29 June 2016

Professor Helena Mitasova
Editor for the Special Issue of Hydrology and Earth System Sciences
"Geomorphometry: advances in technologies and methods for Earth system sciences"
(NHESS/HESS inter-journal SI)

Dear Editor,

I hereby submit the revised manuscript entitled "Observing river stages using unmanned aerial vehicles" (hess-2016-49) by Tomasz Niedzielski, Matylda Witek and Waldemar Spallek.

The detailed responses to comments offered by the Reviewers are submitted below. The responses follow my previous responses published as interactive comments. I would like to express our thanks to the Referees for evaluating our work. I believe that their remarks led to a significant improvement of the manuscript, both in terms of scientific completeness and the presentation. I hope the revised version is suitable for publication in Hydrology and Earth System Sciences.

I would like to take this opportunity and thank you very much for handling the manuscript.

Yours sincerely
Tomasz Niedzielski, Ph.D., Dr hab.
Professor at the University of Wrocław, Poland

Responses to Reviewers' comments

The shortened versions of the Reviewers' remarks are provided in brackets and typed using bold. The responses are fully provided, along the lines of our responses published in the interactive discussion (please note that certain repetitions occur when a given problem is raised by both Referees). The bullet points help to identify places in the revised (annotated) manuscript where key modifications have been made. The annotated manuscript is located in this document, below responses to Reviewers' comments.

1. **Responses to comments offered by the Reviewer #1**

   (a) **(General comment on needs for clarifying the manuscript and explaining methods)** We thank the Reviewer #1 for assessing that the manuscript presents reasonable results. Having read the reviews offered by two Referees we entirely agree that the manuscript should be substantially modified so that some parts on methods are better explained. The revised version of the manuscript clarifies many aspects, and uses new material (numerical example and table) to explain methods in detail.

(b) **(Need for parameters of all UAV flights)** The five flight missions have been performed with the comparable parameters. We double checked the UAV log files and confirmed that heights (both planned and measured during the missions), which determine the ground resolution, were kept approximately at a similar level.

- (Tab. 1) We included a new table (Tab.1 – please note that numbering of the subsequent tables was modified after incorporating a new Tab. 1).
- (2.1. Study area, fifth paragraph) We wrote a few sentences which refer to the new Tab. 1 and emphasize similar heights of all UAV missions.

(c) **(Need for explaining manual georeferencing to the LIDAR data)** In order to response to this comment we firstly put an emphasis on our key assumption which may be formulated as follows: "presence of a potential shift between two spatial data sets does not cause meaningful changes in area of the considered objects" (this is expressed in line 5 on page 11 of our HESS Discussion Paper). For instance, if one replicates an orthophotomap and applies a translation vector to such a newly produced spatial data set, the same objects will reveal the same areas (no change in scale and rotation). To support this finding we refer to a recent paper by Mesas-Carrascosa et al. (2014) [Mesas-Carrascosa F.J., Notario-García M.D., Meroño de Larriva J.E., Sánchez de la Orden M., García-Ferrer A., 2014. Validation of measurements of land plot area using UAV imagery. International Journal of Applied Earth Observation and Geoinformation 33, 270–279]. These authors argue that "Other shortcomings include the lack of vertical adjustment of the aerial camera and the unknown or variable interior orientation of the camera. These factors affect point position accuracy but do not necessarily decrease the accuracy of area measurements".

- (References) We added the paper by Mesas-Carrascosa et al. (2014) to a list of references.
- (2.2. UAV data processing, second paragraph) We added a few sentences on a relation between area accuracy and point position accuracy.
- (4. Results and discussion, eight paragraph) While discussing the results, we added a few sentences to emphasize the importance of what Mesas-Carrascosa et al. (2014) claim.

We also described the spline-based procedure that fixes all orthophotomaps to a single LIDAR data. Our explanation reads as follows: "We identified characteristic features in the LIDAR digital terrain model (DTM) which were evenly distributed and possible to identify in the orthophotomap. These features comprise: crossings of bounds, crossings of drainage ditches, and centres of bridges or passages (crossings of streams and roads). More than 10 points were used to perform georeferencing, as the spline method requires. A spline function allowed us to precisely georeference the control points (i.e. the aforementioned mutual features) and transform raster data set with continuity and smoothness, such as the rubber sheeting method."

- (2.2. UAV data processing, first paragraph) We literally added the abovementioned explanation to the manuscript.

(d) **(Correction of spelling in sentences on visible light images)** We agree that the sentence highlighted by the Reviewer #1 does not read well in the initial version of the manuscript. We propose to rephrase the sentence so that it reads as follows: "For observing water surface area, the use is made of the following satellite-acquired measurements: high-resolution visible light images or infrared images, passive microwave data and radar images.". We went through several research papers and double checked that the notion of "visible light images" is properly used in the revised proposition.

- (1. Introduction, fourth paragraph) The above-mentioned corrected sentence was included in the introduction.

(e) **(Need for information on the accuracy of expert-based digitizing water extents)** The Reviewer #1 pointed out an important problem of the accuracy of a manual digitization carried out under several conditions (lines 27–31 on page 6 and the subsequent part of Subsection 2.2 in our HESS Discussion Paper). One of the most important factors that may potentially constrain a digitization accuracy is related to vegetation. Mapping vegetation with UAVs becomes popular as a recent paper by Husson et al. (2014) shows [Husson E., Hagner O., Ecke F., 2014. Unmanned aircraft systems help to map aquatic vegetation. Applied Vegetation Science 17, 567–577]. These authors focus on delineating edges between water and non-submerged aquatic as well as riparian species. They write that "In practise delineation was done by hand on paper printouts" and "Vegetation mapping, i.e. digitizing the UAS orthoimages, was performed manually by a human interpreter in a GIS using ArcGIS software". Although we concentrate on a fluvial environment, the idea behind our manual expert-based digitization remains similar to what Husson et al. (2014) proposed. It is worth noting that our digitization was practically carried out by two experts (GIS specialist + fluvial geomorphologist). Given this introduction, we unequivocally reply that the procedure met the assumed criteria (this is attained by the expert-based digitization). We also believe that the accuracy of the produced water surface area is acceptable. However, it was our intention to include Fig. 4 and Fig. 5 which help the reader to identify potential sources of errors.

- (References) We added the paper by Husson et al. (2014) to a list of references.
- (2.2. UAV data processing, fourth paragraph) A new paragraph has been added about impact of manual expert-based digitization on the accuracy of the polygon generation procedure. We referred to the above-mentioned paper by Husson et al. (2014) to support our approach.
- (2.2. UAV data processing, fifth paragraph) The beginning of the next paragraph has been rephrased so that we clearly discriminate between the impacts of vegetation and morphology on the accuracy of estimating water surface areas.

(f) **(Correction of spelling in sentences on ground control points)** Yes, indeed, the "GSPs" is a typo and in the revised manuscript is replaced by "GCPs".

- (2.2. UAV data processing, first paragraph) The correction has been made in the last sentence of the first paragraph.

(g) **(Need for detailed information on why non-chronological multitemporal data are used)** Being grateful for notifying that the formulation of the hypotheses H0 and H1 is unclear, we hereby clarify the issue. The two sample Student's t-test is used to test a null hypothesis (H0) that means of two samples are equal, but three alternative hypotheses (H1) are allowed. These three alternatives include: means of two samples are different, mean of the first sample is bigger than mean of the second sample, mean of the second sample is bigger than mean of the first sample. In the latter two alternatives, the order of samples is important and has impact on where rejection region is located. Knowing the aforementioned basics, we stated the research hypothesis H0 with its alternative H1 on purpose, in the way that rejection of the null hypothesis implies acceptance of the alternative one (and this unequivocally indicates which area is meaningfully bigger). To clarify the entire problem, we suggest to consider two combinations of $L(j)$ and $L(k)$ (notations are explained in our HESS Discussion Paper). Recall that we test if mean$[L(j)]$ = mean$[L(k)]$ with the alternative that mean$[L(j)] <$ mean$[L(k)]$.

CASE 1 (based on real data)

j = '27/11/2012'

k = '13/05/2013'

mean[L('27/11/2012')] = −1.71727

mean[L('13/05/2013')] = −1.501393

Arithmetically, mean[L('27/11/2012')] is smaller than mean[L('13/05/2013')]. This inequality has also been confirmed statistically (the Student's t-test) at the significant level of 0.01 (see newly-numbered Tab. 6, grey box indicates that the difference in means is statistically significant). Hence, in this case a subsequent episode (time step k) revealed meaningfully bigger water surface area than the preceding one (time step j).

CASE 2 (based on artificially modified data – changed order of dates)

j = '13/05/2013'

k = '27/11/2012'

mean[L('27/11/2012')] = −1.71727

mean[L('13/05/2013')] = −1.501393

Arithmetically, mean[L('13/05/2013')] is not smaller than mean[L('27/11/2012')]. If we test (mean$[L(j)]$ = mean$[L(k)]$ with alternative mean$[L(j)] <$ mean$[L(k)]$) we cannot reject the null hypothesis with the Student's t-test at the significance level of 0.01. Hence in this case a subsequent episode (time step k) does not reveal a meaningfully bigger water surface area than the preceding one (time step j).

- (3.2. Interpretation through numerical exercise, entire subsection) We produced a new subsection which includes the description of the aforementioned numerical exercise. In addition, a new Subsection 3.1 has been added in order to present the previously published details on methods.

Since the newly-numbered Tab. 6 juxtaposes all cases of the above type (j does not equal to k), we removed the following phrase "(but in practice $j < k$)"

which appeared in lines 3–4 on page 9 of the initial version of the HESS Discussion Paper. The deletion of the sentence will make the conclusions straightforward. Along these lines, we removed "$k = 2, \ldots, 5$" from results and discussion (in fact we analyse all possible transitions, not only from state 1 to states $k = 2, \ldots, 5$).

- (3.1. Concept, second paragraph) The inequality which suggests the chronological order has been removed.
- (4. Results and discussion, third paragraph) The list $k = 2, \ldots, 5$ has been deleted.

(h) **(Explanation why non-chronological transitions between characteristic stages have been used)** As we explained above, the order of $L(j)$ and $L(k)$ matters and influences the final results, however it is not necessary that $j < k$. The stages and transitions listed on page 10 are examples of low, mean, intermediate and high water levels. They have been recorded by real UAV flights on different dates. We used the UAV-observed water surface areas as true data that represent the aforementioned stages. We believe that, for the analysis that aims to check the procedure proposed in this paper, the chronological order of transitions between stages is not important. Of course, we agree with the Reviewer #1 that it would be ideal to have the chronological set of transitions, however such a data set is not available. Thus, we mixed the order to check various potential combinations of transitions.

- (4. Results and discussion, sixth paragraph) A new paragraph has been added to the main section on results and discussions. The paragraph explains why we used non-chronological transitions.

(i) **(Need for juxtaposing our data in a table)** The areas, fractions and logarithms (hence all input data used for the analysis) have already been juxtaposed in Tab. 5 of the initial version of the manuscript. This table received no. 6 in the revised version of the manuscript (new Tab. 1 included).

2. **Responses to comments offered by the Reviewer #2**

(a) **(Need for correcting the usage of English language)** We accept the criticism and thank the Reviewer #2 for spotting linguistic problems. The text has been corrected according to the marked suggestions. In addition, the entire manuscript has been edited.

- (Entire manuscript) Numerous corrections have been made to improve the level of English language used in the paper. They are all clearly marked in the annotated version of the revised manuscript.

(b) **(Two requirements: stability of height parameters and channel properties)** We thank the Reviewer #2 for finding our concept of reconstructing river stages using UAV-taken photographs a useful practice. We accept the criticism and believe that the revised manuscript does the above-mentioned idea sufficient justice. Our detailed responses are the following.

Indeed, flight altitude (and the resulting ground resolution) influences the water surface area observations. Our flight characteristics were kept stable over the five observational campaigns, hence the resolution is also stable over the entire experiment. The similar comment has been also offered by the Reviewer #1. We double checked the flight logs and confirmed the comparability of UAV height parameters. The statistics calculated from the log data are juxtaposed in a new table to which we refer in the revised manuscript.

- (Tab. 1) We included a new table (Tab.1 – please note that numbering of the subsequent tables was modified after incorporating a new Tab. 1).
- (2.1. Study area, fifth paragraph) We wrote a few sentences which refer to a new Tab. 1.

We are grateful to the Reviewer #2 for mentioning the influence of channel morphology, mainly the slope of banks, on the observation of water surface area with the UAV. We agree that such a relationship exists. We also entirely accept the comment that the results, prepared for a specific river in the SW Poland, are not transferable to other rivers with different cross-sectional parameters. In fact, this has been already pointed out in the context of the relationship between water surface areas and river stages by Smith (1997) who argues that "Until additional empirical rating curves relating inundation area to ground measurements of stage or discharge are made, it is difficult to assess their potential for extrapolation to other rivers of similar morphology. However, it seems likely that such curves will vary significantly between rivers and therefore must be constructed for each site." [Smith L.C, 1997. Satellite remote sensing of river inundation area, stage, and discharge: a review. Hydrological Processes 11, 1427–1439]. However, our approach is centred on a statistical analysis of water surface areas, not river stages themselves. In fact, we quantitatively infer on statistically meaningful changes in water surface area (this is a key part of our procedure) and only qualitatively, through the existence of a relationship between water surface areas and river stages published by Usachev (1983) [Usachev V.F., 1983. Evaluation of food plain inundations by remote sensing methods. In: Proceedings of the Hamburg Symposium, IAHS Publ. 145, 475–482], extrapolate our results into changes in river stages. We believe that our quantitative approach (recall that this concerns seeking changes in water surface areas in the orthophotomaps produced from the UAV-taken photographs) forms a general method that – under several conditions clearly identified in the manuscript – may be applied in other regions. However, the use of the approach to infer on river stages should be made with caution, since such an extrapolation requires a knowledge about the relationship between water surface areas and river stages (and the characteristics of this relation are vulnerable to sites-specific river morphology, especially bank slopes). The relation between water surface area and stage is quasi-linear for rivers (Usachev, 1983) and strongly linear for lakes (Xia et al., 2983) [Xia L., Shulin Z., Xianglian L., 1983. The application of Landsat imagery in the surveying of water resources of Dongting Lake. Proceedings of the Hamburg Symposium, IAHS Publ. 145, 483–489]. In the revised manuscript we write about the strength of the relationship. Since our motivation was to offer a new method for checking if UAV-based observations of water surface area may be suitable for implementing the HydroProg-FloodMap-UAV procedure (described in the introduction), we also refer to a recent paper on the performance of HydroProg [Niedzielski T., Miziński B., 2016. Real-time hydrograph modelling in the upper Nysa Kłodzka river basin (SW Poland): a two-model hydrologic ensemble prediction approach. Stochastic Environmental Research Risk Assessment, DOI: 10.1007/s00477-016-1251-5].

- (4. Results and discussion, tenth paragraph) A new paragraph has been added to the main section on results and discussions. The paragraph focuses on the impact of channel slopes on estimates of water surface area.
- (References) We added the paper by Xia et al. (1983) to a list of references.
- (4. Results and discussion, fourth paragraph) We mentioned about the strength of the relationship between water surface area and water levels, referring to papers by Usachev (1983) and a newly cited paper by Xia et al. (1983).
- (References) We added the paper by Niedzielski and Miziński (2016) to a list of references.
- (1. Introduction, second paragraph) The paper by Niedzielski and Miziński (2016) has been cited to provide a reference for HydroProg and its performance.

(c) **(Need for explaining manual georeferencing with respect to the LIDAR data)** Yes, we are aware of possible problems that may be associated with measuring the area of polygons that are generated on a basis of orthophotomaps produced without GCPs. We also know that a procedure for delineating boundaries of water surface area needs to be clarified. The similar remarks have been also offered by the Reviewer #1, and the responses below use the arguments which we raised when replying to the comments provided by the Referee #1. Our detailed explanation below focuses on: area computation when GCPs are unavailable and delineating edges of water surface areas.

In line 5 on page 11 of our HESS Discussion Paper we argue that a presence of a potential shift between two spatial data sets does not cause meaningful changes in area of the considered objects. The arguments that support this statement can be found in a recent paper by Mesas-Carrascosa et al. (2014) [Mesas-Carrascosa F.J., Notario-García M.D., Meroño de Larriva J.E., Sánchez de la Orden M., García-Ferrer A., 2014. Validation of measurements of land plot area using UAV imagery. International Journal of Applied Earth Observation and Geoinformation 33, 270–279]. These authors argue that "Other shortcomings include the lack of vertical adjustment of the aerial camera and the unknown or variable interior orientation of the camera. These factors affect point position accuracy but do not necessarily decrease the accuracy of area measurements".

- (References) We added the paper by Mesas-Carrascosa et al. (2014) to a list of references.
- (2.2. UAV data processing, second paragraph) We added a few sentences on a relation between area accuracy and point position accuracy.
- (4. Results and discussion, eight paragraph) While discussing the results, we added a few sentences to emphasize the importance of what Mesas-Carrascosa et al. (2014) claim.

Having justified a stability of area measurements in the case of smaller point position accuracy, i.e. also in the case of shift of orthophotomaps produced without GCPs, we hereby describe the spline-based procedure that fixes all orthophotomaps to a single LIDAR data. We identified characteristic features in the LIDAR DTM which were evenly distributed and possible to identify in the orthophotomap. These features comprise: crossings of bounds, crossings of drainage ditches, and centres of bridges or passages (crossings of streams and roads). More than 10 points were used to perform georeferencing, as the spline method requires. A spline function allowed us to precisely georeference the control points (i.e. the aforementioned mutual features) and transform raster dataset with continuity and smoothness, such as the rubber sheeting method.

- (2.2. UAV data processing, first paragraph) We literally added the above-mentioned explanation to the revised manuscript.

In lines 27–31 on page 6 and the subsequent part of Subsection 2.2 in the HESS Discussion Paper we listed three criteria labelled as (1), (2) and (3). While the latter two issues are associated with GIS methods (the same scale should be kept when carrying out a vectorization procedure and a cartographic projection as well as reference system should be unified before measuring areas), the first one is strongly related to environmental factors, mainly vegetation. This first statement has been explicitly highlighted by the Reviewer #2 as an element that needs to be clarified. Mapping vegetation with UAVs becomes popular as a recent paper by Husson et al. (2014) shows [Husson E., Hagner O., Ecke F., 2014. Unmanned aircraft systems help to map aquatic vegetation. Applied Vegetation Science 17, 567–577]. These authors focus on delineating edges between water and non-submerged aquatic as well as riparian species. They write that "In practise delineation was done by hand on paper printouts" and "Vegetation mapping, i.e. digitizing the UAS orthoimages, was performed manually by a human interpreter in a GIS using ArcGIS software". Although we concentrate on a fluvial environment, the idea behind our manual expert-based vectorization remains similar to what Husson et al. (2014) propose. It is worth noting that our vectorization was practically carried out by two experts (GIS specialist + fluvial geomorphologist). Given this introduction, we unequivocally reply that the procedure met the assumed criteria (this is attained by the expert-based vectorization). We also believe that the accuracy of the produced water surface area is acceptable. However, it was our intention to include Fig. 4 and Fig. 5 which help the reader to identify potential sources of errors.

- (References) We added the paper by Husson et al. (2014) to a list of references.
- (2.2. UAV data processing, fourth paragraph) A new paragraph has been added about impact of manual expert-based digitization on the accuracy of the polygon generation procedure. We refer to the above-mentioned paper by Husson et al. (2014) to support our approach.
- (2.2. UAV data processing, fifth paragraph) The beginning of the next paragraph has been rephrased so that we clearly discriminate between the roles of vegetation and morphology in the accuracy of estimating water surface areas.

(d) **(Need for commenting on statistical independence)** All assumptions of the Student's t-test have been checked using: the Ljung-Box test (independence), the Shapiro-Wilk test (normality), the D'Agostino test (symmetry as a feature of the Gaussian distribution), the Anscombe- Glynn test (mesokurticity as a feature of the Gaussian distribution). The tests, performed with the significance level of 0.01, suggest that each sample (we analyze 5 samples corresponding to five dates) is "internally" independent and normally distributed. In particular, the Ljung-Box test provides arguments for independence since p-values are equal to 0.059, 0.092, 0.444, 0.713, 0.828 (Tab. 3 in our HESS Discussion Paper, which is equivalent to Tab. 4 in the revised manuscript), for five consecutive dates. Hence, from a definition of statistical independence we infer that they cannot reveal autocorrelation. We would like to take this opportunity and put an emphasis on spatial independence which has not been investigated in our work. In addition, variances of paired data sets have been found to be similar (Tab. 4 in the HESS Discussion Paper, which is Tab. 5 in the revised manuscript).

- (4. Results and discussion, second paragraph) Four new sentences have been added to clarify the issue of "internal" independence which implies lack of autocorrelation.

(e) **(Need for the ANOVA test)** Indeed, the ANOVA test is a generalization of the t-test to more than two groups. However, although we process five samples our intention is to allow a pairwise comparisons. In other words, our approach is targeted at solving a simple operational problem: we have two sets of UAV-acquired observations carried out on two different dates, and would like to know if water surface area increased in comparison to the preceding observation. In our manuscript we simply have five observations, and this allows us to carry out many tests to make the inference more evident. However, the pairwise comparison is a fundamental feature of our procedure.

- (3.1. Concept, third paragraph) We explicitly wrote that we aim to carry out the pairwise comparison.

(f) **(Need for shortening the description of the study area)** We entirely agree with the Reviewer #2 that the description of the study area is too detailed.

- (2.1. Study area) General description of the study area was meaningfully shortened. In the present form, it focuses on geomorphological aspects which are relevant for understanding the paper. All unnecessary fragments have been deleted.
- (From 2.1.1. to 2.1.9.) All sub-subsections have been removed.

(g) **(Need for considering linguistic remarks offered by the Reviewer #2 as a supplementary file)** We are grateful to the Reviewer #2 for offering us the remarks in the supplement. They have been conscientiously considered in a revised manuscript.

Observing river stages using unmanned aerial vehicles

Tomasz Niedzielski[1], Matylda Witek[1], and Waldemar Spallek[1]

[1]Department of Geoinformatics and Cartography, Institute of Geography and Regional Development, Faculty of Earth Science and Environmental Management, University of Wrocław, pl. Uniwersytecki 1, 50-137 Wrocław, Poland

Correspondence to: Tomasz Niedzielski (tomasz.niedzielski@uwr.edu.pl)

Abstract. We elaborated a new method for observing water surface areas and river stages using unmanned aerial vehicles (UAVs). It is based on processing multitemporal [c1]five orthophotomaps produced from the UAV-taken [c2]visible light images of [c3]nine sites of the river, acquired with a sufficient overlap in each part. Water surface areas are calculated in the first place, and subsequently expressed as fractions of total areas of water-covered terrain at a given site of the river recorded on [c4]five dates. The logarithms of the fractions are later calculated, producing [c5]five samples of size [c6]nine. In order to detect statistically significant increments of water surface areas between two orthophotomaps we apply the asymptotic and bootstrapped versions of the Student's t-test, preceded by other tests that aim to check model assumptions. The procedure is applied to five orthophotomaps covering nine sites of the Ścinawka river (SW Poland). The data have been acquired during the experimental campaign, at which flight settings were kept unchanged over nearly [c7]three years (2012–2014). We have found that it is possible to detect transitions between water surface areas [c8]associated with all characteristic water levels (low, mean, intermediate and high stages). In addition, we infer that the identified transitions hold for characteristic river stages as well. In the experiment we detected all increments of water level: (1) from low stages to: mean, intermediate and high stages; (2) from mean stages to: intermediate and high stages; (3) from intermediate stages to high stages. Potential applications of the elaborated method include verification of hydrodynamic models and the associated predictions of high flows [c9] as well as monitoring water levels of rivers in ungauged basins.

[c1] ~~m~~
[c2] ~~visual-light photographs~~
[c3] ~~n~~
[c4] ~~m~~
[c5] ~~m~~
[c6] ~~n~~
[c7] ~~3~~
[c8] ~~produced by~~
[c9] ~~using on-demand UAV flights performed in near real-time~~

1 Introduction

A key problem in assessing [c10]performance of distributed [c11]hydrodynamic models, which predict water depth across a river channel and [c12]can therefore be used to simulate flood extent, is access to up-to-date information on true inundation. There are numerous approaches used to carry out such observations [c13]of inundation. They include: terrestrial observations of flood damages carried out by volunteers who witnessed the flood, following the concept of volunteered geographic information (VGI) (e.g. Poser and Dransch, 2010), geomorphological survey and a subsequent mapping of landforms produced as a consequence of a high flow (e.g. Latocha and Parzóch, 2010), aerial photogrammetry (e.g. Yu and Lane, 2006a), use of satellite remote sensing (e.g Smith, 1997; Kouraev et al., 2004), application of airborne light detection and ranging (LIDAR) measurements (Lang and McCarty, 2009) as well as use of photographs taken by unmanned aerial vehicles (UAVs) (Witek et al., 2014). However, [c14]only a few on demand solutions exist that allow real time acquisition of such data (e.g. Schnebele et al., 2014).

[c10] ~~skills~~
[c11] ~~hydrologic~~
[c12] ~~thus~~
[c13] *Text added.*
[c14] ~~there exist only several on-demand solutions which can serve a purpose of~~

One [c15]of these solutions is the integration of HydroProg, FloodMap and UAV, known hereinafter as HFU, which has been proposed by Niedzielski et al. (2015) after the initial feasibility study offered by Witek et al. (2014).

The HFU approach utilizes the UAV observations carried out in near real-time, i.e. when the integrated HydroProg (Niedzielski et al., 2014; Niedzielski and Miziński, 2016) [c1] and FloodMap (Yu and Lane, 2006a, b) solutions produce a real-time warning of predicted inundation. According to Niedzielski et al. (2015), the workflow of the HFU is the following: (1) HydroProg computes a hydrograph prediction [c2]based on a multimodel ensemble for three hours into the future [c3] ([c4]this is done routinely in real time with a [c5]predefined frequency), (2) FloodMap uses the above-mentioned forecast as an input and enables mapping the hydrograph prognosis into the spatial domain ([c6]this is also done routinely in real time with the same frequency), (3) the warning is [c7]issued and the UAV team is notified (to be done only when a number of inundated raster cells exceeds a certain threshold), (4) the UAV team carries out the survey in order to take aerial photographs of the river channel (not routinely, but only after a warning has been issued). It is known that [c8]hydrodynamic models [c9]may produce incorrect simulations, and this is also likely in the case of the HydroProg-FloodMap integration. The outputs from this integration are maps of predicted extent of terrain covered by water, known also as water surface area. Thus, in order to verify such outputs we propose to compare the aforementioned maps with the orthophotomaps produced from the UAV-acquired [c10]visible light photographs taken in near real-time.

Although such a stepwise procedure is conceptually complete, there is no clear picture of whether it is possible to detect changes in water extent using the UAV-based orthophotomaps. [c11]This paper aims to check the meaningfulness of the UAV-based observations of water surface areas. In order to prove the aforementioned HFU concept we herein aim to verify the research hypothesis which reads as follows: "small changes in water surface areas are observable using the UAV". Such small changes may occur, for instance, when river stages rise from mean to high levels which does not always produce inundation (i.e. when water does not pass embankments or river banks, but only sinks into old river channels, flows through flood shortcuts or fills the current river channel). In order to explain such changes we graphically present the difference between water extents during low and high stages (Fig. 1). Since water surface area is directly associated with river stage (Usachev, 1983; Smith, 1997), our problem of detecting the above-mentioned changes is equivalent to seeking significant transitions in river stages. In other words, our hypothesis can also read as follows: "meaningful changes in river stages are observable using the UAV".

Both flood extents and water levels of large rivers are observable from satellites. [c12]For observing water surface areas, the use is made of the following satellite-acquired measurements: high-resolution visible light images or infrared images, passive microwave data and radar images. For observing water levels from satellites researchers utilize: radar altimetry and high-resolution satellite imagery. Since 1997, when the extensive review of the above-mentioned methods was published (Smith, 1997), numerous studies on observing water surface areas and water levels using remote sensing techniques have been carried out (Cobby et al., 2001; Kouraev et al., 2004; Prigent et al., 2007; Schnebele et al., 2014). However, these approaches are targeted at large rivers, and there are few methods to observe water surface areas, and hence water levels, of small rivers. This paper aims to propose such an approach and to confirm its potential experimentally.

In order to verify the above-mentioned hypothesis we use a time series of five orthophotomaps produced from aerial photographs taken by [c13]a UAV at different hydrologic situations that occurred along the Ścinawka river (SW Poland). The obser-

[c1] Recent paper by Niedzielski and Mizinski (2016) is cited
[c15] *Text added.*
[c2] ~~for such attempts on a basis of multi-modelling~~
[c4] ~~being~~
[c5] ~~pre-assumed~~
[c6] ~~also being~~
[c7] ~~distributed amongst the UAV team~~
[c8] ~~hydrodynamical~~
[c9] ~~may be incorrect~~
[c10] ~~visual light~~
[c11] ~~Hence, this~~
[c12] ~~For observing water surface area, the use is made of the following satellite-acquired measurements: high-resolution visual or infrared images, passive microwave data and radar images.~~
[c13] ~~the~~

vations were made in the experiment during which [c14]aerial images were acquired with a UAV flying on different dates, at the same altitude and over the same terrain. We adopt a rigorous statistical analysis, [c15]based on the asymptotic and bootstrapped Student's t-test, the use of which is essential in the process of detecting changes in water surface area. The remainder of this paper is organized as follows: the second section presents the study area and data, the subsequent section focuses on the UAV-based photo acquisition techniques and statistical methods, the fourth section shows the results and their discussion, while the last section concludes the paper.

2 Data

2.1 Study area

The research was conducted in [c1]southwestern Poland, in Kłodzko County located in [c2] Central and [c3] Eastern Sudetes (Fig. 2). The main river of the region is Nysa Kłodzka (left tributary of the Odra river), and one of its key tributaries is the Ścinawka river.

[c4] The majority of [c5] rivers in Kłodzko County in their upper sections are typical mountain streams. The middle and lower sections of the channels, located in the foothills of the mountains, [c6]have alluvial character – wide channels with numerous large cutbanks, bars and meandering parts. The complex topography and the extensive hydrographic network contribute to rapid and catastrophic floods in this area (Dubicki et al., 2005; Kasprzak, 2010).

One of the alluvial-type river sections is a fragment of the Ścinawka river channel located directly upstream the Gorzuchów gauge ($50°29'$ N, $16°34'$ E, 8+030 km of the course of the river). [c7] The analyzed part of the channel has length of 1500 m and belongs to the lower part of the basin, within which the Ścinawka river flows through a wide valley (250–400 m)[c8] with a flat bottom. The river banks in the studied part are asymmetrical. [c9] The width of the channel, in the investigated part, varies between 5 and 25 m, and the average slope of the channel is 3.4 per mil. This part of the river has winding character, and is contemporary formed mainly by lateral erosion. The analyzed section is located far from human settlements, hence regulation works have not been undertaken here. Soft material forming the river bed and banks as well as lack of engineering structures and occurrence of frequent flood episodes provide profound conditions for development of erosion and accumulation channel landforms. Evident channel bedforms are visible, for instance steep banks of erosional [c10]origin reveal heights [c11] of 1.5–2 m. As regards accumulation-driven forms, various types of bars are common in the studied channel, with point bars and longitudinal ones that reflect the characteristics of a meandering stream.

The channel morphology of the studied part of the Ścinawka river may be linked to the pool-riffle channel pattern, with exposed bars and highly turbulent flow through riffles and more tranquil flow through pools. The average annual discharge at the Gorzuchów gauge is approximately equal to 4.63 m^3/s (1951–2011), whereas the average annual water level is of 71.6 cm (1981–2011).

In the studied fragment of the Ścinawka channel nine sites of variable lengths have been selected and coded as S1,S2,...,S9 (Fig. 3). Water extents in different seasons are analyzed in these sites. The [c12]UAV observations have been carried out on: 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014. [c13]Tab. 1 [c14]presents detailed parameters of the UAV flight

[c14] ~~the same conditions of data acquisition were kept~~

[c15] *Text added.*

[c1] ~~the South-western~~

[c2] ~~the~~

[c3] ~~the~~

[c4] ~~The channel system in Kłodzko County is directly related to the bedrock and refers to the tectonic structures and rock resistance. This region has unique topographical conditions – rivers and streams flow down from surrounding morphologically-differentiated mountain ranges to the Nysa Kłodzka Valley.~~

[c5] ~~the~~

[c6] ~~present an~~

[c7] ~~The headwaters of the Ścinawka river are located in the Walbrzyski Moun-~~

trajectories, with a particular emphasis put on the UAV vertical position. It is apparent from the table that those parameters were kept similar and stable over the above-mentioned five flight missions. Hence, the resulting data sets are of comparable resolution, and the level of details of aerial images and the resulting orthophotomaps is similar.

The selection of the sites is based on the following conditions: (1) all sites are covered by the observations from the above-mentioned five dates, (2) there are no distortions of the produced orthophotomaps (i.e. [c1]no-data masks or incorrect peripheries, both arising from the limited coverage of aerial photos), (3) the sites are characterized by different morphological positions, [c2]they cover channel [c3]landforms and enable to observe water extent, (4) the sites cannot be covered [c4]by lush vegetation which [c5]prevents the identification of [c6]riverbanks.

[c7]

2.2 UAV data processing

We carried out the UAV survey using the swinglet CAM fixed-wing solution manufactured by senseFly. Swinglet CAM is lightweight (0.5 kg) and its payload includes a single consumer-grade RGB camera that records the photographs as JPG files. The individual pictures are geotagged. In order to produce orthophotomaps we process these files with the Structure-from-Motion (SfM) algorithm (Westoby et al., 2012) in the Photoscan software provided by AgiSoft, without use of ground control points (GCPs). We produced the georeferenced orthophotomaps in Photoscan which for the purpose of georeferencing uses coordinates extracted from the geotagged images. Such orthophotomaps were compared with the LIDAR digital terrain model (DTM), and we identified offsets between the two. The resolution of the LIDAR data was of 1 m, and the data acquisition was carried out in 2010. To remove the offsets we used the spline function in ArcMap 10.2.2 by ESRI. [c8]We identified characteristic features in the LIDAR DTM which were evenly distributed and possible to identify in the orthophotomap. These features comprise: crossings of bounds, crossings of drainage ditches, and centres of bridges or passages (crossings of streams and roads). More than 10 points were used to perform georeferencing, as the spline method requires. The spline function allowed us to precisely georeference the control points (i.e. the aforementioned mutual features) and transform raster data set with continuity and smoothness, such as the rubber sheeting method. Use of LIDAR data to improve spatial references of UAV-acquired materials is known (Liu et al., 2007). However, these authors use LIDAR data to improve [c9]GCPs quality, and our approach is different as it applies splines to provide a spatial fix and correct for errors.

Although we did not use GCPs in the process of orthophotomap generation, we believe that for the purpose of the proposed analysis the absolute fit of orthophotomap to the Earth-fixed reference is not as crucial as the internal accuracy (within the orthophotomap). Indeed, the accuracy of area computation is not sensitive to linear motions of the cartographic source, but is vulnerable to the quality of the sources, and the latter is guaranteed by the above-mentioned LIDAR-based procedure that can be repeated at any time. Temporal analysis of landform topography is associated with a need of high accuracy which is guaranteed by the SfM-based materials (Clapuyt et al., 2015). We believe that our approach, carried out without use of GCPs, is also accurate because the accuracy is kept within every single orthophotomap as discussed above. We do not use the digital elevation model (DEM) of differences (DoD) and hence the highly accurate Earth-fixed reference is not needed. [c10]We believe that the presence of a potential shift between two spatial data sets does not cause meaningful changes in area of the

[c1] ~~no data~~

[c2] *Text added.*

[c3] ~~forms,~~

[c4] ~~too~~

[c5] ~~prevent~~

[c6] ~~the riverbank~~

[c7] ~~Site S1 The site is located in the central part of a large channel bend (length of the meander about 250 m, amplitude of 150 m, average radius about 90 m). The part of the channel is approximately 61 m long and its width varies between 13 and 15 m. Both banks are intensively eroded, especially the right one. Longitudinal underwater forms are visible. At the left bank, the exposed sand bar with vegetation is located. This large form is about 26~~

considered objects. To support this assumption we refer to a recent paper by Mesas-Carrascosa et al. (2014) [c11]who focus on UAV-based area calculation and argue that “Other shortcomings include the lack of vertical adjustment of the aerial camera and the unknown or variable interior orientation of the camera. These factors affect point position accuracy but do not necessarily decrease the accuracy of area measurements”.

Water extent during high flow, or inundation if overbank flow occurs, is identified on [c1]orthophotomaps as maximum range of terrain covered by water. Calculations of water surface areas were carried out to compare water extents recored on different dates. Thus, having a series of five orthophotomaps for each site (S1,S2,...,S9), corresponding to the above-mentioned dates of observations, we produced polygons in order to calculate the areas of water extent. To accurately carry out such a polygon generation procedure, the following method-related problems should be addressed: (1) the procedure to determine the edges of water extent should be well-documented to enable its repetition, (2) the accuracy of [c2]digitization may vary across cartographic scales and experts, and [c3]therefore the impact of these factors should be controlled, (3) there should be a recommended procedure [c4]for computing water surface area.

[c5]One of the most important factors that may potentially constrain the polygon generation accuracy is related to vegetation. Mapping vegetation with UAVs becomes popular as a recent paper by Husson et al. (2014) [c6]confirms. These authors focus on delineating edges between water and non-submerged aquatic as well as riparian species. They delineated the edges by hand on paper printouts and argued that “vegetation mapping, i.e. digitizing the UAS orthoimages, was performed manually by a human interpreter in a GIS using ArcGIS software”. Although we concentrate on a fluvial environment, we followed the concept of Husson et al. (2014) [c7]of the manual expert-based digitization. Our digitization was practically carried out by two experts (GIS specialist and fluvial geomorphologist). Therefore, we believe that the accuracy of the produced water surface areas is acceptable and are aware of limitations, the reasons of which are graphically presented in Fig. 4 [c8]and Fig. 5.

[c9]Not only vegetation but also morphology was found to be important when determining the boundaries of water extent. The extent in question is relatively easy to identify if the water reaches clear barrier, such as for instance undercut river banks, defense river banks, levees or dams. The water extent within plains as well as for rivers of indistinct and small slope banks, which additionally may be accompanied by bars, is difficult to determine. A similar problem refers to [c10] banks of mid-channel forms.

Soil-turf overhangs on undercut river banks [c11]as well as clumps of grass growing on the low banks [c12]make the line along which water meets the land [c13]invisible (Fig. 4). Hence, the extent is determined as a line connecting the gaps between the clumps of grass (Fig. 5A and Fig. 5B). Bushes as well as small trees growing on the edge of a river channel also [c14]make a riverbank [c15]invisible. [c16]In such cases, water extent is drawn as a line interpolated between last exposed parts of [c17]a riverbank at both ends of woodlots or bushes (Fig. 5C and Fig. 5D). This procedure is verified against the field observations as well as against orthophotomaps for November 2012, January 2013 and December 2013 [c18](absence of leaves). Sections of river channel, for which it was impossible to determine the water extent in accordance with the procedure described above, were withdrawn from the analysis. The procedure enables the determination of water extent with certain approximation. Following

[c11] *Text added.*
[c1] ~~ortophotomaps~~
[c2] ~~digitalization~~
[c3] ~~hence its impact~~
[c4] ~~to compute~~
[c5] *Text added.*
[c6] *Text added.*
[c7] *Text added.*
[c8] *Text added.*
[c9] ~~Morphology and vegetation were the most important factors in planning the procedure to determine~~
[c10] ~~the~~
[c11] ~~and~~
[c12] ~~cover~~
[c13] *Text added.*
[c14] ~~cover~~
[c15] *Text added.*
[c16] ~~Then~~
[c17] *Text added.*
[c18] ~~, when the leaves fell down~~

the above discussion on the temporal analysis of landform topography without GCPs, it is assumed that determination errors are similar for all nine sites and five dates[c19]. This allows us to compare areas computed for different dates.

[c20]Digitization of water extent was conducted using ArcMap 10.2.2. To accurately measure the area, the spatial data were transformed into the cylindrical equal area projection in secant normal aspect, with longitude of the central meridian at 13.5° W and standard parallels at 51° S and 51° N. [c21]The accuracy of [c22]digitization (minimum dimension of digitized features, e.g. channels between clumps or width of islands) was 10 cm, while the resolution of [c23]orthophotomaps was approximately equal to 3 cm.

[c20] ~~Digitalization~~ [c19] ~~which~~
[c21] ~~Accuracy~~
[c22] ~~digitalization~~
[c23] ~~ortophotomaps~~

2.3 Riverflow data

As a hydrologic reference [c1]for the low-, normal- and high-flow situations we use the water level data recorded at the adjacent gauge in Gorzuchów (south of S8 in Fig. 3) which belongs to a larger Local System for Flood Monitoring, named LSOP (Lokalny System Osłony Przeciwpowodziowej). The observations at the gauge are carried out in the real-time fashion every 15 minutes.

[c1] ~~to~~

Fig. 6 presents the hydrographs observed [c2]over one complete week when UAV flights were performed, with superimposed dots that highlight water level at the time of the UAV observation. In all cases the warning and emergency (alarm) water levels were depicted for reference.

[c2] ~~during one week~~

In order to classify water levels into low-, normal-, and high-flow stages we analyzed the daily data from the same gauge, measured since the beginning of the records in 1981 by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). For the hydrologic years 1982–2014 (note that in Poland a hydrologic year begins on 1 November), hence for the period 01/11/1981–31/10/2014, we computed (in brackets abbreviations used in the Polish hydrologic nomenclature are given): (1) minimum from a time series of annual minimum water levels (NNW), (2) maximum from a time series of annual minimum water levels (WNW), (3) minimum from a time series of annual mean water levels (NSW), (4) maximum from a time series of annual mean water levels (WSW), (5) minimum from a time series of annual maximum water levels (NWW), (6) maximum from a time series of annual maximum water levels (WWW). Fig. 7 presents three graphs (annual min, annual mean, annual max) from which we extracted the above-mentioned characteristics. There exist three classes of water levels – i.e. low, mean and high stages – and additionally a distinct intermediate class between mean and high stages (Fig. 7). In contrast, there is no intermediate class between low and mean stages since NSW is smaller than WNW. It is apparent form Figs. 6, 7 and Tab. 2 that we consider two low-stage situations (27/11/2012, 21/08/2013), one mean-stage situation (27/09/2013), one [c3]intermediate-stage situation (02/06/2014) and one high-stage situation (13/05/2013).

[c3] ~~intermediate stage~~

3 Methods

3.1 Concept

[c4]

[c4] Section on "Methods" has been divided into subsections to clearly identify new part on how the outputs should be

Let us assume that we have m UAV-based orthophotomaps that consist of observations of the same part of river channel carried out at times $t_1, \ldots, t_n$. Let us consider only such fragments of the orthophotomaps which meet the criteria outlined in

Subsection 2.1. [c5]Therefore, for each orthophotomap we obtain n sites, coded as S1,...,Sn, in which water extent should be estimated. Such water-covered areas are expressed by polygons (coded as $s_1, \ldots, s_n$), the production of which should follow the procedure outlined in Subsection 2.2. Having produced the polygons, we are able to calculate water surface areas. Hence, we consider a matrix $\mathbf{A}$:

[c5] ~~Thus~~

$$
\xrightarrow{\textit{TIME}} \qquad
\textit{SPACE}\downarrow
\begin{array}{cccc}
A_1(1) & A_1(2) & \ldots & A_1(m) \\
A_2(1) & A_2(2) & \ldots & A_2(m) \\
\vdots & \ddots & & \vdots \\
A_n(1) & A_n(2) & \ldots & A_n(m)
\end{array}
$$

where $A_s(t)$ is water surface area [c1]at site s at time t. In order to obtain the version of these data which is independent of sizes of S1,...Sn (and the corresponding polygons $s_1, \ldots, s_n$), we transform the areas by computing the ratio of water surface area at a given section s_i ($i = 1, \ldots, n$) and at a given time t_j ($j = 1, \ldots, m$) to a sum of water surface areas in m episodes that occurred at times $t_1, \ldots, t_m$ at the same site s_i. This ratio matrix, denoted by $\mathbf{R}$, is composed of the following elements:

[c1] ~~in~~

$$R_i(j) = \frac{A_i(j)}{\sum_{k=1}^{m} A_i(k)}. \tag{1}$$

The transformation allows us to consider m samples $R(1) = [R_1(1), \ldots, R_n(1)]$,..., $R(m) = [R_1(m), \ldots, R_n(m)]$, however, they should follow the i.i.d. (independent and identically distributed) property to be analyzed as statistical samples. The popular transformation that helps to attain this goal is based on a logarithmic function which, in our case, produces a new matrix $\mathbf{L}$, the elements of which are computed as $L_i(j) = \ln[R_i(j)]$. The corresponding samples are denoted as $L(1) = [L_1(1), \ldots, L_n(1)]$,..., $L(m) = [L_1(m), \ldots, L_n(m)]$.

Let us now formulate a research hypothesis to be verified. Consider two samples $L(j)$ and $L(k)$, $j \neq k$ [c2]. We aim to check whether water surface areas at the time k are significantly greater than at the time j. The hypothesis may be expressed in terms of means, i.e.

[c2] ~~(but in practice j<k)~~

- H0: two samples have the same mean water surface areas,
- H1: the mean water surface area is greater in the subsequent, $L(k)$, sample than in the preceding one, $L(j)$.

Such a problem of [c3]pairwise comparison of samples may be solved using the Student's t-test, however, numerous assumptions must be fulfilled prior to its application. Indeed, each of the samples $L(j)$ and $L(k)$ should be i.i.d., follow the normal distribution, and the two datasets should have the same variances. Several standard statistical tests can be used to check these assumptions:

- independence, Ljung-Box test (Ljung and Box, 1978),
- normality, Shapiro-Wilk test (Shapiro and Wilk, 1965; Royston, 1995),
- symmetry, D'Agostino test (D'Agostino, 1970),
- mesokurticity, Anscombe-Glynn test (Anscombe and Glynn, 1983),
- equality of variances, F test (Box, 1953).

If the assumptions are fulfilled, the Student's t-test can be applied to test H0 against H1. However, if the sample size is small [c1] the bootstrapped Student's t-test should be applied to verify the asymptotic results. Following the idea of Efron (1979), B values of the Student's statistics should be computed, and their mean leads to the bootstrapped solution. If the bootstrapped solution confirms the asymptotic one, the decision on the hypothesis can be made.

3.2 Interpretation through numerical exercise

[c2]

[c3]The two sample Student's t-test is used to test a null hypothesis (H0) that means of two samples are equal, but three alternative hypotheses are allowed. These three alternatives include: means of two samples are different, mean of the first sample is bigger than mean of the second sample, mean of the second sample is bigger than mean of the first sample. In the latter two alternatives, the order of samples is important and has impact on where rejection region is located. Knowing the aforementioned basics, we stated the research hypothesis H0 with its alternative H1 on purpose, in the way that rejection of the null hypothesis implies acceptance of the alternative one (and this unequivocally indicates that the second area is meaningfully bigger).

[c4]In order to clarify the formulation of the hypotheses H0 and H1 the following numerical exercise is proposed. Let us consider two combinations of $L(j)$ [c5]and $L(k)$. [c6]Recall that we test if means of $L(j)$ [c7]and $L(k)$ [c8]are equal, with the alternative that the mean of $L(j)$ [c9]is smaller than the mean of $L(k)$. [c10]Let us consider two cases based on data borrowed from Tab. 2.

[c11]CASE 1 [c12]

Let us assume that

$j =$ '27/11/2012',

$k =$ '13/05/2013',

mean of $L($'27/11/2012'$)]$ -1.71727,

mean of $L($'13/05/2013'$)] = -1.501393$.

[c3] *Text added.*

[c1] ~~what is often the case,~~

[c2] Section on "Methods" has been divided into subsections to clearly identify new part on how the outputs should be interpreted (new Subsection "Interpretation through numerical exercise").

[c3] *Text added.*

[c4] *Text added.*

[c5] *Text added.*

[c6] *Text added.*

[c7] *Text added.*

[c8] *Text added.*

[c9] *Text added.*

[c10] *Text added.*

[c11] *Text added.*

[c12] The

Arithmetically, mean of L(‘27/11/2012’) is smaller than mean of L(‘13/05/2013’). This inequality has also been confirmed statistically (the bootstrapped Student’s t-test) at the significant level of 0.01 (latter it is shown that the difference in means is statistically significant). Hence, in this case a subsequent episode (time step k) revealed meaningfully bigger water surface area than the preceding one (time step j).

[c1]CASE 2 [c2]

Let us unrealistically assume a reverse order of the above-mentioned numbers, namely

$j =$ ‘13/05/2013’,

$k =$ ‘27/11/2012’.

Arithmetically, mean of L(‘13/05/2013’) is not smaller than mean of L(‘27/11/2012’). If we test the null hypothesis (mean of $L(j)$ is equal to mean of $L(k)$) against the alternative hypothesis (mean of $L(j)$ is smaller than mean of $L(k)$) we cannot reject the null hypothesis with the bootstrapped Student’s t-test at the significance level of 0.01. Hence, in this case a subsequent episode (time step k) does not reveal a meaningfully bigger water surface area than the preceding one (time step j).

4 Results and discussion

It is apparent from Fig. 8 that fragments of sites S1–S9 are covered with water, the extent of which is dissimilar at different dates of UAV observations. These dates correspond to low-, normal-, intermediate- and high-flow situations (see Subsection 2.3). Water surface areas in sites S1–S9 are juxtaposed in Tab. 3. Along the lines of Eqn. 1, Tab. 3 presents the ratios $R_i(j)$ and their logarithms $L_i(j)$ – for $i = 1, \ldots, 9$ and $j = 1, \ldots, 5$. The latter numbers become input data for the subsequent analysis.

Since we aim to compare five samples $L(1), \ldots, L(5)$, we first have to verify if they follow the i.i.d. structure. The p-values of the Ljung-Box, Shapiro-Wilk, D’Agostino and Anscombe-Glynn tests – juxtaposed in Tab. 4 – indicate that the five data sets are trajectories of statistical samples (sequences of i.i.d. random variables) [c3]from the normal distribution. This can be inferred at the significance level of 0.013 or smaller. [c4]It is worth commenting here on statistical independence which should be understood in our exercise as an “internal” independence within each sample. Every sample is produced from areas of polygons spatially distributed along the river. In particular, the Ljung-Box test provides arguments for such an independence since p-values are equal to 0.059, 0.092, 0.444, 0.713, 0.828, for five consecutive dates. Hence, from a definition of statistical independence we infer that they cannot reveal autocorrelation. In addition, variances between each pair of $L(1), \ldots, L(5)$ are shown to be similar at the significance level of 0.03 or smaller, as the Fisher’s test suggests (Tab. 5). The statistical inference [c5] shows that the assumptions of the Student’s t-tests are fulfilled.

Subsequently, we apply the Student’s t-test to verify the above-mentioned hypothesis H0 against H1 (see Section 3), and we do so for each pair from $L(1), \ldots, L(5)$. The results are presented in Tab. 6 which juxtaposes p-values of the test, computed as asymptotic and bootstrapped solutions. Gray background boxes indicate statistically significant differences in water surface areas, which suggests the rejection of the H0 hypothesis. This means that the mean water surface area is shown to be greater in the subsequent $L(k)$ sample[c6] than in the preceding one.

[c1] *Text added.*

[c2] The numbers below, borrowed from Tab. 2, are included in the revised version of the manuscript

[c3] ~~which are normally distributed~~

[c4] *Text added.*

[c5] ~~unequivocally~~

[c6] ~~, k=2,...,5,~~

It is known that water surface area is correlated with river [c7]stage. The characteristics of such relationships are reviewed by Smith (1997). Usually, the correlations are positive, [c8]quasi-linear for rivers (Usachev, 1983) [c9]and even strongly linear for lakes (Xia et al., 1983)[c10]. Hence, when water surface areas are analyzed in this paper in combination with river stages and their classes (Fig. 7) the following transitions are found to be meaningfully observable.

[c7] ~~stages~~
[c8] ~~with different degree of departure from a linear relation~~
[c9] *Text added.*
[c10] A reference by Xia et al(1983) has been added

- Low stages (27/11/2012 and 21/08/2013) →
  → mean stage (27/09/2013),
  → intermediate stage (02/06/2014),
  → high stage (13/05/2013).
- Mean stage (27/09/2013) →
  → intermediate stage (02/06/2014),
  → high stage (13/05/2013).
- Intermediate stage (02/06/2014) →
  → high stage (13/05/2013).

Noteworthy is the fact that the other transitions are found to be insignificant. To verify the adequacy of the detected changes between the water surface areas, we again refer to Fig. 6 and Tab. 2 which present stages observed at the Gorzuchów gauge at the time of the UAV observations. The visual examination of the graphs and table [c1]indicates that no changes in water-covered areas correspond to no changes in river stages and, conversely, significant differences in water surface areas observed by the UAV at dissimilar times correspond to visually well seen changes of water levels. This inference allows us to positively verify the research hypothesis stated in this paper. Namely, even small changes in water surface areas are observable using the UAV and – in addition – meaningful changes of river stages can also be [c2]inferred from the orthophotomaps based on the UAV-taken [c3]visible light photographs.

[c1] ~~indi-cate~~
[c2] ~~ex-tracted~~
[c3] ~~visual~~

[c4]A remark should be given here about the non-chronological order of the above-mentioned transitions. These numbers serve as examples of low, mean, intermediate and high water levels. They have been recorded by a real UAV on different dates. We used the UAV-observed water surface areas as true data that represent the aforementioned stages. We believe that, for the analysis that aims to check the procedure proposed in this paper, the chronological order of transitions between stages is not important. It would be ideal to have the chronological set of transitions, however such a data set is not available for our experiment. Thus, we mixed the order to check various potential combinations of transitions in order to test the procedure on the real UAV-acquired data.

[c4] *Text added.*

A note should be given on the accuracy of the elaborated approach. We believe that potential sources of error may reside in: (1) the SfM accuracy, (2) application of the SfM without GCPs, (3) problems with the determination of water boundaries due to presence of vegetation and undercuts. The quality of outputs from the SfM procedure depends on many factors – e.g. texture and light [c5]which influence a number of keypoints in every image – and hence not uncommonly we produce incomplete

[c5] *Text added.*

orthophotomaps from well-overlapped photographs. Despite these constraints the SfM procedure is well-established in scientific applications and is probably the most commonly used and accepted method for producing dense point clouds from the photographs taken by the consumer grade cameras (Westoby et al., 2012). As stated in Subsection 2.2, we do not use GCPs and believe that this does not undermine our approach. Indeed, we infer from multitemporal UAV-acquired data, [c6]in a similar way to [c7]the analyses by Clapuyt et al. (2015) and Miřijovský and Langhammer (2015), and calculate water surface areas which are accurate due to internal accuracy of every single orthophotomap (shifts of dissimilar orthophotomaps due to lack of GCPs are negligible).

[c6] ~~similarly~~ [c7] *Text added.*

[c1]As mentioned in Subsection 2.2 [c2], we refer to the reasoning of Mesas-Carrascosa et al. (2014) [c3]who claim that the computation of area is not vulnerable to changes in point position accuracy. Such changes may be due to neglecting GCPs. [c4]We perform manual georeferencing which was also carried out in a different way by Peter et al. (2014) [c5]who omitted measuring GCPs in the field and identified them manually on external spatial data sources.

[c1] *Text added.* [c2] *Text added.* [c3] *Text added.* [c4] ~~Similarly,~~ [c5] *Text added.*

Finally, a comment should be given on how vegetation and undercuts constrain the determination of water boundaries. In Subsection 2.2 we proposed a procedure to cope with the problem, but we are aware of its subjectivity. However, even satellite-based observations, using different sensors including radar, reveal similar limitations (Smith, 1997).

[c6]It is also important to discuss limitations which may constrain extrapolation of the results to other rivers. Channel morphology, mainly the slope of banks, may have a significant impact on the observation of water surface area with the UAV. Therefore, the results prepared for a specific river in the SW Poland are not transferable to other rivers with different cross-sectional parameters. Indeed, Smith (1997) [c7]argues that "Until additional empirical rating curves relating inundation area to ground measurements of stage or discharge are made, it is difficult to assess their potential for extrapolation to other rivers of similar morphology. However, it seems likely that such curves will vary significantly between rivers and therefore must be constructed for each site". However, our approach focuses mainly on a statistical analysis of water surface areas, not river stages themselves. In fact, we quantitatively infer on statistically meaningful changes in water surface area (this is a key part of our procedure) and only qualitatively, through the existence of a relationship between water surface areas and river stages published by Usachev (1983) [c8], extrapolate our results into changes in river stages. We believe that our quantitative approach (recall that this concerns seeking changes in water surface areas in the orthophotomaps produced from the UAV-taken photographs) forms a general method that – under several conditions clearly identified in the manuscript – may be applied in other regions. However, the use of the approach to infer on river stages should be made with caution, since such an extrapolation requires a knowledge about the relationship between water surface areas and river stages (and the characteristics of this relation are vulnerable to sites-specific river morphology, especially bank slopes).

[c6] *Text added.* [c7] *Text added.* [c8] *Text added.*

5 Conclusions

We have shown that it is possible to detect even small changes in water surface area, using multitemporal orthophotomaps based on the UAV-acquired images. This can be done by the UAV equipped with the RGB consumer-grade camera which takes photographs with a sufficient overlap to produce the SfM-based dense point cloud and, consequently, an orthophotomap.

It is likely that transitions from normal or low flow to high flow does not produce large water surface area, as exemplified in Fig. 1. Our approach, verified in the experiment that uses the UAV data acquired at nine study sites during the campaign consisted of five observations, shows that it is possible to detect transitions between water surface areas produced by all characteristic water levels (low, mean, intermediate and high stages), and such a detection is statistically significant. Since water surface areas are correlated with river stages our approach can also be used as a tool for observing characteristic river stages.

More specifically, we detected any rise of water level from low stages to: mean, intermediate and high stages. We also found any increase in water level from mean stages to: intermediate and high stages. Moreover, we detected rise of water level from intermediate stages to high stages. The detection was based on a rigorous statistical inference, based on several statistical tests performed in the asymptotic and bootstrap fashion.

Finally, it is important to identify potential applications of our approach. To do this we recall our motivation, stated in Section 1. We developed a solution, known as the HFU, which integrates the real-time flood warning system (HydroProg) with the [c1]hydrodynamic model (FloodMap) and their near real-time verification using UAVs (Niedzielski et al., 2015). A key problem in the HFU approach is the uncertainty of estimating water surface areas. The results presented in this paper unequivocally show that the UAV observes water extent with acceptable accuracy and, in addition, river stages can be inferred from the observations. The later feature opens new perspectives for applications of the approach in the process of monitoring water levels of rivers in ungauged basins.

[c1] ~~hydrodynamical~~

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[c2] ~~We are also grateful to the authorities of the Commune Office in Kłodzko for access to the UAV take-off and landing site.~~

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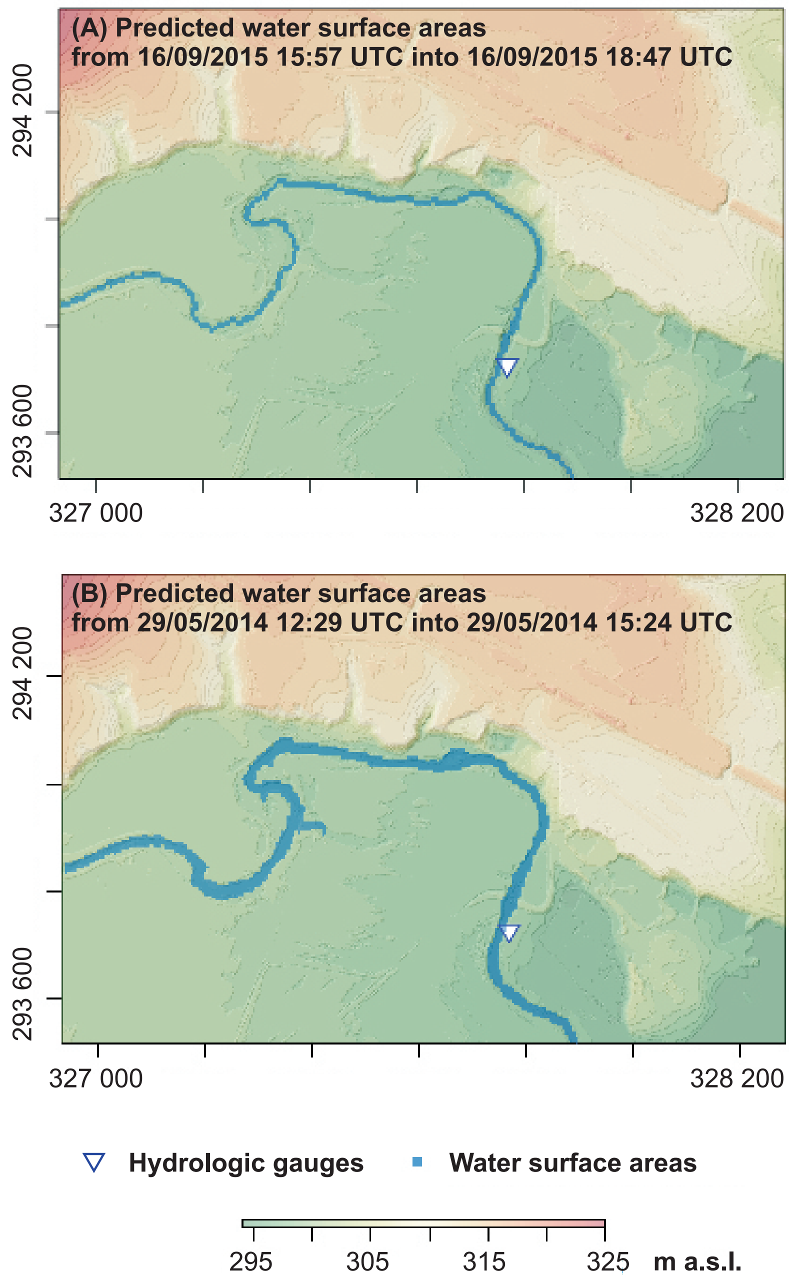

Figure 1. Predictions of water surface areas derived by the HydroProg-FloodMap solution extracted from the real-time web map service experimentally implemented for Kłodzko County: A – low flow situation, B – high flow situations.

Figure 2. Map of study area.

Figure 3. Study sites on the Ścinawka river in Gorzuchów. Numbers in site codes increase in a downstream direction.

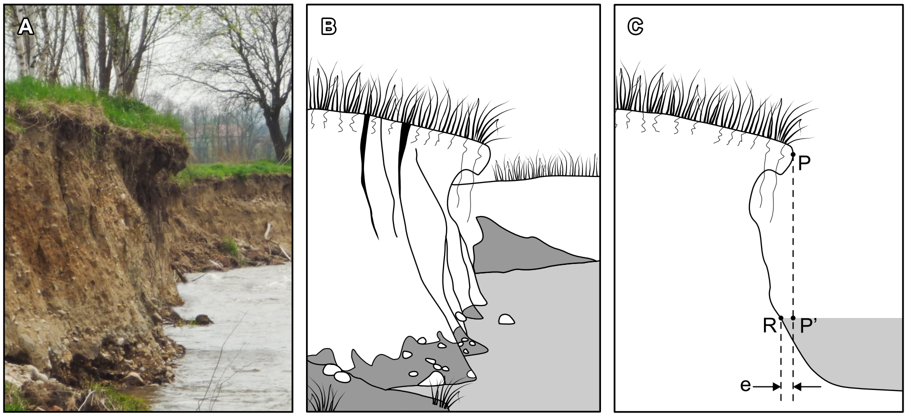

Figure 4. Undercut river bank: A – photograph, B – 3D sketch, C – 2D cross-section with edge P and its projection onto water surface P' (water surface visible from the UAV) as well as true bank R (UAV-unobservable water surface, denoted in the figure as "e", stretches between R and P').

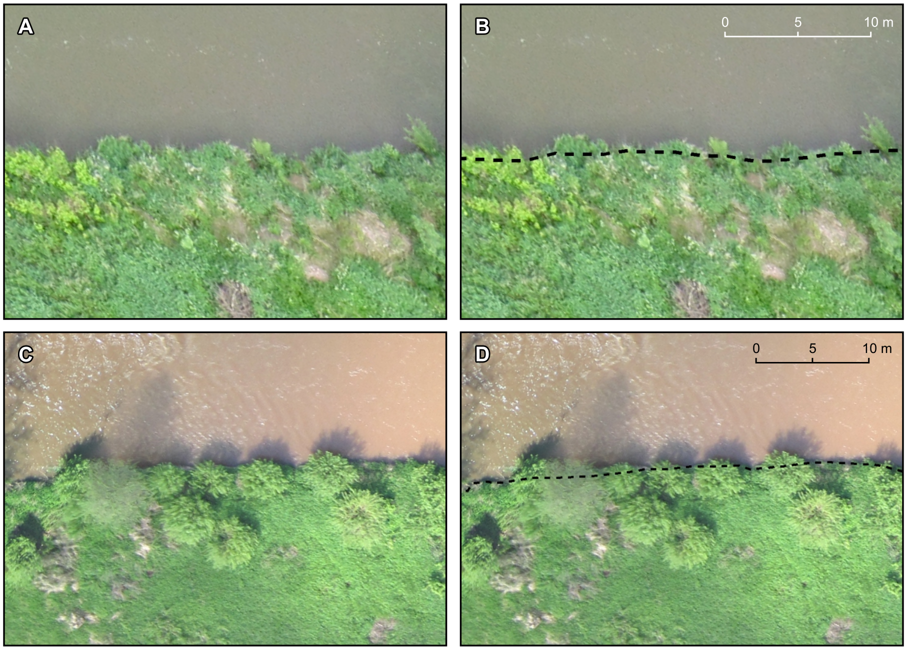

Figure 5. Determination of water surface areas: A and B – as a line connecting the gaps between the clumps of grass on undercut river bank covered by soil-turf overhangs, C and D – as a line interpolated between last exposed parts of riverbank at both ends of woodlots or bushes.

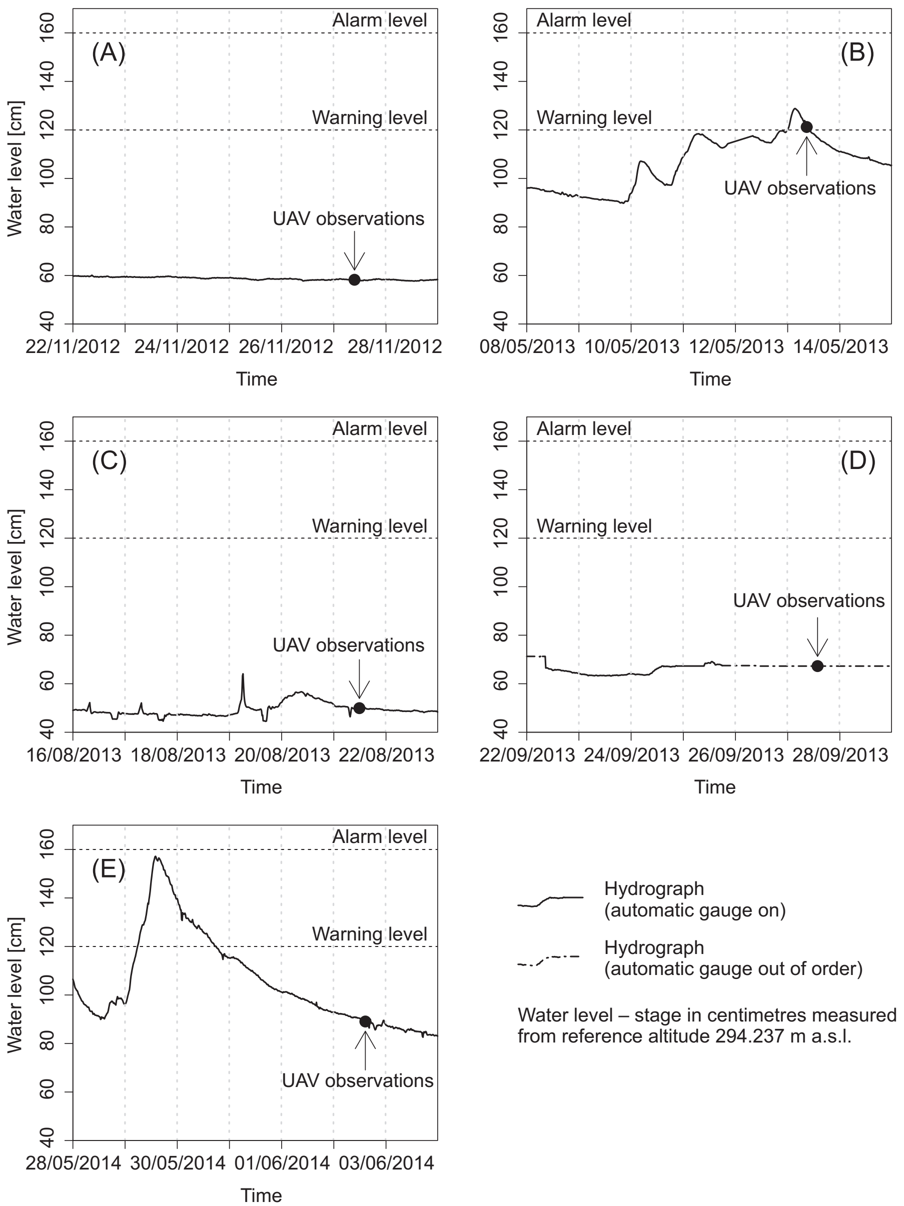

Figure 6. Hydrographs recorded in Gorzuchów before (approx. 5 days) and after (approx. 2 days) UAV flights on: A – 27/11/2012 , B – 13/05/2013, C – 21/08/2013, D – 27/09/2013, E – 02/06/2014.

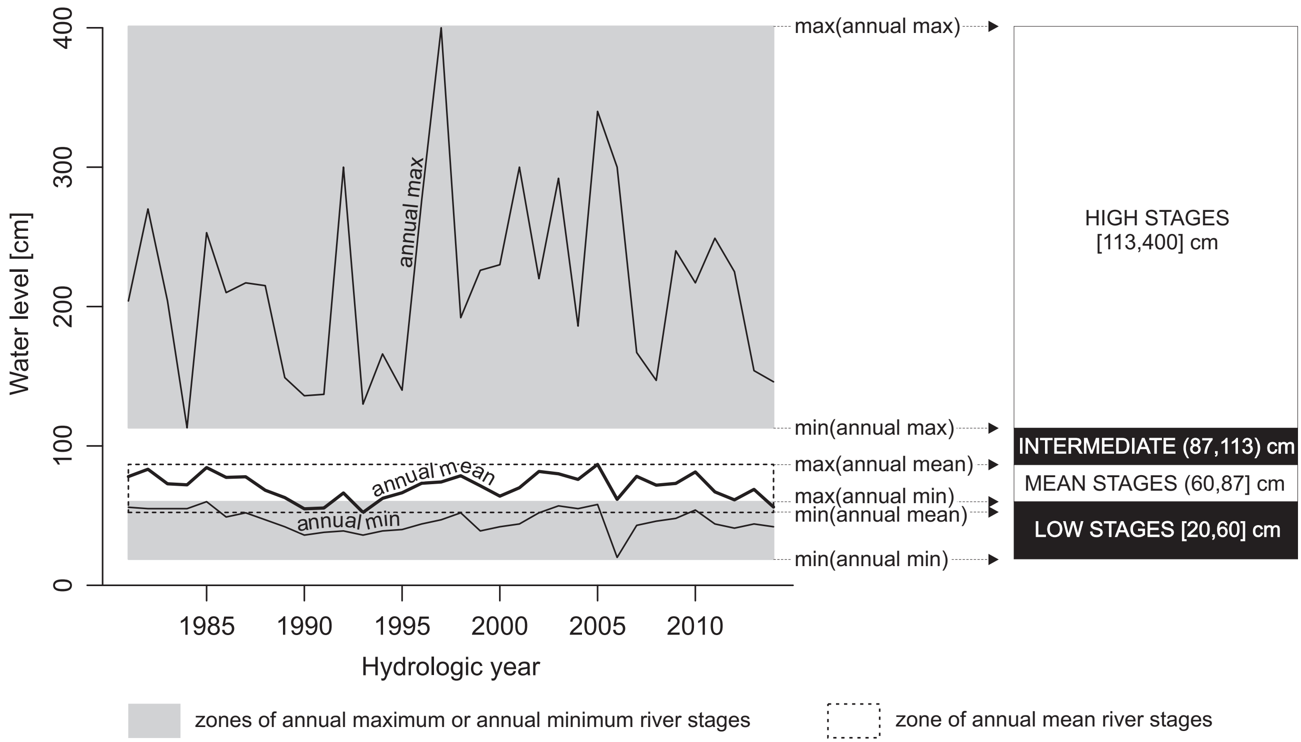

Figure 7. Time series of annual minimum, annual mean, annual maximum river stage computed for Gorzuchów in hydrologic years 1982–2014 (note that in Poland a hydrologic year begins on 1 November) along with their main statistics and the resulting characteristic river stage classes.

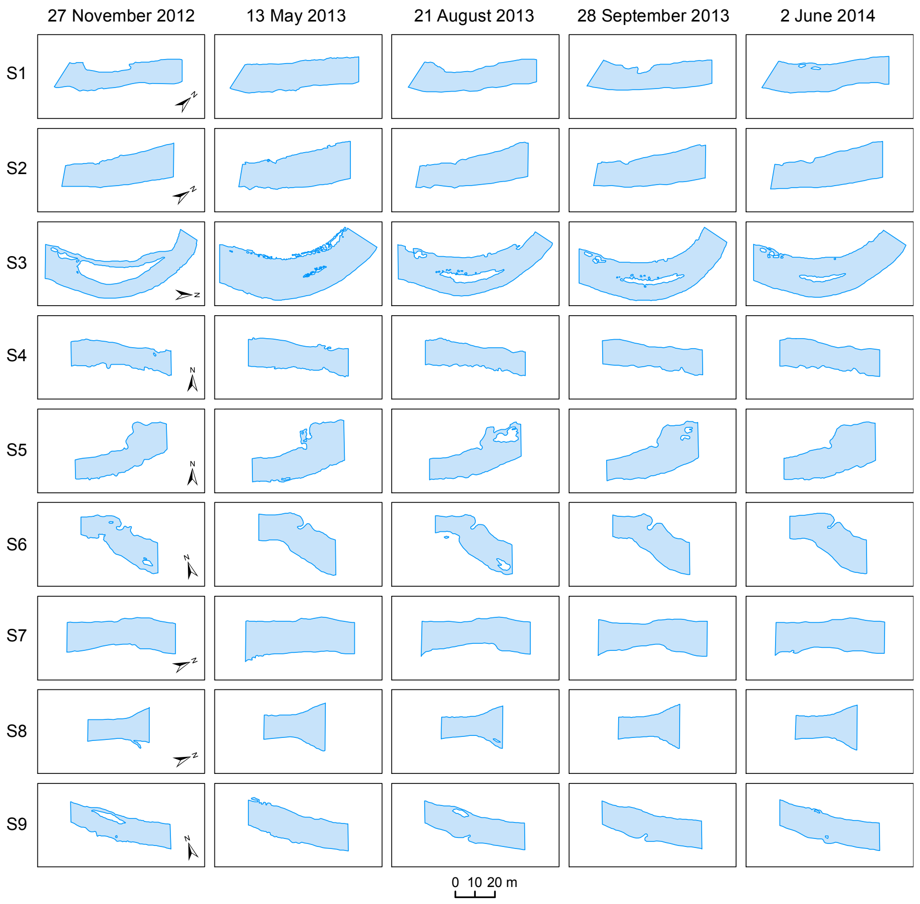

Figure 8. The water extents in the analyzed sections in the Ścinawka channel in Gorzuchów on: 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014. Numbers of the sites (on the left) are the same as in Fig. 3.

Table 1. Vertical flight parameters during the UAV missions on 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014.

Date and number of flight	Planned height above takeoff location [m]	Takeoff altitude [m a.s.l.]	Maximum height [m]	Mean height [m]	Maximum altitude [m a.s.l.]	Mean altitude [m a.s.l.]	Maximum altitude WGS84 [m]	Mean altitude WGS84 [m]
27/11/2012 (1)	109.0	296.4	113.6	109.2	410.0	405.6	451.0	447.5
27/11/2012 (2)	109.0	296.5	112.4	109.1	408.9	405.7	453.5	447.9
13/05/2013 (1)	109.0	297.7	116.0	108.9	413.7	406.6	456.2	449.9
13/05/2013 (2)	109.0	299.8	118.1	109.0	417.9	408.8	458.6	450.4
21/08/2013 (1)	109.0	301.1	117.0	108.2	418.2	409.3	458.8	450.6
21/08/2013 (2)	109.0	295.2	115.0	108.9	410.2	404.1	450.0	444.8
27/09/2013 (1)	109.0	294.5	114.8	108.8	409.3	403.4	452.7	455.5
27/09/2013 (2)	109.0	295.5	114.5	109.1	410.0	404.6	454.3	446.4
02/06/2014 (1)	109.0	305.3	115.3	108.3	420.7	413.6	452.7	461.0
02/06/2014 (2)	109.0	294.3	114.3	108.9	408.6	403.1	451.1	445.4

c1

[c1] Followin Reviewers' comments and our responses to the remarks offered by the Referees, the table below has been added in order to juxtapose flight parameters. It is now well seen that UAV flights were performed with the similar parameters. As a consequenc of incorporatin the new table, the numbers of subsequent tables has been modified (+1).

Table 2. Water levels in Gorzuchów during the UAV flights on 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014 along with description of hydrograph features and stage classification.

Date	Water level in centimetres at UAV flight	Phase or shape of hydrograph at or around UAV flight	Stage classification based on Fig. 7
27/11/2012	58	flat	low stage
13/05/2013	121	peak flow	high stage
21/08/2013	50	flat	low stage
27/09/2013	67	flat (uncertain)	mean stage
02/06/2014	89	recession limb	intermediate stage

Table 3. Areas, fractions and logarithms, calculated according to Section 3, at dissimilar sites and on different dates of UAV flights.

Site	27/11/2012			13/05/2013			21/08/2013			27/09/2013			02/06/2014		
	Area	Fraction	Logarithm	Area	Fraction	Logarithm	Area	Fraction	Logarithm	Area	Fraction	Logarithm	Area	Fraction	Logarithm
1	650.35	0.1740495	-1.748415	835.01	0.2234691	-1.498482	716.41	0.1917288	-1.651673	721.52	0.1930964	-1.644566	813.29	0.2176563	-1.524838
2	790.08	0.1894899	-1.663420	904.56	0.2169464	-1.528105	794.73	0.1906051	-1.657551	811.13	0.1945384	-1.637125	869.01	0.2084202	-1.568199
3	1025.64	0.1605611	-1.829081	1559.12	0.2440759	-1.410276	1193.84	0.1868923	-1.677223	1288.73	0.2017471	-1.600741	1320.52	0.2067237	-1.576372
4	577.83	0.1873954	-1.674534	664.41	0.2154741	-1.534915	582.58	0.1889359	-1.666348	602.13	0.1952761	-1.633341	656.53	0.2129185	-1.546846
5	651.93	0.1793238	-1.718562	804.13	0.2211889	-1.508738	628.35	0.1728378	-1.755402	747.58	0.2056339	-1.581658	803.50	0.2210156	-1.509522
6	545.03	0.1820140	-1.703672	654.68	0.2186319	-1.520366	542.64	0.1812159	-1.708066	602.50	0.2012062	-1.603425	649.59	0.2169320	-1.528171
7	778.58	0.1891130	-1.665411	931.68	0.2263002	-1.485893	779.56	0.1893510	-1.664153	800.30	0.1943886	-1.637896	826.89	0.2008472	-1.605211
8	369.24	0.1807900	-1.710419	456.38	0.2234561	-1.498540	385.50	0.1887513	-1.667325	403.04	0.1973394	-1.622830	428.21	0.2096633	-1.562252
9	584.76	0.1751838	-1.741920	724.80	0.2171373	-1.527225	658.02	0.1971312	-1.623886	678.10	0.2031468	-1.593826	692.30	0.2074009	-1.573102

Area – water surface area in m^2
Fraction – water surface area as a fraction of total area of water-covered terrain at a given site (sum from all dates)
Logarithm – natural logarithm of fraction

Table 4. P-values of a few statistical tests applied to input data for the UAV flights on 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014.

Test	P-value for a given observation				
	27/11/2012	13/05/2013	21/08/2013	27/09/2013	02/06/2014
Independence (Ljung-Box)	0.059	0.092	0.444	0.713	0.828
Normality (Shapiro-Wilk)	0.208	0.013	0.178	0.321	0.863
Symmetry (D'Agostino)	0.265	0.076	0.247	0.758	0.979
Mesokurticity (Anscombe-Glynn)	0.193	0.017	0.132	0.171	0.759

Table 5. P-values of the Fisher's test applied to check if variances of input data are the same in each pair of the UAV observations.

Date	P-value of Fisher's test between two observations				
	27/11/2012	13/05/2013	21/08/2013	27/09/2013	02/06/2014
27/11/2012	1.000	0.385	0.373	0.030	0.144
13/05/2013	0.385	1.000	0.980	0.170	0.536
21/05/2013	0.373	0.980	1.000	0.178	0.552
27/09/2013	0.030	0.170	0.178	1.000	0.440
02/06/2014	0.144	0.536	0.552	0.440	1.000

Table 6. P-values of asymptotic and bootstraped the Student's t-test applied to identify significant differences between water surface areas observed on 27/11/2012, 13/05/2013, 21/08/2013, 27/09/2013 and 02/06/2014. Grey boxes indicate statistically significant transitions.

	27/11/2012		13/05/2013		21/08/2013		27/09/2013		02/06/2014	
	Asymptotic	Bootstrapped	Asymptotic	Bootstrapped	Asymptotic	Bootstrapped	Asymptotic	Bootstrapped	Asymptotic	Bootstrapped
27/11/2012	0.5000000	0.5000000	0.0000000	0.0000000	0.0318682	0.0240133	0.0000377	0.0000100	0.0000002	0.0000000
13/05/2013	1.0000000	1.0000000	0.5000000	0.5000000	1.0000000	1.0000000	0.9999997	1.0000000	0.9978170	0.9987431
21/08/2013	0.9681318	0.9769138	0.0000000	0.0000000	0.5000000	0.5000000	0.0006099	0.0002194	0.0000007	0.0000001
27/09/2013	0.9999623	0.9999903	0.0000003	0.0000000	0.9993901	0.9997737	0.5000000	0.5000000	0.0000703	0.0000258
02/06/2014	0.9999998	1.0000000	0.0021830	0.0012121	0.9999993	0.9999999	0.9999270	0.9999738	0.5000000	0.5000000

Student's t-test with right-sided alternative; in Bootstrap $B = 10000$; gray boxes indicate statistically significant ($\alpha = 0.01$) changes in water surface areas.