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Airborne Geophysical Investigation of Groundwater Resources in Northern Sumatra after the Tsunami of 2004

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1. Introduction

The earthquake and the tsunami event on December 26th, 2004, caused not only the loss of life of a huge number of people and the destruction of houses, basic infrastructure and public facilities but also large scale salt-water intrusions and destruction of thousands of shallow water wells in the coastal region of the Province of Nanggroe Aceh Darussalam in northern Sumatra, Indonesia. The supply of a sufficient amount of potable water in all populated areas was complicated as many water pipes were broken by the earthquake and a huge number of dug wells were unusable after the tsunami. Furthermore, many new drillings were not successful in finding potable water due to the lack of information about local hydrogeological conditions. Therefore, the Indonesian and German governments set up a project dedicated to re-install the public life of the people living in the coastal regions of northern Sumatra. The focal point of this project was water assessment along the shorelines of Aceh about nine months after the tsunami.

In order to get a fast overview on the remaining freshwater resources and to assist the Indonesian authorities such as the Directorate General for Geology and Mineral Resources (DGGMR), the National Development Planning Agency (BAPPENAS) and the Executive Agency for the Rehabilitation and Reconstruction in Nanggroe Aceh Darussalam Province and Nias Islands (BRR) as well as numerous aid organisations in finding suitable locations for drilling new water wells, it was decided to use airborne geophysics. The helicopter-borne surveys including electromagnetics, magnetics and gamma-ray spectrometry were conducted by the airborne group of the German Federal Institute for Geosciences and Natural Resources (BGR) from August to November 2005. As the mineralisation of water correlates with its electrical conductivity and therefore freshwater and salt water can be distinguished in general, it was hoped that electromagnetic data would reveal freshwater resources not destroyed by the tsunami, particularly close to the populated coastal areas.

The target areas (Fig. 1) of the German-Indonesian cooperation project HELP ACEH (HELicopter Project ACEH) were the city of Banda Aceh with the district of Aceh Besar on the north coast and the area on the west coast between the towns of Calang and Meulaboh in the district of Aceh Barat (Siemon et al., 2007). In addition to that, Coca-Cola Foundation Indonesia (CCFI) funded a further survey on the north-east coast around the town of Sigli in the district of Aceh Pidie (Steuer et al., 2008).

Fig. 1. BGR survey areas (red dotted lines) in the Province of Nanggroe Aceh Darussalam, northern Sumatra. The elevation map was derived from SRTM data.

2. Method

The extremely fast airborne measurements are generally carried out on parallel flight lines. BGR uses a helicopter, a Sikorsky S-76B, to carry the geophysical equipment (Fig. 2). The helicopter-borne electromagnetic (HEM) system as well as the magnetic, GPS and laser altimeter sensors are housed in a 10 m long tube, which is dragged at a mean altitude of about 40 m above ground level. The HEM system (RESOLVE, manufactured by Fugro Airborne Surveys) consists of five small transmitter and receiver coil pairs, which are separated about 8 m. The gamma-ray spectrometer as well as further GPS and altimeter sensors are installed into the helicopter. From the three geophysical methods used simultaneously electromagnetics contributes most to groundwater investigation purposes due to the dependency of a) the electrical conductivity from the salinity of the groundwater, i.e., the groundwater quality, and b) the clay content of the subsurface, i.e., the aquifer conditions.

The HEM transmitter signals, the primary magnetic fields, induce eddy currents into the subsurface which are dependent on the electrical conductivity distribution. The relative secondary magnetic fields from these induced currents are measured at the receiver coils in parts per million (ppm) as they are related to the primary fields.
The use of different frequencies ranging from 387 Hz to 133 kHz enables investigation of different depths: High frequencies resolve the shallower parts of the subsurface and lower frequencies the deeper parts. The depth of investigation also depends on the subsurface conductivity distribution: The higher the conductivity the lower the penetration of the electromagnetic fields into the subsurface. Typical maximum investigation depths of the RESOLVE system range from about 30 m (salt-water saturated sediments) to about 150 m (freshwater saturated sandy sediments or hard rocks).

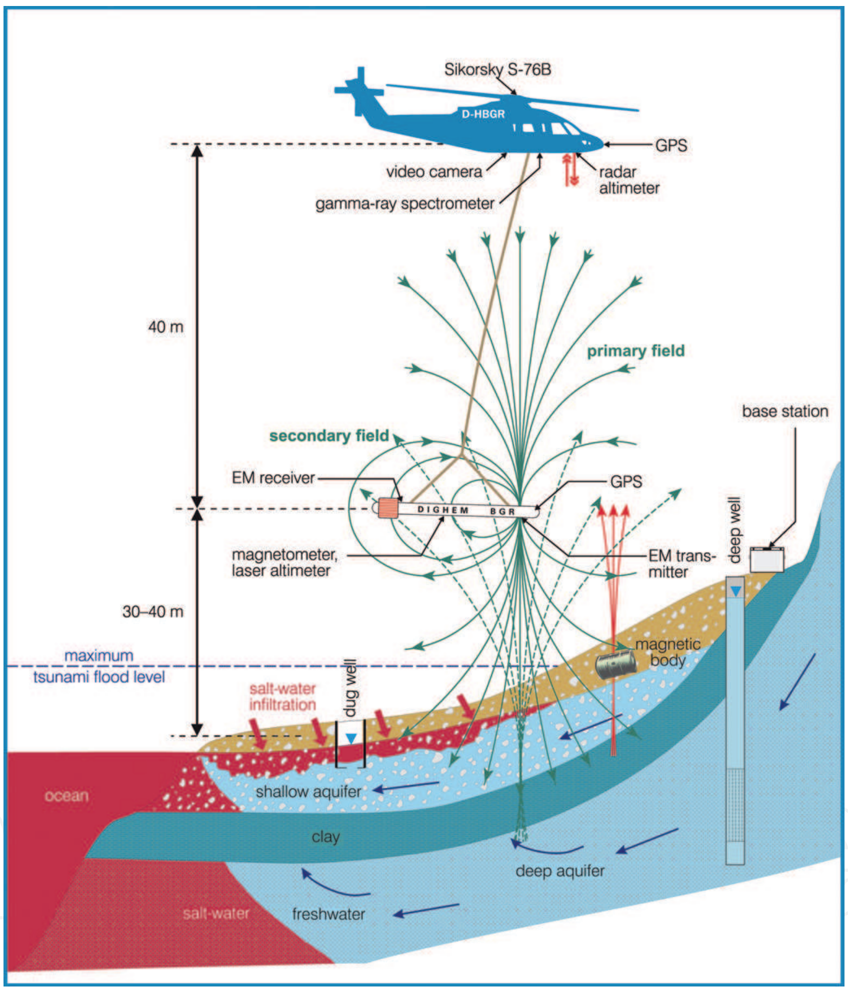

Fig. 2. Sketch of the BGR helicopter-borne geophysical system and the hydrogeological situation expected along the coasts of northern Sumatra.

At the beginning of each survey flight the HEM system was calibrated at high flight altitude (>350 m above ground level) using internal calibration coils. Phase and gain were checked several times during a survey flight at high altitude. Minor remaining calibration errors were corrected by applying correction factors obtained over the sea, where the responses of the HEM system were calculated using the conductivity of seawater and the system altitude. Siemon et al. (2006a,d,e) presented a detailed description of all survey operations.

The in-phase (I) and quadrature (Q) components of the secondary magnetic fields are generally converted to the resistivity (inverse of conductivity) of a layered half-space. The simplest one is a homogeneous half-space (Model 1 in Fig. 3). Its parameter, the apparent resistivity ρ_a [Ωm] is normally derived from the data of a single frequency (f). As two data values (I and Q) are available, a second parameter, the apparent distance D_a [m] from the sensor to the top of the conducting half-space, can be derived. The difference between apparent distance (D_a) and system height (h) measured by a laser altimeter is the apparent depth d_a (Fraser, 1978). It is a measure of how conductive the cover is with respect to the half-space: Positive or negative apparent depth values indicate resistive or conductive cover layers, respectively. In addition, the centroid depth is defined as $z^* = d_a + p_a/2$ (Siemon, 2001), where $p_a = 503.3\ (\rho_a/f)^{1/2}$ is the apparent skin depth. The centroid depth can be regarded as a centre depth of the homogeneous half-space. The resulting sounding curves, $\rho_a(z^*)$, provide an initial approximation of the vertical resistivity distribution. They are used to derive appropriate starting models for the one-dimensional (1D) inversion. A Marquardt–Levenberg inversion procedure iteratively calculates the model parameters, resistivity ρ and thickness t of the layers (Model 2 in Fig. 3), from the data of all frequencies available (Sengpiel & Siemon, 2000). The inversion procedure stops when a given threshold (e.g. 10%) is reached, which is defined as the differential fit of modelled and measured HEM data.

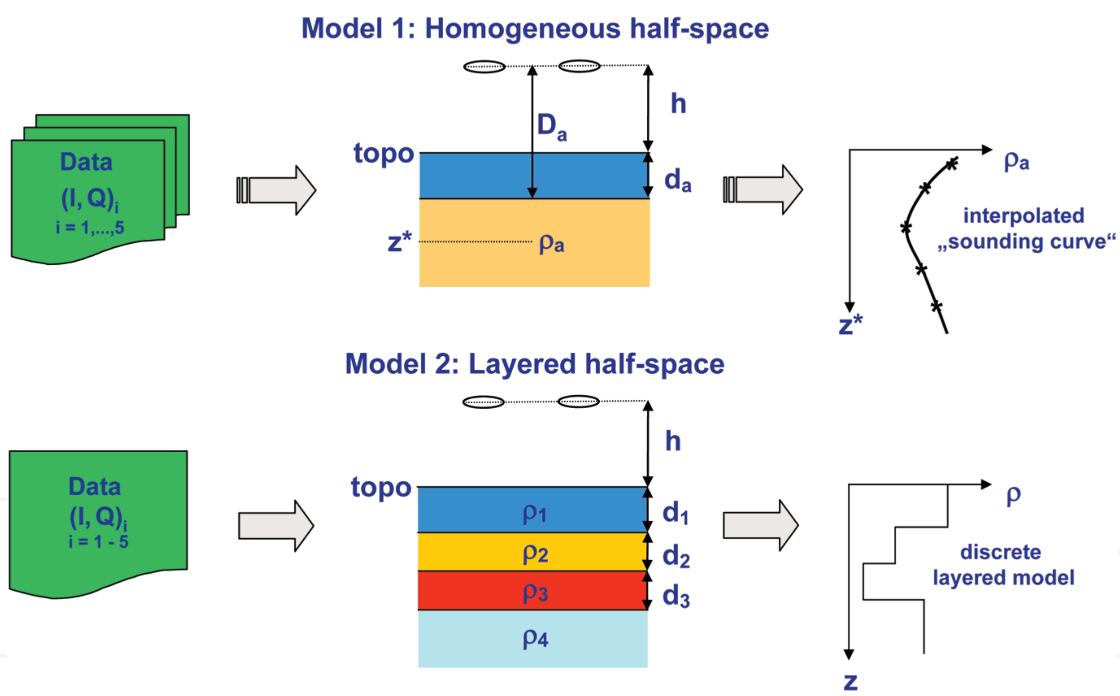

Fig. 3. Sketch of HEM inversion based on a homogeneous half-space or a layered half-space.

The results of the 1D inversion are presented as vertical resistivity sections (VRS) and as resistivity maps. The VRS are constructed by placing the resistivity models for each sounding point along a survey profile next to each other using the topographic relief in metres above sea level (m asl) as base line. The resistivity maps are derived from the apparent resistivities of single frequencies or from the 1D inversion models at selected depths below ground level (bgl). VRS in combination with resistivity maps provide a three-dimensional image of the resistivity distribution in the subsurface. All sections and maps are plotted with respect to UTM coordinates (WGS 84, zone 46N).

3. Airborne geophysical surveys

The survey areas were jointly selected by the German and Indonesian project partners in order to assist Indonesian authorities and international aid organisations in finding freshwater resources not affected by the tsunami that are located close to areas where the people suffering the catastrophe were displaced. The focus was set on populated coastal areas which were heavily destructed by the earthquake and tsunami and where water supply was a major concern.

The airborne surveys funded by BGR covered a) the city of Banda Aceh on the north coast including the valley of the Krueng Aceh as well as two coastal areas on the north-west and north-east coast (survey area Banda Aceh) and b) a broad coastal strip comprising the towns of Calang and Meulaboh as well as a number of villages on the west coast (survey area Calang-Meulaboh). Directly after completing the HELP ACEH surveys another airborne survey funded by CCFI was conducted covering the Sigli Coastal Plain on the north-east coast (survey area Sigli).

All airborne surveys were accompanied by hydrogeological reconnaissance surveys conducted by BGR and funded by the German Federal Ministry for Economic Cooperation and Development (BMZ).

3.1 Banda Aceh

Regional geology and hydrogeology

The Krueng Aceh valley is bounded to the south-west by the Aceh Fault and to the north-east by the Seulimeum Fault (Fig. 4). The West Coastal Range to the south of the Aceh Fault is built up by the pre-Tertiary limestones. The volcanics of Pleistocene to Holocene age cover most of the North Coast Foothills on either side of the Seulimeum Fault. Within the upper Krueng Aceh valley, the Tertiary rocks are covered by up to 500 m thick Plio-Pleistocene semi-consolidated calcareous and tuffaceous sandstones. From upstream of the town of Jantho to downstream of the town of Indrapuri, the Pleistocene coarse-grained partly volcanic sands and gravels form a prominent terrace surface on either side of the Krueng Aceh. These older terrace deposits may attain a thickness of up to 75 m. The alluvium near the coast of the city of Banda Aceh extends to a depth of more than 200 m below ground level becoming thinner upstream (Bennett et al., 1981a; IWACO, 1993).

The Hydrogeological Map Banda Aceh (Soetrisno, 1993a) indicates the alluvium as the main productive aquifer system within the Krueng Aceh valley. Downstream of Indrapuri, the alluvial deposits can be subdivided into a shallow aquifer system and a deep aquifer system. The top 20 metres, ranging from sandy clays to sands and gravels, are considered to be the shallow aquifer system that is directly recharged from rainfall and is still the major traditional resource for domestic water supply. The deep aquifer system comprises a few thin sand-gravel horizons below thick clay layers within the coastal belt. The thickness of the freshwater-bearing aquifer ranges from 3 to 15 m. At a depth ranging from 75 to 140 m bgl, these sandy to gravelly layers bear highly confined fresh groundwater. Upstream of Indrapuri, the alluvial sandy-gravelly deposits in the vicinity of the river courses, the older terrace sand-gravel deposits and the semi-consolidated sandstones are assumed to constitute the main aquifers of the upper part of the Krueng Aceh valley (Ploethner & Siemon, 2006a).

Helicopter-borne survey

The northernmost survey area, Banda Aceh, is bounded towards the north and west by the Andaman Sea and the Indian Ocean, respectively. It comprises the city of Banda Aceh and the valley of the Krueng Aceh (red dots in Fig. 4). The 20 km by 50 km wide area was surveyed with 24 flights within three weeks from August 23rd to September 12th, 2005. The nominal flight-line spacing of the 156 SW–NE lines was 300 m, increased to 900 m in the southern quarter of the survey area, and the 24 NW–SE tie lines were 1000 m apart, resulting in a total flight-line length of about 4000 km. The small area of 2 km by 14 km along the north-east coast was covered with one flight on September 13th, 2005, with a line spacing of 200 m for the 11 NW–SE lines. The survey flights commenced from Blang Bintang airport south-east of Banda Aceh (Fig. 1).

HEM survey results

The most important task of the project was to map the tsunami-affected salinization of shallow groundwater resources and to outline remaining shallow occurrences of potable water. Due to the dependence of the electrical conductivity on the pore-water salinity, this

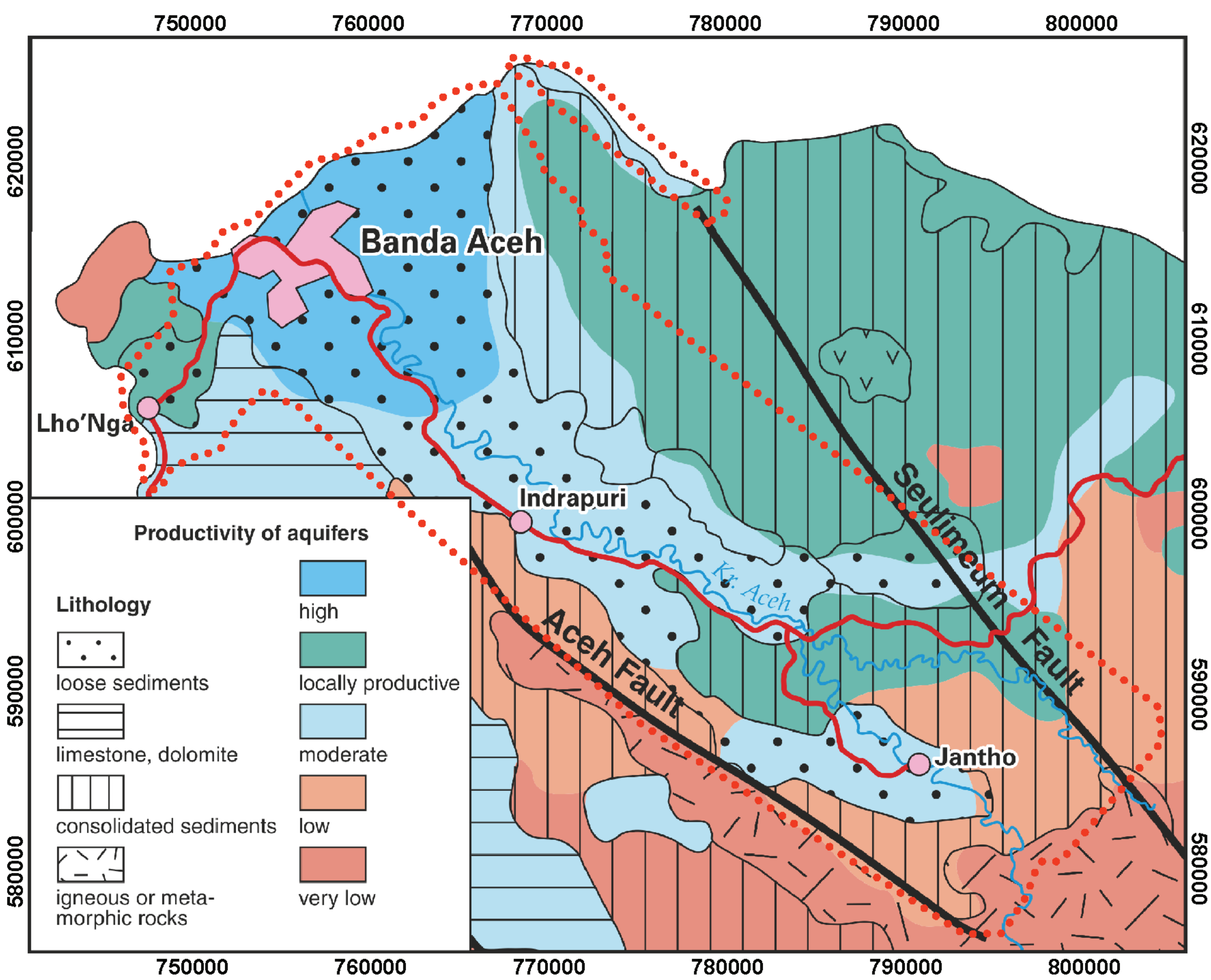

Fig. 4. Hydrogeological situation in the northernmost part of Sumatra (after Soetrisno, 1993a and Setiadi, 2004); main roads, rivers and faults are marked by red, blue and black lines, respectively, and the boundary of the airborne survey area is indicated by red dots.

task could successfully be realized by calculating and displaying the resistivity at several depth levels. About four million 1D resistivity models were calculated from five-frequency HEM data. Maps displaying the resistivity distribution at selected depths below ground level were derived from these models. Fig. 5 shows exemplarily the resistivity distribution at 10 and 30 m bgl for the entire survey area. These maps reveal very conductive areas indicated by red colours near the coasts which are obviously due to seawater saturated sediments. Freshwater resources can be expected where green and blue colours occur which represent fairly resistive areas. Low to medium resistivities (orange to yellow colours) may be caused by brackish groundwater or clayey sediments. Some of the small blue spots on the resistivity map at 10 m bgl, however, are due to laser altimeter readings affected by palm trees. The automatic procedure used for detection and correction of such misleading laser altimeter readings failed in case of widespread dense palm forests resulting in reduced laser altitude values and, thus, in elevated (virtual) ground-level values.

In order to outline shallow freshwater resources an apparent resistivity map being not affected by misleading laser altitude measurements was produced based on the data of the highest frequency (133 kHz). The very low apparent resistivities (less than 3 Ωm) along the coast close to the city of Banda Aceh clearly demonstrate that the salinization of the shallow groundwater was apparent up to several kilometres inland still nine months after the tsunami. This area, however, is definitely smaller than the extent of the tsunami flooding denoted by the dashed line in Fig. 6 (DLR, 2005a,b). It is also evident from Fig. 6 that the shallow salt-water intrusion on the north-west coast as well as that on the north-east coast is restricted to small areas close to the shoreline.

About 5 km inland the apparent resistivity map outlines an about 3 km wide strip of elevated apparent resistivities indicating freshwater resources within the Krueng Aceh valley. One is situated about 10 km to the east of the city of Banda Aceh. The lateral and vertical extents of this freshwater lens on top of saline water are clearly delineated by resistivity maps and vertical sections, e.g. along profile 29.1 in Fig. 7. The simplified lithology of borehole (B) shows exemplarily that shallow and deep aquifers are separated by clayey layers at a depth where saline water obviously occurs.

Electrical conductivity (EC) values (coloured dots and squares in Fig. 6) derived from water samples of mostly shallow boreholes, dug wells and surface waters sampled by Planéte Urgence (2005) in February 2005 and by BGR from August to October 2005 (Ploethner & Siemon, 2006a) are in good agreement with the airborne data. Discrepancies occur where water samples were taken from deep (sometimes artesian) wells. Some BGR EC samples are located within the salt-water area. They indicate deep freshwater occurrences below the salt water, not revealed by the airborne data due to the limited penetration depth of the HEM fields in highly conducting salt-water areas.

Resistivity maps, particularly at 30 m bgl (cf. Fig. 5), also outline areas of deep salt-water occurrences not directly affected by the tsunami. Saline water was found in at least two boreholes (located less than 2 km to the south of borehole (B) in Fig. 6) at 30–50 m depth before the tsunami, confirming that deep salt water occurs several kilometres inland. Therefore, all red to pink coloured areas can be regarded as affected by salt water. Freshwater resources are restricted to the hard-rock area and along the bed of the Krueng Aceh palaeoriver.

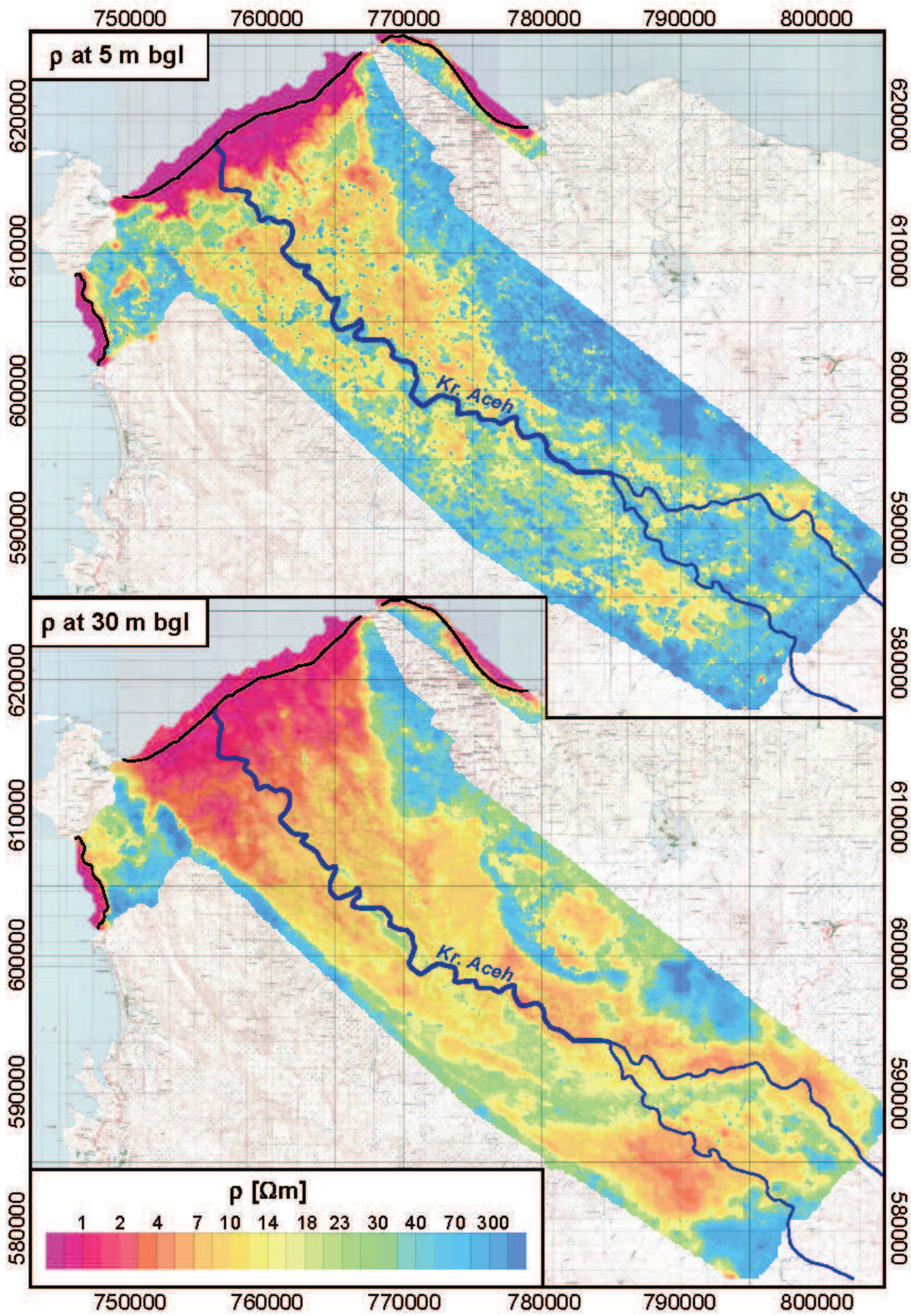

Fig. 5. Resistivity distribution at 5 and 30 m bgl derived from 1D inversion models of the Banda Aceh survey area with coast line (black) and rivers (blue). Background: TMI (1978).

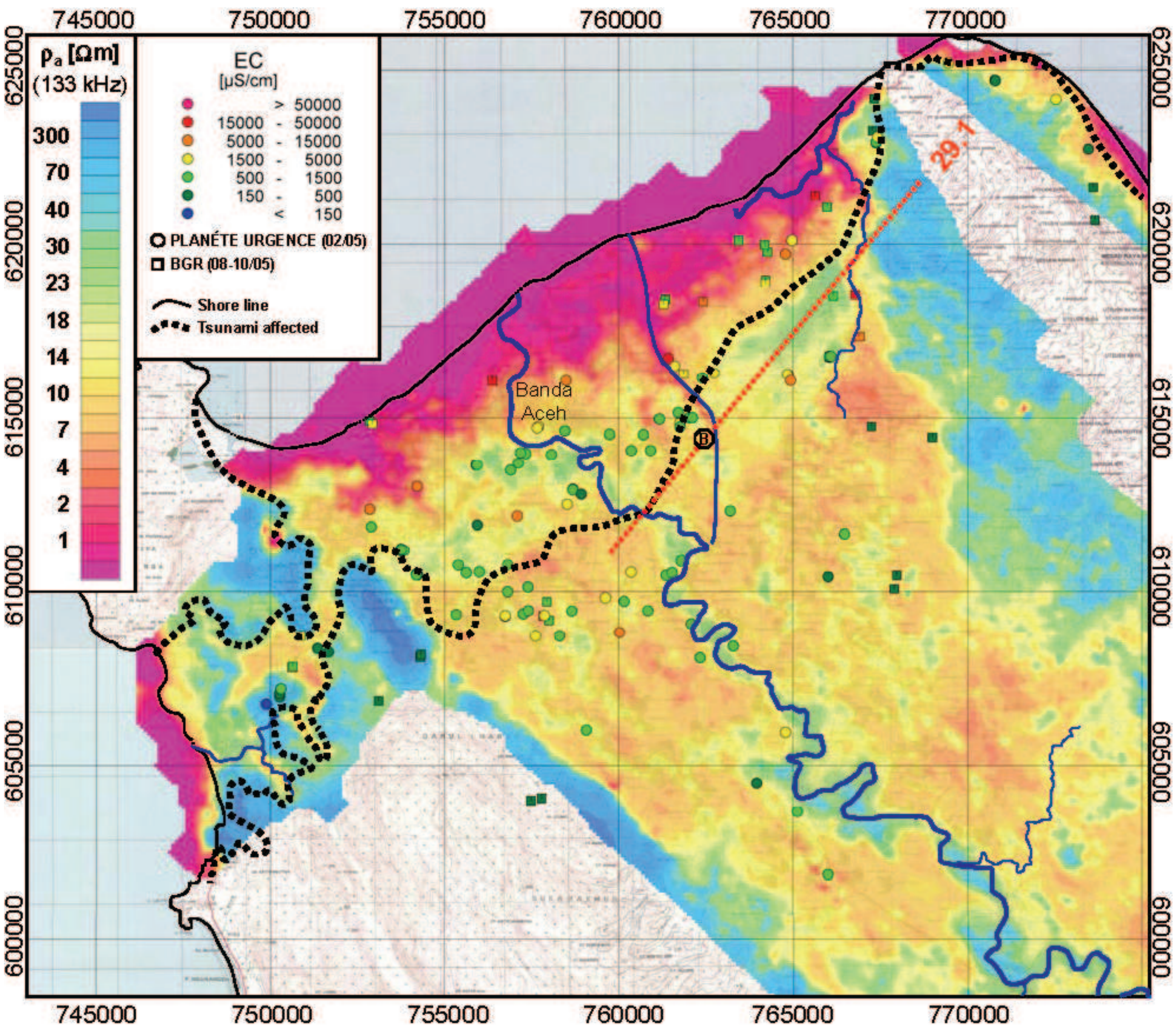

Fig. 6. Apparent resistivity at a frequency of 133 kHz revealing the lithology and the salinization of the shallow groundwater in the northern part of the Banda Aceh survey area. Water conductivity samples (coloured dots and squares), maximum extent of the tsunami flooding (dashed black line) and main rivers (blue lines) are plotted on top.

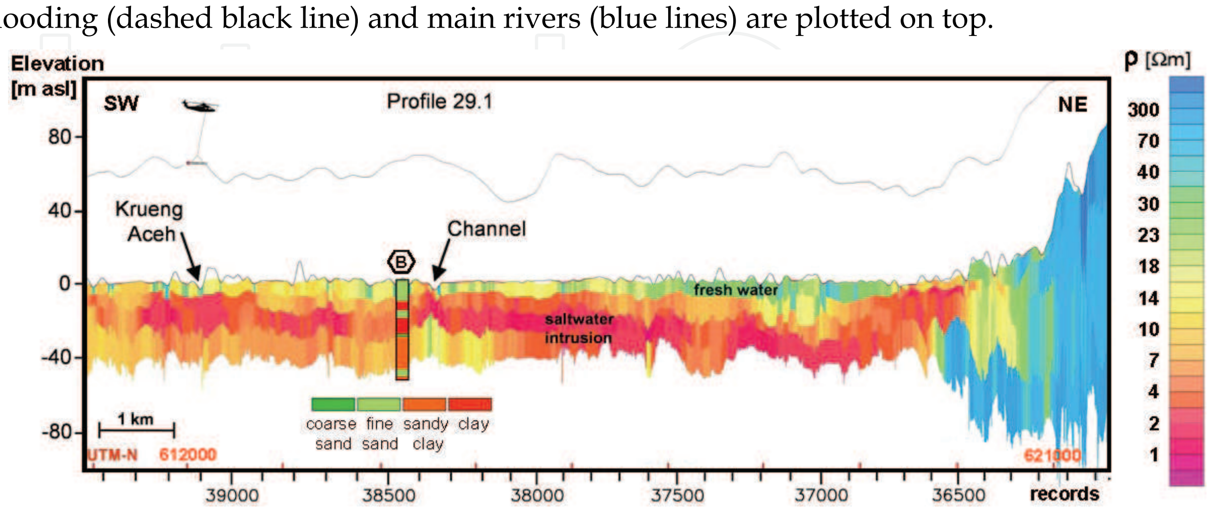

Fig. 7. Resistivity section along a profile 29.1 (cf. Fig. 6) showing a freshwater lens on top of salt-water saturated sediments; simplified lithology of a borehole (B) is plotted on top.

3.2 Calang - Meulaboh

Regional geology and hydrogeology

The central and southern parts of the Calang-Meulaboh survey area belong to the Meulaboh Embayment, an extensive coastal plain of very low relief. It has a maximum width of 50 km at Meulaboh and rarely exceeds elevations of 100 m asl (see Fig. 1). To the north-west, the coastal belt gradually becomes narrower and, to the north-east, the Meulaboh Embayment is terminated by the major westwards throwing Batee Fault whose scarp defines the north-eastern edge of the embayment. The Meulaboh Embayment is underlain to a great extent by sediments such as conglomerates, sandstones, claystones and lignites (Bennett et al., 1981b; Cameron et al., 1983).

Several rivers continuously transporting a substantial volume of suspension load cut the coastal belt (Fig. 8). By the process of sedimentation of the suspension load in the lower

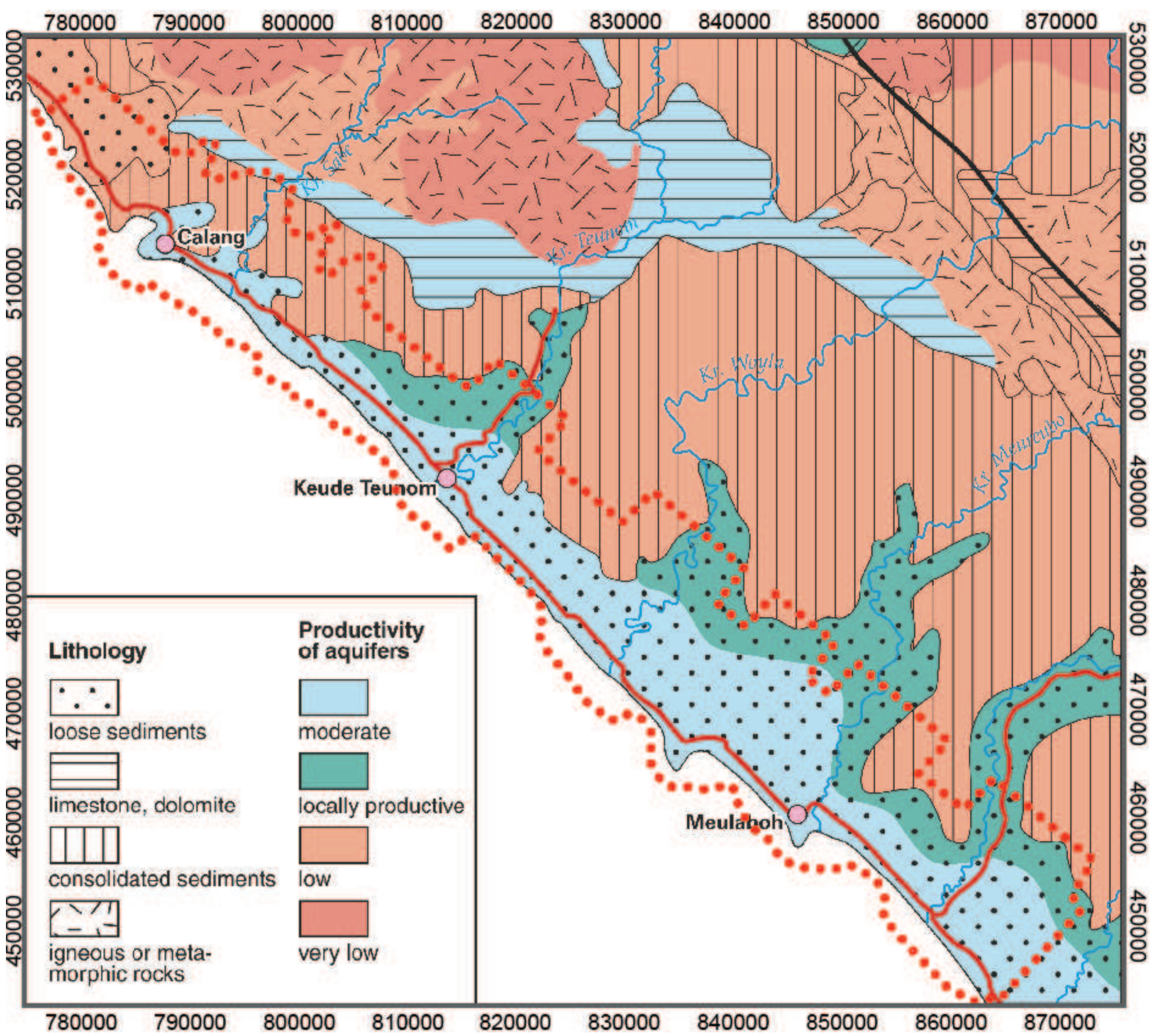

Fig. 8. Hydrogeological situation along the west coast of northern Sumatra (after Setiadi, 2004); main roads, rivers and faults are marked by red, blue and black lines, respectively, and the boundary of the airborne survey area is indicated by red dots.

reaches of the river valleys, these valleys were elevated compared with the deep-lying interfluvial swamps. In the upper 10 to 20 metres of the fine to coarse sands, a shallow unconfined aquifer is traditionally tapped by dug wells. A deep aquifer exists about 50 m below the clay-rich sediments. In the surroundings of Calang, Tertiary volcanic rocks and sedimentary rocks, like sandstones to siltstones, constitute poorly productive fissured aquifers (Ploethner & Siemon, 2006b).

Helicopter-borne survey

The survey area along the west coast (red dots in Fig. 8) in the district of Aceh Barat covers a 10–20 km by 120 km wide area. Thirty-two survey flights including 151 SW–NE profile lines and 25 NW–SE tie lines were flown, totalling about 4715 line kilometres. The nominal flight-line spacing was 500 m for both the profile lines and the tie lines. The tie lines were flown first in a 10 km wide strip parallel to the coast, and then the lines were flown perpendicular to the shoreline in the vicinity of the rivers. The helicopter-borne survey covered the area of 1700 km^2 within five weeks, from September 14^{th} to October 21^{st}, 2005. The survey flights commenced from a small local airport to the south-east of Meulaboh.

HEM survey results

It is obvious from the resistivity distribution at 10 m bgl (Fig. 9) that shallow freshwater occurrences can be expected in the entire survey area due to resistivity values above 40 Ωm, which represent sand, gravel and hard rock. Only close to the coast and along river-beds, where low resistivity values (below 5 Ωm) occur, contamination of the groundwater with salt water is apparent.

At greater depths (e.g. at 30 m bgl), lower values caused by clayey material dominate the resistivity maps. Areas where the top of the clay is lowered due to erosion by former rivers appear more resistive (green colours) as they were refilled with more sandy material. The blue coloured zones occurring in the central and southern parts of the survey area are correlated with swampy areas, where the top of the clay is generally lowered.

Along the coast, the conductive zone is broader than at shallow depths, correlating with a normal coastal salt-water intrusion. Unlike the situation along the coastal area close to the city of Banda Aceh (Fig. 6), shallow salt-water occurrences are mostly restricted to a small strip close to the shoreline. The two detail maps of coastal areas close to the towns of Calang and Meulaboh illustrate that, about ten months after the tsunami event, the salt-water area was smaller than it had been at the end of December 2004 (DLR, 2005c,d).

Most of the EC values derived from water samples collected in boreholes, dug wells and rivers (Ploethner & Siemon, 2006b) represent freshwater and confirm the airborne results. Only along the river valleys of the Krueng Rigaih and Krueng Meureubo (Fig. 9), resistivity and EC values indicate the presence of salt water.

3.3 Sigli

Regional geology and hydrogeology

The near-surface sediments of the Sigli Coastal Plain (Fig. 10) consist of Holocene alluvial sediments which are predominantly silty clays with intercalations of sand layers. The surrounding foot hills are built up of mainly clastic sediments of the Tertiary succession. In the north-western part of the Sigli Coastal Plain semi-consolidated tuffaceous and calcareous sandstones and coralline limestones are exposed in a horst structure (Bennet et al., 1977).

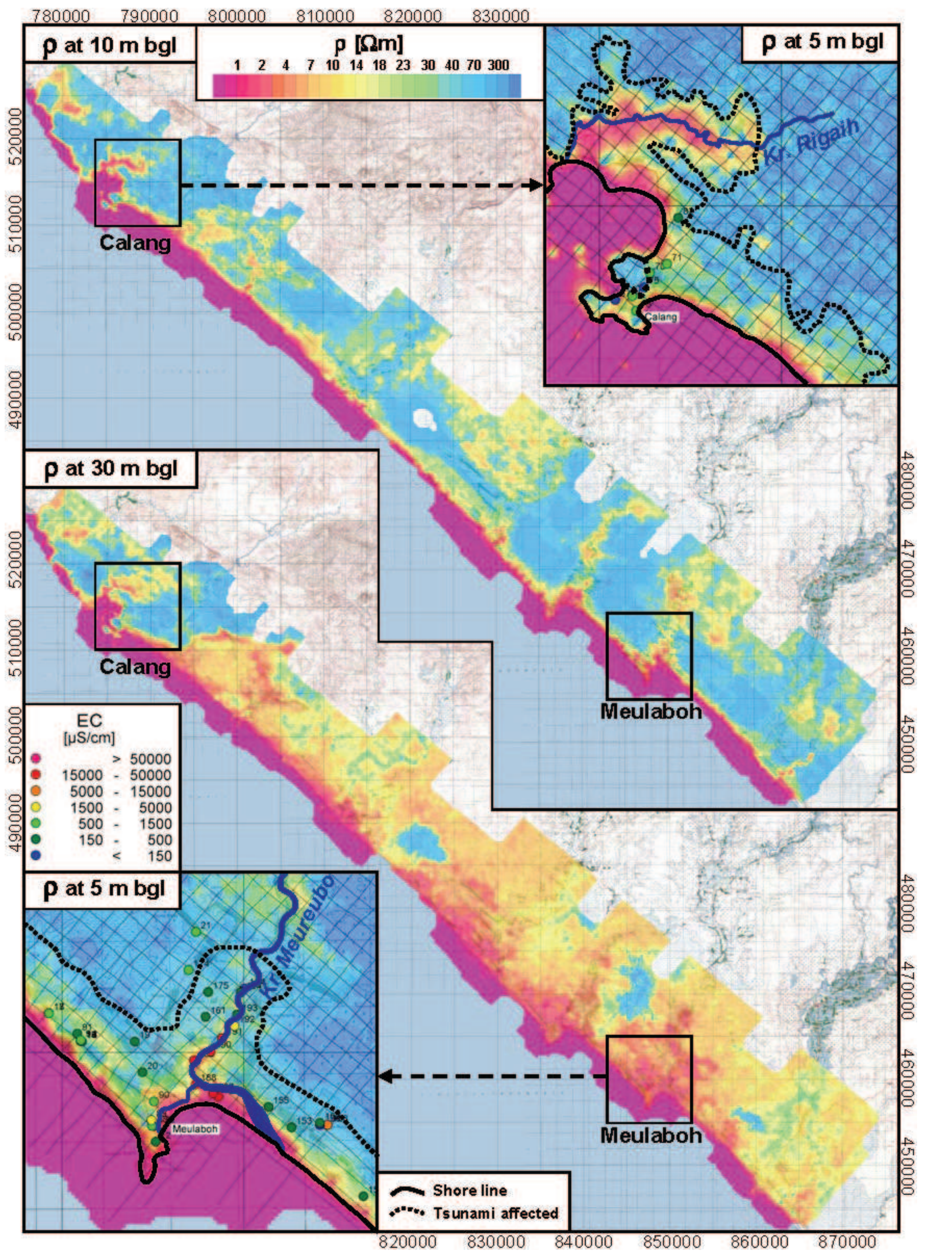

Fig. 9. Resistivity distribution along the west coast at 5, 10 and 30 m bgl derived from 1D inversion models of the Calang-Meulaboh survey area. Water conductivity samples (coloured dots) and maximum extent of the tsunami flooding (dashed line) are plotted on top of the Calang and Meulaboh detail maps. Background: TMI (1978).

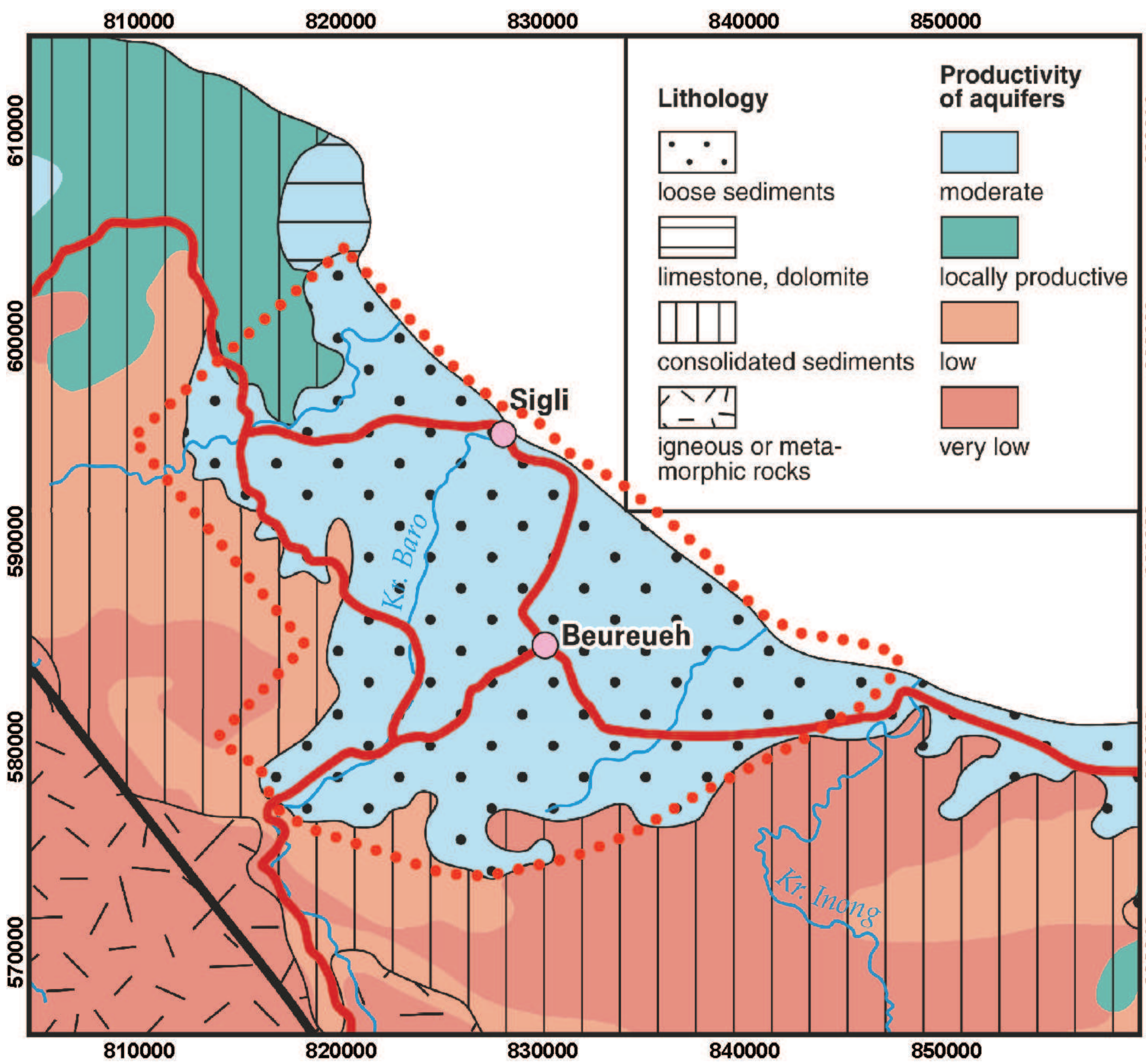

Fig. 10. Hydrogeological situation in the Sigli Coastal Plain (after Soetrisno, 1993a,b and Setiadi, 2004); main roads, rivers and faults are marked by red, blue and black lines, respectively, and the boundary of the airborne survey area is indicated by red dots.

According to IWACO (1993) and Soetrisno (1993a,b), the Tertiary sediments of the foothills at the southern and south-western margin of the plain are generally low productive. Limited shallow groundwater resources can be obtained in weathered zones. The carbonate rocks and the tuffaceous and calcareous sandstones at the north-western margin of the plain are moderately or locally productive aquifers. The alluvium of the coastal plain forms a multilayer aquifer of low to moderate transmissivity and piezometric heads of groundwater near or above land surface. It can be separated into a shallow and a deep aquifer system.

The top 10 to 20 metres of the alluvium are considered to be the shallow aquifer system within the coastal plain. The aquifer is sandy near the coast and primarily loamy further inland. It is directly recharged by rainfall. The shallow aquifer is still the major traditional resource for domestic water supply from numerous shallow dug wells. Before the tsunami, villages lying directly along the coast were also supplied with drinking water from shallow wells. In February 2005, two months after the tsunami, Planète Urgence (2005) revealed high water conductivities in most of the affected wells due to the infiltration of salt water into the groundwater. Control measurements in November 2005 in dug wells in the south-eastern corner of the plain indicated that the shallow groundwater in this area was still highly saline (Eberle et al., 2006). The deep groundwater of the Sigli Coastal Plain is supposed to be recharged in the surrounding foothills where the coastal aquifers are hydraulically in contact with older Tertiary sediments. Here, the piezometric head is being built up, which sustains the flow in the deep lying aquifers towards the coast. The groundwater along the coastal strip is largely artesian because of the apparently continuous clay layers.

Helicopter-borne survey

The survey area of approximately 700 km^2 (red dots in Fig. 10) was covered with twelve survey flights carried out between October 25^{th} and November 7^{th}, 2005. The spacing of the SW-NE lines was 500 m; tie lines running perpendicular to the lines were 3,000 m apart. In total 1,300 line kilometres were flown. The survey flights commenced from Blang Bintang airport, Banda Aceh.

HEM survey results

In the Sigli Coastal Plain, the 1D inversion results provide information on the vertical resistivity distribution to a maximum depth of about 100 m. At the coast, the investigation depth is limited to less than 30 m due to the high conductivity of the salt water. Fig. 11 shows the resistivity maps derived from the 1D inversion models at selected depth levels of 5, 15 and 60 m bgl. Pink to red colours ($\rho < 3\ \Omega m$) indicate very conductive material like salt water; orange to yellow colours ($\rho = 3\text{-}18\ \Omega m$) display conductive material like sediments with high clay content; potential freshwater, limestone and volcanics are more resistive (green to blue colours, $\rho > 18\ \Omega m$).

It is obvious from Fig. 11 that the surface salinization along the coast extents less than 3 km inland (red coloured area). In the central part of the coastal zone, the low resistivity strip is smallest with only 500 m width at places, particularly adjacent to rivers where freshwater is running from the hinterland. The low resistivity strip is widest towards the north-west and south-east corners of the survey area.

An extended system of ponds used for fish breeding lying immediately behind the shore line is thought to enable the permanent influx of seawater through tides. The discovered surface salinization covers for the most parts the area of the pond system. Therefore it is not obvious that the observed shallow salinization was produced by the tsunami waves – in opposite to the situation in the survey areas Banda Aceh and Calang-Meulaboh (Siemon et al., 2007).

In the hinterland, resistivity is generally decreasing with increasing depth. It is strongly supposed that this phenomenon can be explained by the occurrence of thicker clayey Quaternary/Tertiary sediments (mudstones) with a decreasing number of calcareous and sand intercalations. Focusing on depth levels greater than 15 m bgl (Fig. 11), it becomes evident that a resistivity high extending in the central plain over a distance of more than 20 km from the south-west down to the coast is quite consistent with increasing depth. It is considered the most favourable in terms of its potential for freshwater resources. The results of the resistivity-depth mapping infer that quite a strong groundwater flow to the coast must be assumed as the coastal low resistivity strip is smallest in the central part. The boundary between seawater and freshwater even appears to be pushed back off-shore at depths of about 60 m bgl (Fig. 11).

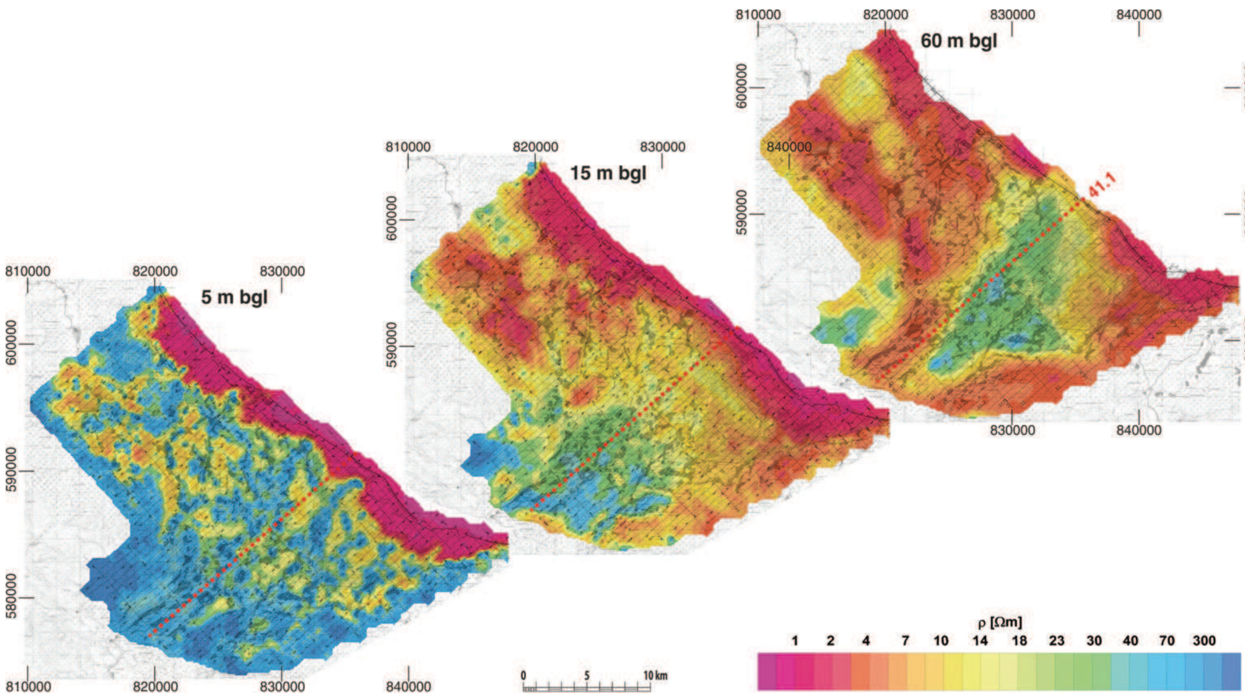

Fig. 11. Resistivity maps at selected depth levels of 5, 15 and 60 m bgl derived from HEM 1D inversion models. Additionally flight line 41.1 (cf. Fig. 12) is indicated by red dots. Background: TMI (1978).

The VRS of flight line 41.1 (Fig. 12) clearly supports this assumption of a strong groundwater flow to the coast. In the south-west resistive sediments, presumably sandstone and conglomerates, are underlain by conductive siltstone and mudstone. In the central part of the flight line, the conductive substrate dives down and the thickness of the sandstone and conglomerates grows. Towards the coast, this potential freshwater aquifer is covered by clayey material that obviously shields this aquifer against seawater intrusion.

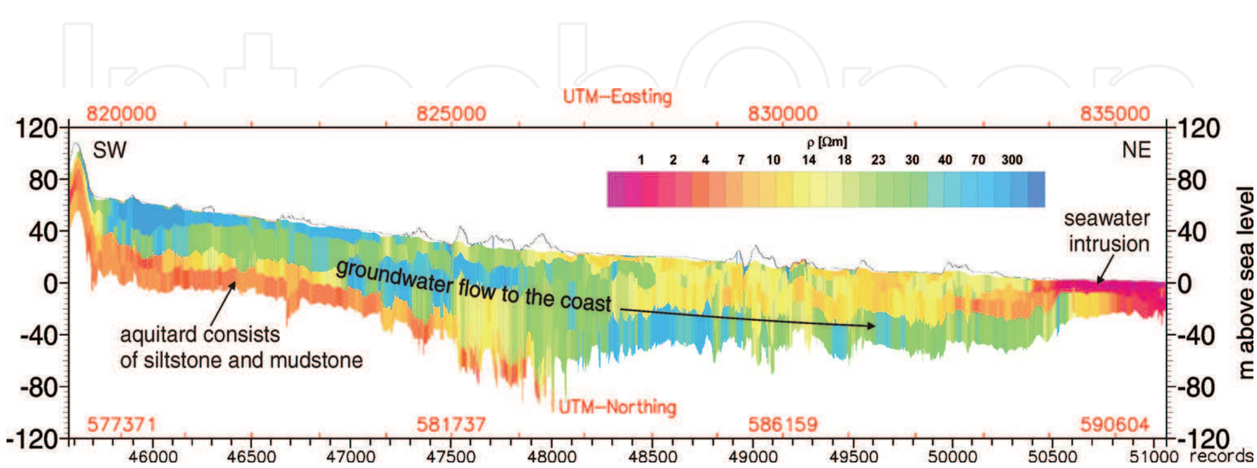

Fig. 12. The vertical resistivity section along profile 41.1 (cf. Fig. 11) crossing the central part of the plain indicates a strong groundwater flow to the coast.

4. Benefit of the airborne survey results

As the aim of the project was to assist Indonesian authorities, which were responsible for planning and realizing the sustainable reconstruction of community infrastructure, the focus was set on groundwater surveys in order to map the remaining salt-water contamination and to outline potential freshwater resources. Particularly the airborne electromagnetic results helped to get a better understanding of the hydrogeological situation as the derived resistivity maps and sections clearly showed where salt water was present and where potential freshwater resources could be expected.

On the north coast (survey area Banda Aceh) shallow salt water was found in a broad strip (about 3 km) whereas deep salt water occurred at around 30 m depth up to more than 10 km inland. On top of these deep salt-water occurrences potential freshwater lenses were mapped in an area 5-10 km from the coast (see Fig. 6) and in the palaeoriver bed of the Krueng Aceh.

The salt-water occurrences along the west coast (survey area Calang-Meulaboh) were mostly restricted to a small strip close to the shore line or some river valleys flooded by the tsunami, and thus, shallow freshwater occurrences could be expected in the entire survey area.

On the north-east coast (survey area Sigli) seawater intrusion appeared to be not strengthened by the tsunami event. The reason for that may be that in the central part of the shoreline groundwater flow from the hinterland is strongly supposed to push back seawater even to off-shore areas. A major potential freshwater occurrence was located beneath the central Sigli plain from the hilly hinterland down to the coast.

Several aid organizations drilled water-wells in order to provide the population of the tsunami affected areas with potable water. Often these drillings were not successful in finding potable water due to the lack of knowledge on the local hydrogeological situation. Many drillings ended up in salt-water aquifers or were stopped before a freshwater aquifer was reached. During and after the airborne survey BGR received many requests for appropriate drilling sites or, if a site had already been chosen, for information about the lithology to be expected. As the airborne survey was accompanied by a hydrolgeological survey those requests could be evaluated based on both geophysical and hydrogeological data. From the numerous requests evaluated for aid organisation (Siemon et al., 2006a,b), one example is shown in Fig. 13. It is evident from the vertical resistivity sections close to the proposed groundwater well (4) located about 35 km to the south-east of the town of Calang on the west coast that salt-water saturated sediments have to be expected below 15 m depth. Therefore it was recommended to drill a shallow well to tape the fresh groundwater of that sandy aquifer.

Besides requests for suitable locations for groundwater wells, a number of potential sites for a new sanitary landfill were evaluated in the vicinity of the city of Banda Aceh with respect to the existence of appropriate geological barriers. Clay as such a geological barrier is detectable, particularly in the vertical resistivity sections, due to the corresponding low resistivity of 3–30 Ωm. As a result of this evaluation, the pre-selected sites (Krause, 2005) had to be re-ranked.

Most of the requests could be answered successfully but not all – particularly if the sites for planned drillings were close to the coast where the high conductivity of salt water reduced the maximum penetration depth of the helicopter-borne electromagnetic fields. In those cases the use of deep-penetrating time-domain electromagnetics is necessary. This method was successfully applied in a ground-based follow-up survey on the north-east coast and it revealed more than 70 m deep potential freshwater resources along the shoreline close to town of Sigli (Steuer et al., 2008).

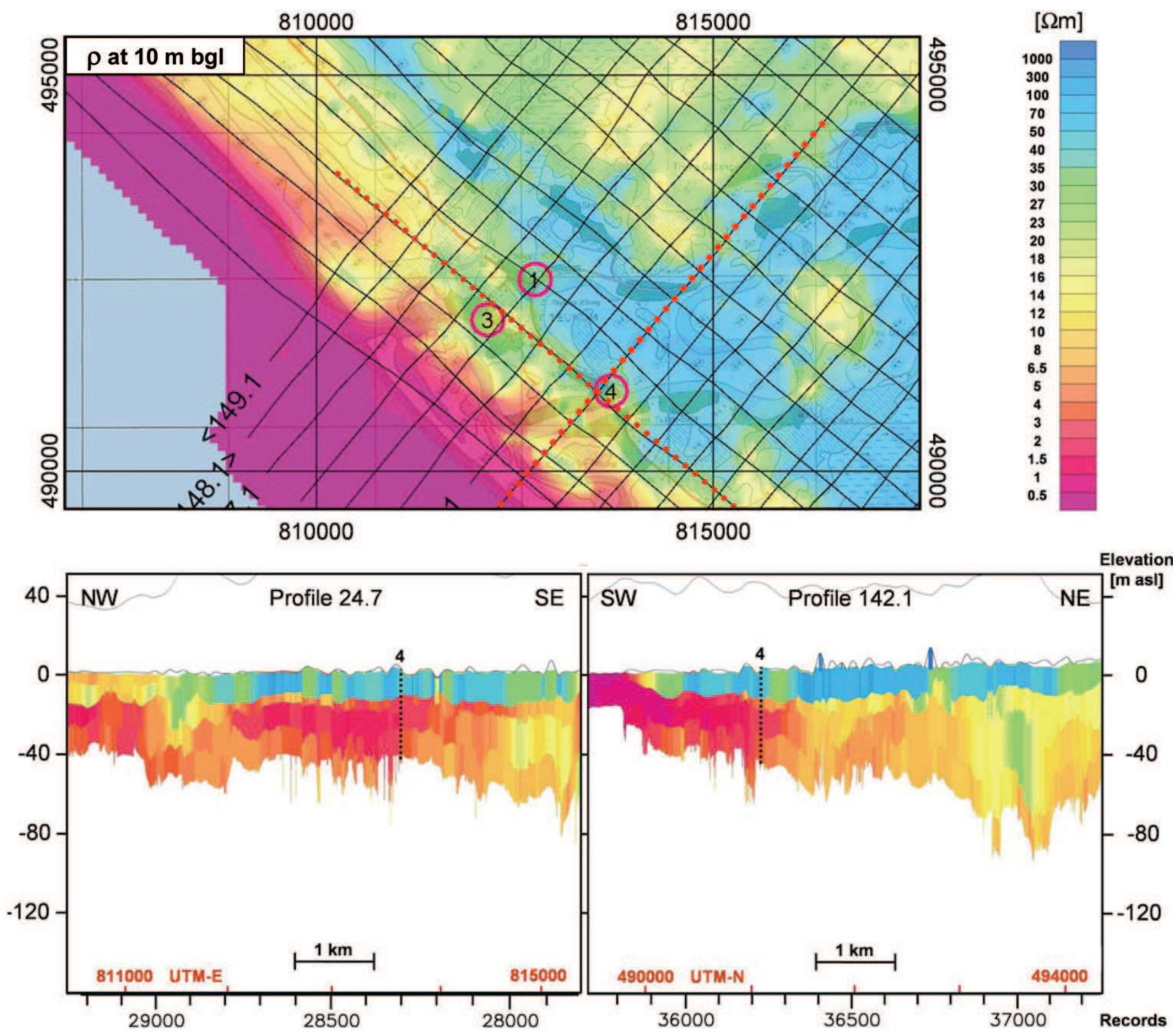

Fig. 13. Evaluation of a request by an aid organisation for an appropriate site for a new well (4); profiles 24.7 and 142.1 are indicated by red dots on the resistivity map.

5. Conclusion

Airborne geophysics is very useful to survey large areas in relatively short time at reasonable costs and provides base-line data on a local to regional scale that may be used for small-scale ground follow-up studies as well as for regional geological or hydrogeological mapping. As the electrical conductivity depends on parameters such as pore-water salinity and clay content, emphasis in the groundwater surveys along coasts of northern Sumatra was placed on the evaluation of the airborne electromagnetic data. Magnetic and radiometric data, which may also contain hydrogeological information, e.g. on fault systems and the lithology on the surface of the earth, respectively, were also evaluated but these results have not been considered in this chapter.

The electromagnetic surveys revealed several potential freshwater resources and areas of salt-water occurrences close to the coasts were mapped in detail. Many requests by aid organisations for information on the local geological and hydrogeological conditions for planned water wells were evaluated and could be successfully answered in most cases.

Close to the coasts, however, the investigation depth of the HEM system was constrained due to highly conductive near-surface salt water and, thus, ground-based time-domain electromagnetic measurements were necessary to reveal deeper coastal freshwater resources. The combination of airborne and ground-based electromagnetic techniques increased the efficiency to estimate the freshwater potential.
The airborne geophysical surveys helped to close the gaps between task-force measures and long-term planning as well as between spatial surface mapping and local borehole data. Particularly airborne electromagnetics proved to be a very efficient tool to assess the newly established post-tsunami groundwater situation and to supply hydrogeological baseline data for rehabilitation programs.

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Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.