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SUSTAINABLE DEVELOPMENT OF WATER RESOURCES, WATER SUPPLY AND ENVIRONMENTAL SANITATION

Assessing Groundwater Resources in Coastal Area: a Case Study in Myanmar

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Coastal aquifers are of a great relevance for human needs because coastal areas are often densely populated. To meet the needs of the people living in coastal area and to assess the groundwater resources for the future, we need to know the main characteristics of these aquifers.

A preliminary hydrogeological assessment is conducted in order to point out the main questions encountered. Then, a geophysical survey is designed to answer these questions. Finally, the economical impact of integrated hydro-geophyscial approach is calculated.

This paper presents the main results of a survey conducted in Myanmar. We found that the joint use of hydrogeological data (boreholes and pumping tests) with appropriate geophysics (magnetic resonance sounding and electrical resistively measurements) improves significantly the knowledge of coastal groundwater resources. The presence of groundwater, its available quantity but also its salinity can be reasonably estimated from surface geophysical measurements.

Introduction

Why hydro-geophysics?

TO MEET the current needs of water supply and to manage the environment in such a way as to preserve the resources for the future needs, the knowledge of water resources is essential. The groundwater resources are usually known by hydrogeologists from in situ surveys. One of the most reliable ways to gather information is the direct observation of the medium (e.g. geomorphology, field geology, etc…) and drilling exploration boreholes. Important aquifer hydrogeological properties are storativity, e.g. the quantity of water stored in the aquifer and available for use by well pumping, and transmissivity, e.g. the productivity that controls the theoretical yield of exploitation well. Storativity and transmissivity are usually quantified thanks to pumping tests interpretation (Kruseman and de Ridder, 2000). It consists in pumping water from a borehole and monitoring the discharge of the borehole, and the drawdown in the borehole and in observation wells. These measurements are used to resolve well-flow equations that lead to calculate storativity and transmissivity of aquifer. A borehole and at least one observation well need to be drilled to setup hydraulic test, and pumping operations can last several days. Hydraulic tests are time and money consuming compared to non-invasive surface geophysics that can provide rapid and low cost dense data coverage, but still at less reliable hydrogeological output.

Measurement of the electrical resistivity of the sub-surface is a common geophysical method. It is widely used for aquifers characterization because of the link that exists between the electrical resistivity of the subsurface, the rock water content and the water salinity (Archie, 1942). In a coastal area, the measurement of electrical resistivity is essential because salinity of the water is a main question. Recently developed magnetic resonance sounding method (MRS) provides additional useful hydrogeological information as any MRS signal means groundwater presence (Legchenko *et al.,* 2002). However, both MRS and electrical resistivity methods are not self-sufficient because geophysical parameters need to be compared with boreholes and pumping tests data prior to quantify storativity, transmissivity and water salinity (Vouillamoz *et al.,* 2002). Moreover, the uncertainty of geophysical interpretation can be notably reduced when several methods are jointly used (Albouy *et al.,* 2001, Goldman *et al.,* 1994).

As a result, integrated hydro-geophysical surveys are recommended to know better the aquifers.

The study area

Action contre la Faim (AcF) is a NGO that works in Myanmar since 1994. It conducts a program of drinking water supply for the vulnerable population of the North Rakhine State (NRS, Figure 1). AcF drilled more than 1,000 boreholes in the coastal area, while 59% of them turned unsuccessful. As a consequence, an integrated hydro-geophysical survey was carried out to know better the aquifers in order to meet both the current and future needs.

The population of the surveyed Maungdaw and Buthidaung townships is about 720,000, mainly living in rural area where agriculture is the first economical sector with rice farming. Water is traditionally supplied by ponds dug by villagers to catch and store rainwater. These ponds do not supply secure water as they are very difficult to protect from faecal contamination. Shallow hand dug wells are also used in some areas, but their poor lining and sanitary seals as well as the unsafe water lifting devices lead the water to be also unsafe. Finally, safe and secure drinking water is only provided by AcF constructed boreholes and protected wells that are accessible to 32% of the townships inhabitants (2004).

The NRS is bordered by the Gulf of Bengal to the West, and it is partly a deltaic zone with low lands that can be flooded both by river/runoff water during heavy rain, and by sea water at high tie. Climate is wet tropical in a monsoonal regime. The average annual rainfall is 4,900 mm and the average air temperature is 26°C.

NRS rocks are recent heterogeneous sediments composed of clay, silt and sand that lie on Miocene shale, claystone and siltstone (Chatenoux *et al.*, 2004). The deposits sequence consists of both continental and marine sediments that are strongly heterogeneous at large scale: the cuttings of drilled boreholes are often different from those of observation wells 20 metres away.

Hydro-geophysical methodology
Hydrogeological questions

According to the analysis of data obtained from a selection of 551 boreholes, two main sets of aquifers are identified. A first set of shallow aquifers extends from few metres below ground level to about 70 metres deep. Their geometry and properties are heterogeneous at a large scale (i.e., few tens of metres). Both the specific capacity calculated from air lift development (that is well correlated to the transmissivity) and the groundwater salinity estimated with its electrical conductivity (EC) have various values (Figures 2A&B). The second set of aquifers are located below 70 metres deep. They

are more homogeneous with almost always higher specific capacity and less risk of high groundwater EC. The EC of groundwater ranges from low mineralized water close to the local rainwater ($60\mu S/cm$) to high mineralized water close to the gulf of Bengal water ($28,000\mu S/cm$). This mineralization can be explained by the rocks sedimentation process with marine sequences, but also by the actual infiltration of ocean water at high tie.

Looking at the data of 1,044 boreholes, several reasons explain unsuccessful boreholes: (1) Holes are dry in 26% of the sites, (2) Borehole productivity is too low in 3.4% of the holes (yield less than $0.5m^3/h$), (3) Water EC is too high for human consumption in 22% of the sites ($EC>3,000\mu S/cm$) and (4) Technical problems do not allow to complete drilling.

The main questions encountered by hydrogeologists are identified with hydrogeological and drilling analyses:
- Is aquifer present in the surveyed location?
- If present, what depth and thickness?
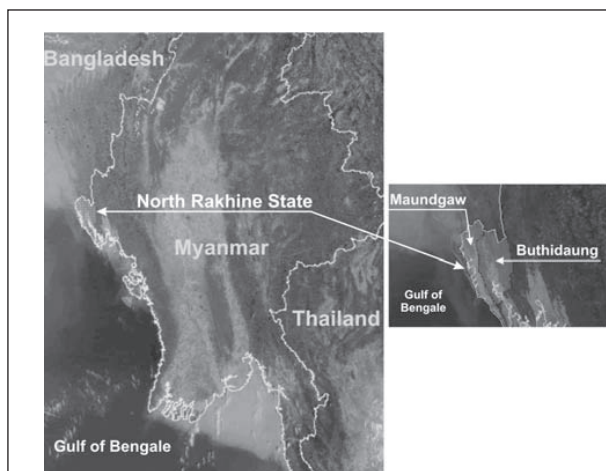- What productivity?
- What groundwater EC?

Figure 2. Aquifer characteristics
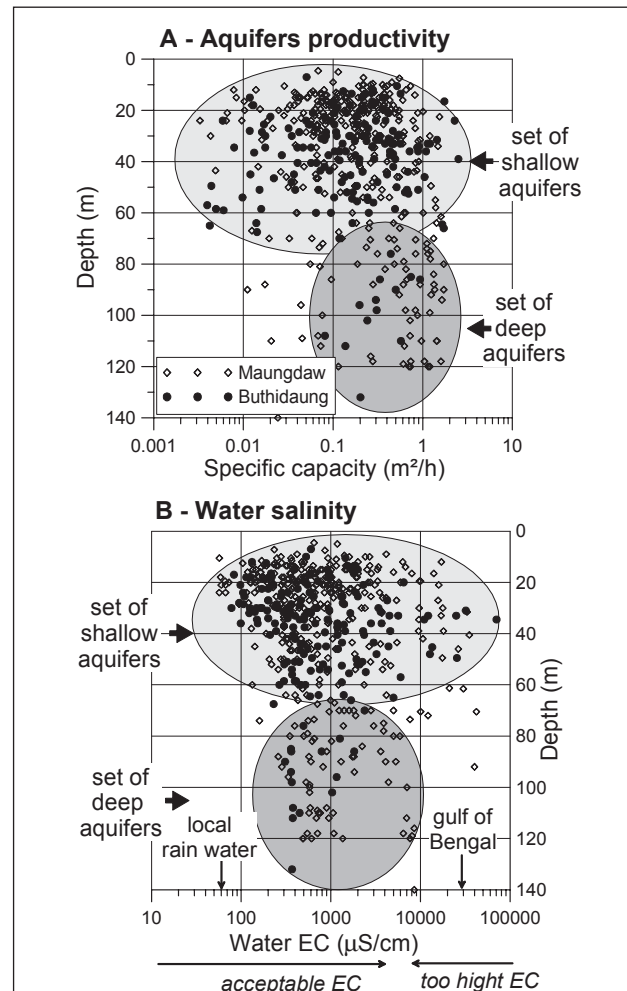A. Productivity of aquifers
B. Water salinity measured in water samples

Figure 1. Location of the survey area

Use of geophysics for hydrogeology

The field geophysical measurements are interpreted as geophysical parameters. To answer the hydrogeological questions, we look for the links between these geophysical parameters and the hydrogeological properties of aquifers. These links are expressed as conversion equations between geophysical and hydrogeological parameters. The methods and tools used in Myanmar are presented Table 1.

Use of MRS to estimate storativity of aquifers

The main advantage of magnetic resonance sounding (MRS) compared to other geophysical method is that any MRS signal means groundwater presence. Indeed, MRS aims to energize the nucleus of the hydrogen of groundwater molecules and to measure the magnetic resonance signal that is sent out by protons after the stimulation signal is cut off (Legchenko *et al.,* 2002). To send the excitation pulses an electrical wire loop of typically 50 to 100 metres in diameter is put on the ground and is energized by an alternating current (Figure 3).

To set up a sounding, i.e. to implement measurements at various depths, the amplitude of the excitation current is increased: the higher is its amplitude, the deeper is the investigation. A typical number of 16 depth steps is used to carry out a sounding. When the excitation pulse is switched off, the magnetic resonance signal send by the water molecules is recorded through the wire loop for every depth steps. The geophysical parameters obtained from these signals are the distribution in depth of MRS water content (w_{MRS})

Table 1. Methods and tools used in the survey

Method	Material	Interpretation software
MRS	Numisplus (IRIS Instruments)	Samovar (IRIS Instruments)
VES	Syscal R1+ (IRIS Instruments)	IPI2Win (Moscow State University)
Drilling	PAT 201&301 (PAT company)	
Pumping test	2" submersible pump	AquiferTest (WHI software)

Figure 3. MRS setup

and the signal decay constant that is linked to the mean size of the pores containing water (T_1) (Figure 4). These output parameters provide two types of hydrogeological estimators: storage related parameters and flow related parameter.

To calculate storativity, two MRS conversion equations have been proposed according to the confining property of the aquifers (Vouillamoz, 2003). The release from storage in unconfined aquifer is due to the dewatering of pores, whereas release from storage in confined aquifers is because of the effect of water expansion and aquifer compaction caused by change in fluid pressure. In confined aquifer, storativity is measured by the so-called storage coefficient that depends on the elastic properties of aquifer and water. It is quantified by (Freeze and Cherry, 1979):

$$S = \rho \cdot g \cdot b \cdot (\alpha + n\beta) \tag{1}$$

where ρ is the mass per unit volume of water, g is the acceleration of gravity, b is the saturated thickness, α is the aquifer compressibility, β is the compressibility of water and n is the total porosity. In unconfined aquifers, the amount of water released from aquifer storage by well abstraction is mainly due to gravity forces (the elastic component is neglected). The storativity is quantified by the specific yield S_y.

Because the NRS aquifers are confined, we used the storage coefficient S_{MRS} that is derived from equation (1), replacing the total porosity n with the MRS water content w_{MRS}, and the thickness b with the thickness of saturated layer Δz obtained from MRS:

$$S = \rho \cdot g \cdot b \cdot (\alpha + n\beta) \rightarrow S_{MRS} = C_1 \cdot w_{MRS} \cdot \Delta z \tag{2}$$

where C_1 is a parametric factor that needs to be calculated comparing MRS estimators with storativities derived from pumping test.
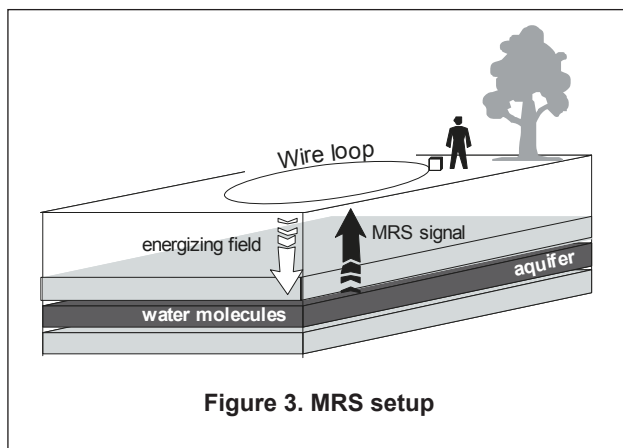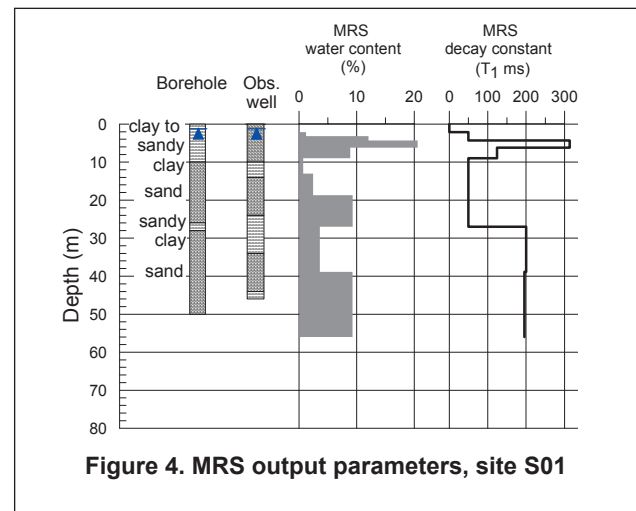

Figure 4. MRS output parameters, site S01

Use of MRS to estimate transmissivity of aquifers

Legchenko *et al.* (2002 and 2004) proposed to use the following conversion equation to estimate the transmissivity from MRS signal:

$$T_{MRS} = C_p \cdot w_{MRS} \cdot T_1^2 \cdot \Delta z \qquad (3)$$

where C_p is a parametric factor that need to be calibrated from pumping test data. This conversion equation is robust since it has been tested in a variety of geological contexts (Vouillamoz, 2003; Vouillamoz *et al.,* 2005)

Use of electrical resistivity to estimate water EC

Electrical resistivity of rocks can be measured with direct current (DC) or electromagnetic (EM) methods. Time domain electromagnetic soundings (TDEM) has major advantages compared to DC method in heterogeneous coastal aquifers (Goldman *et al.,* 1989, Goldman and Neubauer, 1994). However, the TDEM apparatus was not available on time for the survey due to logistics problem. Because the resistivity parameter is essential in coastal environment as it is sensitive to water salinity, we used the common DC vertical electrical sounding method (VES, Photograph 1).

To reduce the main problem of VES interpretation that is the non-uniqueness of the interpreted solution, we used the thickness and depth of saturated aquifer derived from MRS interpretation as fixed parameters to calculate the resistivity of aquifers from VES data (Figure 5).

Many attempts have been made to quantitatively determine the porosity of the aquifer and the water conductivity from electrical resistivity measurements. The basis of these calculations is the Archie equation (Archie, 1942):

$$\rho_w = \rho_a \cdot \frac{n_a^m}{a} \qquad (4)$$

where ρ_w is the resistivity of the water, ρ_a is the resistivity of the aquifer, *m* and *a* are material empirical factors and n_a is the Archie porosity. However, equations (4) can not be used in clayey environment where current flow is governed by more complex phenomena that describe by Archie equation.

Because we knew from boreholes that clayey layers are common in NRS, a simplified form of Archie equation was used to estimate the water resistivity from VES interpretation:

$$\rho_w = \frac{1}{EC} = C_3 \cdot \rho_a \qquad (5)$$

where C_3 is a parametric factor. The conversion equation (5) links the geophysical parameter ρ_a with the hydrological parameter ρ_w that is the inverse of the water EC.

Main results

Hydro-geophysical characterization of aquifers

The survey conducted at site S01 is presented as an example. An observation well was drilled at a distance of 19.9 metres from an existing borehole (Figure 6A). The rocks are clay and sand, and the medium is heterogeneous as the layers thickness differs from the borehole to the well. The sandy aquifer, confined by a clayey layer, is found 10 to 13 metres below the ground level. The thickness of the aquifer is estimated between 30 and 40 metres.

An hydraulic test was conducted, pumping 4.5 hours at $1.95 m^3/h$ in the borehole, and monitoring water level in both borehole and well. The maximum drawdown did not reach the bottom of the confining layer at the observation well. At the borehole, the depleting of water below the confining layer is negligible compared to the aquifer thickness. As a consequence, both Theis and Jacob methods were used to interpret the raw data (Kruseman and de Ridder, 2000, Figure 6 B&C). The hydrogeological properties estimated from this interpretation were pumping test transmissivity $T_Q = 2.4 10^{-4} m^2/s \pm 18\%$ and pumping test storativity $S_Q = 2.8 10^{-4} m^2/s \pm 5\%$. The water EC, that was monitored during the pumping duration, was stable ranging between 955 and 977 $\mu S/cm$, what means an average water resistivity of $\rho_w = 10.4 \Omega.m$.

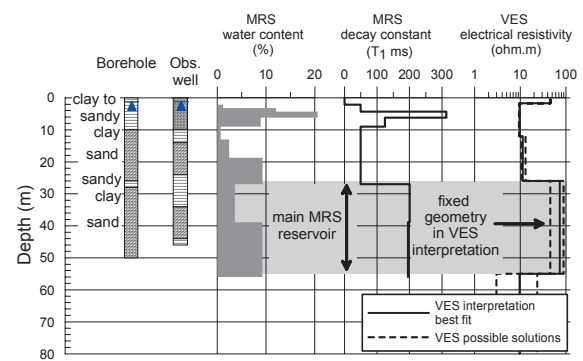**Photograph 1. VES implementation**

**Figure 5. MRS output parameters
used to interpret VES data, site S01**

A square loop of 75 metres length side was laid around the borehole to set up a MRS. MRS interpretation produced a multilayered aquifer with a shallow saturated level between 3 and 9 metres deep and a main saturated level from 12 to 55 metres deep that was obviously the target (Figure 5). The deeper aquifer ha s two distinct levels: it has short decay constant T_1 from 12 to 26 metres deep ($T_1 \approx 50ms$) and longer decay constant below 26 metres ($T_1 = 200ms$). The short and long T_1 may be understood as a fine to clayey sand overlaying a coarser sand respectively.

A Schlumberger VES was implemented nearby the borehole. The aquifer geometry (i.e., depth and thickness) obtained from MRS interpretation was used as fixed parameters to interpret VES data. According to the analysis of possible interpretation solutions (e.g., equivalence) the resistivity of the targeted aquifer ranges between $23\Omega.m < \rho_a < 89\Omega.m$ (Figure 5).

A comparison between geophysical data and pumping tests interpretations was conducted for all the surveyed sites. The parametric factors in equations (2), (3) and (5) were determined, which leads to the estimation of storativity and transmissivity with MRS, and estimation of groundwater EC with VES (Table 2).

Figure 7A&B illustrates the relationship we found between storativity and transmissivity estimated from pumping tests and from MRS using conversion equations (2) and (3). The strong point of MRS method is the acceptable accuracy of storativity and the transmissivity estimation (Table 2). However, we also found that the main limitation to the use of MRS in NRS context is an insufficient depth of investigation because of shallow electrically conductive layers that may screen a deeper aquifer (Roy, J. and Lubbczynski, M., 2003). The maximum penetration depth of a sounding can be estimated as:

$$h = \frac{500}{\sqrt{\rho_a / f}} \quad (6)$$

with h the maximum penetration depth that is the depth where the signal is reduced by about 30% (skin depth), ρ_a is the electrical resistivity of the media and f is the signal frequency that was about 1900Hz in NRS.

As overall result, MRS was useful in 68% of the sites (10 sites with insufficient depth of penetration and 1 rejected because of poor signal to noise ratio over a total of 34).

The water EC measured with a light conductivity-meter in water samples was compared with the water resistivity calculated with equation (5) (Table 2). Because of the non-uniqueness in VES interpretation but also because of lateral heterogeneities that add uncertainty to the interpretation, it is not possible to estimate a reliable water EC from aquifer resistivity. For example, the resistivity of targeted aquifer at site S01 was $23\Omega.m < \rho_a < 89\Omega.m$, corresponding to an EC of groundwater calculated with equation (5) between $261\mu S/cm < EC < 1011\mu S/cm$. This low accuracy will not always allow distinguishing between acceptable and too high EC for human use. However, a guideline can be proposed as illustrated in Figure 8:

1. If the interpreted resistivity of aquifer $\rho_a < 5\Omega.m$, the water will be probably salty.
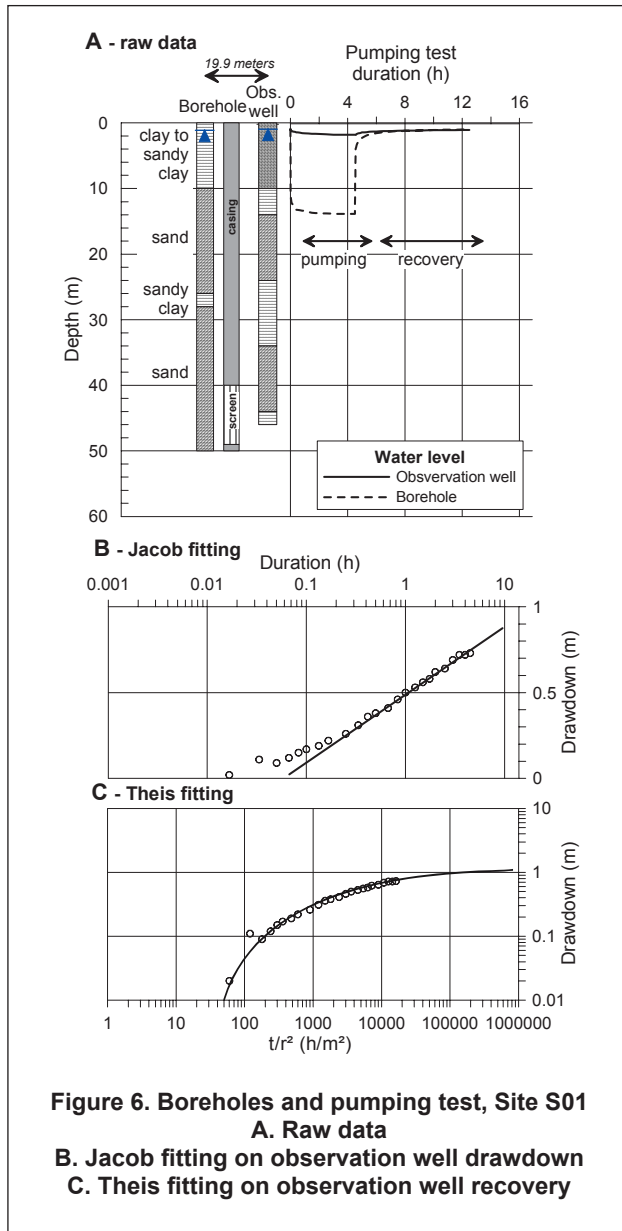

Figure 6. Boreholes and pumping test, Site S01
A. Raw data
B. Jacob fitting on observation well drawdown
C. Theis fitting on observation well recovery

Table 2. Conversion equation and mean difference between hydrogeological properties obtained from pumping tests and geophysical estimators

Geophysical estimators / Conversion equation	Parametric factor	Mean difference
MRS storage coefficient $S_{MRS} = (w_{MRS} . \Delta z) . C_1$	$C_1 = 2.42 \times 10^{-4}$	8%
MRS transmissivity $T_{MRS} = C_p . w(z) . T_1^2 (z) . \Delta z$	$C_p = 6.68 \times 10^{-9}$	45%
VES water EC $\rho_w = 1/EC = C_3 . \rho_a$	$C_3 = 0.43$	75%

2. If $<\Omega.m<\rho_a<12\Omega.m$ the risk of salinity is high.
3. If $\rho_a>12\Omega.m$ the water will be probably accepted by the people.

The VES measurements provided sufficient signal to noise ratio in 83% of the sites (6 VES were rejected over a total of 35).

Joint use of MRS and VES

MRS and VES can complete each other efficiently. MRS is used to locate productive aquifers and to quantify their storativity and transmissivity. VES is used to estimate the salinity risk of groundwater identified with MRS. Finally, the maximum penetration depth of MRS is calculated with VES resistivity (equation 6) and compared to the depth that was targeted.

The exploration site S31 illustrates the proposed methodology (Figure 9). Two aquifers are identified by MRS. The deeper reservoir is located from 25 to 65 metres deep and bears a water that is less mineralized than the shallower

one according to the VES interpretation ($EC = 110\mu S/cm$ against $EC = 560\mu S/cm$ on average). This reservoir will be targeted by the drilling, and its storativity is estimated with MRS to be $S_{MRS} = 6.10^{-4}$ and its transmissivity to reach $T_{MRS} = 1.10^{-3}\ m^2/s$.

Economical considerations

Presented economical analysis aims to estimate the financial impact of geophysics on drilling programme. The calculations are carried out considering the real AcF costs that include the human staff, the logistics, the geophysical equipment (buy-
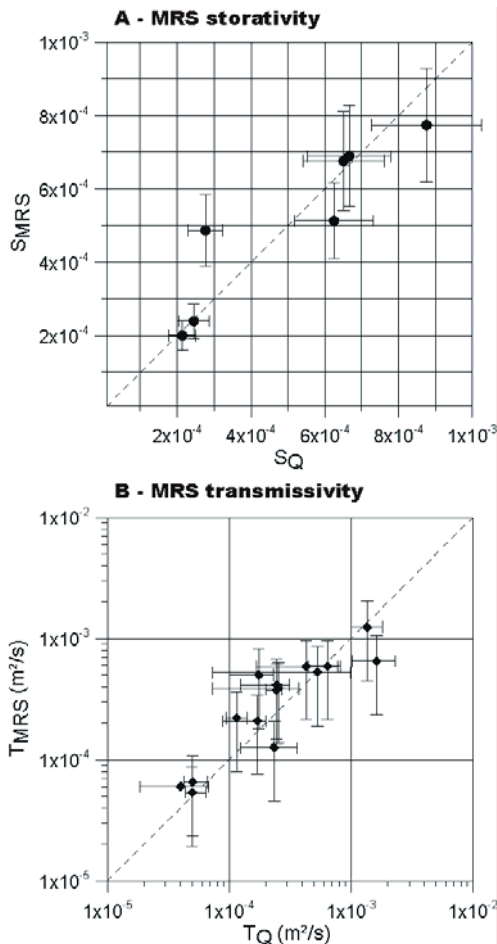

Figure 8. Evaluation of salinity risk from VES measurements

Figure 7. MRS estimators
A. Storativity calculated with equation (2)
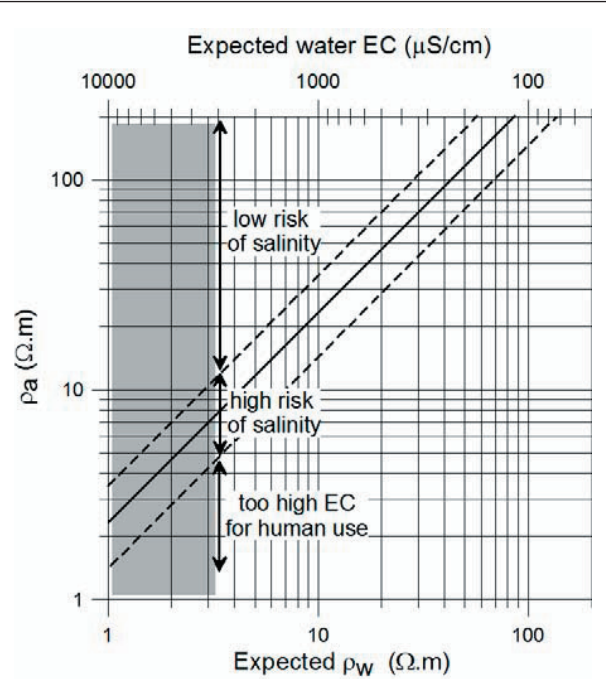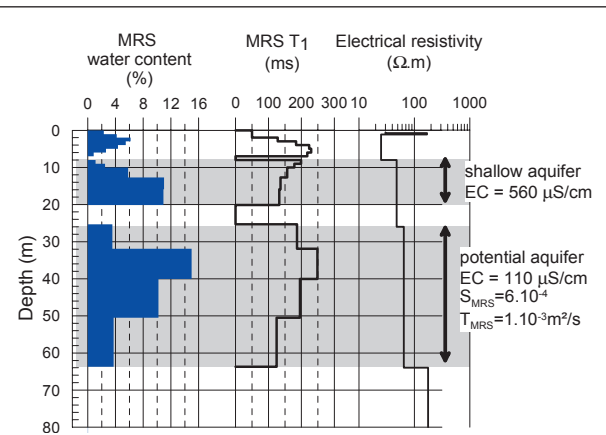**B. Transmissivity calculated with equation (3)**

Figure 9. Example of aquifer identification and characterization, site S31

ing, maintenance and depreciation) and the administrative costs. The depreciation duration is assumed to be 2 years for the drilling rig, 5 years for the VES apparatus and 8 years for the MRS instrumentation. Eight working months and 54 successful borehole implementations per year are assumed. The local average cost of a successful borehole is 664 € and 502 € for an unsuccessful one.

Calculations show that geophysics saves money when (Vouillamoz *et al.,* 2002):

$$G \le bh^- \cdot \left[\frac{r_2}{r_1} - 1 \right] \tag{8}$$

with r_2 the actual borehole success rate, r_1 the success rate with the use of new geophysics, bh^- the average cost of an unsuccessful borehole and G the average cost of geophysical surveys per borehole. Starting from the known or suspected borehole success rate, one can calculate the minimum improvement of success rate that is needed to save money using geophysics. For example, the average number of successful boreholes drilled by AcF in Myanmar between 1995 and 2003 ranges between 30 and 55% of the total number of drilled holes. Calculation shows that the joint use of VES and MRS is economically acceptable in complex areas where the success rate of drilling is not more than 30%, that is common in NRS sandstone area.

Conclusions
In North Rakhine State of Myanmar, combined use of MRS and VES allows reliable detection of coastal aquifers, and acceptable estimation of their storativity, transmissivity and water salinity risk. Average accuracy of the estimation was found to be ±6% for the storativity and ±45% for the transmissivity. The MRS transmissivity estimator seems to be robust, but the MRS storativity estimator still needs to be validated with a larger number of data. The estimation of water salinity is not accurate enough to know if the water will be acceptable for human use, but a salinity risk can be estimated.

Existence of shallow electrically conductive layers may screen MRS signal and reduce the maximum depth of investigation. During the survey time, 32% of MRS soundings were not able to reach targeted aquifers below 20 to 70 metres because of this screening effect. 83% of VES had sufficient signal to noise ratio.

The cost of geophysics have to be compensated by an increase of the knowledge that is used according to the objective: evaluation of the water resources for the future needs and overall resource management, and/or current exploitation of the groundwater resources. In Myanmar, the objective was to improve the success rate of drilled boreholes. Economical analysis of AcF activities for the period of 1995-2003 shows that application of joint MRS and VES methods is saving money when the initial drilling success rate is less than 30%.

Finally, hydro-geophysical survey was efficient to characterize complex coastal aquifer. The preliminary hydrogeological survey precises the questions that need to be answered integrating hydrogeology and geophysics. The main advantage of geophysics is to obtain a dense data coverage at lower cost and shorter duration time than obtained with hydrogeological methods. But geophysical parameters need hydrogeological data to calibrate conversion equations. Hydro-geophysical characterization of aquifers has to be a continuous process: the geophysical characterisation is validated by drillings and pumping tests, and the calibration of geophysical conversion equations is improved with new hydrogeological data.

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