# An Appraisal of the Application of Surface and Borehole Geophysical Techniques to Groundwater Assessment in Wellfields in The Bahamas.

**by E.E.Hall***

**Abstract**

An increase in composite salinity as a reaction to an increase in abstraction rate and a decline in composite salinity as a reaction to an increase in rainfall coupled with a decline in abstraction rate are classical characteristics displayed by an overstressed system. The identification and location of localized upconing are vital to wellfield rehabilitation and expansion schemes which can lead to reductions in composite salinity.

The application of surface and borehole geophysical techniques;

a. Surface resistivity (Offset Wenner Method)
b. Electromagnetic ground conductivity (EM34-3)

and c. Borehole fluid conductivity and temperature versus depth profiling

to the assessment of groundwater in wellfields in The Bahamas are evaluated. Surface and borehole geophysical exploration techniques can provide very rapid and accurate information on the status of freshwater lenses, for example, freshwater lens thickness, depth to the fresh/salt water interface and the identification and mapping of salt water encroachment.

## INTRODUCTION

The Commonwealth of the Bahamas is an archipelago of more than seven hundred islands that extends over nine hundred kilometres in a south easterly direction away from the east coast of South Florida [Fig. 1]. Its total land mass is approxiimately thirteen thousand and eighty square kilometres, but only sixteen islands have a land mass that exceeds fifty square kilometres. The main annual rainfall varies from fifteen hundred millimetres in the north to seven hundred millimetres in the south.

Pleistocene limestones and Holocene sands dominate the geology of the islands. Fossil coral reefs are evident along the coastlines. The reefs outcrop as terraces and are indicators

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of past sea-levels which were higher than present sea-level. All hills and ridges on the islands are windform features'. Subtle variations in subsurface geology have been indicated in recent research, and it is suggested that these variations impart a controlling influence on the occurrence and characteristics of the Ghyben-Hertzberg lenses that underlie the islands(Cant & Weech, 1985). Groundwater resources of the major islands have been studied in some detail in the past and have been mapped and roughly quantified using conventional exploration techniques.

The areas of study comprise existing wellfields and proposed locations for wellfield expansion on the major islands in the Commonwealth of the Bahamas including: Grand Bahama; Andros; Bimini; Abaco; Eleuthera; Exuma; Long Island; San Salvador and Inagua. These islands occur unevenly over the Great and Little Bahama Banks. The islands are long and narrow having a northwest to southeast orientation with elevations below 60 metres.

Rainfall varies from northwest to southeast [Fig. 11 across the Bahama Platform with the southeast islands receiving less than half of the rainfall received in the northwest islands. The wet season is from May to October with June and October being the wettest months.

## GROUNDWATER OCCURRENCE

The occurrence of fresh groundwater on the islands takes the form of entrapped rainwater that has infiltrated down through the unsaturated zone and reached the water table. Because of the relative densities of the freshwater and saline water the freshwater floats upon the saline water. The bodies of subsurface waters are known as Ghyben-Hertzberg lenses and the theory of their occurrence suggests that the lens thickness is directly related to the relative elevation of the water table above mean sea level. A 1:40 relationship has been described by B.G. Little et al, 1976.

Hadwen and Cant (1977), defined freshwater lenses as being confined to the Lucayan formation. The geometry of these lenses are controlled by geological features such as the "hard brown crust". It is believed, from local knowledge, that this crust acts as a semi-

'Hadwen & Cant, 1977.

impermeable horizontal layer which lessens the degree of mixing between fresh and saline waters. The physical and chemical characteristics of the freshwater lenses are subject to varying influences, but usually present a salinity depth profile which comprises:

a) a freshwater or potable zone with salinity of less than 600 parts per million (ppm Cl-)

b) a brackish zone with salinity between 600-1200 ppm Cl-

and c) a saline water zone with salinity greater than 1200 and increasing rapidly towards levels of seawater salinity.

The freshwater lenses on the islands have been mapped by B.G. Little, et al, 1967 and documented by the work of Bahamas Lands Resources Survey(1977). Approximately sixty eight wellfields have been constructed and/or expanded in these freshwater bodies throughout The Bahamas. Unfortunately, the integrity of these lenses have being compromised by the classical problem of over abstraction which is too often associated with supply and demand.

This paper briefly evaluates the application of surface and borehole geophysical techniques to wellfield rehabilitation and expansion schemes in the Bahamas.

## MEETHODS OF INVESTIGATION

### *ASSUMPTIONS*

For the purpose of this assessment two basic assumptions are made:

a. the earth material remains constant

and b. any changes in ground conductivity and resistivity indicate a change in the salinity of the water contained in the earth material.

### *BOREHOLE LOGGING*

Existing and/or newly constructed monitor boreholes in and around the wellfields along with supply wells were logged using YSI model 3000 T-L-C meter. A salinity "cut off" of 600 ppm Cl- was selected. The objective was to generate a salinity depth profile of the aquifer and to identify the depth to the fresh/salt water interface. Parameters logged were:

a) the depth to the water table

b) the temperature of the borehole fluid

and c) the conductivity of borehole fluid.

*ELECTROMAGNETIC GROUND CONDUCTIVITY SURVEYS*

The electromagnetic ground conductivity survey method used is based on a well established surface geophysical method.[2] The instrument used was the Geonics EM 34-3 terrain-conductivity meter. A change in conductivity of 5 mS/cm was assumed to be measurable with the instrument.

The EM 34-3 is a dual-loop, frequency-domain, electromagnetic profiling system. The equipment operates at three different frequencies and coil spacings and provides a maximum exploration depth of 40 metres [Table 1].

Table 1

EXPLORATION DEPTH (METRE)

| COIL SPACING (M) | VERTICAL COILS | HORIZONTAL COILS |
|---|---|---|
| 10 | 7.5 | 15 |
| 20 | 15 0 | 30 |
| 40 | 30.0 | 60 |

Table 1. Exploratim depths for the EM 34-3 on oceanic islands

The application and limitations of electromagnetic profiling techniques to the mapping of groundwater configurations of small oceanic islands has been described by Stewart (1988). The Geonics EM 34-3 is capable of making six apparent-conductivity measurements. The six data points, used to develop two

[2] McNeil, 1980a.

geometric sounding curves, were obtained by taking measurements in both the vertical and horizontal coplanar coil orientations at three intercoil spacings.

Traverses ranging between eighty to four hundred metres were set up along access tracks in the in the wellfields and/or proposed areas for expansion.

*SURFACE RESISTIVITY SOUNDING SURVEY*

The surface resistivity sounding method used in this study was the Offset Wenner surface resistivity sounding technique. The instrument used was an A.B.E.M. Terrameter (model SAS 3000 B), a multicore resistivity cable and a switch box to allow for a tri-potential validation to be carried out in the field. Surface resistivity spreads were set up along access tracks in the wellfields and/or the proposed area for expansion. The soundings were laid out to 128 metres which allowed or a depth of investigation of approximately 64 metres below land surface (bls). At each spread location five resistances were measured for eight spacing switch positions.

## Findings

*BOREHOLE LOGGING*

The fresh/salt water interface was able to be mapped and estimates of freshwater lens thickness were obtained along with additional estimates of the thickness of the mixing zone using depth versus salinity profiles. It was determined that where the freshwater lens was relatively thick, the mixing zone was relatively thin, while the inverse was true where the freshwater lens was thin. It was determined that areas of localized upconing were prolific in the wellfields. These areas were easily identified.

The depth versus temperature profiles indicated fissure flows into the borehole along discontinuity beds and suggest that a reverse geothermal gradient exists in the subsurface waters in The Bahamas where temperature declined with increasing depth below land surface.

*ELECTROMAGNETIC GROUND CONDUCTIVITY SURVEY (EM-34)*

The results from the EM-34 surveys indicated that the overall configuration of groundwater in the Bahamas could be determined with the application of electromagnetic ground conductivity techniques and layered earth modelling:

a) two layer model - water table near land surface having fresh/salt water interface

and b) three layer model - unsaturated zone and freshwater/salt water interface.

Measurements taken with the coils in the horizontal coil coplanar orientation were filtered out because the high apparent conductivity values diverted from linearity [Fig. 2]. Therefore, measurements were taken only with the coils in the vertical coplanar orientation. In cases where the mixing zone was relatively thick additional layers could be modelled because salinity declined with depth in incremental steps by orders of magnitude. The depth to the fresh/salt water interface oscillated along the traverses. Ground conductivity values dramatically increased near points of abstraction and defined a zone of influence [Fig. 3].

EM-34 traverses were restricted to areas away from overhead and underground utility cables and buried iron pipe lines.

*SURFACE RESISTIVITY SOUNDING SURVEY (OFFSET WENNER METHOD)*

The results indicated that the overall groundwater configuration was satisfactorily determined with the application of the Offset Wemer surface resistivity sounding method and the Offix Layered - Earth Modelling software. A great degree of difficulty was encountered with the installation of surface electrodes because of the hardness of the surface rock and the absence of soil cover greater than two inches thick. Reliable data was obtained out to 32 metres only and unreliable data out to 128 metres was filtered out. Subsequently the depth of investigation was reduced to approximately 16 metres below land surface. The depth to the fresh/salt water interface could still be determined but the base of the mixing zone could not because of the restricted depth of investigation. Thus the theoretical field curve could not be simulated [Fig. 4]

## DISCUSSION

The overall groundwater configuration in wellfields in The Bahamas can be determined by using surface and borehole geophysical techniques and layered-earth modelling:

1 Given that there exists a reverse geothermal gradient in the subsurface waters of The Bahamas, any anomaly in the depth versus borehole fluid temperature profile serves as an indicator of fissure flow into the borehole. Temperature logs have been useful in groundwater pollution studies by indicating zones of warmer water at depth(i.e. a leaking disposal well);

2. The fluid conductivity logs were successfully used to estimate the thickness of the freshwater lens and brackish zone. Where localized upconing occurred in individual supply wells the electrical conductivity logs were very useful in indicating the depth to which the wells should be back filled with the intention of blocking off the saline zone. Where the brackish zone was closer to land surface, it was relatively thick and where the brackish zone was at depth (> 10m), it was relatively thin. It was also noted that the brackish zone could be separated into at least three distinct phases. These phases could affect the interpretation of sounding curves by introducing additional layers;

3 The application of the Geonics EM 34-3 ground conductivity technique in an oceanic, hydrogeological environment like The Bahamas proved to be a valid technique. Localized upconing and its related zone of influence was readily indicated. However, the application of the EM34-3 ground conductivity method was limited in wellfields where the fresh/salt water interface was less than 10 metres below land surface. Observed conductivity readings measured in the vertical dipole orientation diverted from linearity with the true conductivity beyond a measurement of 10 mS/cm. Thus, valid measurements could not be taken in the horizontal dipole orientation. In wellfields where the fresh/salt water interface was greater than 10 metres below land surface valid measurements could be observed in both the vertical and horizontal dipole orientations;

The Offset Wenner resistivity sounding method was successfully applied to the mapping of freshwater lenses. However, its application was restricted by the degree of urban development on the islands and overhead and underground utilities and buried iron pipes. Difficulties arising from the absence of a thick soil cover coupled with the relative hardness of the surface limestone made the rendered the surface resistivity method unfriendly and force a strong reliance on the EM34-3 method.

Overall, the current status of the groundwater configuration in wellfields in the Bahamas were easily, cheaply and rapidly assessed. Areas of salt water encroachment was readily identified using borehole and surface geophysical techniques. In proposed areas for wellfield expansion the thickness of the freshwater lens was easily estimated and mapped. The application of these techniques proved to be more rapid and cheaper than conventional methods. Manpower requirement was reduced and the need for heavy equipment was removed. The portability of the light weight geophysical equipment provided easy access into remote islands where the mobilization of heavy plant and equipment often preclude the execution of any groundwater exploration exercise.

The surface geophysical methods provided a view of the groundwater configuration in a "natural " state, for example, boreholes offer a somewhat distorted view because the water in the boreholes are a composite of different mixed up waters.

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Figure 4. Illustration of a theoretical field curve for surface resistivity

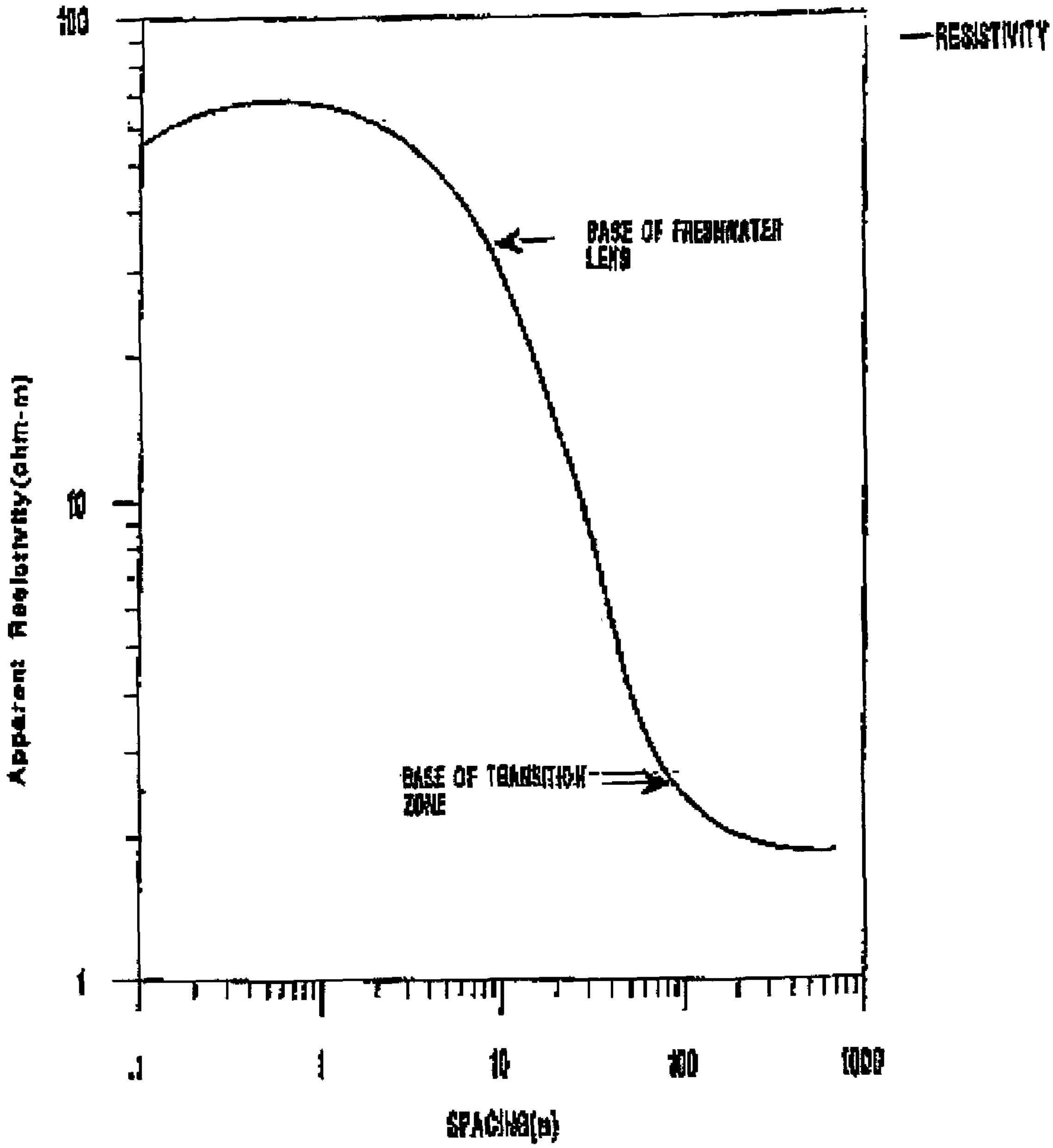


Figure 3. Illustration localized up coning across an abstraction trech in the Bahamas.

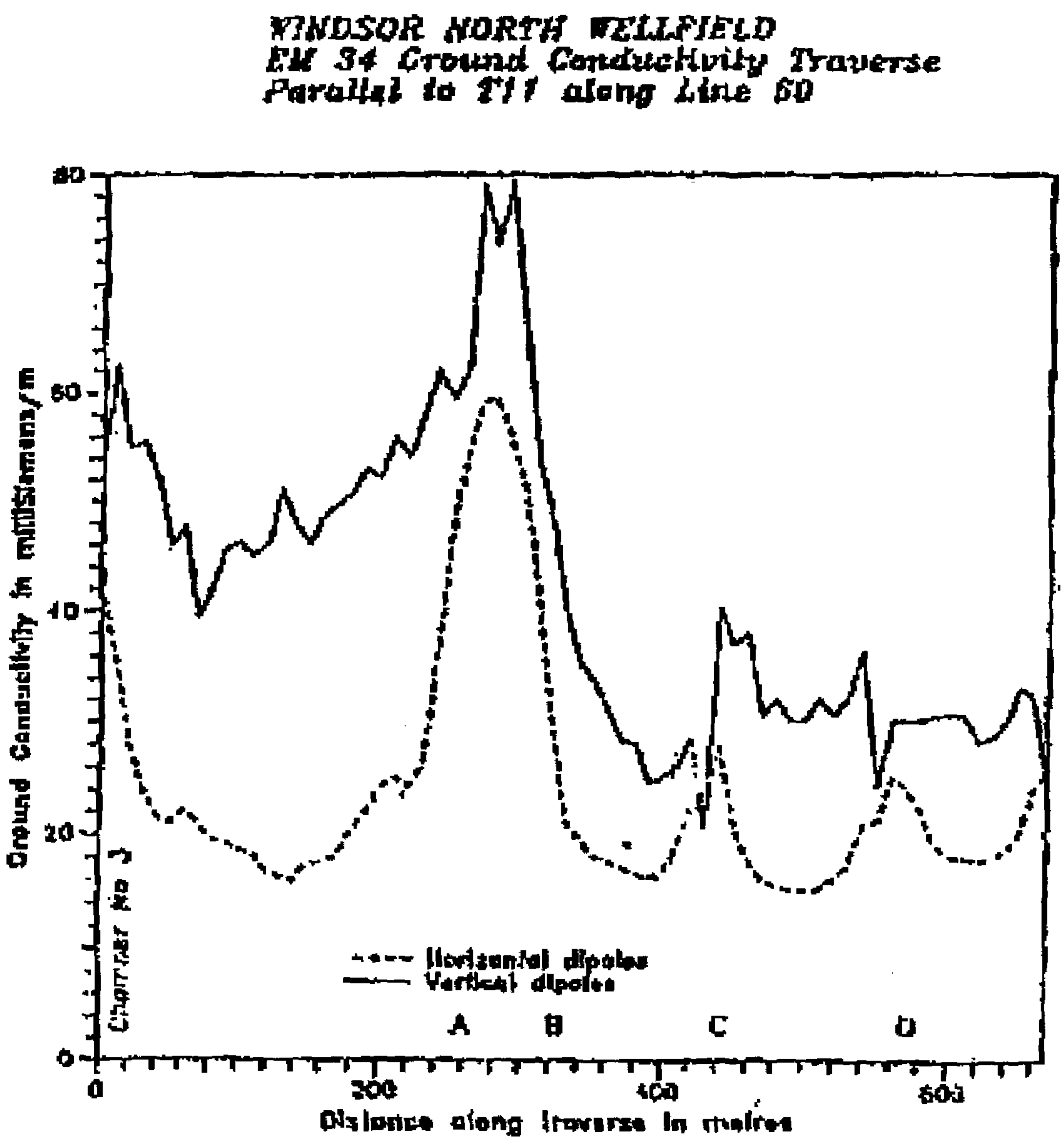
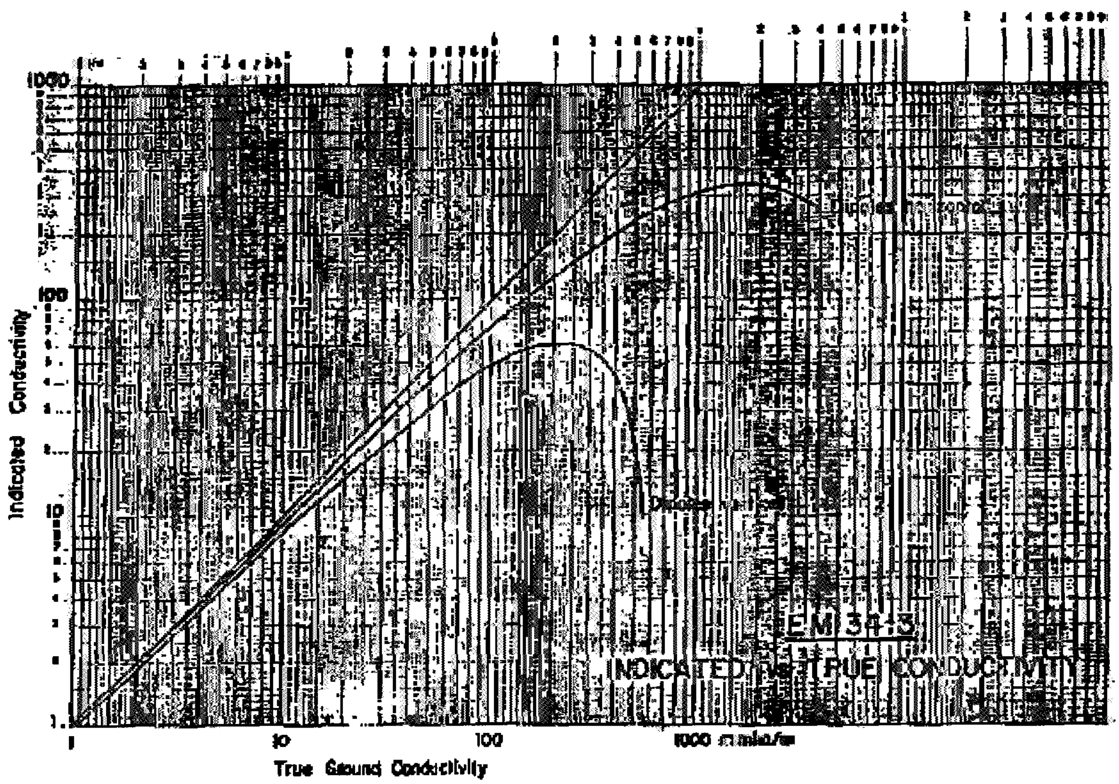


**Figure 2. Graph of Indicated versus True Ground Conductivity**

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