Using terrestrial laser scanning in inventorying of a hybrid constructed wetland system

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ABSTRACT

The goal of this paper was to evaluate the possibility of using terrestrial laser scanning (TLS) for inventorying of a hybrid constructed wetland (CW) wastewater treatment plant. The object under study was a turtle-shaped system built in 2015 in Eastern Poland. Its main purpose is the treatment of wastewater from the Museum and Education Centre of Polesie National Park. The study showed that the CW system had been built in compliance with the technical documentation, as differences between values obtained from the object and those given in the design project (max. ± 20 cm for situation and ±5 cm for elevation) were within the range defined by the legislator. It was also shown that the results were sufficiently precise to be used for as-built surveying of the aboveground elements of the CW system. The TLS technique can also be employed to analyse quantitative changes in object geometry arising during long-term use (e.g. landmass slides or erosion), the identification of which can help in selecting the hot-spots at risk of damage and thus restore the object to its original state as well as prevent new changes.

Key words | as-built survey, hybrid constructed wetland, inventorying, terrestrial laser scanning, wastewater treatment plant

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INTRODUCTION

Recently, significant growth has been observed in the use of constructed wetland (CW) systems to treat household wastewater in rural, non-built-up areas, in which conventional wastewater treatment plants and sanitary sewers are uneconomic (Brix & Arias 2005a, 2005b; Vymazal 2011; Jóźwiakowski *et al.* 2015). The first CWs, used in the 20th century, were one-stage systems, but wastewater treatment was not effective enough in the case of these systems as demonstrated by numerous studies. Such one-stage CWs have been proven to ensure only sufficient removal of total suspended solids and organics, with limited removal of biogenic substances (Albuquerque *et al.* 2009; Gajewska & Obarska-Pempkowiak 2009; Jóźwiakowski *et al.* 2017; Mucha *et al.* 2017). High effectiveness of wastewater treatment can be achieved using hybrid CW systems (Gajewska 2011; Gajewska & Obarska-Pempkowiak 2011; Gajewska *et al.* 2015; Gizińska-Górna *et al.* 2016), a solution that has been used in many branches of industry (Vymazal 2014). For example, hybrid CWs have been used in the treatment of leachate from municipal landfills (Wojciechowska & Obarska-Pempkowiak 2008; Lavrova & Koumanova 2010; Wójcik 2010) and in sludge dewatering (Nielsen 2003; Uggetti *et al.* 2010).

Hybrid CW systems have recently been built in protected areas, e.g. in national parks (Masi *et al.* 2007; Osaliya *et al.* 2011; Jóźwiakowski *et al.* 2014, 2016; Sanchez-Ramos *et al.* 2015) or in mountain areas (Jucherski *et al.* 2017). They are mainly used to treat domestic wastewater from museums, forester lodges or tourist hostels. In addition, some of them, for educational or promotional purposes, are designed to resemble natural objects, e.g. a fir tree, a turtle (Jóźwiakowski *et al.* 2014, 2016) or a butterfly (Brix *et al.* 2011). The construction of systems of any kind requires geodetic supervision including post-construction monitoring of compliance with the design project. Hybrid CWs are often characterised by a complex geometry, and the use of traditional geodetic measuring techniques in their case is often complicated and time- and labour-consuming, but still more affordable as far as the

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prices of measuring devices are concerned (Angeli *et al.* 2000; Malet *et al.* 2002). Recent years have seen a growth in the popularity of terrestrial laser scanning (TLS), a technique used for measuring objects characterized by a complex geometry, which allows specialists to collect massive amounts of data in a comparatively short time. This method can be applied, among others, in the monitoring of geomorphological processes (Prokop & Panholzer 2009; Afana *et al.* 2010; Kociuba *et al.* 2014), condition control of hydrotechnical structures (Alba *et al.* 2006), virtualization of a city environment (Lim & Suter 2009) or assessment of spatial structure of vegetation and biomass estimation (Feliciano *et al.* 2014; Richardson *et al.* 2014; Luo *et al.* 2015; Olsoy *et al.* 2016).

The goal of this paper was to evaluate the possibility of using the TLS method for as-built surveying of a hybrid CW wastewater treatment plant.

MATERIALS AND METHODS

Characteristics of the experimental setup

A hybrid CW system built in 2015 in Stare Załucze, Poland ($\varphi = 51^\circ\ 23'\ 44''$ N, $\lambda = 23^\circ\ 7'\ 19.8''$ E) (Figure 1) was investigated using TLS, a remote data acquisition technique.

The capacity of the system was 1 $m^3\ d^{-1}$, and its main purpose was to treat wastewater from the Museum and Education Centre of Polesie National Park. The main features of the system are shown in Table 1.

The system comprised two sections. The first section was where wastewater was mechanically cleaned. The second section was a two-stage CW system (HF + VF) in which wastewater was treated using biological methods. The entire system consisted of a three-chamber primary settling tank with an integrated sludge-dewatering installation (Polish patent no. 218897) (Jóźwiakowski 2015), a wastewater pumping station, a 42.4 m^2 vertical flow bed (I) with reed mannagrass (*Glyceria maxima* (Hartm.) Holmb.), a four-part horizontal flow bed (II) with a total area of 55.2 m^2 planted with *Phragmites australis* (Cav.) Trin. ex Steud, a phosphorus-removing filter, and an infiltration pond serving as a receiver of treated wastewater (Figure 2). The main body of the system, containing beds with a wastewater distribution installation (a distributing and collecting drainage system, collecting wells) was a turf-strengthened earth structure of two dykes – an internal and an external one. The latter, 0.6 m tall, gave the wastewater treatment plant the shape of a turtle (Polesie National Park is running a restoration programme for the European pond turtle). The internal, ellipse-shaped dyke (0.5 m height) was in the centre of the system and

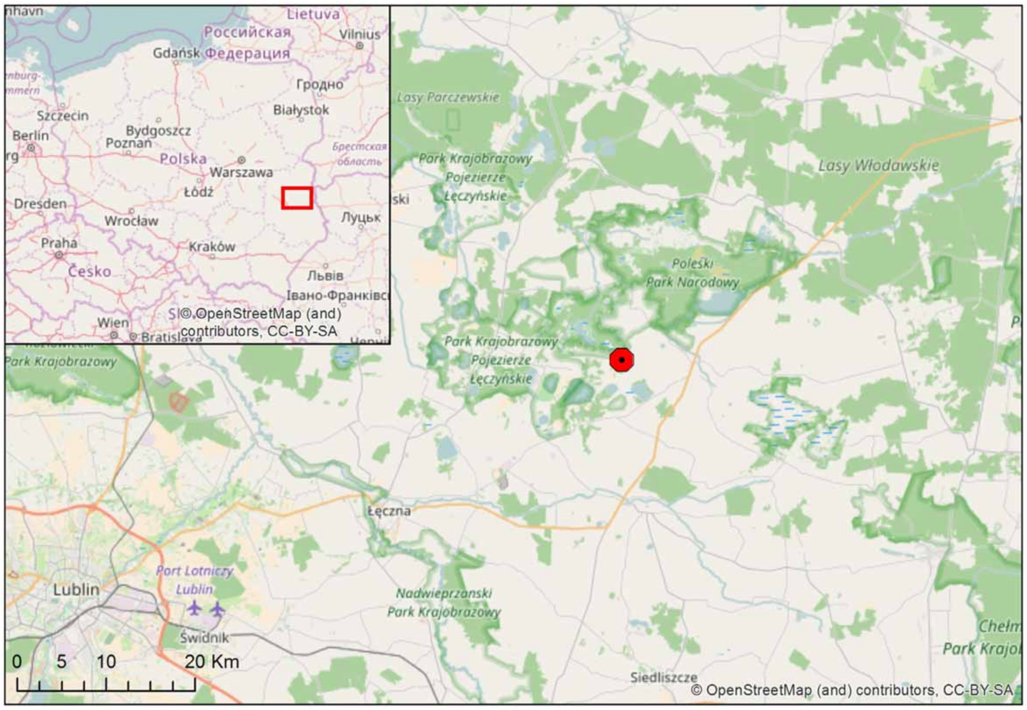

Figure 1 | Location of the hybrid constructed wetland system.

Table 1 | The main technological parameters of analysed hybrid constructed wetland system (HCW)

Parameters	HCW in Polesie National Park
Number of person equivalent	10
Flow, Q [$m^3 \cdot d^{-1}$]	1.0
Active capacity of the septic tank. V [m^3]	3.0
Mannagrass bed [m^2]	I – 42,4 (VF)
Reed beds [m^2]	II - 4 x13,8 (HF)
P-filter for phosphorus removal [m^3]	0.5

surrounded bed no. I. Four parts of bed no. II were located between the two dykes. The maximum elevation of the system was approx. 1.1 m above ground level (external dyke crown). The slopes of the dykes were very steep, with inclinations from 1:1 to 1:0.5 (Malik *et al.* 2015).

Experimental procedures

Study data in the form of a point cloud were acquired using a Topcon GLS 2000 scanner set to eight separate scanning locations (Figure 3). The device is capable of capturing a full scan (360°) horizontally and 270° vertically, within a range of up to 250 m. Scanning density for a distance of 150-m was ±3.5 mm. The XYH coordinates of the scanning locations (set to capture the whole object) were collected using the GNSS-RTN technique (with corrections obtained from TPINETpro reference stations, forming a horizontal geodetic control network) and a Topcon HiPer V device. The coordinates were registered in the National Geodetic Reference System PL-2000 (zone 8). The altitudes of the locations were set in the Kronstadt 60 system using the national vertical control network and precise geometric levelling with digital level Leica DNA 03 and an Invar levelling staff. The described approach and methods are common in cases of post-construction inventorying and are in accordance with technical standards of elevation and situational measurements (Journal of Laws of 2011, No. 263, item. 1572). The eight separate point clouds were combined and cleaned manually using Topcon ScanMaster software. The clouds were joined using well-visible markers placed in selected locations in the field during the scanning process. The final result, at this stage, was a digital, three-dimensional (3D) model of the system (Figure 3). This 3D model was then used to generate longitudinal and transverse sections which were processed and analysed using ZWCad software. An additional 3D model was created in ArcGIS programme using a triangulated irregular network (TIN).

RESULTS AND DISCUSSION

The numeric data collected during field work were processed in order to check the usefulness of TLS as a tool for as-built surveying of the hybrid CW system under study.

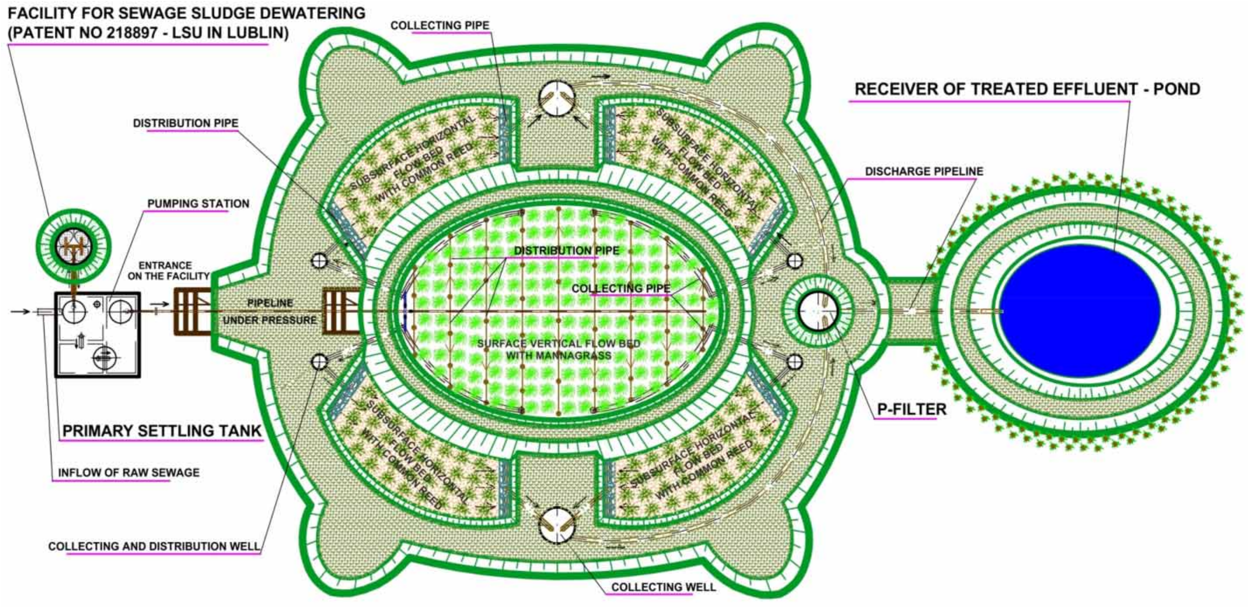

Figure 2 | The hybrid constructed wetland wastewater treatment plant in Stare Załucze (Malik *et al.* 2015).

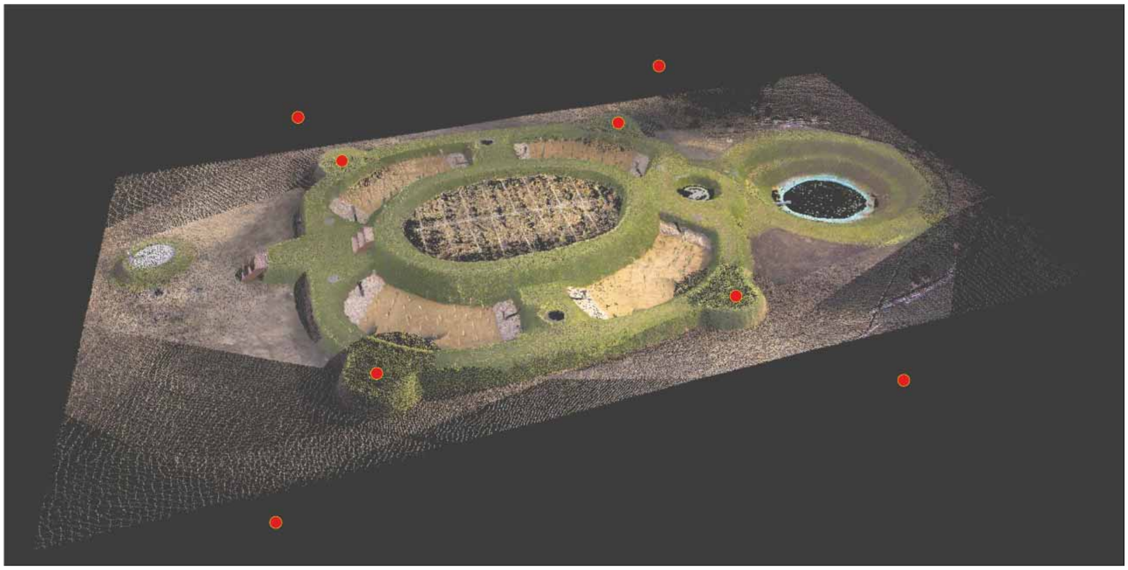

Figure 3 | Visualisation of the combined point cloud with scanning locations (marked with grey dots).

Data preparation

3D data were used to assess the system's geometry based on sections traced through a point cloud. Such sections are typically used in documentation of engineering objects (Kašpar *et al.* 2004). To generate sections, eight separate point clouds in *.sta* format were imported into Topcon ScanMaster. The clouds were combined, cleaned manually and exported to . *sdf* file format. The three-dimensional model of the sewage treatment plant was a basis on which locate section lines were planned. 17 longitudinal and 31 transverse sections were done. The main longitudinal section was planned along the main axis of symmetry while the main transverse section crossed bed no. I. All the remaining sections were done at 1 m intervals. The sections are shown in Figure 4. Next, each section was saved in *.dxf* format and imported into ZWCad programme.

Measurements and data assessment

The sections were then measured to determine the actual metric dimensions of the scanned structural elements of the HCW system. Additional measurements were done using Topcon ScanMaster programme. The results were compared with corresponding data from the technical documentation of the system's design project. Both projected and

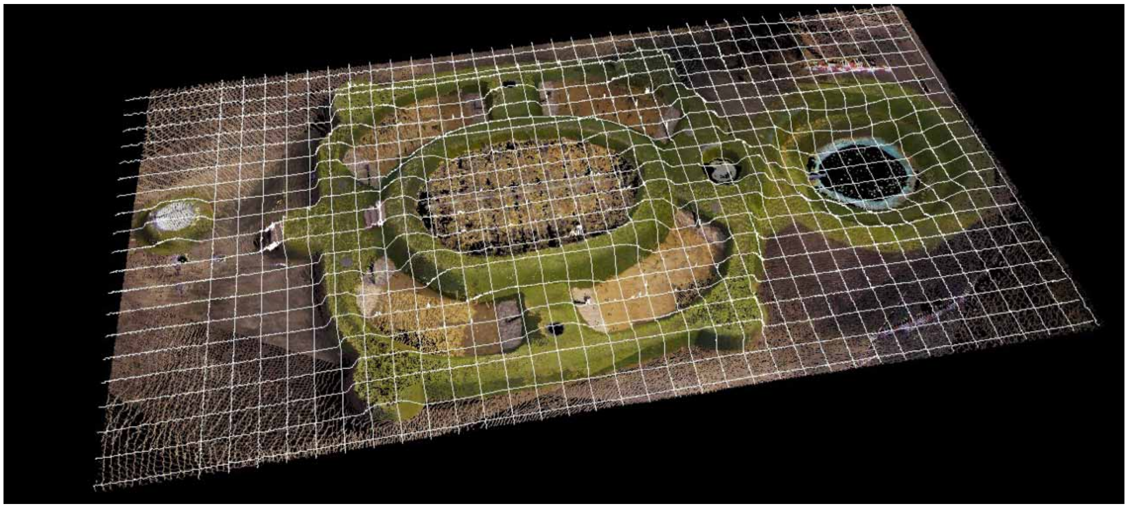

Figure 4 | Longitudinal and transverse sections draped over the 3D model of the system.

Table 2 | Construction parameters of analysed hybrid constructed wetland system (HCW)

Parameters	Unit	Measured value	Designed value	Difference
Total length of HCW	m	30.50	29.06	1.44
Total width of HCW	m	16.00	14.50	1.50
Length of level I	m	8.94	8.98	0.04
Total length of level II	m	23.00	23.20	−0.20
Width of level I	m	6.00	6.00	0.00
Width of level II	m	2.50	2.40	0.10
Altitude of level I	m a.s.l.	173.85	173.85	0.00
Altitude of level II	m a.s.l.	173.38	173.35	0.03
Altitude of earth dykes crowns I	m a.s.l.	174.27	174.25	0.02
Altitude of earth dykes crowns II	m a.s.l.	173.75	173.70	0.05
Area of bed I	m^2	42.30	42.40	−0.10
Area of bed II	m^2	54.80	55.20	−0.40
Total area of beds	m^2	97.10	97.60	−0.50

measured values for the system are shown in Table 2. Figure 5 shows an example of a section (the main longitudinal section). The values obtained showed that there were discrepancies between the design project and the real object. The maximum horizontal (distance) error was no greater than ±20 cm, with the exception of the crowns of both the internal and the external dyke for which the difference was approximately 40 cm. This, however, cannot be regarded as a construction error. The investor, Polesie National Park, wanted the system (located next to the education centre) to be a part of the exhibition accessible to visitors. The idea was that innovative, university-born, ecological technologies of sewage treatment could this way be popularised in society. The width of the earth dykes specified in the design project (40 cm) would be too small to make them safely and easily accessible and could lead to a destruction of the dykes themselves. That is why the dykes were widened by 40 cm (to about 80 cm) during the construction of the system. It caused the increase of total length and width by 1.44 and 1.50 m, respectively, compared to the project (see Table 2), but, despite this, the other parameters remained unchanged. In the case of the height, the differences observed were much smaller – up to ±5 centimetres. The only exception was the ordinate of the chemical phosphorus-removal P-filter top, which was 173.40 m a. s. l. at the time of the survey, that is 35 cm lower compared to the design project. This difference was the result of using a corrugated PVC pipe, 1.1 m in diameter, which was only 1.95 m long. As it was important to keep the designed ordinate values of both P-filter bottom and the outflow of treated wastewater to pond unchanged, the plate had to be fitted lower than planned. By using TLS, we also discovered differences between the western and the eastern dyke – the elevation of the crown of the former was 5 cm higher compared to the crown of the eastern dyke. This means that the construction process was not precise at the

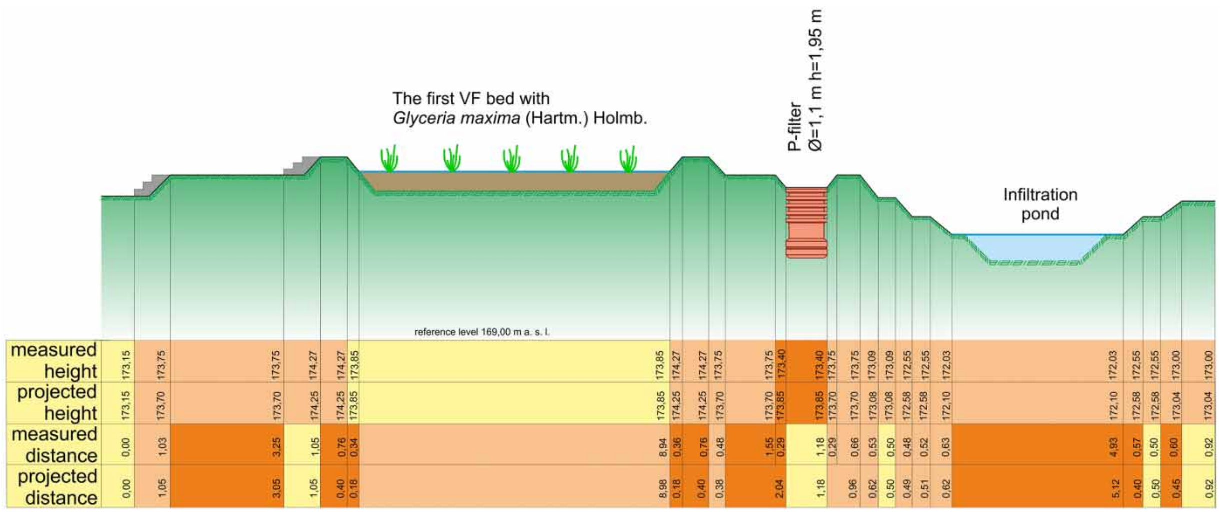

Figure 5 | Main longitudinal section with measured and projected values in metres for each element (white indicates no differences, light grey – differences of 10 cm or less and grey – differences of more than 10 cm).

stage of levelling. This, however, did not pose any danger to the operation of the system and the system itself.

The comparison of measurement results with data from the technical documentation of the CW system showed that the actual state of the structure (with the exception of the previously mentioned P-filter and dyke crowns) was in compliance with this documentation. According to the Regulation of the Polish Ministry of Interior and Administration of 9th November 2011 (Journal of Laws of 2011, No. 263, Item 1572), the accuracy of localisation of prominent, permanent features, especially earth structures such as ditches, banks and dykes, should be 0.3 m for situational and 0.1 m or less for elevation measurements. Having these precision values defined, it is justified to claim that real dimensions of the construction are within a range given by the legislator.

3D analyses

The next step in the processing of the 3D data was to create a TIN model in ArcGIS programme. The point cloud in *.las* format was exported from Topcon ScanMaster software and imported into ArcMap of the ArcGIS package. The resulting file was a discrete vector point dataset. To transform it into continuous TIN information, a conversion was done, using 3D Analyst Tool. A TIN model is a continuous vector-based representation of terrain, made up of triangles whose vertices are high-density points with attributes of elevation. This kind of model is a very accurate virtual representation of the actual shape of the system (Figure 6). The main goal of generating a TIN in the present study was to visualise the investigated CW system and obtain a high-resolution raster digital elevation model (DEM) of it to be used for long-term spatio-temporal monitoring of object deformation using TLS. The idea of TLS monitoring involves generating a series of models from TLS scanning data collected over time. Subtraction of one model from another ($DEM_2 - DEM_1$) will provide information about changes in the system's geometry resulting from its constant operation. This kind of monitoring is successfully used in quantitative assessment of erosion processes (Afana *et al.* 2010; Kociuba *et al.* 2014). One problem that can affect the reliability of TLS monitoring are measurement errors (noise) caused by the growth of vegetation in the system's beds. This problem, however, can be avoided, according to Brodu & Lague (2012), by dividing point cloud information into the background and vegetation datasets using classification algorithms.

CONCLUSIONS

The TLS technique has changed the way the environment can be analysed, as a step forward has been made from ground geodetic measurements to complex 3D modelling. TLS allows a specialist to collect very precise, high density data very fast. These data, which provide an extremely accurate description of an object, can be used to conduct spatial

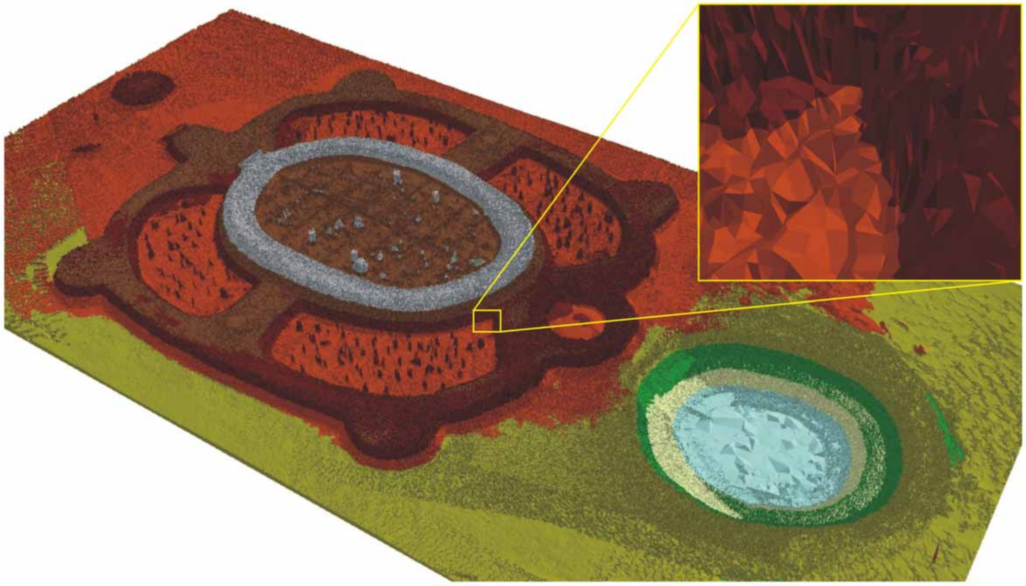

Figure 6 | A TIN model of the constructed wetland system and a magnified detail (greyscale represents the values of the height attribute).

analyses, including assessment of the geometry of key elements of the structure of the system being surveyed. It is important in cases of as-built surveying conducted to check the accordance of the construction with its technical documentation. In case of discrepancy exceeding legal ones, three solutions can be considered. First, the object should be, if possible, reconstructed so it matches original technical documentation. Second, if differences between a project and an object are insignificant, a designer can update an existing project according to the physical state of the object and building authorities issue a permission to use it. Third, in case of significant differences, a new project has to be created and all legal procedures have to be entered. The present study demonstrated that the investigated HCW system had been built in compliance with the technical documentation, as differences between the values obtained from the object and those specified in the design project were within the range defined by the legislator. It was also shown that the results were accurate enough to be used in an as-built survey of the aboveground elements of the CW system. Surveying of underground elements (e.g. a distributing and collecting drainage system, collecting wells) requires the use of other geodetic techniques. The TLS technique can also be employed to analyse quantitative changes in object geometry arising during long-term use (e.g. landmass slides or erosion), the identification of which can help select the hot-spots at risk of damage and thus restore the original state as well as prevent new changes.

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