ABSTRACT
In Peru, there are not many aqueduct systems, only in Nasca region. They are popularly known as “puquios”, hidden in the dry landscape. Most of them are around the city of Nasca known mainly for the nearby famous Nazca lines and geoglyphs. According to some theories they were built by pre-Hispanic civilization, but others doubt that. However, there is no doubt that they were constructed to provide water to the people living in the dry landscape along the Peruvian coastline, where the lack of water is a typical phenomenon. The construction of aqueducts is often connected to climatic changes after 400 AD. Some of these systems are still in use and provide fresh drinking water or water for irrigation of fertile fields in the neighbourhood. The aim of our research was to document and map aqueduct systems in Nazca region. Five aqueduct samples were selected, which describe the various types of the systems – aqueducts in both good and bad condition, open trenches, systems with circular or rectangular-shaped access holes. These selected sites were documented by a RPAS. The acquired data was processed to an orthophoto and a digital surface model (DSM). The outputs help to document the variety in construction of these systems and provide a better understanding of their function before many of them disappear forever.

Introduction
Peru is very rich in cultural monuments commemorating defunct civilizations. Many meritorious research and documentation works on cultural monuments were carried out by German experts, in the last two decades, such as the academic research called the “Nasca project” (since 1995) can be mentioned (Nasca project, 1995), carried out by HTW Dresden, Germany (Richter & Teichert, 2011; Richter, 2007; Richter, Teichert, Pavelka, & Cerveny, 2017). Based on a long-term cooperation of the Faculty of Civil Engineering, Czech Technical University in Prague with HTW Dresden and Maria Reiche Association in Dresden, several expeditions to Peru were held with Czech participation (experts and students in 2006, 2008, 2012 and 2016). Most expeditions were focused on the documentation and mapping of world-famous lines and geoglyphs on the Nasca Plain, such as on nearby located sites with petroglyphs and other valuable historical sites. A number of publications and books emerged from this research (Pavelka, Teichert, Richter, 2008, 2011, 2013). In 2016, it was noted that more area measurements of geoglyphs and lines apparently cannot be made with the current equipment and financial support. Therefore, based on modest finances, it was decided to focus on lesser-known objects and their simple documentation; as an interesting object for research, aqueducts were selected especially around Nasca city. It should be noted that this was a small expedition with limited resources of technology and finance focused on simple mapping using GNSS, RPAS a terrestrial photography.

The Peruvian coastal area is relatively dry and there is a lack of perennial rivers. Extreme weather such as long-lasting drought or intense precipitation, connected to climate change, has caused collapse of a number of civilizations. There is no doubt that the retrieval of water has been the main issue for every civilization which settled in this area. The aqueducts in the Nazca region belong to the oldest irrigation systems in the Andes; they were important technical constructions for the serving of vital water. Aqueducts were built most likely by the Paracas culture (between approximately 800 BCE and 200 BCE) and later by the Nazca culture (between approximately 200 BCE and 650 AD). More about the dating of the Nazca irrigation system can be found in (Clarkson & Dorn, 1995; Barnes, 1992; Schreiber, Rojas, & Lancho, 2003). The formations popularly called “puquios” represents the most typically visible part of the irrigation systems observed in the Nazca region. These systems usually consist of underground canals, open trenches and basins. A typical system starts with a horizontal tunnel which intersects with the underground aquifer. These tunnels are excavated laterally or constructed by digging an open trench and covering it after building the walls of the tunnel (Figure 1). The system ends with an open trench or basin allowing access
to the water for drinking, bathing, washing clothes, and for agricultural use (Proulx & Rickenbach, 1999; Schreiber & Lancho, 1995). The “puquios” are funnel-shaped holes, which provided access to the water in the tunnels. The spiral holes could also funnel wind into the aqueduct system to keep the water moving (Lasaponara & Masini, 2012). In general, the word “puquio” means “well” or “spring”.

The name “puquio” is often used popularly in Peru for the whole aqueduct, sometimes only for the “access hole” (in Spanish called “ojo” – “eye”). Therefore, the terms “aqueduct” and “access hole” are used for unambiguous determination.

It is interesting that analogical solution for utilization of underground water sources can be observed in different places around the world, e.g. in northern Iraq near the town of Makhmour (Figure 2) (Kopanias, MacGinnis, & Ur, 2015; Matoušková et al., 2016; Šedina, Pavelka, & Housarová, 2016) and in China (Luo et al., 2014, 2017).

Study areas

In 2016, an expedition based on an academic collaboration between HTW Dresden and Czech Technical University in Prague was realized as a part of a long-term German project called Nasca. The aim in this case was the documentation of all the existing aqueducts in this region and the measurement of some of them with RPAS to get 3D models of aqueducts and their closest surroundings. Five sites were selected for RPAS measurement: Cantalloc (next to the town of Nasca) – the most well-known touristic site with still functional aqueduct system, Orcona – an almost unknown site and in a greater distance from the town of Nasca), Santa Maria and San Carlos – two touristically unknown sites with systems used nowadays for fields irrigation, and the site Gobernadora, where the section with access holes of the aqueduct system was destroyed and only the trench at the end of the system and the basin (cocha) remained. The selected sample describes the various types of the systems – aqueducts in both good and bad condition, open trenches, and systems with circular or rectangular-shaped access holes. Those which are not in use are in a bad condition, and it is only a matter of time when they will disappear forever.

Data and methods

The aim of the project is to document the variety and geometry of the construction of these unique water management systems and provide a better understanding of their function before many of them disappear forever. This includes not only the direct known access holes, but also the whole aqueduct with nearby neighbourhood. All the existing aqueducts were measured with Garmin GPS to create the basic map (Figure 3). The GCP’s for RPAS were signalised by simple crosses from stones and by natural formations and after this measured with DGPS.

After measurement, thematic maps of selected areas were created based on these observations. Five aqueducts were documented in detail by RPAS. During expedition in 2016, only the RPAS eBee from the Swiss company SenseFly was used (Figures 4 and 5). This fixed wing RPAS system of an ultra-light construction included changeable camera sensors. In 2016, there were five camera types at the disposal of the Czech Technical University in Prague: multispectral camera (MultiSpec4C), thermal camera (ThermoMap), NIR – near-infrared camera (Canon S-110-NIR and Canon ELPH 110 HS-NIR), red-edge

Figure 1. Schema of Nazca irrigation systems, based and modified on (Proulx & Rickenbach, 1999).
Figure 2. Aqueducts in the world: Makhmour/Iraq; orthophoto based on observation acquired by RPAS eBee, pixel size – 4 cm; 2015, (photo K. Pavelka, 2015). China (Google Earth, N 42° 45´ 34´´, E 88° 34´ 51´´).

Figure 3. Thematic map of aqueducts in Nazca (Preussler, 2017).

Figure 4. Spectral response of NIR and RGB cameras (Canon ELPH 110 HS-NIR, Canon IXUS 127 HS, SenseFly materials).
camera (Canon S-110-RE) and classical RGB camera (Canon IXUS 127 HS) for use. For this project only cameras acquiring images in the near infrared band (Canon ELPH 110 HS-NIR) and in the visible range (RGB, Canon IXUS 127 HS) were used. The NIR camera was used for the potential detection of unknown or defunct objects using vegetation indices or crop marks based on high reflectivity of healthy vegetation in NIR. This camera takes images in false colour (green, red and near-infrared channel), in which healthy vegetation is in red (Figure 5). Of course, there are other types of RPAS like multicopters, which can be may be more suitable for mapping of small areas. However, we operated in Peru only with fixed wing RPAS for transportation and other technical reasons; there was not a scope and funding for the transport of another RPAS. A very important fact was that fixed wing EBeé flights were absolutely autonomous, and it wasn’t so noisy like multicopters (which causes unwanted publicity and interest from people) and it is better for large areas (we overflighted other areas during the expedition in 2016, not only aqueducts). On the other hand, whit fixed wing it wasn’t possible to take oblique photos, which would have been good for the modelling of aqueducts access holes – from an altitude of about 130 m, with fixed wing, the detail in access holes is not sufficient (for this reason a set of terrestrial images with high detail from access holes was taken). However, we didn’t have other instruments or time; and so it was difficult to get an official permit for imaging from the Nasca municipality and collaboration with the municipal police escort.

Results and discussion

For the data processing, well known software’s were used: Agisoft Photoscan and Pix4D. Both software’s work fully automatically, use the bundle adjustment and the image correlation technology for image data processing. Aerial images acquired during a number of flights were used for the orthophoto (GSD - geometrical resolution up to 4 cm, Figure 6), the Digital Surface Model (DSM) and the difference Digital Surface Model (dDSM) production (Figure 7). The dDSM can be created by the following workflow (processing was done in ArcGIS software): the original DSM is smoothed using digital filter (for example, applying a flowing 3 × 3 or bigger image mask, where for the central mask pixel a new value is inserted as an arithmetic average of the entire mask) and the smoothed model is subtracted from the original one. The resulting new model highlights small terrain variations, which are normally not visible or hardly to detect. This approach is often used in archaeology for the visualisation of small terrain structures or features.

For all five aqueducts the DSM were processed such as the orthophoto. All image results were geocoded by using on-board GNSS and IMU primarily and during the processing by precisely measured ground control points (GCP’s) measured with a D-GNSS system Leica with some decimetres accuracy after post-processing. However, during photogrammetric image processing using bundle adjustment, it was found that some GCPs have gross errors in meters (they could not be used). These problems have already occurred during field measurements, some measurements had to be
repeated, and the reason for the errors were not found (may be, the probable reason was an influence by the radio link of the nearby airport). Fortunately, an excess of GCP points were measured. The final accuracy of the transformation of the results into the reference frame was estimated in decimetres.

The aqueducts are similar in construction and use, but each is a little different – especially the access holes. Some access holes are spiral-shaped (Cantalloc), other rectangular with steps (Orcona, San Carlos), and some are wells, later reinforced with wooden beams (Santa Maria). All these aqueducts are similar in dimensions (length), but not identical. Interestingly, the Cantalloc aqueduct has a total of 20 access holes (19 spiral access holes), of which 15 rotate to the left and 4 to the right. Unity or similarity with the spirals on Nazca Plain has not been proven.

**Table 1.** For information: depth of water in the access hole (numbering from the first in landscape, from the beginning).

| Access hole Nr. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | ... | 14 |
|----------------|------|------|------|------|------|------|------|-----|----|
| San Carlos     | -    | 5,9  | -    | 5,2  | -    | 4,0  | -    | 4,0 |    |
| Santa María    | -    | 5,2  | 6,1  | -    | 4,6  |      |      |     |    |

The DSM created by RPAS is interesting, but individual access holes don’t have the necessary detail. For this reason, all access holes were photographed by hand (manually) from the surface. 3D models (DSM) of the aqueducts based on RPAS images were complemented by ground-based images to get a more detailed model of a well-preserved aqueduct (Figure 8). More than 15 aqueducts were documented in detail from the ground, while only five of the above-mentioned aqueducts were photographed from RPAS. In this case, both image sets (from RPAS and ground-based) were processed using Pix4D and Agisoft Photoscan software. The datasets were processed separately. A common processing of both datasets was not possible due to high differences in image scales and image orientations (of both RPAS and ground-based image sets). Point clouds were generated from the datasets of oriented images; when using RPAS, with terrestrial photos, in this case a point cloud represents always one access hole. The point cloud sampling distance was approximately 70 mm in RPAS-based point cloud and 15 mm in ground-based point cloud. The detailed point cloud of each access

![Figure 7](image1.png)

**Figure 7.** The aqueduct “Santa María” (Valle de Taruga), geocoded DSM and differential DSM (dDSM), RPAS eBee, based on approximately 90 images.

![Figure 8](image2.png)

**Figure 8.** Aqueduct near the town of Nasca (Cantalloc); image from RPAS.
hole documented from the ground contained anywhere from 4 to 10 million of points.

After creating basic separately processed models (point clouds, Figure 9) all models were joined to one model (one-point cloud). Geomagic Studio was used for the registration of RPAS and ground-based point clouds. The standard workflow for point cloud merging in Geomagic Studio is based on manual identification of identical points in both point clouds for the preliminary transformation and later application of the ICP (Iterative Closest Point) method for transformation adjustment. This workflow failed in this case due to the high difference in the level of detail in both datasets. The correct scale of the ground-based model/point cloud was set by using a measured distance acquired from an RPAS-based point cloud (the scale of the RPAS-based model was set by using GCPs – ground control points observed by GNSS with a final absolute accuracy in decimetres). Once both models had the same scale, the transformation of the ground-based model to the coordinate system of the RPAS-based model was accomplished. The transformation was done manually, then an expert observed the models from different views and continuously changed the transformation parameters, until the models did not fit to each other in all views (Figures 10, 11).

If we want to define the absolute accuracy of the aqueduct model, merged from aviation and ground measurements, it will not be easy. The model from aerial images has a GSD of 4–5 cm, with GCPs having an absolute accuracy of about 5 cm in position and 10 cm in height. Due to inaccurate GNSS measurements and a small number of GSPs along the aqueduct, the error may be even greater.

But that does not affect the results. With the result there is an important detail of the model, that has been significantly improved by merging with ground measurements of the individual access holes (GSD of which reached 15 mm and the overall accuracy of each access hole is in the order of cm). When we realize that these are bulk boulders, it is certainly sufficient. The model has a documentation character and can be used to visualize and realize subsequent experiments. The

![Figure 9](image)

**Figure 9.** (a)–(c) Access hole Nr.1 – Cantalloc (first from the left). (a) textured point cloud of access hole with camera stations (b) front view of the access hole (c) oblique view on textured 3D mesh. All models were created using Agisoft Photoscan.

![Figure 10](image)

**Figure 10.** Merging of RPAS and terrestrial-based point clouds (Geomagic Studio), top view.
resulting model (RPAS and ground-based together) offers a complex view on the entire situation of the documented site as well as detailed description of the most interesting parts – access holes.

Conclusion

Overall, 10 flights were performed and five aqueduct systems were documented in detail using RPAS within a resolution (GSD) of 4–5 cm during the expedition in 2016. 3D models of the documented sites were created based on a combination of RPAS and ground-based images.

The major aim of this project was the documentation of valuable technical monuments, and the creation of precise maps and 3D models, which can help understand the reasons and the technology of its construction. The transformation of ground- and RPAS-based data into one coordinate system was challenging, however, the effort was rewarded. Some aqueducts were restored, some were, even after many centuries still in use in agriculture, and totally destroyed aqueducts were found as well. Despite all the efforts of the last decades, it is still not clear, how exactly these water management systems were conducted.

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