RESPONSES TO REVIEWER #1 COMMENTS ON "*ASSESSING THE QUALITY OF DIGITAL ELEVATION MODELS OBTAINED FROM MINI-UNMANNED AERIAL VEHICLES FOR OVERLAND FLOW MODELLING IN URBAN AREAS*"

The authors would like to thank Reviewer #1 for taking the time to review this manuscript and for the positive impression on this work, as well as for the suggested improvements.

(1) The Authors state that one of the objectives of the research is to understand how UAV flight parameters affect the DEM quality, but within the article such aim is not adequately described. 14 DEMs have been produced (plus 2) with different flight parameters from flight altitude to weather conditions, and only one has been compared with the LIDAR DEM.

Answer: We believe that we indeed did describe the aim in sufficient detail (section 1.4). The results of the statistical analysis involving four flight parameters and four qualitative metrics and four quantitative metrics did not show significant differences for the 16 flights analysed in this study. Based on this, we decided to carry out the comparison between the UAV DEMs and the conventional LiDAR DEM based only on one flight: flight no. 4. Flight no. 4 produced the best quality DEM based on the metrics considered in this study. As this has not been raised by any of the other reviewers, we would like to keep it as is.

(2) The Authors state that the impact of the flight parameters on the DEM quality metrics was not substantial, but I believe some data should be presented.

Answer: This is a very good point. Additional results from the statistical analysis were added in the revised version of the manuscript (as well as plots visualising the collected data to the supporting information) to support the conclusion that different flight parameters did not produced significantly differences in terms of the DEM quality (based on the metrics considered in this study) and some additional quantitative results from the statistical analysis in the form of tables (Section 4.1).

The Tables 3 and 4 and a more thorough description of the results were added to Section 4.1. These tables present the quantitative results (Estimated value and P-value) of the statistical analysis conducted to assess the impact of UAV flight parameters on DEM generation for overland flow modelling.

(3) In the discussion section, the comments are quite generic and not supported by quantitative data; some paragraphs of the discussion could be more suitable in the introduction section, hence I believe that introduction and discussion should be rearranged based on more results.

Answer: as proposed in point (2), we included additional results in the revised manuscript to support the findings of the study presented in the manuscript. These will also aim at addressing this comment. In our view, a discussion can also, maybe even should, include subjective information of the authors which may be not countable or quantitative, but will help the readers to better interpret the obtained results.

(4) 5637, first paragraph: it could be useful to report a small description on the surveying points, in terms of quantity and characteristics, since the DEMs comparison is based on such points.

Answer: Thanks a lot for this suggestion. A brief description of the surveying points was included in the revised version of the manuscript (see new Section 3.4 in the revised manuscript).

(5) 5640, rows 10-12. It could be interesting to test a different flow routing scheme, in particular a multiple one, that can contribute to better represent the surface flow in particular within the urban context, often characterized by small slopes.

Answer: In this paper, we used the D8 flow accumulation algorithm (Jenson and Domingue, 1988) to generate overland flow paths. We agree with the reviewer that there are many other algorithms to generate overland flow paths based on DEM (e.g., Lea, 1992; Tarboton, 1997; Leitão 2013, …). However, the D8 algorithm is perhaps one of the most widely used algorithms to generate overland flow paths based on DEMs as it is implemented in most of commercial GIS software packages and thus most widely use in consulting or design work. As the focus of this study is less on the flow path analysis, and more on the UAV characteristics we think it is justified to use D8 as standard algorithm and omit a sensitivity analysis for the sake of brevity and to keep the manuscript more concise.

(6) 5648, row 23. J.B. Vilmer reference is missing. Reference section: Hutchinson and Gallant (2000) is not cited in the manuscript

Answer: Thank you for spotting this. Please excuse our sloppiness on this point, the list of references was updated and corrected in the revised manuscript.

Lea, N. J. (1992). An aspect driven kinematic routing algorithm. In Parsons, A. and Abrahams, A., editors, *Overland Flow: Hydraulics and Erosion Mechanics*, pages 393407. Chapman and Hall, New York, USA.

Leitão, J. P., Prodanovic, D., Boonya-aroonnet, S., Maksimovic, Č. (2013). Enhanced DEM-based flow path delineation methods for urban flood modelling. Journal of Hydroinformatics, 15(2), 568-579. doi: 10.2166/hydro.2012.275

Tarboton, D. G., (1997), "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," *Water Resources Research*, 33(2): 309-319.

RESPONSES TO MR ABILY'S COMMENTS ON "*ASSESSING THE QUALITY OF DIGITAL ELEVATION MODELS OBTAINED FROM MINI-UNMANNED AERIAL VEHICLES FOR OVERLAND FLOW MODELLING IN URBAN AREAS*"

The authors would like to thank Mr. Morgan Abily for taking the time to review this manuscript and for the positive impression on this work, as well as for the suggested improvements.

(1) LiDAR data is a different technology compare to photogrammetry. These topographic data gathering technologies do not offer same advantages and limitation for a given application (such as gathering topography in an urban environment). This should be quickly recalled in more detailed way (for contextualization) (e.g. in section 2.2). More over the objective or context for the LiDAR topographic campaign should be emphasis (this dataset might has been gathered for a multipurpose use, which is different to the UVA –Photogrametric campaign dedicated to urban sector DEM elaboration).

Answer: We agree with the reviewer. The point regarding the multiuse purpose is interesting and valid. Additional discussion about the properties (flight parameters, objectives and spatial extent) of the two DEMs was included in section 2.2 of the revised manuscript:

"UAV systems are being used for relatively localised surveys, and these surveys are usually targeted to a specific application. The resolution of the imagery produced using UAVs is, in general, of very-high resolution as the flying altitude is low. In the specific case of this study, the UAV DEM was generated based on photogrammetry. The LiDAR-based DEM used in this study covers the whole Switzerland and was obtained to be applied in multiple purposes. By definition, the flight altitude is much higher than that of the UAV, allowing to cover larger areas in a reasonable amount of time. The LiDAR-based DEM was generated based on LiDAR technology, which is completely different from photogrammetry technique used to generate the UAV DEM.

From the general description above, one can say that the DEMs used for the comparison have distinct characteristics. However, the DEM comparison performed in this study is still valid as the analysis conducted in the study aims at comparing the two by practical use in engineering project and not by technological standards or DEM generation methodologies."

(2) UVA, which is the vector for the photogrammetric campaign whereas, if I get it right the LiDAR campaign has been gathered using specific flight as vector (having probably a high flight elevation and different properties).This should be linked with previous comment (regarding objective/spatial extend of the LiDAR campaign).

Answer: see response to point (1).

(3) Results are not as comparable between the two categories of DEM as presented by authors (important differences are presented in figures 5), or at least, a longer discussion regarding explanation for the differences should be provided. Are vegetation and leaves (terrain physical properties) the only explicative point regarding differences or are vector (UVA and airplane flight) parameters responsible for some of the differences (my intuition is, yes here)?

Answer: we totally agree with the reviewer's comment; terrain physical properties can explain the differences between the two DEMs, but may not be the unique reason to explain the differences. Additional discussion was added regarding this issue in Section 4.2.2 of the revised version of the manuscript:

"From this, one may say that most of the elevation differences between the two DEMs are due to existing vegetation; non-static features, such as vehicles on the roads, which are present in one DEM but not in the other, and due to differences along the buildings edges (this could explain the seldom differences of more than five meters between the two DEMs)."

(4) Lastly, conclusion regarding this part enhance that advantages of UAV born DEM. It should be interesting to open the conclu/discussion on possibilities of photogrammetric data to be photointerpreted/classified which is an interesting perspective for objective/tailored DEM creation. Limits should be recalled in conclusion as well : practical difficulties regarding legislative framework for UVA flight, limitation regarding spatial extend of gathering campaign with UVA and the data manipulation (possibly "big data" not easy to handle by standard operator/practitioners without decreasing the quality).

Answer: The authors totally agree with the reviewer. UAV imagery can also be used to generate other very interesting data sets for urban drainage modelling applications based on image classification, such as: identification of pervious/ impervious areas; automatic identification and location of sewer inlets and manholes and other man-made features relevant to overland flow (e.g., walls). A paragraph was added to the *Conclusions* section to discuss these possibilities:

"In addition to the generation of DEMs, UAV imagery can also be used to generate other very interesting data sets for urban drainage modelling applications based on image classification. These are, for example: identification of pervious/ impervious areas (Tokarczyk et al., accepted); automatic identification and location of sewer inlets and manholes and other man-made features relevant to overland flow (Moy de Vitry, 2014)."

RESPONSES TO REVIEWER #3 COMMENTS ON "*ASSESSING THE QUALITY OF DIGITAL ELEVATION MODELS OBTAINED FROM MINI-UNMANNED AERIAL VEHICLES FOR OVERLAND FLOW MODELLING IN URBAN AREAS*"

The authors would like to thank Reviewer #3 for taking the time to review this manuscript and for the suggested improvements.

(0) The paper discusses the advantage of DEM derived from UVA compared to the Lidar DEM; and analyzes the performance and application of UVA DEM. The paper does not seem to bring any advancement in the knowledge of UAV DEM mainly because only simple comparisons are conducted without any quantitative analysis. Here are some suggestions:

Answer: We would like to thank the reviewer for taking the time to read the manuscript. We regret that he does not have the same viewpoint as the other reviewers and will try our very best to convince him about the novelty and scientific soundness of our work. We think that addressing his constructive criticism will improve the focus and clarity of the revised manuscript. However, we would like to stress that the reviewed manuscript contained a quantitative statistical analysis (see sub-section 2.1.3).

(1) The authors need to explain what is the innovation of this paper, which should be clear in Section 1.

Answer: As outlined in the introduction on sub-section 1.4, our study has three innovative elements: (i) uses for the first time DEMs produced from UAV photogrammetry in the context of urban drainage – more specifically on overland flow modelling; (ii) presents dedicated field experiments specifically tailored to understand how UAV flight parameters affect DEM quality and, eventually, overland flow representation, and (iii) compares the quality of the UAV obtained DEM with a DEM used by Swiss engineers (LiDAR-based DEM).

(2) The overlapping degree is one of the most important parameters for high-res DEM generation, which should be discussed deeply.

Answer: We fully agree with this comment, because it also corresponds to our experience and expectation when we conducted the study (all flights conducted in this study have a frontal and lateral overlapping larger than 70%). Thus, to our surprise the influence of the overlap was not statistically significant in the statistical analysis conducted in this study. To make this point clearer, we (i) included more results to support this finding and (ii) extended the discussion about the importance the overlapping degree for generation of HR DEMs from photogrammetry in the revised version of the manuscript.

(i) Section 4.1. - Inclusion of Tables 3 and 4

(ii) Revised text Section 3.3*: "Image overlap. Image overlap is expressed in percent for both frontal and lateral directions, and is an important parameter in the*

photogrammetric process. First, a high overlap increases redundancy of point identification, which improves the 3D precision of the point cloud. Second, it reduces distortions in the orthophoto. In order to achieve acceptable matching between images, it is recommended to have a frontal overlap of 60% or more. This lower limit should be increased in the case of complex terrain (for example forest), or in the case of unstable platforms (for example UAVs)."

(3) In page 15, above section 5, what is the virtual flight purpose? And why was it made virtual for flight 14 and 11? Please clarify.

Answer: This is a good point. Actually, the two additional virtual flights were created to (i) increase the number of "flights" used in the statistical analysis with different parameters and (ii), specifically, to investigate the effect of image overlapping on the quality of UAV imagery DEMs. This contributed to a more robust statistical analysis of the impact of UAV flight parameters on DEM quality (based on the selected DEM evaluation metrics). More details on this and why we used material from flight 14 and 11 were added to the revised manuscript (end of Section 3.3.):

"These two additional virtual flights were created to (i) increase the number of "flights" used in the statistical analysis with different parameters and (ii), specifically, to investigate the effect of image overlapping on the quality of UAV imagery DEMs. This contributed to a more robust statistical analysis of the impact of UAV flight parameters on DEM quality (based on the selected DEM evaluation metrics)."

(4) Lidar DEM is a completely different type of technology, while UVA DEM is from low height UVA. If this Lidar was mounted on the UVA, the comparison would have more fair. The results are not comparable.

Answer: we agree that LiDAR and photogrammetry are different methodologies to generate elevation data (e.g., DEMs) and airplanes and UAVs are also different platforms (with different parameters, such as flight altitude). We should have emphasised that the results are indeed comparable, not by technological standards, but by practical use in engineering projects. In our experience, urban drainage consultants in practical projects hardly ever perform a dedicated DEM generation, but rather use what the available data sets. Two new paragraphs were added to the revised manuscript (section 2.2) stating that the focus of the present study is not on the comparison of methodologies and platforms, but instead on the evaluation of UAV DEMs to other products which are practically available:

"UAV systems are being used for relatively localised surveys, and these surveys are usually targeted to a specific application. The resolution of the imagery produced using UAVs is, in general, of very-high resolution as the flying altitude is low. In the specific case of this study, the UAV DEM was generated based on photogrammetry. The LiDAR-based DEM used in this study covers the whole Switzerland and was obtained to be applied in multiple purposes. By definition, the flight altitude is much higher than that of the UAV, allowing to cover larger

areas in a reasonable amount of time. The LiDAR-based DEM was generated based on LiDAR technology, which is completely different from photogrammetry technique used to generate the UAV DEM.

From the general description above, one can say that the DEMs used for the comparison have distinct characteristics. However, the DEM comparison performed in this study is still valid as the analysis conducted in the study aims at comparing the two by practical use in engineering projects and not by technological standards or DEM generation methodologies."

(5) In section 4.2.1, the river is clear from Lidar DEM; why does it disappear from UVA DEM?

Answer: We thank the reviewer to point out this interesting detail. In the LiDAR DEM, the surface of the river is also not visible due to trees located along the water stream. The fact that the river is also not visible in the UAV DEM is due to the lack of matching points in this area due to the high visual complexity created by tree branches and twigs present in the photos used to generate the DEM: this resulted in a small number of points used in the interpolation – clearly visible in the UAV DEM. A couple of sentences on this were added in the revised version of the manuscript (Section 4.2.1):

"It is possible to qualitatively assess the quality of a DEM using hillshaded DEMs (Figure 5). One clear difference between the two DEMs is that around the creek and wooded ravine (① in Figure 5), neither the terrain nor the trees are represented in the UAV DEM. This is due to the fact that photogrammetry is ill-suited to the high spatial complexity of the trees' branches and twigs: when captured by the drone's camera from different angles, the many overlapping elements of vegetation form complex visual patterns that are specific to each point of view and therefore cannot be matched in the photogrammetric process.

As a result, only a few areas below the vegetation can be regenerated in the photogrammetric point cloud. Because of the visual noise caused by overhead branches, the 3D accuracy of the point cloud in these areas is compromised which predisposes the points to be removed during the automatic point cloud filtering process. The shadows captured in the images used in the orthorectification on the left side of the water stream might also have contributed to this problem. In order to confirm this, other flights, and corresponding DEMs, would need to be evaluated."

(6) In section 4.2.3, the argument is focused on the tree (line 11, page 19); some quantitative analysis should be presented.

Answer: Unfortunately, we disagree with the reviewer who might have missed our description of the quantitiative statistical analysis. Indeed, the results of our regression analysis are presented in Table 4. In this table we quantitatively evaluate the slope differences between the two DEMs and for three types of areas in the study area (all areas, roads and buildings).

(7) In page 21, the first conclusion is obvious and basic knowledge for a researcher. Furthermore, the Lidar can now be easly mounted on UVA, so it is not really a challenge for Lidar (in line 15).

Answer: To our knowledge, this study is the first time DEMs produced based on photogrammetry utilising UAV imagery are used in the context of urban drainage, more specifically on overland flow modelling. Although we agree that some experiences have been carried out using LiDAR mounted on quadcopter-type of UAVs with a comparable reach, this is still not possible with mini-UAVs such as the one used in this study. To the best of our knowledge, LiDAR equipment is still heavier and consumes much more power than a mass-consumer point&shoot camera. As this type of mini-UAV is very lightweight, which is an important characteristic due to safety issues, especially in urban areas, its load capacity is not yet LIDAR-ready. We added this in the Discussion section:

"Although detailed and accurate representation of terrain is of paramount importance for overland flow and flood modelling and assessment, it is challenging for DEMs acquired with traditional methods such as LiDAR or aerial surveys. To our knowledge, this study is the first time DEMs produced based on photogrammetry utilising UAV imagery are used in the context of urban drainage, more specifically on overland flow modelling. Although some experiences have been carried out using LiDAR mounted on quadcopter-type of UAVs with a comparable reach, this is still not possible with mini-UAVs such as the one used in this study. To the best of our knowledge, LiDAR equipment is still heavier and consumes much more power than a mass-consumer point & shoot camera. As this type of mini-UAV is very lightweight, which is an important characteristic due to safety issues, especially in urban areas, its load capacity is not yet LiDAR-ready."

(8) From the Figure7, the difference between is UVA DEM and Lidar DEM is more than 20m, which influences the flowing overland flow model seriously. In this paper, the actual experiment, should be carried to validate the UVA DEM 's performance. The analysis in the paper is rather simple; it cannot support the authors' view-of-point.

Answer: although we generally understand the concern of the reviewer with this comment, we do not entirely understand which specific improvement he or she suggests with "*the actual experiment, should be carried to validate the UVA DEM 's performance*".
We also agree with the point that the DEM differences lead to substantial flow differences. Nevertheless, we still consider that our approach, its results and the drawn conclusions are valid. From Figure 5a, we can see that (i) the major differences located along the water stream are due to the presence/ absence of tree-leaves and (ii) some other considerable elevation differences are located in the buildings surroundings. The area without buildings or trees (left-centre of the figure) has elevation differences of less than 1 m. This is not a problem of the UAV DEM used, but more an issue of the LiDAR DEM; As mentioned above, the LiDAR DEM was acquired for multi-purposes and during a leaves-on conditions. It is expected that it shows some problems when used on urban overland flow applications.

(9) Please check references and citations.

Answer: See comment (6) of reviewer #1.

RESPONSES TO REVIEWER #4 COMMENTS ON "*ASSESSING THE QUALITY OF DIGITAL ELEVATION MODELS OBTAINED FROM MINI-UNMANNED AERIAL VEHICLES FOR OVERLAND FLOW MODELLING IN URBAN AREAS*"

The authors would like to thank Reviewer #4 for taking the time to review this manuscript and for the positive impression on this work, as well as for the suggested improvements.

(1) page 1, line 2: You should explain traditional sources of DEM. The traditional way is changing rapidly

Answer: by "traditional sources of DEM" we meant conventional methods used to generate DEMs, such as, for example: airplane LiDAR DEMs, point and contour surveying. We rearranged the sentence to make this clear:

"…, such as airplane LiDAR DEMs and point and contour maps".

(2) 5637 line 5: I don't agree with the vertical accuracy with a standrad Deviation of 7,5 cm for a manhole

Answer: the source of this standard deviation value is a document cited in the text. As mentioned in the text, we do not know the elevation accuracy of these type of points in our case study area. Due to the lack of better information, we adopted this reference value. If the reviewer has complementary or different information, we would be very grateful if he or she could suggest other references or sources of "default" values, so that we include it in the revised manuscript.

(3) 5637, line 8: it is not the reality that only for large overland flow events the runoff flows over sidewalks. This could be in a traditional assumption, that the manholes and inlets are flooded and the runoff is mainly on the streets. In the real world it Comes from everywhere

(4) 5637, line 18: more or less the same comment as before. It assumes that the runoff mainly occurs on the street

Answer: We totally agree with the reviewer. What we meant by this sentence was that overland flow in urban areas tends to concentrate on streets because they are approximately 10 cm lower than the surrounding areas. This assumption is no longer valid if the amount of overland flow is large enough to "fill" the streets and consequently flow over the surrounding areas too. This sentence was totally revised and included in the revised version in the manuscript:

"Despite runoff occurs all over the catchment area, overland flow tends to concentrate in roads in urban areas; for large runoff events (e.g. flooding events) the overland flow will flow over sidewalks."

(5) 5644 line 18: you should not compare nationwide available DEM with a one which is collected by an UAV. There are also other possible solutions.

Answer: This critique touches on the same point as comment (4) of reviewer #3. We agree that there are indeed solutions to generate DEMs other than nationwide and UAV DEMs, such as: ground-based LiDAR, which are capable of producing very-fine resolution DEMs along streets and are flexible too. However, this method also has disadvantages: such as the limitations to cover the areas behind the buildings. Furthermore, this should not be considered a conventional DEM source, as it is not frequently used (available for) in urban flood modelling.

Based on this, we consider that the comparison is valid in order to show the advantages and limitations of DEMs produced based on mini-UAV imagery when compared to conventional and commonly used DEMs (such as the ones generated based on LiDAR and provided nationwide). The following paragraph was added to the revised version of the manuscript:

"In addition to the generation of DEMs, UAV imagery can also be used to generate other very interesting data sets for urban drainage modelling applications based on image classification. These are, for example: identification of pervious/ impervious areas (Tokarczyk et al., accepted); automatic identification and location of sewer inlets and manholes and other man-made features relevant to overland flow (Moy de Vitry, 2014)."

(6) 5647, line 15: why don0 t you use a hydraulic model instead of delineation the flow paths. It would be a bit more correct

(7) 5649: line 15: same as before

Answer:
This is an interesting point. We have been thinking of using a shallow-water equation-type model and then discarded the idea during our study. Our main criticism was that it was difficult to assess how "correct" and uncalibrated overland flow model with default parameters is. To avoid this discussion, we agreed to "keep it simple" and focus on flow paths, which is common practice.

(8) 5649 line 22: they deliver basic data and no satisfactory results

Answer: Good point. This sentence was revised, as follows:

"*UAV platforms and software are a mature technology that deliver basic data leading to satisfactory results for urban overland flow modelling.*"

(9) 5650 line 28: the problem of the presence of Vegetation and trees is in any Approach present

Answer: we agree with the reviewer. However, due to the UAVs flexibility one can chose the appropriate time of the year (i.e., season) and fly without tree leaves. Of course, in areas with perennial trees, this assumption is no longer valid and the UAV flexibility is not an advantage when compared to other less flexible DEM generation methods or other methods that are not influenced by tree leaves (e.g. ground-based methods).

(10) 5651 line 4 ff: once again the trees..., beside UAV there are other Solutions possible, which deliver more accurate data mainly on the streets and are also very flexible

Answer: please refer to response to point (5). In the revised version of the manuscript, we will mention the advantages of other sources of DEMs (e.g. ground-based LiDAR) that do not have problems with tree leaves or vegetation.

Assessing the quality of Digital Elevation Models obtained from mini-Unmanned Aerial Vehicles for overland flow modelling in urban areas

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Abstract

Precise and detailed Digital Elevation Models (DEMs) are essential to accurately predict overland flow in urban areas. Unfortunately, traditional sources of DEM, such as airplane LiDAR DEMs and point and contour maps, remain a bottleneck for detailed and reliable overland flow models, because the resulting DEMs are too coarse to provide DEMs of sufficient detail to inform urban overland flows. Interestingly, technological developments of Unmanned Aerial Vehicles (UAVs) suggest that they have matured enough to be a competitive alternative to satellites or airplanes. However, this has not been tested so far. In this this study we therefore evaluated whether DEMs generated from UAV imagery are suitable for urban drainage overland flow modelling. Specifically, fourteen UAV flights were conducted to assess the influence of four different flight parameters on the quality of generated DEMs: i) flight altitude, ii) image overlapping, iii) camera pitch and iv) weather conditions. In addition, we compared the best quality UAV DEM to a conventional Light Detection and Ranging (LiDAR)-based DEM. To evaluate both the quality of the UAV DEMs and the comparison to LiDAR-based DEMs, we performed regression analysis on several qualitative and quantitative metrics, such as elevation accuracy, quality of object representation (e.g., buildings, walls and trees) in the DEM, which were specifically tailored to assess overland flow modelling performance, using the flight parameters as explanatory variables. Our results suggested that, first, as expected, flight altitude influenced the DEM quality most, where *lower flights* produce better DEMs; in a similar fashion, *overcast* weather conditions are preferable, but weather conditions and other factors influence DEM quality

much less. Second, we found that for urban overland flow modelling, the UAV DEMs performed competitively in comparison to a traditional LiDAR-based DEM. An important advantage of using UAVs to generate DEMs in urban areas is their flexibility that enables more frequent, local and affordable elevation data updates, allowing, for example, to capture different tree foliage conditions.

1 Introduction

1.1 Urban drainage modelling

Densely urbanised areas, where most economic activities take place, face high probability of flood occurrence due to: (i) the large percentage of impervious areas, which consequently increase the runoff volume; and (ii) alterations of natural water streams and existence of sewer systems which increase flow velocities, thus reducing catchments' time of concentration and duration of the critical rainfall events. In addition, climate change may increase rainfall intensity and frequency in some regions of the Globe, which will affect ecosystems and human life. These more frequent extreme conditions can ultimately increase the probability that urban drainage system capacity is exceeded, which may lead to higher urban flood risks (when flood consequences are maintained).

Hydrological and hydraulic models are important tools to estimate urban flood risk and help engineers and decision makers designing urban drainage systems that inherently reduce these risks. Urban drainage models should be represented by coupling the sewer system (one-dimensional model, 1D) with the overland flow system (1D or two-dimensional models, 2D). Several studies have tested and compared different urban drainage modelling approaches (e.g. Apel et al., 2009; Villanueva et al., 2008; Allitt et al., 2009), such as 1D sewer system (e.g., Vojinović and Tutulić, 2009), coupled 1D sewer system with 1D overland flow system (1D/1D) (e.g., Maksimović et al., 2009; Leandro et al., 2009) and coupled 1D sewer system with 2D overland flow system (1D/2D) (e.g., Chen et al., 2007). The different coupled modelling approaches rely on the quality of the Digital Elevation Model (DEM) to represent the terrain and then locate flood-prone areas – this is especially important for local (and more frequent) floods when compared to large floods (e.g., fluvial, coastal flooding, or a combination of these two types).

1.2 Model input elevation data sources and UAVs

From the literature, it is clear that a great effort has been made to develop new and improve existing numerical solutions for hydraulic models. However, DEMs, as all input data, may have a significant impact on overland flow modelling results (Fewtrell et al., 2011; Leitão et al., 2009). Leitão et al. (2009) showed the effect that DEM sources, resolution and accuracy have on the delineation of overland flow paths in urban catchments; fine resolution DEMs are required to obtain accurate 1D overland flow networks in urban areas. Fewtrell et al. (2011) who evaluated two different hydraulic models on a DEM of resolution varying from 0.5 to 5 m, also concluded that the data resolution has a greater effect on results than the model used, especially if not calibrated. While it is evident that the representation of roads is critical, requiring a minimum resolution of 2 to 3 m, walls and street curbs are also elements that influence the propagation of a flood wave (Sampson et al., 2012), but to represent these elements in the DEM, a finer resolution (< 1 m) is required. Realistic and detailed representation of terrain plays thus a fundamental role in overland flow modelling.

Interestingly, DEMs with a resolution finer than 1 m suitable for urban overland flow modelling can now be generated using imagery captured with Unmanned Aerial Vehicles (UAVs). UAVs are uninhabited aircrafts that are reusable; thereof their operation can be either autonomous, remote controlled, or a combination of the two.

The recent developments of UAVs and their increasing availability make them a new potential source of terrain elevation data. The fine spatial resolution than can be obtained (e.g., 0.05 m) is well-suited to conduct detailed urban overland flow studies. Furthermore, UAVs make repeated flights feasible to capture different conditions, such as tree leaves-off or tree-leaves-on conditions, and better characterize impervious areas, which is important for urban flood modelling, and they can be applied in remote areas. The handling of UAVs is simplified to a degree that can be managed by non-expert professionals, such as civil engineers and engineering consultants.

1.3 Generation of very fine-resolution digital elevation models using UAV imagery

1.3.1 Photogrammetric process

Photogrammetry is often the preferred methodology when collecting three-dimensional (3D) data using UAVs. Photogrammetry produces 3D point clouds based on overlapping images. Other useful by-products can be derived, such as urban façade textures (Leberl et al., 2010). For UAV's, photogrammetry is an interesting alternative to the predominant LiDAR (Light Detection and Ranging) method. LiDAR techniques are precise and allow for multi-returns – e.g., in areas with trees the ground elevation can be automatically measured. However, due to the weight and high-energy demand of LiDAR devices, there are not adequate for UAVs and impossible to use with mini-UAVs. On the other hand, the images can be taken with light equipment (e.g. consumer cameras) that does not require high energy. The question of photogrammetry versus LiDAR has been raised and discussed in a few past publications (Baltsavias, 1999; Leberl et al., 2010; Strecha et al., 2011). Specific applications of UAV photogrammetry are presented in Remondino et al. (2011).

The main photogrammetry steps to generate 3D elevation models from overlapping images are presented in Strecha et al. (2011):

1. Images are scanned for characteristic points, such as, for example, marks created in the ground specifically to support the survey or manholes. If Ground Control Points (GCPs) are used to geo-reference the model, they are usually labelled in the images before this step.
2. Based on the characteristic points, image geo-information and the known camera parameters, a sparse point cloud model is derived with a so-called bundle block adjustment algorithm (Triggs et al. 2000). It is sparse since formed only of the characteristic points from step 1.
3. Based on the sparse point cloud, dense image matching is performed to increase the spatial resolution of the point cloud model and the 3D elevation model generated.

1.3.2 Digital Elevation Model generation process

The resulting point cloud may contain errors, such as image shadows, mismatches and lens distortion. Therefore, algorithms for outlier removal and smoothing can be applied. If a

Digital Surface Model (DSM) is required, vegetation, buildings, and other objects need to be filtered out. Finally, the resulting point cloud is triangulated to a triangulated irregular network (TIN), which may then be rasterised and used, for example, in hydraulic modelling software.

1.4 Study objectives

In this paper we aim at demonstrating the benefit of using high-resolution DEMs produced from mini-UAV acquired data on urban drainage modelling, as opposed to DEMs based on standard aerial LiDAR elevation data. Specifically, our study presents three distinct novelties.

- First, to the best of our knowledge, it uses for the first time DEMs produced from UAV photogrammetry in the context of urban drainage – more specifically on overland flow modelling.
- Second, it presents dedicated field experiments specifically tailored to understand how UAV flight parameters affect DEM quality and, eventually, overland flow representation.
- Third, it compares the quality of the UAV obtained DEM with a DEM used by Swiss engineers (LiDAR-based DEM) and discusses advantages and disadvantages for urban drainage and flood modelling.

Our results suggested that UAVs are a very promising technology for our purpose and that results are relatively robust to not optimal flight parameters. Given the current developments, we expect that the quality of the products generated using these systems will quickly improve in the near future due to better software that manufacturers provide together with the UAV platforms. However, important limitations might arise from regulatory affairs. This will also be discussed below.

This paper is organised as follows: Section 2 describes the methods proposed in this study to evaluate the UAV DEM and assess the impact of flight parameters on DEM quality. In Section 3 the case study location and the flight parameters are presented; UAV and camera used are also described in this section. Analysis of findings are presented and discussed in Section 4. Finally, Section 5 summarises the major findings of the study, identifying also potential further research.

2 Methods

2.1 Impact of UAV flight parameters on DEM generation for overland flow modelling

The adequacy of a DEM for urban urban flood assessment cannot be defined objectively as the existing criteria (e.g., elevation, slope or aspect differences to a benchmark DEM) are not specific to each of the possible DEM applications. As a pragmatic solution, we propose a set of four qualitative and four quantitative evaluation metrics to evaluate the DEM quality. First, DEM values were compared with field measurements using, for example mean absolute errors and visual classification. Second, two statistical models were developed to explore the relations between the flight parameters and the DEM quality through the evaluation metrics: i) an odds logistic regression model was applied for the qualitative metrics and ii) a linear regression model was used to evaluate the quantitative metrics.

2.1.1 Qualitative metrics to assess DEM for overland flow modelling

Representation of voids between two closely located objects. This metric describes the space between two closely placed objects, such as buildings. This is an essential feature of a good-quality DEM for overland flow modelling, as in many flood events water flows through such small openings, which, consequently, can have a significant impact on the modelling results.

Quality of building edges representation. Building edges can be subject to distortions and to a "salt and pepper" effect caused by multiple 3D points being identified one over the other; this is commonly associated with pixel-based classifications (de Jong *et al.*, 2001). This metric describes the severity of building wall distortion and is important to assess the quality of the representation of linear features in the DEM which can divert overland flow.

Representation of walls. Walls are very relevant for overland flow modelling because they can obstruct and redirect water movement. This metric describes to what extent these elements are represented in the DEM.

Presence of trees. This metric describes whether trees are represented in the DEM, or not. It is desirable not to have trees represented because tree canopies, which are what is represented in the DEMs, do not influence overland flow.

The qualitative metrics were calculated based on a visual analysis of the DEM; a class was assigned to each analysis location. The classes are on an ordinal scale, where class 0 is the least favourable and class 3 the best class (Table 1).

2.1.2 Quantitative metrics to assess DEM for overland flow modelling

The following quantitative metrics may be considered a first attempt to define objective evaluation criteria to assess DEM quality for overland flow modelling. The metrics aim at describing the deviations from the reality of the representation of terrain features that may influence overland flow.

Absolute elevation differences. The vertical correctness of the DEM is relevant for urban drainage modelling. Suitable reference elevation data can be surveying points and a sewer manhole cadastre. In our case study, the vertical precision of the surveying points was given for each point and varied between 0.5 and 3 cm (1σ). The vertical accuracy of the manholes is not known; however, it is assumed to have a standard deviation of 7.5 cm (VBS, 2008).

Curb height differences. The height difference between road and sidewalk is relevant for relatively low overland flow. Despite runoff occurs all over the catchment area, overland flow tends to concentrate in roads in urban areas; for large runoff events (e.g. flooding events) the overland flow will flow over sidewalks. Curb heights can be measured repeatedly at various locations in the area of study. To assess the curb height from the different DEMs representing different flight parameters, the average elevation difference between 1 m^2 areas on the road and on the sidewalk close to the curb height measurement location was calculated.

Flow direction (i.e. terrain aspect). Flow direction was measured on the field by pouring water and measuring orientation of flow direction with a compass (see Figure 1a). In the DEM, the aspect was calculated, based on a 3x3 cell moving window (Burrough and McDonnell, 1998).

Flow path delineation. It is important that delineated flow paths are properly represented (mainly along the side of the roads), so that modelled overland flow runs into (or pass by in the vicinity of) sewer inlets. To assess the representativeness of the DEM-based delineated flow paths, real flow paths were observed by pouring water onto the road (Figure 1a) and measuring the distance between the stabilized flow and the road curb (① in Figure 1b). Often, the water flowed exactly on the side of the road. In the DEM, water flow paths were estimated using the flow accumulation method (Jenson and Domingue, 1988).

2.1.3 Statistical models

To identify the important flight parameters that determine DEM quality, two simple statistical models were used; one for the qualitative and a different one for the quantitative assessments.

Because the qualitative metrics are measured on an ordinal scale, the influence of the flight parameters was investigated with a proportional odds logistic regression model (see, e.g., Venables and Ripley, 2002). This model considers the natural order of the metrics, e.g. that class 3 is better than class 2. The probability that the *j*th observation of metric *Y* is at least as good as class *k* is modelled as

$$P(Y_j \leq k) = \frac{1}{1+\exp(\varsigma_k - \eta_j)} \quad (1)$$

where the thresholds $\varsigma_0 = -\infty < \varsigma_1 < \cdots < \varsigma_4 = \infty$ are coefficients that are estimated additionally to the *coefficients* of the linear predictor η_j which is defined in Eq. (2).

For every quantitative metric, a linear regression model was setup to model the absolute differences between the values obtained from the DEM and the corresponding ones measured in the field

$$\eta_j = \beta_0 + \beta_1 z_{j1} + \beta_2 z_{j2} + \cdots + \beta_r z_{jr} \quad (2)$$

$$Y_j = \eta_j + \epsilon_j \quad (3)$$

where z_{jr} are the corresponding explanatory variables for the *j*th observation, ε is a Gaussian random error term and the β_r, r = 0, 1, ..., r regression coefficients to be estimated. As explanatory variables all five flight parameters i) flight altitude, ii) camera pitch, iii) frontal and iv) lateral overlap, and v) weather conditions (see Section 3.3) were used. As the *weather condition* provides qualitative information, it was included using dummy variables (see, e.g., Montgomery *et al*., 2012).

2.2 Comparison between a UAV DEM and a conventional LiDAR-based DEM

UAV systems are being used for relatively localised surveys, and these surveys are usually targeted to a specific application. The resolution of the imagery produced using UAVs is, in general, of very-high resolution as the flying altitude is low. In the specific case of this study, the UAV DEM was generated based on photogrammetry. The LiDAR-based DEM used in this study covers the whole Switzerland and was obtained to be applied in multiple purposes. By definition, the flight altitude is much higher than that of the UAV, allowing to cover larger

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areas in a reasonable amount of time. The LiDAR-based DEM was generated based on LiDAR technology, which is completely different from photogrammetry technique used to generate the UAV DEM.

From the general description above, one can say that the DEMs used for the comparison have distinct characteristics. However, the DEM comparison performed in this study is still valid as the analysis conducted in the study aims at comparing the two by practical use in engineering projects and not by technological standards or DEM generation methodologies.

The UAV DEM was generated based on flight 4 data (see Table 2), after a thorough comparison of the different flights (Moy de Vitry, 2014), which showed the good quality of the DEM produced from this flight. The LiDAR DEM is a 3D height model that covers the whole Switzerland at a resolution of one data point per 2 m^2 and was then interpolated from the raw model to generate a 2 m raster grid. It is provided by Swisstopo[2] and represents all stable and visible landscape elements such as soil, natural cover, woods and all sorts of built infrastructure, such as buildings. The data acquisition method used is aerial LiDAR with a vertical accuracy of ±0.5 m (1σ) in open terrain, and in terrain with vegetation the vertical accuracy is ±1.5 m (1σ). The smallest UAV DEM pixel size was 5 cm, whereas the LiDAR DEM[3] had a pixel size of 2 m.

To compare the two DEMs, we built on the work of Podobnikar (2009), who discuss various visual assessment methods for identifying problems in DEMs that are otherwise not measured, like discontinuities. Also we used suggestions by Reinartz *et al.* (2010) who used elevation differences and several terrain properties, like slope and land cover to compare two DEMs. Specifically, we used the following metrics for this specific purpose:

a. Visual DEMs comparison with hillshade[4];
b. Elevation differences between the two DEMs for diverse land uses (absolute differences and mean absolute differences);

[2] http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/height/dom_dtm-av.html
[3] Swiss Federal Office of Topography (Article 30, Geoinformation Ordinance)
[4] A hillshade is a greyscale visualization of the 3D surface, with a lateral light source.

c. Slope and aspect differences between the two DEMs. These two terrain surface characteristics are essential when considering overland flow modelling as they are associated with flow speed and direction, respectively, and
d. Delineation of flow paths. The flow paths were delineated using the D8 flow direction algorithm (Jenson and Domingue, 1988). This metric is meant to help understanding the correctness of overland flow representation.

To compute the values for metrics (b) and (c), the 2 m downsampled UAV DEM was used to match the resolution of the LiDAR DEM used in the comparison.

3 Material: UAV and case study

3.1 Unmanned Aerial System

3.1.1 General

The mini-UAV platform, called "eBee", (from year 2013) developed by senseFly was used in this study. The eBee UAV is a fully autonomous fixed-wing electric-powered aircraft, with a wingspan of 0.96 m and weighs approximately 0.7 kg including a payload of 0.15 kg. The UAV can cover relatively large areas in a reasonable amount of time (maximum of 12 km^2 per 50-min flight – this value is strongly related to flight altitude and, consequently, to maximum image resolution), which is important for the economic viability of UAV remote sensing. Detailed information about the UAV used in this study is presented in Appendix A.

We selected this specific Unmanned Aerial System over other platforms for two main reasons. First, it is delivered as a complete system with flight planning and photogrammetry software, designed to work seamlessly with one another in a straightforward and intuitive way and does not requiring flying expertise. Second, the construction of the UAV itself provides passive safety, because it is lightweight and electric powered, has a foam body and, most important, glides if out of power. In addition, the autopilot has built-in safety procedures; which is crucial for flights over urban areas.

3.1.2 Camera

The UAV was equipped with a customised Canon IXUS 127 HS that is triggered by the UAV autopilot. The camera has RGB bands and operates in auto mode, making, for example, the photo exposure (e.g., speed and aperture) different from photo to photo. Thus it is not possible to configure the settings for a given flight; for that, a different camera would be required. Detailed characteristics of the camera are presented in Appendix A.

3.1.3 Photogrammetry software

The photogrammetry tasks, such as bundle block adjustment, point cloud generation and filtering were performed using the *Pix4D*[5] *software* (Strecha *et al.*, 2011). This is one of the leading software for UAV photogrammetry (Sona *et al.*, 2014); its main strength is a good handling of rather imprecisely referenced images.

3.2 The case study area

Adliswil is a city near Zurich (Switzerland) and was chosen to be the case study area mainly because (i) it is a typical, rapid growing Swiss city (approx. 20,000 inhabitants) that (ii) needed up-to-date elevation data to be used in other urban drainage studies. Six areas in Adliswil were initially considered and evaluated to conduct the UAV flights. The experimental area was selected based on several criteria related to overland flow, such as including different road types and sidewalks, different terrain types, significant terrain elevation difference, high road density and roads that are relatively free of cars. In addition, practical criteria, such space for UAV taking-off and landing, visibility of UAV during flight from the take-off point had to be considered. The chosen location has an area 0.04 km^2 (approx. 130x300 m) and is illustrated in Figure 2.

The case study location is outside the Swiss Air controlled zone[6], hence no permission was required to fly the UAV, as long as it always remained in line-of-sight.

3.3 Experimental field work: flights with different parameters

In total, 14 flights were conducted (flights 1 to 14) on the case study area to test the influence of flight parameters on the adequacy of DEMs for overland flow modelling. The flight parameters considered in this study are presented as follows.

Flight altitude. The flight altitude is one of the main factors that determines the scale and accuracy of the point cloud (Kraus 2012); it is directly related to the Ground Sampling

[5] http://pix4d.com/
[6] http://www.skyguide.ch

Distance (GSD). Therefore it is expected that a low flight altitude will have a positive influence on the representation of the terrain details on DEMs. In theory, flight heights of up to 1000 m are possible with the eBee. There is no lower limit, although safety and image overlap (the camera frequency is limited) become issues below 70 m above ground. In Switzerland, line-of-sight flight is required by the legislation, which limits the maximum elevation that is typically reached in flight.

Camera pitch. Camera pitch can be assumed to have influence on the representation of steep surfaces; high values of camera pitch are assumed to generate better representations of steep surfaces, such as façades. While façades are of limited interest in urban drainage modelling, it is of interest to see whether camera pitch variation affects the representation of objects, such as cars or walls, which influence overland flow. With the eBee, the camera pitch can be defined between 0 and 15°.

Image overlap. Image overlap is expressed in percent for both frontal and lateral directions, and is an important parameter in the photogrammetric process. First, a high overlap increases redundancy of point identification, which improves the 3D precision of the point cloud. Second, it reduces distortions in the orthophoto. In order to achieve acceptable matching between images, it is recommended to have a frontal overlap of 60% or more. This lower limit should be increased in the case of complex terrain (for example forest), or in the case of unstable platforms (for example UAVs).

Weather conditions. Lighting and the presence of shadows may have a strong effect on photogrammetry results. We deliberately did not adjust the flight plans to weather conditions. All the flights took place within a two days' time interval; some of the flights were performed under cloudy conditions whereas others were performed with direct sunlight.

Additionally to the 14 flights, two virtual flights (flight 15 and flight 16) were generated from two of the 14 flights to simulate the effect of image overlapping. Flight 15 was generated from every third flight line of flight 14. Similarly, flight 16 was generated from every third image from flight 11. These two additional virtual flights were created to (i) increase the number of "flights" used in the statistical analysis with different parameters and (ii), specifically, to investigate the effect of image overlapping on the quality of UAV imagery DEMs. This contributed to a more robust statistical analysis of the impact of UAV flight parameters on DEM quality (based on the selected DEM evaluation metrics). The parameters of all 16 flights are presented in Table 2.

3.4 Surveying points

3.4.1 Georeferencing points

Five ground control points were used to geo-reference the digital elevation models (see Figure 3). These points are of known location and measured in the local coordinate reference system.

During the photogrammetric process, the cadastral measurement points were identified by their access covers. It was assumed that the cadastral points were directly underneath their covers. For this reason, the elevation difference between the points and their covers was measured and compensated for, but horizontal discrepancies were neglected.

3.4.2 DEM quality assessment locations

Figure 4 presents the locations surveyed to then allow calculating the (a) qualitative and (b) quantitative metrics.

4 Results and discussion

In this section we first present the results of the influence of parameters on DEM quality, and second the results from the comparison of the UAV DEM to the LiDAR DEM.

4.1 Impact of UAV flight parameters on DEM generation for overland flow modelling

The statistical models set up for the qualitative metrics showed that, as expected, lower flight altitude produces better DEMs for overland flow modelling; lower flights tend to increase the quality of the DEM (Figure 5a).

Also, flights performed under overcast conditions led to better results (Figure 5b), most likely due to the more uniform illumination and absence of hard and moving shadows. The influences of other flight conditions are clearly not significant; Table 3 contains the summarized statistical results.

Surprisingly, none of the quantitative metrics could have been related to the flight parameters. This may indicate that the variability of the metrics between flights with the same parameters is larger than the influence of the parameters; one can also say that the performance of the UAV is robust regarding the flight configuration. The results of this statistical models are presented in Table 4 (see also the visualization in the supporting information). The significant result of the overcast weather condition for terrain elevation should not be over interpreted: first only one flight was conducted under such conditions, second the model suggest that the error is larger for overcast than for clear conditions, which is counterintuitive and contradicts the result for the qualitative metrics.

The camera mounted in the UAV is a *point&shoot* consumer camera; we expect that we would have observed larger differences if a better camera had been used. For example, a better camera could have been operated with manual exposure, settings, and would have produced more equally exposed images. This alone could have substantially improved the identification of characteristic points.

4.2 Comparison between UAV DEM and LiDAR DEM

The objective of comparing the UAV DEMs and a nation-wide available and commonly used DEM is to evaluate whether UAV DEMs have a similar or better quality, especially in the urban areas which are relevant for overland flow modelling.

We expect that DEMs made available nation-wide (e.g., data sets provided by Swisstopo: the Swiss Federal Office of Topography[7]) are always less accurate in the vertical dimension ($0.5 < \sigma < 1.5$ m) than the DEMs generated based on UAV imagery. Experience shows that the vertical accuracy of the latter is usually about two to three times the GSD (Pix4D Support Team 2014), which corresponds to a standard deviation of 0.1 to 0.2 m for the DEMs of our case study.

4.2.1 Visual comparison

It is possible to qualitatively assess the quality of a DEM using *hillshaded* DEMs (Figure 6). One clear difference between the two DEMs is that around the creek and wooded ravine (①

[7] www.swisstopo.ch

in Figure 6), neither the terrain nor the trees are represented in the UAV DEM. This is due to the fact that photogrammetry is ill-suited to the high-spatial complexity of the trees' branches and twigs: when captured by the drone's camera from different angles, the many overlapping elements of vegetation form complex visual patterns that are specific to each point of view and therefore cannot be matched in the photogrammetric process.

As a result, only a few areas below the vegetation can be regenerated in the photogrammetric point cloud. Because of the visual noise caused by overhead branches, the 3D accuracy of the point cloud in these areas is compromised, which predisposes the points to be removed during the automatic point cloud filtering process.

The tree-leaves-off conditions during the UAV flight in early March makes it difficult to identify matching points in the canopy/on bare thin branches which are often less wide than the GSD. In our experiments with the image dataset, it was fully possible to reconstruct the tree trunks and branches of many of the trees in the above-mentioned area, but it required an image overlap far superior than what is common for cartographic photogrammetry missions. Not having the tree canopies represented is though not a problem for overland flow modelling.

4.2.2 Elevation comparison

The map of the elevation differences between the UAV DEM and the LiDAR DEM (Figure 7) was calculated subtracting the LiDAR DEM from the UAV DEM (Eq. 4) with 2 m pixel^{-1} resolution (Figure 6b).

$$\Delta z_{ij} = UAV_{ij} - Swisstopo_{ij} \qquad (4)$$

where Δz_{ij} is the elevation difference between the two DEMs in the cell *ij*, UAV_{ij} represents the elevation value of the cell *ij* of the UAV DEM and $Swisstopo_{ij}$ represents the elevation value of the cell *ij* of the LiDAR DEM. Figure 7 shows that absolute elevation differences show virtually no bias (slight positive bias) (mean: -0.199 m). It can also be seen that the LiDAR DEM elevation values are in general higher than those of the UAV DEM; this is clearly visible through the blueish colours along the water stream in ① of Figure 7a. This is in agreement with the results obtained in the visual comparison of the DEMs (see sub-section 4.2.1).

It is however noteworthy that the majority of the elevation differences in the *Buildings* areas are small (±0.10 m). From this, one may say that most of the elevation differences between the two DEMs are due to existing vegetation; non-static features, such as vehicles on the roads, which are present in one DEM but not in the other, and due to differences along the buildings edges (this could explain the seldom differences of more than five meters between the two DEMs).

From Figure 8 one can see that the data set with less spread is the *Buildings* one – this may be explained by the absence of trees on the top of buildings; the number of outliers for the *All areas* data set is significant and relatively higher when compared to the other two data sets. The variation on the *Roads* data set may be explained by the presence of cars and in some cases by tree canopies that cover part of the road. A summary of the elevation differences statistics is presented in Table 5.

The elevations of the two DEMs were also compared on a selected road area (see dashed polygon in Figure 8a). This area was defined based on the visual analysis of the aerial orthophoto used to generate the UAV DEM; the LiDAR DEM has only stable and visible landscape elements represented. This area covers approximately 1,500 m^2 and his free from cars, trees and man-made elements such as constructions. As can be seen from Figure 8 and Table 5, the differences between the two DEMs in this area are almost negligible.

4.2.3 Slope and aspect comparison

As can be seen in Figure 9a, the value of the slope of the two DEMs is similar when there are no trees or vegetation, such as on the top of the buildings. Contrary, the major slope differences occur around buildings where vegetation like bushes and trees exist.

Table 6 presents the descriptive statistics of the slope for the two DEMs and considering two specific land-uses, roads and buildings, plus a mix of all land uses in the case study area. The differentiation of land-uses was obtained using cadastre data. As can be seen, the descriptive statistic values of the two DEMs are not significantly different. The major difference occurs with the maximum slope for all areas and roads; in this case the maximum slope values are significantly different between the two DEMs, and may be due to the presence of trees in the LiDAR DEM that are not represented in the UAV DEM due to the tree-leaves-off condition during the UAV flight. As can be seen in Figure 10, the terrain aspect distribution of the two DEMs is very similar.

4.2.4 Delineation of flow paths

Flow paths were delineated using the conventional D8 flow direction algorithm (Jenson and Domingue, 1988) for the three UAV DEMs at different resolutions (0.5, 1.0 and 2.0 m pixel^{-1}) as well as for the LiDAR DEM. The results are presented in Figure 11 and show that the flow paths delineated using the UAV DEMs followed a realistic path along the side of the road. This behaviour was retained even when the UAV DEM was downsampled to 2 m pixel^{-1} (Figure 11c); this is in close agreement with the results presented by Sampson *et al.* (2012), who downsampled terrestrial LiDAR for use in urban inundation models. In comparison to the LiDAR DEM, it is clearly seen that the UAV DEMs can add additional detail to overland flow modelling applications; flow paths obtained using the LiDAR DEM are slightly different from the ones obtained using the UAV-based DEM.

4.3 Discussion

The impact of the flight parameters considered in this study on the DEM quality metrics was not substantial. For example, the quantitative metrics could not have been related to the flight parameters considered in this study. Other flight parameters than the ones considered in this study may have contributed to these results; these factors could be external, such as wind conditions or internal, such as the camera quality and operation mode. This needs further investigation/a different experimental design and goes beyond the scope of this study.

The comparison of the UAV DEM with a LiDAR DEM showed that the two are comparable; the original high resolution of the UAV DEM may contribute to obtain more realistic overland flow patterns even when the DEM resolution is downsampled. UAV imagery can be more frequently updated than conventional DEM production imagery, which is also an important advantage of UAV DEMs.

The range of applications of UAVs in the civil context is already vast, e.g., archaeology (Sauerbier and Eisenbeiss 2010), precision agriculture (Zhang and Kovacs, 2012) and crowd monitoring (Duives *et al.*, 2014). UAVs have however a strong negative connotation which has motivated both civilian and military sectors to propose alternative names, such as Remotely Piloted Aircraft (RPA) or Unmanned Vehicle System (UVS) (Bennett-Jones, 2014; Eisenbeiss, 2009). While their application in military operations was perhaps their first use, the industry of civil UAVs has been increasing steadily, as illustrated by the number of civil UAVs that has more than doubled since 2008 (Colomina and Molina, 2014). Applications of

UAVs are also getting significant visibility in the media, mostly due to privacy (Vilmer, 2015; Wildi, J., 2015) and safety issues.

UAVs can take the form of single- or multiple-blade helicopters and fixed-wing aircraft, though other possibilities exist. Eisenbeiss (2009) gives an extensive historical background of the various UAV types. These different UAV forms incorporate different safety features in order to prevent injuries and damages in the event of a flight failure; these are for example, the incorporation of a parachute. In the case of the eBee UAV, used in this study, its extremely light frame and its gliding capability make it safe in the case of flight failure and hence safe to fly in urban areas. This safety issue is of course a serious concern of the public and of the managers of public space. To respond to this concern, different countries have legislation already in place or being prepared to regulate the public use of UAVs in urban areas and mass gathering events. Nevertheless, we consider that the use of UAVs for civil applications will continue to increase, following the development and improvement of the Unmanned Aerial Systems technology, such as UAV, UAV control and navigation software and sensor technology. As an example of possible new civil applications of UAV imagery, we are currently investigating the potential of UAV imagery for automatic location of sewer inlets and manholes of urban drainage systems, based on image analysis methods.

Although detailed and accurate representation of terrain is of paramount importance for overland flow and flood modelling and assessment, it is challenging for DEMs acquired with traditional methods such as LiDAR or aerial surveys. To our knowledge, this study is the first time DEMs produced based on photogrammetry utilising UAV imagery are used in the context of urban drainage, more specifically on overland flow modelling. Although some experiences have been carried out using LiDAR mounted on quadcopter-type of UAVs with a comparable reach, this is still not possible with mini-UAVs such as the one used in this study. To the best of our knowledge, LiDAR equipment is still heavier and consumes much more power than a mass-consumer *point & shoot* camera. As this type of mini-UAV is very lightweight, which is an important characteristic due to safety issues, especially in urban areas, its load capacity is not yet LiDAR-ready.

5 CONCLUSIONS

In this study, we demonstrate the applicability and the advantages of using UAVs to generate very-high-resolution DEMs to be used in urban overland flow and flood modelling. To

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address this objective, we assessed (i) the influence of flight parameters in the quality of the DEMs produced using UAVs technology, and (ii) the quality of the UAV-based DEM in comparison to the conventional LiDAR-based DEM available in Switzerland. We concluded that:

- UAV platforms and software are a mature technology that deliver basic data leading to satisfactory results for urban overland flow modelling.
- Interestingly, only few dependencies between the flight parameters and DEM quality could be identified. This might be due to variability introduced by other external and internal factors not investigated in detail in this study. Although, at first sight, this might leave only little potential for optimal experimental design, at second sight this also means that the technology is rather robust against flight altitude, camera pitch settings, image overlapping parameters and thus suitable for practitioners.
- As expected, the most influential flight parameter was the flight altitude, where *lower flights* produce better DEMs. Other flight parameter, such as the effect of sun (e.g., weather conditions), showed some effect on the DEM quality but its effect was clearly weaker than the flight altitude – *overcast weather conditions* are better. Other relationships could not be observed as hypothesized, e.g., camera pitch and image overlapping. For a given flight parameter, the number of samples (flights) may have been a limiting factor to observe trends. In future studies, it would be recommended to conduct additional flight campaigns. By repeating flights with the same parameters in order to quantify how much DEM quality may vary, independently of flight parameters one may also evaluate uncertainty in the elevation data generated.
- Comparing the UAV DEM to a commonly available LiDAR-based DEM, we found that the quality of both DEMs is comparable. The differences between the two DEMs are not substantial, especially when the comparison was conducted in a flat road area without cars, buildings, trees or vegetation. In general, the observed differences are probably mainly explained by the presence of tree leaves in the LiDAR DEM and their absence in the UAV DEM. This is due to fact that the time of the year when the UAV flights were conducted: late winter in tree-leaves-off conditions. When comparing flow paths delineated using the different DEMs, it could be seen that the flow paths obtained using a DEM downsampled (2 m pixel size) from the finer resolution UAV DEM (0.05 m pixel size) retained the major flow path patterns. The flow paths

obtained using the LiDAR DEM were slightly different from those obtained using the UAV DEMs; this is mostly due to the presence of vegetation and trees in the first DEM. The UAV DEM has two main/practical advantages over the LiDAR DEM, despite the similarities mentioned above. First, it is more flexible to acquire elevation data using UAVs, especially for small to medium size areas (or catchments), and the second is that if the UAV flights are conducted during winter with tree-leaves-off conditions, DEMs with no tree canopies represented can be produced, which are especially beneficial for land use classification and overland flow processes. It is however important to mention that there are other solutions to generate DEMs other than nationwide airborne LiDAR-based and UAV-based solutions, such as ground-based LiDAR. In particular, ground-based LiDAR solution is flexible too as the UAV solution, capable of producing very-fine resolution DEMs and may not have the problem of obstruction by tree-leaves as photogrammetric mini-UAV solutions. However, it also has disadvantages: the major one is perhaps related to the limitation of covering areas located behind the buildings, i.e., it does not allow for covering the whole area of interest (e.g., an urban catchment).

- Our findings suggest that UAVs can greatly improve overland flow modelling by increasing the detail of terrain representation and also by their inherent flexibility to update existing elevation datasets. The very high resolution possible to obtain using UAV DEMs is also an advantage for urban overland flow and flood modelling purposes. Further research should be carried out towards the development of an urban drainage modelling application in order to assess the real benefit of using very-high resolution DEMs and hydraulic models.

In addition to the generation of DEMs, UAV imagery can also be used to generate other very interesting data sets for urban drainage modelling applications based on image classification. These are, for example: identification of pervious/ impervious areas (Tokarczyk et al., accepted); automatic identification and location of sewer inlets and manholes and other man-made features relevant to overland flow (Moy de Vitry, 2014).

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Appendix A. Unmanned Aerial System

The mini-UAV platform used in the study is a fully autonomous fixed-wing aircraft developed by senseFly SA[8]. The UAV is electric-powered, has a wingspan of 0.96 m, and weighs approximately 0.7 kg including a payload of 0.15 kg. The UAV can cover large areas in a reasonable amount of time, which is important for the economic viability of UAV remote sensing. Detailed information is provided in Table A1.

Table A1. Detailed characteristics of the UAV

Wingspan	0.96 m
Wing area	0.25 m
Typical Weight	0.7 kg
Payload	16 MP camera, electronically integrated and controlled
Battery	3-cell Lithium-Polymer
Capacity	1800 mAh
Endurance	45 minutes of flight time
Propulsion	Electric brushless motor
Nominal cruise speed	36-72 km h^{-1} (10-20 m s^{-1})
Wind resistance	up to 45 km h^{-1} (12 m s^{-1})
Mapping area	coverage up to 10 km^2
Remote control	2.4 GHZ, range: approx. 1 km, certification: CE. FCC
Data communication	2.4 GHZ, range: approx. 3 km, certification: FCC Part 15.247
Navigation	Autonomous flight and landing, up to 50 waypoints direction
Material	Styrofoam
Cost (in 2015)	Approx.. CHF 20,000 (UAV + camera + software)

[8] http://www.sensefly.com

The specifications of the IXUS 127 HS camera part of the Unmanned Aerial System used in this study are presented in Table A2.

Table A2. Specifications of the Canon IXUS 127 HS

Camera effective pixels	Approx. 16.1 million pixels
Lens focal length	5x zoom: 4.3 (W) — 21.5 (T) mm
	(35mm film equivalent: 24 (W) — 120 (T) mm)
File formats	Exif 2.3 (JPEG)
Dimensions	93.2x57.0x20.0 mm (Based on CIPA Guidelines)
Weight	Approx. 0.135 kg (including batteries and memory card)

Table 1. Qualitative metric classes

Class	Representation of voids	Representation of buildings edges	Representation of walls	Presence of trees
3	100% open	Sharp edges	Perfectly represented wall	Not visible
2	50% open	Little noisy	A straight object	Freckles
1	25% open	A lot noisy	Unclear	Almost complete
0	0% open	Chaotic	Nothing	Complete

Table 2. Characteristics of the 16 flights

Flights	Flight altitude (m)	GSD (cm)	Camera Pitch (º)	Frontal overlap (%)	Lateral overlap (%)	Weather conditions[b]
1	145	4.5	0	80	70	Clear
2	145	4.5	0	70	80	Clear
3	145	4.5	7	70	80	Clear
4[a]	145	4.5	15	70	80	Clear
5	205	6.5	0	70	80	Clear
6	205	6.5	7	70	80	Clear
7	205	6.5	15	70	80	Clear
8	85	2.5	0	70	80	Overcast
9	310	10	0	70	80	Partly cloudy
10	220	7	5	70	80	Clear
11	220	7	5	85	80	Partly cloudy
12	220	7	5	55	80	Clear
13	220	7	5	70	65	Clear
14	220	7	5	70	90	Clear
15	220	7	5	70	70	Clear
16	220	7	5	60	80	Partly cloudy

[a] DEM generated from flight 4 was used for the comparison with the LiDAR DEM.

[b] http://www.erh.noaa.gov/er/box/glossary.htm

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Table 3. Results of the statistical models for the qualitative metrics.

	Representation of voids		**Representation of building edges**		**Representation of walls**		**Representation of trees**	
	Estimated value	**P-value**	**Estimated value**	**P-value**	**Estimated value**	**P-value**	**Estimated value**	**P-value**
Flight altitude (m)	-0.00778	0.1554	-0.02531	**0.001**	-0.02950	**0.046**	-0.02685	**0.000**
Camera Pitch (º)	0.00046	0.9876	0.02550	0.465	-0.09347	0.215	-0.05554	0.069
Frontal overlap (%)	-0.03073	0.4775	-0.02024	0.682	-0.01141	0.901	0.00911	0.829
Weather conditions: (Overcast)	1.17177	0.2455	-0.37471	0.748	14.00542	**0.000**	15.03059	**0.000**
Weather conditions: (Partly cloudy)	0.16054	0.7792	-0.53598	0.438	-1.11497	0.419	-0.44932	0.426

Table 4. Results of the statistical models for the quantitative metrics.

	Terrain elevation		**Curb height**		**Aspect**		**Flowpath distance**	
	Estimated value	**P-value**	**Estimated value**	**P-value**	**Estimated value**	**P-value**	**Estimated value**	**P-value**
Flight altitude (m)	0.00011	0.629	-0.00009	0.993	0.04405	0.801	0.00153	0.497
Camera Pitch (º)	-0.00200	0.264	-0.00274	0.974	-1.04400	0.434	0.00213	0.903
Frontal overlap (%)	0.00032	0.800	-0.00027	0.996	-0.28786	0.759	-0.01938	0.117
Weather conditions: (Overcast)	0.14273	**0.001**	0.00921	0.996	-15.21044	0.629	-0.16416	0.680
Weather conditions: (Partly cloudy)	-0.00218	0.929	-0.02515	0.982	-11.16398	0.539	-0.02149	0.925

Table 5. Summary statistics of elevation differences

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	Elevation differences (m)			
	All areas	Buildings	Roads	Selected road
Minimum	-12.880	-5.698	-22.880	-0.468
Mean	0.259	0.031	-0.212	0.06
St. deviation	2.037	1.144	2.164	0.119
Maximum	11.930	11.930	6.290	0.306
Number of comparison cells	8,700	1,099	974	375

Table 6. DEMs' slope descriptive statistics (%)

	All areas		Roads		Buildings	
	UAV	LiDAR	UAV	LiDAR	UAV	LiDAR
Minimum	0.017	0.051	0.107	0	0.077	0.088
Maximum	430.592	595.917	153.929	595.917	214.135	310.699
Mean	38.036	21.908	10.916	21.620	29.206	36.540
St. deviation	48.394	20.560	11.521	60.791	34.684	42.121

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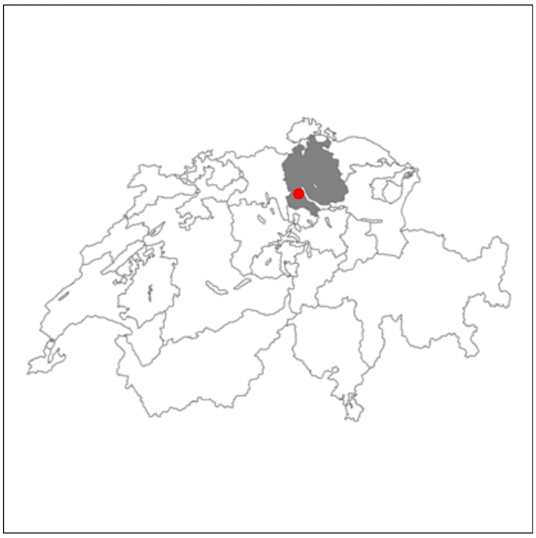
(a) Terrain aspect and Flow path field experiment preparation

(b) Aerial photo of field experiment location

Figure 1. Example of the field experiments conducted to calculate the terrain flow direction and flow path delineation metrics



(a) Adliswil (Zurich Canton, Switzerland)

(b) Case study areal aerial photo (130x300 m)

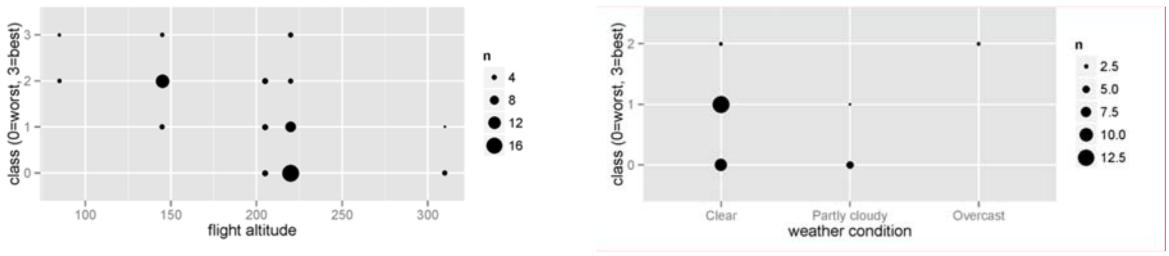
Figure 2. Case study location and area aerial photo

Figure 3: Location of the georreferencing points used in the study (the points are represented by red crosses)

(a) Qualitative assessment

(b) Quantitative assessment

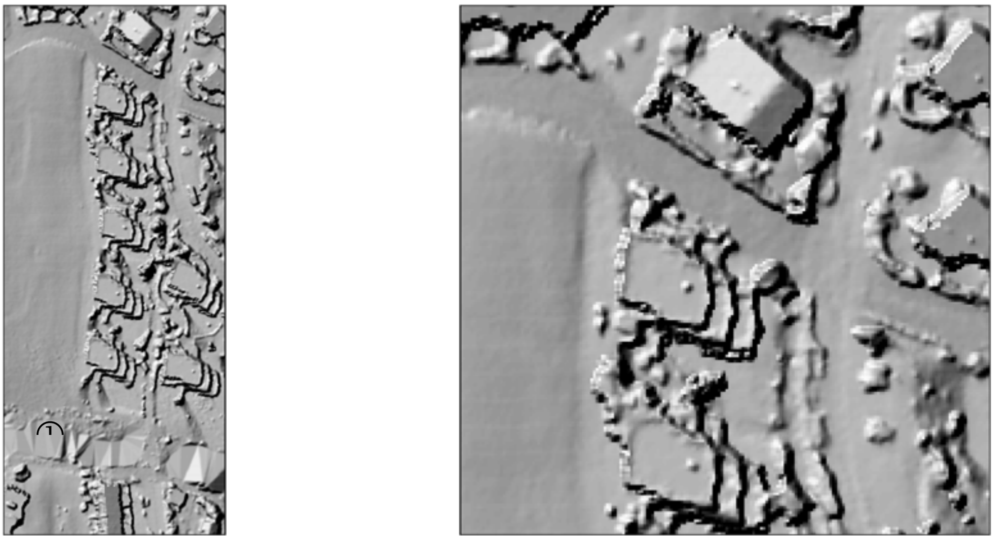
Figure 4. Location used to calculate the metric values



(a) Representation of building edges

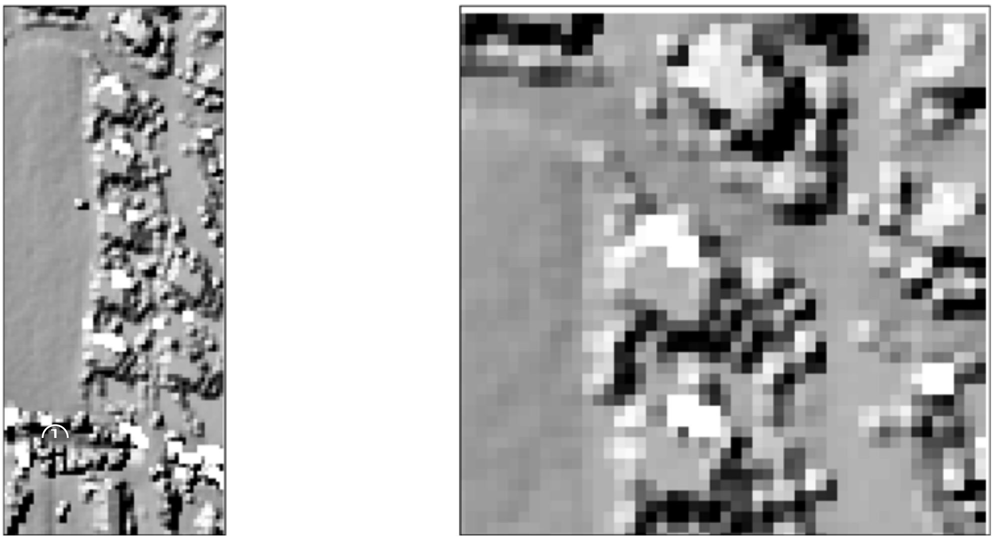
(b) Representation of walls

Figure 5. Relationship between the quality of the representation of building edges and flight altitude and between wall representation and weather conditions. The size of the dots is proportional to the number of observed metrics with identical quality class and altitude or weather condition, respectively.



(a) UAV DEM (downsampled to 0.5 m pixel^{-1})

(b) UAV DEM (downsampled to 2 m pixel^{-1})



(c) LiDAR DEM (2 m pixel^{-1})

Figure 6. Visual comparison of the UAV DEM and LiDAR DEM

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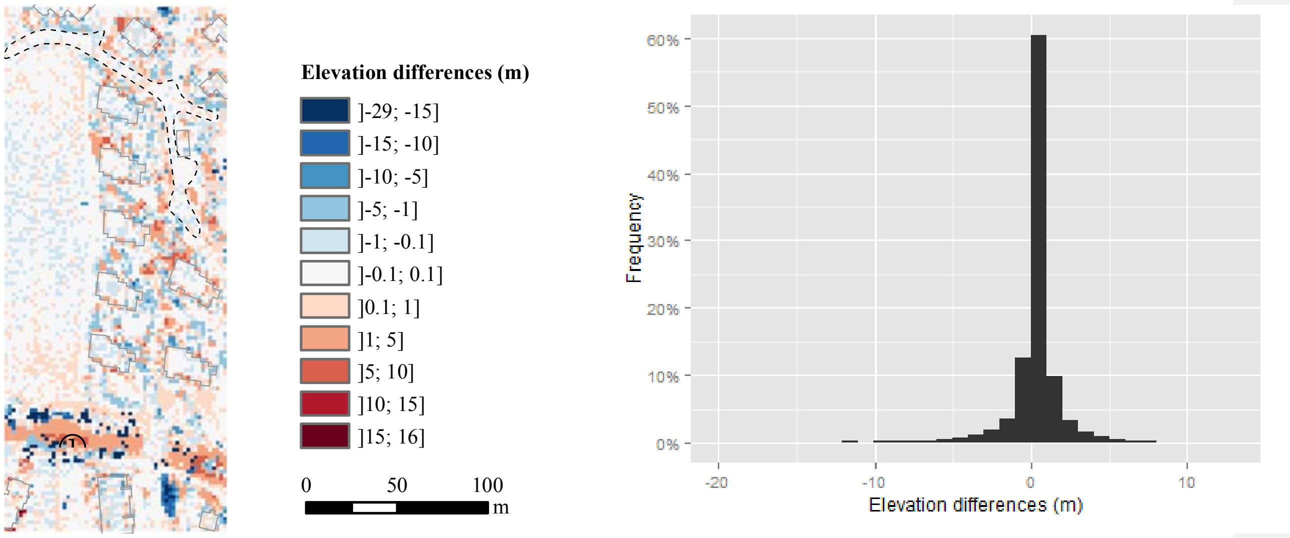

(a) Spatial distribution (b) Histogram

Figure 7. Elevation differences between the UAV DEM and the LiDAR DEM (both with 2 m pixel^{-1} resolution). The dashed line polygon represents a road area selected based on visual analysis of the UAV orthophoto and used to compare the elevation of the two DEMs without objects such as trees, cars or other man-made elements; light grey polygons represent buildings.

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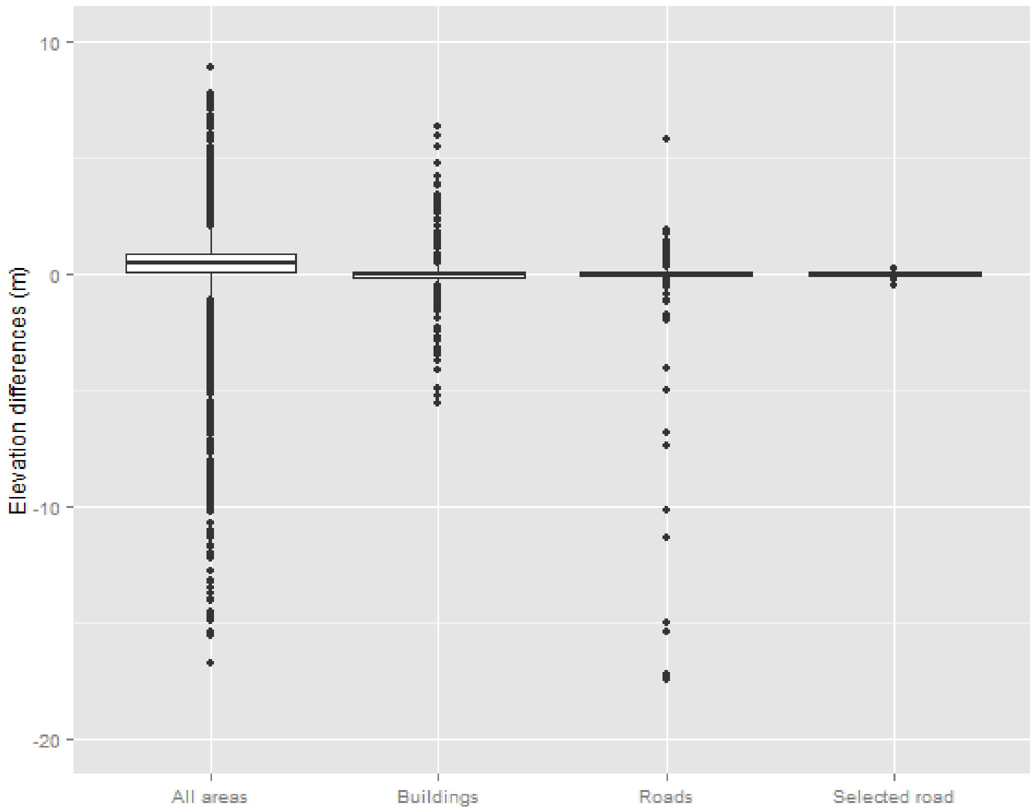

Figure 8. Elevation differences between the UAV DEM and the LiDAR DEM for three types of areas (width of box plot represents the amount of data points used to generate the box-plot).

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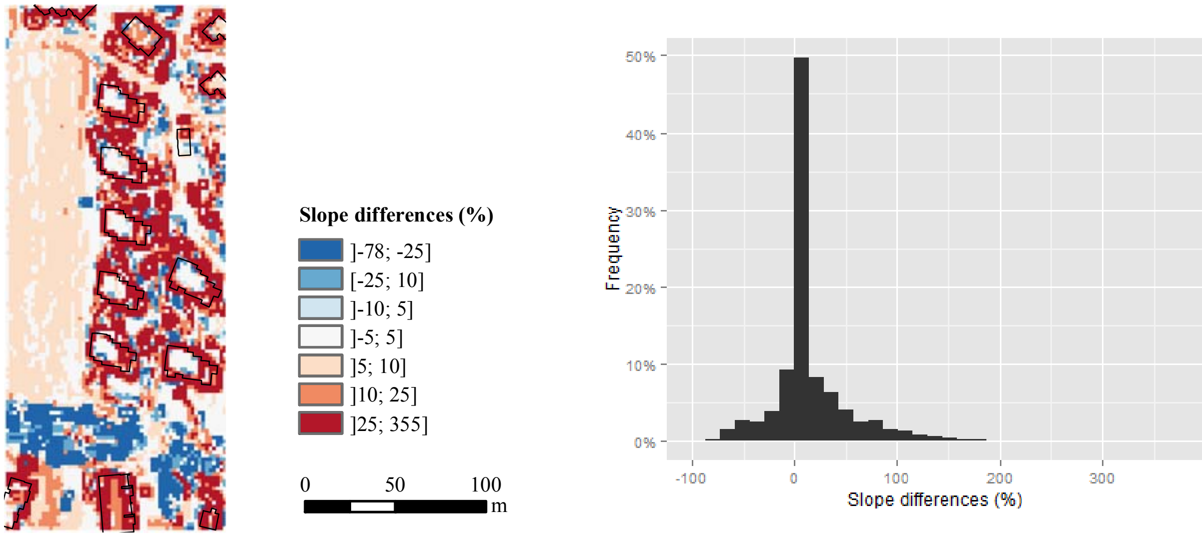

(a) Spatial distribution

(b) Histogram

Figure 9. Slope differences between the UAV DEM and the LiDAR DEM

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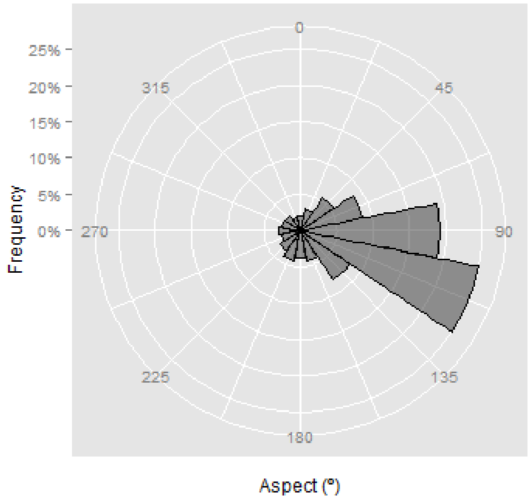
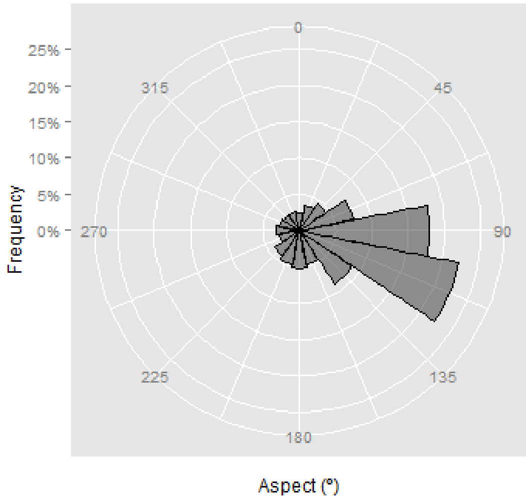


(a) UAV DEM



(b) LiDAR DEM

Figure 10. Distribution of terrain aspect. The aspect values are in degrees. The outer number represent the cardinal directions in degrees.

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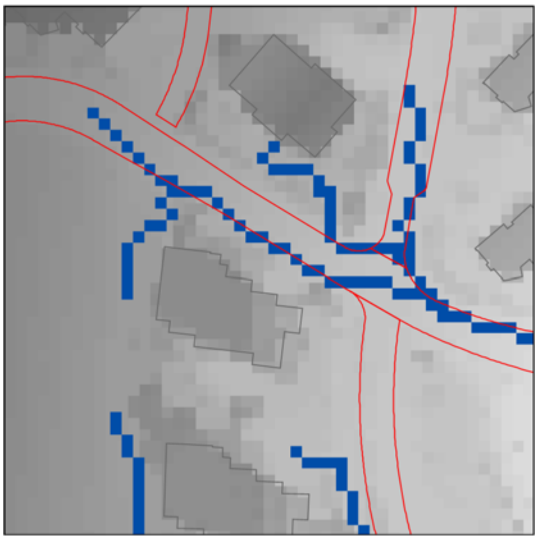
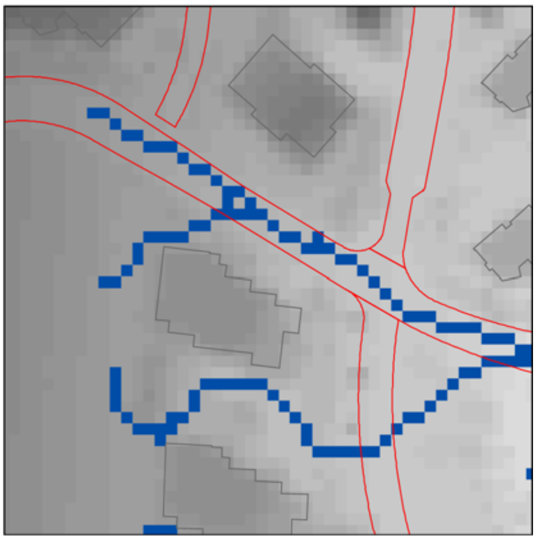
(a) UAV DEM (0.5 m $pixel^{-1}$)

(b) UAV DEM (1 m $pixel^{-1}$)



(c) UAV DEM (downsampled to 2 m $pixel^{-1}$)



(d) LiDAR DEM (2 m $pixel^{-1}$)

Figure 11. DEM-based flow path delineation

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