Aquifer interactions with a polluted mountain river of Nicaragua

Mendoza, Jose Alfredo; Ulriksen, Peter; Picado, Francisco; Dahlin, Torleif

Published in:
Hydrological Processes

DOI:
10.1002/hyp.6822

2008

HYDROLOGICAL PROCESSES
Hydrol. Process. **22**, 2264–2273 (2008)
Published online 4 October 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6822

Aquifer interactions with a polluted mountain river of Nicaragua

Jose Alfredo Mendoza,[1,2]* Peter Ulriksen,[2] Francisco Picado[3] and Torleif Dahlin[2]

[1] *Universidad Nacional Autónoma de Nicaragua - Centro de Investigaciones Geocientíficas Recinto Universitario Rubén Darío Managua, Apdo. Postal E-1 Managua, Nicaragua*
[2] *Lund University, Department of Engineering Geology, John Ericsson v1 Lund 22100, Sweden*
[3] *UNAN-Managua - Centro de Investigcion en Recursos Acuaticos, Managua, Nicaragua*

Abstract:

The interactions between a stream and nearby shallow aquifers were investigated in a mountain basin being polluted by mercury released during mining in central Nicaragua. Hourly data series of water levels and temperatures were analysed using cross-correlation. Resistivity imaging was used to map the subsurface and to complement the hydrological data interpretation. The results show the complex hydrogeological conditions that characterize the region, with weathering and fractured rock as main contributors to groundwater transport. The resistivity images suggest the presence of two vertical dykes perpendicular to the stream, and zones rich in clay. The data series indicate a rapid response from the aquifers to recharge events, followed by immediate discharge on a yearly basis. Furthermore, alternating periods of stream infiltration and aquifer discharge were identified. This work demonstrates that surface water pollution is a threat to groundwater quality in the area. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS time series analysis; resistivity imaging; cross-correlation; surface water; groundwater; pollution; Nicaragua

Received 6 March 2006; Accepted 1 May 2007

INTRODUCTION

Understanding the relationship between surface waters and groundwater is an important task in hydrological sciences. Characterizing this interaction becomes critical as environmental stress on surface waters increases and may be transferred to subsurface waters. Commonly, the interactions occur in the in-stream and near-stream areas where exchange of water and biological processes take place (Sophocleous, 2002). In streams there can be three modes of interaction; gaining flow sections, losing flow sections and steady pressure (Winter *et al*., 1998). When pollutants are present they may contaminate either resource.

Mining using the mercury method to refine gold has led to continuous contamination of streams in the central region of Nicaragua since the 19th century. The most polluted river is Río Artiguas (known locally as Sucio, meaning dirty), where a cluster of small-scale mills releases mining waste directly into the river water. Thus, the mercury concentrations in the river water are frequently above the guidelines for drinkable water (Silva, 1994; Albuquerque, 1996; Romero, 1996; André *et al*., 1997). In addition, sewage from the nearby village of Santo Domingo is discharged into the river (Figure 1). An understanding of the connections between the stream waters and the nearby channel aquifers is necessary because the water supply to the population is provided from sources located close to the polluted streams.

Among the methods for studying stream–aquifer connections, a frequently used approach is the surface water gains–losses method (Lerner, 1997). This method is based on the identification of gain and loss sections along the river channel by estimating the differences in stream flow budgets. Mendoza (2002) used the gains–losses method in the Río Artiguas channel but no conclusive results were obtained because of measurement errors and rapid changes in stream velocities. Additional attempts using seepage meters failed due to the river rocky bed (Grunander and Nordenberg, 2004).

The study of time series data can reveal temporal variations and impulse response characteristics in aquifers (Duffy and Gelhar, 1986; Padilla and Pulido-Bosch, 1995). During the last two decades various studies have shown the applicability of time series analyses for understanding hydrological processes. For instance, time series analyses of piezometric data have been used to identify recharge mechanisms (Lee and Lee, 2000), forecast the water level in wells (Bierkens *et al*., 2001), study river base flow and estimate groundwater recharge (Zhang and Schilling, 2004; Crosbie *et al*., 2005). Generally, the measured parameter used for the time series analyses is hydraulic head but electric conductivity and temperature have also been used (Laroque *et al*., 1998; Sheets *et al*., 2002; Kim *et al*., 2005).

Geophysical mapping of the subsurface can provide complementary information on the subsurface geology, which can be used for interpretation of the hydrological

* Correspondence to: Jose Alfredo Mendoza, Universidad Nacional Autónoma de Nicaragua - Centro de Investigaciones Geocientíficas Recinto Universitario Rubén Darío Managua, Apdo. Postal E-1 Managua, Nicaragua. E-mail: alfredo@terrambiente.se; alfredo.mendoza@tg.lth.se

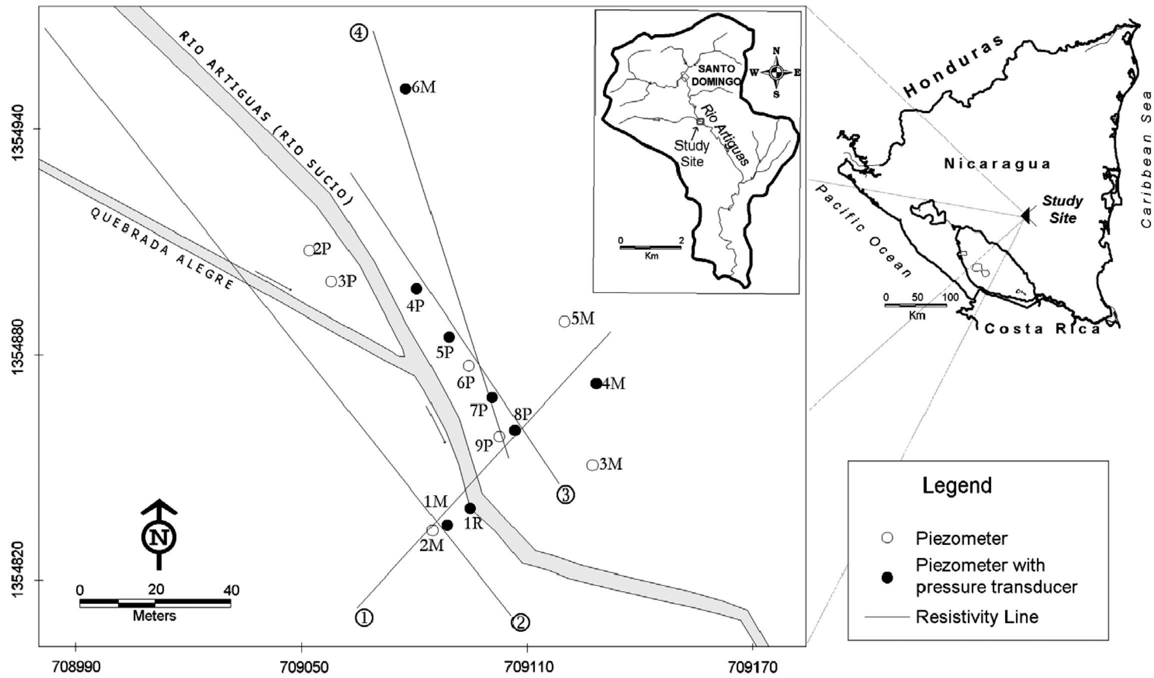

Figure 1. Location of the study site in the Río Artiguas basin (inset), central Nicaragua

data. Resistivity imaging is a suitable method for hydrogeological mapping as the electrical resistivity of earth materials is dependent on electrolytic conduction through the pore fluid. The multi-electrode technique permits the acquisition of large amounts of resistivity data (Dahlin, 1996) and fast inversion methods allow interpretation of the subsurface resistivity distribution (deGroot-Hedlin and Constable, 1990; Ellis and Oldenburg 1994, Loke and Barker, 1996). Recently, resistivity imaging has been used for hydrogeological mapping in the Río Artiguas basin (Mendoza, 2002; Mendoza *et al*., 2005).

The objective of this study is to examine time series of hydraulic heads and water temperature data in combination with resistivity imaging to determine the factors controlling the shallow groundwater dynamics at the study site. A second objective is to verify if the river water infiltrates the near channel aquifers carrying heavy metals to pollute the local groundwater. This information is important in promoting groundwater protection in the central regions of Nicaragua, where the majority of the population depends on both groundwater and surface water for human consumption. This article presents an application of time series analysis and resistivity imaging to explain a relevant environmental and hydrogeological problem. The work has been developed within the framework of a broad environmental programme funded by the Swedish International Development Agency (Sida/SAREC) with the aim of assessing the environmental effects of mining activity in Nicaragua.

THE RÍO ARTIGUAS BASIN AND THE STUDY SITE

The study site is located in the Río Artiguas basin, in the eastern part of the central highlands of Nicaragua. The basin has experienced a century of gold mining using the mercury extraction method. A weather station recently installed in the basin reports temperatures with a minimum of 15 °C and maximum of 34 °C, for the period November 2004 to March 2005. Historic average precipitations of 2400 mm year^{-1} have been recorded in the area by INETER (1991). The rainy season extends for nine months from April to December having a large influence on the river flow, which indicates a discharge from 2×10^4 m^3 day^{-1} during the dry season to 9×10^4 m^3 day^{-1} during the wet season. The young drainage system for surface waters has developed under a structural control where faults, fractures and joints lead to a geometrically rectangular flow pattern.

Geologically, most of the Río Artiguas basin is covered by Tertiary volcanic rocks, mainly basalts and andesitic lava flows. These lava flows overlie rhyolitic-dacitic pyroclastic flows towards the south of the basin (Hodgson, 1972). The quartz veins and tectonic zones, in combination with fracturing and weathering, are considered the major factors contributing to groundwater occurrence and transport. Consequently, the saturated zone is a composite horizon of both weathered layers and fractured bedrock. Mendoza *et al*. (2005) suggested a hydrogeological model for the basin; water infiltrating the weathered nonsaturated zone travels through the saturated zone but quickly discharges in a spring or along the streams. If water infiltrates through open fractures, tectonic contacts or bed contacts, it can travel longer distances and eventually form regional groundwater flows. However, such a hydrogeological model is insufficient to explain the interactions between surface waters and groundwater and a smaller area had to be investigated in detail.

A site in the centre of the basin was selected for this study because it is regarded as a typical tectonic

DOI: 10.1002/hyp

setting, with fracturing along the river (Hodgson, 1972) and a smooth valley that allowed accessibility and drilling in the otherwise rough relief of the basin. Aerial photographs indicate fracturing perpendicular to the river, and field documentation verified that fractured bedrock underlies, on average, 3 m thick soils. The groundwater table is usually found within 3 m and much of the shallow groundwater is expected to discharge into the river (Mendoza *et al*., 2004). The Río Artiguas is joined by the generally clean Quebrada Alegre tributary at the site. The area is used for grazing and grass covers a wetland on the east side of the river (Figure 1).

METHODOLOGY

Fourteen piezometers were installed at the site and one level gauge in the river (1R). The piezometers are cased with 6 cm diameter PVC pipe, and in the uppermost part 1-m metal tubes with a lock to prevent theft. The piezometers were packed with a mixture of gravel and clay and the upper part sealed with cement to prevent direct infiltration along the casing. The maximum depth to the fractured bedrock in the piezometers is 2·35 m, occurring at piezometer 6M. The piezometers located closer to the river channel have shallower depth as they reach the bedrock. Most piezometers are located on even terrain but piezometers 6M, 5M and 4M are located on hillsides. The soil at the outer piezometers had more clay loam content, while greater sand content was found in the piezometers closer to the river. The elevations of the piezometers were determined by differential-GPS (global positioning system) measurements. In cases where the GPS observation error was high, traditional levelling was carried out.

Continuous hydraulic head and temperature measurements were taken hourly in eight piezometers, including the gauge height at the river (1R), using pressure transducers from March 2004 until March 2005. Furthermore, piezometer 4M was equipped with an additional barometric pressure transducer for post-processing correction. The pressure transducers were all Van Essen Divers Instruments with 2 mm and 0·01 °C resolution for hydraulic head and temperature, respectively. Daily precipitation data were measured with a standard rain gauge located 800 m from the site and since November 2004 an automatic weather station located 300 m from the site records hourly precipitation. Data were retrieved from the data loggers every three months and occasionally manual measurements were made for data quality checks.

Preparation of the data series for analysis included (a) removing values from occasional perturbations in water levels following slug tests and water sampling, and (b) applying a high-pass filter to remove seasonal trends and DC components from the original data. The analysis of the hydrological data was performed using the cross-correlation function as described by Jenkins and Watts (1968), Padilla and Pulido-Bosch (1995) and Laroque *et al*., (1998). The cross-correlation function establishes an interrelationship between an input and an output signal. In this study the river data are considered input signals and the water level fluctuation in the piezometers as output signals. A particular case of cross-correlation is autocorrelation, a function which quantifies the linear dependency of successive values over time. Thus, the autocorrelation function checks the data suitability before a cross-correlation analysis is carried out. The main output of correlation is the correlation coefficient (C), which ranges from $-1{\cdot}0$ to $+1{\cdot}0$. The time at maximum C is the lag time between the input and output signal. A coherence function was applied in cases where relevant cross-correlation was found. The coherence function expresses the linear contribution of an input signal to an output signal and is analogous to cross-correlation in the frequency domain (Padilla and Pulido-Bosch, 1995).

For the geophysical survey, the ABEM Lund Imaging System (Dahlin, 1996) was used to explore the electrical resistivity distribution in the subsurface of the site. The system is based on the automation of collection, processing and presentation of resistivity data. The data collection was performed as 2D resistivity imaging by using a roll-along technique, in which cables are moved upward or downward along a succession of stations. As it was important to get information about the resistivity distribution in the upper subsurface, the minimum electrode spacing was 1 m. A multiple gradient electrode array was used for the measurements, since it has proved to have good resolution capability and to be robust in the field (Dahlin and Zhou, 2004, 2006). Four resistivity lines were performed, line 1 was 100 m, line 2 was 160 m, line 3 was 100 m, and line 4 was 120 m (Figure 1).

Once the resistivity survey was carried out, data processing was performed using the Res2Dinv algorithm (Loke, 1997). Interpretation of the 2D resistivity data was performed using the robust (L_1-norm) inversion method, which minimizes the absolute differences between measured and calculated apparent resistivity values (Loke *et al*., 2003). This is an appropriate method for interpreting data from areas where subsurface regions separated by sharp boundaries are expected. Furthermore, a finite element grid was used in the data inversion as inclusion of the topography was necessary for precise relation of the object's position in space along the survey lines.

The hydraulic conductivities of the unsaturated and saturated zones were investigated at a few points of the site using a constant head permeameter (Amoozegar, 1989) and slug tests (Hvorslev, 1951), respectively. The permeability can contribute to the interpretation of the cross-correlation analyses.

To complement the time series data and geophysical survey, chemical analyses of hazardous substances were carried out. Four water samples for bacterial analyses were collected from 1M, Río Artiguas, the river at Quebrada Alegre, and from an old mining gallery that serves as water supply for the village and is located just upstream from the site. It is assumed that high presence of coliform bacteria in groundwater would originate from Río Artiguas as this river is highly contaminated

DOI: 10.1002/hyp

with sewage. The bacterial analyses were carried out at the National University in Managua (UNAN-Managua). Later, 1M, 3P, 8P and the river were sampled for Hg analyses, which were performed with a Perkin Elmer model Elan 6000 ICP Mass Spectrometer (PerkinElmer, Canada).

RESULTS

The water levels of the river indicate a rapid response to precipitation during most of the monitoring period (March 2004–March 2005) (Figure 2). In general, the hydraulic heads in 5P, 7P, 8P and 1M have a tendency to change together with the river levels (1R). A smaller response is observed at 6M, 4P and 4M. The temperatures also have a similar trend among the piezometers during the period studied, except for 4M and 6M, which present a rather straight curve (Figure 2).

The autocorrelation functions show that the changes in water level at 6M, 4M and 4P occur gradually throughout the period studied (Figure 3). Conversely, the changes in water levels in all the other piezometers and the river take place rapidly, within a lag time of 24 h.

The cross-correlation analyses between the river data and each piezometer are presented in Figure 4. The strongest correlation between hydraulic heads is observed at 8P, which has a correlation coefficient (C) of 0·62, followed by 1M ($C = 0{\cdot}57$), 7P ($C = 0{\cdot}50$) and 5P ($C = 0{\cdot}32$). In contrast, low or weak correlation is found with 6M ($C = 0{\cdot}06$), 4P ($C = 0{\cdot}22$) and 4M ($C = 0{\cdot}09$). In the case of temperatures, cross-correlation is strong in all cases, being highest at 8P ($C = 0{\cdot}93$) and lowest at 6M ($C = 0{\cdot}70$). The lag times in level fluctuations at the piezometers located near the river channel are short and positive, except for 4P which precedes the river signal by 64 days (Figure 4). The temperatures at 7P, 4P, 8P, 4M

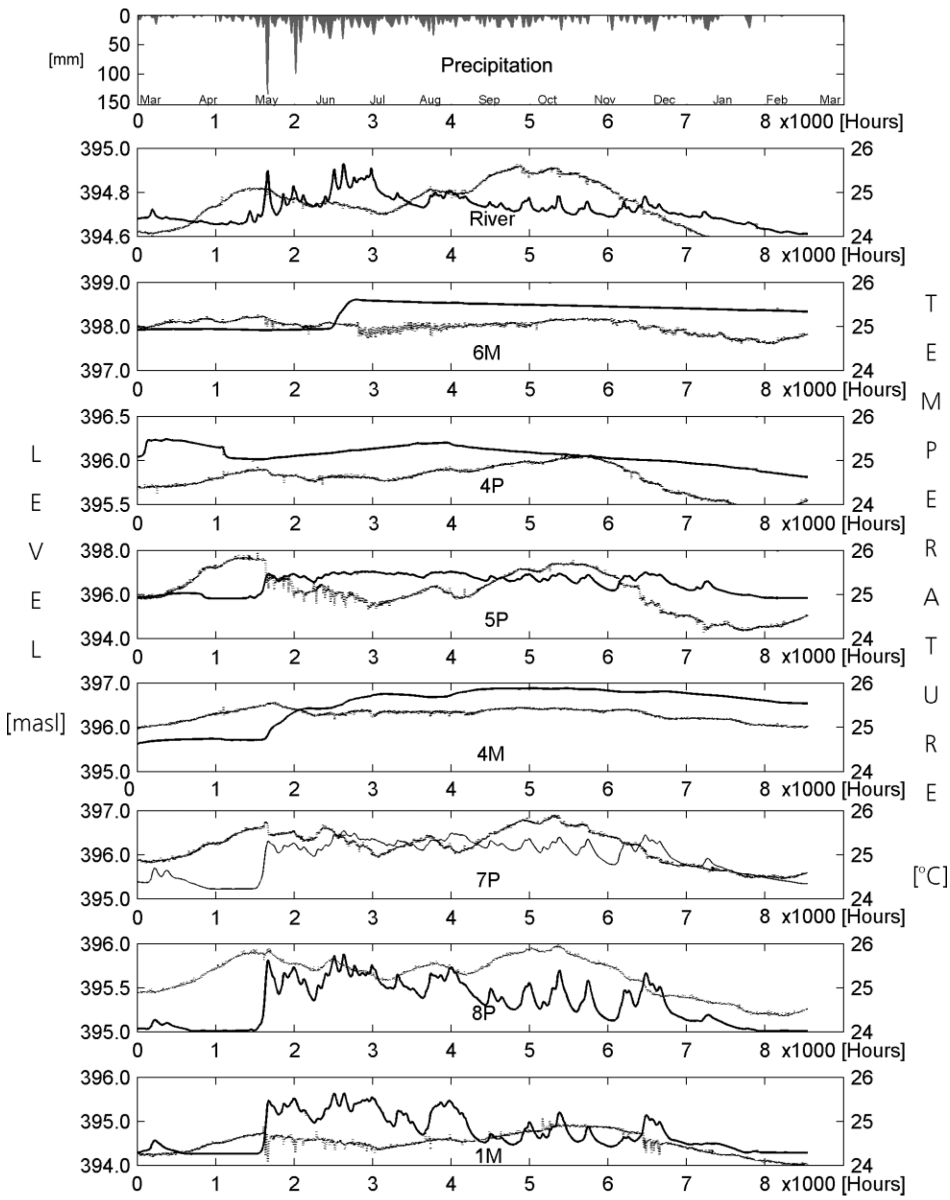

Figure 2. Rainfall, river water and groundwater levels and temperatures measured from March 2004 to March 2005. Continuous lines represent levels and dashed lines represent temperatures

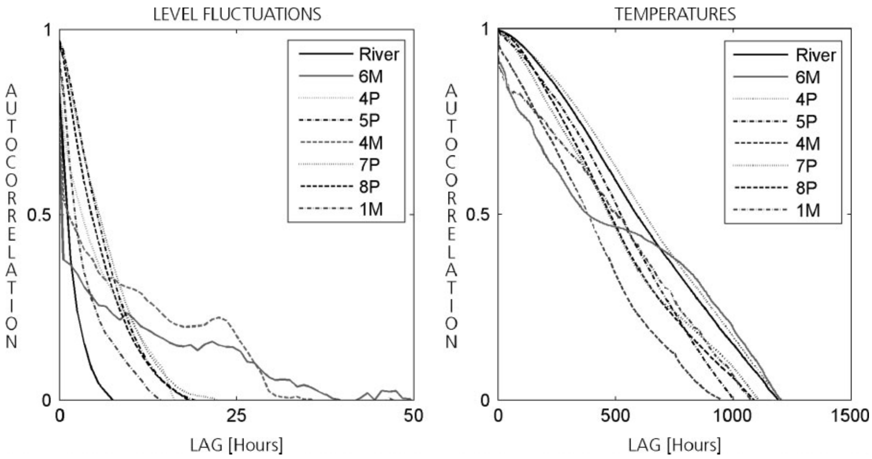

Figure 3. Autocorrelation functions for the groundwater levels (left) and for temperatures (right)

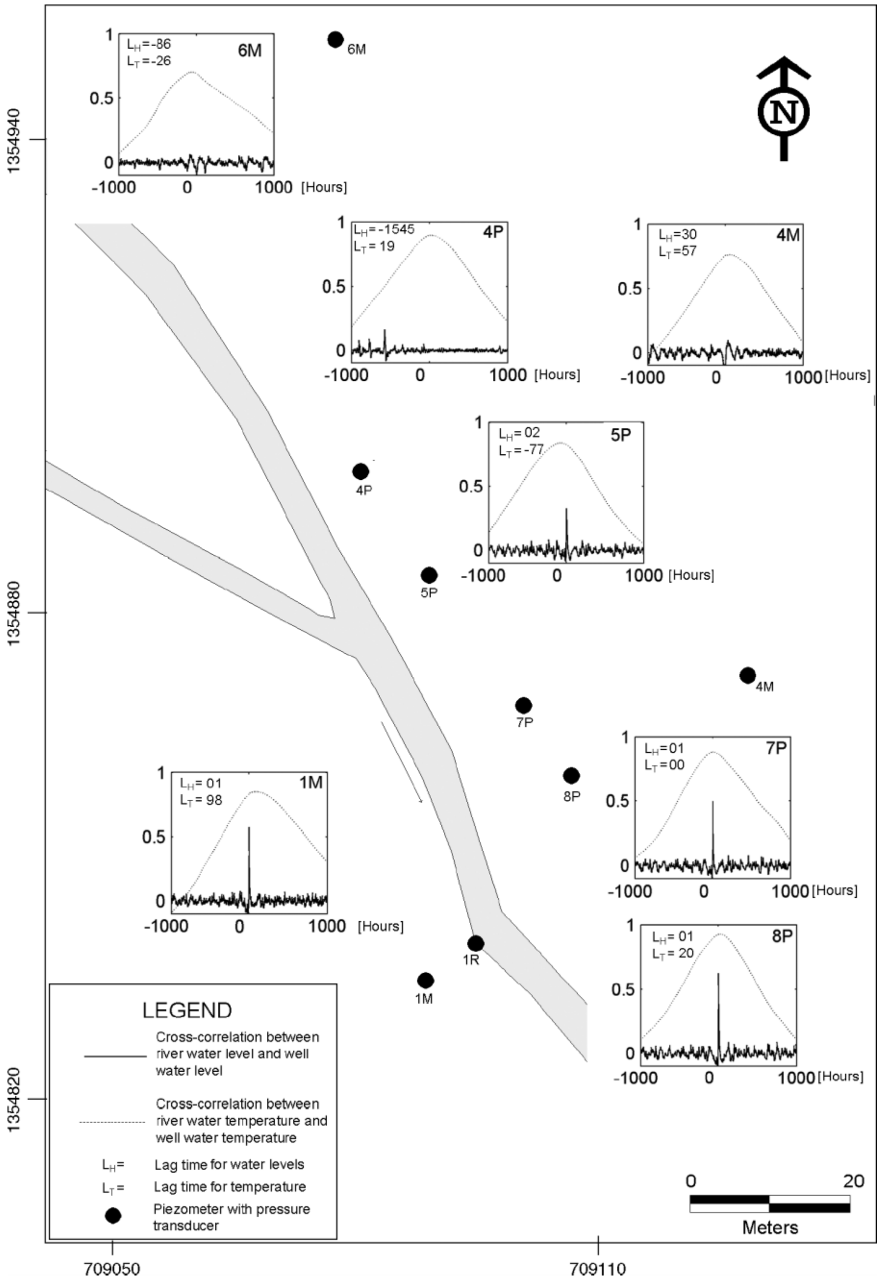

Figure 4. Cross-correlation between river level and each of the monitored piezometers at the site

and 1M lag the temperature in the river, while a negative lag is found for 6M and 5P.

Since the highest cross-correlations were found between the river level and the piezometers situated near the channel, a coherence function was applied to explore the linear connection between those points. The coherence functions shown in Figure 5 indicate that, in general, there is a strong connection between the river levels and piezometers 7P, 9P and 1M at periods of 12 h. Similarly high coherences are found between 7P and 5P, 8P and 1M. However, poor or no coherence was found between the river and 5P and 4M.

Based on the time series data, two scenarios were interpreted for the periods with lowest groundwater level and the periods with higher groundwater level. During the long wet season a clear gradient towards the river is observed (Figure 6a and 6c). During the dry season (January–March 2004) groundwater levels were lower and infiltration from the river to 1M and 2M occurred (Figure 6b and 6c). At the east side of the river, the groundwater gradient does not indicate river intrusion during the dry season.

The inversion results of electrical resistivity surveys are presented in Figure 7. Line 1 was placed crossing Río Artiguas perpendicularly, while lines 2 and 3 were located parallel to the river. Line 2 crosses the tributary stream and line 4 crosses the wetland up to the hillsides. The inversion models indicate the presence of a 3–7 m thick high resistivity top layer (>160 Ωm) at lines 2 and 1, particularly at the sections where the lines cross the streams. Similarly, high resistivity zones extending vertically are found at the north ends of lines 2 and 4, and at the south side of line 2. Other highly resistive zones appear at the southern extremities of lines 2, 3 and 4. The clay content in a swamp located next to the river has a clear effect, decreasing the resistivity, as shown along the upper zones of line 4 and at the east side of line 1. Deeper low resistivity zones are located below the areas where the lines intersect and at deeper zones below the river beds (<40 Ωm).

The permeabilities at the site are generally low at the clay-rich vadose zone (upper 1 m), but show an increase at the saturated zone near the river channel (5P, 7P, 8P and 1M). In contrast, permeability tests at the hillsides indicate very low or no measurable permeability (4M, 5M and 6M). Figure 8 shows hydraulic conductivity results obtained at different points along resistivity line 3. Higher permeabilities are found in areas of high electrical resistivity. The hydraulic conductivities of the vadose zone, as estimated with the constant head permeameter, indicate a permeability ranging from 8×10^{-8} m s^{-1} in the proximity of 5P to 10^{-5} m s^{-1} at the southern extremity of resistivity line 3. A test performed next to 5M show a permeability of 10^{-6} m s^{-1} at that side of the wetland. The slug tests performed in the piezometers indicate permeabilities ranging from 2×10^{-5} m s^{-1} at 5P to 10^{-4} m s^{-1} at 8P. The estimated permeability at 1M was 5×10^{-6} m s^{-1}.

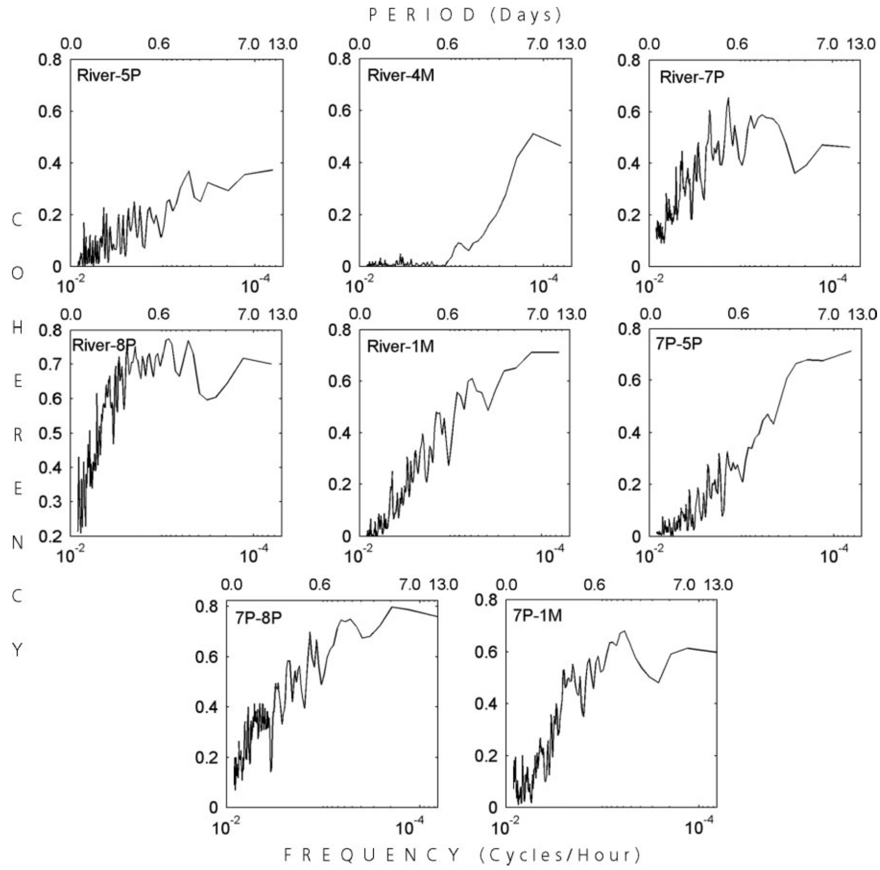

Figure 5. Coherence functions between river and nearest piezometers and between 7P and nearest piezometers

DOI: 10.1002/hyp

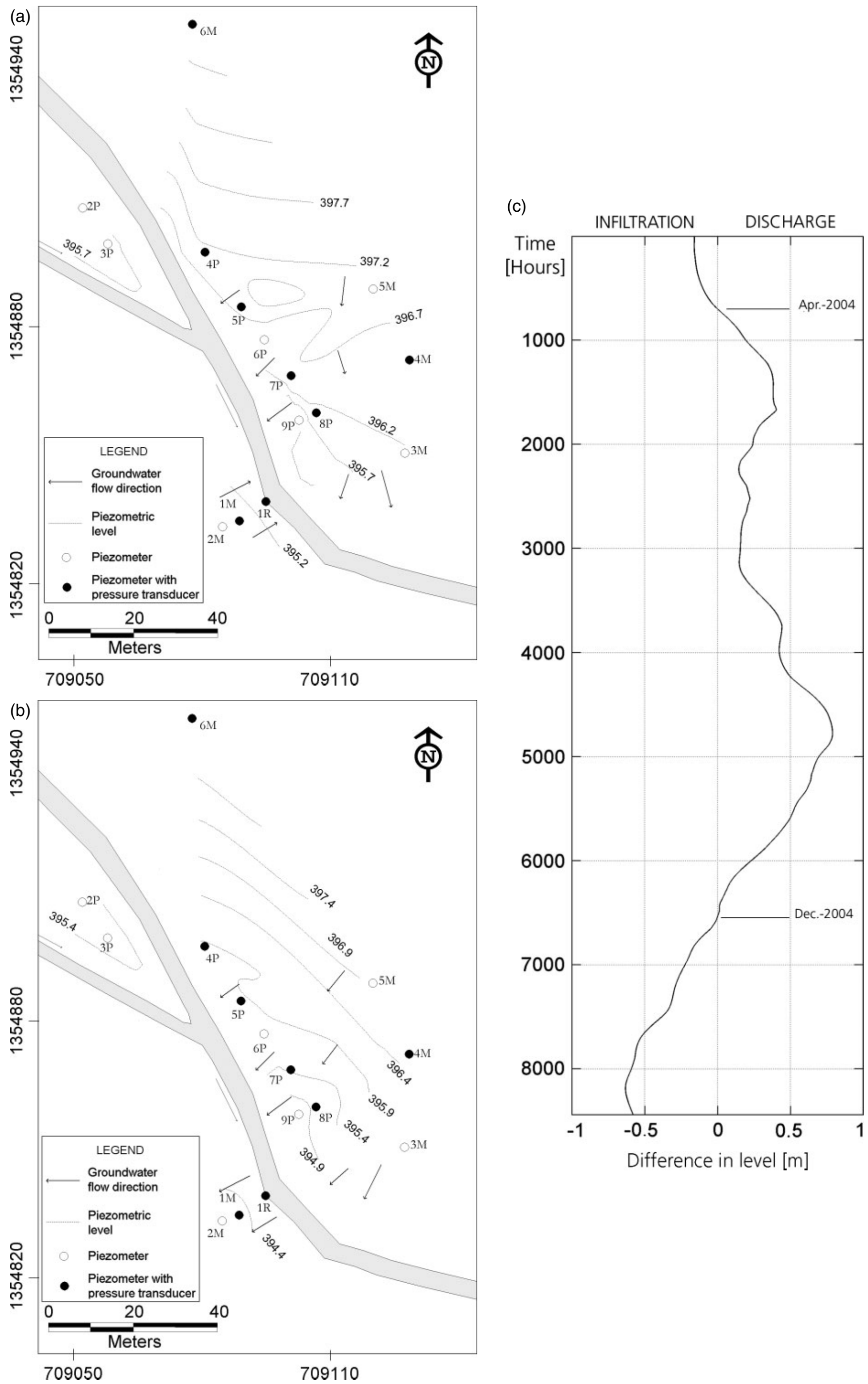

Figure 6. Groundwater table (a) period of highest hydraulic heads and (b) period of lowest hydraulic heads and (c) periods of infiltration from the river and discharge to the river as observed at 1M

Bacterial analyses show a low number of *Escherichia coli* in the main source of drinking water for Santo Domingo (300 bacterial per 100 mL), which it is not a health concern. However, in the Río Artiguas a high concentration of bacteria was found (10^4–10^5 bacterial per 100 mL). Moreover, an important concentration of *Escherichia coli* was detected at 2M ($\sim 10^3$ bacteria per 100 mL). Detectable mercury concentrations were found in water samples from the piezometers and the river, the highest value was found at 1M (0·11 μg L^{-1}), followed by the river (0·04 μg L^{-1}), 8P (0·03 μg L^{-1}) and 3P (0·01 μg L^{-1}).

DISCUSSION

The river water level is strongly influenced by the heavy precipitation regime that characterizes the basin. Additionally, the groundwater level fluctuations appear to be controlled by rapid infiltration following rainfall.

This strong link between changes in the river level and groundwater table fluctuation suggests a seasonal character of the shallow aquifers. In the areas near the hillsides (6M and 4M) groundwater fluctuations are less influenced by infiltration, probably due to a high clay content, which also contributes to the formation of the wetland. In contrast, the relatively high cross-correlation ($>C = 0{\cdot}32$) found in all piezometers located next to the river channel denotes faster infiltration and transport of water through the fractured rock. However, considering the short distance between piezometers and the low cross-correlation found at 4P ($C = 0{\cdot}22$), high spatial variability of the hydraulic properties should be expected in the area. Moreover, the coherence functions indicate a marked connection in the frequency domain between fluctuations at the south side of the site (1R-7P-8P-1M), but this strong relationship is not present between the piezometers elsewhere. The strong cross-correlation of temperatures found in all cases reflects the similar origin of river water and groundwater.

The high variability of hydraulic properties at the site is also supported by the electrical resistivity surveys. The resistivity response from the top areas varies from high resistivity zones (>160 Ωm) associated with coarse-grain material and hard rock to the low resistivity zones rich in clay (<40 Ωm) (Figures 7 and 8). There are strong lateral variations in the resistivity over short distances, which indicate intense vertical fracturing. Furthermore,

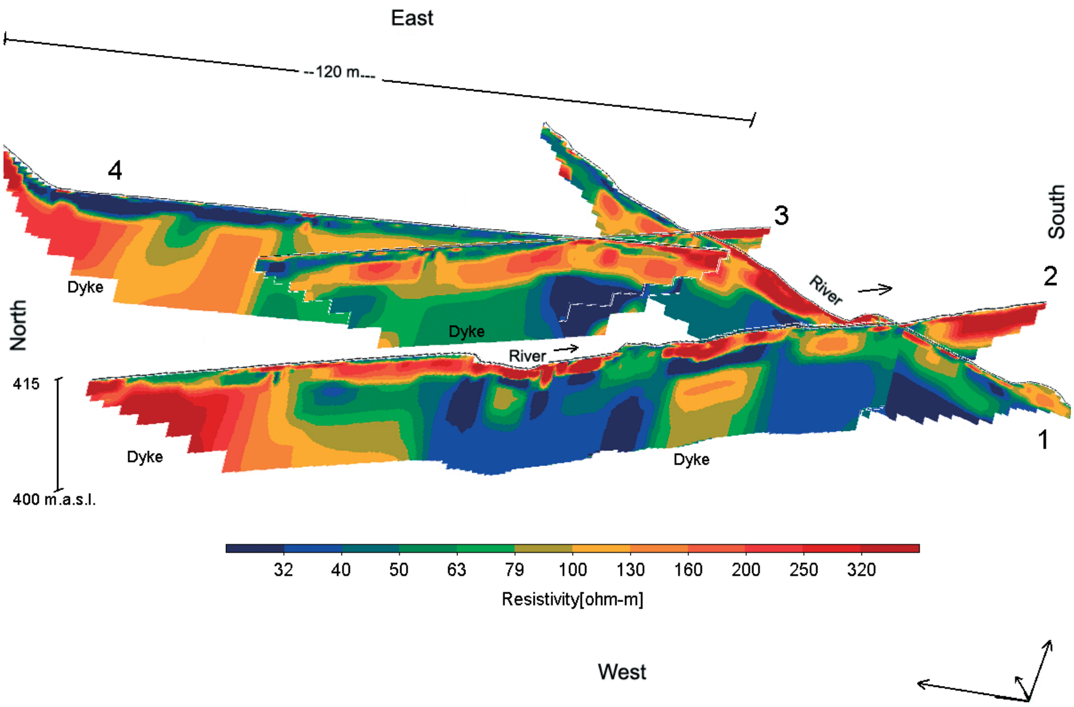

Figure 7. Electrical resistivity images

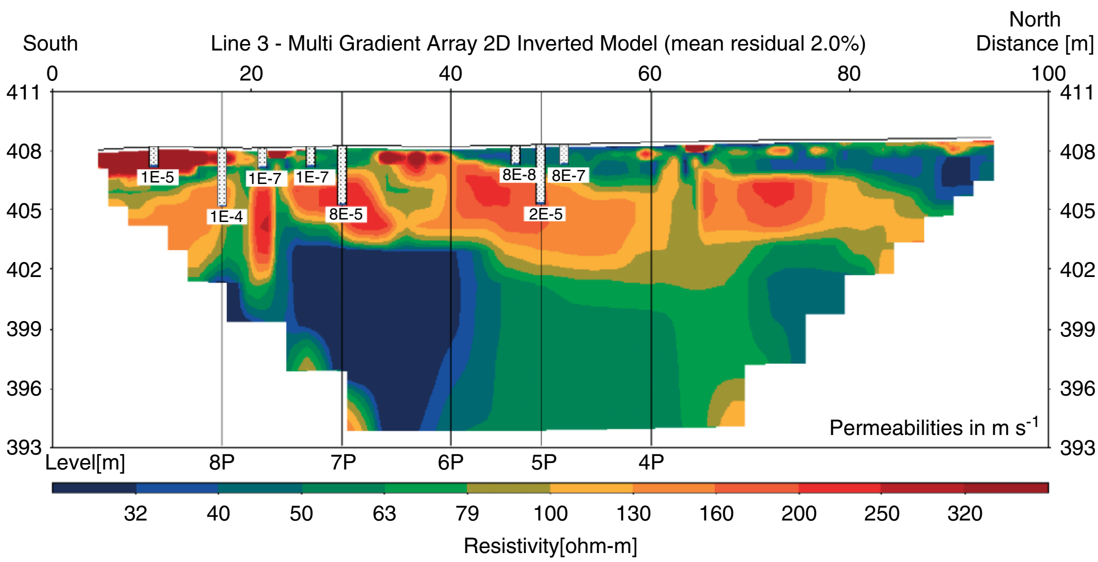

Figure 8. Electrical resistivity image of line 3 including values from permeability tests

DOI: 10.1002/hyp

previous aerial photointerpretation, field documentation and geophysical surveys in the basin (Mendoza, 2002) suggest that the vertical zones of high resistivity present in the resistivity images of lines 2, 3 and 4 might be associated with two basaltic dykes crossing the river.

Zones of discharge near the channel of the river cannot be interpreted from the resistivity images. Nevertheless, areas with high resistivity values associated with bedrock were observed near the channel in line 1. This may be an indicator that discharge to the river does not occur through sediments but through fractures in the bedrock.

Regarding the groundwater table, there was a hydraulic gradient towards the river for most of the monitoring period. This gradient is maintained by the heavy precipitation and expected high infiltration rate. However, as the rain season finished the hydraulic gradient changed on the west side of the river, allowing river water infiltration (Figure 6). The topographically controlled hydraulic gradient on the north-east side of the river permitted a continuous flow to the south-west during the short dry season. This situation explains the bacterial concentrations in 2M, similar to the concentration found in the river water. The Hg concentrations found in 1M are higher than in 3P and the piezometers located on the other side of the river channel.

The interpretation of hydraulic data and resistivity imaging is supported by the hydraulic conductivities estimated at different points of the site. Higher permeability was found at 8P, which also presents higher cross-correlation (Figure 4). The top layers commonly have lower hydraulic conductivities due to the higher clay content, but there may be an increase when reaching the fractured rock at depth and close to the fractured dykes.

In general, these results are in agreement with the findings of Mendoza *et al.* (2005), who suggested that there is rapid groundwater circulation through the basin. From these local groundwater systems water travels relatively fast when moving through joints and fractures until discharging into the river. When precipitation decreases, the situation could be the inverse, with channel water infiltrating the nearby shallow aquifers.

CONCLUSIONS

This paper has shown that rainfall infiltration is the main factor controlling the shallow groundwater dynamics in the near channel aquifers along the Río Artiguas river. Cross-correlation analyses of river levels against hydraulic heads revealed a rapid response of the groundwater table to river infiltration and direct recharge. The piezometers located far from the river channel showed poor correlation with the river, indicating a lack of contact with the nearby groundwater. This may be caused by the high clay content found at those areas, as interpreted from the electrical resistivity images. Less weathered or fresh rock is related to the deeper high resistivity zones, where flow through fractures may be of major hydrogeological significance.

The high bacteria concentrations found in the river and in the groundwater at 2M confirm that there is a connection between the river and the adjacent shallow aquifers. This is also supported by the hydraulic heads, which suggests that most of the river infiltration to aquifers occurs during the dry season. However, the frequent river floods can also spread the pollutants to the nearby aquifers.

The results presented here showing the exposure of groundwater systems to pollution in basins characterized by fractured media, such as the highlands of Nicaragua, are a major concern. In this case, waste disposal in surface water can also lead to direct pollution of groundwater. The seasonal character of the aquifers suggests limited availability of groundwater resources, as they seem to depend on recent recharge. Further research could be aimed at characterizing the recharge and discharge processes throughout the river basin, which can increase the understanding of groundwater–surface water relationships.

ACKNOWLEDGMENTS

This work was conducted as part of a multidisciplinary research programme funded by the Swedish International Development Agency (Sida/SAREC). Technical and logistical support was provided by the Department of Engineering Geology at Lund University (Sweden) and Centro de Investigaciones Geocientíficas at UNAN-Managua, respectively. Professor Göran Bengtsson suggested valuable ideas for the study. Kjell Andersson assisted in the piezometers installation and Tommy Olsson carried out the mercury analyses at the Department of Ecology, Lund University. Jonas Hedberg installed the meteorological station and Marvin Corriols retrieved divers' data. Family Duarte is specially acknowledged as their assistance made fieldwork less difficult under the tropical conditions at Río Artiguas. Suggestions by an anonymous reviewer helped to improve the manuscript.

REFERENCES

Albuquerque N. 1996. Estudio de Impacto Ambiental. [Environmental Impact Study] Empresa Asociativa de Pequeños Mineros de SD Chontales.

Amoozegar A. 1989. A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. *Soil Science Society of America Journal* **53**: 1356–1361.

André L, Rosén K, Torstendahl J. 1997. *Minor field study of mercury and lead pollution from gold refining in Central Nicaragua*. MSc thesis, ISBN 1402–1617. Luleå University of Technology, Sweden.

Aronsson M, Wallner C. 2002. *Inventory of springs and hydrochemical investigations of groundwater in the drainage basin of Sucio river, Nicaragua*. MSc thesis, ISRN LUTVDG/TVTG–5078–SE. Lund University, Sweden.

Bierkens MFP, Knotters M, Hoogland T. 2001. Space-time modeling of water table depth using a regionalized time series model and the Kalman filter. *Water Resources Research* **37**: 1277–1290.

Crosbie RS, Binning P, Kalma JD. 2005. A time series approach to inferring groundwater recharge using the water table fluctuation method. *Water Resources Research* **41**(1): W01008. DOI:10·1029/2004WR 003077.

Dahlin T. 1996. 2D resistivity surveying for environmental and engineering applications. *First Break* **14**(7): 275–283.

Dahlin T, Zhou B. 2004. A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting* **52**: 379–398.

Dahlin T, Zhou B. 2006. Gradient array measurements for multi-channel 2D resistivity imaging. *Near Surface Geophysics* **4**: 113–123.

deGroot-Hedlin C, Constable S. 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics* **55**: 1613–1624.

Duffy CJ, Gelhar LW. 1986. A frequency domain analysis of groundwater quality fluctuations: interpretation of field data. *Water Resources Research* **22**: 1115–1128.

Ellis RG, Oldenburg DW. 1994. Applied geophysical inversion. *Geophysical Journal International* **116**: 5–11.

Grunander K, Nordenberg L. 2004. *Investigation of groundwater—surface water interaction in the drainage basin of the River Sucio, Nicaragua*. MSc thesis, ISRN LUTVDG/TVTG–5090–SE. Lund University, Sweden.

Hodgson G. 1972. Geological map of La Libertad, Catastro e Inventario de Recursos Naturales: Nicaragua.

Hvorslev MJ. 1951. Time lag and soil permeability in ground water observations. Waterways Experimental Station, Corps of Engineers, US Army, Bulletin no. 36.

INETER. 1991. Anuarios Meteorológicos (1990, 1991) [meteorological charts] Catastro e Inventatio de Recursos Naturales: Nicaragua.

Jenkins GM, Watts DG. 1968. *Spectral Analysis and its Applications*. Holden-Day series in time series analysis: San Francisco.

Kim JH, Lee J, Cheong TJ, Kim RH, Koh DC, Ryu JS, Chang HW. 2005. Use of time series analysis for the identification of tidal effect on groundwater in the coastal area of Kimje, Korea. *Journal of Hydrology* **300**(1–4): 188–198.

Larocque M, Mangin A, Razack M, Banton O. 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *Journal of Hydrology* **205**(3–4): 217–231.

Lee JY, Lee KK. 2000. Use of hydrologic time series data for identification of recharge mechanism in a fractured bedrock aquifer system. *Journal of Hydrology* **229**: 190–201.

Lerner DN. 1997. Groundwater recharge. In *Geochemical Processes, Weathering and Groundwater Recharge in Catchments*, Saether OM, deCaritat P (eds) AA Balkema: Rotterdam, Holland; 109–150.

Loke MH, Barker RD. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting*, **44**(1): 131–152.

Loke MH. 1997. Rapid 2D resistivity inversion using the least squares method, Manual for RES2DINV, Geolectrical Imaging 2D and 3D.

Mendoza JA. 2002. *Geophysical and hydrogeological investigations in the Rio Sucio watershed, Nicaragua*. Lic Thesis, ISBN 91-972406-0-X. Lund University, Sweden.

Mendoza JA, Dahlin T, Barmen G. 2004. Use of resistivity imaging in a surface water—groundwater interactions study, Proc. XXXIII Congress IAH—7° ALHSUD 11–15 October, 2004, Zacatecas City, Mexico.

Mendoza JA, Dahlin T, Barmen G. 2006. Hydrogeological and hydrochemical features of an area polluted by heavy metals in central Nicaragua. *Hydrogeology Journal* **14**: 777–784.

Padilla A, Pulido-Bosch A. 1995. Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *Journal of Hydrology* **168**(1–4): 73–89.

Romero F. 1996. Contaminación de Hg y Pb en fuentes de agua. area de Santo Domingo, Chontales [Hg and Pb contamination in water wells], Centro de Investigaciones Geocientíficas: Managua, Nicaragua; 21.

Sheets RA, Darner RA, Whiteberry BL. 2002. Lag times of bank infiltration at a well field, Cincinnati, Ohio, USA. *Journal of Hydrology* **266**: 162–174.

Silva G. 1994. Diagnóstico da contaminação ambiental gerada pela atividade minerária sobre os rios Súcio, Mico e Sinecapa, Nicaragua [Diagnose of the contamination caused by the mining activity in the rivers Sucio, Mico and Sinecapa, Nicarágua]. Universidade Federal do parã Centro de Geociências Curso de Postgraduação, Belem, Brasil.

Sophocleous M. 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal* **10**: 52–67.

Winter TC. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal* **7**: 28–45.

Winter TC, Harvey JW, Franke OL, Alley WM. 1998. Ground water and surface water—a single resource. US Geological Survey Circular 1139, Denver, USA.

Zhang YK, Schilling K. 2004. Temporal scaling of hydraulic head and river base flow and its implication for groundwater recharge. *Water Resources Research* **40**(3): W03504. DOI:10·1029/2003WR002094.