers allows the unseeded techniques (LSPIVu and BIV) to measure extremely shallow flows. However, these techniques are more affected by raindrop impacts, which even lead to erroneous velocities in the case of high rain intensities."*

47 – sentence starting with 'For instance' is not clear to me. Should be rewritten in a more direct style.

Response:

The sentence have been rewritten in a more direct style as follows (Pg 2, Ln 52):

> *"Zhu et al. (2019) achieved errors below 14% using this technique in a full-scale stormwater detention basin, although in some bordering points these could rise up to 44%."*

61 – sentence starting with 'That study' is too complex. Should be split into two ideas.

Response:

The sentence has been rewritten for a better understanding (Pg 3, Ln 67):

> *"The presence of raindrops in the experiments can generate disturbances in the water surface and also interfere in the visualization of images, so that study used UV illumination and fluorescent particles as artificial tracers to satisfactorily address these issues."*

87 and 106 – is Naves et al 2019b an archive? Data availability should be clarified.

Response:

Yes, the reference is from a dataset published by the authors in the open access repository Zenodo. This includes videos, images, and related information to replicate our study or produce new results. This has been specified within the text as follows (Pg 4, Ln 96 and Pg 4, Ln 117):

> *"The freely available experimental dataset (Naves et al. 2019b) described in Naves et al. (2020b) was used in this study for the assessment of different imaging velocimetry techniques.*
>
> *"Examples of these images obtained from UV seeded and LED unseeded experiments, which are openly available for others to use in the dataset published by the authors (Naves et al., 2019b), are included in Fig. 2."*

101 - Best to say what was done step by step. e.g. Videos were recorded at 4K resolution and 25Hz. 1500 frames (eq. to 60 s) were extracted from the longer recording for analysis.

Response:

As recommended, the sentences have been rewritten to clarify the methodology (Pg 4, Ln 111):

> *"During the experiments, videos were recorded at 4K resolution and 25 Hz. 1500 frames of steady flow (equivalent to 60 s) were then extracted from the longer recording and processed for analysis. To do this, frames were scaled and ortho-rectified using the known 2D coordinates of 28 and 24 reference surface points for each camera and the Matlab functions 'fitgeotrans' and 'imwarp'. Finally, the reference points placed in the intersection between the recorded areas of each camera were used to crop and join the images, resulting in raw images where 1 pixel corresponds to 1 mm in real-world coordinates."*

120 – so all particles are assumed to be moving? Is this realistic? Is there a velocity threshold?

Response:

Some of the particles used as tracers may settle on the road surface due to the extreme low depths developed in some areas of the road surface and to the rugosity of the concrete surface. While the rest of particles follow the runoff generated, these particles appear immobile in the images recorded. This can lead to erroneous velocity results when the PIV cross-correlation is performed, because the null velocity of these particles can reduce the mean velocity of the particles of a determined interrogation area. The sliding background preprocess avoids this issue removing the immobile particles and focusing the analysis on the particles that are being transported by the flow. In addition, this procedure does not produce any velocity threshold in the results since only the particles that remain immobile between two consecutive frames are removed from the analysis, as can be also checked in the previous work published by the authors (Naves et al. 2019a). However, as stated within the text, the seeded techniques are not able to measure velocities in areas with extreme shallow flows (Area 2) because the artificial particles cannot be transported, and unseeded techniques appear as suitable tools to be further explorer for these conditions.

The sentence has been rewritten to clearly explain the removal of immobile particles (Pg 5, Ln 130):

> *"That methodology requires pre-processing of images through a sliding background (SLB), which eliminates the background of the images and particles that remain immobile between frames. These particles, which are deposited due to the extreme low depths developed and the rugosity of the concrete surface, should be removed to avoid that the null velocities resulted from them condition the PIV analysis."*

156 – restatement of the aim/objective. Not necessary in the methods.

180 – again repetition of aim, but shouldn't be necessary.

183 – novelty should be addressed in intro with aim and objectives.

193 – more repetition of the aim

195 – I think that the reference technique statement should also be used as a scoping statement at the end of the introduction with the aim/objectives. Mixing it in here reduces the clarity of what is being done and what the starting point for the new contribution is.

Response:

We agree with the reviewer. The final statement of the introduction section has been completed to include clearer the aim, the novelties, and the starting point of the new contribution (Pg 3, Ln 79). This content has been removed from the rest of the manuscript where, as noted by the reviewer, it is not necessary.

> *"Therefore, experimental videos of the overland flow generated by three different rain intensities, under laboratory-controlled conditions and recorded with and without artificial particles, are used in this study to comparatively assess the performance of different seeded and unseeded imaging velocimetry techniques under rainy conditions. First, the sensitivity of the velocity results to the analysis parameters is investigated in order to test the robustness of each method. Then, the resulting velocity fields are compared to analyze the feasibility of using each visualization technique in different characteristic flows developed in urban catchments, and to investigate the influence of rain intensity in velocity measurements as novel contribution. The LSPIV procedure, already validated in Naves et al. (2019a), is used as the reference technique in this analysis. Finally, the feasibility of these imaging techniques to measure runoff velocities in real field applications is discussed."*

166 – Description of correlation matrix calculation is too brief. Need to help readers who may want to apply this technique themselves. Is this following what was done for other publications?

Response:

The correlation matrix was computed using the Discrete Fourier transform (DFT) in the frequency domain, which is calculated using a fast Fourier transform (FFT). This is a common procedure to estimate particle displacement that is detailed in the bibliography of reference about PIV (Raffel et al., 2007; Adrian et al., 2011). The PIVLab software has this procedure implemented (Thieckle and Stamihus, 2014), where multi-pass window and deformation algorithm were used to improve the signal to noise ratio. The window size at the second pass achieves a higher spatial resolution. The searching area (SA) matches with the IA and 50% of overlapping was selected in all cases in the present work. The following text and references have been included in the text to complete the information about the correlation matrix calculation (Pg 7, Ln 184):

> *"Common procedures to estimate this particle displacement, and thus flow velocity, has been applied in the present work (Raffel et al., 2007; Adrian et al., 2011). The discrete Fourier transform (DFT), calculated using a fast Fourier transform (FFT), was used to compute the correlation matrix in the frequency domain. Moreover, two passes of a multi-pass window deformation algorithm were used in the present work, having the window size at the second pass to achieve a higher spatial resolution. The searching area (SA) matches with the IA and 50% of overlapping was selected in all cases in the present work. These procedures are included in most of the conventional PIV algorithms such as PIVLab (Thieckle and Stamihus 2014), or OpenPIV (Taylor et al. 2010)."*

174 – not clear what you mean by 'which were investigated as an optimum'.

Response:

These values were selected after some preliminary tests where the good performance detecting spurious vectors was checked. The sentence has been modified (Pg 8, Ln 196):

> *“After preliminary tests assessing the performance detecting spurious vectors in the PIV results, the values of the two parameters of this filter were set to ε = 0.15 and threshold = 3. “*

226 – ‘This was to approach the conditions of worse devices . . .’ is not clear.

Response:

The sentence has been rewritten as follows (Pg 10, Ln 251):

> *“This simulates the FAR of some already installed devices that may serve as media source to measure urban runoff velocities in field applications, such as traffic or surveillance cameras following the ideas stated in Leitão et al. (2018).”*

279 – what type of flow specifically is in the area? The shallowness? Should be clarified.

Response:

Yes, it corresponds with the lowest depths analyzed. This has been clarified (Pg 12, Ln 305):

> *“The very low depths developed in this area also increases the variability of the mean velocities depending on the pair of frames analyzed.”*

284 – should note that there is a degradation of quality with FAR, as expected.

Response:

We agree that it is a useful remark and it has been included as follow (Pg 13, Ln 311):

> *“Finally, an expected degradation was noted when FAR is reduced, but within assumable ranges that make it possible to consider cameras with lower FAR as media source for field applications.”*

317 - change phrasing. The current sentence uses a double negative. I think you mean that the unseeded technique is not able to measure the highest velocities, but i’m not sure.

Response:

Yes, we wanted to explain why unseeded techniques are not able to measure velocity when rain intensity and flow velocities are high. The text has been rewritten as follows (Pg 14, Ln 350):

> *“*Then, the problems of unseeded techniques (LSPIVu and BIV) measuring velocities with high rain intensity are not produced because of a lack of tracers since, as can be observed in the videos provided in Naves et al. (2019b), the number of bubbles in that area increases with the rain intensity. These are caused by the erratic trajectory of the bubbles observed in the unseeded videos for high rain intensities due to the impact of raindrops on the water surface.*”*

322 – 'non-artificial' is again kind of a double negative. Just say what it is - the natural bubbles.

Response:

Thanks for the remark, 'non-artificial bubbles' has been substituted by 'natural bubbles' (Pg 15, Ln 356).

445 – do you mean that the problem is not trivial?

Response:

We referred to the difficulties of applying the seeded experiments methodology in real urban catchments during rain events, especially seeding particles. The sentence has been rewritten to avoid confusion as follows (Pg 22, Ln 500):

> *"However, the ability of measuring extremely shallow flows where particles tend to be deposited, and their easy implementation without the need of adding artificial particles, make unseeded techniques worthy of future investigations as new source of runoff velocity data in urban catchments."*

24 – replace 'Specifically' with 'However'?

117 – 'estimate' is better than 'obtain' for this sentence.

117 – 'from the analysis of the images presented in the previous point' is not necessary.

224 – suggest 'typical of' rather than 'in consonance with'

261 – Acronym not introduced until next page (FAR)

325 – suggest 'prevents' rather than 'avoids'.

325 – 'from' obtaining

414 – should be Figure 10

Response:

Thanks again for the detailed review, we agree with the comments and these mistakes have been corrected in the revised version of the manuscript.

References:

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COMMENTS TO REVIEWER 2

General comment

Naves at all present a lab comparison of different particle imaging velocimetry techniques under (indoor) rainy conditions. I believe that analyzing this is a valuable addition to the scientific literature. I especially am happy that the authors have shown that not all PIV techniques perform equally under different rainy conditions, something very relevant when analyzing (urban) flood impact from video images. I commend the authors on their thorough effort of making the data on which they build their conclusions available to the public in true Open Science spirit.

I have a few minor issues with the paper in its current form, but am overall of the opinion that this paper should be published in HESS.

Response:

We would like to sincerely thank the reviewer for the time and effort invested in reviewing our manuscript and for the interest showed in our work. In the following, we provide detailed responses to reviewer's minor comments.

Minor issues:

The paper focusses on the application of urban flooding of streets and this is reflected in the literature cited. In river hydrology there are quite some papers also looking into using seeding for better LSPIV results. Multiple papers by Flavia Tauro and her team come to mind. Perhaps (but I'm not sure) adding these in the introduction would better frame the current research.

Response:

Thanks for the recommendation. We think that including papers related to river PIV applications will benefit the Introduction section. We have included the works of Tauro et al. (2016), Tauro et al. (2018), Pearce et al. (2020) and Manfreda et al. (2018) as follows (Pg 2, Ln 44):

> *"Imaging techniques are thus expanding in open and large-scale environments as non-intrusive methods for the characterization of surface velocity fields (Aberle et al., 2017), and their use is increasingly common in river monitoring (e.g. Tauro et al., 2016; Tauro et al., 2018; Manfreda et al., 2018; Pearce et al., 2020)."*

While the authors do make all their data available, and they do state which software packages they use for part of their analyses, it is impossible for me to check their results, since the code they use to generate their results is not shared. I would like to ask the authors to upload the code that generates the figures presented in the paper to Zenodo and cite it in the manuscript. This would also facilitate reproducing the result of this study, or expand on it.

Response:

As stated by the reviewer, our compromise with Open Science is clear, as can be seen in the experimental dataset cited in the manuscript where we made freely available our data for others to be used in replicating our work or in conducting new research. In addition, we agree with the reviewer that sharing codes is a very recommendable practice to demonstrate more robustly and transparently the reliability of the results achieved, definitely benefiting research community. In this investigation, we have used existing and available codes during all the methodology, and the original code developed have been limited to facilitating computation of a considerable number of study cases and parameters by using simple loops.

The main functions and software used during the present work were: (1) 'fitgeotrans' and 'imwarp' Matlab functions to orthorectificate the frames analyzed, and 'rgb2gray' and simple comparisons using 'if' statements to apply sliding background and binarization during the preprocessing; (2) the command line script of PIVLab to compute the PIV cross-correlation (available at https://ch.mathworks.com/matlabcentral/fileexchange/27659-pivlab-particle-image-velocimetry-piv-tool?s_tid=mwa_osa_a); and (3) 'averf' and 'showf' functions from the 'pivmat' toolbox to visualize the mean velocity fields (available at http://www.fast.u-psud.fr/pivmat/).

In view of this, we consider that we have not developed any significant original code and we preferred to cite the sources within the text. However, we will be grateful to share our code on demand in the future if researchers need help to replicate our work or expand on it. As it did not appear in the manuscript, we have specified that the Matlab functions 'fitgeotrans' and 'imwarp' have been used to perform the orthorectification (Pg 4, Ln 113):

> *"To do this, frames were scaled and ortho-rectified using the known 2D coordinates of 28 and 24 reference surface points for each camera and the Matlab functions 'fitgeotrans' and 'imwarp'."*

The authors make use of the "jet" colormap for their figures, a choice that is known to results in figures that highlight differences not present in the data. (See among others https://www.jstor.org/stable/24862699?seq=1) Please switch to a different colormap. (this is a pet peeve of mine)

Response:

Thanks for sharing the reference, interesting issue. We have analyzed and compared 'jet' colormap results against 'haline' colormap from the mentioned reference. The results, which are included in the following figures, showed that in this particular case the 'jet' colormap do not include confusing data and, as stated in the reference mentioned by the reviewer, the sharp gradients of 'jet' colormap allow proximal colors to be distinguished, showing clearer the differences between techniques. In view of this, we have preferred to maintain 'jet' colormap to facilitate comparison with our previous work using LSPIV (cited in the text as Naves et al. 2019a). In any case, we thank the reviewer for the comment, and we will have this information into account for next communications.

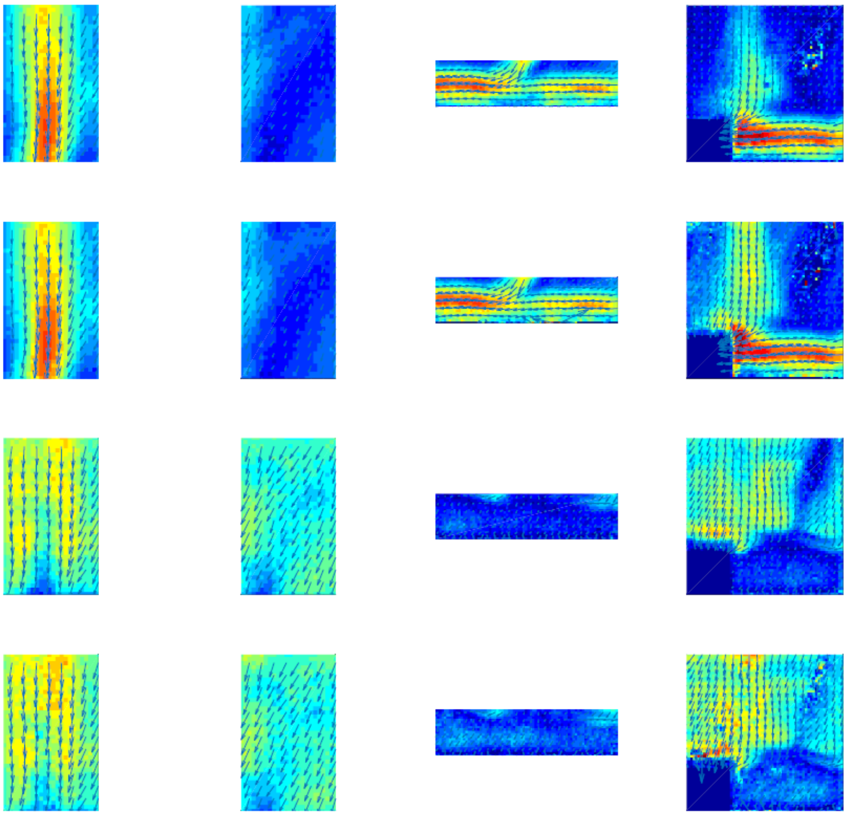

Figure R1. Velocity fields representations for the rain intensity of 50 mm/h, the four techniques (rows) and the four study areas (columns), using “jet” colormap.

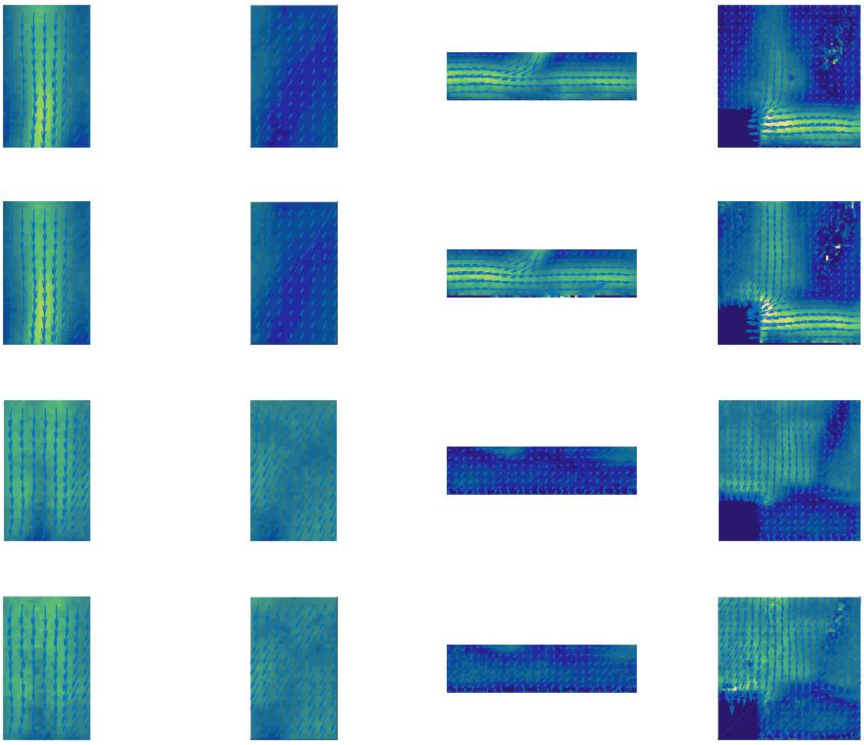

Figure R2. Velocity fields representations for the rain intensity of 50 mm/h, the four techniques (rows) and the four study areas (columns), using “haline” colormap.

Concluding: I really like the paper, the science, as presented, is sound although the actual claims cannot be verified without the software that generated their results shared alongside the paper.

Response:

Thanks again for your time and your interest in our work

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Tauro, F., Petroselli, A., Porfiri, M., Giandomenico, L., Bernardi, G., Mele, F., ... & Grimaldi, S. (2016). A novel permanent gauge-cam station for surface-flow observations on the Tiber River. Geoscientific Instrumentation, Methods and Data Systems, 5(1), 241-251. https://doi.org/10.5194/gi-5-241-2016

Assessing different imaging velocimetry techniques to measure shallow runoff velocities during rain events using an urban drainage physical model

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Abstract. Although surface velocities are key in the calibration of physically based urban drainage models, the shallow water depths developed during non-extreme precipitations and the potential risks during flood events limit the availability of this type of data in urban catchments. In this context, imaging velocimetry techniques are being investigated as suitable non-intrusive methods to estimate runoff velocities, when the possible influence of rain has yet to be analyzed. This study carried out a comparative assessment of different seeded and unseeded imaging velocimetry techniques~~: ~~ based on Large Scale Particle Image Velocimetry (LSPIV)~~; Surface Structure Image Velocimetry (SSIV);~~ and Bubble Image Velocimetry (BIV)~~,~~ through six realistic but laboratory-controlled experiments where the runoff generated by three different rain intensities was recorded. First, the use of naturally-generated bubbles and water shadows and glares as tracers allows ~~the ~~unseeded techniques ~~(SSIV and BIV) ~~to measure extremely shallow flows~~,~~. However, ~~but ~~these techniques are more affected by raindrop impacts, which even lead to erroneous velocities in the case of ~~the ~~high~~est~~ rain intensities. At the same time, better results were obtained for high intensities and in complex flows with techniques that use artificial particles. Finally, the study highlights the feasibility of these imaging techniques to be used in measuring surface velocities in real field applications and the importance of considering rain properties to interpret and assess the results obtained.

1 Introduction

Since the last years of the 19th century, urban drainage systems have fulfilled a fundamental mission that has enabled us to guarantee the hygienic-sanitary conditions and growth of denser cities (Butler et al., 2018; Brown et al., 2009). ~~Specifically~~However, the sustainability and flood response capacity of urban drainage systems are today threatened by several factors. These are led by the increment in impervious areas, due to urbanization (Shuster et al., 2005; Yao et al., 2016) and ongoing climate change, resulting in a higher and more frequent number of heavy rainfall events (Willems et al., 2012; Arnbjerg-Nielsen et al., 2013). The increased flood risk is a consequence of these factors (Chen et al., 2015) which must be accurately assessed (Apel et al., 2004; Martinez-Gomariz et al., 2016). This continuous development of impervious areas also leads to a significant increase in the load and peak concentrations of pollutants, which are accumulated on urban catchments surfaces and can be washed off and transported by runoff into drainage systems and eventually to aquatic media (Lee and Bank 2000, Anta et al., 2006; Zafra et al., 2017; Muthusamy et al., 2018). This process depends on multiple factors (Hatt et al., 2004; García et al., 2017) and requires a clear understanding of the surface drainage in urban areas from the hydrodynamic point of view.

In this context, physically-based urban drainage models can help to assess complex cases, such as the definition of the inlet capacity of different storm drains to transfer runoff stormwater into sewers (Martins et al., 2018; Rubinato et al., 2018) or to assess particle wash-off processes (Hong et al., 2016; Naves et al., 2020a). A precise characterization of the surface velocities and flow depths is required when calibrating these models due to their key role in flood risk assessment and in the detachment and transport of surface pollutants. However, punctual velocity measurement equipment such as Acoustic Doppler Velocimetry (ADV) does not allow a two-dimensional velocity field to be obtained in large urban areas during flood events without requiring a huge deployment of instrumentation and a~~t~~ great risk to workers. Furthermore, due to the shallow runoff flows during non-extreme events, ADV reliability is reduced as it is an intrusive technique that also needs about 5-7 cm to obtain velocity measurements (Cea et al., 2007). Imaging techniques are thus expanding in open and large-scale environments as non-intrusive methods for the characterization of surface velocity fields (Aberle et al., 2017), and their use is increasingly common in river monitoring (e.g. Tauro et al., 2016; Tauro et al., 2018; Manfreda et al., 2018; Pearce et al., 2020). Large-Scale Particle Image Velocimetry (LSPIV) is an image velocimetry technique that provides velocity fields in large areas, even in the proximity of hydraulic structures (Muste et al., 2008; Fujita et al., 1998; Kantoush et al. 2011). LSPIV velocity determination can be affected by deficient illumination, diffuse light reflections or free-surface waviness generated by wind or large-scale turbulence structures. Seeding is also a key parameter of the technique that may need to be artificially improved (Aberle et al., 2017). ~~For instance, the differences achieved in a full-scale stormwater detention basin, compared with the reference values, were below 14% although in some bordering points these could rise up to 44% (Zhu et al., 2019).~~Zhu et al. (2019) achieved errors below 14% using this technique in a full-scale stormwater detention basin, although in some bordering points these could rise up to 44%.

In addition, ~~other~~ LSPIV-based methods ~~imaging techniques may~~can be applied to determine runoff velocities without the presence of particles~~.~~ such as in Leitão et al. (2018), where a method called Surface Structure Image Velocimetry (Lüthi et al., 2014; Hansen et al., 2017~~SSIV~~) ~~is a LSPIV-based method which~~ introduces some improvements based on image pre-processing analysis to measure shallow flows in a flood experimental facility~~(Lüthi et al., 2014; Hansen et al., 2017; Leitão et al., 2018)~~. ~~Hence, shadows and immovable objects detected from a set of images are removed by subtracting the averaged image to the temporal series, and the structures presented on free-flow surfaces such as the water reflections are enhanced.~~ In addition, bubbles are used as tracers to estimate overland velocities in the technique known as bubble imaging velocimetry (BIV). The BIV technique was first introduced to measure the velocity field in high aerated flows from backlit images analysis without the need for laser-like illumination (Ryu et al., 2005). Bubbly flows are illuminated by a uniform light source while a high-speed camera captures shadow textures created by gas-liquid inter-faces (Aberle et al., 2017). Lin et al. (2012) have already used this technique to measure the flow structure in hydraulic jumps in the aerated zone.

In Naves et al. (2019a), a variation of the LSPIV technique was applied to measure the surface velocity fields generated by three different rain intensities in a full-scale urban drainage physical model. The presence of raindrops in the experiments can generate disturbances in the water surface and also interfere in the visualization of images, so that study used UV illumination and fluorescent particles as artificial tracers to satisfactorily address these issues ~~the problems caused by the presence of raindrops in the experiments, which are the interference of raindrops in the visualization of images and the disturbances generated in the flow because of raindrop impacts~~. To the best of the authors' knowledge, that was the first and only study where an imaging velocimetry technique has been applied during rainy conditions. Despite the good results achieved and the great suitability for laboratory applications of the proposed methodology, its transferability to field studies is restricted by the difficulties in using artificial particles and special illumination. However, in addition to the interferences mentioned above, the raindrop impacts also generate bubbles and some other structures on free-flow surfaces that may be used as tracers by ~~the SSIV and BIV~~unseeded techniques. Due to the great potential of these unseeded techniques to obtain overland flow velocity data in field applications using, for example, pre-installed surveillance cameras (Leitão et al., 2018), studying their performance under rainy conditions is an interesting and novel research gap to be addressed.

Therefore, experimental videos of the overland flow generated by three different rain intensities, under laboratory-controlled conditions and recorded with and without artificial particles, are used in this study to comparatively assess the performance of different seeded and unseeded imaging velocimetry techniques under rainy conditions. First, the sensitivity of the velocity results to the analysis parameters is investigated in order to test the robustness of each method. Then, the resulting velocity fields are compared ~~in order~~ to analyze the feasibility of using each visualization technique in different characteristic flows developed in urban catchments, and to investigate the influence of rain intensity in velocity measurements as novel contribution. The LSPIV ~~method~~procedure, already validated in Naves et al. (2019a), is used as the reference technique in this analysis. Finally, the feasibility ~~the potential usability~~ of these imaging techniques to measure runoff ~~measuring surface~~ velocities in real field applications is discussed.

2 Materials and methods

The experimental work performed to record the overland shallow flows generated by three different simulated rainfalls in an urban drainage physical model is introduced first, in Sect. 2.1. Then, Sect. 2.2 includes a description of the procedure followed to obtain velocity results from the original video frames. Sect. 2.3 describes the strategy to assess the performance of different image velocimetry techniques depending on rain intensity and the typology of flow. Finally, the surface areas where the analysis was focused, the ranges of variation of the parameters involved in the assessment of the robustness of each technique, and the procedure implementation details are explained in detail in Sect. 2.4, 2.5, and 2.6.

2.1 Experimental data

The freely available experimental dataset (Naves et al., 2019b) described in Naves et al. (2020b) ~~and freely available at Naves et al. (2019b)~~ was used in this study for the assessment of different imaging velocimetry techniques. The dataset comprises a series of videos where the surface runoff was recorded in a 36 m^2 urban drainage physical model. The facility (Fig. 1a) consists of a full-scale street section where the rainfall-runoff generated by a dripper-based rainfall simulator, which is able to produce three different rain intensities (30, 50 and 80 mm h^{-1}), drains into a pipe system through two gully pots. Two types of configurations have been used to visualize overland flow: a) experiments using fluorescent particles and UV illumination; and b) using white-LED lamps without artificial particles to highlight air bubbles and water reflections generated by raindrops in the flow. While seeded videos were already used in the application of a modified LSPIV technique in Naves et al. (2019a) as stated in the introduction section, unseeded videos are used for the first time in this work to consider ~~SSIV and BIV~~ imaging velocimetry techniques that do not require artificial ~~particles~~tracers. Figure 1b shows a scheme of the configuration of the experiments where the videos were recorded.

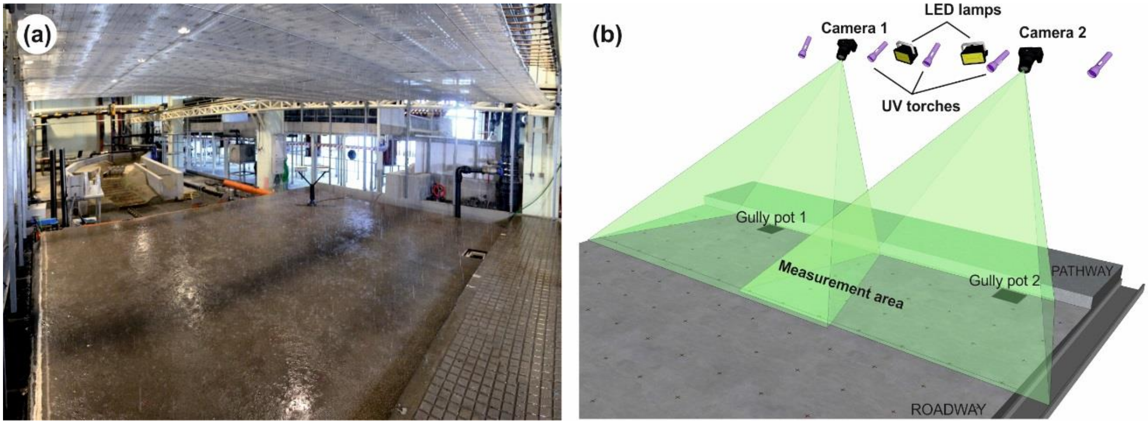

Figure 1: General image of the urban drainage physical model with the rainfall simulator (a) and experimental setup of the PIV experiments (b).

As seen in Fig. 1b, two Lumix GH4 cameras with 28 mm focal length recorded the first 2 m attached to the curb along 5 m of the physical model. UV torches and LED lamps were installed next to the cameras 2.2 m above the pathway. During the experiments, videos were recorded at ~~Once~~ 4K resolution and 25 Hz. ~~videos were recorded,~~ 1500 frames of steady flow (equivalent to 60 s) were then extracted from the longer recording and processed for analysis. To do this, frames ~~. The frames extracted~~w~~ w~~ere scaled and ortho-rectified using the known 2D coordinates of 28 and 24 reference surface points for each camera and the Matlab functions ‘fitgeotrans’ and ‘imwarp’. Finally, the reference points placed in the intersection between the recorded areas of each camera were used to crop and join the image, resulting in raw images where 1 pixel corresponds to 1 mm in real-world coordinates. Examples of these images obtained from UV seeded and LED unseeded experiments, which are openly available for others to use in the dataset published by the authors (Naves et al., 2019b), are included in Fig. 2. These six sets of images considering both the experimental setup and the three rain intensities were used as the basis for the different imaging velocimetry techniques assessed in this study. A more detailed description of the physical model, the simulated rain, or the procedure to extract the images can be consulted in Naves et al. (2020b, 2020c, 2019a), respectively.

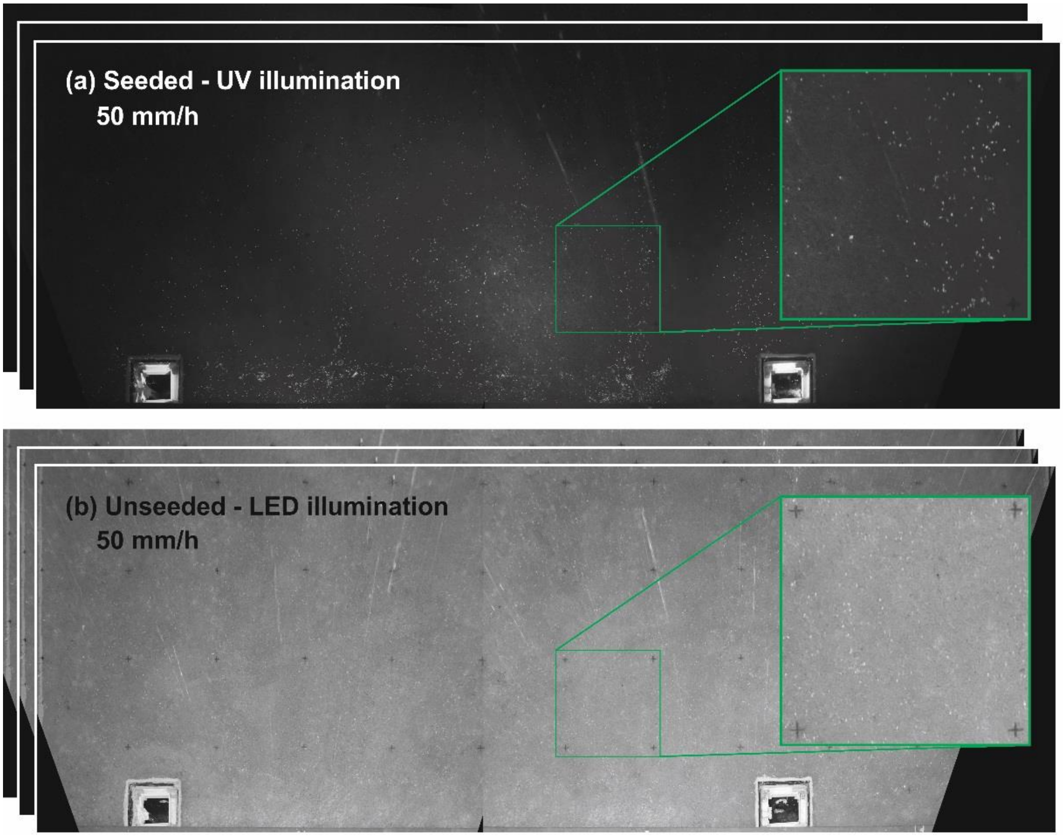

Figure 2: Example of frames used for the assessment of different imaging velocimetry techniques. Images correspond with the two experiments performed for the rain intensity of 50 mm h^{-1}: using fluorescent particles and UV illumination (a) and using led lamps to highlight water reflections and air bubbles present in the flow (b).

2.2 Analysis procedure and imaging velocimetry techniques

Four imaging velocimetry techniques were considered in this study to ~~obtain~~ estimate ~~the~~ overland flow velocities ~~from the analysis of the images presented in the previous point~~. First, the LSPIV methodology was assessed using the images with fluorescent particles and UV illumination. That methodology requires pre-processing of images through a sliding background (SLB), which eliminates the background of the images and particles that remain ~~still~~ immobile between frames. These particles, which are deposited due to the extreme low depths developed and the rugosity of the concrete surface, should be removed to avoid that the null velocities resulted from them condition the PIV analysis. Then, ~~the~~ a LSPIV-based method named as LSPIVu in this work ~~SSIV~~ and the BIV technique~~s~~ were used to obtain velocity fields from the unseeded and LED-illuminated experiments. ~~SSIV~~ LSPIVu is inspired in the non-open SSIV ~~software~~procedure employed in Leitao et al. (2018) and uses a

~~the same~~ SLB image pre-processing to remove the background from the analysis and satisfactorily trace the movement of air bubbles and surface water reflections generated by raindrops. Additionally, BIV implements a previous binarization of the grayscale images to highlight bubbles from a determined threshold. Finally, a slight variation of the LSPIV methodology named LSPIVb was implemented to investigate the influence of binarization ~~pre-process~~ also in the analysis of~~, adding the binarization pre-process also for~~ seeded UV experiments. This strategy seeks to isolate the brightest pixels, which in this case correspond with the fluorescence particles, to ensure that other elements such as bubbles or water reflections are not interfering in the PIV analysis. Therefore, the image velocimetry techniques differ in the pre-processing of the images and the experiments used for the analysis. A diagram of the procedure followed for each technique is presented in Fig. 3, which includes a common PIV cross-correlation analysis and a post-processing of the velocity results. The different image velocimetry techniques and the steps of the analysis are further explained below.

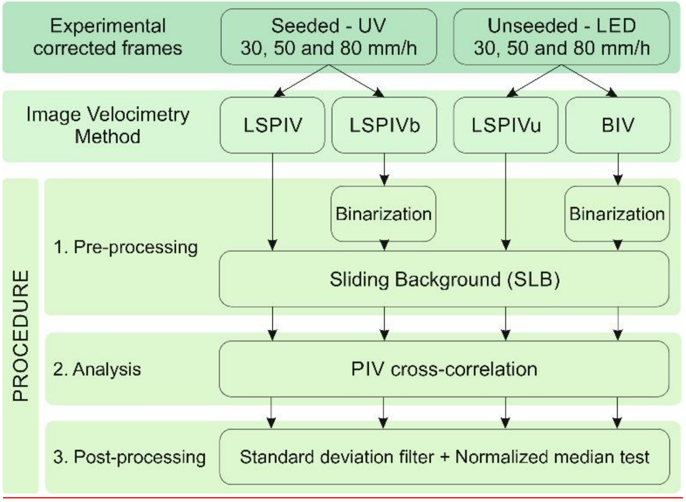

Figure 3: Diagram of the procedure performed to obtain velocity fields from video frames for the different image velocimetry techniques.

2.2.1 Pre-processing

As seen in Fig. 3, the first step in the analysis procedure was the pre-processing of the images depending on the technique employed. The objective of this part of the analysis was to optimize the input images through different strategies to enhance the objective tracers and then measure their movement with PIV algorithms in the next step. The specific procedure followed for each technique is now described:

LSPIV velocity determinations were undertaken using the experimental videos with fluorescent tracers and UV illumination as in Naves et al. (2019a). The pre-processing in the implementation of this method consists of a sliding background filter. This filter compares the gray values of the pixels of a frame with the same pixels of the following one, turning those pixels with a certain percentage of agreement between them to black. Therefore, it is necessary to determine a certain threshold of similitude to remove the background of the images and the particles that stay still between frames, whilst keeping those that are transported by flow. Thus, it is possible to avoid interferences in the cross-correlation of the particle movement that may reduce the mean velocity obtained.

In the case of the LSPIVb procedure, a binarization of the images was performed in the image pre-processing, prior to applying the sliding background filter. This converts the grayscale images to binary images, turning the pixels with gray values greater than a certain threshold to white and all other pixels to black. This filter ensures that only the fluorescent particles are being considering in the PIV cross-correlation, preventing possible small interferences that bubbles or water reflections may produce despite the special illumination (Zhou et al. 2013). Due to this binarization, the subsequent sliding background filter is applied considering a threshold of 100% of similitude to remove the pixel, so only the binarization threshold should be adjusted. ~~The procedure seeks to better remove background and shadows from the original frames in the estimation of velocities from the seeded and UV illumination experiments.~~

In contrast to LSPIV and LSPIVb, the LSPIVu~~SSIV~~ technique was applied to the images taken from the unseeded and LED illuminated experiments. ~~SSIV~~LSPIVu is analogous to LSPIV procedure, applying the sliding background filter below a certain threshold to remove the background of the original images. In this technique, the pre-processing of the images seeks to analyze the movement of both surface air bubbles and water reflections generated by raindrops. Lastly, the procedure of the BIV technique additionally includes an image binarization filter, as was used in the LSPIVb ~~procedure~~methodology, to isolate air bubbles to be used as tracers in the analysis of the images taken from the unseeded experiments. ~~The assessment of these methods, which obtain velocity fields directly from videos recorded from the catchment surface without adding particles, is an important task in order to study the feasibility of implementing this technology in real catchments, which would be an interesting source of velocity data to calibrate shallow water and dual drainage models.~~

2.2.2 PIV cross-correlation

The different alternatives of image processing, depending on the image velocimetry technique (LSPIV, LSPIVb, ~~SSIV~~LSPIVu or BIV), were applied to 60 s of images taken in steady flow conditions, and the resulting frames were then analyzed by the PIV image software PIVLab (Thielicke and Stamhuis, 2014). This software performs a cross-correlation analysis between consecutive frames, which are divided into different interrogation areas (IA), to obtain the mean displacement vector for each of the IA~~.~~, being ~~T~~the size of the ~~this~~ IA ~~is~~ a parameter that must be adjusted as a function of the mean displacement in order to achieve suitable results. Common procedures to estimate this particle displacement, and thus flow velocity, has been applied in the present work (Raffel et al., 2007; Adrian et al., 2011). The discrete Fourier transform (DFT), calculated using a fast Fourier transform (FFT), was used to compute the correlation matrix in the frequency domain. Moreover, two ~~To compute the correlation matrix in the frequency domain, the Discrete Fourier transform (DFT) was proposed, calculated using a fast Fourier transform (FFT). Two~~ passes of a multi-pass window deformation algorithm were used in the present work, halving the window size at the second pass to achieve a higher spatial resolution. The searching area (SA) matches with the IA and 50% of overlapping was selected in all cases in the present work. These procedures are included in most of the conventional PIV algorithms such as PIVLab (Thieckle and Stamihus 2014), or OpenPIV (Taylor et al. 2010).

2.2.3 Post-processing

Two filters for the detection of spurious vectors were applied to the velocity fields obtained. First, the results were filtered to remove those velocity vectors that differed four times the standard deviation from the mean velocity of the individual velocity fields. Then, the normalized median test was applied in a 3×3 neighborhood as proposed in Westerweel and Scarano (2005). After preliminary tests ~~testing~~assessing the performance detecting spurious vectors in the PIV results, the values of the two parameters of this filter were set to ε = 0.15 and threshold = 3~~The values of the two parameters of this filter were ε = 0.15 and the threshold = 3, which were investigated as optimum;~~. Outliers and missing data were removed and not replaced in any case. The average velocity field was obtained from the 1500 velocity results in steady conditions obtained for each case of study, which makes them comparable to the results achieved in Naves et al. (2019a) using the LSPIV technique. In this case, the velocities were compared as measured from the movement of tracers without applying velocity indexes to estimate depth-averaged velocities.

2.3 Comparative evaluation of image velocimetry methods

~~The present work seeks to perform a comparative assessment of different image velocimetry techniques in realistic but controlled laboratory conditions.~~ The repetitiveness of the experiments has allowed the evaluation of techniques that require different experimental setups varying the seeding ~~or~~ and illumination. ~~In addition, the properties of the simulated rain (Naves et al., 2020c) include the presence of raindrops in the analysis as a novel scientific contribution.~~

First, following the specific procedure explained in the previous section (Sect. 2.2) for each technique, ~~the first step of~~ the analysis ~~was~~ started with the individual assessment of the robustness of the velocity results achieved by each technique. This assessment was carried out in a manner similar to Legout et al. (2012). The key parameters of the procedure were varied one-at-a-time within reasonable ranges to investigate their influence on the average velocity results. The parameters considered were: a) the pre-processing parameter, which corresponds with the sliding background or the binarization threshold depending on the image velocimetry technique; b) the IA initial size in the cross-correlation algorithm; and c) the frame acquisition rate (FAR) of the experimental videos. The entire analysis was focused on four areas of the model surface in order to separately consider different types of flow that are developed in real catchments.

Moreover, a detailed comparison of the mean velocity fields achieved from one minute of steady conditions using each technique was performed considering each of the three rain intensities and each of the four surface areas, and using the LSPIV method ~~is used~~ as ~~the~~ reference ~~technique~~. ~~In this way, it was possible to study the differences observed and discuss the possibilities of imaging velocimetry techniques in different flow conditions during rain events. In this analysis, the LSPIV method is used as the reference technique since it was already validated in Naves et al. (2019a).~~ Finally, the transferability of the previous imaging velocimetry techniques to field studies is discussed considering the previous results and an additional convergence analysis, which assesses the uncertainties of measuring velocities in transient conditions. Further details of the studied areas, the ranges of the parameters and the implementation methodology are included in the following Sect. 2.4, 2.5, and 2.6.

2.4 Areas considered for analysis

The urban drainage physical model considered in this study enables typical flows such as those that are developed in real catchments to be reproduced. Figure 4 includes the previous velocity field results obtained in Naves et al. (2019a) for the rain intensity of 50 mm h^{-1} and the drainage basin of gully pot 2. As can be observed, the runoff generated by the rainfall simulator produces two perpendicular flows: a very shallow flow towards the curb, and a longitudinal curb flow with depths up to 10 mm that drains the runoff into the gully pots. In addition, some preferential drainage channels, where velocities are significantly increased, have been detected in the overland flow perpendicular to the curb due to irregularities in the model surface.

The comparative analysis performed in this study was focused on four specific areas of the model surface in order to assess the performance of the techniques considered for different types of water flows that may be found in real catchments. These are: straight one-main-direction overland flow as presented in Area 1, where a preferential channel with high velocities is distinguished; a parallel overland flow out of the main drainage channels with very low velocities and water depths (Area 2); the curb flow gathering different secondary flows with a vertical boundary (Area 3); and a combination of the previous type of flows in the vicinity of gully pot 2 (Area 4). Figure 4 includes the specific position in the model surface of each area considered in the analysis performed.

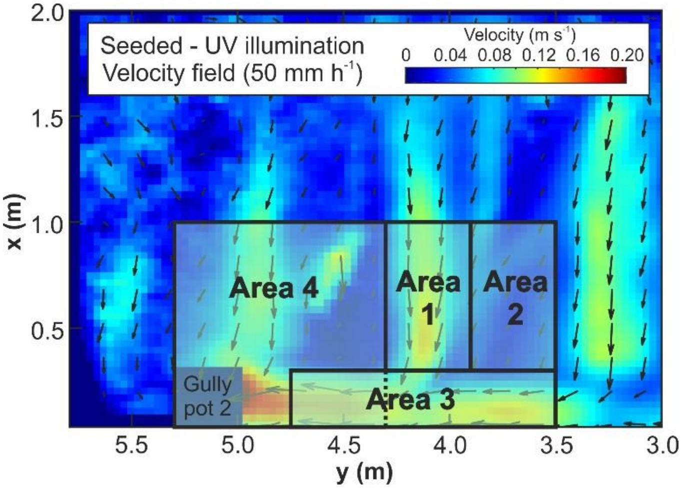

Figure 4: Areas of the model surface analyzed with the image velocimetry methods considering different types of flows that are developed in urban catchments such as perpendicular drainage to the curb (Areas 1 and 2), curb flow (Area 3) and vicinities of gully pot 2 (Area 4). The velocity field plotted to understand the choice of the analyzed areas was taken from Naves et al. (2019a), where the LSPIV was satisfactory applied.

2.5 Parameters ranges

As stated in Sect. 2.3, the first part of the analysis performed seeks to assess the robustness of the velocity results and their sensitivity to changes in the different input parameters of the procedure, depending on the image velocimetry technique used. The base parameters established in the analysis and their ranges of variation are given in Table 1. First, the FAR of the videos taken from the experiments was 25 Hz, which was established as the reference value since it is ~~in consonance~~typical of with most imaging devices available on the market. However, those cases in which only one of each two images (12.5 Hz) and one of each three images (6.25 Hz) are used for the analysis were also investigated in this study. This simulates the FAR of ~~worse~~ some already installed devices that may serve as media source to measure urban runoff velocities in field applications, such as traffic or surveillance cameras following the ideas stated in Leitão et al. (2018).~~ was to approach the conditions of worse devices that could already be installed, in accordance with the ideas developed in Leitão et al. (2018), where the use of surveillance cameras to obtain overland velocities was proposed.~~

Table 1. Ranges of the parameters considered in the analysis of the different image velocimetry methods. Values in parentheses specify the base value of the parameters used as reference.

Image velocimetry method	FAR (Hz)	Pre-processing thresholds		IA size (px)
		Binarization	SLB (%)	
LSPIV	6.25 - 25 (25)	-	0 - 50 (25)	16 - 48 (32)
LSPIVb	6.25 - 25 (25)	0.15 - 0.35 (0.25)	100	16 - 48 (32)
LSPIVu~~SSIV~~	6.25 - 25 (25)	-	5 - 25 (15)	16 - 48 (32)
BIV	6.25 - 25 (25)	0.50 - 0.70 (0.60)	100	16 - 48 (32)

The variations produced in the velocities because of changes in the pre-processing parameters were also investigated. In the cases of LSPIV and LSPIVu~~SSIV~~, only the sliding background threshold was considered since binarization was not performed. In contrast, LSPIVb and BIV required the definition of the binarization threshold, but the sliding background threshold had to be fixed at 100 % to delete those pixels that appear in white in two consecutive and binarized frames. The reference value of these thresholds and their range of variation during the analysis were determined based on expertise and preliminary tests, resulting in variations of the SLB threshold from 0 % to 50 % for LSPIV and from 5 % to 25 % for LSPIVu~~SSIV~~; and binarization thresholds from 0.15 to 0.35 for LSPIVb and from 0.50 to 0.70 for BIV. Reference values were thus established as the mean value for each range.

The reference value for the IA size during the cross-correlation process was set following the recommendations in Raffel et al. (2007) and Adrian et al. (2011). As the maximum velocity vectors are around 10 pixels/frame in absolute values, the reference interrogation area (IA) is set at 32x32 pixels. This assures the rule of thumb that displacements cover around 25 % of the total size of the IA. The range of IA sizes was established within 16 and 48 pixels.

2.6 Implementation

The variations of the velocity results because of changes in the parameters were analyzed by varying the reference value of one determined parameter within its established range. In addition to the reference value, four different values were also considered using uniform steps for the IA size and the pre-processing parameter. For example, IA sizes of 16, 24, 32, 40, and 48 pixels were investigated whilst keeping the remaining parameters constant. As commented in Sect. 2.5, the FAR has been modified between 25, 12.5, and 6.25 Hz. This resulted in 11 different parameter sets for each of the four different image techniques, three different rainfalls and four different areas. Therefore, a total of 528 cases were considered when analyzing the 1500 raw frames recorded in the seeded or unseeded experiments. The representation of velocity fields was performed through the Matlab toolbox ‘pivmat’ (Moisy, 2017).

3 Results and discussion

In the present section, the differences obtained in the velocity fields resulting from analyzing the experimental videos by four image velocimetry techniques (LSPIV, LSPIVb, LSPIVu ~~SSIV~~ and BIV) are presented and discussed. First, the sensitivity of the different methods to image processing variables is investigated to assess their robustness and performance in analyzing shallow flows with the presence of raindrops. Then, velocity results are compared and the feasibility of using these techniques in transient flow conditions is analyzed.

3.1 Sensitivity to image processing analysis

The changes in the mean velocities obtained by varying the key parameters of the analysis for the three study areas, the four imaging velocimetry techniques and the rain intensity of 50 mm h^{-1} are shown in Fig. 5. The graph includes velocity results as the average of the mean velocities resulting from each pair of frames analyzed (1500 in the case of frequency acquisition rate~~FAR~~ of 25 Hz), plotting their standard deviation using whiskers. The reference value and the range of variation of the parameters considered, which are the pre-processing parameter (binary threshold or sliding background depending on the technique used), the interrogation area size (IA), and the frequency acquisition rate (FAR), have been previously defined in Sect. 2.5. This analysis focused on the intermediate rain intensity experiments, although similar results were obtained for 30 and 80 mm h^{-1}, which are included in the supplementary information. Generally speaking, Fig. 5 shows how the variation of the parameters within the established ranges did not produce significant variations in the mean velocity results. Therefore, the methodology and the imaging velocimetry techniques analyzed in this work are presented as being robust and the reference values can be considered when comparing the velocity results obtained by each technique.

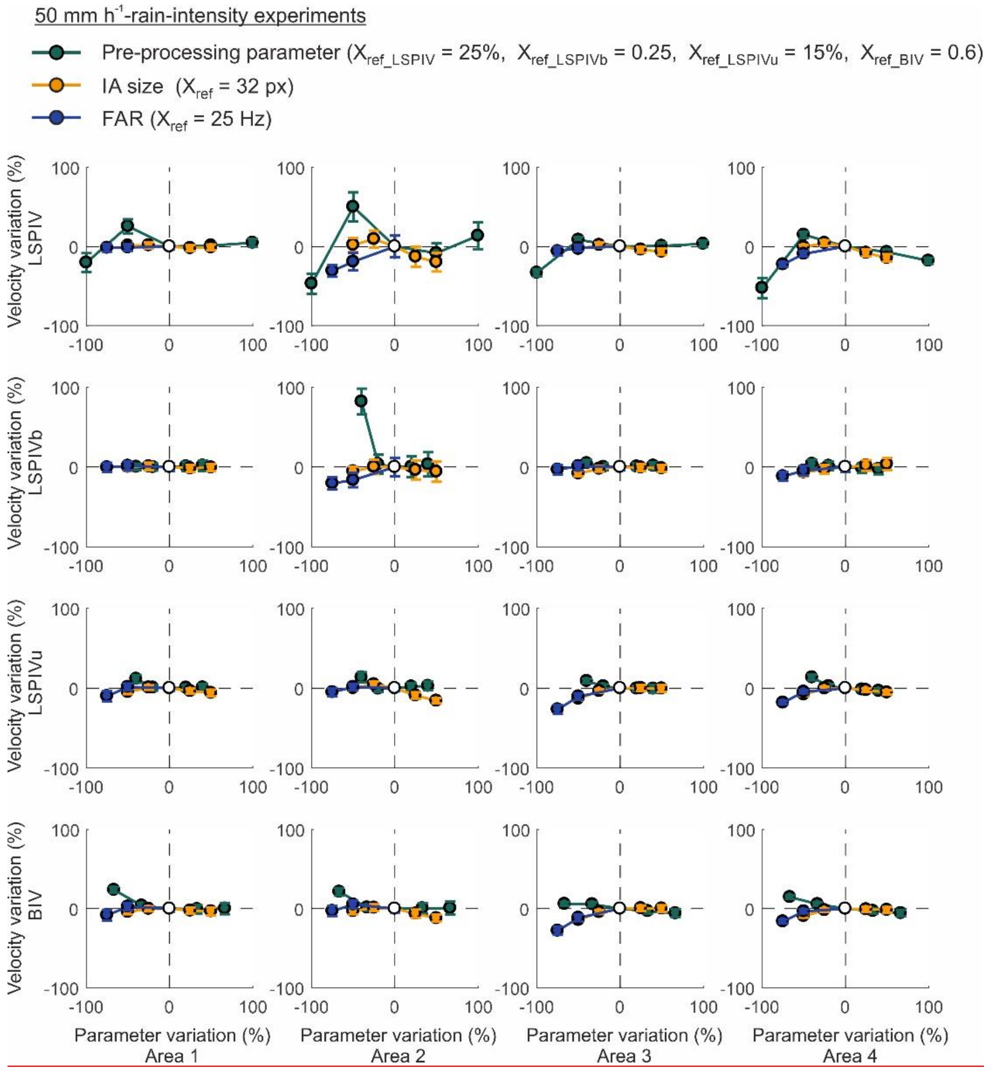

Figure 5: Percentage of variation in the mean velocities when varying parameters of the analysis for the four studied areas (columns) and the four imaging velocimetry techniques considered (rows) in the case of 50 mm h^{-1} rainfall. Mean velocity variability for the different pairs of frames analyzed are included using whiskers.

Considering techniques that use seeded experiments (LSPIV and LSPIVb), the pre-processing parameter showed the greatest influence on the results. This is due to the importance of removing particles that remain still on the model surface in order to achieve reliable results. As seen in the results, the binarization considered in LSPIVb reduces this sensitivity to the pre-processing parameter, except in Area 2 where the extremely shallow flow considered greatly favors particle deposition. The ~~type of flow~~very low depths developed in this area also increases the variability of the mean velocities depending on the pair of frames analyzed, which remains low for the rest of the cases, as can be seen from the plotted whiskers. The techniques that analyze the videos without particles (LSPIVu~~SSIV~~ and BIV) are slightly less sensitive to variations in the parameters. In summary, the results obtained by the imaging velocimetry techniques are presented as being quite stable and the velocities do not depend on the parameters being within reasonable ranges established by expertise. Therefore, the velocity results obtained from the reference parameter values are representative of each technique and can be used to assess their performance. Finally, an expected degradation was noted when FAR is reduced, but within assumable ranges that make it possible to consider cameras with lower FAR as media source for field applications.

3.2 Velocity results comparison

The performance of each technique was assessed by comparing the velocity field results obtained in the study areas by each technique for the three rain intensities considered. To do this and following the previous results (Sect. 3.1), the velocities obtained using the reference values of the parameters (Table 1) have been considered for this comparison. In addition, the LSPIV technique was used as the reference results since it had been previously validated in Naves et al. (2019a). The comparative results are presented separately below for each study area in order to analyze the performance of each technique in detail for the different types of flow developed on the model surface.

First, Fig. 6 shows the comparison of the velocity fields in Area 1, which corresponds to a main drainage channel perpendicular to the curb where high velocities are developed. The velocity fields obtained and a derived disparity plot using the LSPIV results as ~~the~~ reference were included in Fig. 6 for the three different rain intensities. The first result to highlight is that the implementation of binarization in the pre-processing of the frames introduced no significant improvements in the velocity field results. In contrast, very important differences were observed by comparing techniques that analyze videos with (LSPIV and LSPIVb) and without (LSPIVu~~SSIV~~ and BIV) particles. ~~Considering the results~~ A~~for the lowest rain intensity (first row), a~~All ~~the~~ visualization techniques presented a similar velocity distribution for the lowest rain intensity (first row), although an ~~gap~~ offset of approximately 0.05 m s^{-1} was obtained for the unseeded techniques. This ~~gap~~ offset is ~~because~~ produced because the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Considering the novel application of these techniques in presence of rain, it can be deduced that ~~different types of tracers are being analyzed in each case and, while fluorescent particles are transported in suspension inside the flow, bubbles and water reflections follow the higher velocities developed on the water surface. Therefore,~~ all ~~the~~ techniques obtained a ~~very~~ good performance for 30 mm h^{-1} rainfall and ~~it is deduced~~ that lower velocity indexes are required in the case of ~~the~~ unseeded techniques to convert the results to depth-averaged velocities, as observed in previous references (Leitão et al., 2018; Martins et al., 2018; Naves et al., 2019a). However, the velocity fields obtained for rain intensities of 50 and 80 mm h^{-1} showed that both the LSPIVu~~SSIV~~ as well as the BIV techniques resulted in erroneous ~~presented important differences regarding~~ velocity distributions, being more affected the areas where greater velocities are developed. In the case of the rain intensity of 50 mm h^{-1}, there is an unexpected reduction in velocities for the unseeded techniques, which is greatly incremented as the velocities are roughly higher than 0.10 m s^{-1} for the LSPIV technique. Considering the 80 mm h^{-1} results, it can be deduced that this ~~unexpected decrease~~issue measuring ~~in~~ velocities is clearly related with the rain intensity, since the perturbations in the velocity results started to occur for lower LSPIV velocities and to a greater extent as the rain intensity increases.

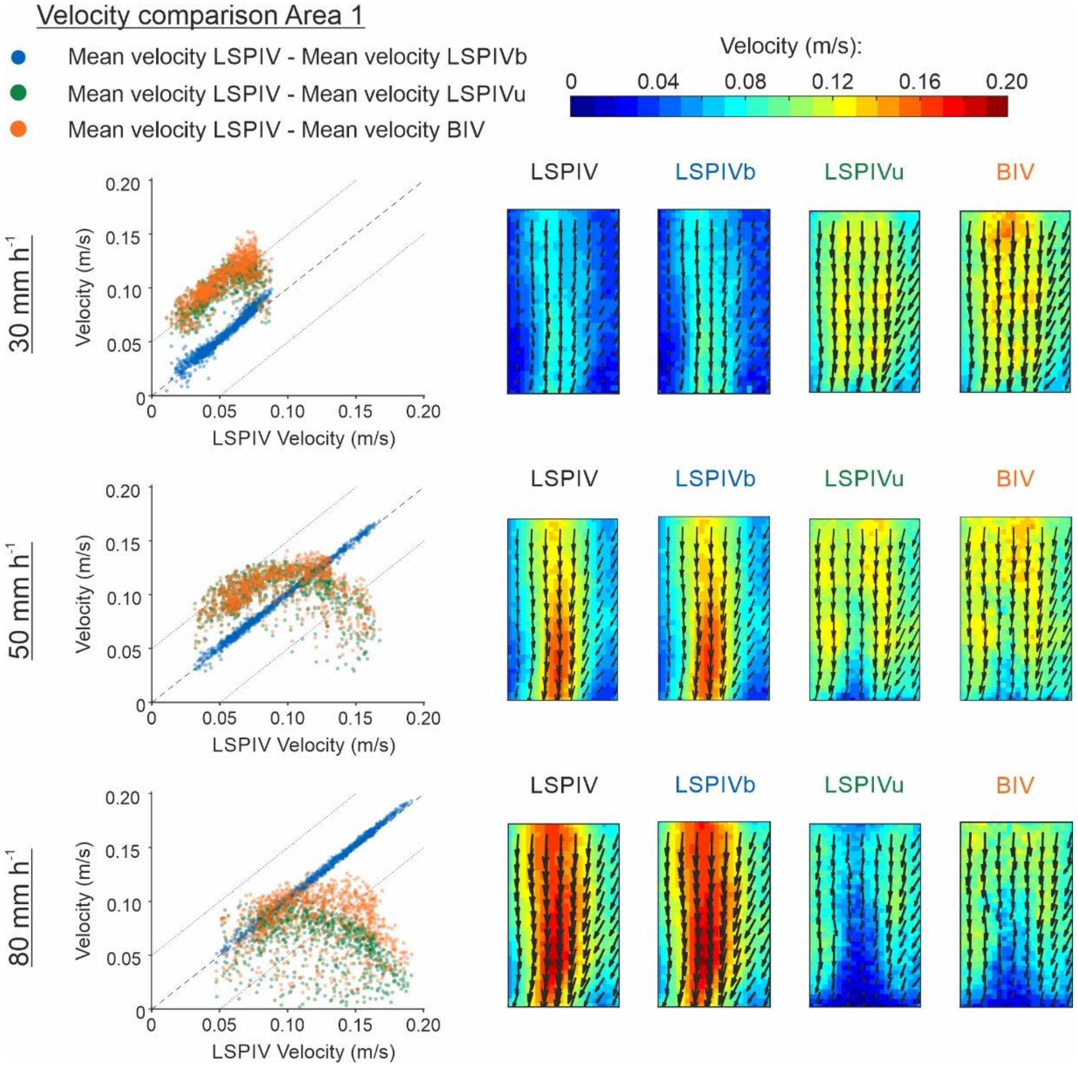

Figure 6: Velocity comparison between imaging velocimetry techniques results (LSPIV, LSPIVb, LSPIVu~~SSIV~~ and BIV) in Area 1 for the three different rain intensities (30, 50, and 80 mm h^{-1}). The velocity fields obtained for each case are also plotted for a qualitative comparison.

This phenomenon can be explained by the combination of two different processes. First, the reduction in the gap between velocities obtained from the seeded and unseeded techniques for LSPIV velocities lower than 0.10 m s^{-1} is explained because of the turbulences generated by the raindrop impacts, which decrease the flow surface velocity. The velocity index to estimate depth average velocities therefore depends on the rain intensity. Then, the ~~inability~~ problems of ~~the~~ unseeded techniques (LSPIVu~~SSIV~~ and BIV) ~~to measure the highest~~measuring velocities with high rain intensities ~~is~~ are not produced because of a lack of tracers since, as can be observed in the videos provided in Naves et al. (2019b), the number of bubbles in that area increases with the rain intensity. ~~The problem~~These are ~~is~~ caused by the erratic trajectory of the bubbles observed in the unseeded videos for high~~er~~ rain intensities~~, also~~ due to the impact of raindrops on the water surface. It is assumed that raindrops, when falling, interrupt part of the existing flow and produce acceleration of the flow in all directions in the surrounding area to the impact (Kilinc and Richardson, 1973). The ~~non-artificial~~natural bubbles used as tracers for the LSPIVu~~SSIV~~ and BIV techniques are highly affected by these accelerations, producing very fast, random and major changes in the position of the tracers; these are exacerbated as the velocity of the bubbles and the rain intensity increases. This ~~avoids~~ prevents cross-correlation algorithms from obtaining displacements of tracers and results in erroneous velocities. The mass of the fluorescent particles used as tracers in the case of LSPIV and LSPIVb, with a density slightly higher than water, confers themselves inertia to avoid such sudden movements and allows cross-correlation between consecutive frames.

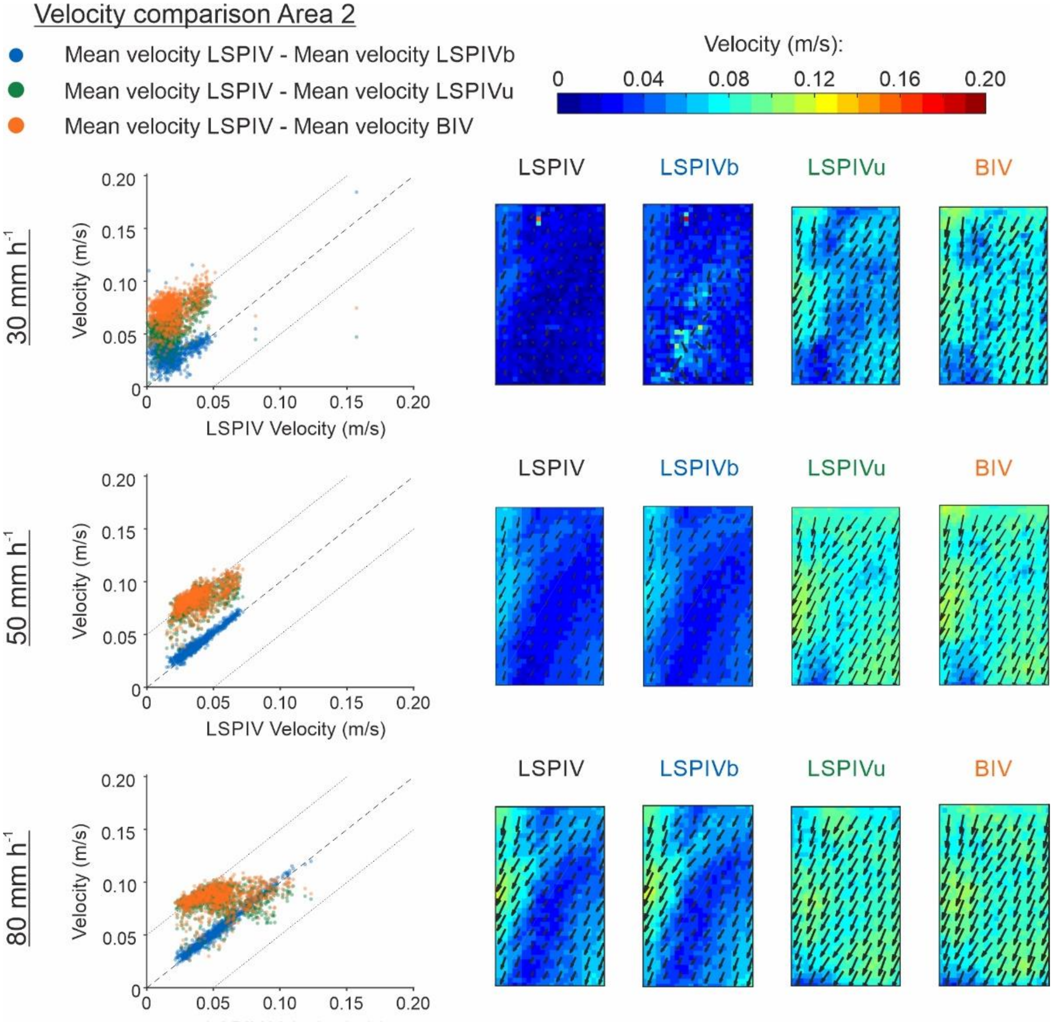

Figure 7: Velocity comparison between imaging velocimetry techniques results (LSPIV, LSPIVb, LSPIVu~~SSIV~~ and BIV) in Area 2 for the three different rain intensities (30, 50, and 80 mm h^{-1}). The velocity fields obtained for each case are also plotted for a qualitative comparison.

Despite these problems in measuring ~~high~~ velocities with high rain intensities, the use of bubbles as tracers can be an opportunity with low rain intensities to measure velocities in extremely shallow flows where the particles tend to be deposited, as can be seen on the sides of the drainage channel in the velocity fields of Fig. 6~~, especially for lower rain intensities~~. This is better assessed in the analysis of the results in Area 2 (Fig. 7), which is attached to Area 1 and considers a perpendicular flow to the curb, out of the main drainage channels and where very shallow flows are developed.

As can be seen in Fig. 7, there is a central zone in Area 2 where the methods that use particles as tracers (LSPIV and LSPIVb) are not able to obtain velocity data (dark blue areas in the respective velocity fields). ~~Despite~~ In this zone, which corresponds with the lowest water depths~~, becoming~~ and becomes smaller as the rain intensity is higher and the water depths increase, it is necessary to use the LSPIVu~~SSIV~~ or BIV techniques to obtain reliable results~~ in the whole study area~~. As can be checked in the recorded videos, this is because bubbles are able to pass through the extremely shallow areas where fluorescent particles tend to be deposited. Regarding the influence of the rain intensity on the results, a similar behavior to that for Area 1 is observed but in this case, only the experiment with the highest rain intensities results in erroneous velocities~~seems to be affected,~~ due to the low velocities registered.

Figure 8 presents the comparison between the velocity results in Area 3. The velocity fields in this area refer to the channel attached to the curb that runs perpendicular to the flows presented in Areas 1 and 2, and where most of the overland flows are gathered on their way to the drain inlet. Figure 8 only includes velocity fields for the rain intensity of 50 mm h^{-1} since no interesting differences were found between rain intensities; the rest of the velocity field can be consulted in the supplementary information. In the recorded videos of the unseeded experiments, it was observed that raindrop impacts do not produce bubbles in that area due to the greater water depths and moreover, existing bubbles cannot access to this flow from the rest of the catchment and stay retained in the confluence of flows. This results in a lack of tracers and thus the impossibility of measuring velocities correctly with the LSPIVu~~SSIV~~ and BIV techniques. In contrast, LSPIV and LSPIVb present a high density of particles and accurate velocity results with a high concordance between both techniques. Therefore, it can be concluded that it is not possible to measure velocities in those conditions ~~without the presence of bubbles~~ using the LSPIVu~~SSIV~~ technique to trace water reflections without the presence of bubbles, so the use of particles as tracers is highly recommendable in this type of complex flows.

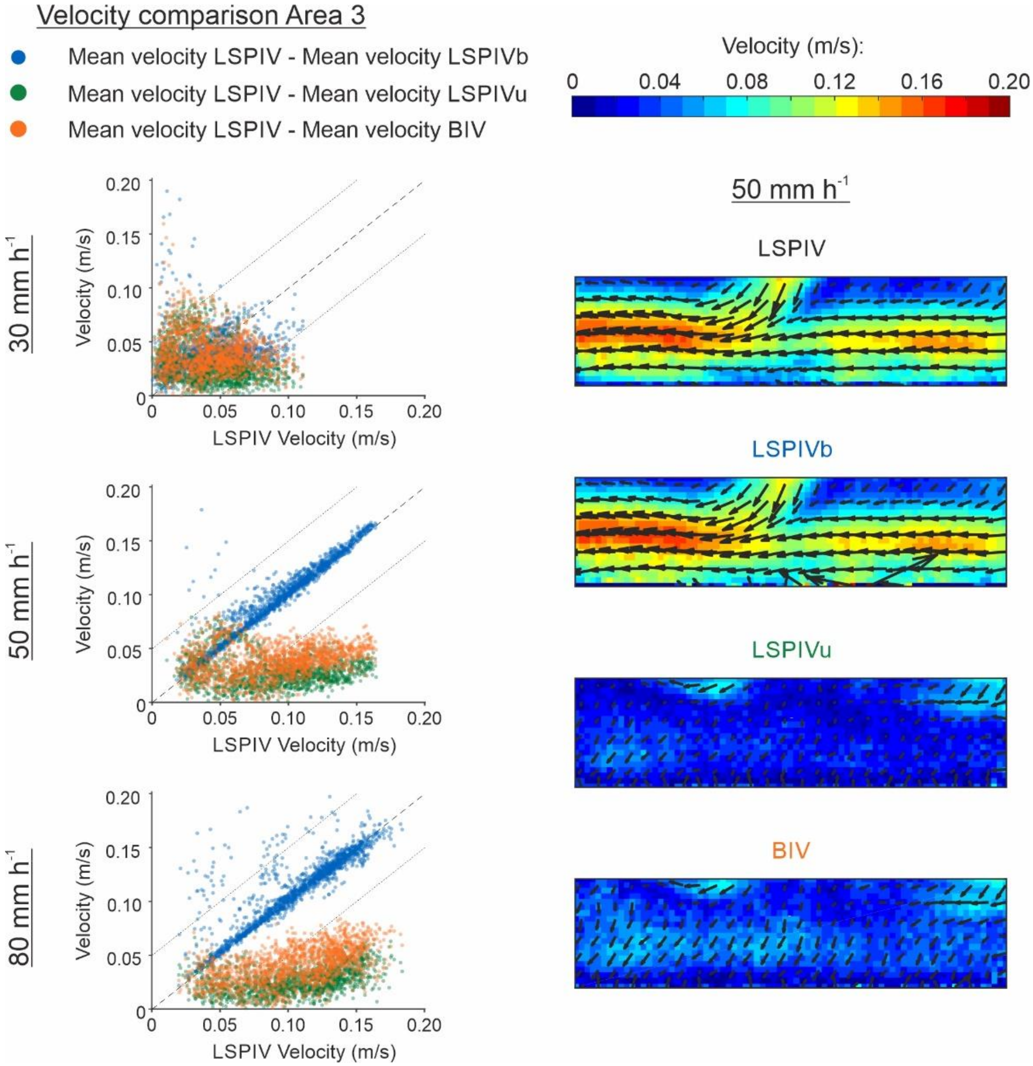

Figure 8: Velocity comparison between imaging velocimetry techniques results (LSPIV, LSPIVb, LSPIVu~~SSIV~~ and BIV) in Area 3 for the three different rain intensities (30, 50, and 80 mm h^{-1}). The velocity fields obtained for the case of 50 mm h^{-1} are also plotted for a qualitative comparison.

Finally, Fig. 9 shows the velocity fields obtained in Area 4 for the case of 50 mm h^{-1} and the comparison between the results obtained by using the four imaging velocimetry techniques and the three rain intensities. The velocity fields for the rain of 30 and 80 mm h^{-1} can be consulted in the supplementary information. This area covers the vicinity of gully pot 2 and is a combination of the previous cases studied considering overland flows perpendicular to the curb, such as those in Areas 1 and 2, and the curb flow analyzed in Area 3. The results plotted in Fig. 9 agree with the observations made for the previous areas and confirm the insights achieved.

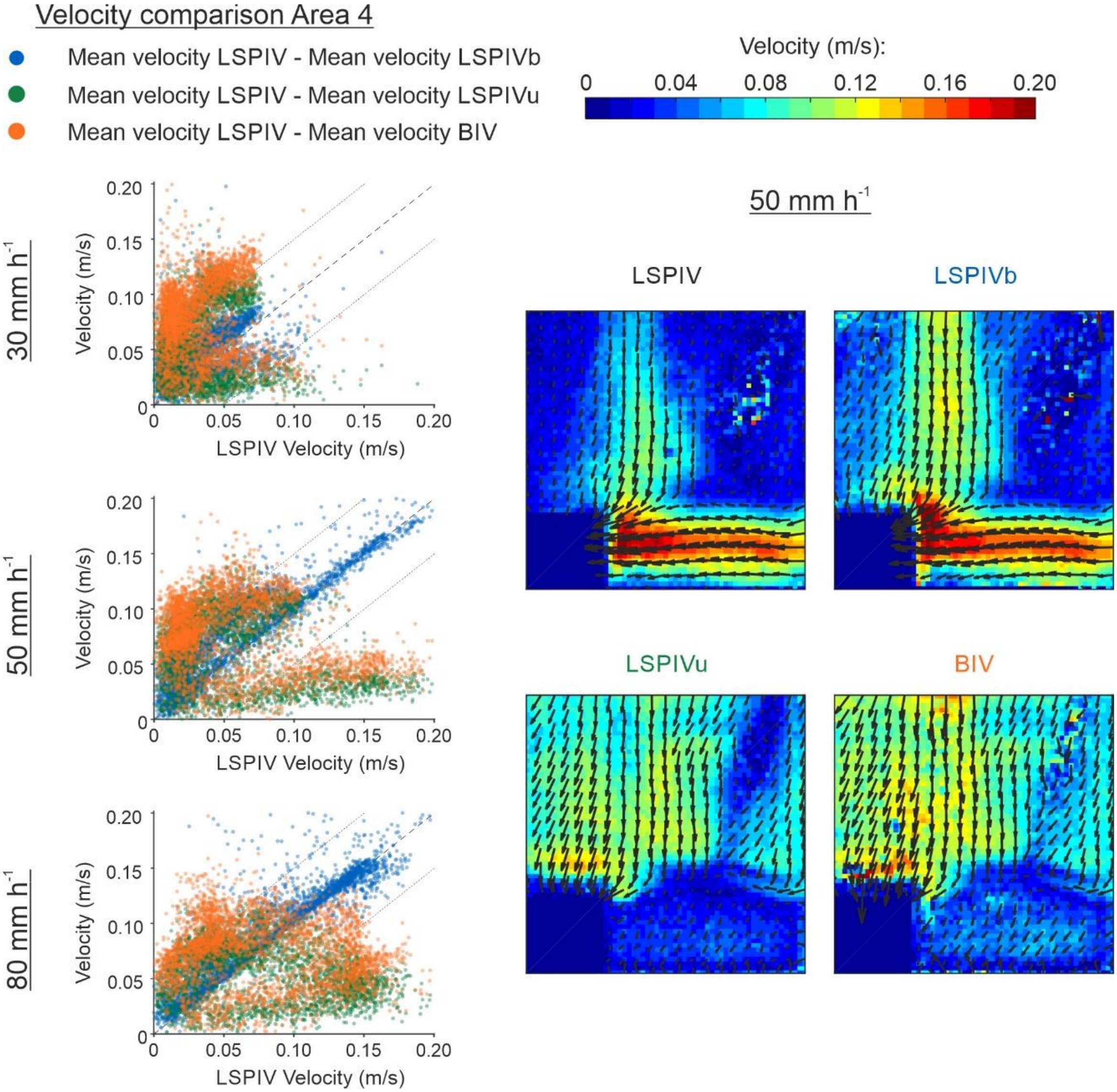

Figure 9: Velocity comparison between imaging velocimetry techniques results (LSPIV, LSPIVb, LSPIVu~~SSIV~~ and BIV) in Area 4 for the three different rain intensities (30, 50, and 80 mm h^{-1}). The velocity fields obtained for the case of 50 mm h^{-1} are also plotted for a qualitative comparison.

As seen in Naves et al. (2019a), LSPIV obtained suitable results for the entire model surface, with some difficulties in extremely shallow flows with depths of around 1 mm where particles tend to be deposited. Then, the velocity fields showed ~~a good correspondence~~very similar results between LSPIV and LSPIVb and between LSPIVu~~SSIV~~ and BIV with slightly ~~different performance~~higher velocities measured by~~ of~~ methods using binarization pre-processing (LSPIVb and BIV). ~~Binarization removes pixels that seem to be still between consecutive frames more frequently since it does not consider the different shades of gray. Although this may improve velocity results in very shallow areas because all the deposited particles~~

~~and still tracers are removed.~~ This similarity indicates that, except particles and bubbles, cameras did not record many other moving elements that disturb the results, so binarization does not includes significant benefits in these experiments. In addition, it has been observed that techniques that include binarization result in noisier velocity results (see velocity fields for 30 and 80 mm h^{-1} in the supplementary information). This may be due to the fact that, if binarization is applied, the sliding background filter may ~~also~~ remove parts of tracers in motion that are overlapped in consecutive frames since no different grey values are considered, ~~obtaining~~ which also might explain the slightly higher velocities obtained. ~~noisier velocity results (see velocity fields for 30 and 80 mm h^{-1} in the supplementary information).~~ Therefore, this filter should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements. ~~-~~In the case of the lowest rain intensity, all the techniques resulted in similar velocity distributions with ~~a~~ the ~~gap~~offset of around 0.05 m s^{-1} observed in the previous areas between the seeded and unseeded techniques ~~of around 0.05 m s^{-1}~~, which is due to the different tracers analyzed. ~~The use of bubbles and water reflections as tracers results in higher velocities in the case of SSIV and BIV because they are transported on the water surface in contrast with the in-flow transportation of particles. This~~The use of bubbles as tracers ~~also~~ gives unseeded techniques ~~that use bubbles as tracers~~ an ~~great~~ opportunity to measure velocities in extremely shallow flows where particles tend to be deposited. However, LSPIVu~~SSIV~~ and BIV are more affected by the impact of raindrops ~~unexpectedly reducing their velocities as the rain intensity is increased~~leading to erroneous results for high rain intensities, especially for high velocity flows. These techniques also presented problems in the flow attached to the curb because of the absence of bubbles in that area.

3.3 Transferability to field applications

The assessment of different imaging velocimetry techniques and the analysis of the influence of different factors on the velocity results contribute to understanding how these methodologies could be adequately transferred to real urban catchments. Although the reliability of the velocity data obtained using the unseeded techniques (LSPIVu~~SSIV~~ and BIV) is compromised for high rain intensities, previous results showed unseeded techniques as a very promising solution for measuring velocities in field applications for low rain intensities or without the presence of raindrops, even in extremely shallow flow conditions. This is because of the good results obtained for ~~low~~ the rain intensity of 30 mm h^{-1}~~ies~~ and the benefits in terms of simplicity in their implementation by not having to add artificial particles to the flow. The use of these techniques in urban catchments would favor new velocity data sources to calibrate physically-based urban drainage models, such as traffic, public or surveillance cameras (Leitão et al., 2018; Moy de Vitry et al. 2020) or even unmanned aerial vehicles, which have already been used in river flow measurements (Lewis and Rhoads, 2018; Pearce et al., 2020). At the same time, the use of particles ~~in the~~using the LSPIV technique ~~enabled~~ is recommended to obtain velocities in complex flows such as those developed in Area 3 of the present study (Fig. 8)~~ to be measured~~, ~~and~~ being the velocity results obtained ~~were~~ suitable even for high rain intensities~~,~~ since particles are less affected by raindrop impacts. Therefore, the use of these seeded techniques may also be very interesting in real urban catchments in order to analyze specific areas of special relevance, such as for example the vicinity of manhole inlet grates, where more complex methodologies could be implemented.

Besides the ability of each technique to adequately measure overland flow velocities in urban catchments with shallow water flows and the presence of raindrops, it is important to assess the minimum requirements of the recording devices when evaluating the feasibility of using these techniques in field studies. This work has proven that a low frequency acquisition rate of 6.25 Hz could be used ~~without~~ incorporating ~~significant~~ assumable errors into the velocity results obtained. However, in light of the problems observed in Leitão et al. (2018) for rates lower than 20 Hz using only water reflections as tracers, this requirement varies according to the magnitude of the measured velocities and the tracer used. Therefore, it is deduced that artificial particles and naturally generated bubbles considered in the present study favor cross-correlation when the time step between frames is increased. The outdoor study carried out by Leitão et al. (2018) also concluded that a LSPIV based method~~SSIV~~ provides robust results analyzing images with a resolution as low as 256×144 pixels for an area of around 5 m^2. These values are easily overcome by most imaging devices available on the market so, although low acquisition rates and image resolutions will decrease the precision and quality of the velocity results, these are not presented as a major constraint to transferring imaging velocity techniques to real applications in urban catchments.

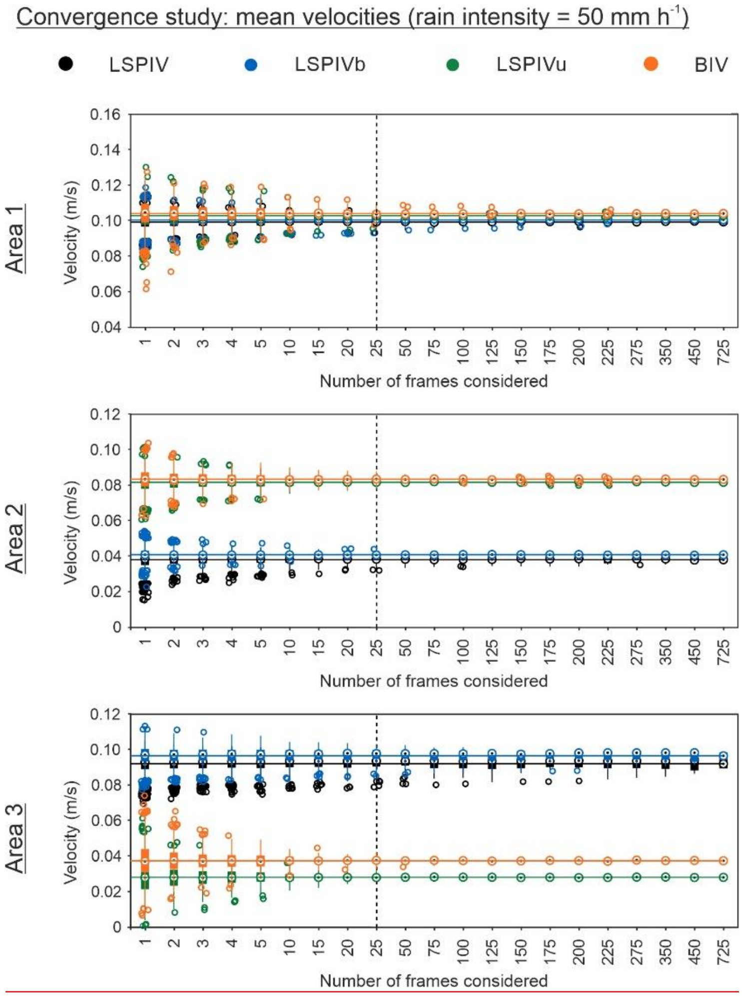

Figure 2~~1~~0: Mean velocity convergence study for rain intensity of 50 mm h^{-1} and Areas 1, 2, and 3. The horizontal line represents the mean velocity considering all the frames available (1500) for LSPIV (black), LSPIVb (blue), LSPIVu~~SSIV~~ (green) and BIV (orange) techniques. Then, the variability in the mean velocity when the frames are divided into groups of different numbers of frames was represented by boxplots.

Finally, the analysis presented in this article has been performed for steady flows comparing average velocity fields obtained from one minute of steady conditions. This allows the comparability of the results with those obtained in Naves et al. (2019a) and reduces the uncertainties in velocity estimations~~,~~ but is not representative of field conditions. Therefore, another important point to address is the uncertainties assumed when using these techniques in transient flows, such as those that would be recorded in real catchments. A convergence analysis is presented in Fig. 10 for the experiments with 50 mm h^{-1} of rain intensity and for Areas 1, 2, and 3, showing the variations in the mean velocities that arise when the number of frames considered is reduced. The first result to highlight is that the mean velocities obtained from each method and from each area follow the insights presented and discussed in Sect. 3.2. In addition, the variations in the mean velocity remain low considering 25 frames in the analysis, which corresponds to one second in the present case study. This value is considered to be enough to ensure reliable velocity results analyzing transient flows and to enhance the possible usability of these imaging velocimetry techniques in future real field studies, meriting further investigation. Convergence results for other rain intensities and for Area 4 are similar and can be consulted in the supplementary information.

4 Conclusions

In this study, the performance of different seeded and unseeded imaging velocimetry techniques has been assessed from videos of the overland flow generated by three different rain intensities in an urban drainage physical model. These techniques use artificial-seeded particles or existing bubbles and water reflections as tracers to estimate surface velocity distributions. The influence of the rain intensity on the reliability of the results has also been explored as a novel scientific contribution by comparing the velocity fields achieved from each study case. Based on the results obtained, the following conclusions can be drawn:

~~-~~ The variation in the parameters of the imaging velocimetry techniques within the established ranges did not produce significant variations in mean velocity results. Therefore, the methodology and the imaging velocimetry techniques analyzed in this work are presented as being robust, and expertise can be used to set the required parameters for the analysis.

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- Both seeded and unseeded techniques provide suitable velocity distributions for lower rain intensities in case of unidirectional flows, observing an ~~gap~~ offset of approximately 0.05 m s-1 ~~in velocities~~between them ~~due to the different tracers being analyzed~~. This offset is a consequence of the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Lower velocity indexes are thus required in the case of unseeded techniques to convert the results to depth-averaged velocities. In case of more complex flows, unseeded techniques are not able to adequately measure velocities since bubbles have difficulties to follow the runoff generated. ~~The mobilization of bubbles on the water surface results in higher velocities for unseeded techniques, but gives them a great opportunity to measure extremely shallow flows where particles tend to be deposited, and to be applied in field applications where the distribution of artificial particles in urban catchments during rain events is not trivial.~~
- Unseeded techniques are highly affected by raindrop impacts. First, the gap between seeded and unseeded techniques is reduced as the rain intensity is increased, so rain intensity should be also considered to determine the velocity index for estimating depth-average velocities. Then, raindrop impacts also produce fast and random changes of position of the bubbles used as tracers, leading to erroneous velocities for ~~the~~ high~~est~~ rain intensities. However, the ability of measuring extremely shallow flows where particles tend to be deposited, and their easy implementation without the need of adding artificial particles, make unseeded techniques worthy of future investigations as new source of runoff velocity data in urban catchments.

- The similarity found between LSPIV and LSPIVb and between LSPIVu~~SSIV~~ and BIV indicates that binarization preprocessing has not significant benefits in these experiments since cameras did not record moving elements that significantly disturb the results. In addition, it has been found that this procedure lead to noisier results, so binarization should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements.
- The rapid convergence of velocity results makes the analysis of transient flows feasible. This fact, as well as the not very demanding requirements of the recorded videos, favor the transferability of these techniques to field studies, where they can be used as a novel tool to obtain runoff velocities in order to calibrate physically-based urban drainage models.

~~Thus, t~~This work ~~highlights not only~~ evaluated the reliability of different imaging techniques obtaining urban runoff velocities in different type of flows and ~~the feasibility of using both seeded and unseeded imaging techniques to obtain surface velocities in shallow flow conditions and~~ with the presence of raindrops, ~~but also~~highlighting ~~-~~the importance of considering rain properties to interpret and assess the results obtained by these ~~type of~~ techniques. Future research should be oriented towards the application of these techniques in real urban catchments.

Author contribution

J.N. performed the experiments with the supervision of J.A.~~,~~ and J.P.~~ and J.S.~~. J.N. processed the experimental data with the supervision of J.G. and J.A. J.N., J.G. and J.A. conceptualized the study, interpreted the results, structured the ~~paper~~paper, and prepared the original draft. All authors revised the manuscript critically for important intellectual content.

Competing interests

The authors declare that they have no conflict of interest.

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