Project manager: dr Joanna Ewa Szafraniec

Affiliation: University of Silesia in Katowice, Faculty of Natural Sciences, Institute of Earth Sciences, Będzińska 60, 41-200 Sosnowiec, Poland, e-mail: joanna.szafraniec@us.edu.pl

Title of the project: **Development of a high-resolution digital elevation model (DEM) of the kettle-holes of the glacial flood origin at Skeiðarársandur (S Iceland)**

Task: **DATABASE OF THE DIGITAL ELEVATION MODELS OF THE SKEIÐARÁRSANDUR KETTLE-HOLES, JUNE 2022**

Description of the purpose and context of the research

Skeiðarárjökull (S Iceland) is one of the outlet valley glaciers from the Vatnajökull ice cap. Its accumulation field extends, among others, on the caldera of the Grimsvötn volcano. Despite episodes of a glacial surge, this glacier is constantly retreating, enlarging its inner marginal zone. Its location in the area of increased influx of geothermal heat and volcanic activity is the cause of catastrophic glacial floods, the so-called jökulhlaup, every 6–11 years on average. The last small flood occurred at the end of November 2021, and another minor was in October 2022 (Icelandic Meteorological Office – IMO, 2022). Thanks to the floods, the glacier forefield, the vast, most extensive European active outwash plain Skeiðarársandur, is subject to intensive relief transformations. As a result, numerous outwash levels, water outflow routes and clusters of small depressions of various ages, the so-called kettle-holes, emerge, which are the object of research in this project.

Kettle-holes are formed when ice blocks from the collapse of subglacial tunnels are detached from the glacier head due to flooding. The flood waters carry them to the glacier's forefield. With the decrease of the stream energy, fragments of ice settle on the outwash, wholly or partially covered by fluvioglacial deposits. After the ice has melted, small depressions remain on the sandy-gravel plains. Numerous variables affect their size, spatial distribution and the state of vegetation coverage, e.g. the energy of the released glacial waters, the dynamic state of the glacier (advance or recession), the glacio-geomorphological situation (the presence or absence of terminal moraines), the age, the amount of sedimentation, the size of the ice blocks and their distance from the glacier front (proximal or distal part of the outwash), meteorological conditions and animal grazing as well as the intensity of tourist traffic, which affects the surface runoff and the activation and intensity of mass movements.

Similar depressions have been identified in NW Poland on the Gwda sandur (Pomerania). Morphometric studies as well as geological and geomorphological premises argue that extreme glacial floods occurred here at the end of the Pleistocene. Maximum flows could average 5×10^3–10^5 m^3 s^{-1} (Szafraniec, 2009, 2010, 2013; Mleczak and Pisarska-Jamroży, 2021). The possibility of catastrophic glacial runoffs has also been described for NE Poland (Weckwerth et al., 2019).

Initial analysis based on digital elevation models (DEM) with a resolution of 2 m for the examples from Skeiðarársandur (~10–100 years) and Pomerania (approx. 10,000 years) indicated that morphometric relationships could describe changes in the parameters of the depressions over time. It was found that the volume of the kettle-holes is, on average, 20–25% of the ellipsoid volume, the axes of which correspond to the maximum depth and diameter of the depressions (Szafraniec, 2019). Unfortunately, for the Icelandic landforms, the available field size of the 2 m × 2 m raster is not satisfactory, as some small depressions have a diameter of less than 2 m. **The project aimed to obtain high-resolution DEMs for different-age landforms on Skeiðarársandur**. The acquired video material made it possible to develop models with the optimal raster size of 0.05 m × 0.05 m. They reflect the details of the depressions, which is essential in the case of new forms.

The created database will be the basis for tracking how depression relief develops in the near future (up to 5–10 years). Learning about the conditions and rate of sedimentation in the initial period of depression formation (Iceland) and confronting this knowledge with the current rate of transformation of the kettle-holes relief in Northern Poland will, in turn, allow determining the conditions of deglaciation of this area in the early Holocene.

Methodology

The development of the DEMs database for kettle-holes consisted of fieldwork and laboratory work, primarily within the software.

Fieldwork

Fieldwork took place between 18 and 27 June 2022 in the forefield of the Skeiðarárjökull glacier in S Iceland (Fig. 1). The favourable weather conditions made it possible to film 105 landforms (94 videos). The selection of the depressions for filming resulted from the observation network established in 2021, aimed at studying the sedimentation rate within the depression. It is possible to learn about different shapes and correlations between the characteristics of the depressions by examining the clusters of filmed landforms with diverse morphometry.
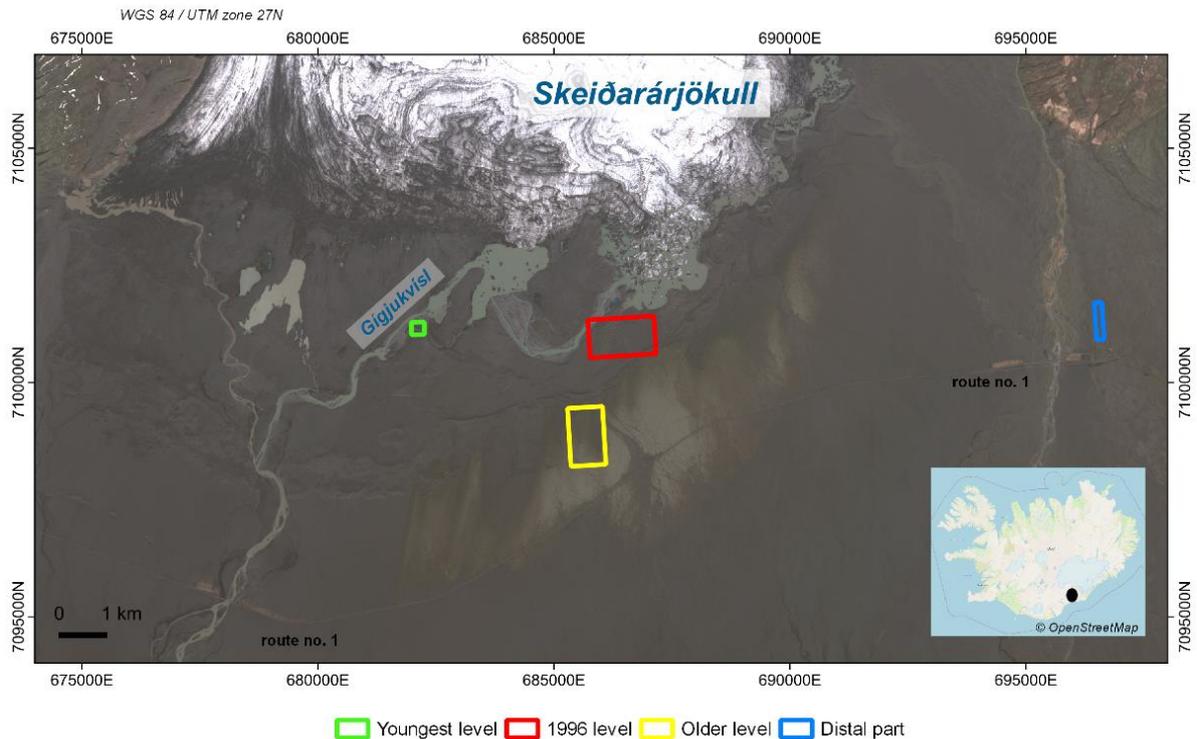
Fig. 1. Location of the study area – marginal zone of the Skeiðarárjökull glacier (Sentinel 2, L1C_T27WXM_A035885_20220506T125306, TCI; EarthExplorer), insert map – Iceland (OpenStreetMap); the black dot indicates the location of the research area against the background of the entire island.

The examined depressions come from three different age outwash levels (Fig. 2): 1) 43 forms (38 videos) at an altitude of approx. 78–111 m a.s.l. from the older outwash level from the 1930s in the Haodukvísl area near the gorge of the terminal moraines from the end of the Little Ice Age – MEL); 2) 54 forms (51 videos) at an altitude of approx. 92–101 m a.s.l. from the younger outwash level associated with the outflow of catastrophic flood waters from the beginning of November 1996 (located within the terminal depression) + 1 kettle-hole (1 video) from the distal part of the dry Skeiðará channel; 3) 7 forms (4 videos) at an altitude of approx. 60–61 m a.s.l. from the floodplain of the current outflow route of the Gígjukvísl river, which experienced flooding in 2011 (depressions) and 2021 (transformation and transfer of channels). During the field research, selected depressions were filmed in accordance with the Structure from Motion (SfM) technique, and photographic documentation and form measurements were made. As a result, seven films were disqualified from which no models could be obtained due to either an incorrect filming technique or the lack of visibility of at least two adjacent stakes. These materials are not included in the database.
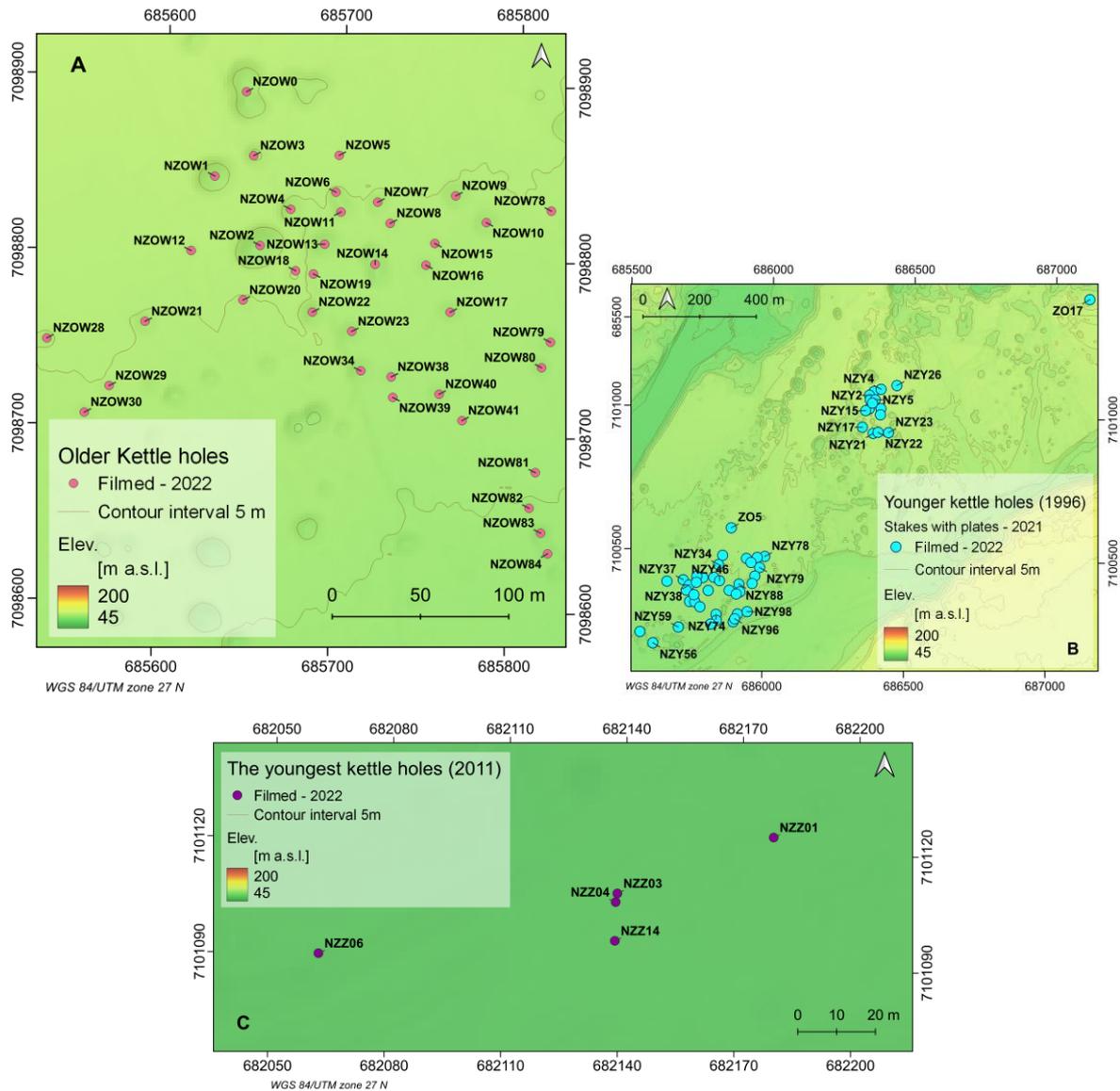
Fig. 2. Location of filmed kettle-holes during field research carried out in June 2022 against the background of the hypsometry of the area of the Skeiðarárjökull forefield: A) on the older outwash level from the 1930s; B) at the younger outwash level after the flood in 1996; C) within the current floodplain of Gígjukvísl after the 2011 flood (based on 2 × 2 m digital laser scanning elevation models, 2012; files no. IslandsDEMv1.0_2x2m_zmasl_isn93_61.tif; National Land Survey of Iceland, https://www.lmi.is/is).

First, coloured wooden stakes (diameter – 22 mm, length – 0.5 m) were driven in the kettle-hole perimeter (Fig. 3); in the amount of 4 to 6 pieces depending on the size of the depression. The distance between the stakes was measured with a measuring tape at an accuracy of ±5 mm. The height of the poles was further measured with a folded wooden ruler at an accuracy of ±1 mm.

Fig. 3. Measuring instruments used in fieldwork, except for the camera (photo by J.E. Szafraniec).

A Nikon D3100 digital camera with a Complementary Metal Oxide Semiconductor (CMOS) sensor and 14.2 million pixels was used for filming. Movies were saved in **.mov** format with a frequency of 23.98 frames per second at a focal length of 18 mm. The standard extracted frame from the film had a size of 1920 × 1088 pixels and a resolution of 96 dpi.

The filming took place along the perimeter of the polygon, whose vertices were located near the stakes. With a walking step, two loops around the kettle-holes were completed (Fig. 4). The first loop focused on filming the stakes and the opposite edge of the form, and the second was on the form bottom. The duration of the operation ranged from 100 to 600 seconds on average, depending on the size of the depression. After filming was complete, the location of each stake was marked in the field to record future changes within the kettle-hole.

Fig. 4. Arrangement of selected film frames along the route around an example of a kettle-hole against the background of a sparse point cloud of the model (screenshot from VisualSfM; own elaboration).

Laboratory work

The study by Wróżyński et al. (2017) inspired the building of digital elevation models utilizing the SfM approach and free software.

Step 1. Extracting frames from the video (VLC media player)

The **VLC media player** (https://www.videolan.org/vlc/) developed by the VideoLAN team was used in this process. It is a famous free, open-source media player licensed under the GPL, working on all operating systems. Thanks to scene filters, one of the advantages of this program is the ability to obtain film frames (here: **.mov**) in a given graphic format (here: **.jpg**), size and frequency. An average frequency of one frame per second was used for the area of the kettle-hole. This value is optimal for obtaining point coverage that allows making a DEM with a resolution of 5 cm × 5 cm with the least processing time. The frequency for visualising the stakes ranged from 3 to 12 frames per second. The set of depressions' frames was combined with the set of stakes' frames.

Step 2. Point cloud generation (VisualSfM and CMVS-PMVS master)

At this stage, the free **VisualSfM** GUI application (http://ccwu.me/vsfm/index.html) was used to identify identical points on the stereoscopic model from selected photos and connecting them, generating a point cloud. Cooperation with the **Yasutaka Furukawa PMVS/CMVS** algorithm also allowed the creation of a dense point cloud (Fig. 5), which was exported as a **.nvm** model together with a version in the **.ply** format. A noise-free point cloud can be created with this program.

Fig. 5. An example of a dense point cloud with noise obtained with the VisualSfM application and the PMVS/CMVS algorithm (screenshot from VisualSfM; own work).

Step 3. Scaling the point cloud to actual terrain dimensions (MeshLab v. 2021.05)

MeshLab (https://www.meshlab.net/#description) (Cignoni et al., 2008) is another free tool utilized to process point clouds. The Visual Computing Lab of ISTI-CNR developed this program under the GPL license. The **.ply** format was loaded to MeshLab. In this environment, clearing the point cloud of noise is also possible. In addition, it was used to scale the model based on the measured distances between the stakes during fieldwork (Fig. 6). The essential task was to calculate the scale factor, which is the ratio of the field distance to the distance measured on the model. The coefficient calculation was based on all possible distances provided the stake was visible on the model. The calculated scale factor values for all polygon sides were subsequently averaged.
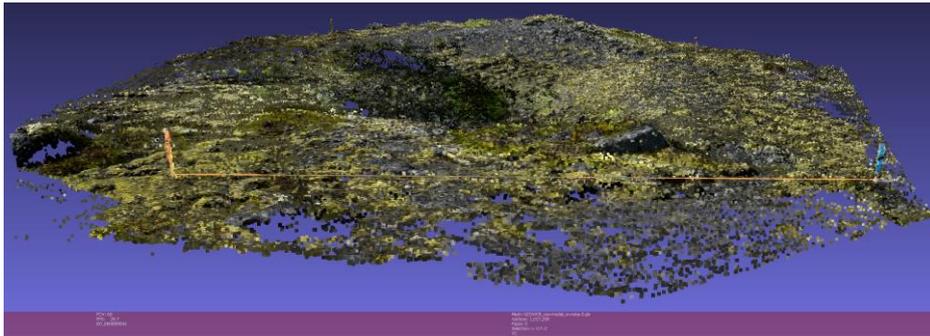

Fig. 6. An example of a point cloud cleared of noise with visible stakes – measuring the distance between stakes on the model to calculate the scale factor (screenshot from MeshLab; own work).

After rescaling, the field distance between the stakes on a model was checked by measuring it ten times and averaging the result; similarly, for stake heights, provided they are fully generated on the 3D model. This procedure made it possible to calculate the horizontal and vertical errors of the models. Because the model was not rectified to the selected coordinate system, the data remains in the local Cartesian system for each kettle-hole and are not oriented to north (units: meters). Nevertheless, MeshaLab, thanks to the GEOREF (Reference scene) tool, also allows georeferencing of the point cloud. This step was omitted here due to the small size of the landforms. By marking the locations of the stakes in the field, it will be possible to connect the models created in the following years to the base model from 2022.

Step 4. Model filtering and data export (CloudCompare 2.11.3 Anoia)

This stage was performed in **CloudCompare** (https://www.cloudcompare.org/) – an open-source program under the GNU GPL license. A scaled point cloud in **.ply** format was loaded and processed using the PoissonRecon plug-in. With the tool, the density of points is obtained as a scalar field, which reduces the cloud's extent to the desired density. Filtering the cloud by the minimum (7) and maximum (no change) density values and the smoothing function (Laplacian) gives a product (Fig. 7), which can then be exported, e.g. to the text file in **.txt** format. Data exported in this way include, among others: X, Y, and Z coordinates, colour components in the RGB model and the point density value.
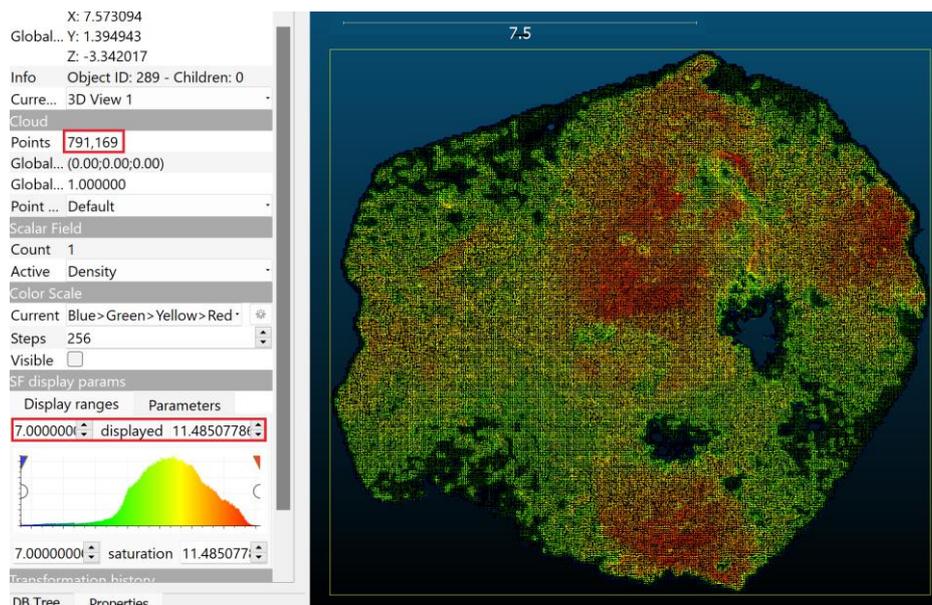
Fig. 7. The model filtered in CloudCompare by the set minimum and maximum density of the point cloud with a histogram and information about the number of points (screenshot from CloudCompare; own elaboration).

Step 5. Work in geoinformation software (Surfer 12.8.1009, QGIS 3.24 Tisler, SAGA GIS 7.8.2)

First, in **Surfer** (Golden Software LLC), the height values (relative) were recalculated so that the lowest point of the kettle-hole had a value of 0. Thanks to this procedure, repeating the models in subsequent years will allow for determining changes in height concerning this base point. Vector model files **.shp** with depression outline were also generated in this program. In the case of hollows covered with vegetation, trees (birches and willows) were cut out from the model.

The next step was the interpolating points to obtain digital terrain models (DTM) in **.tif** format, made in the open-source **QGIS** software under the GNU GPL license (https://www.qgis.org/en/site/). Here, the triangulation method (TIN) was used. The resolution of 0.05 m × 0.05 m was adopted for all kettle-holes (Fig. 8). This is the lowest resolution value of all landforms. Additionally, DTMs were produced for each depression in the range of 0.005 m to 0.04 m (depending on points density), which was the optimal kettle-hole resolution. The area of the kettle-hole was calculated using vector geometry tools. The stakes were removed from the model.
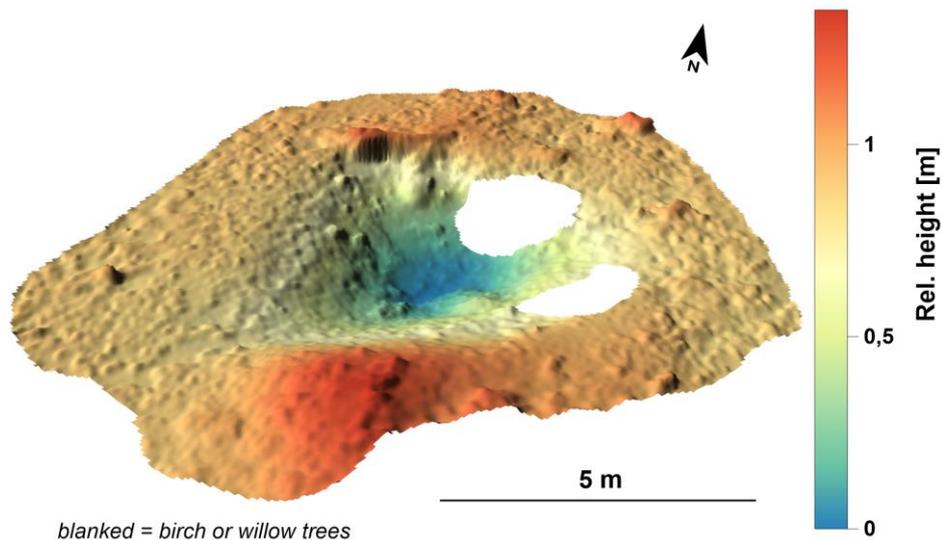
Fig. 8. An example of a DTM of a depression in a 3D view with a raster field resolution of 0.05 m × 0.05 m with fragments cut out due to birch colonisation (own elaboration).

Reconstruction of the bottom of the depression after cutting trees from the model was performed in QGIS, using the GDAL algorithm => Raster analysis => Fill nodata (Fig. 9).
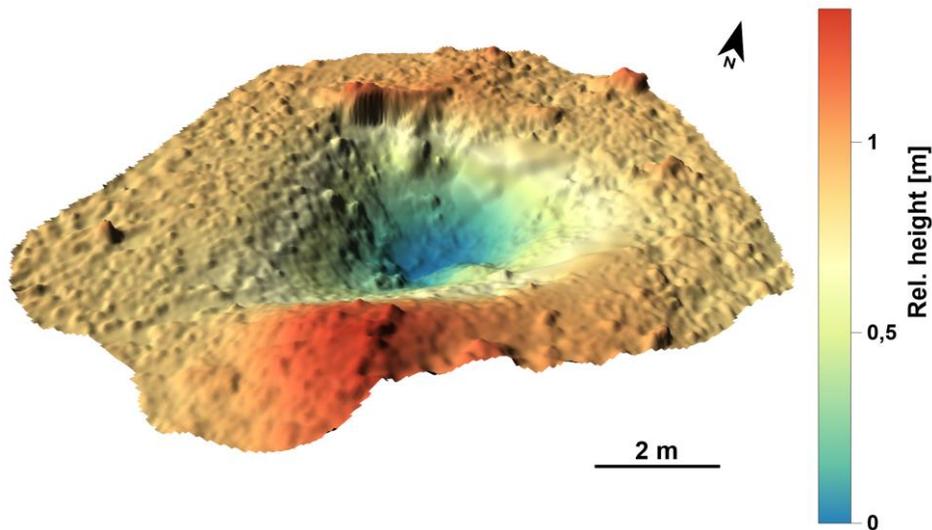

Fig. 9. An example of a DTM of a kettle-hole in a 3D view with a raster resolution of 0.05 m × 0.05 m with bottom relief reconstruction in the place of trees (own elaboration).

To calculate the kettle-hole volume, another open-source program, **SAGA GIS** (https://sourceforge.net/projects/saga-gis/) (Conrad et al., 2015), was used: Tools => Grid => Calculus => Grid Volume.

The organisation of data in the database

The database consists of two parts:

<u>Part I</u> – DOI: 10.5281/zenodo.7449082:

- Project documentation: **Documentation_2021-05-X-ST10-00710.pdf**.

- A short description of the database content: **ReadMe.txt**.

- Map representing the location and codes of the kettle-holes: **Map_kettle-holes_2022.png**.

- Folder for the coordinates of the depression centroids for the three CRS: ISN93 / Lambert 1993 in meters (EPSG:3057), WGS84 in decimal degrees (EPSG:4326) and WGS84 / UTM zone 27N in meters (EPSG:32627) – **KH_centroids_coord** (text files **Code_filmed_UTM_coord** with the **.csv**, **.txt** format and shapefile vector model layer – 28 files in total).

- **Kettle-holes_parameters_2022.xls** – parameters describing kettle-holes, movies and points cloud.

- Kettle-holes **zipped** files – contains folders for each landform, in which there is a spreadsheet file with calculated errors **Errors_code.xls** (e.g. Errors_NZOW01.xls) and **Errors_code.xlsx** (stakes color abbreviations used: RE – red, BL – blue, YE – yellow, GR – green, OR – orange and PI – pink), a text file with the height of the stakes used for field measurements and the distance between them **Code_stakes.txt**, a graphic file of the 3D view of each form in hypsometric tints with shading and without exaggeration **Kettle-hole_code .png**, digital elevation model text file **Code_DEM.txt**, a scaled and mostly noise-free point cloud **Code_model_w-noise.1.ply**, a polygon vector model layer in shapefile format with the shape of the analysis area (depression with a rim) **Code_shapePoly** (4 files: **.cpg**, **.dbf**, **.shp**, **.shx**), 2 raster model files containing a digital terrain model with optimal resolution for given DTM and for all kettle-holes – with resolution of 0.05 m **Code_TIN_resolution_w-stakes_blanked_norm.tif**, the **Code_frames** folder containing frames selected from the film in **Code.jpg** format used to develop the DEM. In addition, the kettle-holes with removed fragments of trees have files relating to the reconstruction of the bottom relief – the word **_recon** was added to file names (3D view, kettle-hole shape and DTM). All data was organised into three collections:

  - **KH_JUNE2022_OLDER_Code**:

    - 36 folders **NZOW**Number

  - **KH_JUNE2022_YOUNGER_Code**:

    - 43 folders **NZY**Number; 3 folders **ZO**Number; 1 folder **ZVO**02

  - **KH_JUNE2022_YOUNGEST_Code**:

    - 4 folders **NZZ**Number + videos

Part II – DOI: 10.5281/zenodo.7451375: as a database collecting video files in the **.MOV** format + **ReadME.txt** file. It concerns the kettle-holes from older and younger levels.

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