Wellfield Design for a Reverse Osmosis Plant located over a Fresh Water Lens in Lower Valley, Grand Cayman, Cayman Islands

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ABSTRACT

In 1994 the Water Authority-Cayman determined that the drinking water production capacity for the piped water supply of Grand Cayman needed to be expanded from 5,000 m^3/day to 6,500 m^3/day in 1998 and to 8,000 m^3/day in 1999 in order to meet projected demand. Thus, a new reverse osmosis plant was planned for Lower Valley, approximately 15 km east of the plant in George Town.

In the Cayman Islands the saline water needed for reverse osmosis plants is typically abstracted from deep wells whereas the dense brines produced by this process are disposed into zones located deeper than the abstraction zones. The challenge of this project was to design and install a wellfield that would not result in degradation of the shallow freshwater lens. The geology of the Cayman Islands does not provide confined or semi-confined aquifer zones, which would preclude migration of the shallow fresh groundwater to the deeper feed wells or migration of brine to shallower depths. A preliminary groundwater model of the aquifer was created to simulate the effects of different wellfield designs under varying horizontal and vertical permeabilites in the aquifer. A pilot well was drilled at the site, rock samples from this well provided site specific detailed geological information.

The freshwater lens is located within the Ironshore Formation and the underlying transition zone is located within the Pedro Castle Formation. The low porosity cap rock of the Cayman Formation effectively isolates the freshwater lens from water circulation in the deeper part of the succession. The wellfield abstracts saline water from an open zone below the cap rock of the Cayman Formation at a depth of 45–65 m with brine disposal at a depth of 62–86 m, the bottom of the brine disposal zone is highly cavernous.

The plant became operational in 1998, and production capacity was doubled in 1999. To date the Lower Valley reverse osmosis plant has been operating successfully without adverse effects on the Lower Valley freshwater lens. This is evidenced by water quality data obtained from a network of monitoring wells designed to monitor the effects of the plant on the freshwater lens.

Key Words: Grand Cayman, wellfield design, freshwater lens, Ironshore Formation, Pedro Castle Formation, Cayman Formation, Cayman Brac Formation, groundwater monitoring, reverse osmosis.

INTRODUCTION

The provision of high quality drinking water is a challenge for any island that has limited fresh ground water resources, lacks a surface water supply and is faced with an ever increasing population of permanent residents and tourists. Under such a scenario, the traditional water supplies obtained from small, localized freshwater lenses and individual rainfall catchment will eventually prove inadequate. Such has been the case on Grand Cayman, Cayman Islands. The Cayman Islands, a British Crown Colony, consists of three flat limestone islands located in the northwest Caribbean, latitude 19°20'N and longitude 81°20'W, 724 km south of Florida (Fig 1A, insert).

The Water Authority of the Cayman Islands, established by law in 1982, commenced the installation of the George Town Piped Water Supply System in 1987 to meet the growing demand for a reliable water supply in Grand Cayman. Potable water for this system is obtained from desalination of saline groundwater, as fresh groundwater resources in George Town are insufficient for large scale commercial exploitation. Initially the water supply system was designed to supply 1,000 customers in the George Town district; currently it has been expanded to supply 8,000 customers in the districts of George Town, Bodden Town and East End (Fig 1). It is the Authority's intention to expand the system to the North Side district. The demand for piped water has increased significantly from an annual average of 800 m^3/day in 1988 to 6,000 m^3/day in 2000 as a result of the rapid increase of the population in Grand Cayman from 24,000 in 1989 to 37,500 (Cayman Islands Census 1999) and the expansion of the distribution system from 40 km of mains in 1988 to 300 km by the end of 2000 (Fig 2).

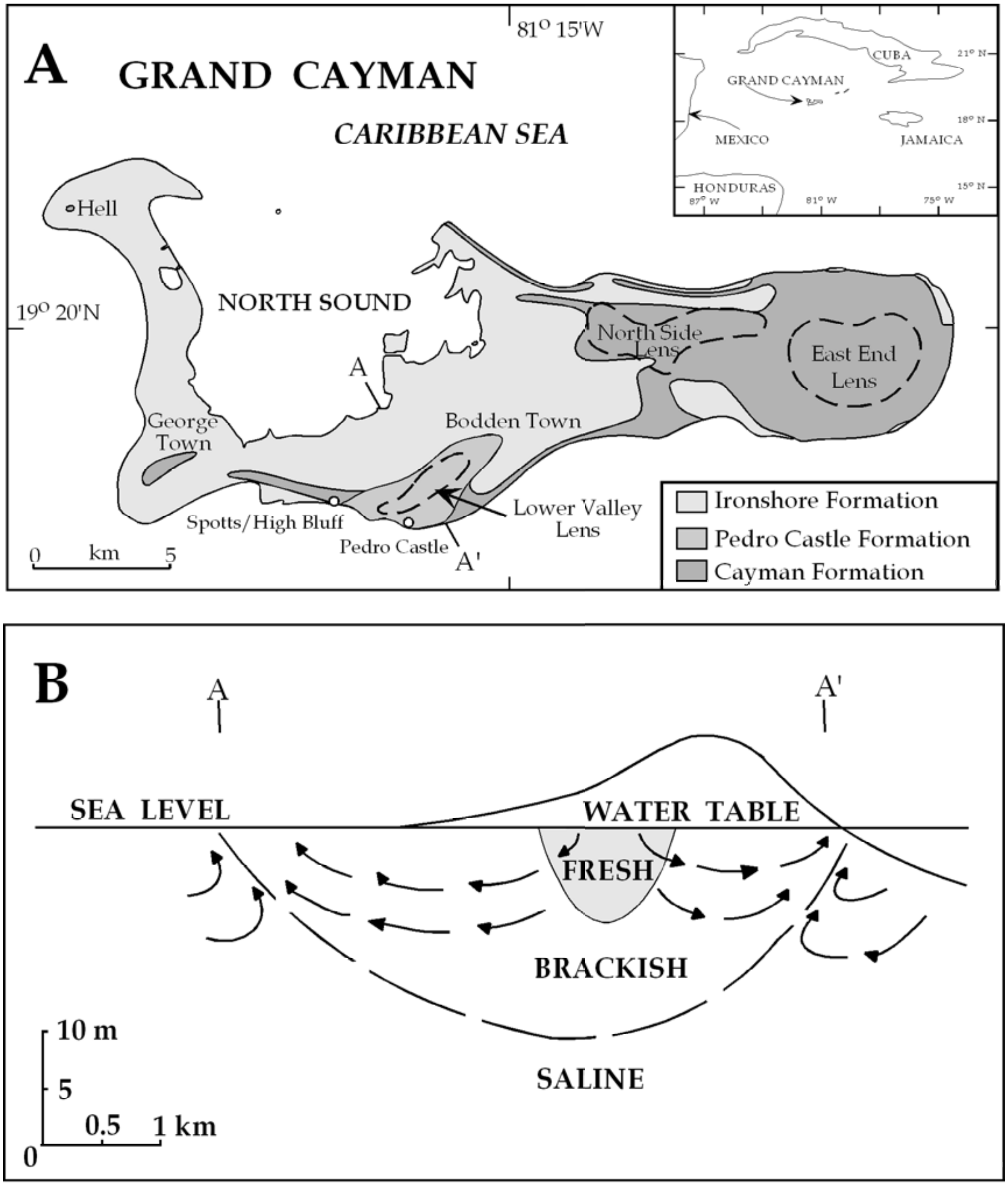

Figure 1. Geology of Grand Cayman, location of major fresh water lenses (A) and cross section of Lower Valley freshwater lens (B). Modified from Ng (1990).

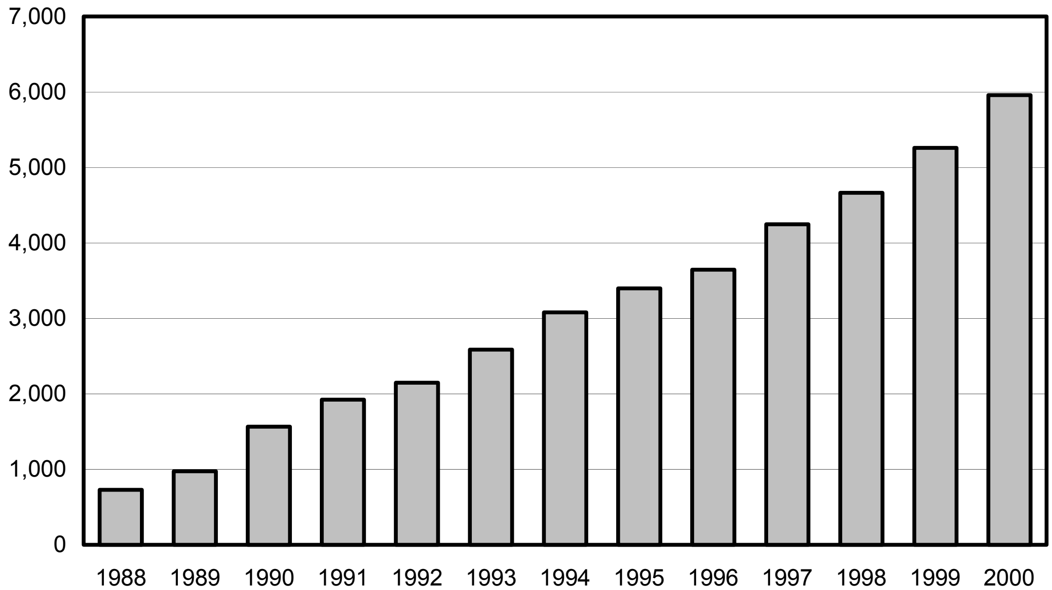

Figure 2. Water Authority Cayman sales of piped water, average daily demand by year, 1988 to 2000 (m^3/day)

In 1994 the Water Authority determined that the water production capacity needed to be expanded to meet increasing demand from 5,000 m^3/day to 6,500 m^3/day in 1998 and to 8,000 m^3/day in 1999 (Water Authority 1994) to satisfy dry season demands, which can be 20 to 25 % higher than average demand. Such an increase could only be met by construction of a new reverse osmosis plant. As the original plant was located in George Town, it was determined that the new plant should be located further east to continue operational reliability of the water supply system. The most suitable location from an operational and practical point of view was Lower Valley, which is located about 15 km east of George Town (Fig. 1). This inland site was selected because the Water Authority already owned the land and zoning laws precluded an alternative suitable location within the distribution area.

In the Cayman Islands the saline water needed for reverse osmosis plants is typically abstracted from deep wells whereas the dense brines produced by this process are disposed into zones located deeper than the abstraction zones. Locating the reverse osmosis plant at Lower Valley meant that it had to be built over one of the three freshwater lenses on Grand Cayman (Fig 1) (Ng 1990; Ng et al. 1992; Ng and Jones 1995). This was a major challenge as the limestone-dolostone geology of the Cayman Islands does not provide confined or semi confined aquifer zones, which would preclude the migration of the shallow fresh groundwater to the deeper abstraction wells or the migration of brine to shallower depths. Consequently, the wellfield for the reverse osmosis plant had to be designed and installed so that it had no adverse effects on the quality of the freshwater lens, which was to be maintained for local usage. Faced with this prime mandate, the challenges were to (1) identify a highly permeable abstraction zone that would allow long-term abstraction of large volumes of saline water, without affecting the shallower freshwater lens, (2) identify a highly permeable disposal zone, located deeper than the abstraction zone, where the concentrated brines produced by the desalinization process could be disposed, and (3) ensure that the brines introduced into the disposal zone would not migrate upwards into the abstraction zone. It was immediately recognized that the solution to these challenges lay in (1) developing a preliminary groundwater model to predict the effects of abstraction of saline groundwater and disposal of brine on the shallow fresh water lens, (2) obtaining detailed information on the subsurface geology of the area, and (3) careful installation of the wells. Furthermore, in order to verify that the lens would not be impacted by the wellfield operation the condition of the lens had to be closely monitored.

PRELIMINARY GROUNDWATER MODEL

The dolostone aquifer of the Lower Valley area is characterized by secondary porosity in the form of open joints, fissures, solution channels and caverns. Due to lack of availability of specific data on permeability of the deeper aquifers and the high degree of anisotropy and heterogeneity of the aquifers in the Cayman Islands, groundwater modeling was limited to comparison of several scenarios for abstraction: variations in casing length, variations in permeability of different layers of the aquifer and variations in vertical and horizontal permeabilities. Data for the model were based on the literature and limited field data from previous testing on shallow aquifers in the Cayman Islands. Due to these limitations the model could not make quantitative predictions, however it was possible to predict the effects on the aquifer qualitatively. A finite-difference model was created using the Excel spreadsheet program; the model is a steady-state three dimensional multi-layer ground water model with optional different horizontal and vertical permeabilities. The model consists of 18 layers, with 144 nodes per layer; each node represents an area 10 m thick by 20 m long and 20 m wide. In preparing the model the following assumptions were made: (1) Darcy's Law is applicable (i.e. groundwater flow is laminar), (2) an impermeable layer exists at 170 m below the groundwater table, and (3) a constant head condition exists at 220 m distance from the well. Brine disposal was not included in the model, as this was not identified as a direct threat to the shallow fresh water lens. It is practice in the Cayman Islands to construct the open zone of brine disposal wells below the open zone of abstraction wells. Vertical anisotropy, high permeability of the aquifer and the higher density of the brine will promote lateral and vertical downward flow over vertical upward flow (Water Authority 1995). The results of the model calculations for the abstraction wells were that:

- The contribution from the shallower layers (fresh to 8 m below water table and brackish water from 8 to 25 m below water table) to the total yield of the wells will reduce significantly with increasing length of the cased portion of the wells. This reduction is even more pronounced if the aquifer has a vertical anisotropy (higher horizontal permeability compared to vertical permeability), in which case water can flow freely in a horizontal direction but the vertical flow is greatly retarded.
- A slight increase of the horizontal permeability with depth (less than one order of magnitude) significantly reduces the contribution of the shallower layers to the total yield, in particular with increased length of casing.
- Individual layers of high permeability strongly influence the distribution of the contributing layers, in particular if the open section of the well crosses it or is very close.
- A strong vertical anisotropy significantly reduces the height of the aquifer that contributes to the total yield (Water Authority 1995).

As the results of the preliminary groundwater model showed that it was feasible to install the wellfield within the Lower Valley freshwater lens area it was decided to carry out a geological investigation to obtain more specific information on the aquifer. Accordingly, an exploratory deep well was drilled at Lower Valley so that the subsurface geology could be examined in detail, and the subsurface waters could be sampled and analyzed. The geological succession found in the well at Lower Valley was interpreted in the context of the geological framework of the island (Figs. 1, 3 and 4), which is well known through detailed studies of surface exposures and other wells (e.g., Jones 1994).

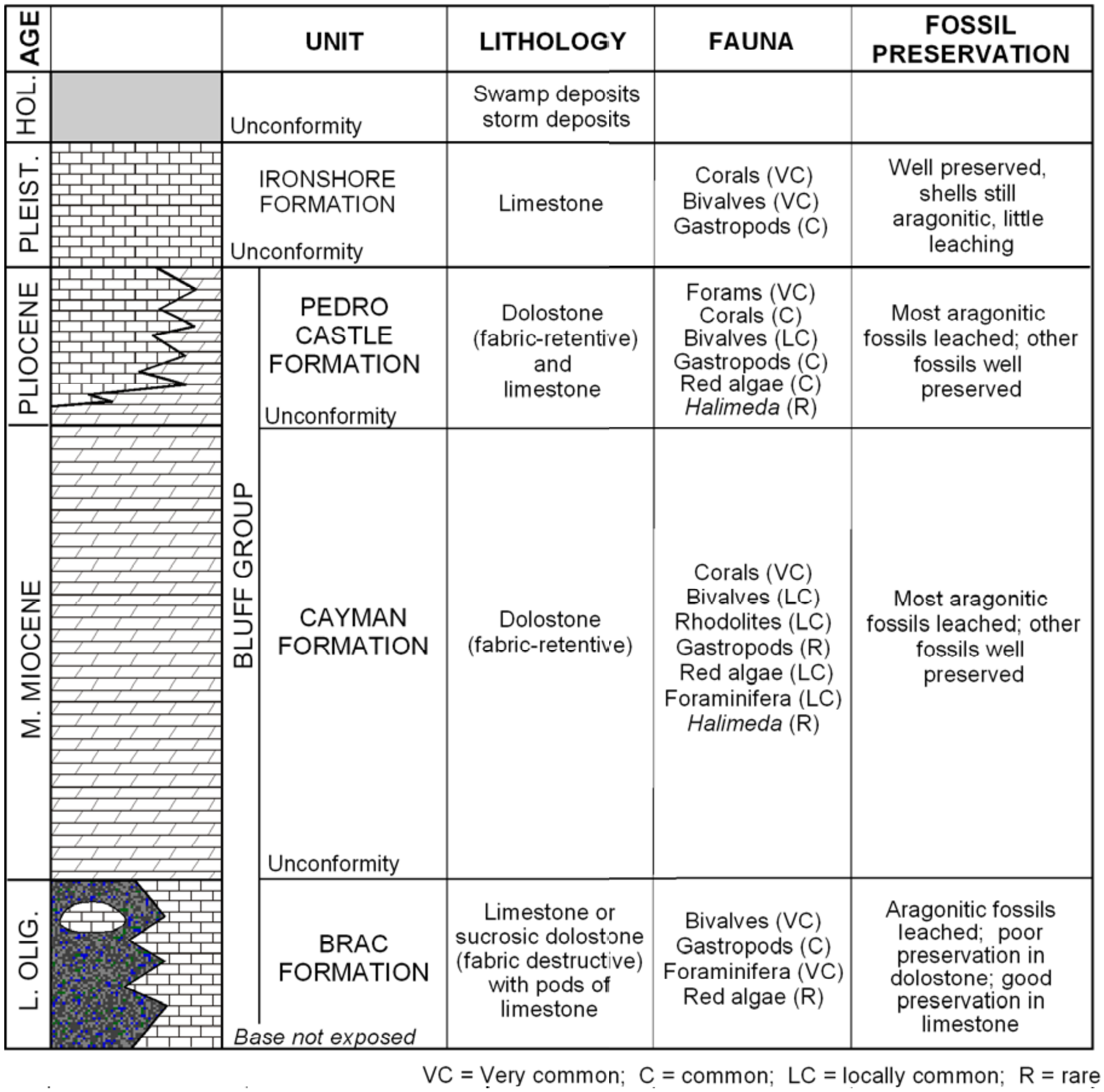

Figure 3. Stratigraphic column for the Cayman Islands showing the consistent formations, their lithology, fossils, and style of fossil preservation (Jones 1994).

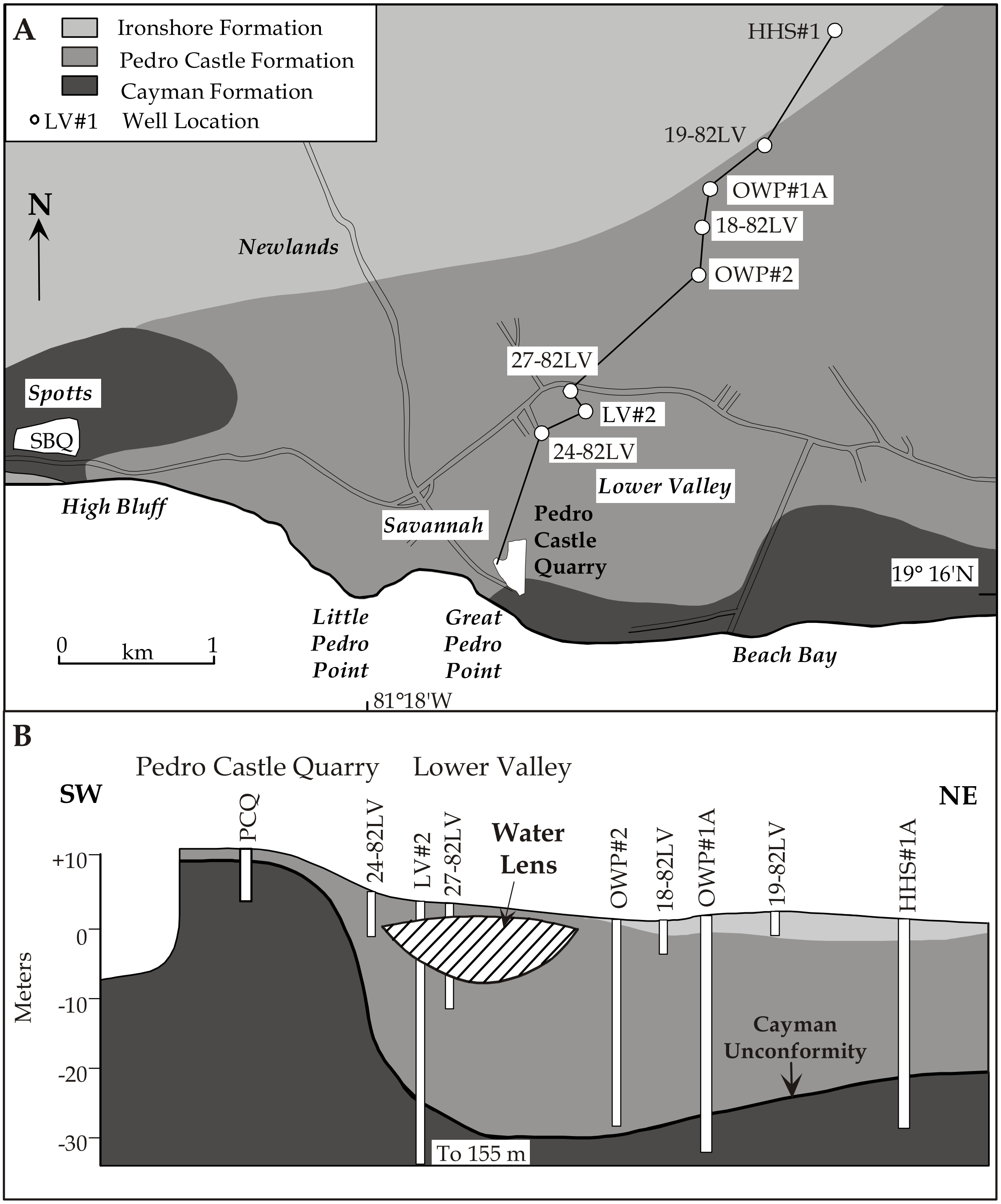

Figure 4 (A) Map of area around Lower Valley showing surface geology, location of Pedro Castle Quarry, and location of wells used to construct cross-section shown in Figure B. (B) Southwest to northeast cross section through Lower Valley showing architecture of the formations, location of the Cayman Unconformity, and location of Lower Valley water lens.

METHODS FOR GEOLOGICAL INVESTIGATION

In 1996, a 150 mm diameter exploratory well (LV#2) was drilled to a depth of 122 m (Fig. 4). In 1997, that well was deepened to 152 m so that more information could be obtained on the subsurface geology of the area. In 1996, 1.5 m cores were obtained every 4.5 m from the top of the Cayman Formation (24.4 m) to a depth of 122 m (Fig. 5). Well-cuttings were obtained from the intervals between the cores until circulation was lost below 82 m (Fig. 5). The porosity and permeability of selected samples from the cores were obtained by the helium injection method. The composition of the rocks was determined by hand sample analysis, thin-section analysis, and scanning electron microscope analysis. Detailed geochemical analyses, which have been obtained for samples from this well, are not reported in this paper because they are not germane to the issue being considered herein.

GEOLOGY OF GRAND CAYMAN

The central part of Grand Cayman is formed of dolostones and limestones that belong to the Bluff Group (Jones 1994). This group is formed, in ascending order, of the Brac Formation (Oligiocene), the Cayman Formation (Middle to Upper Miocene), and the Pedro Castle Formation (Pliocene) (Fig. 3). The Bluff Group is surrounded by and partly onlapped by the Ironshore Formation that is formed of limestones which were deposited during the Pleistocene (Vézina et al. 1999).

The Brac Formation, named for a succession of dolostones and limestones found on the east end of Cayman Brac (Jones et al. 1994), is not exposed on the surface of Grand Cayman. The overlying Cayman Formation, widely exposed on the eastern half of Grand Cayman (Fig. 1), is formed entirely of finely crystalline white to off-white dolostones. It contains numerous fossils including a diverse biota of corals, red algae, bivalves, foraminifera, and gastropods. Any skeletal components originally formed of aragonite were dissolved during early diagenesis and are now represented by fossil-mouldic porosity. The Pedro Castle Formation, which is found mainly on the western part of Grand Cayman (Fig. 1), is formed of fossiliferous limestones, dolostones, and variably dolomitized limestones. There is no systematic distribution to the dolomite in this formation. As in the Cayman Formation, fossil-mouldic porosity is common.

The Ironshore Formation is formed of friable, highly fossiliferous limestones that are largely formed of aragonite (Vézina et al. 1999). No dolomite has been found in this formation. Well-preserved corals, bivalves, gastropods, algae, and foraminifera are common in these strata. None of the fossils have been dissolved.

The subsurface geology of Grand Cayman is complex and it is commonly difficult to correlate successions from different parts of the island because (1) the boundaries between successive formations are unconformities that are commonly characterized by substantial relief, and (2) the rock types in each formation are very similar and intra-formation correlations are virtually impossible. For example, the Cayman Unconformity that separates the Pedro Castle Formation from the underlying Cayman Formation has a relief of at least 40 m (Jones and Hunter 1994). This unconformity is a physical record of the rugged karst topography that developed on Grand Cayman at the end of the Miocene (~ 5 million years ago) when sea-level was at least 40 m below present-day sea-level (Jones and Hunter 1994). This is a critical boundary because the characteristics of the underlying Cayman Formation appear to be intimately linked to the diagenetic processes that took place when that erosional land surface was formed.

GEOLOGY OF THE LOWER VALLEY AREA

The geological framework of the Lower Valley area has been established by examination of all surface outcrops, cores and well cuttings from this area (Fig. 4). Compared to most of Grand Cayman, this area is geologically complex because (1) there is significant relief on the Cayman Unconformity, and (2) partly as a result of the relief on the Cayman Unconformity, there are complex vertical and lateral relationships between the Cayman Formation, Pedro Castle Formation, and Ironshore Formation (Fig. 4).

The upper part of the Cayman Formation, the Cayman Unconformity, and the Pedro Castle Formation are well exposed in Pedro Castle Quarry, which is located on the south coast of Grand Cayman (Fig. 4A). There, the Cayman Unconformity, which dips at 1-2° to the northwest, is located ~ 10 m above sea-level (Fig. 4B). In LV#2, which is located ~1 km northeast of Pedro Castle Quarry, the Cayman Unconformity is 24.4 m below sea-level (Fig. 4B). Thus, there is ~ 35 m of relief on the Cayman Unconformity over a distance of ~ 1 km. In well LV#1, located about 100 m to the north of LV#2, the boundary is ~ 30 m below sea-level. Thus, between LV#1 and LV#3, there is ~ 6 m of relief on the Cayman Unconformity.

The Cayman Formation is divided into the informally named “cap rock” and “porous unit” (Fig. 5). The cap rock is typically ~ 15 m thick. Located immediately below the Cayman Unconformity, it is formed of very hard finely crystalline dolostones that are characterized by low porosity (< 10 %) and low permeability. The underlying porous unit is formed of friable, finely crystalline dolostones that are characterized by high porosities (35-40%) and locally, high permeability (Fig. 5). The location of cap rock is critical to any assessment of reservoir conditions. The cap rock is present irrespective of the elevation of the Cayman Unconformity. Thus, it appears to be product of diagenesis associated with the formation of the unconformity rather than an original depositional unit.

GEOLOGICAL SUCCESSION IN WELL LV#2

Well LV#2 penetrated the Ironshore Formation (0-8.5 m), the Pedro Castle Formation (8.5-24.4 m), the Cayman Formation (24.4-121.9 m), and the Brac Formation (121.9-155.4 m) (Fig. 5).

The matrix porosity of the finely crystalline dolostones in the Cayman Formation, which is 9-48% (Fig. 5), is formed of small (< 20 µm) intercrystalline pores and hollow dolomite rhombs. Locally, the total porosity of the dolostones is increased by the presence of fossil-mouldic cavities (after corals, bivalves, gastropods), fissures, and caves. In the LV#2 well there are two significant sets of caves, one from 82 to 86 m and one from 94 to 96 m (Fig. 5). These caves have a significant affect on water circulation in the area. For example, once the drill bit had passed through the caves from 82-86 m water no longer returned to the surface and it was therefore no longer possible to collect well cuttings from the lower part of the Cayman Formation (Fig. 5). Clearly, the caves mark a significant change in the subsurface properties of the Cayman Formation.

The permeability of the finely crystalline dolostones in the Cayman Formation is typically below 2,500 mD (Fig. 5). In the 45 to 62 m interval, however, the horizontal and vertical permeabilities are up to ~ 10,000 mD (Fig. 5).

The "cap rock" in the Cayman Formation is characterized by low porosity (< 10 %) and low permeability (Fig. 5). Of particular importance is the fact that the vertical permeability in the cap rock is at or close to zero (Fig. 5). The underlying porous unit can be divided in to two parts according to its porosity and permeability characteristics. The upper part of the porous unit (~45 to 62 m), located immediately under the cap rock, is formed of dolostones with high porosity (>35%) and high permeabilities (Fig. 5). The lower part of the porous unit is formed of dolostones with high porosity (> 35%) but low permeability (Fig. 5). The underlying geological reasons for the difference in the permeabilities of the dolostones in the lower and upper parts of the porous unit are unknown. Large caves are found in the lower part of the porous unit (Fig. 5).

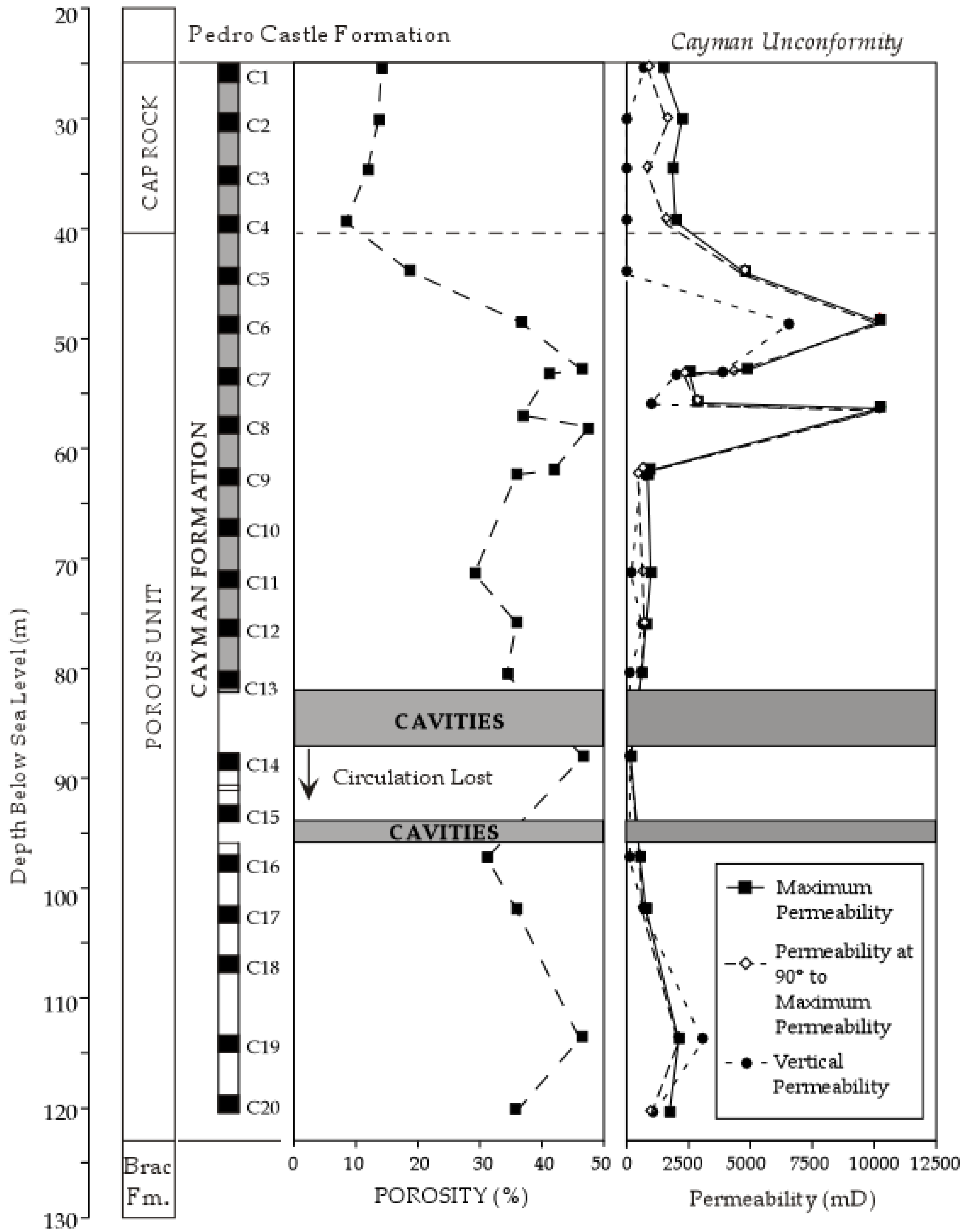

Figure 5. Stratigraphic column for well LV#2 showing location of cores (black), core numbers, intervals from which well cuttings were collected (shaded), and porosity and permeability trends.

DISCUSSION

On Grand Cayman, the Cayman Formation and Pedro Castle Formation are formed of highly porous and permeable dolostones. Locally, the porosity and permeability is accentuated by the presence of fossil-mouldic cavities, fissures, and caves. As a result, the aquifers on Grand Cayman are unconfined and virtually impossible to model on a consistent basis. The complexity of the aquifer is increased by the fact that the low porosity, low permeability cap rock of the Cayman Formation is genetically linked to the Cayman Unconformity, which is characterized by significant relief. Accordingly, well-field designs must rely on site-specific information if they are to be successful.

At Lower Valley, the abstraction zone was located at 45 – 65 m for the following reasons:

- This zone is formed of finely crystalline dolostones that are characterized by high porosity and high horizontal and vertical permeabilities (Fig. 5).
- This zone is overlain by the cap rock of the Cayman Formation, which is formed of finely crystalline dolostones that have low porosity and low permeability (Fig. 5). The very low vertical permeability of these dolostones meant that the probability of any connection between the abstraction zone and the freshwater lens was very low. In effect, the cap rock acts as a very effective barrier that isolates the freshwater lens from the saline water found at greater depths.
- The dolostones immediately beneath the abstraction zone are characterized by low permeability despite their high porosity (Fig. 5).
- Initial tests indicated sustained abstraction could be maintained from this zone without any problems.

The disposal zone was located at 62 - 86 m for the following reasons:

- Large caves and cavities characterized the lower parts of this zone. The loss of circulation while drilling through this zone indicated that this was a highly transmissive zone that was capable of absorbing vast quantities of fluid.
- The upper part of the disposal zone, from 62 - 82 m, is formed of finely crystalline dolostones with very low horizontal and vertical permeability. Thus, there the probability of dense brines being able to migrate vertical upwards into the abstraction zone appeared to be very low.

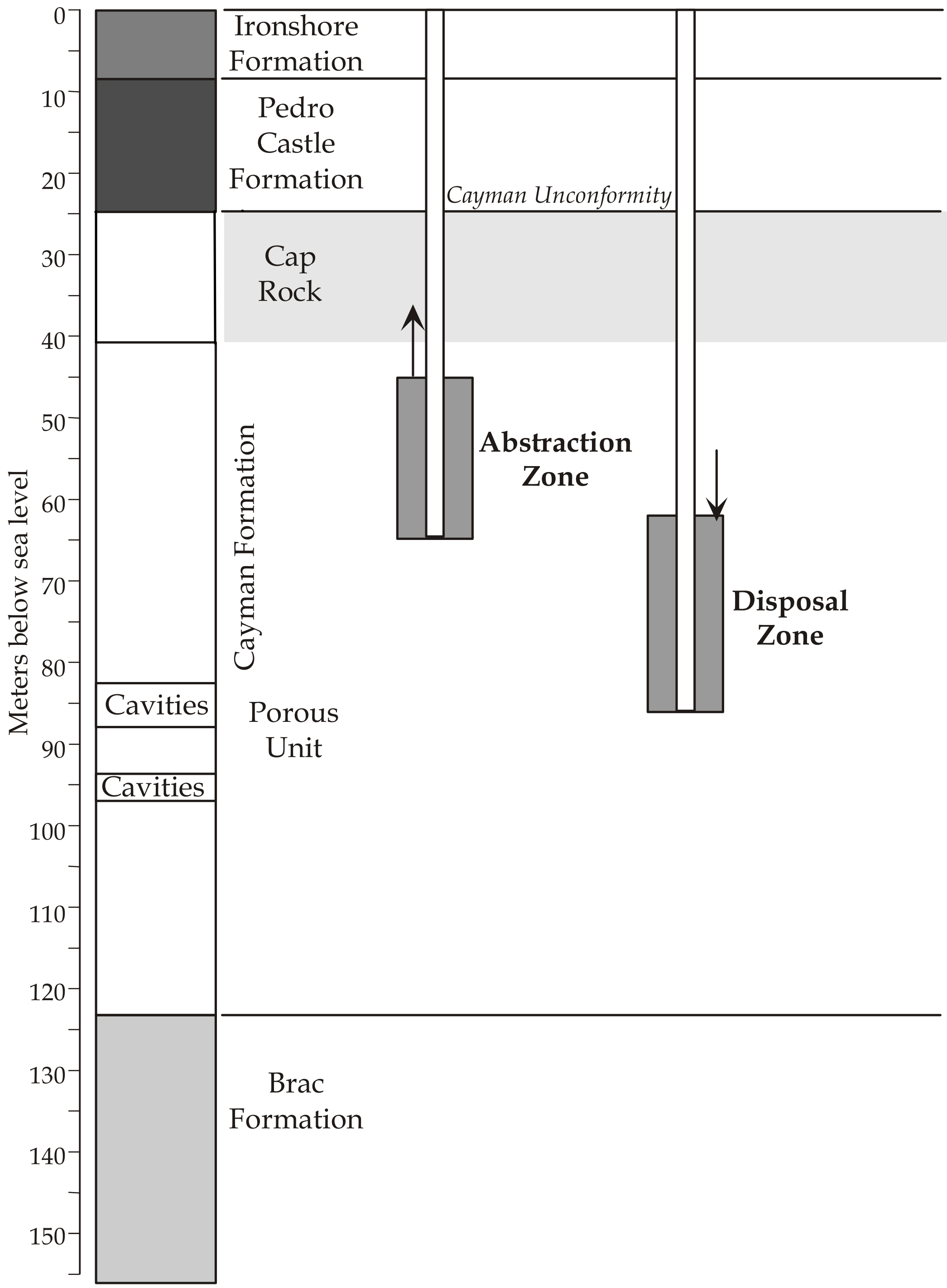

Figure 6. Schematic diagram of Lower Valley area showing locations of abstraction and disposal zones relative to the geological succession.

The wellfield consists of 2 abstraction wells and 1 brine disposal well. The horizontal separation between the abstraction and disposal wells is approximately 110 m; the open zone in the abstraction well is from 45 to 65 m whereas the open zone in the disposal well is from 62 to 86 m (Fig 6). During construction of the wells ultimate care was taken to ensure that no large quantities of saline water were disposed on the fresh water lens and that the well casing was properly installed and grouted. Prior to the installation of these wells the air rotary method was always used in the Cayman Islands to drill wells; however, continued use of that method would have resulted in the disposal of large volumes of saline water on the Lower Valley lens. Thus, Industrial Services and Equipment Ltd., the local well drilling company that was awarded the contract, carried out the drilling using the reverse air rotary method in order to minimize the volume of saline water that was disposed on the lens.

The ultimate test of any wellfield design is its successful implementation and its subsequent operation through time. The reverse osmosis water plant became operational in March 1998 with the abstraction of 3,750 m^3/day of saline water from one abstraction well. On a daily basis this produced 1,500 m^3 of fresh water for drinking and 2,250 m^3 of brine for disposal. In 1999, the production capacity was doubled by additional abstraction of 3,750 m^3/day from a second well. This produced 3,000 m^3/day of freshwater and 4,500 m^3/day of brine. These production levels have been constantly maintained and no problems have been encountered in the abstraction of the saline water or the disposal of the brines. Such efficient productivity clearly indicates that the system is operating as it was designed.

One of the prime mandates in the construction and operation of the reverse osmosis plant at Lower Valley was that it should have no impact on the existing fresh water lens that is still used by surrounding farms and residences. Accordingly, a network of 25 shallow monitoring wells was established around the Lower Valley reverse osmosis plant to monitor the quality of the fresh water lens on an ongoing basis. These wells are located within a radius of 200 m from the plant with depths varying between 2.5 m to 12.4 m below the groundwater table (Water Authority 1997). Water quality data have been collected from these wells since September 1997, 6 months prior to the inception of the reverse osmosis plant, to date. These data clearly demonstrate that there has been no degradation of the water quality in the Lower Valley lens (Fig. 7). Groundwater quality is influenced by rainfall and consequent recharge of the lens, this is shown by fluctuations in Electrical Conductivity of the groundwater in the piezometer. Electrical Conductivities increase during the dry season (December-June) when recharge is limited and decrease during the wet season when recharge increases (June-November) (Fig 7). Furthermore the Electrical Conductivity of the feedwater of the reverse osmosis plant has remained constant throughout the lifetime of the plant, this is a strong indication that the hyper saline brine does not migrate towards the abstraction wells. This evidence further underlines the success of the wellfield design.

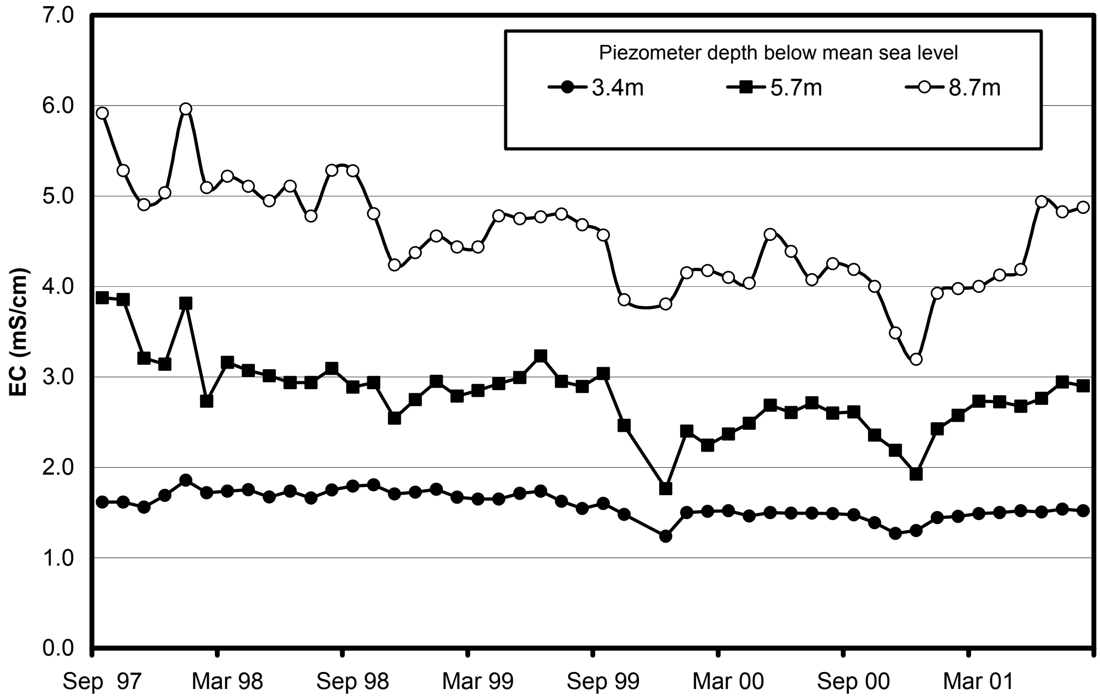

Figure 7. Electrical Conductivity in the open zone of 3 piezometers from September 1997 – August 2001.

CONCLUSIONS

The Water Authority-Cayman has successfully designed a wellfield for the reverse osmosis plant located over a freshwater lens in Lower Valley. Operational data from the plant and data obtained from wells specifically installed to monitor the effects of the plant on the shallow freshwater lens indicate that the abstraction of saline groundwater and the disposal of brine have not resulted in adverse impacts on the freshwater lens. In designing the wellfield careful consideration was given to the potential negative effects that this project could have on local groundwater conditions. Initially a preliminary groundwater model was established to determine under what conditions the wellfield design would be successful, however due to lack of actual site specific data it was decided to carry out a geological investigation of the site. This geological investigation produced a wealth of data that supported the feasibility of the project. Careful installation and grouting procedures of the abstraction and disposal wells were crucial to ensure that feedwater is abstracted and that brine is disposed in suitable zones. The project's success has been verified by monitoring of groundwater conditions of the shallow freshwater lens. It is crucial to realize that none of the elements of groundwater modeling, geological investigation, installation and groundwater monitoring in isolation would be sufficient to design a wellfield that does not adversely impact the shallower fresh water lens.

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