Seismic imaging to help understand and manage water quality in coastal Bénin, West Africa

Final Project Report
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ABSTRACT

The coastal city of Cotonou in Bénin, West Africa, is a large population center that is facing a serious threat to the sustainability of its fresh water supply. Cotonou is Bénin's largest city with approximately 1.5 – 2.0 million people. It relies on the Godomey aquifer for its domestic water supply. The aquifer is undergoing saltwater intrusion and this problem is likely to worsen without significant steps to improve management of the water supply. Lake Nokoué is a nearby water body that has high salinity levels throughout much of the year and is thought to be the primary source of salinity in the aquifer. Within Lake Nokoué is Ganvié (a city of greater than 30,000 inhabitants built entirely on stilts in the lake) and several other population centers. The presence of these lake urban areas and the fact that the lake is heavily relied upon for fishing has resulted in severe manipulation of the lake for waste disposal, navigation and fish farming. The continuity of the aquifer and saltwater flow paths are poorly understood but this information is critical to ensure sustainable access to fresh water in this growing urban center.

The primary well field for the city of Cotonou is located along the southwest shore of Lake Nokoué, and the lake is suspected to be the primary source of saltwater intrusion. Over three field campaigns, we acquired 9 linear km of high-resolution seismic reflection data extending from the center of the well field to the lake shore. The objective of the seismic investigation was to better constrain aquifer geometry and to identify preferential flow paths between the lake and the well field. The seismic profiles were tied to existing well logs and integrated into a global interpretation framework. The aquifer map produced through seismic reflection analysis resulted in an aquifer geometry that differed significantly from that produced based on well logs alone. We used this improved aquifer geometry to update the regional groundwater flow model and found that the new model predicts substantially higher recharge from Lake Nokoué and from the Djonou River, a small tributary to the south. These new results are consistent with field observations of the advance of aquifer salinization and may help with the development of an improved water management strategy.

In addition to the technical aspects highlighted above, this project resulted in a number of indirect additional benefits. (i) We conducted two, three day short courses in Bénin to provide training in hydrogeophysics and modern geophysical techniques for more than 25 Béninois students. These students then participated in the field data acquisition component of the project. (ii) Through additional support from Boise State and an unplanned partnership with the University of Nice, 3 students from Boise State, and 4 students from the University of Nice were able to participate in the training and field project in Bénin. (iii) One graduate student at Boise State (Kyle Lindsay) completed his MS Thesis on this project. (iv) We developed a partnership in Idaho with Micron Technology who built a lightweight portable seismic source that we used during the field project. (v) In partnership with Mala Geosciences, Boise State provided a refurbished Mala ground-penetrating radar system to the Department of Earth Sciences, University of Abomey-Calavi, for training and research. (vi) This project produced several publications including 2 abstracts for the SEG annual meeting, 1 abstract for an SEG post-convention workshop, 1 abstract for the SAGA conference in South Africa, 1 TLE article, and 1 peer reviewed article in Geophysics.
1. Report Format

This report is divided into two sections. In the first section we describe the non-technical aspects of the project. This includes a background summary, the human element, lessons learned, partnerships and cost sharing, and conclusions. The second section is comprised of Kyle Lindsay’s MS Thesis entitled “Seismic Imaging to Constrain Groundwater Models for a Better Understanding and Management of Water Quality in Coastal Benin, West Africa: A Saltwater Intrusion Problem”. This thesis gives detailed background information, a thorough technical discussion of the field studies, seismic data processing, data interpretation, and hydrologic modeling. In addition, we have included a copy of a paper published in The Leading Edge as Appendix A, and a proof of a paper published in Geophysics as Appendix B.

2. Background Summary

Of the eight goals identified by the United Nations Development Program (UNDP), the seventh is “Ensuring Environmental Sustainability”. Within this framework, Target 7c states, by 2015 “Reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation.” By 2012, 89% of the global population had access to improved sources of drinking water. This number is up from 71% in 1990 (United Nations, 2014) and met the UN’s 2015 goal. While this is encouraging, a significant gap between urban and rural areas remains. This gap has focused much attention on improving the situation in rural areas, however, sustainable access to safe water in urban areas is by no means universal and significant population centers remain at risk, particularly in the developing world. One such area is the coastal city of Cotonou in Bénin, West Africa.

2.1 History and Geography

Bénin is bordered to the east by Nigeria, to the west by Togo and on the north by Niger and Burkina Faso. To the south is the South Atlantic coast. The official language of Bénin is French, but a number of local languages are common. Fon and Yoruba are widely spoken in the south with over half the population speaking Fon. Numerous other regional and local languages are spoken throughout Bénin.

Its position on the Bight of Bénin made it a prime trading port in centuries past and Bénin has seen a long and complex history. The first Europeans arrived in 1556 and by the 1600s the slave trade had begun along the coast. Around 1650 the kingdom of Abomey (Dahomey) was established near the southern coast and became an active participant in the slave trade as the kingdom expanded. The kingdom captured slaves in conquered territories and exchanged them for Portuguese, French and Dutch weapons. In 1863 the first French protectorate was established with the King of Porto-Novo. In 1889, the last independent ruler of Abomey sought to forcefully expel the French but was defeated, and in 1894 Dahomey was colonized by France. In 1904, Dahomey was incorporated into French West Africa. In 1958, the country gained independence from France and following a period of political turmoil came under the leadership of a military government. Between 1989 and 1991 the country underwent a peaceful transition to a democratically elected government and became the Republic of Bénin.

2.2 Economy
According to the World Economic Forum, Bénin has become the most competitive economy in the West African Economic and Monetary Union due to a number of economic reforms enacted over the past decade. Despite these advances, Bénin remains economically underdeveloped with a significant dependence on subsistence agriculture (CIA World Factbook; https://www.cia.gov/library/publications/the-world-factbook/geos/bn.html). Bénin currently ranks 167 out of 187 countries on the UN’s International Development Indicator that integrates information such as economic growth, income, education, and health. This index also indicates that roughly 42% of the population lives below the poverty threshold.

2.3 Hydrogeologic Setting

Cotonou is Bénin’s largest city with a population of 1.5 – 2.0 million people. It is located along the Atlantic Coast and is also bordered by Lake Nokoué, which has extremely high salinity through the majority of the year. Lake Nokoué is a large shallow lake, reaching a maximum depth of ~3m during the rainy season. The lake is connected to the Atlantic Ocean via a shallow canal. Salinity in the lake is highly variable ranging from less than 500 mg/L during the rainy season to greater than 30,000 mg/L during the dry season (unpublished recent data). Further complicating the system is the city of Ganvié, which has greater than 30,000 inhabitants, and other population centers that are built entirely on stilts within the lake. The presence of these lake cities and the fact that the lake is heavily relied upon for fishing has resulted in severe manipulation of the lake for waste disposal, navigation and fish farming.

The sole source of drinking water for Cotonou is the Godomey aquifer. The Godomey well field is the city’s primary water well field and lies roughly 5 km from the Atlantic coast, but adjacent to Lake Nokoué. The well field consists of 20 wells that withdraw water from one or more of three semi-confined aquifers ranging in depth from 30 m – 180 m. Currently, the annual rate of urbanization in Bénin is approximately 4%. The growth of the urban population has necessitated an increase in the pumping rate from the Godomey well field. Since 1990, the pumping rate has increased steadily at about 900,000 m$^3$/yr/yr. The increased pumping rate has been accommodated by adding new wells at progressively increasing distances from Lake Nokoué. Increased pumping has been accompanied with an increase of salinity in the wells. There are two potential sources of the increasing salinity in the wells; 1) the Atlantic Ocean, and 2) Lake Nokoué. Several of the deeper aquifer units extend beneath the Atlantic and therefore may be hydraulically connected to ocean waters. However, the wells closest to the ocean give no indication of increased salinity in the deeper aquifers. Conversely, all of the wells showing increased salinity are close to Lake Nokoué.

In an effort to understand this large, complex system, an initial groundwater model was developed (Boukari et al., 2008) and then improved through interpretation of the structure of the local geology (Silliman et al., 2010). While not yet at the stage of a quantitative management tool, the groundwater model provides general information about the system and can be used to identify areas where further study is needed. For example, the model indicates that there is a groundwater divide between the ocean and the Godomey well field, consistent with observations showing little sea water encroachment from the south. Additionally, the model predicts that increased pumping will result in greater recharge being derived from the western part of Lake Nokoué. This is consistent with observations of increased salinity in the wells nearest the lake.
The combined field observations and numerical modeling indicate that Lake Nokoué is the likely source of saline intrusion into the Godomey aquifer system.

While intrusion of saline waters from Lake Nokoué is the immediate threat to the sole source of drinking water for the city of Cotonou, rising levels of chloride in shallow rural wells near the coast indicate that the encroachment of sea water into the shallowest aquifer may have begun and this risk will likely increase as the groundwater resource is increasingly stressed. Additionally, urbanization is resulting in increased development in the immediate vicinity of the Godomey well field leading to greater risk of anthropogenic release of hazardous groundwater contaminants. In light of the various factors conspiring to endanger the drinking water supply, it is critical that good management decisions are made now to sustain a viable source of fresh water for this growing urban area. The management plan must actively minimize the encroachment of saline water from the Lake Nokoué while at the same time mitigating the risk of sea water intrusion from the south and hazardous chemical contamination related to increased development. As noted by Silliman et al. (2011), the key management questions related to sustainability of the Godomey well field are “(i) for what period of time can the aquifer be expected to provide water for this urban population, (ii) what sources of contamination represent the most severe threats to this groundwater resource, (iii) what hydrologic properties of the recharge zones and deep aquifer system need to be more thoroughly characterized to assist in modeling this groundwater system, and (iv) what hydrologic properties of the recharge zones are likely to be impacted by climate change, population migration, or changing land-use practices.” They go on to conclude that the current groundwater model and field characterization efforts have not yet reached the level where sound, data-driven management decisions can be made. Substantially greater characterization, coupled with refined groundwater modeling, is needed.

3. Human Element

A key component of the project was the involvement of students in all aspects from data acquisition to processing and interpretation. Of several objectives for student involvement, perhaps the two most important were 1) to provide cross-cultural interaction between students from the U.S. and Europe and students from Bénin, and 2) to provide hydrogeophysics training to all students involved in the project. Additionally, students were critical to data acquisition and the project could not have been completed without their hard work.

To facilitate interaction, students and faculty traveling from outside of Bénin were required to either speak French, or to study French prior to departure. Also, the majority of the Béninois students had English language training which facilitated communication. At the beginning of each field season, a two to three day short course on seismic methods in hydrogeophysics was given in French at the University of Abomey-Calavi. European and U.S. students participated in the course alongside their Béninois counterparts. After the short course was completed the students and faculty deployed to the field for seismic data acquisition.

Field work was conducted through the crowded neighborhoods of Godomey on the northern outskirts Cotonou. This provided the opportunity for close interaction with the locals most of whom spoke French, and but some spoke only the local language. The Béninois students not only helped with the field work but served as ambassadors and interpreters as we worked through the city. The interactions we had with the locals were universally positive and this was one of the truly rewarding aspects of the project. Additionally it was clear that the locals were
cognizant of the salt water intrusion problem, and they were both welcoming and interested in our work.

4. Lessons Learned

Our initial field project consisted of land seismic reflection acquisition along a set of profiles that ranged in length from < 200m to greater than 1.5 km. Logistics for the seismic reflection were complicated by conducting the work in this congested urban area. Road surfaces were highly variable and many were not amenable to planting geophones. Heavy traffic and the associated safety concerns for the seismic crew further limited our seismic coverage. Where seismic acquisition was feasible, the roads typically ran through crowded neighborhoods with many roadside shops along with heavy foot and vehicle traffic. These challenging conditions limited our seismic coverage to somewhat sparse and irregular coverage grid.

In addition to the logistics, operations were challenging relative to expectations of those used to conducting field work in western countries. Shipping equipment and supplies in and out of the country was difficult and it was therefore essential to travel with backups for all technical components. Gathering basic supplies such as batteries and work gloves was often a time consuming task, since many items taken for granted in the developed world are not as readily available and sometimes surprisingly expensive. Nevertheless, with a bit of patience and willingness to reset expectations, the work was completed within both the time and monetary budget. And to balance the challenges, some aspects of the work were amazingly easy. For example, on our last field campaign, our home built seismic source broke. At 6 p.m. we were able to get a new piece machined and installed in less than 30 minutes, and all in the open air at a busy Cotonou intersection. Finally, it must be said that the Béninois students were exceptionally resourceful and hard working. This smoothed field acquisition as numerous field equipment repairs were made on the fly while collecting large amounts of data in a relatively short period.

One of the key lessons learned is that traveling from North America to conduct a complex field project in a developing country in West Africa is not possible on the GWB budget alone. A successful project requires strong financial and logistic partnerships. A detailed breakdown of our project partners is provided in Section 5. It was relatively easy to secure additional support and partnerships after having been awarded the GWB grant. However, it would be ideal if the required partnerships were assured prior to the project being awarded, however potential partners and supporters are unlikely to commit prior to the project being awarded. Therein lies a paradox

5. Partnerships and Cost Sharing

During the course of this project we developed several partnerships, without which it would not have been possible to complete the project successfully. The partnership between collaborating institutions was especially beneficial. Dr. Silliman’s long record of experience in running hydrologic projects in Bénin proved invaluable in planning the surveys and understanding the logistics. Without Dr. Yalo and the support of the University of Abomey-Calavi the project could not have been completed. Our driver served as a guide, assistant, interpreter, and ambassador and was crucial to the project. Our intent is that the good working relationship that developed between the three partner universities during this project will lead to a long term collaboration and partnership. In an additional unplanned partnership, Dr. Dylan
Mikesell obtained additional support from CGG Veritas and the University of Nice to integrate a field course into our project for 4 French undergraduate geophysics students. Their assistance during the first field season proved helpful and was a welcome addition to the project. The Boise State College of Arts and Sciences and Department of Geosciences provided additional support to enable 3 BSU graduate students to travel to Bénin to participate in the hydrogeophysics short course and first field campaign.

In addition to the formal project partners, a number of companies provided in kind support that led to the project’s success. This includes Mala Geosciences who refurbished one of BSU’s older ground-penetrating radar systems which we in turn provided to UAC for training and research. Micron Technology in Boise donated engineer and machining time to help with design and construction of a custom built, lightweight marine seismic source which we utilized during the final field campaign. Delta Airlines donated extra baggage allowances and fees which enabled us to send most of our equipment via checked baggage, ultimately saving the project thousands of dollars and enabling the third field campaign. The Boise State Geophysics Club donated t-shirts to the students who participated in the hydrogeophysics field course in Bénin. The table below summarizes the estimated dollar value of in kind support provided by our project partners. The key point to note here is that the total in-kind support is about 30% greater than the support provided by GWB. It would not have been possible to complete the project without this additional support.

<table>
<thead>
<tr>
<th>Company or Institution</th>
<th>Estimated In-Kind Support</th>
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<tbody>
<tr>
<td>Boise State University</td>
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<tr>
<td>Gonzaga University</td>
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<tr>
<td>University of Abomey-Calavi</td>
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<tr>
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<td>Mala Geosciences</td>
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</tr>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$122,400</strong></td>
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6. Conclusions

Conducting a field geophysics project in the developing world is fraught with challenges particularly in an urban environment. These include potential language barriers, difficulties in both shipping and repairing equipment, traffic congestion, and differing cultural and safety expectations. Despite these challenges, the intercultural exchange between students and faculty is invaluable and the willingness of all parties to work diligently toward the projective objectives meant that the project was completed on time and within budget.

We found that the Godomey aquifer system is substantially more complicated than previously mapped. The complexities must be included in the hydrologic model if it is to have value as a predictive management tool. We identified some large features, such as an incised paleo-channel system that could be mapped directly, however, a geostatistical analysis will be required to extract information about the smaller scale heterogeneity. The seismic study substantially enhanced our understanding of the aquifer system and the information gleaned from it will help inform future management decisions.
7. References


SECTION 2
SEISMIC IMAGING TO CONSTRAIN GROUNDWATER MODELS FOR A BETTER UNDERSTANDING AND MANAGEMENT OF WATER QUALITY IN COASTAL BENIN, WEST AFRICA: A SALTWATER INTRUSION PROBLEM

by

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of the thesis submitted by

Kyle Michael Lindsay

Thesis Title: Seismic imaging to constrain groundwater models for a better understanding and management of water quality in coastal Benin, West Africa: A saltwater intrusion problem

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The following individuals read and discussed the thesis submitted by student Kyle Michael Lindsay, and they evaluated their presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

John H. Bradford, Ph.D. Chair, Supervisory Committee
Lee M. Liberty Member, Supervisory Committee
James P. McNamara, Ph.D. Member, Supervisory Committee

The final reading approval of the thesis was granted by John H. Bradford, Ph.D., Chair, Supervisory Committee. The thesis was approved for the Graduate College by John R. Pelton, Ph.D., Dean of the Graduate College.
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I express my profound gratitude to my advisor, Dr. John Bradford, for his invaluable teaching and guidance during my career at Boise State University. I have had the pleasure of learning, working, and traveling with Dr. Bradford and feel truly lucky to have had such an exceptional mentor and travel buddy. I also sincerely thank Dr. Stephen Silliman, Dr. Nicaise Yalo, and Dr. Moussa Boukari for all of their support on this project. This work would not have been possible without their help and expertise.

I thank Geoscientists Without Borders for providing funding for this project and making this work possible. I also thank the Society of Exploration Geophysicists for a travel grant that provided funding to a conference to present this work, and Boise State University for a research grant that helped fund field work for this project. I also thank Micron Engineering and Mala Geoscience for donating equipment to the project, and Delta Airlines for allowing us to ship our equipment free of charge.

I thank my committee members Lee Liberty and Dr. James McNamara for their interest in this work as well as their time and suggestions. I especially thank Lee Liberty for all of his guidance over the last six years as well as the many opportunities he has given me for work and research.

I thank Dr. Esther Babcock, Dr. Thomas Blum, and Dr. Dylan Mikesell for being a huge part of this project and for their invaluable help with data collection, presentation preparation, and thoughtful discussions.

For this project I spent one month at the University of Lausanne, Switzerland,
working on extracting geostatistics from seismic reflection data we collected in Bénin. I thank Dr. James Irving for hosting me during this trip and sharing with me his knowledge of stochastic theory and geostatistics.

I thank all the students from the Université d’Abomey Calavi and l’Université Nice Sophia Antipolis. I especially thank Bénito Koukpo Hounsi and Romuald Kopessi for their help with data collection and for showing me an unforgettable time in Bénin. I also especially thank our driver and ambassador to Bénin, Yakoubou, for all of his help with logistics and data collection.

Last but not least, I thank all my friends and family, especially my parents Denise and Robert for all of their support, and Larry Otheim, Clinton Colwell, Erin Murray, and Mitchell Hopkins for making sure I had plenty of distractions from work.
ABSTRACT

The coastal city of Cotonou in Bénin, West Africa, is a large population center that is facing a serious threat to the sustainability of its fresh water supply. Cotonou relies on groundwater derived from the Godomey aquifer for its domestic water supply. The aquifer is undergoing saltwater intrusion due to an increase in pumping to accommodate a growth in population. Hence, there is substantial interest in better characterizing the groundwater system for the purpose of determining appropriate management strategies to ensure sustainability of this freshwater resource.

I collected seismic reflection data along 15 transects to characterize the geometry of the Godomey aquifer system. I used standard high-resolution seismic methods to image the upper 200 meters using a sledgehammer source and a 120-channel recording system. Three transects were processed with an iterative updating flow that includes prestack depth migration, residual moveout analysis and reflection tomography, while the remaining 12 transects were processed with routine processing flows and poststack time migration. I identified one unconfined aquifer and three confined aquifers separated by reflective clay layers. Some transects showed areas of truncated reflectors which I interpret as channels that could provide potential high permeability conduits for saltwater flow to the Godomey well field.

I updated the aquifer geometry of the existing hydrologic model based on the seismic reflection data and used a three-dimensional finite difference groundwater model to evaluate the impact of the updated geometry on groundwater flow. The updated groundwater model predicts increased recharge from Lake Nokoué, a shallow...
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5.1 Map of the modeled area with finite-difference grid overlain. The red box shows the areal extent of the seismic data. The elevations of the cells within the red box were modified based on the seismic reflection data.

5.2 Fence plot of the depth converted time migrated sections of the 9 lines closest to Lake Nokoué. The view is looking to the southwest (refer to Figure 2.3). The horizons delineate the tops and bottoms of aquifer units and confining clay layers. U1, C1, C2, and C3 label my interpreted unconfined aquifer and three confined aquifers respectively. I have omitted the first horizon (surface elevations) for display purposes.
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5.7 (top) Flow lines predicted by particle tracking for the original model and (bottom) the updated model based on seismic data. Particles were started at the yellow crosses and the green lines indicated the path the particles take to the Godomey well field. The updated model predicts significantly more recharge from Djonou River, making it a likely source of saltwater intrusion to the well field. The areal extent of the seismic data is show with black box.
CHAPTER 1

INTRODUCTION

Coastal groundwater resources represent a critical component of available fresh water for rising population densities in coastal cities. Enhanced dependency on coastal groundwater has resulted in symptoms of over-extraction in many coastal regions around the world, namely excessive storage depletion and saltwater intrusion into fresh water aquifers (Bray et al., 2007; Vandenbohede et al., 2009; Werner, 2010; Silliman et al., 2011). While saltwater intrusion is the primary concern for these coastal regions, many coastal aquifers are also susceptible to pollution by urban, industrial, and agricultural activities (Boukari et al., 1996). Additionally, coastal aquifers are highly sensitive to the influences of climate change, which is expected to produce rising ocean levels and modified groundwater recharge. As a result of anthropogenic pressures, detailed characterization of groundwater quality and quantity in coastal regions has become necessary to properly manage these water supplies. While saltwater intrusion is a problem for coastal populations around the world, developing countries often lack the expertise and equipment to properly characterize and manage saltwater intrusion. As a result of these resource deficiencies, the problem of saltwater intrusion is likely to worsen in developing countries, where access to fresh water may already be limited. One such area that is experiencing these pressures is the coastal city of Cotonou in Bénin, West Africa.
According to the World Economic Forum (Schwab et al., 2010), Bénin has become the most competitive economy in the West African Economic and Monetary Union due to a number of economic reforms enacted over the past decade. Despite these advances, Bénin remains economically underdeveloped with a significant dependence on subsistence agriculture (CIA World Factbook, 2010). Bénin currently ranks 165 out of 187 countries on the United Nation’s International Development Indicator that integrates information such as economic growth, income, education, and health (Khalid, 2014). This index also indicates that roughly 47% of the Bénin population lives below the poverty threshold.

Cotonou is Bénin’s largest city with a population of 1.5 - 2.0 million people. The city lies in the southeast of the country along the Atlantic Ocean (Figure 1.1). Currently, the annual rate of urbanization in Bénin is approximately four percent. The growth of the urban population has necessitated an increase in the pumping rate from the city’s primary well field, known as the Godomey well field. The well field lies approximately 5 km north of the Atlantic Ocean and is bordered on the east by Lake Nokoué, a large shallow lake with elevated chloride concentrations through the majority of the year. Increased pumping has been accompanied by an increase in salinity in the eastern portion of the well field, closest to Lake Nokoué.

The two potential sources of salinity in the well field are the Atlantic Ocean and Lake Nokoué. Several of the deeper aquifer units extend beneath the Atlantic Ocean, and therefore may be hydraulically connected to ocean waters. However, a previous study by Silliman et al. (2010) showed that wells closest to the ocean give no indication of increased salinity in the deeper aquifers. Conversely, all of the wells showing increased salinity are close to Lake Nokoué. Additionally, initial hydrologic models indicate that there is a groundwater divide between the Atlantic
Ocean and the Godomey well field and that Lake Nokoué is the likely source of salinity (Boukari et al., 2008). These models predict that increased pumping will result in greater recharge being derived from the western part of Lake Nokoué, consistent with observations of increased salinity in wells closest to the lake (Silliman et al., 2010).

While intrusion of saline waters from Lake Nokoué is the immediate threat to the Godomey aquifer, urbanization is resulting in increased development in the immediate vicinity of the Godomey well field, leading to greater risk of anthropogenic release of hazardous groundwater contaminants. Further complicating the system is the city of Ganvié, a city of approximately 30,000 people, built entirely on stilts in Lake Nokoué. The presence of this lake city and a large reliance on the lake for fishing has resulted in severe manipulation of the lake for waste disposal, navigation, and fish farming.

In light of the various factors endangering the drinking water supply of Cotonou, it is critical that good management decisions are made now to sustain a viable source of fresh water for this growing urban area. The management plan must actively minimize the encroachment of saline water from Lake Nokoué while at the same time mitigating the risk of hazardous anthropogenic contamination related to increased development. To achieve these management goals, an accurate groundwater model is needed to confidently predict groundwater flow and recharge behavior based on future water management scenarios (i.e. new well locations and pumping strategies).

While initial hydrologic models by Boukari et al. (2008) and Silliman et al. (2010) provide general information about the aquifer system, they are not yet at the stage of a quantitative management tool where data driven management decisions can be made. In particular, challenges remain in the modeling effort in terms of the temporal/spatial distribution of hydraulic head. The aquifer geometry of the current hydrologic model is based on analysis of well log data that is limited by the areal
extent of the wells in the Godomey well field. There have been no wells drilled in Lake Nokoué. Consequently, little is known about the geology underlying the lake and how it is connected to the geology in the well field.

One of the key characterization needs identified by Silliman et al. (2010) is mapping of the primary water bearing units to better understand and quantify the lateral continuity of flow paths. Quantifying the continuity of these units is necessary to improve the spatial resolution of the current hydrologic model and to determine transport pathways between the recharge areas in Lake Nokoué and the Godomey well field.

This research aims at using geophysical techniques to characterize the Godomey aquifer and address the need for a more refined hydrologic model.

1.1 Background

The Republic of Bénin (Figure 1.1) is located in Western Africa, and is bordered by Nigeria and Togo on the east and west respectively, with the southern coastline bordering the Atlantic Ocean. Bénin has a total land area of approximately 111,000 km$^2$, comprised mostly of flat plains in the south with some hills and low mountains in the north. The 2013 census estimated a population of 10.3 million, with an annual growth rate of 2.8%/yr (CIA world factbook, 2010).

The Document of National Policy of Water (Lafia, 2005) estimates the internal and external contributions to Bénin water resources to be approximately 25 billion m$^3$/yr. The same document notes that an increase in population would drastically reduce the quantity of water available per capita, assuming that these resources remain constant. In 1990 for example, the population was approximately 4.5 million people,
and the availability of water resources per capita was 5825 m$^3$/yr (Boukari et al., 2008). Conservative estimates at the time of that study estimated the population of Bénin to be 11.3 million people by 2025, which reduces the quantity of water available per capita to 2293 m$^3$/yr. It is evident from the most recent census data that population growth has been far more rapid than even conservative estimates, with the new projected population estimate of almost 14 million people by 2025. This reduces the quantity of water available per capita to 1785 m$^3$/yr, placing Bénin in the category of countries with a grave shortage of water. These estimates assume that water availability in Bénin remains the same, and does not change as a result of climatic variability.

To accommodate this rapid population growth, more production wells have been added and pumping rates have increased. For example, eight additional wells were drilled during the period of 2001-2002, placing the total number of production wells at 24, each pumping 24 hours a day (Boukari et al., 2008). The pumped discharge has continuously increased, from 5000 m$^3$/day in 1970 to 50,000 m$^3$/day in 2004 (Boukari et al., 2008). The impact of intensive pumping on the groundwater is observed as a progressive decline of hydraulic heads in observation piezometers, and saltwater intrusion in select production wells (Boukari et al., 1996) (Figure 1.2).

### 1.2 Survey Area

While saltwater intrusion has affected aquifers in all coastal regions of Bénin, this work focuses on south-central Bénin, near the population center of Cotonou. In particular, this study was undertaken near the the city’s primary well field, known as the Godomey well field (Figure 1.1). Land use in the region varies from major urban
development around Cotonou to small rural villages (Silliman et al., 2010). Economic growth has driven an increased need for infrastructure in the region. As a result, substantial portions of the land have been manipulated for construction, leading to decreased local recharge and increased runoff. Consequently, surface flooding during the rainy season has become a serious problem for urban Cotonou (Silliman et al., 2010). Outside of the urban area, much of the land remains open wetlands. These wetlands are interspersed with small villages, where the population has infilled the wetlands in support of construction of homes and agricultural activities. Again, this manipulation of land has led to decreased recharge and increased runoff, causing flooding during the rainy season in many of these rural villages. This manipulated land use not only modifies the recharge of groundwater in these areas, but also increases the potential risk of anthropogenic pollution due to the standing flood waters in the city and rural villages.

1.3 Hydrogeological Setting

The Godomey well field lies on the south-eastern portion of the Plateau of Allada, in the coastal sedimentary basin of Bénin (Figure 1.3). The geology of the sedimentary basin has been previously described by multiples authors (Blivi et al., 2002; Barthel et al., 2008; Boukari et al., 2008; Barthel et al., 2009; Alassane et al., 2009) and is comprised of three primary lithologic units consisting of a clayey-sand, sandy-clay, and sand of Pleistocene, Pliocene, and Miocene age respectively. These layers make up the coastal aquifer system and rest in angular unconformity on a highly heterogeneous clay/marl Eocene substratum between 180 - 220 m depth.

The geology in the production zone is comprised of interbedded sands, silts, and
clays that form four primary aquifers separated by confining clay layers (Figure 1.4). For clarity, I will refer to these aquifers as U1, C1, C2, and C3 where U1 is the top unconfined aquifer and C1, C2, and C3 are the three confined aquifers in order of increasing depth (Figure 1.4). Thicknesses range from 10 - 50 m for the sandy aquifer units and 5 - 10 m for the confining clay layers. The lithology dips slightly to the south, with several of the deeper aquifer units extending below the Atlantic Ocean, potentially exposing them to seawater influx directly from the ocean.

Recent hydrologic data has brought into question the validity of this simplified geologic model and suggests the confinement of aquifers in the region may not be complete (Figure 1.5). Figure 1.5 shows relative water levels in two piezometers screened at different depths and located approximately 1.3 km apart (PZ-PADER and PZ-SONEB; refer to Figure 2.3). The shallow aquifers (C1 and C2) and the deep aquifer (C3) are responding to variations in pumping pressure simultaneously, indicating the aquifers are hydraulically connected in this region.

1.4 Surface Hydrology

The study area near the Godomey well field lies approximately 5 km north of the Atlantic Ocean and is bordered on the east by Lake Nokoué, a large shallow lake (up to 3 m depth)(Figure 1.3). Lake Nokoué is dynamic in terms of both hydraulics and water quality. Field data (water levels and measures of specific conductance in both the lake and groundwater) suggest active interaction of the lake with river inflows from the north, the ocean to the south (via an open channel connecting the lake to the ocean), and the groundwater system. Specifically, during periods of low precipitation, there is strong similarity in water level variations observed in the lake and in wells
within the region of the Godomey well field. These periods are accompanied by active exchange of lake and ocean via the channel connecting the lake to the ocean and increasing conductivity in the lake to a maximum (dependent on location in the lake) between 50% and 100% of the conductivity (salinity) of the ocean water (Silliman et al., 2010). In contrast, periods of heavy precipitation are accompanied by increase in water level in the lake disproportionate with water level increase observed in the groundwater. Further, water inflow via the rivers during periods of precipitation results in flushing of salinity from the lake. Significantly, the southwestern region of the lake (the region closest to the well field) shows elevated conductance (salinity) even during periods in which the lake water is elevated following precipitation. This suggests this region of the lake as a possible region of recharge to the groundwater immediately east of the Godomey Well Field with water containing elevated salinity.

Lake Nokoué is fed from the Sô River in the northwest and the Djonou River in the southwest (Figure 1.3). During the rainy season, these rivers carry freshwater to Lake Nokoué. During the dry season, sea water from the Atlantic enters Lake Nokoué (Boukari et al., 2008). This seasonal increase in Lake Nokoué saltwater causes reverse flow into the tributaries, making the portions of the Sô and Djonou Rivers near the lake brackish for the majority of the year.

1.5 Motivation

One of the key characterization needs for improving the current hydrologic model is to map the primary hydrostratigraphy to constrain the continuity of the flow pathways. Quantifying the continuity of these units is necessary to determine transport pathways between the recharge areas in Lake Nokoué and the Godomey well field. While
well borings, pump tests, and chemical sampling provide critical information about bulk aquifer properties, these measurements are limited in areal extent and do not adequately constrain the lateral continuity of aquifer units, which has a major impact on the aquifer response to pumping.

In the coastal plain environment, seismic reflection and electrical methods are well suited to imaging the primary geologic units (to establish continuity or lack thereof), identify regional variation in water levels, and constrain the spatial/temporal distribution of saltwater/freshwater interfaces. The two geophysical methods are sensitive to different physical properties and a number of authors have demonstrated that these measures provide complimentary information that can substantially improve the subsurface characterization (Bowling et al., 2007; Chen et al., 2006; Demanet et al., 2001; Ferguson et al., 1999; Sumanovac, 2006; Shtivelman and Goldman, 2000).
Figure 1.1: Inset map of Africa highlighting the location of Bénin, shown in black, and the regional map of coastal Bénin showing the city of Cotonou and Lake Nokoué. The Godomey well field is shown with the dashed box.
Figure 1.2: Evolution of the pumping rate in the Godomey well field (black) and chloride concentration in well F11 (blue). The pumping rate of the Godomey well field has increased on average by about 900,000 m$^3$/yr/yr since 1990, and has been accompanied by a rapid increase in chloride concentration beginning in the year 2000 (modified from Silliman et al., 2010).
Figure 1.3: Map of lakes and rivers in the area of study (highlighted in red box). The Godomey well field (gray box) lies along the western shores of Lake Nokoué, with its southern edge bounded by the Djonou River. Lake Nokoué is connected to the Atlantic Ocean via a man-made canal. The western portion of Lake Nokoué is fed by the Djonou River which carries brackish water (modified from Boukari et al., 2008).
Figure 1.4: Schematic cross section of the regional geology along transect A-A’. GWF represents the location of the Godomey well field. The geology of the well field is comprised of an unconfined sand aquifer (U1) and three confined sand/gravel aquifers (C1, C2, C3). The confining layers are comprised of silts and clays (cross section modified from Silliman et al., 2010).
Figure 1.5: Relative water levels in piezometers PZ-SONEB (blue) and PZ-PADER (red) for a period of 210 days. The piezometers are located ~1.3 km apart (Figure 2.3). PZ-SONEB is screened between 75-90 m depth and PZ-PADER is screened between 165-180 m depth. The aquifers between 75 - 90 m depth and 165 - 180 m depth are responding to variations in pumping pressure simultaneously, indicating aquifer confinement is not complete in this region, and the aquifers are hydraulically connected. Because the baseline for the water level is arbitrary, we added 400 cm to the PZ-SONEB data for easier comparison with the PZ-PADER data.
CHAPTER 2

GEOPHYSICAL SURVEYS

2.1 Summary

In this chapter I present the geophysical surveys I collected to characterize the Godomey aquifer. I would like to note that while I acquired multiple survey types, the majority of data collected did not help meet the study objectives due to many complicating factors, as will be discussed. The exception to this is the land seismic data that I collected, which will be the focus of Chapter 3. Even though certain surveys were unable to help meet study objectives, I believe it is useful to briefly discuss these surveys here, for the benefit of potential future work in the region.

2.2 DC Resistivity

A typical direct current (DC) resistivity survey injects either DC current or low frequency alternating current into the subsurface between two current electrodes. Two additional electrodes are then used to measure potential difference at different points on the surface. The ratio of the measured voltage to the input current is referred to as the resistance, which is related to the bulk resistivity of the subsurface.

Typically pore-water is by far the strongest contribution to subsurface resistivity measurements, making the DC resistivity method a commonly used technique for
groundwater exploration. When the ionic content of pore water is increased, due to chloride for example, resistivities drop significantly, making DC resistivity an ideal tool for saltwater intrusion problems. Many authors have shown the DC resistivity method to be highly effective at delineating the saltwater/freshwater interface in coastal regions affected by saltwater intrusion (Yang et al., 1999; Batayneh, 2006; Sherif et al., 2006; Adepelumi et al., 2009; Nguyen et al., 2009).

2.2.1 Acquisition

I collected a total of 10 surveys ranging in length from 100 m - 500 m. The surveys were located along the western edge of Lake Nokoué, along the same lines as the seismic surveys (refer to Figure 2.3). Acquisition parameters are given in Table 2.1. I inverted the apparent resistivity pseudo-sections for true resistivity using the RES2DINV software (Loke and Barker, 1995). An example of these results is shown in Figure 2.1.

One notable feature from these data is the low resistivity upwelling located between 80 m - 130 m (Figure 2.1). A local, hand-dug well for domestic use is located on top of this feature. The very low resistivity values (<10 ohm-m) are typical of saline water. The water in the well was identified as saltwater via communication with the well owner. This suggests that saltwater recharge is happening on a localized scale in the upper unconfined aquifer nearest the lake.

While these results are interesting, the DC resistivity data do not penetrate deep enough to provide any information regarding the deeper confined aquifers. This is due to two reasons. First, I was limited by my equipment. I only had access to the IRIS Syscal Kid resistivity meter, a system that is designed for rapid acquisition of shallow surveys, which is limited to 24 electrodes and a relatively low injection
Recording instrument | IRIS, Syscal Kid Switch-24
---|---
Electrode array | Wenner
Number of electrodes | 24
Electrode spacing | 5 m
Injection Cycle | 4 s
Stack Max | 6
Stack Min | 3
Q max | 3

Table 2.1: Survey and recording parameters used for resistivity surveys.

current. The 5 m takeout cables gave a maximum current electrode spacing of 120 m for the Wenner array, limiting the depth of investigation to an approximate depth of 15 m by the AB/8 rule of thumb.

Second, the presence of very high conductivity clay layers and saline water limits the penetration depth of the current lines. Even with a larger system with more electrodes and greater injection current, I would require very large offsets to reach the target depth of 200 m, making this method unfeasible for this study.

2.3 Transient Electromagnetics

The transient electromagnetic (TEM) method is based on the principle of electromagnetic induction. In a typical TEM survey, sources and receivers are usually wire coils or loops, and in many surveys the source loop is also used as the receiver loop. The coils are described as either horizontal or vertical according to the plane in which the windings lie. An alternating electric current is run through the transmitter wire which induces a magnetic field, which in turn induces eddy currents in the subsurface. The current flow is then abruptly terminated and the receiver loop measures the rate of decay of the secondary field due to the induced eddy currents
Figure 2.1: (top) Measured apparent resistivity for line 10a and (middle) calculated apparent resistivity for line 10a. (bottom) The inverted resistivity model for line 10a. The deepest penetration is approximately 17 m. The low resistivity upwelling between 80 m - 130 m is located near a domestic well that was confirmed by the owner to produce saline water.

in the subsurface. This decay curve can then help identify conductivity values of the subsurface through data inversion. The TEM method is frequently applied to a wide range of environmental problems, and is commonly used in groundwater exploration due to its high sensitivity to conductive contaminants (e.g. saltwater) and clay layers that often represent impermeable boundaries to groundwater flow (Fitterman and Stewart, 1986; Metwaly et al., 2001; Albouy et al., 2001; Kontar and Ozorovich, 2006). Additionally, the TEM method provides significantly greater depth of penetration in
conductive environments relative to the DC resistivity method.

2.3.1 Acquisition

I collected a total of 12 TEM soundings, six were located along the western shores of Lake Nokoué and six were collected further inland and to the north of the well field. I used a Zonge GDP-16 NanoTEM system with a 30 x 30 m transmitter loop and 3 x 3 m receiver loop. I was extremely limited in the location of the measurements due to the presence of cultural noise in the survey area. All of the data from the TEM measurements were completely unusable, and is not included in this work. I believe that this was due to the cultural noise from the urban environment.

2.4 Seismic

The seismic reflection technique involves exciting a wavefield in the subsurface with a source and recording the resulting wavefield. While seismic reflection methods have been used in the oil and gas industry since the early 1900’s, only in the last 35 years has the technique gained popularity for hydrogeological purposes (Steeples and Miller, 1990; Bachrach and Nur, 1998; Whiteley et al., 1998; Cardimona et al., 1998; Bradford, 2002; Bradford and Sawyer, 2002; Giustiniani et al., 2008, 2009). In the coastal plain environment, fine grained material at the surface coupled with a shallow water table result in favorable conditions for seismic reflection surveys. While the seismic reflection technique cannot provide direct information regarding the distribution of saline water like the DC resistivity and TEM methods, it can provide greater depth of penetration, and may provide better vertical and horizontal resolution.
2.4.1 Marine Seismic Acquisition

I acquired marine seismic data within the western portion of Lake Nokoué encompassing the area from the Godomey well field south to the channel connecting the lake to the Atlantic Ocean. I used a novel source that is a mechanical adaptation of the pneumatic source developed by Pugin et al. (2003). Shot cycle time was approximately 1 s resulting in a shot spacing of about 3 m. The receiver was a single channel hydrophone recorded with a Geometrics 24-bit seismograph. Two example profiles of the data collected are shown in Figure 2.2.

Our seismic source generates a high frequency signal (~ 500 - 3000 Hz), providing very high resolution data in the upper 20 ms (~ 15 m), but no reflections are seen below this depth. Part of the reason for the lack of penetration is the presence of biogenic gas in the lake sediment (Figure 2.2 (bottom)). Biogenic gas rapidly attenuates high frequencies resulting in a lack of signal penetration (Bradford and Sawyer, 2002; Liberty et al., 2009). The gas is present in the majority of the survey area and is most likely due to the decay of organic material (mostly palm stems) that has been brought into the lake by local fisherman to create fish habitats for fish farming. Gas is not present near the channel connecting the lake to the Atlantic Ocean (Figure 2.2 (top)). This region has not been manipulated for fish farming and is subject to tidal flushing, preventing the formation of gas zones. Due to the presence of gas and a high frequency source signal, the marine seismic data do not provide adequate depth of penetration in the capture zone near the well field and are not discussed further.
Recording instrument | Geometrics, 24-bit, 120-channel seismograph  
Receiver array | 10-Hz vertical geophones  
Source | 10-kg sledge hammer  
Geometry | in-line  
Receiver spacing | 3 m (lines 1-11), 5 m (lines 12-13)  
Source spacing | 6 m (lines 1-11), 5 m (lines 12-13)  
Number of geophones | 48-120  
Sampling interval | 0.5 ms  
Record length | 1 s  
Record stacks | 5 (stacked in field)  

Table 2.2: Survey and recording parameters used for seismic surveys.

2.4.2 Land Acquisition

Land seismic data were collected along 15 transects during two field season for a total of approximately 9 km of reflection data (Figure 2.3) The study site is located in a large urban center which complicated data acquisition due to lack of road access and environmental noise caused by road traffic, construction and agricultural activities. Seismic profiles were chosen based on the above logistical considerations and research objectives. I focused the seismic acquisition on the eastern side of the Godomey well field to investigate the lateral continuity of hydrostratigraphic units between Lake Nokoué and the well field. I also collected data along two transects located near the center of the well field that are adjacent to three production wells.

Survey design parameters were chosen based on the primary objective of obtaining a high resolution image of the Godomey aquifer system (<250 m depth) and are given in Table 2.2. Despite the noisy cultural environment, surface conditions provided excellent source and receiver coupling resulting in data with a high signal-to-noise ratio as evidenced in Figure 2.4.
2.5 Discussion

The study site is located in a large urban center where logistical obstacles and high levels of cultural noise made many preferred survey sites either inaccessible or unfit for collecting high quality data. Additionally, a lack of proper electrical resistivity equipment and the presence of biogenic gas in the lake sediment produced data that was insufficient for meeting project objectives. As stated previously, the electrical surveys and marine seismic surveys did not provide data that helped meet the project objective of refining the geometry of the Godomey aquifer hydrologic model. Despite this, the electrical resistivity and marine seismic surveys do provide high resolution data in the upper 15-20 m of the subsurface. While this data does not meet our project objectives, it may be of use for very shallow subsurface investigations in the area. These surveys also provide information about what kinds of sources and survey parameters may be necessary for deeper geophysical investigations in our study area. For example, future work in this area might include a marine seismic survey with a more powerful and lower frequency source that is able to image through the shallow gas zone in the lake (Liberty et al., 2009). Additionally, future resistivity surveys targeting greater depths (>20 m) would benefit from using larger offsets, a greater injection current, and survey geometries targeted at deep investigation (pole-pole, pole-dipole).
Figure 2.2: (top) Marine seismic section along a transect that crosses the channel connecting Lake Nokoué to the Atlantic Ocean. The center of the channel can be seen at shot number 600. This area has not been manipulated for fish farming and is subject to tidal flushing, preventing biogenic gas accumulation. (bottom) Marine seismic section along the western portion of Lake Nokoué in an area of intensive fish farming. Areas where biogenic gas is present have been identified by reflection hyperbolas generated by the gas pockets and 'shadow' zones beneath these gas pockets.
Figure 2.3: Map of the Godomey well field showing the locations of the 15 seismic profiles (black lines) acquired along with the location of wells and piezometers (triangles) in the area. Piezometers are labeled with the prefix PZ. All other triangles are production wells.
Figure 2.4: (a-b) Raw shot gathers from lines 5b and 6a respectively with AGC (50 ms window) applied for display. (c-d) The same shots with a spectral whitening filter (40-60-200-300 Hz) and AGC (50 ms window) applied to enhance reflections. Data quality is excellent despite the noisy urban environment, with clear reflections seen down to 400 ms. Note the effectiveness of the simple spectral whitening filter in removing high amplitude ground roll and traffic noise.
CHAPTER 3

DATA PROCESSING AND ANALYSIS

3.1 Summary

In this chapter, I present the processing flow and analysis of the land seismic data. Imaging and positioning problems are intrinsic to poststack migration methods due to the assumptions of normal moveout (NMO) processing, namely hyperbolic moveout and small lateral and vertical velocity variations. While the majority of the seismic transects I collected exhibit relatively flat lying reflectors and simple velocity fields that can be addressed with basic processing methods (Yilmaz, 2001), three of the transects contain stratigraphic complexity that likely violate assumptions of uniform stratigraphy. As a result, I apply two different processing strategies to the data.

I first discuss a routine processing flow using poststack time migration applied to the 12 transects with relatively flat lying reflectors. I then discuss the processing flow applied to the remaining three transects, which includes prestack depth migration (PSDM), residual moveout (RMO) analysis, and reflection tomography in the post migration domain. This approach improves velocity and image accuracy which helps to better constrain my interpretation (Guo and Fagin, 2002a,b; Bradford et al., 2006, 2009a,b; Bradford, 2006, 2007; Bradford and Wu, 2007; Adler et al., 2008). I do not include a discussion of the data processing for any of the other survey types collected (DC resistivity, TEM, marine seismic) as the surveys do not contribute to the project.
goals and are therefore not relevant to the remainder of this work.

3.2 Seismic Data Processing

3.2.1 Simple Processing Flow

Processing steps applied to the 12 transects with little or no stratigraphic complexity (lines 1a, 2a, 2b, 3a, 4a, 5a, 6a, 7a, 9a, 11a, 12a, and 13a; refer to Figure 2.3.) were similar and shown in Figure 3.1. Pre-migration processing included spectral balancing (40-60-200-300 Hz) to enhance reflections and suppress ground roll, top muting to remove first arrivals, surgical muting to remove the noise cone, automatic gain control (AGC, window length = 50 ms) to boost amplitudes, elevation statics, stacking velocity analysis, normal moveout (NMO) corrections (stretch mute = 50%), residual statics to remove near surface irregularities, and common depth point (CDP) stacking. Figure 3.2 shows a CDP supergather (four adjacent CDPs summed) with various processing steps applied.

Because the data show some scattering of energy, I applied poststack time migration to the CDP stacked seismic profiles. I used a phase shift migration algorithm based on the method of Gazdag (1978) with a maximum migration frequency of 300 Hz and a maximum dip angle of 90 degrees. To derive the migration velocity models, I converted the smoothed stacking velocities to time-interval velocity models via a smoothed gradient method. The smoothed gradient method produces a smoothed time-interval velocity model using the Dix equation and cubic spline interpolation (see Dix, 1955).

Because of high levels of cultural noise, I did not attempt true amplitude processing and applied AGC early in my processing flow to enhance reflection signal. To
accurately compare depths between different seismic profiles, all profiles were moved to a final datum elevation of 43 m. This datum is the highest elevation of all 15 seismic transects and is located on line 8a near the center of the well field. The highest elevation was chosen for the datum due to the presence of a shallow water table. I completed all processing steps using ProMAX\textsuperscript{TM}.

3.2.2 Reflection Tomography Processing Flow

I applied a reflection tomography processing flow to lines 5b, 8a, and 10a (refer to Figure 2.3). The modeling flow adopted for this work is based on an iterative updating procedure for refining an initial depth-velocity model consisting of prestack depth migration (PSDM), residual moveout (RMO) analysis, and reflection tomography. RMO analysis is applied to common image gathers (CIG) that have been output from a prestack depth migration algorithm, and operates in the same way as conventional velocity analysis. If the migration velocity is incorrect, the reflection event is over-corrected or under-corrected, and the remaining moveout, or residual, is used as input to the reflection tomography to generate a corrected velocity model. At each iteration, both velocity and reflector geometries are updated until reflectors on CIGs are flat lying (Stork, 1992). A flow chart demonstrating the processing scheme is show in Figure 3.1.

Pre-migration processing steps for lines 5b, 8a, and 10a were identical to the previous 12 lines up to velocity analysis (Figure 3.1). To derive a starting interval-velocity model in depth, I applied a dip moveout (DMO) correction prior to velocity analysis. I then converted the smoothed stacking velocities to depth-velocity models via the smoothed gradients method. I used a Kirchhoff migration method in the common offset domain and migrated the data from topography with a maximum frequency of
300 Hz and maximum migration aperture set to half the length of the spread. After two iterations of reflection tomography, there were no significant changes in velocity models and reflectors were sufficiently flat in the common image point domain. The PSDM images and final velocity models for lines 5b, 8a, and 10a are shown and discussed in Chapter 4.
Figure 3.1: Flow chart illustrating the processing steps for both the simple processing flow (bottom left) and the reflection tomography flow (bottom right).
Figure 3.2: (top left) Raw CDP supergather (4 adjacent CDPs summed) from line 1a with (top right) spectral balancing (40-60-200-300 Hz), (bottom left) top mute, and (bottom right) NMO corrections. Note how flat the reflectors are after NMO correction.
CHAPTER 4

RESULTS AND INTERPRETATIONS

4.1 Summary

For geophysical surveys to be of any practical use, the data ‘picture’ needs to be represented as a geological cross-section. This conversion is done by utilizing prior geologic knowledge of the survey area, and/or, by actually estimating some physical properties of the subsurface from the measured data. In this chapter, I present the results of applying my processing strategy to the seismic data, and give my interpretations of the data based on the geology of the area.

4.2 PSDM Lines

I identified three distinct velocity zones from my tomographic inversion results that correlate with the top unconfined aquifer (U1), the three confined aquifers (C1, C2, and C3), and the clay/marl base (Figure 4.1). Based on the correlation with well logs from the area, I interpret the high amplitude reflections in the seismic data as the contacts between sand aquifers and confining clay layers (Figure 4.1d,f). A strong reflection at approximately 200 m depth is seen on all 15 profiles and is interpreted as the contact between aquifer C3 and the clay/marl aquifer base. This interpretation is based on the velocity increase from 1900 m/s to 2100 m/s (Figure 4.1b,d,f) and is
consistent with the expected depth of the clay/marl contact based on the geology of the area. For clarity, when I refer to depth, I refer to depth below the datum elevation of 43 m.

The dominant frequency of the reflections is about 80 Hz. Taking the average velocity to be about 1800 m/s gives a dominant wavelength of 22.5 m, giving a vertical resolution of approximately 5.5 m by the 1/4 wavelength rule (Widess, 1973). Using the 1/2 wavelength rule gives a more conservative, and probably more realistic, vertical resolution estimate of approximately 11.25 m. Given that the thicknesses of the confining clay layers range from 5 - 15 m, I do not expect to be able to fully resolve the confining clay layers with the seismic data.

4.2.1 Line 5b

Line 5b (Figure 4.1,a-b) shows most clearly the general hydrostratigraphy of the study area with the four primary aquifer units easily distinguished by the laterally continuous reflections. I interpret two channel features within the upper two aquifer units that extend from 50 - 300 m distance and 400 - 800 m distance (yellow dashed lines Figure 4.1b). This interpretation is based on the reflector geometry and low velocity zones located in the axes of these channels. The two high amplitude reflections beneath each of the channels at approximately 75 m depth (red dashed lines Figure 4.1b) have similar geometries to the overlying channels and are interpreted as older channel deposits in a stacked paleochannel sequence.

4.2.2 Line 8a

Line 8a (Figure 4.1c-d) is located near the center of the Godomey well field and runs adjacent to production wells F13, F4bis and F5bis. Lithology logs from the three
wells are plotted on the seismic section for comparison.

The thickness and depth of the unconfined aquifer is highly variable along this transect. The thickness of the unconfined aquifer increases from about 25 m depth in the south to approximately 50 m depth in the north, evidenced by the package of reflections between 30 m - 75 m depth on the southern half of the profile pinching out to a single reflection at approximately 50 m depth on the northern half of the profile. This interpretation is further supported by the well logs and the lateral velocity decrease of approximately 300 m/s from south to north. This velocity decrease correlates with the transition from clay to sand in wells F5bis and F4bis respectively. This observation is the opposite of what is expected as saturated clay is typically slower than saturated sand.

Definitive identification of aquifers C1, C2 and C3 is not possible across the transect due to the lack of reflections on the northern half of the profile between 60 m and 200 m depth (yellow dashed circle Figure 4.1d). Most notably, the strong reflection at 125 m depth, identified as clay in wells F4bis and F5bis on the southern half of the profile, is truncated at 600 m distance along the line. I interpret this to mean that aquifers C1, C2, and C3 are connected in this region due to an absence of confining clay layers. Note the absence of confining clay layers would not be predicted by the well logs due to the lack of depth penetration by well F13 (Figure 4.1d). One important point to note is that I lack dense ray coverage in this area for my velocity inversion due to the absence of reflectors. Therefore, the velocity in the region is not well constrained. Despite this issue, I believe my interpretation to be valid given the high quality of data and the chances of extreme lateral velocity variations are unlikely in my study area.
4.2.3 Line 10a

Line 10a (Figure 4.1e-f) runs approximately parallel to the lake shore with piezometer PZ7 located on the eastern end of the line. The lithology log from PZ7 is approximately 200 m deep and is plotted on the seismic section for comparison. The package of reflections between 50 - 110 m depth is related to interbedded clays and clayey sands based on the well log data. This package of reflections is cut between 75 - 150 m depth on the western portion of the transect by what I interpret as an erosional channel (yellow dashed line Figure 4.1f). My interpretation is supported by the lateral velocity contrast between the interpreted channel and aquifers C1 and C2.

4.3 Poststack Lines

Figure 4.2 shows the final stacked and migrated section for line 1a as an example of the results of my simple processing flow. Note that all reflectors are approximately flat lying, and dip slightly to the south at an angle of approximately 1° - 2°. The reflection from the clay/marl base is seen at approximately 230 ms, and is laterally continuous across the length of the transect. The package of reflectors between 75 - 110 ms is also laterally continuous across the length of the transect, and is interpreted as interbedded sands and clays based on the lithology log from nearby piezometer PZ7 (refer to Figure 2.3 for location of PZ7 and Figure 4.1 for lithology log). Between these two laterally continuous reflectors, it becomes difficult to confidently trace reflections across the length of the profile. I interpret this as a lack in continuity of confining clay layers, meaning that aquifers C1, C2, and C3 could be hydraulically connected in this area.
This can be seen more clearly in Figure 4.3, which shows a fence plot of the 9 lines closest to Lake Nokoué. The lateral continuity of the confining clay layers is highly variable along the southern portion of the lake, between the interpreted clay/marl base at 200 m depth (~225 ms) and the interpreted clay layer at 70 m depth (~100 ms). The four aquifer units (U1, C1, C2, and C3) are easily identified along lines 5b and 11a. South of line 11a, the confining clay layers become less distinct, and the confined aquifers are difficult to confidently distinguish (black rectangle in Figure 4.3).

Additionally, the continuation of the channel feature on line 5b is seen on lines 11a and 12a (black circle in Figure 4.3). This interpretation is supported by the absence of the shallow reflections in the upper 100 ms on these two lines, which are seen on all lines south of line 12a. This would orient the axis of the channel slightly southeast-northwest, running from Lake Nokoué through the northern portion of the Godomey well field.

### 4.4 Discussion

The lines closest to the lake and line 8a show abrupt discontinuities in confining clay layers suggesting aquifers C1, C2, and C3 are connected in the southern portion of the lake shore as well as further inland. These findings could explain the hydrologic data (Figure 1.5) that indicate the confinement of aquifers in this region is not complete, and aquifers C1, C2, and C3 are hydraulically connected. Hydraulically connected aquifers could have a substantial impact on the aquifer’s response to intense pumping from the Godomey well field.

Erosional channels are present on lines 10a, 5b, and 11a, near the lake shore. The channel on line 5b and 11a appears to be cutting through the shallow package of clays
and clayey sands. I interpret the channel to be filled with saturated sands based on velocity estimates and well logs. Paleochannels filled with high permeability material, such as unconsolidated sands, could provide preferential flow paths for saline water from Lake Nokoué to the Godomey well field.

4.5 Conclusions

Seismic reflection profiles from the Godomey well field show the subsurface lithology to be a complex system of discontinuous and topographically variable strata. The current hydrologic model is based on a series of continuous sand, silt, and clay layers with little variability along dip. The seismic data prove these models assumptions to be invalid. The confining layers in the aquifer system are not continuous but show lateral variability on the scale of hundreds of meters. Additionally, there appear to be multiple locations of connectivity between confined aquifers due to the presence of erosional channels. These channels could be acting as preferential flow paths for saltwater between Lake Nokoué and the Godomey well field. The seismic data extends critical information about lithology to the surrounding area. This information can be integrated into the current hydrologic model to better constrain the geometry of the Godomey aquifer and improve model accuracy.
Figure 4.1: (a,c,e) PSDM sections for lines 5b, 8a, and 10a. (b,d,f) Interpreted PSDM sections overlain on final velocity models. Available well logs are overlain on lines 8a and 10a. Well log colors correspond to: yellow = sand, brown = clay, tan = clayey sand. U1 ranges in velocity from 1500 m/s to 1600 m/s on lines 5b and 8a. U1 has a higher velocity of 1700 m/s on line 10a, which is located next to Lake Nokoué. Velocities within the confined aquifers increase gradually with depth, starting at approximately 1700 m/s in C1 and increasing to 1900 m/s at the base of C3. The velocity jumps to 2100 m/s across the interpreted clay/marl base. Note the good correlation between clay layers identified in the well logs and high the amplitude reflections in the seismic data. Dashed lines indicate areas of interest discussed in the text.
Figure 4.2: Poststack time migrated profile for line 1a. Reflectors at approximately 100 ms and the reflector at approximately 225 ms are laterally continuous across the entire transect, while reflectors between these two horizons are laterally variable with respect to their continuity. Note that all reflectors are flat lying with a slight dip (approximately 1° - 2°) to the south.
Figure 4.3: Fence plot of the time migrated sections of the 9 lines closest to Lake Nokoué. The view is looking to the southwest (refer to Figure 2.3). For comparison with the poststack time migrated transects, the time migrated versions of lines 5b and 10a are shown. The labels U1, C1, C2, and C3 indicate the interpreted unconfined and three confined aquifers. The black dashed circle highlights the area of laterally discontinuous confining clay layers in the southern portion of the lake shore. The black dashed rectangle highlights the absence of shallow reflectors in the unconfined aquifer in the northern portion of the study area, which I interpret as the continuation of the channel feature on line 5b. Reflectors below the clay/marl base (>250 ms) dip to the south more steeply.
CHAPTER 5

HYDROLOGIC MODELING

5.1 Summary

In this chapter, I develop a hydrologic framework based on my seismic interpretations for use in a numerical hydrologic model of the study region. I review the existing hydrologic model developed by Boukari et al. (2008), and refine the model geometry in the region surrounding the Godomey well field based on my seismic reflection interpretations. In chapter 4 I discussed some of the small scale features (paleochannels and interconnected aquifers) identified in the seismic data. For the initial refinement of the hydrologic model, I do not incorporate these features and assume that all aquifers are completely confined, and refine the geometry of the original seven layer model (four aquifers and three confining layers) to best match the observed seismic data. While I recognize that this assumption simplifies the geometry of the aquifer and violates some of the observed seismic data, this initial refinement in modeling helps to identify how relatively local scale geophysical data can influence the predictions of a regional hydrologic model. Hence, this effort represents the initial step in a transition from a regional model based on sparse borehole data to a model with highly detailed local geology in the zone of production based on relatively dense seismic data. I find that under the same boundary conditions and pumping rates, the refined model predicts greater recharge from Lake Nokoué than the original model.
5.2 Introduction

A number of sequential studies have focused on developing a groundwater flow and transport model for the Godomey aquifer system (Boukari et al., 2008; Borum, 2009; Silliman et al., 2010). The most recent groundwater model has evolved from the initial steady-state model to a transient model that includes more complex distributions of hydraulic conductivity and density dependent effects (Borum, 2009). The initial effort by Boukari et al. (2008) modeled flow (without transport) assuming steady-state conditions for both the monthly mean well production data measured during the period from 1991 - 2000 and again for anticipated rate of production in 2011. This modeling resulted in two significant predictions regarding groundwater flow to the Godomey well field. First, that even under increased pumping rates a groundwater divide still exists between the Atlantic Ocean and the well field. Second, while low levels of recharge from Lake Nokoué were predicted based on the earlier study, significant recharge from Lake Nokoué was predicted under the 2011 pumping rates.

In order to best evaluate the impact of the seismic data on the prediction of hydraulic head, I refine the geometry of the initial steady-state state model. While I recognize that the most current model has been calibrated with more available data and includes transient behavior and density-dependent effects, I feel that refining the initial model without these complicating factors will provide the most direct estimate of the impact of modifying the aquifer geometry based on local scale seismic surveys.
5.3 Numerical Model

5.3.1 Conceptual Model

My conceptual hydrologic model was constructed using the Groundwater Modeling Software (GMS) program. GMS is a graphical software package that allows construction of a conceptual hydrological model for input to the MODFLOW finite-difference groundwater program developed by the United States Geological Survey (USGS). The numerical hydrologic model is 26 km in the east-west direction by 31 km in the north-south direction (Figure 5.1). It extends 27 km to the north of the coastline to a boundary defined by the mean piezometric contour of 15 m above mean sea level (amsl), and 4 km south of the coastline to the mean bathymetric contour of -10 m. The model is bordered on the east by the western portion of Lake Nokoué and the Só river, and bordered on the west by a topographic depression known as the Dati Valley (Figure 1.3). Under natural conditions, the direction of groundwater flow is SSW. As such, the model was rotated 15° clockwise so that flow lines are approximately parallel to the grid.

The geological layers were constructed based on interpolation of lithologic logs from exploratory boreholes, pumping wells and piezometers. The aquifer was modeled as a homogeneous, horizontally-isotropic ($K_x = K_y ≠ K_z$), three-dimensional system with seven layers, four of which are aquifers and three are confining layers (Boukari et al., 2008). A variable grid size was used with the highest level of discretization being 230 m north-south x 250 m east-west around the well field, with cells gradually increasing with distance to a maximum dimension of 1850 m north-south x 1850 m east-west along the edges of the grid (Figure 5.1). The grid consists of 55 rows by 50 columns, for a total 2750 cells per layer.
5.3.2 Boundary Conditions and Parameters

To the north, cells in the first two layers that lie completely above the water table ('dry cells') were set as inactive. The northern most active cells in layers 3 - 5 were set to a constant head of 15 m amsl. To the south, cells in the first layer located within the Atlantic Ocean were set to a constant head of 0 m amsl. Cells in layer 1 located in Lake Nokoué, the Sô River, and the channel connecting Lake Nokoué to the Atlantic Ocean were set to a constant head of 0.5 m amsl. All cells in layers 2 - 7 located along the eastern, western and southern edges of the model were set as no-flow boundaries. The eastern part of the Djonou River is incorporated into the top layer using the river option in MODFLOW. The Bakamé and Dati valleys were modeled as drains using the drain option in MODFLOW. Layer 1 of the model was simulated as a free surface, allowing the water table to fluctuate in response to recharge.

Mean precipitation varies spatially and was modeled as three distinct recharge zones with values of 25 mm/yr in the northern part of the model, 100 mm/yr for the intermediate part of the model, and 200 mm/yr for southern coastal part of the model (Boukari et al., 2008). The means of the monthly yield for each production well during the period of 1991-2000 were used for the steady-state simulations. These values range from 500 - 1800 m$^3$/d.

Initial estimates of horizontal and vertical conductivities as well as storage coefficients were based on available pumping data. These estimates were then adjusted by a trial and error calibration process to achieve an acceptable match between observed and predicted hydraulic head. Table 5.1 lists the values for horizontal and vertical conductivities as well as storage coefficients used in the model. Further details
Table 5.1: Hydraulic conductivities of the Godomey aquifer system as they are implemented in the numerical groundwater model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Horizontal Conductivity (m/s)</th>
<th>Vertical Conductivity (m/s)</th>
<th>Specific Storage ($S_s$)</th>
<th>Specific Yield ($S_y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (U1)</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^{-5}$</td>
<td>0.1</td>
</tr>
<tr>
<td>2 (clay)</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>3 (C1)</td>
<td>$2 \times 10^{-4}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$10^{-6}$</td>
<td>0.15</td>
</tr>
<tr>
<td>4 (clay)</td>
<td>$10^{-6}$</td>
<td>$10^{-7}$</td>
<td>$10^{-6}$</td>
<td>0.15</td>
</tr>
<tr>
<td>5 (C2)</td>
<td>$2 \times 10^{-4}$</td>
<td>$2 \times 10^{-5}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6 (clay)</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7 (C3)</td>
<td>$2 \times 10^{-4}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$10^{-6}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

regarding the model and calibration process can be found in Boukari et al. (2008).

5.4 Refinement with Seismic Data

The seismic reflection data cover an areal extent of approximately 3 km x 3 km within the Godomey well field that corresponds to approximately a 13 x 12 cell grid in the discretized hydrologic model (Figure 5.1). To build the updated hydrologic model, I picked eight horizons on the seismic data that I interpreted as the tops and bottoms of the four aquifer units and three confining clay layers (Figure 5.2). These horizons were then interpolated to a 3 km x 3 km grid, discretized at 10 m. As discussed previously in chapter 4, I am not able to confidently resolve the top and bottom of the confining clay layers in many parts of the seismic data. For these areas, I simply picked the top and bottom of the wavelet to represent the top and bottom of the clay layer, fully recognizing that this results in some error in surface elevation. For the purposes of this study, the error in elevations will be negligible and I feel this approach is justified.

To incorporate these elevations into the existing hydrologic model, each horizon
was interpolated to a 13 x 12 cell grid (230 m north-south x 250 m east-west) to maintain the same resolution as the original hydrologic model. I then replaced the existing elevations of the eight horizons within the 13 x 12 cell grid with the new horizon elevations based on the seismic data. I then applied a 4 x 4 2-dimensional mean smoothing filter to the whole grid to remove the sharp contacts between the existing grid and the refined grid within the Godomey well field. Figure 5.3 shows an example of this procedure.

Figure 5.4 shows a comparison of cross sections between the original model and the updated model. It is visually evident that the smoothing procedure has significantly smoothed details along the edges of the model where cell discretization is coarsest. I tested different smoother lengths and found that the results of the finite difference model near the well field were relatively insensitive to the geology along the model boundaries. Therefore, even though the smoothed model oversimplifies the geology along the outer cells, there is no significant impact on the modeled hydraulic head results in the area of interest.

Table 5.2 shows the percentage difference in volume between the original aquifer model and the updated aquifer model within the areal coverage of the seismic data (red box Figure 5.1). The new model has increased volume in aquifers U1 and C1 and decreased volume in aquifers C2 and C3. The greatest change of the four aquifers is in aquifer C2, which has a decrease in volume by 55%. It is worth noting that this aquifer is the most intensely pumped of the four aquifers, and is responsible for 81% of total water withdrawn from all four aquifers (Boukari et al., 2008).
<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Percentage Difference in Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1 (layer 1)</td>
<td>+ 21 %</td>
</tr>
<tr>
<td>C1 (layer 3)</td>
<td>+ 45 %</td>
</tr>
<tr>
<td>C2 (layer 5)</td>
<td>- 55 %</td>
</tr>
<tr>
<td>C3 (layer 7)</td>
<td>- 25 %</td>
</tr>
</tbody>
</table>

Table 5.2: Percentage difference in aquifer volumes between the original hydrologic model and the updated hydrologic model.

5.5 Results

Figure 5.5 shows the steady-state head contours for both the original model and the updated model for aquifers U1 and C2. The two models were run with the same boundary conditions, initial conditions, and pumping rates. There are two notable features observed on the head contours for the updated model. First, the updated model predicts the 2 m amsl head contour, marking the groundwater divide between the Atlantic Ocean and the well field, migrates further to the west in aquifer U1. Second, the cone of depression within the well field has migrated approximately 400 m to the east, extending further out into the western edge of Lake Nokoué.

To evaluate the impact these differences in head contours have on groundwater recharge to the Godomey well field, I used the MODPATH package to track water particles from the western portion of Lake Nokoué and the eastern portion of the Djonou River. All particles were started from the water table. The results of the particle tracking are shown in Figure 5.6 and Figure 5.7. The results show that the expanded cone of depression leads to significantly more groundwater recharge being derived from both Lake Nokoué and the Djonou River.
5.6 Discussion

Presently, I have not been able to validate my updated model with any existing hydrologic data, making it impossible to conclude that I have improved the predictive capabilities of the existing model. Therefore, this work represents a sensitivity analysis from which I can derive valuable information.

Most importantly, decreasing the percentage volume of aquifer C2 by 55%, expands the zone of recharge captured by the Godomey well field by approximately 400 m. This extends the cone of depression further into Lake Nokoué than the original model, resulting in a significant contribution to groundwater recharge directly from Lake Nokoué. Similar contributions to groundwater from Lake Nokoué were predicted by the original model, but, under the projected 2011 pumping rates that were approximately three times larger than the pumping rates used in the current simulation. These results indicate that the modified aquifer geometry can produce recharge contributions from the lake that are equivalent to recharge contributions produced by increasing the pumping rates by a factor of three. This would suggest that Lake Nokoué is a significant source of salinity even under historical pumping conditions. Additionally, the increased recharge from Lake Nokoué increases the threat of anthropogenic pollution from the lake city of Ganvié. Combine this result with projected increased pumping rates, and Lake Nokoué becomes a major, long-term threat of anthropogenic pollution and saltwater intrusion.

The expanded zone of recharge also causes the lagoon region south of the Godomey well field to become active, which again, is only seen in the original model under the projected 2011 increased pumping rates. The updated model predicts that the surface water in the lagoon region, which is brackish, will account for a greater contribution
of recharge to the well field. In particular, more recharge will be derived from the Djonou River to the south, which is brackish for most of the year (Figure 5.7), thus increasing the threat of salt-water intrusion from this source.

Additionally, the southern lagoon region of concern coincides with land that is highly desired for urban development and agricultural use, particularly along the Djonou River. The increased contribution from surface water to groundwater recharge in the lagoon area increases the threat of anthropogenic contamination in the deep confined aquifers, and ultimately in the water produced in the well field.

5.7 Conclusions

Seismic reflection data were used to refine the geometry of an existing hydrologic model for the Godomey well field. Though the model has not been validated with existing hydrologic data to evaluate it’s accuracy, the model provides useful insight into how recharge behavior is affected by modifying the aquifer geometry. Under the same historical pumping conditions, the updated model predicted a substantial contribution to groundwater recharge from two sources that pose a threat of saltwater intrusion into the Godomey well field: Lake Nokoué and the coastal lagoon region. Additionally, surface water recharge from both sources increases the likelihood of anthropogenic contamination due to the presence of the lake city Ganvié in Lake Nokoué, and industrial development and agricultural activities in the southern lagoon region. While the original model predicts similar outcomes, these predictions are based on the projected 2011 pumping rates that are three times higher than pumping rates used in this study. These results indicate that aquifer geometry plays a substantial role in the recharge behavior of the Godomey aquifer, and combined with projected increased
pumping rates, may indicate the threat to this freshwater resource is more immediate than previous studies suggest. Thus, the seismic results provide a potentially critical parameter for the groundwater model.
Figure 5.1: Map of the modeled area with finite-difference grid overlain. The red box shows the areal extent of the seismic data. The elevations of the cells within the red box were modified based on the seismic reflection data.
Figure 5.2: Fence plot of the depth converted time migrated sections of the 9 lines closest to Lake Nokoué. The view is looking to the southwest (refer to Figure 2.3). The horizons delineate the tops and bottoms of aquifer units and confining clay layers. U1, C1, C2, and C3 label my interpreted unconfined aquifer and three confined aquifers respectively. I have omitted the first horizon (surface elevations) for display purposes.
Figure 5.3: (top left) Original elevations for the base of the unconfined aquifer (second horizon). (top right) New elevation model with the updated grid around the Godomey well field based on the seismic data and (bottom center) the same elevation model after applying the 2D smoothing filter.
Figure 5.4: (top) Map showing the locations of cross sections E-W and N-S (yellow lines) that run through the center of the well field. (bottom) E-W and N-S cross sections comparing the original model (top) and updated model based on the seismic data (bottom). The red boxes indicates the portion of the grid that was modified. Aquifer layers are shown in yellow while the confining clay layers are shown in brown. The numbers identify the aquifers in order of increasing depth.
Figure 5.5: Map of predicted hydraulic head values for the original model in aquifer 1 (top left) and aquifer 3 (top right) compared with the map of predicted hydraulic head values for the updated model based on seismic data in aquifer 1 (bottom left) and aquifer 3 (bottom right). Warm and cool colored contour lines correspond to high and low hydraulic head values respectively. The areal extent of the seismic data is shown in the red box. The updated model predicts the cone of depression will expand by about 400 m within the region around the Godomey well field. The updated model also predicts the 2 m head contour, marking the groundwater divide between the Atlantic Ocean and the well field, has migrated to the west in aquifer U1.
Figure 5.6: (top) Flow lines predicted by particle tracking for the original model and (bottom) the updated model based on seismic data. Particles were started at the yellow dots and the green lines indicated the path the particles take to the Godomey well field. The updated model predicts significantly more recharge from Lake Nokoué, making it a likely source of saltwater intrusion to the well field. The areal extent of the seismic data is show with black box.
Figure 5.7: (top) Flow lines predicted by particle tracking for the original model and (bottom) the updated model based on seismic data. Particles were started at the yellow crosses and the green lines indicated the path the particles take to the Godomey well field. The updated model predicts significantly more recharge from Djonou River, making it a likely source of saltwater intrusion to the well field. The areal extent of the seismic data is show with black box.
CHAPTER 6

CONCLUSIONS AND DISCUSSION

6.1 Overview

The coastal city of Cotonou in Bénin, West Africa relies almost entirely on groundwater from the Godomey aquifer for its source of fresh water. The Godomey aquifer is currently threatened by the intrusion of saltwater into the primary production well field. To properly manage this problem, water agencies in Cotonou are in need of an accurate groundwater model to make reliable predictions of groundwater flow based on future management strategies. Initial efforts to build a regional aquifer model have had some success, but challenges still remain in terms of modeling the temporal and spatial distribution of hydraulic head. The current aquifer model is based on sparsely spaced borehole data. One of the key characterization needs identified to improve the model is mapping of the lateral continuity of the aquifer units and confining clay layers.

To address this problem, I collected a number of geophysical surveys to map the geometry of the Godomey aquifer. For this work, I focused primarily on land seismic surveys. In chapter 2 I discuss the survey design and acquisition parameters. Acquisition was focused on eastern portion of the Godomey well field in order to map the stratigraphy connecting the well field to Lake Nokoué, the likely source of the salinity. I collected 15 seismic transects for a total of approximately 9 km
of seismic data. Parameters were chosen to acquire a high resolution image of the Godomey aquifer system, which extends to a depth of approximately 200 m. I also discussed other geophysical surveys that I collected where the data quality was poor or depth of penetration was insufficient to contribute to this work. I have included that information for the benefit of potential future researchers.

In chapter 3 I discuss my processing strategy that I applied to the seismic data. While routine processing and poststack time migration were sufficient for the majority of the lines, three lines exhibited interesting complexity worthy of further investigation. For these lines I applied a processing flow that included PSDM, RMO analysis, and reflection tomography. This flow produced an accurate seismic image and velocity profile that helped constrain interpretation of these complexities.

Chapter 4 presented the results and interpretations of my processing strategy. I identified three distinct velocity zones from my tomographic inversion that correlate with the upper unconfined aquifer (U1), the three confined aquifers (C1, C2, and C3), and the clay/marl base. I also identified the presence of multiple erosional channels that provide connectivity between aquifer units. These channels could be filled with highly permeable sands and gravels, providing preferential flow paths between Lake Nokoué and the Godomey well field for saline water.

Finally, in chapter 5, I used the seismic reflection data to modify the geometry of the existing hydrologic model. This resulted in increasing the volumes of aquifers U1 and C1 by 20% and 45% respectively, and decreasing the volumes of aquifers C2 and C3 by 55% and 25% respectively. The resulting finite difference simulations predicted a significant increase in recharge from both Lake Nokoué and the coastal lagoon region, relative to the original model. These predictions are similar to predictions from the original model based on increased 2011 pumping rates, that are approximately
three times larger than the historical pumping conditions used for the updated model simulation. While I have not validated the updated model with hydrologic data, this result would mean that anthropogenic pollution and saltwater intrusion into the Godomey aquifer are more dire and immediate threats than previously suggested in prior studies.

6.2 Discussion

The seismic profiles in the vicinity of the existing well records enable us to correlate and extrapolate lithologies beyond the single data point at each well location. This information has been integrated into the current hydrologic model to better constrain the geometry of the Godomey aquifer and improve model accuracy. While previous studies have shown Lake Nokoué to be the primary source of salinity in the Godomey aquifer, the updated model suggests that saline water from Lake Nokoué may be recharging the Godomey aquifer more rapidly than previously thought, thus making the problem of salt water intrusion more immediate. Additionally, the updated model suggests that the Djonou River may also be a significant source of salinity to the Godomey well field, a threat that was not identified in previous studies. The implication of these findings is that any treatment or remediation plan must consider both the new threat of salt water intrusion from the Djonou River in the south and the immediacy of the threat to Cotonou’s fresh water supply. The following are my thoughts on potential future geophysical surveys in the study region, the potential future of the hydrologic modeling, and recommendations on the current treatment strategy that has been proposed by the water agency in Bénin.

As stated previously, I have included a description of all geophysical surveys. Some
of these produced inadequate data for inclusion in this work. I have done this with the hopes that my successes and failures can be used as a guide for future geophysical work in the region, and I believe that there is still ample opportunity for geophysical investigations in Bénin and similar locations. In particular, there is still a severe lack of information about the geology underlying Lake Nokoué, which is a missing critical piece of information in the hydrologic model. Future work in this area might include a marine seismic survey with a more powerful and lower frequency source that is able to image through the shallow gas zone in the lake (Liberty et al., 2009). Future research in this area would also benefit from deep electrical resistivity surveys in order to correlate stratigraphy from seismic reflection data with electrical conductivities. This would allow water agencies to target certain aquifers for pumping strategies based on electrical conductivity values (salinity). Resistivity surveys using larger offsets, a greater injection current, and survey geometry targeted at deep investigation (pole-pole, pole-dipole) could potentially reach the target depth of 200 m.

With regards to the hydrologic modeling, I believe that the work presented in this thesis is only the first step in building a completely refined hydrologic model. The obvious next step is to simulate the observed channels which are probably the most hydrologically significant outcome of the seismic study. The final step would be to incorporate the refined geometry into the most recent hydrologic model that has been calibrated with more data, and includes density-dependent effects that more accurately model groundwater flow in the presence of saltwater. This model then needs to be validated with transient models to compare predicted vs. observed hydraulic head, in order to evaluate whether the updated model improves prediction over the original model.

For this work, I retained the relatively coarse hydrologic model discretization in
order to avoid further refinement of the finite-difference grid. I believe future modeling efforts would benefit from finer discretization of the finite-difference grid in the area of the Godomey well field. This would allow the model to take full advantage of the high resolution seismic data, and also allow the incorporation of the local scale features, such as the erosional channels and interconnected aquifers, that are currently below the resolution of the finite-difference grid.

While the above considerations present many opportunities to improve the hydrologic model further, the initial model refinement presented in this work brings to light some recommendations for the initial treatment of salt water intrusion into the Godomey aquifer. The most significant of which would be to decrease the pumping pressure on aquifer C2. Aquifer C2 is currently the most intensely pumped aquifer with more than 80% of the well field yield coming from aquifer C2. The work presented in this thesis shows that the volume of aquifer C2 is 55% less than previously thought and likely the primary cause of the expanded cone of depression. Increasing pumping from aquifer C1, which this study has shown has a 45% greater volume than previously thought, and decreasing the pumping from aquifer C2, may slow the immediate advance of saline water from Lake Nokoué to the Godomey well field, while providing the same amount of total water yield.

Finally, due to the severity of the saltwater intrusion into the Godomey aquifer, water management agencies in Bénin are currently planning a new production well field about 8 km to the north of the Godomey aquifer. The present planning for this new well field does not include the acquisition of any geophysical data in the proposed new area of the well field. I believe this proposed project would benefit greatly from a seismic survey in terms of cost and effectiveness. Not only have countless case studies proven that drilling production wells informed by seismic reflection data increase
the chances of a productive well and decrease cost relative to drilling randomly, but the seismic data can be used for future modeling research similar to the work presented in this thesis. A proactive strategy like this is needed to properly manage this endangered resource in the face of climate change and population growth, in order to prevent this same scenario repeating itself.
REFERENCES


Barthel, R, Jagelke, J, Götzinger, J, Gaiser, T, and Printz, Andreas. 2008. Aspects of choosing appropriate concepts for modelling groundwater resources in regional integrated water resources management–Examples from the Neckar (Germany) and
Ouémé catchment (Benin). *Physics and Chemistry of the Earth, Parts A/B/C, 33*(1), 92–114.


APPENDIX A
Abstract

The coastal city of Cotonou in the developing country of Bénin, West Africa, is a large population center that is facing a serious threat to the sustainability of its freshwater supply. The city relies on the Godomey aquifer for domestic water, but the aquifer is undergoing saltwater intrusion. This problem is likely to worsen without significant steps to improve management of the water supply. Aquifer continuity and saltwater flow paths are poorly understood, but that information is critical to ensure sustainable access to freshwater in this growing urban center. In January 2012, a two-year geophysical investigation was begun with the prime objective of using the seismic-reflection method to better understand the continuity of the primary aquifer units. That information then can be used to inform and improve the regional groundwater flow model. The project presented many challenges, both technical and cultural, including the language barrier, conducting fieldwork in the developing world with a limited budget, and the complicated logistics of acquiring seismic data in a congested urban environment. Despite these challenges, the seismic investigation was completed successfully, and results show that the aquifer system is substantially more complicated than previously thought. Critical-ly, at least one paleochannel cuts through a substantial portion of the aquifer system and truncates multiple aquifer/aquitard boundaries. These boundary truncations appear to provide connected pathways among aquifers that previously were thought to be isolated and might explain recent hydrologic observations. Although the full impact of these findings is yet to be determined, it is clear that the seismic study has provided valuable information that improves the understanding of the system and ultimately will aid in management of the groundwater resource in Cotonou.

Introduction — Motivation and background

Of the eight goals identified by the United Nations Development Program (UNDP), the seventh is “Ensuring Environmental Sustainability.” Within this framework, Target 7c states that by 2015, the goal is: “Reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation.” By 2012, 89% of the global population had access to improved sources of drinking water. This number was up from 71% in 1990 (United Nations, 2014) and met the UN’s 2015 goal.

Although this is encouraging, a significant gap between urban and rural areas remains. This gap has focused much attention on improving the situation in rural areas. However, sustainable access to safe water in urban areas is by no means universal, and significant population centers remain at risk, particularly in the developing world. One such area is the coastal city of Cotonou in Bénin, West Africa.

History and geography.

Bénin is bordered to the east by Nigeria, to the west by Togo, and to the north by Niger and Burkina Faso (Figure 1). To the south is the South Atlantic coast. The official language of Bénin is French, but local languages are in common use. Fon and Yoruba are spoken widely in the south, with more than half the population speaking Fon. Numerous other regional and local languages are spoken throughout Bénin.

Its position on the Bight of Bénin made Bénin a prime trading port in centuries past, and Bénin has a long and complex history. The first Europeans arrived in 1556, and by the 1600s, the slave trade had begun along the coast. In about 1650, the kingdom of Abomey (Dahomey) was established near the southern coast and became an active participant in the slave trade as the kingdom expanded. The kingdom captured slaves in conquered territories and exchanged them for Portuguese, French, and Dutch weapons.

In 1863, the first French protectorate was established with the king of Porto-Novo. In 1889, the last independent ruler

![Figure 1. (a) Location of the Godomey well field and map of the field area, with inset showing the location of Bénin in West Africa. (b) Map of seismic coverage in the capture zone between Lake Nokoué and the Godomey well field.](http://dx.doi.org/10.1190/tle33121336.1.)

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http://dx.doi.org/10.1190/tle33121336.1.
There are two potential sources of the increasing salinity in the wells: (1) the Atlantic Ocean and (2) Lake Nokoué. Several of the deeper aquifer units extend beneath the Atlantic and therefore might be connected hydraulically to ocean waters. However, the wells closest to the ocean give no indication of increased salinity in the deeper aquifers. Conversely, all the wells that show increased salinity are close to Lake Nokoué.

In an effort to understand this large, complex system, an initial groundwater model was developed (Boukari et al., 2008) and then was improved through interpretation of the structure of the local geology (Silliman et al., 2010). Although not yet at the stage of a quantitative management tool, the groundwater model provides general information about the system and can be used to identify areas where further study is needed. For example, the model indicates that there is a groundwater divide between the ocean and the Godomey well field, consistent with observations that show little seawater encroachment from the south.

Further complicating the system is the city of Ganvié, which has more than 30,000 inhabitants, and other population centers that are built entirely on stilts within the lake (Figure 2). The presence of these lake cities and the fact that people rely heavily on the lake for fishing have resulted in severe manipulation of the lake for waste disposal, navigation, and fish farming.

There are two potential sources of the increasing salinity in the wells: (1) the Atlantic Ocean and (2) Lake Nokoué. Several of the deeper aquifer units extend beneath the Atlantic and therefore might be connected hydraulically to ocean waters. However, the wells closest to the ocean give no indication of increased salinity in the deeper aquifers. Conversely, all the wells that show increased salinity are close to Lake Nokoué.
Lake Nokoué. That is consistent with observations of increased salinity in the wells nearest to the lake. The combined field observations and numerical modeling indicate that Lake Nokoué is the likely source of saline intrusion into the Godomey aquifer system.

Although intrusion of saline waters from Lake Nokoué is the immediate threat to the sole source of drinking water for Cotonou, rising levels of chloride in shallow rural wells near the coast indicate that the encroachment of seawater into the shallowest aquifer might have begun, and that risk likely will increase as the groundwater resource is stressed increasingly. In addition, urbanization is resulting in increased development in the immediate vicinity of the Godomey well field, leading to greater risk of anthropogenic release of hazardous groundwater contaminants.

In light of the various factors conspiring to endanger the drinking-water supply, it is critical that good management decisions are made now to sustain a viable source of freshwater for this growing urban area. The management plan must actively minimize the encroachment of saline water from Lake Nokoué while simultaneously mitigating the risk of seawater intrusion from the south and hazardous-chemical contamination related to increased development.

As noted by Silliman et al. (2011), the key management questions related to sustainability of the Godomey well field are “(i) for what period of time can the aquifer be expected to provide water for this urban population, (ii) what sources of contamination represent the most severe threats to this groundwater resource, (iii) what hydrologic properties of the recharge zones and deep aquifer system need to be more thoroughly characterized to assist in modeling this groundwater system, and (iv) what hydrologic properties of the recharge zones are likely to be impacted by climate change, population migration, or changing land-use practices.”

Silliman et al. (2011) conclude that the current groundwater model and field-characterization efforts have not yet reached the level at which sound, data-driven management decisions can be made. Substantially greater characterization, coupled with refined groundwater modeling, is needed.

Cultural and operational challenges

Student involvement. A key component of the project was the involvement of students in all aspects from data acquisition to processing and interpretation. Of several objectives for student involvement, perhaps the two most important were (1) to provide cross-cultural interaction between students from the United States and Europe and students from Bénin and (2) to provide training in hydrogeophysics to all students involved in the project. In addition, the involvement of students was critical to data acquisition, and the project could not have been completed without their hard work.

To facilitate interaction, students and faculty members traveling from outside Bénin were required to speak French or to study French prior to departure. The majority of the Béninois students also had English-language training, which facilitated communication. At the beginning of each field season, a two- to three-day short course on seismic methods in hydrogeophysics was given in French at the University of Abomey-Calavi, European and U.S. students participated in the course along with their Béninois counterparts (Figure 4). After the short course was completed, students and faculty members were deployed to the field for seismic data acquisition.

Fieldwork was conducted through the crowded neighborhoods of Godomey on the northern outskirts of Cotonou. This provided the opportunity for close interaction with local residents, most of whom spoke French, but some spoke only the local language. The Béninois students not only helped with fieldwork but also served as ambassadors and interpreters as we worked through the city. Our interactions with locals were universally positive, and that was one of the truly rewarding aspects of the project (Figure 5). In addition, it was clear that residents were cognizant of the problem of saltwater intrusion, and they welcomed us and were interested in our work.

Operational challenges. Our initial field project consisted of land seismic-reflection acquisition along a set of profiles that ranged in length from < 200 m to greater than 1.5 km (Figure 1). Logistics for the seismic reflection were complicated by the necessity of conducting the work in a congested urban area (Figure 6). Road surfaces were highly variable, and many were not amenable to the planting of geophones. Heavy traffic and associated safety concerns for the seismic crew further limited seismic coverage. Where seismic acquisition was feasible, the roads typically ran through crowded neighborhoods with many roadside shops, along with heavy foot and vehicle traffic (Figure 7). Those challenging conditions limited seismic coverage to a somewhat sparse and irregular coverage grid (Figure 1).

In addition to logistics, operations were challenging relative to expectations of those who were used to conducting fieldwork in Western countries. Shipping equipment and supplies in and out of the country was difficult, and it was essential to travel with backups...
for all technical components. Gathering basic supplies such as batteries and work gloves was often a time-consuming task because many items taken for granted in the developed world are not as readily available and sometimes surprisingly expensive. Nevertheless, with a bit of patience and willingness to reset expectations, the work was completed within both the time and monetary budgets.

To balance the challenges, some aspects of the work were amazingly easy. For example, on our last field campaign, our home-built seismic source broke. At 6 p.m., we had a new piece machined and installed in less than 30 minutes, in the open air at a busy Cotonou intersection. Finally, it must be said that the Béninois students were exceptionally resourceful and hardworking. This smoothed field acquisition because numerous equipment repairs were made on the fly while the crew collected large amounts of data in a relatively short period.

Seismic data acquisition and processing

Data were acquired with five 24-channel Geometrics Geode seismographs, 3-m geophone spacing, and 6-m source spacing in an off-end geometry. The source was a 10-kg sledgehammer, and we used 10-Hz vertical geophones. Approximately 10 linear km of data was acquired along the 15 profiles shown in Figure 1.

Along all lines, we contended with high levels of coherent noise that included heavy vehicle traffic, small local grain mills in many neighborhoods (Figure 8), and constant pedestrian traffic. Despite those sources of noise, near-optimal surface conditions resulted in excellent source and receiver coupling with good data quality. Although coherent noise masked reflections in the raw records, most of the cultural noise was low frequency (< 40 Hz), and a spectral-balancing filter over the dominant band of reflection energy (40 to 300 Hz) substantially enhanced the reflections.

The processing flow required to produce good-quality stacked sections was most basic and included automatic gain control (often necessary in such high-noise environments), a top mute to remove the first-break refraction, normal-moveout velocity analysis, elevation statics, stacking, and migration.

Results

Despite the high levels of coherent noise, the simple processing flow produced high-quality stacked sections that showed reflections at a depth of as much as 1 km and revealed key characteristics of the Godomey aquifer. The base of the aquifer system is at a depth of ~ 180 m or traveltime of 200 to 250 ms (Figure 9). High-amplitude, laterally continuous reflections above 200 ms correlate with thin clay aquitards identified in well lithologic logs. Those aquitards are separated by relatively thick sandy aquifers.

Although the data throughout the survey generally show significant variability of interbedded aquifers and aquicludes, perhaps the feature with the greatest hydrologic significance that we found is a set of paleochannels approximately 60 m deep and as much as 500 m wide (e.g., along line 10a, Figures 1 and 9). The channels, which cut through the units that comprise the aquifer/aquitude system of the large Godomey aquifier (Figure 9), run roughly north–south along the eastern boundary of the well field and between the well field and the capture zone in the southwestern part of Lake Nokoué. The channels cut multiple aquitlude/aquitard boundaries, providing a connected pathway among aquifers previously thought to be confined.

The presence of these channels might explain recent pumping data, which indicate that the shallow and deep aquifers are connected hydrologically. Because the channels lie between the primary recharge zone of Lake Nokoué and the Godomey well field, they likely have a major impact on mixing between multiple aquifer levels and the flow paths from the lake to the well field. Ongoing work is focused on integrating the channel system explicitly into the hydrologic model.
Conclusions

Conducting a field geophysics project in the developing world is fraught with challenges, particularly in an urban environment. These include potential language barriers, difficulties in shipping and repairing equipment, traffic congestion, and differing cultural and safety expectations. Despite such challenges, the intercultural exchange between students and faculty members is invaluable, and the willingness of all parties to work diligently toward the project objectives meant that the project in Cotonou was completed on time and within budget.

We found that the Godomey aquifer system is substantially more complicated than previously mapped. The complexities must be included in the hydrologic model if it is to have value as a predictive management tool. Some large features such as the incised paleochannel system can be mapped directly, but a geostatistical analysis will be required to extract information about the smaller-scale heterogeneity. The seismic study substantially enhanced our understanding of the aquifer system, and the information gleaned from it will help to inform future management decisions.

Acknowledgments

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References


APPENDIX B
Seismic imaging to help understand and manage water quality in coastal Bénin, West Africa

Kyle Lindsay¹, John Bradford¹, Stephen Silliman², Nicaise Yalo³, and Moussa Boukari³

ABSTRACT

We collected seismic data along 15 transects to characterize the geometry of a coastal aquifer in Bénin, West Africa, that is being contaminated by saltwater. We used standard high-resolution seismic methods to image the upper ∼200 m using a sledgehammer source and a 120-channel recording system. Three transects were processed with an iterative updating flow that includes prestack depth migration, residual moveout analysis, and reflection tomography, and the remaining 12 transects were processed with routine processing flows and poststack time migration. We identified one unconfined aquifer and three confined aquifers separated by reflective confining clay layers. Some transects showed areas of missing reflectors, which we interpreted as sand-filled channels that could provide potential high-permeability conduits for saltwater flow to the Godomey well field.

INTRODUCTION

Coastal groundwater resources are a critical component of available freshwater for coastal cities around the world. Rising population density in many of these areas has resulted in overextraction of groundwater resources, leading to saltwater intrusion into freshwater aquifers (Bray et al., 2007; Vandenhoeke et al., 2009; Werner, 2010; Silliman et al., 2011). This problem is especially prevalent in developing countries where it is difficult to assess and manage water resources due to lack of money, government resource management programs, and technical resources. One such area is the coastal city of Cotonou, Bénin, in West Africa.

Cotonou is Bénin’s largest city with a population of 1.5–2.0 million people and lies in the southeast of the country along the Atlantic Coast (Figure 1a). The sole source of drinking water for Cotonou is the Godomey aquifer, which is currently undergoing saltwater intrusion (Silliman et al., 2010). Currently, the annual rate of urbanization in Bénin is approximately 4%. The growth of the urban population has necessitated an increase in the pumping rate from the city’s primary well field, known as the Godomey well field. The Godomey well field lies roughly 5 km north of the Atlantic Ocean and is bordered on the east by Lake Nokoué, a large saltwater lake connected to the Atlantic Ocean via a canal (Figure 1a). The well field consists of more than 20 wells (Figure 1b), which withdraw water from one or more of three confined aquifers ranging in depth from 30 m to 150 m (Figure 1c).

The pumping rate in the Godomey well field has increased steadily on average by about 900,000 m³/yr from 1990 to 2005 (Figure 2). The increased pumping rate has been accommodated by adding new wells at progressively increasing distances from Lake Nokoué (Silliman et al., 2010). Increased pumping has been accompanied by an increase in salinity in the wells in the eastern portion of the well field, closest to the lake (Figure 2). Since 2001, four wells (F2, F4, F6, and F8 in Figure 1b) on the eastern portion of the Godomey well field have been abandoned due to saltwater intrusion (Boukari et al., 2008).

The two potential sources of salinity in the well field are the Atlantic Ocean and Lake Nokoué. However, previous studies by Silliman et al. (2010) show that wells closest to the ocean give no indication of increased salinity in the deeper aquifers, indicating that saltwater intrusion directly from the Atlantic Ocean is currently not a threat to the Godomey well field. All of the wells showing increased salinity are close to Lake Nokoué. Additionally, initial hydrologic models indicate that there is a groundwater divide between the Atlantic Ocean and the Godomey well field due to a
topographic high that parallels the coast and that Lake Nokoué is the likely source of salinity (Boukari et al., 2008). These models predict that increased pumping will result in greater recharge being derived from the western part of Lake Nokoué, consistent with observations of increased salinity in wells closest to the lake (Silliman et al., 2010).

Although initial hydrologic models provide general information about the aquifer system, they are not yet at the stage of a quantitative management tool in which data-driven management decisions can be made. In particular, challenges remain in the modeling effort in terms of temporal/spatial distribution of hydraulic head. The aquifer geometry of the current hydrologic model is based on analysis of well log data that is limited by the areal extent of the wells in the well field. There have been no wells drilled in Lake Nokoué. Consequently, little is known about the geology underlying the lake and how it is connected to the geology in the well field.

One of the key characterization needs identified by Silliman et al. (2010) is mapping of the primary water-bearing units to better understand and quantify the lateral continuity of flow paths. Quantifying the continuity of these units is necessary to improve the spatial resolution of the current hydrologic model and determine transport pathways between the recharge areas in Lake Nokoué and the Godomey well field.

In studies of the coastal plain environment, numerous authors have demonstrated the success of geophysical surveys applied to saltwater intrusion problems (Yang et al., 1999; Shitivelman and Goldman, 2000; Sumanovac, 2006; Nguyen et al., 2009). Shallow reflection seismology is a technique well suited to determining the lateral continuity of hydrostratigraphic units in the Godomey well field. To investigate the continuity of water transport pathways between the lake and the Godomey well field, we collected seismic data along 15 transects around the southwest coast of Lake Nokoué. In this paper, we first describe the acquisition and processing of our seismic data. Second, we present the results from our seismic campaign and discuss the potential impact they have on the hydrologic model for the Godomey aquifer.

**HYDROGEOLOGIC SETTING**

The Godomey well field lies on the southeastern portion of the Plateau of Allada, in the coastal sedimentary basin of Bénin. The geology of the sedimentary basin has been previously described by multiple authors (Blivi et al., 2002; Barthel et al., 2008, 2009; Boukari et al., 2008) and is composed of three primary lithologic units consisting of a Pleistocene clayey-sand, Pliocene sandy-clay, and Miocene sand (Boukari et al., 2008). These layers make up the coastal aquifer system and rest in angular unconformity on a highly heterogeneous Eocene clay/marl substratum at a depth of 180–220 m.

The geology in the zone of production is comprised of interbedded sands, silts, and clays that form four primary aquifers separated by confining clay layers (Figure 1c). For the remainder of this paper, we will refer to the four aquifers as U1, C1, C2, and C3, where U1 is the top unconfined aquifer and C1, C2, and C3 are...
the three confined aquifers in order of increasing depth (Figure 1c). Thicknesses range from 10 to 50 m for sand units and from 5 to 10 m for confining clay layers. The lithology dips slightly to the south, with several of the deeper aquifer units extending beneath the Atlantic Ocean, potentially exposing them to saltwater influx from the Atlantic Ocean due to excessive groundwater pumping.

Lake Nokoué is dynamic in terms of its hydraulics and water quality. Field data (water levels and measures of specific conductance in the lake and groundwater) suggest active interaction of the lake with river inflows from the north, the ocean to the south (via an open channel connecting the lake to the ocean), and the groundwater system. Specifically, during periods of low precipitation, there is strong similarity in water-level variations observed in the lake and in wells within the region of the Godomey well field. These periods are accompanied by active exchange between the lake and ocean via the channel connecting the lake to the ocean and increasing conductivity in the lake to a maximum (dependent on location in the lake) between 50% and 100% of the conductivity (salinity) of the ocean water. In contrast, periods of heavy precipitation are accompanied by an increase in the water level in the lake disproportionate with water level increase observed in the groundwater. Further, water inflow via rivers during periods of precipitation results in flushing of salinity from the lake. The southwestern region of the lake (the region closest to the well field) shows elevated conductance (salinity) even during periods in which the lake is elevated following precipitation, suggesting this region of the lake as a possible region of recharge to the groundwater immediately east of the Godomey well field with water containing elevated salinity.

SEISMIC REFLECTION DATA

Acquisition

Seismic data were collected along 15 transects during two field seasons for a total of approximately 9 km of reflection data (Figure 1b). The study site is located in a large urban center where logistic obstacles and high levels of cultural noise made many preferred survey sites either inaccessible or unfit for collecting high-quality data. Seismic profiles were chosen based on the above logistic considerations and research objectives. Seismic acquisition was focused on the eastern side of the Godomey well field to investigate the lateral continuity of hydrostratigraphic units between Lake Nokoué and the well field. We also collected data along two transects located near the center of the well field that are adjacent to production wells.

Survey design parameters were chosen based on the primary objective of obtaining a high-resolution image of the Godomey aquifer system (< 250 m depth) and are given in Table 1. Despite the noisy urban environment, surface conditions provided excellent source and receiver coupling resulting in data with a high signal-to-noise ratio as evidenced in Figure 3.

Processing

We processed all lines with a routine processing flow with the exceptions of lines 5b, 8a, and 10a (Figure 4). Although most of the reflectors in the other 12 lines are approximately horizontal, as will be shown, these three lines contain stratigraphic complexity. Imaging and positioning problems are intrinsic to poststack migration methods due to the assumptions of NMO processing, namely, hyperbolic moveout and small lateral and vertical velocity variations. Because lines 5b, 8a, and 10a exhibit structural complexity, we chose to use reflection tomography in the postmigration domain using the method of Stork (1992) to improve velocity and image accuracy to better constrain interpretation.

Simple processing flow

The lines closest to the lake were processed using the simple processing flow shown in Figure 4. Because the data show some scattering of energy, we applied poststack time migration to the

<table>
<thead>
<tr>
<th>Recording instrument</th>
<th>Geometrics, 24-bit, 120-channel seismograph</th>
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<tbody>
<tr>
<td>Receiver array</td>
<td>10-Hz vertical geophones</td>
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<td>Source</td>
<td>10-kg sledgehammer</td>
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<td>Geometry</td>
<td>Inline</td>
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<td>Receiver spacing</td>
<td>3 m (lines 1–11), 5 m (lines 12–13)</td>
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<tr>
<td>Source spacing</td>
<td>6 m (lines 1–11), 5 m (lines 12–13)</td>
</tr>
<tr>
<td>Number of geophones</td>
<td>48–96</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Record length</td>
<td>1 s</td>
</tr>
<tr>
<td>Record stacks</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3. (a and b) Raw shot gathers with AGC applied (50-ms window) from lines 5b and 6a, respectively (Figure 1b). (c and d) The same shots with spectral whitening (40–60–200–300 Hz) and AGC applied (50 ms window). Note that the simple spectral whitening filter was extremely effective in removing high-amplitude ground roll and traffic noise.
common depth point (CDP) stacked seismic profiles. We used a phase-shift migration algorithm based on the method of Gazdag (1978) with a maximum migration frequency of 300 Hz and maximum dip angle of 90°. To derive the migration velocity models, we converted the smoothed stacking velocities to time-interval velocity models via a smoothed gradient method. The smoothed gradient method produces a smoothed time-interval velocity model using the Dix equation and cubic spline interpolation. The smoothed time-interval velocities were used to convert the profiles to depth.

Because of the high levels of cultural noise, we did not attempt true amplitude processing and applied automatic gain control (AGC) early in our processing flow to enhance reflection signal. To accurately compare depths between different seismic profiles, all profiles were moved to a final datum elevation of 43 m. This datum is the highest elevation of all 15 seismic lines and is located on line 8a near the center of the well field and was chosen due to the shallow water table. We completed all processing steps using ProMAX™ data processing software. This simple processing flow produced high-quality stacked images with relatively flat-lying reflectors (Figure 5).

**Reflection tomography**

The modeling flow adopted for this work is based on an iterative updating procedure for refining an initial depth-velocity model, consisting of prestack depth migration (PSDM), residual moveout analysis (RMO), and reflection tomography. PSDM combined with RMO analysis and reflection tomography is common practice in the oil and gas industry and is becoming increasingly used in the shallow near-surface environment (Bradford, 2002; Bradford and Sawyer, 2002; Guo and Fagin, 2002a, 2002b; Bradford et al., 2006; Giustiani et al., 2009). RMO analysis is applied to common image gathers that have been output from a prestack migration algorithm, and it operates in the same way as conventional velocity analysis. If the migration velocity is correct, the reflection event on the gather will be flat. If the migration velocity is incorrect, the reflection event is overcorrected or undercorrected, and the remaining moveout is used as input to the reflection tomography to generate a corrected velocity model. At each iteration, velocities and reflector horizons are updated until reflectors on common image gathers are flat lying (Stork, 1992).

Preprocessing migration steps for lines 5b, 8a, and 10a were identical to the previous 12 lines up to velocity analysis (Figure 4). To derive starting depth-velocity intervals, we applied a dip moveout correction (DMO) prior to velocity analysis. We then converted the smoothed stacking velocities to depth-velocity models. We used a Kirchhoff migration method in the common offset domain and migrated the data from topography with a maximum frequency of 300 Hz and maximum migration aperture set to half the length of a spread. After two iterations of reflection tomography, there were no significant changes in velocity models and reflectors were sufficiently flat. The PSDM images and final velocity models for lines 5b, 8a, and 10a are shown in Figure 6.

**RESULTS**

We identified three distinct velocity zones from our tomographic inversion results that correlate with the top unconfined aquifer, the three confined aquifers, and the clay/marl base (Figure 6). Based on correlation with well logs from the area, we interpret the prominent reflections as originating from the transitions from sand aquifers to confining clay layers (Figure 6d, 6f). The strong reflection at ~200 m depth is seen on all 15 profiles and is interpreted as originating from the transition from aquifer C3 to the clay/marl base. This interpretation is consistent with geologic data and the velocity increase from 1900 to 2100 m/s (Figure 6). The dominant frequency of the reflections is about 80 Hz. Taking the average veloci-

![Figure 4](image-url)  
*Figure 4. Processing flowchart for the simple processing flow and the reflection tomography flow applied to lines 5b, 8a, and 10a.*

![Figure 5](image-url)  
*Figure 5. Final stacked profile of line 1a (Figure 1b) obtained by applying the simple processing flow described in the text and shown in Figure 4. All reflectors are horizontal with a slight dip (~1 °) to the south.*
ity of sediments in our study area to be 1800 m/s gives a dominant wavelength of 22.5 m. For clarity, when we refer to depth, we are referring to depth below the datum elevation.

**Line 5b**

Line 5b (Figure 6a, and 6b) shows most clearly the general hydrostratigraphy of the study area with the four primary aquifer units easily distinguished by the laterally continuous reflections. We interpret two channel features within the upper two aquifer units that extend from 50 to 300 m distance and 400 m to the end of the line (yellow dashed lines in Figure 6b). This interpretation is based on the reflector geometry and low-velocity zones located in the axes of these channels. The two high-amplitude reflections beneath each of the channels at ~75 m depth (red dashed lines Figure 6b) have similar geometries to the overlying channels and are interpreted as older channel deposits in a stacked paleochannel sequence.

**Line 8a**

Line 8a (Figure 6c, and d) is located near the center of the Godomey well field and runs adjacent to production wells F13, F4bis,

Figure 6. (a, c, and e) PSDM sections for line 5b, 8a, and 10a (Figure 1b). (b, d, and f) Interpreted PSDM sections overlain on final velocity models. Available well logs are overlain on lines 8a and 10a in panels (d and f), respectively. Well log colors correspond to yellow, sands/gravels; brown, clays/silts; tan, clayey sand. U1 ranges in velocity from 1500 to 1600 m/s on lines 5b and 8a. U1 has a higher velocity of 1700 m/s on line 10a, which is located next to Lake Nokoué. Velocities within the confined aquifers increase gradually with depth, starting at 1700 m/s in C1 and increasing to 1900 m/s at the base of C3. The velocity jumps to 2100 m/s across the interpreted clay/marl base. Note the good correlation of clay layers with reflections. Dashed lines highlight areas of interest discussed in the text.
and F5bis. Lithology logs from the three wells are plotted on the seismic section for comparison.

The thickness and depth of the unconfined aquifer along this transect is highly variable. The thickness of the unconfined aquifer increases from an approximate 25-m depth in the south to an approximate 50-m depth in the north, evidenced by the package of reflections between 30- and 75-m depth on the southern half of the profile pinching out to a single reflection at an approximate 50-m depth on the northern half of the profile. This interpretation is further supported by the well logs and the lateral velocity decrease of approximately 300 m/s from south to north. This velocity decrease correlates with the transition from clay to sand in wells F5bis and F4bis, respectively.

Definitive identification of aquifers C1, C2, and C3 is not possible across the transect due to the lack of reflections on the northern half of the profile between a 60- and 200-m depth (yellow dashed circle in Figure 6d). Most notably, the strong reflection at the 125-m depth, identified as clay in wells F4bis and F5bis on the southern half of the profile, is truncated at 600 m along the line. We interpret this to mean that aquifers C1, C2, and C3 are connected in this region due to the absence of confining clay layers. Note that the absence of confining clay layers would not be predicted by the well logs due to the lack of depth penetration by well F13 (Figure 6d). One important point to note is that we lack dense ray coverage in this area for our velocity inversion due to the absence of reflectors. Therefore, the velocity in this region is not well constrained. Despite this issue, we believe our interpretation to be valid given the high quality of the data and that, in these sediments, large acoustic velocity variations are unlikely.

**Line 10a**

Line 10a (Figure 6e–6f) runs approximately perpendicular to the lake shore with piezometer PZ7 located on the eastern end of the line. PZ7 is approximately 200 m deep, and the lithologic log is plotted on the seismic section for comparison. Based on the well log, the package of reflections between 50- and 110-m depth originates from the interbedded clays and clayey sands. This package of reflections is cut between 75- and 150-m depth on the western portion of the profile by what we interpret as an erosional channel (yellow dashed line in Figure 6f). Our interpretation is supported by the lateral velocity contrast between the interpreted erosional channel and aquifers C1 and C2 (Figure 6f).

**Lake lines**

The lateral continuity of the confining layers beneath the southern portion of the lake shore is highly variable between the interpreted clay layer at −57 m elevation and the clay/marl base at −157 m elevation (Figure 7). The four aquifer units (U1, C1, C2, C3) are easily identified along lines 5b and 11a. South of line 11a, the confining clay layers become less distinct and the confined aquifers (C1, C2, C3) are difficult to confidently distinguish.

There is a shallow zone on the most northerly profiles (identified with arrows on lines 5b, 11a, and 12a in Figure 7) in which there is an absence of prominent reflectors seen on the southerly lines, which we interpret as the continuation of the western channel feature seen on line 5b (Figure 6b). The axis of the channel is oriented slightly southeast–northwest, running from Lake Nokoué through the northern portion of the Godomey well field.

**DISCUSSION**

The lines closest to the lake and line 8a show abrupt discontinuities in confining clay layers suggesting aquifers C1, C2, and C3 are connected beneath the southern portion of the lake shore as well as further inland. Our findings are supported by hydrologic data indicating the confinement of aquifers in this region is not complete (Figure 8). Figure 8 shows relative water levels in two piezometers...
screened at different depths and located approximately 1.3 km from each other. The shallow aquifers (C1, C2) and the deep aquifer (C3) respond to variations in pumping pressure simultaneously, indicating that the aquifers are hydraulically connected in this region.

Erosional channels are present on lines 5b, 11a, 12a, and 10a near the lake shore. The northern channel (lines 5b, 11a, 12a) appears to be cutting through the shallow package of clays and clayey sands. We interpret the channel to be filled with saturated sands based on velocity estimates and well logs. Paleochannels filled with high-permeability material, such as unconsolidated sand, could provide preferential flow paths for saline water from Lake Nokoué to the Godomey well field.

CONCLUSIONS

Seismic reflection profiles from the Godomey well field show the subsurface lithology to be a complex system of discontinuous strata with variable thickness. The current hydrologic model assumes a series of continuous sand, silt, and clay layers with little variability along dip. The model layers form continuous sand aquifers separated by confining clay layers. The seismic data prove these model assumptions to be invalid. The confining layers in the aquifer system are not laterally continuous, and therefore they do not fully confine the sand aquifers in many areas of the Godomey well field. Additionally, there appear to be multiple locations of connectivity between confined aquifers due to the presence of erosional channels. These channels could be acting as preferential flow paths for saltwater between Lake Nokoué and the Godomey well field.

The seismic profiles in the vicinity of the existing well records enable us to correlate and extrapolate lithologies beyond the single data point at each well location. This information can be integrated into the current hydrologic model to better constrain the geometry of the Godomey aquifer and improve model accuracy.

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REFERENCES


