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Geophysical surveys at selected hot spots

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EXECUTIVE SUMMARY

Geophysical techniques were carried out in an alluvial basin west of Auja to investigate their potential for aquifer recharge. Refraction seismics and electrical resistivity tomography were applied to determine the thickness of the basin fill material. Time-lapse electrical imaging was carried out during an infiltration experiment to monitor the infiltration process, calculate hydraulic parameters and to calibrate a hydrogeological model for the intended storage area. Additionally, classical hydrogeological approaches were applied to compare with the geophysical results and to calibrate models.

1 INTRODUCTION

Between October 2010 and March 2012, different geophysical methods were applied to investigate the potential of the alluvial basin west of village Auja (West Bank) (Figure 1) to act as subsurface water storage. The methods included refraction seismics (RS), electrical resistivity tomography (ERT) and the method of induced polarization (IP). All techniques were carried out both at the central part of the basin as well as at the north-eastern outlet of the basin (here except RS) to characterize the basin fill (alluvial sediments) and to delineate the bedrock boundary (Cretaceous chalk rock). Further, time-lapse ERT was measured during an infiltration experiment to study the dynamic infiltration processes in the alluvial sediments and to infer hydraulic parameters of the subsurface. Additionally, classical hydrogeological investigations (e.g., exploration boreholes, tests with double-ring infiltrometer, falling head borehole injection tests, soil samples and geological field surveys) were made to calibrate their results with the geophysical images.

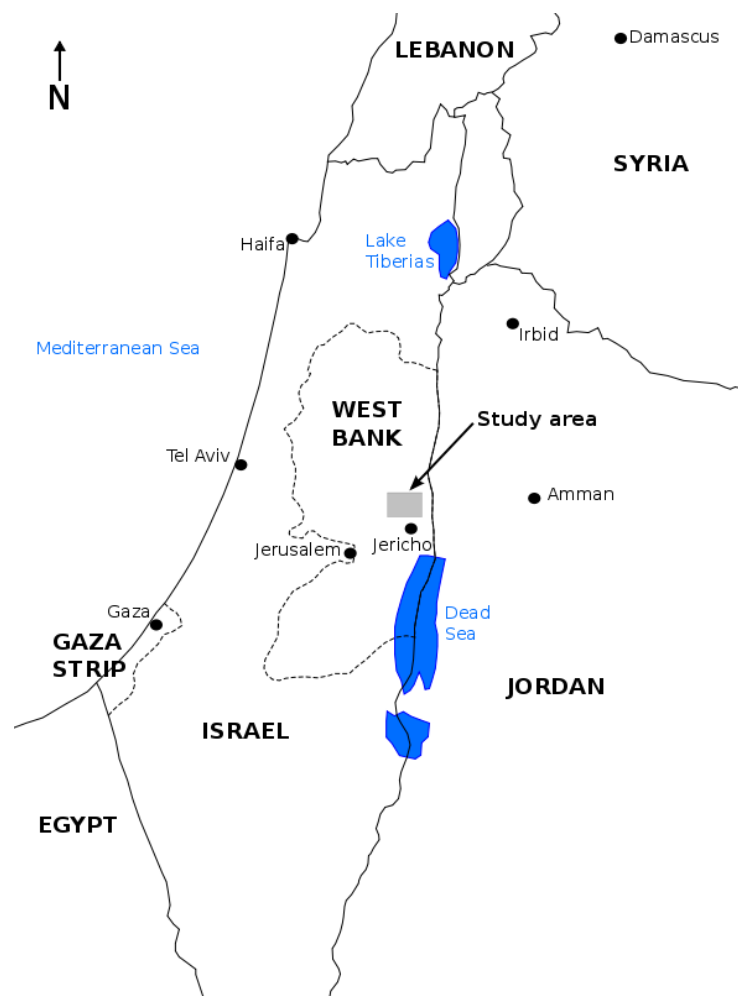


Figure 1: Location map of the study area.

2 SITE DESCRIPTION

The alluvial basin west of village Auja contains clastic sediments from an alluvial fan, deposited during the last glacial period. The sediments are mostly composed of gravels, sands and silts transported from the West Bank Mountains (Figure 2). In the outlet of the basin finer material (mostly silt) exists, which was deposited as marginal sediments in Late Pleistocene (Samra Formation) (Begin, 1974). The unconsolidated sediments are underlain by Cretaceous chalk rocks (Mishash/Abu-Dis Formation, Senonian), which are known as a local aquiclude. The chalk rocks build a syncline, striking northeast to southwest. This synclinal form is also effective on the topography of the site. The geometrical situation makes the basin a well reasonable spot for groundwater storage. The source of water can be both, run-off water from the West Bank Mountains flowing through Wadi Auja to the Jordan River as well as spring water from the seasonally flowing Auja Spring.

To decide for the basin for subsurface storage, some important information is lacking: (1) the thickness of the basin fill material, which is intended to act as an aquifer, and (2) the hydraulic characteristics of the material. The objective of this research is to determine these conditions by using non-invasive geophysical investigation techniques in combination with classical (hydro)geological investigations.

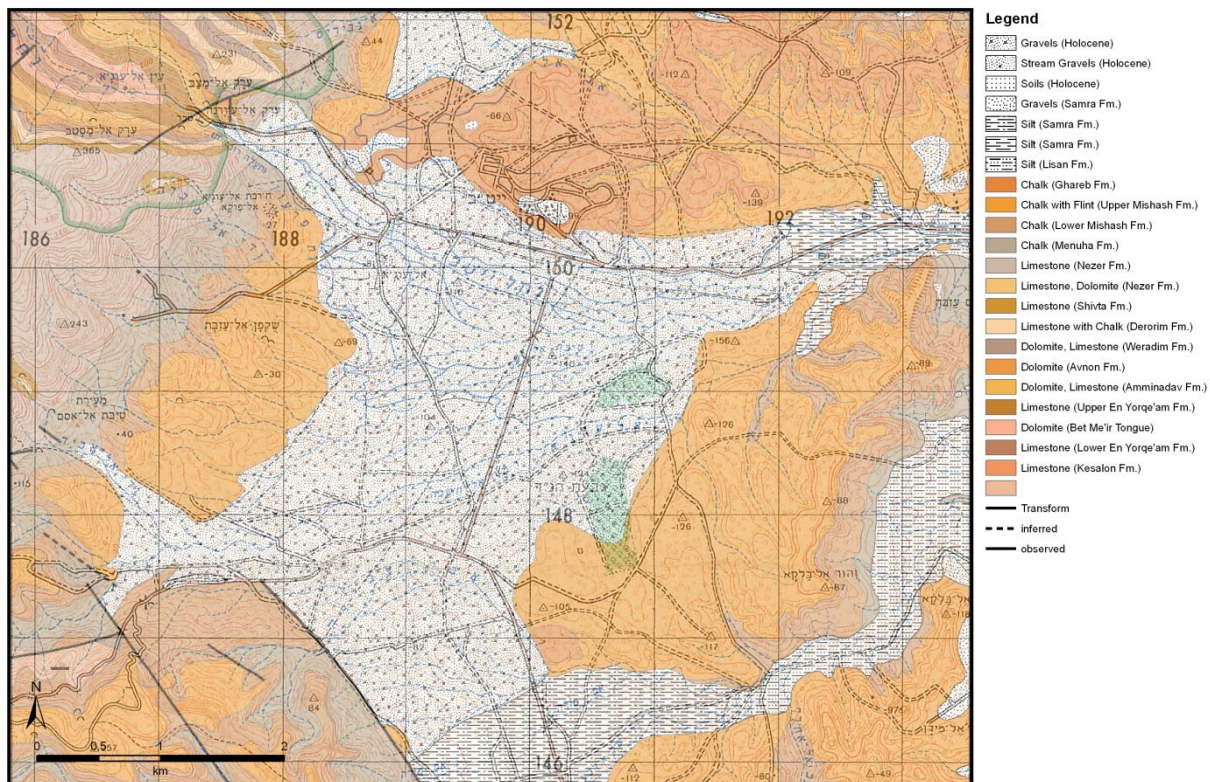


Figure 2: Geological overview map of the alluvial basin west of the village Auja (West Bank) (modified after Begin, 1974).

3 CHARACTERIZATION OF BASIN GEOMETRY

In October and November 2010, investigations for the characterization of the geological geometry of the alluvial basin were done using the methods of RS, ERT and IP along different profiles (Figure 3). The reason for the seismic method was the expected contrast of the seismic velocities between the alluvial sediments (low seismic velocity) and the underlying chalk rocks (high seismic velocity). The velocity contrast was expected to be of about 1000 m/s. The methods of ERT and IP will be used as a characterization and monitoring tool for managed aquifer recharge applications, since electrical methods provide high potential for hydrogeological questions. Here, their results, jointly with the seismic results, deliver a reasonable image of the basin subsurface and build the basis for a geological three-dimensional model of the subsurface basin geometry.

In the following, the geophysical methodologies and their results are described separately and later a combined interpretation of all results will be given.

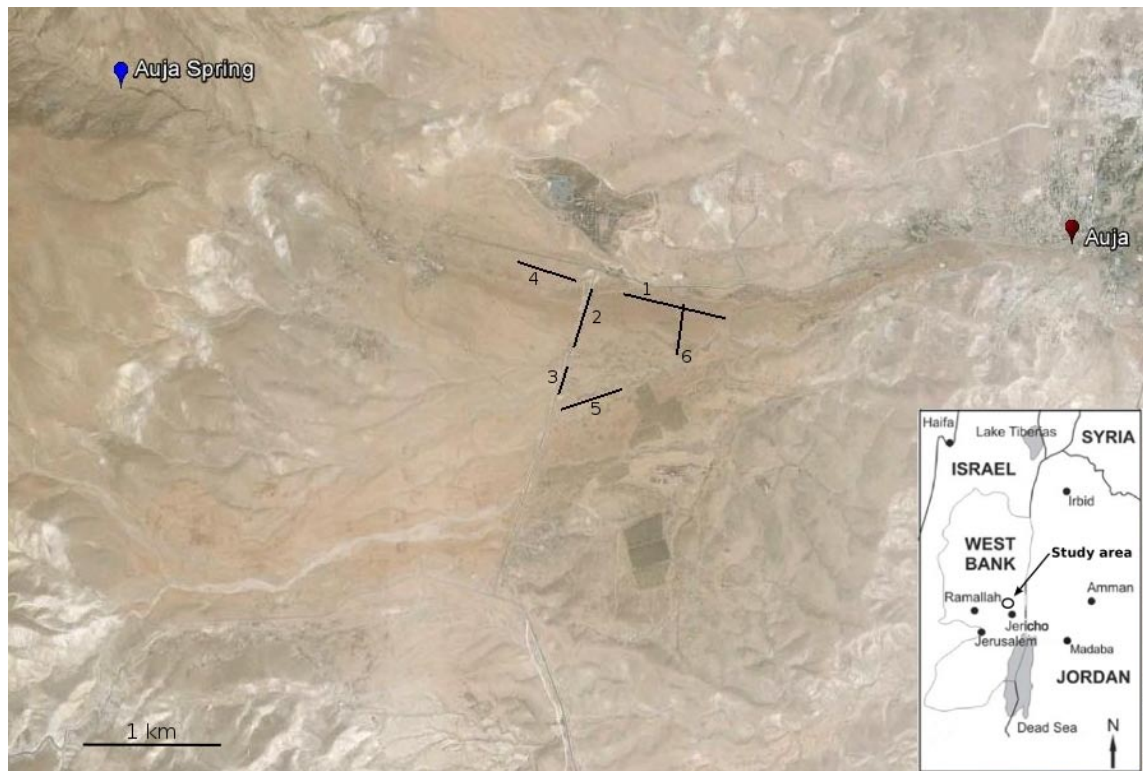


Figure 3: Location map of the geophysical surveys in the central part of the alluvial basin (Picture source: Google Earth).

3.1 Refraction seismic survey

3.1.1 METHODOLOGY

The refraction seismic field survey was conducted by the Geophysical Institute of Israel (GII), Lod. Six arrays in the northern central part of the basin were measured (Figure 4) using 48 geophones with a distance of 10 m between them for four arrays (1, 2, 4, and 5), 5 m distance for array 3 and 40 geophones with 10 m separation for array 6 (complete length of all arrays of 2.5 km). The seismic source was a 50 kg heavy weight, which fell off a defined height of 1 m above the surface. For each array, the source was placed on eight to nine positions along the line of geophones, starting and ending with an offset of 50 m from the first and the last geophone, respectively. The seismic signal, detected by the 10 Hz geophones, was recorded using SUMMIT remote units with a sampling rate of 0.5 ms and a recording interval of 500 ms.



Figure 4: Location map of the refraction seismic arrays (Picture source: Google Earth).

3.1.2 RESULTS

The seismic results were processed and inverted using the software ReflexW 5.6 (Sandmeier Scientific Software, Germany). The results of three selected arrays are shown in Figure 5.

The results show the expected contrast of seismic velocities between the two layers; however, the contrast is lower than expected, which is most likely related to the weathered upper part of the chalk. The thickness of the first layer, which is interpreted as the unconsolidated alluvial deposits, varies along the different arrays between 10 m and 30 m. Small scale structures at the bottom boundary are related to paleo-relief. Velocity variations within the upper layers are caused in lateral changes in lithology, for instance areas with finer material (silt or clay lenses).

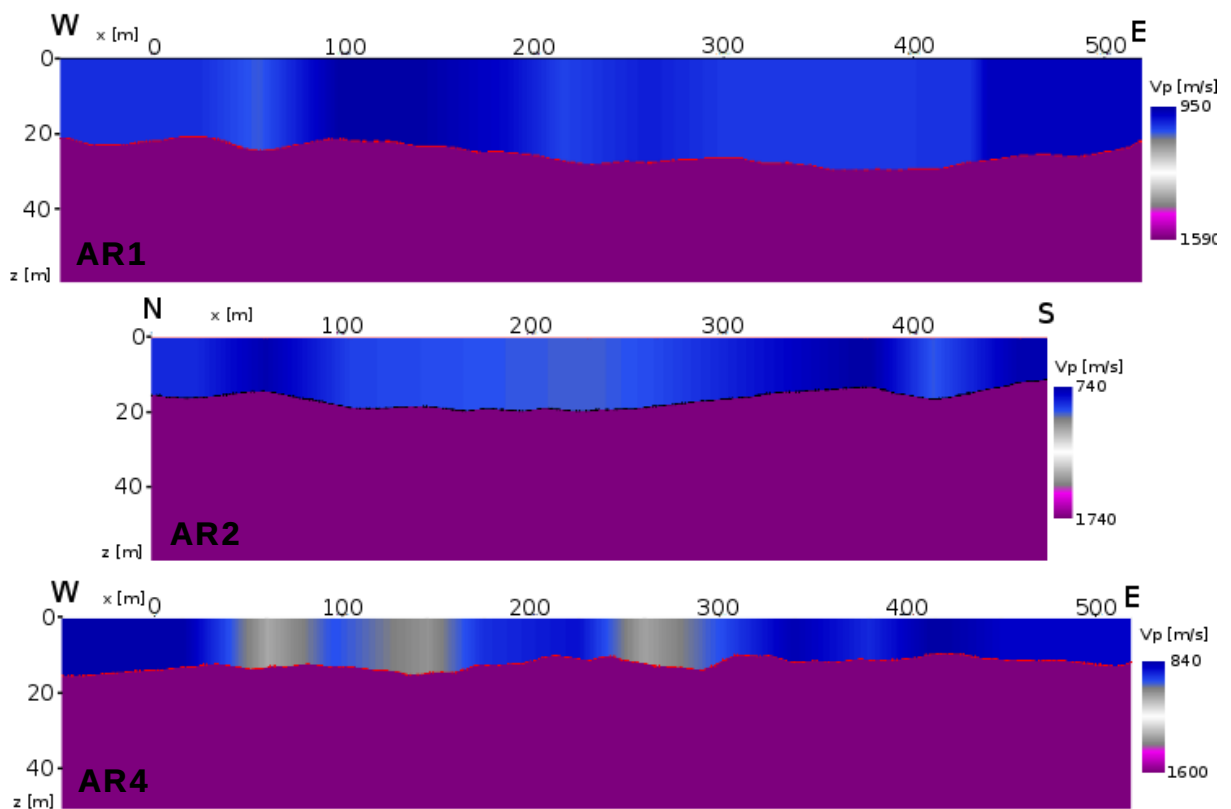


Figure 5: Selected results of refraction seismic arrays 1, 2 and 4. The results reveal that the upper, blue (and grey) layer is correlated with the unconsolidated, alluvial sediments and the lower, purple layer with the bedrock. V_p denotes the seismic velocity of the P-wave.

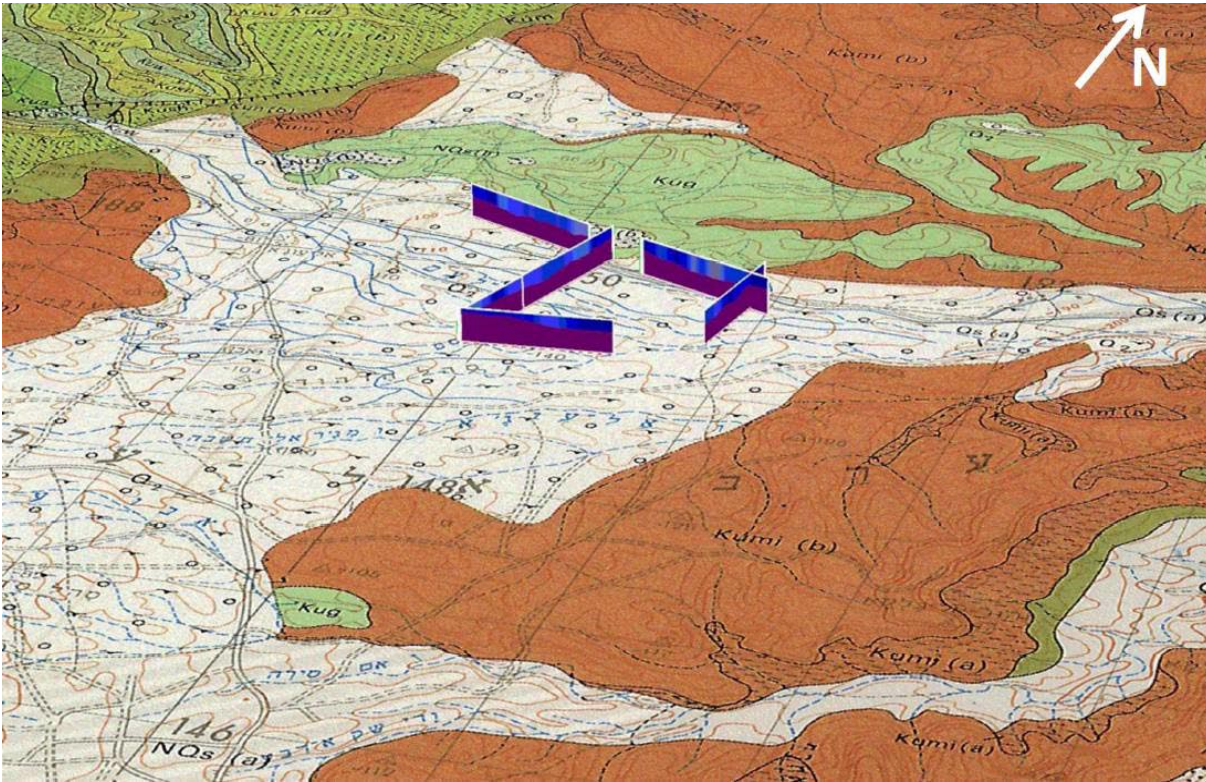


Figure 6: Three-dimensional illustration of the six seismic arrays on the geological map.

3.2 Electrical resistivity tomography, induced polarization

3.2.1 METHODOLOGY

ERT and IP measurements were carried out along two arrays within the basin and two arrays in the outlet at the north-eastern border of the basin using an IRIS Syscal Switch Pro 96 resistivity meter (Figures 7 and 9). The first array (AR1) was the same like array 1 of the seismic survey, but extended to the eastern direction. Altogether for the first long array, 160 electrodes were used, with a distance of 5 m between them. Measurements were done with Wenner and dipole-dipole configurations. The second array (AR4) was the same like array 4 of the seismic survey and 96 electrodes with 5 m separation were used as well as Wenner and dipole-dipole configurations.

For the dipole-dipole configuration, the measurements were conducted as normal and reciprocal, which mean an interchange of current and potential electrode pairs for the reciprocal measurement. Since the normal and reciprocal values should theoretically give the same number, the discrepancy in the measured values provide an order of measurement error in the dataset. For the method of IP, the decay of the voltage signal after switching off the current injection gives information about polarization effects in the subsurface, which can be related to lithological and hydraulic characteristics of the subsurface (Kemna et al., 2004).

Resistance and chargeability data were collected in time domain, using a square-wave current injection with 50% duty cycle and a pulse length of 2 s. 800 mV was set as criterion for the potential readings. The stacking (repetition of measurements) was set to a minimum of 3 and a maximum of 6, with the requirement of reaching a quality factor of less than 5%.

For the two arrays in the outlet area (Figure 8), 96 electrodes were used for each array with 2 m separation for line AM1 and 2.5 m separation for line AM2. Measurements were collected as skip4 dipole-dipole, normal and reciprocal for line AM1, and skip3 dipole-dipole, normal and reciprocal for line AM2. IP was measured in both lines (with same specifications as mentioned above).

After processing of the electrical data, i.e., filtering outliers, estimation of normal and reciprocal errors and estimation of error parameters for the inversion, the data were inverted using the imaging code CRTomo (Kemna, 2000). The results are shown in Section 3.2.2. Due to poor data quality of the chargeability, it was not possible to image the polarization properties of the target area in arrays AR1 and AR4. Probably, the poor data quality is rooted in scarce polarisable material, especially occurring in dry conditions.



Figure 7: Location map of the geoelectrical arrays. Note that the right array is extended towards eastern direction, compared with the seismic array (Picture source: Google Earth).



Figure 8: Location of geoelectrical mapping lines AM1 and AM2.

3.2.2 RESULTS

The electrical data of all arrays were processed and inverted as described above. As shown in Figure 9, in a depth from 40 m to 60 m the electrical resistivity changes significantly from values of about 25 Ωm to 70 Ωm to values of up to 700 Ωm . This change is related to the lithological change of the alluvial sediments to the expected bedrock. However, as seen in the seismic results (Section 3.1.2) the thickness of the alluvium seems less. This is probably caused by the decreasing sensitivity of surface ERT with depth (Figure 10) and therefore, due to the fact of a high resistive layer below a high conductive layer, this can lead to an overestimation of the depth of the intersection.

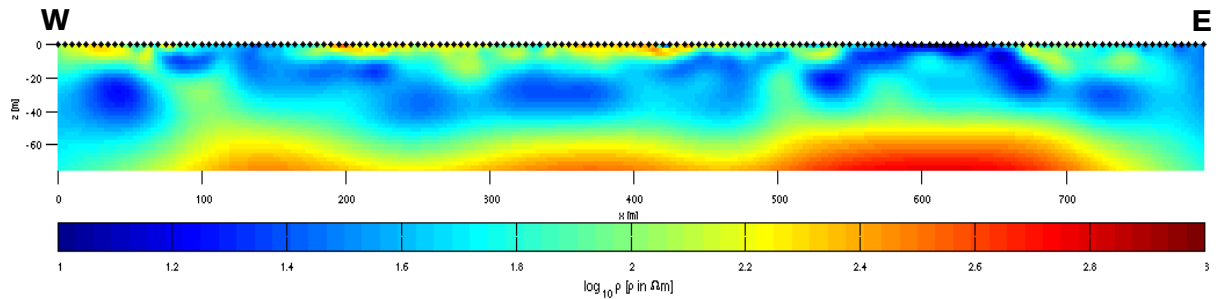


Figure 9: Electrical resistivity image for the extended array AR1. Black dots on the surface denote the electrode positions.

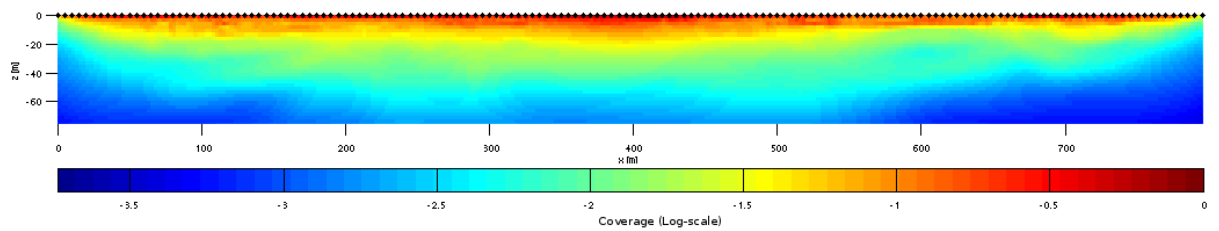


Figure 10: Coverage of the subsurface for array AR1, representing the cumulated sensitivity of all individual measurement configurations. The coverage decreases with depth.

The results of the lines AM1 and AM2 are shown in Figures 11 and 12, respectively. Both images show a high resistive layer in the shallow subsurface (up to about 8 m depth). The depth of the bottom resistive layer is indicated between 20 m and 30 m, which is again related to the chalk bedrock. As observed in a nearby drilled well, the bedrock was reached at 21 m depth. Thus, the ERT images again show probably a little overestimation of the resistive layer below a conductive layer. Figure 11 (resistivity magnitude image) indicates a channel structure which can be related to the paleo-wadi. The high resistive part on the left side of AM1 is most likely related to the chalk rock, which outcrops a few meters south of the profile. The IP results (resistivity phase images) show only small response (low absolute phase values, > -8 mrad). They indicate the existence of fine material (silt, clay), but, also related to low water content, the signal is small and thus the content of fine sediments is low.

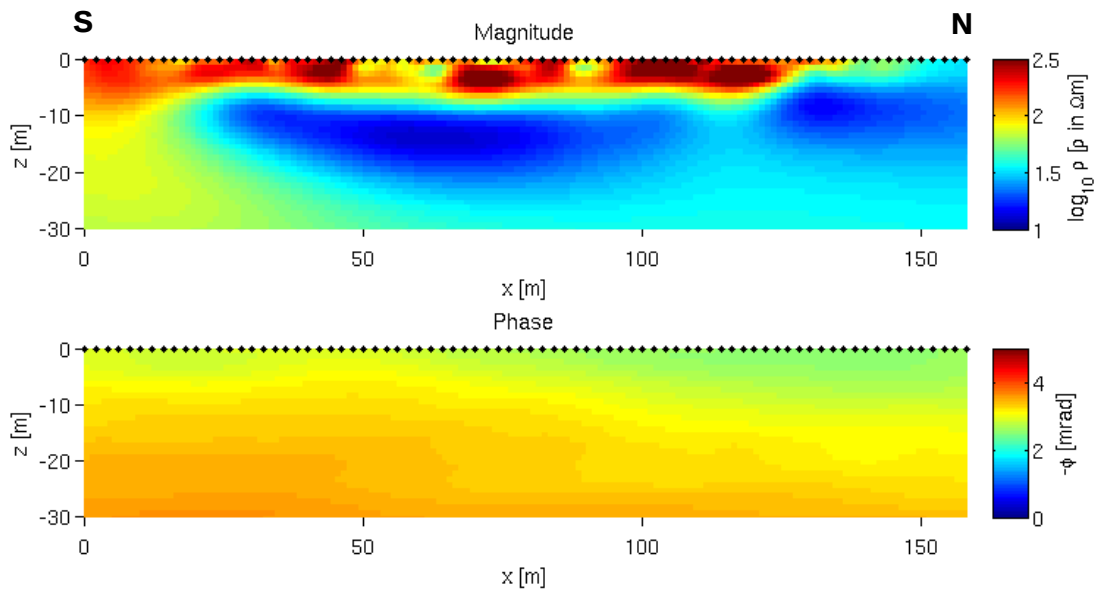


Figure 11: Magnitude and phase images of electrical resistivity for array AM1.

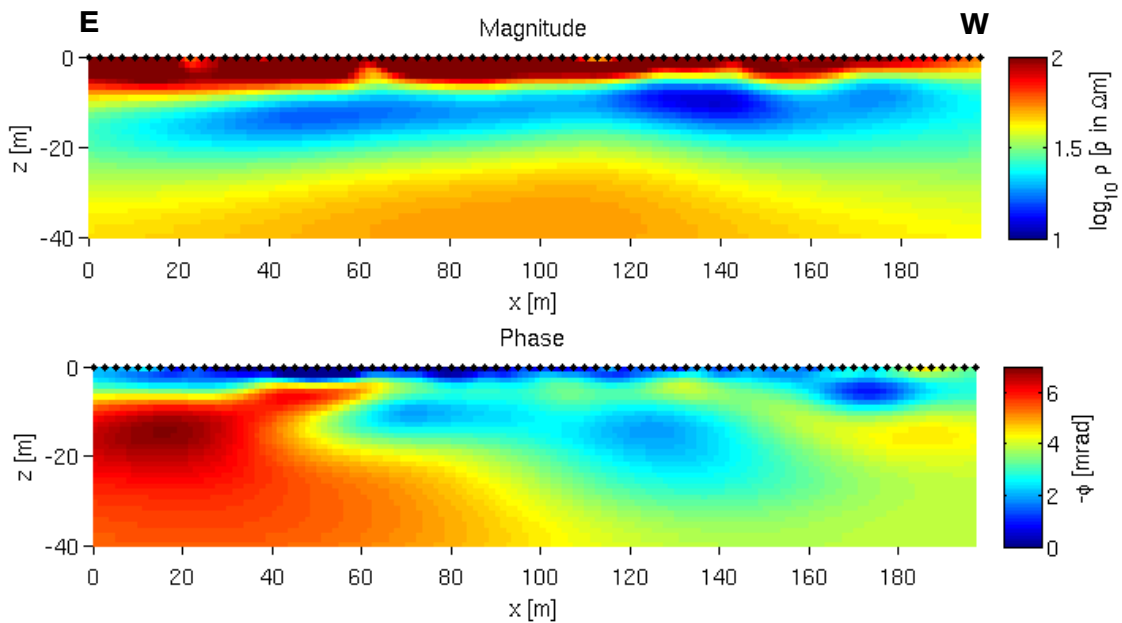


Figure 12: Magnitude and phase images of electrical resistivity for array AM2.

3.3 Combined interpretation of geophysical results

As shown above, the geophysical methods are able to detect the expected two layer system (alluvial sediments overlying chalk rock). However, the comparison of the two methods show discrepancies in the estimated thickness of the alluvium, i.e., the electrical images lead to an overestimation of the bedrock depth of up to 100% compared to the seismic images. To account for this a combined interpretation of both methods is aimed. Therefore, the information of the seismic results (i.e., the bedrock boundary location) will be used as

constraints for the inversion of the geoelectrical data. This shall be done by decoupling of the spatial regularization (within the ERT inversion) at the location of the intersection as observed in the seismic images.

4 GEOPHYSICAL MONITORING OF INFILTRATION EXPERIMENTS

4.1 Experimental setup

For the infiltration experiment in March 2011, a small basin with 3 m in x- and y-direction, respectively, and a depth of 0.5 m was prepared in the north-eastern outlet of the basin (Figure 14), close to the village, where the Wadi Auja enters the Jordan Valley (Figure 13). Twice a volume of 7 m³ of water was infiltrated through the basin into the subsurface. Time-lapse electrical imaging was conducted over a one week time period to monitor the changes in electrical resistivity, caused by changes in water saturation due to the infiltration of water. Therefore, measurements were performed in two perpendicular arrays, having the infiltration basin in the centre of the arrays. For each array, 48 electrodes with 1 m separation were used in a skip3 dipole-dipole configuration. One dataset in each array was collected as background before the start of infiltration in order to compare the background with the following changes over time. For the background measurements, also IP was measured as well as the reciprocal configuration. In order to save time, IP was not measured for the time steps after start of infiltration, since there is no significant IP effect expected in correlation with water infiltration.



Figure 13: Location map of the geoelectrical arrays along the infiltration experiment (white cross). The infiltration basin is located in the centre of the cross. Also shown are the locations of the three exploration boreholes (Picture source: Google Earth).



Figure 14: Pond filled with water for the infiltration experiment. Also the measurement device (orange cables and electrodes in the foreground) for the geoelectrical imaging can be seen.

4.2 Results

As described above (see Section 3.2.1), the processed data were inverted with the code CRTomo (Kemna, 2000). Here, a special difference inversion was used to focus only on the temporal changes in electrical resistivities, which are correlated with the change of water saturation (e.g., Daily et al., 1992; Zhou et al., 2001). The results in Figure 15 show the time-lapse inverted images of the infiltration experiment. The images show the ratio of the difference of time step Tx and time step T0 (i.e., the background measurement before start of infiltration) to time step T0, shown in per cent. The first image shows the background electrical resistivity. Structures close to the surface are related to artefacts in the inversion procedure, for instance rooted in changing electrode positions during the acquisition of measurements, since the electrodes could not be left in the study area for the whole time. The north-south array shows better images due to better data quality, since the used cable for the east-west array for the background measurements caused some trouble and so led to some error in the data.

Table 1: Time steps of infiltration and ERT measurements in hours. T0 represents the background measurement.

Time step	Time after start of infiltration
T0	0 h
Infiltration 1 (7 m ³)	0 h
T1	1.75 h
T2	4.5 h
T3	25 h
T4	49 h
Infiltration 2 (7 m ³)	76 h
T5	96.5 h
T6	147 h

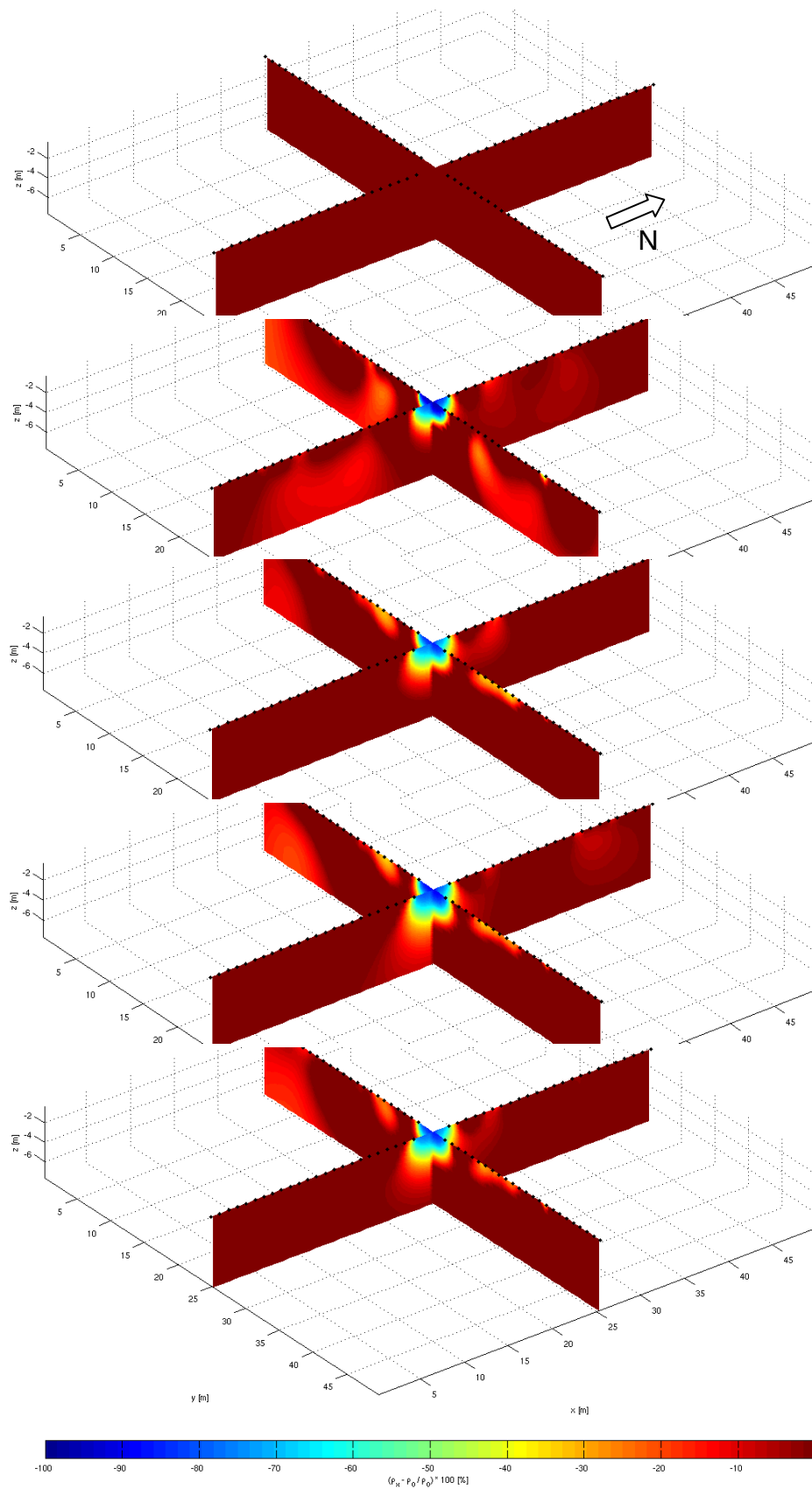


Figure 15: Results of time-lapse ERT along the infiltration experiment. The infiltration occurred in the centre of the two arrays crossing. Black dots are the electrodes.

Figure 16 shows the changes over time of the electrical conductivity with depth. Here, the change in electrical conductivity can qualitatively be related to the change in water saturation. T1 was measured during the first filling of the infiltration pond and T2 was measured after finishing. This explains the significant increase from T1 to T2. T4 was two days after infiltration, and between T4 and T5 the second filling of the pond took place, which is also indicated by an increase in electrical conductivity. T6 is again two days after infiltration. Table 1 gives an overview of the time steps. Thus, the electrical conductivity increases with time and depth, which can be correlated with an increase in water saturation. Using petrophysical relationships (e.g., Archie, 1942), it is also possible to quantify the infiltrated water volume. For this, additional information is needed, like the porosity of the soil as well as empirical parameters of the soil related to cementation and water saturation.

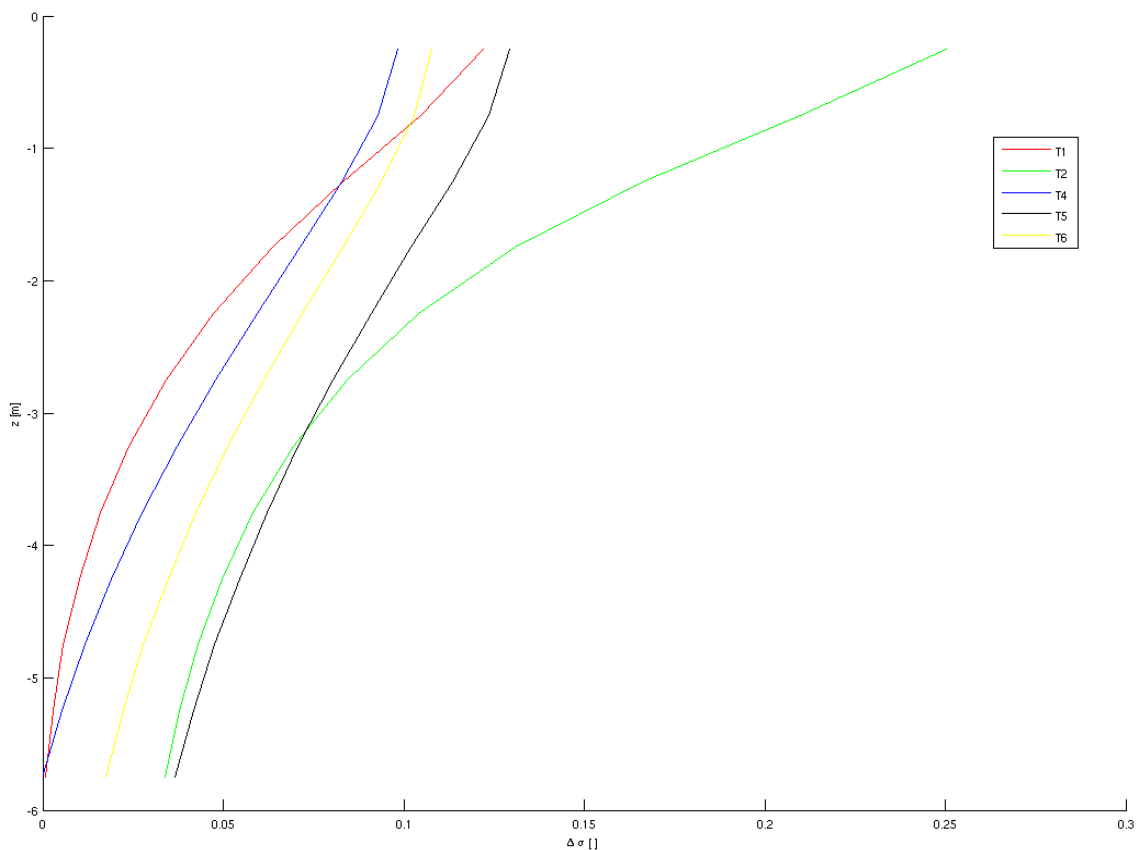


Figure 16: Change in electrical conductivity with depth over time.

Figure 17 shows the IP response of the area along one array. The first image shows the magnitude of resistivity, and in the second image the phase of resistivity is shown. Both images show where the water infiltrated in the shallow subsurface (in the centre of the images).

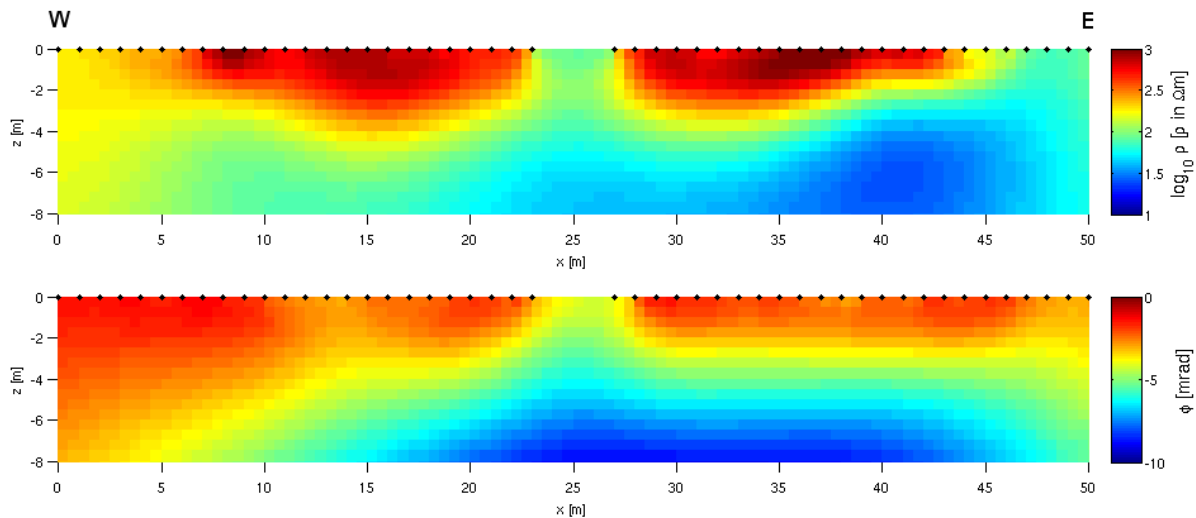


Figure 17: Resistivity magnitude (top) and phase (bottom) images of the West-East array along the infiltration experiment. Results show measurements after infiltration (T6).

4.3 Hydrogeological investigations

In addition, two experiments using a double-ring infiltrometer were conducted within the basin before the start of infiltration in order to calculate the hydraulic conductivity of the very shallow subsurface. Additionally, the hydraulic conductivity of the alluvial sediments was tested with other methods:

- Calculations from sieve analyses from soil and sediments samples (not finished yet).
- Measurements in laboratory from borehole sediments samples.
- Measurements in laboratory from undisturbed soil specimen (not finished yet).
- Calculations from falling head injection experiments in boreholes.

All results of hydraulic conductivity investigations are summarized in Table 2.

In November 2011, three exploration boreholes were drilled in the area close to the village (Figure 8) by GMT (Geotechnical & Material Testing Center, Ramallah). Borehole BH1 reached a depth of 5 m and the other boreholes reached 20 m. Hydraulic conductivity was calculated by GMT in the laboratory using sieve analysis and sediment samples. The values for hydraulic conductivity vary from $1 \cdot 10^{-7}$ m/s (in the very shallow subsurface) to about $8 \cdot 10^{-4}$ m/s. The hydraulic conductivity of the shallow subsurface (i.e., < 2 m depth) is less, since it contains fine soil material.

Table 2: Results from measured hydraulic conductivities using different investigation techniques.

Method of investigation	Hydraulic conductivity
Falling head method in exploration boreholes	BH1: $7.6 \cdot 10^{-4}$ m/s BH2: $9.9 \cdot 10^{-5}$ m/s BH3: $1.1 \cdot 10^{-4}$ m/s
Laboratory test of sediment samples from BH1 at different depths	0-1 m: $1.1 \cdot 10^{-7}$ m/s 1-2 m: $1.7 \cdot 10^{-4}$ m/s 2-3 m: $1.9 \cdot 10^{-5}$ m/s 3-4 m: $3.5 \cdot 10^{-6}$ m/s 4-5 m: $9.7 \cdot 10^{-6}$ m/s
Double-ring infiltrometer tests within infiltration pond	Test 1: $2.8 \cdot 10^{-6}$ m/s Test 2: $1.5 \cdot 10^{-6}$ m/s

From undisturbed soil specimen, a mean porosity of 35% was measured for the alluvial sediments.

5 CONCLUSIONS

Different geophysical methods were applied to investigate the alluvial basin west of village Auja. Refraction seismics as well as electrical imaging was carried out along several arrays in the northern part of the basin.

The results of the geophysical surveys in the basin centre reveal a thickness of the alluvial sediments of up to 30 m with some variations due to paleo-relief of the bedrock boundary. Towards the north-eastern direction of the basin, where its outlet is located, the thickness decreases to about 20 m and the paleo-relief shows a channel structure parallel to the recent Wadi Auja.

An infiltration experiment was carried out in the alluvial sediment to investigate the infiltration behaviour and to characterize hydraulic properties of the sediments. The experiment was monitored using time-lapse electrical imaging, and supplementary hydrogeological investigations were applied to calibrate the geophysical results.

The geophysical results suggest a geometry and hydraulic characteristics of the alluvial basin west of village Auja that make it suitable for subsurface storage. Further investigations are needed (investigation boreholes in the basin centre to calibrate the RS and ERT results) as well as numerical modelling of aquifer recharge scenarios (see Section 6).

6 PERSPECTIVES

A hydrogeological flow model for the alluvial basin is intended to be developed based on the results of the geophysical surveys. The model will allow to test scenarios of artificial recharge for using the basin for subsurface water storage.

Further, boreholes shall be drilled in the central part of the basin, along the seismic and electrical arrays, for calibration of the geophysical results.

A special inversion scheme for the electrical data that were collected along the seismic arrays will be developed. Here, the information from the seismic results will be incorporated as constraints to the inversion of the electrical data (as mentioned in Section 3.3). This will force the strict known boundary between the two layers in the inversion and lead to more appropriate results of the electrical imaging. These results, in combination with the geological information (field investigations, dipping of geological beds, geological map), will be used to develop a geological three-dimensional model of the alluvial basin, which in turn will be used for the parameterization of the hydrogeological flow model.

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