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Optimizing fresh groundwater withdrawals in Cozumel, Quintana Roo, Mexico – A feasibility study using scavenger wells

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ABSTRACT

Cozumel is the largest and most important island belonging to Mexico. Lenses of fresh groundwater accumulate from rainfall percolating through the soil and reside in fragile hydrodynamic equilibrium with the underlying saltwater. The lenses represent the unique naturally occurring freshwater resource in the island. Withdrawal of freshwater from the Cozumel well field containing 173 active wells, all approximately 15 m in depth, has produced upward saltwater coning toward abstracting wells, making the water withdrawn from some wells unfit for human consumption. In most cases, reducing the rate of withdrawal to 1.0 liter per second (lps) per well effectively controls saltwater contamination of the well field. In order to establish criteria for upgrading the Cozumel well field by installing scavenger wells and eliminating wells that admit negligible freshwater when pumped, five wells with different shallow permeability and freshwater environments were examined under static and dynamic conditions to document the behavior of the zone of dispersion and diffusion when stressed by different pumping rates. The results suggest that by operating scavenger-well couples, freshwater production from each well can be increased to as much as 4.5 while controlling the upward advance of saltwater by scavenger-well abstraction. Although provisions must be made for the scavenger wells effluent, the benefits of continuous freshwater abstraction without concern for chloride contamination are evident. At the same time, the total cost of the scavenger-well technology is much less expensive than desalination and assures the long-term development of the highest quality drinking water available from the Cozumel wellfield.

INTRODUCTION

Cozumel, the largest island belonging to Mexico, is located in the Caribbean Sea, 18 km east of the Yucatan Peninsula in the state of Quintana Roo (Fig.1). Cozumel has an area of 473 km^2 with the highest elevation of about 10 meters above mean sea level (msl). It receives approximately 1,500 mm of rainfall yearly with an indistinct rainy season and periodic droughts. Cozumel exhibits carbonate rocks with subterranean drainage provided by a mix of highly permeable soils and widely distributed sinkholes, known locally as “cenotes”. Lenses of fresh groundwater accumulate from rainfall percolating through the soil zone and “cenotes”, and reside in fragile hydrodynamic

equilibrium with the underlying saltwater, separated by slight differences in density. The lenses represent the only naturally occurring freshwater resource in Cozumel.

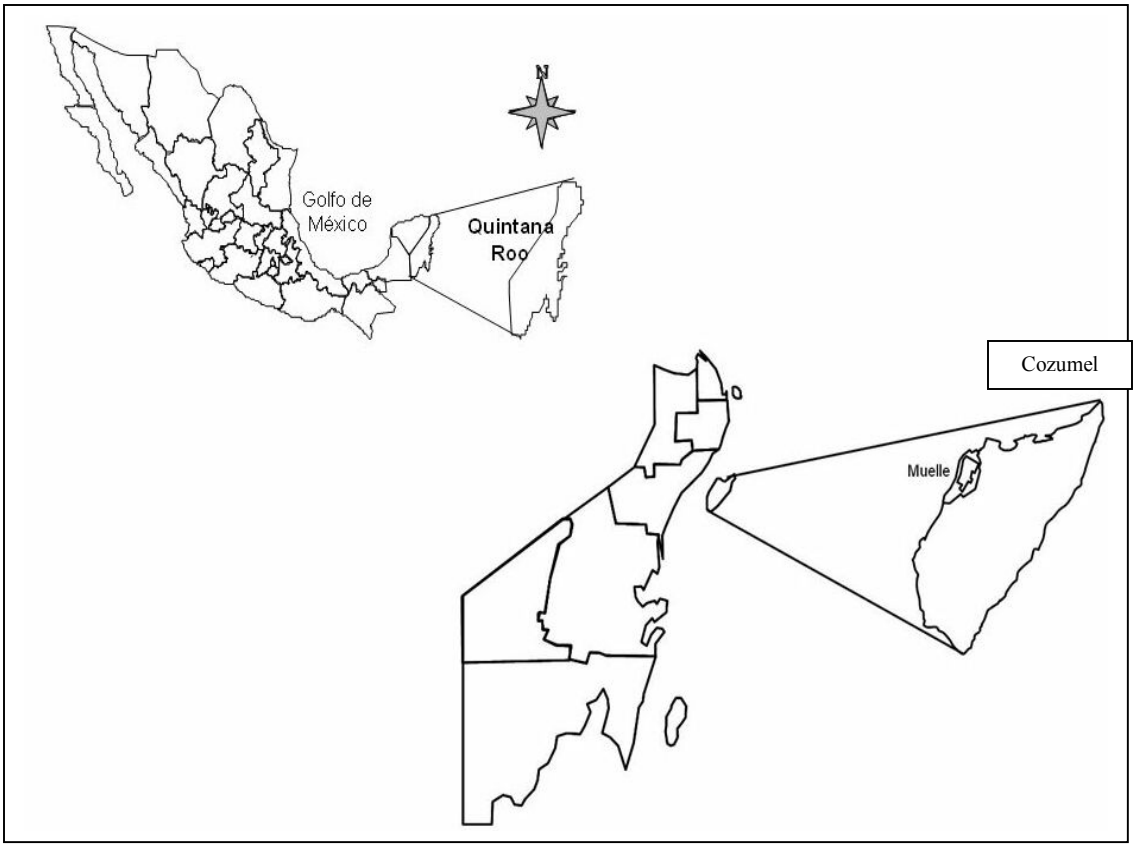

Figure 1: Location Plane

Water levels in wells range between 1.0 meter above msl at the center of the island to about 0.10 meter above msl at coastal locations. Water depth is between 3 and 5 meters below land surface. Pervasive problems with saltwater intrusion by upconing to water-supply wells located in the Cozumel wellfield (Fig.2). have increased chloride levels beyond international standards for drinking water. At present, there are 173 wells having a depth of approximately 15 meters, distributed in linear arrays with an average production of 1.0 lps per well.

The local water administrator is confronting increasing demand for water supply, recognizing that further groundwater production may encourage additional saltwater intrusion. The dynamic behavior of freshwater and saltwater during the abstraction of groundwater has been documented for a variety of wells in the wellfield: i) wells having a history of continuous freshwater production, ii) wells that immediately succumb to saltwater contamination, and iii) wells that form vertical hydraulic gradients within underlying saltwater portions of the aquifer, and can be stabilized with scavenger wells. The role of rainfall recharge in replenishing fresh groundwater has been documented during heavy rainfall where "cenotes" provide subterranean discharge in heavily indurated areas and where permeable land surfaces permit immediate percolation. The

objectives of this study were 1) to demonstrate the utility of scavenger wells in protecting production wells from saltwater contamination by upconing; 2) to generate the required chloride-load (chloride concentration multiplied by flow rate) data for several wells in order to optimize freshwater production by selecting the appropriate conjunctive abstraction rates for the production and scavenger wells; and 3) to establish quantitative criteria for measuring water-quality upgrades made to the Cozumel wellfield as scavenger-wells are operated, historically saline wells eliminated, and additional withdrawals made from wells having high permeability in freshwater portions of the aquifer.

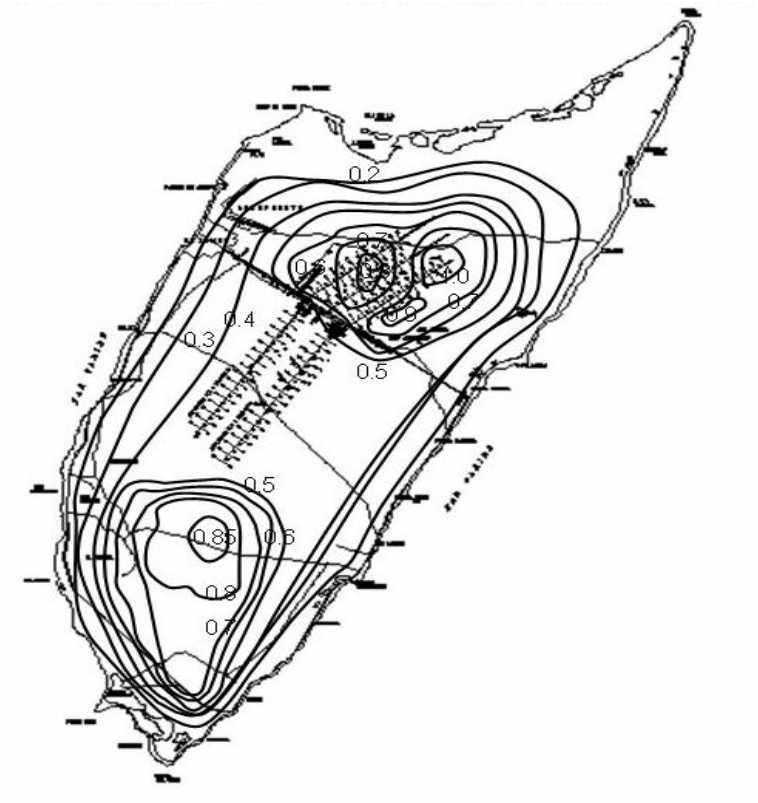

Figure 2: Water Level

Historical performance for all of the 173 wells presently operating in the wellfield were analyzed with respect to vulnerability to saltwater intrusion (upconing) and drawdown (Fig.3). A preliminary classification was generated that revealed that water quality and production could be markedly improved in 29 wells by installing scavenger wells. The analysis also demonstrated that 52 wells should be eliminated from service, and that production could be increased from 92 of the wells, possibly without installing scavenger wells. Logistical difficulties prevented testing all selected sites for scavenger-well applicability. For example, most of the wells were equipped with cemented casings that could not be removed, precluding the installation of scavenger-well couples. In terms of the planned scavenger-well demonstrations, the rainfall had a deleterious effect, and some of the experiments had to be postponed. Also, where abstractions were being conducted during heavy rainfall, power surges and electrical outages suspended pumping for varying periods of time, frustrating the time/drawdown/conductivity continuum.

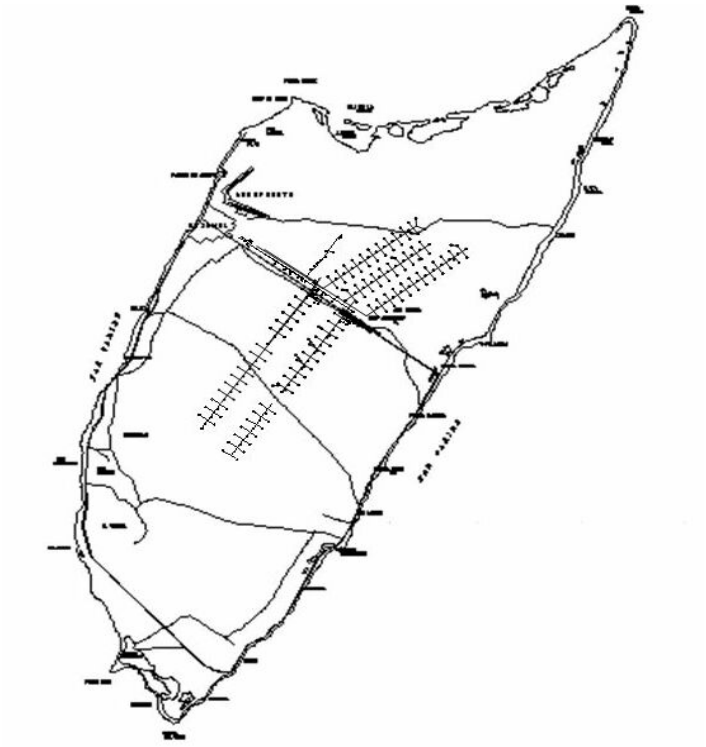

Figure 3: Cozumel Well Field

FIELD SURVEYS

Scavenger wells were installed at each wellsite, adjacent to the production well, as shown in Fig. 4. The wells were operated simultaneously and the salty water extracted by the scavenger well was transported offsite by flexible tubing, 500 m away from the test site. The scavenger-well effluent was disposed into a deep, abandoned well.

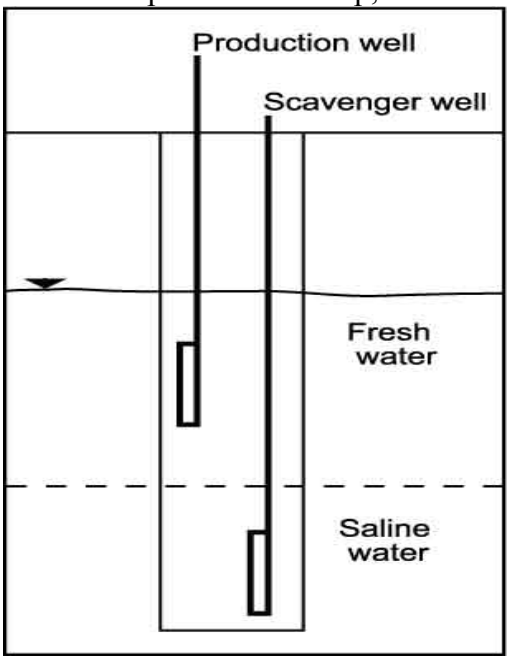

Figure 4: Scavenger-well Abstraction System

CASE HISTORIES-WELL 21

Analysis of historical performance revealed that well 21, pumped continuously at a rate of 1.0 lps, exhibits negligible drawdown and initially provides water having 250 mg/l chloride. However, within one to two weeks, chloride increases to 500 and then 600 mg/l after two months of continuous pumping. The temporal distribution of chloride when the well is pumped at 6.5 lps, from four feet below the static water level, reflects the depth-distribution of salinity and permeability in the well (Fig.5). As pumping by the production well continues, chloride increases in the well to levels above 250 mg/L within 225 minutes

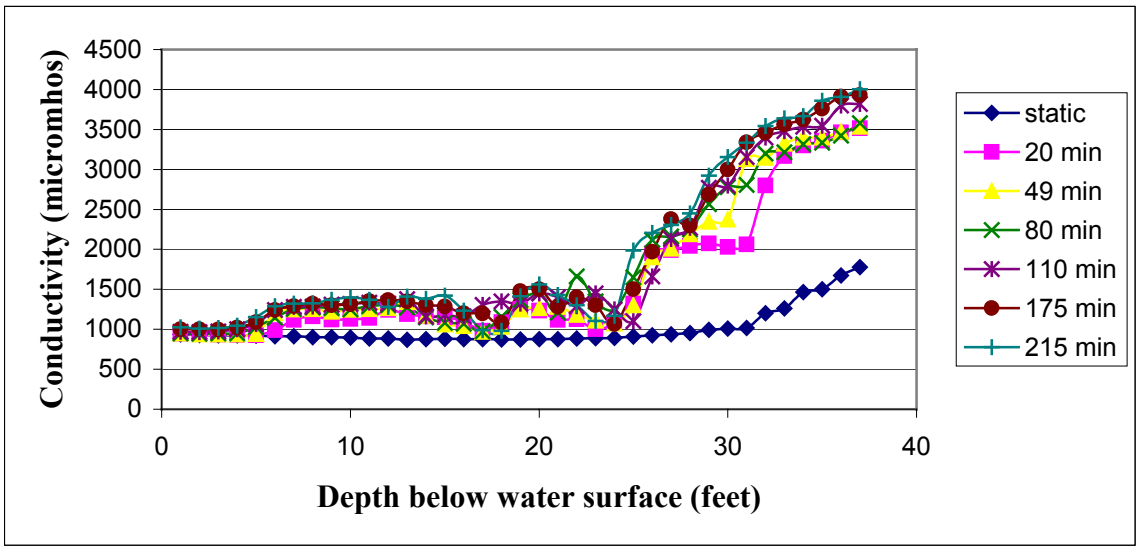

Figure 5: Well 21. Profile Conductivity v.s. Time

Upon installing a scavenger well within the lower portion of the well (Fig.4) – and selecting conjunctive pumping rates for the production and scavenger wells – a dramatic improvement in water quality was obtained for the production well, at greater abstraction rates (Fig.6). For example, protected by a scavenger well (located 30 feet below the static water level and pumping at 1.5 lps, chloride in water withdrawn from the production well (located at 4 feet) stabilized at 180 mg/l at 4.5 lps and at 170 mg/L at 3.7 lps . Testing at 6.5 lps, chloride in the production-well effluent increased to 284 mg/L after 1,494 minutes of continuous pumping demonstrating the inherent instability of the interface at higher withdrawal rates (Fig.7).

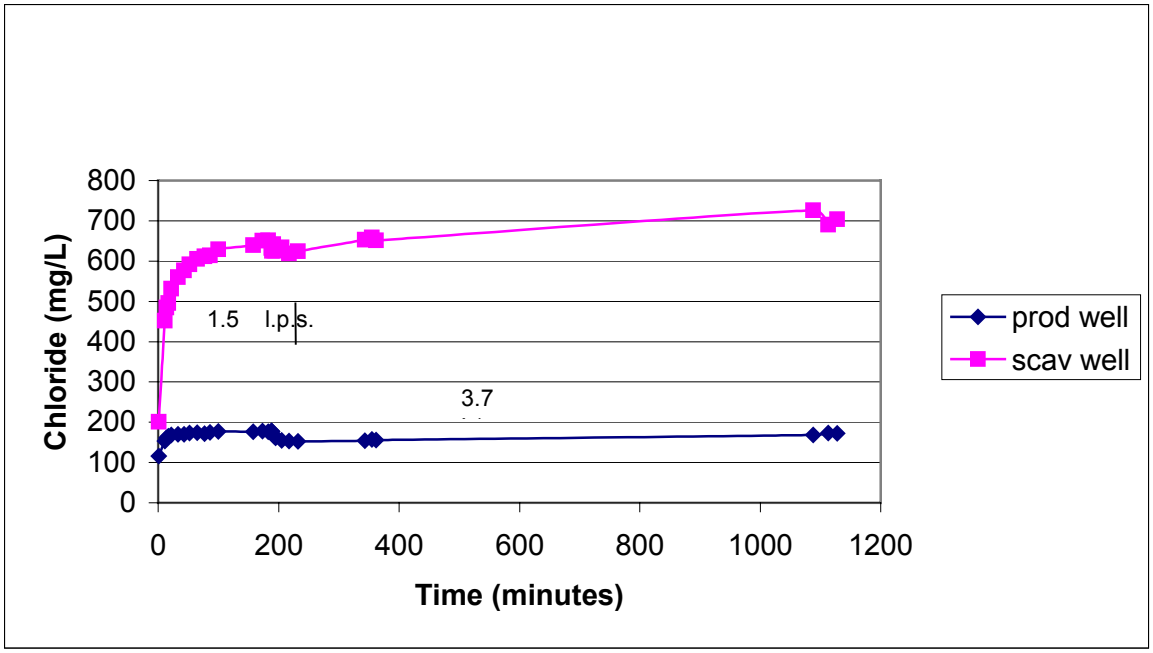

Fig. 6: Well 21. Chloride concentration in water extracted by production and scavenger wells

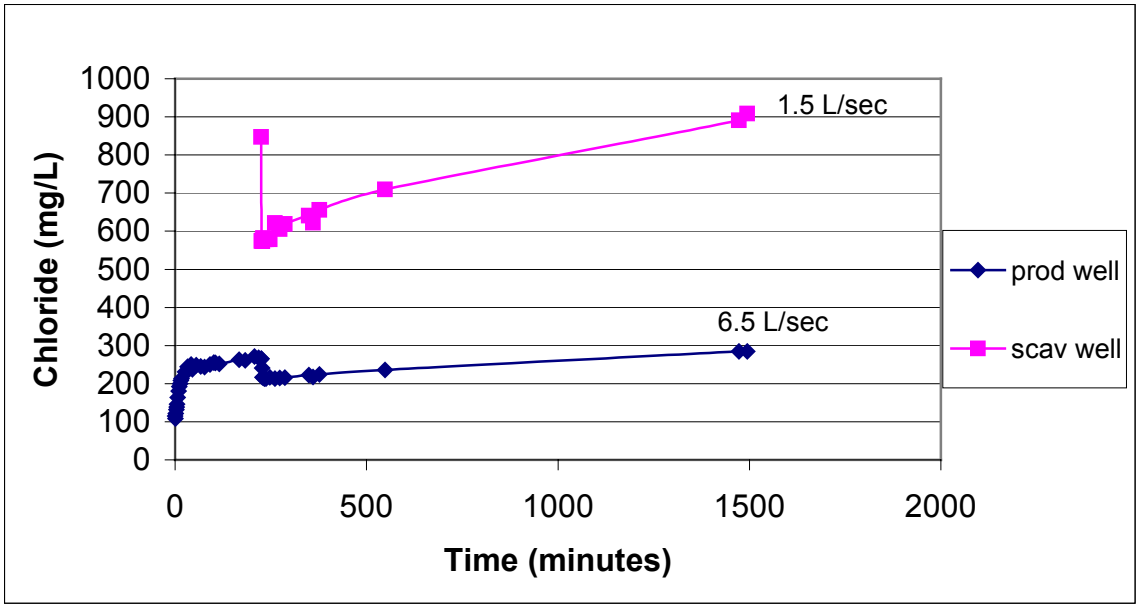

Figure 7: Well 21. Chloride concentration in water extracted by production and scavenger wells

Converting to chloride load, some remarkable relations can be observed, with respect to the hydraulic behavior of the freshwater/saltwater interface to pumping. The chloride load from the scavenger-well effluent is approximately the same, regardless of total withdrawals from the well (Fig.8). This signifies that the upconing saltwater

consistently adds about the same amount of chloride to the system, irrespective of the production-well pumping rate.

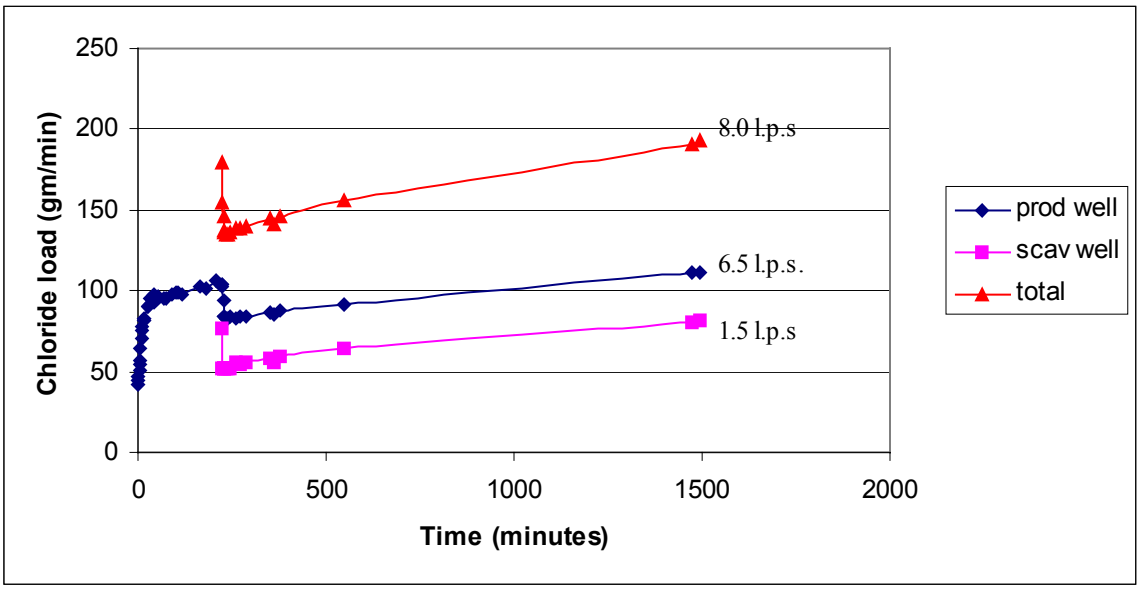

Fig. 8: Chloride load in water withdrawn from well 21

Accordingly, chloride loads are reasonably additive, with mobility of the zone of diffusion and dispersion directly related to hydrodynamic gradients produced by withdrawing groundwater, regardless of the number of abstraction points in the borehole. This simple relation permits the selection of optimal, conjunctive pumping rates for the scavenger and production wells in boreholes such as well 21, where chloride consistently rises above 250 mg/L during simple pumping, even at a rate of 1.0 l.p.s. This example demonstrates that up to 4.5 l.p.s of groundwater having 180 mg/L chloride can be abstracted continuously from well 21, if a scavenger well is pumped simultaneously at 1.5 l.p.s from greater depth within the same borehole.

CASE HISTORIES – WELL-8

Well 8, had recently been idled, owing to an increase in chloride concentration (from 180 to 458 mg/l). With only 2 cm of drawdown, this well experiences dramatic coning from saltwater portions of the aquifer, owing to limited freshwater contribution to the borehole. In the process of providing a scavenger-well couple for well 8, stepped abstraction rates for the production well, pumping alone, and located 4 feet below the water level, were conducted to determine which rate might achieve chloride equilibrium within a reasonable length of time. Fields results reveal that at 3.8 lps, equilibrium appears to be achieved after 388 minutes, but higher rates exceed the density inertia of the underlying saltwater within a reasonable length of time. The equilibrium attained at 3.8 lps can be observed in the conductivity profiles collected throughout the stepped abstraction of groundwater (Fig. 8). At low rates of abstraction, freshwater entering the borehole limits the development of upward hydraulic gradients within the relatively low-

density zone of diffusion and dispersion. Accordingly, chloride equilibrium is achieved at 3.8 lps. However, beginning at 430 minutes, greater abstraction rates (5.2 and 6.5 lps) mobilized the underlying freshwater/saltwater interface, destabilizing the kinetic boundary afforded by slight differences in density. Until such time that equilibrium is achieved, chloride will continue to rise, achieving 339 mg/L after pumping for 1,902 minutes at 6.5 lps and still rising.

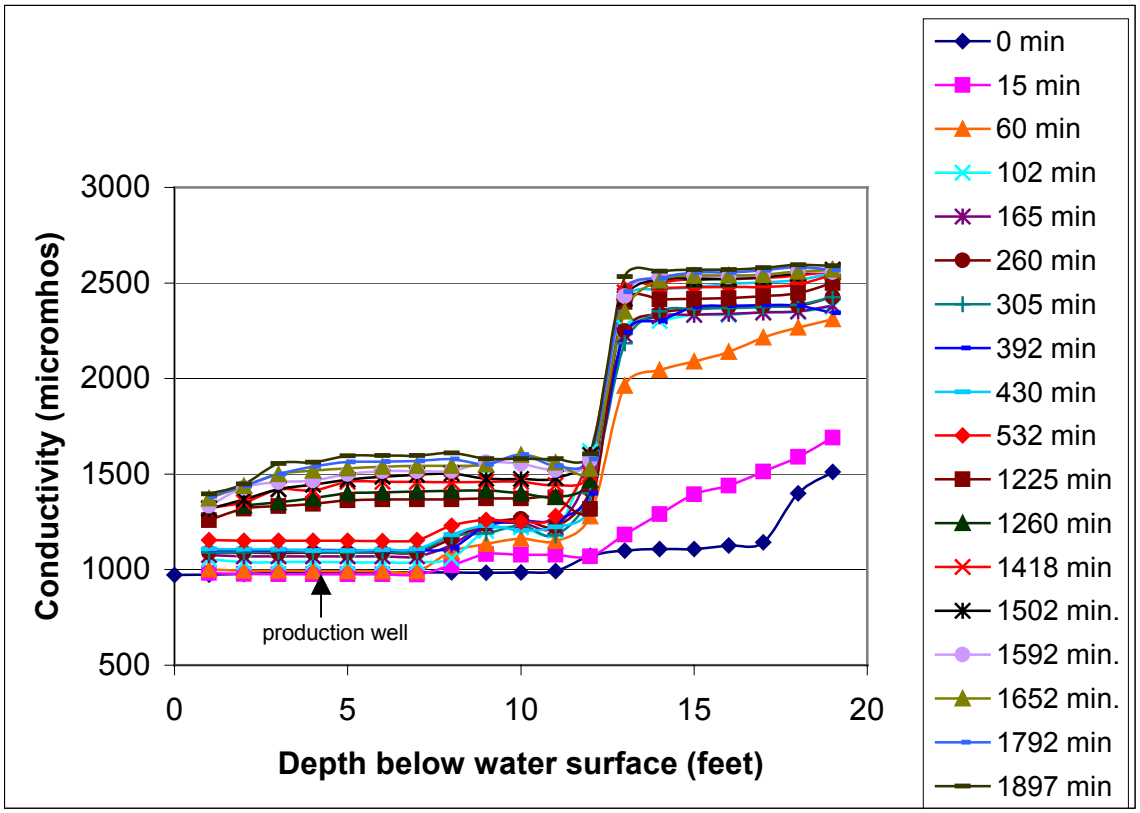

Figure 9: Well 8. Conductivity profles during the stepped abstraction.

A thorough analysis of chloride concentration and load is required in order to make informed decisions regarding the conjunctive pumping rates of the production and scavenger wells. At 3.5 lps, 250 mg/l chloride is reached in the production well and at 2.5 lps, 200 mg/L is approached (Fig.10). In terms of chloride load, approximately the same 50 gr/min limit is reached by the production well pumping 3.5 lps as is reached during the total withdrawals of 4 lps achieved when the production well abstracts 2.5 lps (and the scavenger well 1.55 lps) (Fig.11). Accordingly, the additive nature of chloride load is evident, and can be used to discern optimal, conjunctive pumping rates for the production and scavenger wells, particularly when minimal quantities of freshwater are available to the borehole, as is the case with well 8.

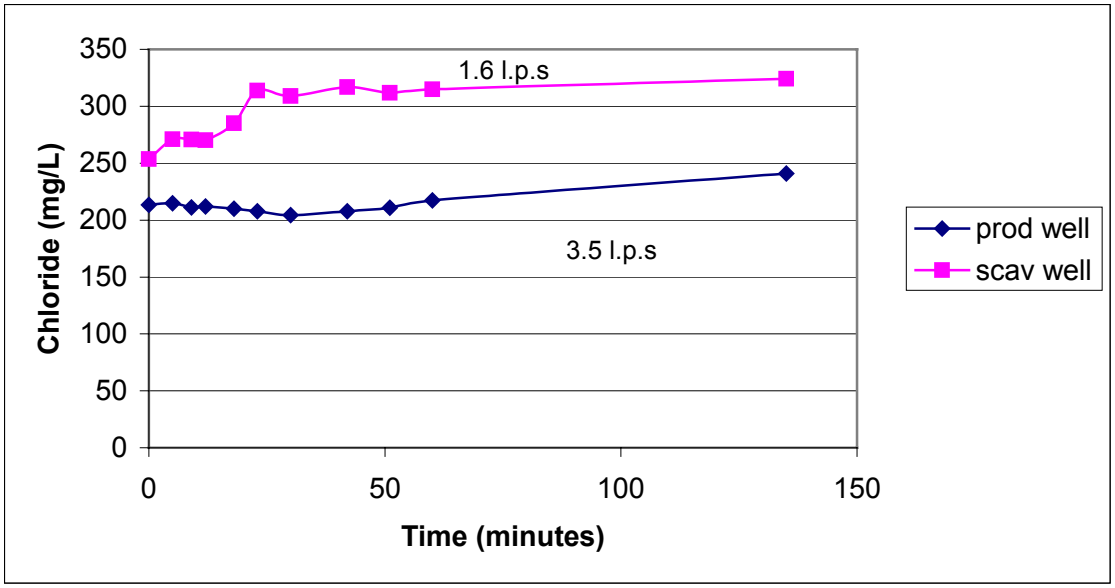

Figure 10: Well 8. Chloride concentration in water withdrawn by the scavenger-well couple

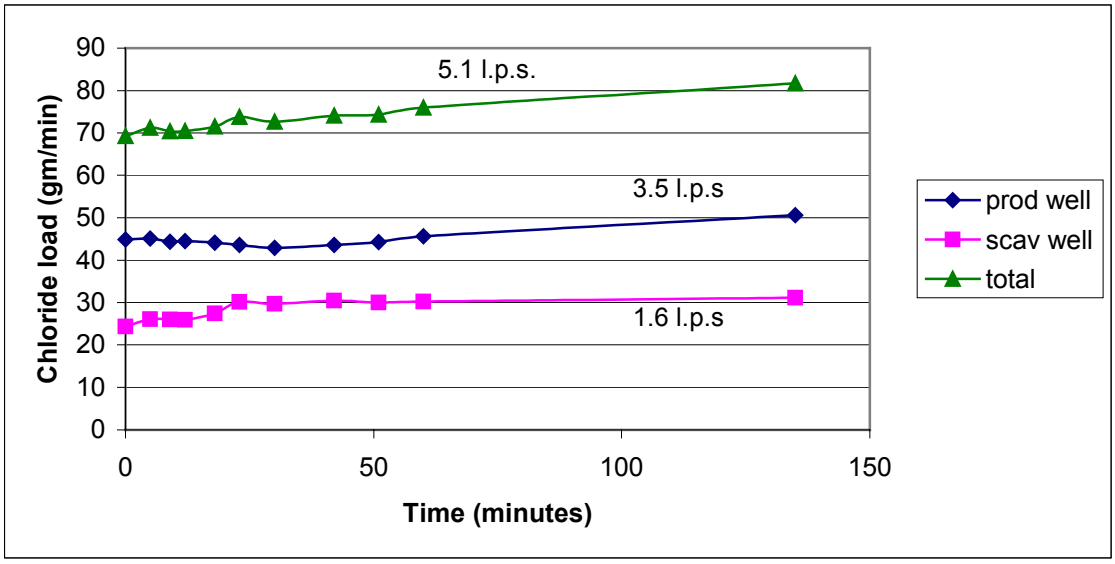

Figure 11: Well 8. Chloride load in water withdrawn by scavenger-well couple

CONCLUSIONS

Evaluation of historical performance for the wells operating in the Cozumel wellfield reveal remarkable variation in vulnerability to saltwater intrusion. Where saltwater intrusion by coning threatens the continued use of a well, production and scavenger wells have been shown to be useful in attenuating the upward advance of saltwater, protecting the production well from chloride contamination. Freshwater production can be increased to as much as 4.5 mg/L while controlling the upward advance of saltwater by scavenger-well abstractions.

Although provisions must be made for the scavenger-well effluent, the benefits of continuous freshwater abstraction without concern for chloride contamination are evident. As the Cozumel wellfield is upgraded, well-by-well, to take advantage of the areal and depth-distribution of permeability and salinity, the quantity and quality of water produced by the wellfield will increase to a maximum chloride concentration of approximately 160 mg/L. In accordance with the findings of the present and previous fieldtrips to Cozumel, the following action plan is required to improve the quality and quantity of abstracted groundwater from the Cozumel wellfield:

i) Install scavenger-well couples in those wells that have the ability of producing large quantities of freshwater, but, with time, develop upward gradients in the underlying saltwater regions, causing saltwater intrusion. Double or triple groundwater abstractions from those wells having no history of saltwater contamination.
ii) Measure the specific capacity for all wells during dry periods in order to determine the location of pumps in wells and for selecting appropriate saltwater wells for scavenger-well effluent.
iii) Install conductivity switches in those wells threatened by eventual saltwater coning that can neither be anticipated nor controlled by hydraulic techniques.

Bibliography:

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