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Application of a 3-Dimensional Coupled Flow and Transport Model in the Gaza Strip

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ABSTRACT

The Gaza coastal aquifer is historically the only natural source of water supply in the Gaza Strip. With a population of about 1.1 million and one of the highest natural birth rates in the world, the water resources of the Gaza Strip are under considerable strain, and future predicted demands far exceed available supplies. Overexploitation of the coastal aquifer has resulted in continuous lowering of regional water levels and a gradual worsening of water quality. The greatest threats to existing water supplies are seawater intrusion and upconing of deep, fossil brines. Continued urban and industrial growth will place additional stress on the system, unless appropriate planning and management actions are instituted immediately.

In recognition of this worsening situation, the United States Agency for International Development (USAID) and the Palestinian Water Authority (PWA) have jointly developed and begun implementation of an Integrated Aquifer Management Plan (IAMP). The IAMP presents overall planning guidelines for water supply and usage through year 2020, with associated investment requirements for infrastructure facilities to meet all goals and objectives. Many of the engineering components of the IAMP were conceptualized and defined through the application of a regional-scale ground water model.

This paper presents the modeling conducted to simulate the effects of the IAMP. The model of the Gaza coastal aquifer is a fully 3-dimensional coupled flow and transport model, capable of simulating seawater intrusion, migration of brines, and transport of brackish water (i.e., density-dependent flow). Modeling results to date demonstrate that implementation of the IAMP will have overall beneficial impacts on the Gaza coastal aquifer, and it is predicted that seawater intrusion and upconing can be significantly reduced and/or stabilized over the next 20 years.

With the existing ground water model, the Palestinian Water Authority now has an added capability to manage its resource, and equally importantly, to demonstrate what will happen if required investments are not made.

AQUIFER STATUS

The Gaza Strip is located at the eastern end of the Mediterranean Sea, and is bordered by Egypt to the south, and Israel to the north and east (see Figure 1). While it covers an area of only 365 km^2, it presently supports an estimated population of about 1.1 million.

In terms of water supply, more than 3,300 municipal and agricultural wells presently pump approximately 140 million cubic meters per year (Mm^3/y) from the Gaza coastal aquifer, far exceeding its estimated long-term average recharge from rainfall (about 40 Mm^3/y). The estimated net water balance of the Gaza coastal aquifer is negative; that is, there is a water deficit. From model calibration, and incorporating all relevant aquifer fluxes (including return flows), the estimated net 'deficit' in 1998 was about 31 Mm^3/y (see Table 1) (Note - 1998 was a drier than average year).

Figure 2 is a three-dimensional representation of the interpreted 1998 ground water flow field in the Gaza Strip. As a result of the overabstraction, large cones of depression, with measured water levels several meters below sea level, have formed near the major wellfields and urban centers in Gaza City/Jabalya and Khan Younis/Rafah.

Implications of the water deficit in the coastal aquifer are lowering of regional water levels (loss of storage) and a reduction in availability of fresh groundwater. Reduction in aquifer storage is documented in many areas of the Gaza Strip by lowering of water levels on a regional scale with time, accompanied by steady increases in aquifer salinity in many areas. Between 1970-1993, water levels in the Gaza Strip dropped 1.6 m on average, mostly in the south. This is equivalent to an average 5 million cubic meters per year (Mm^3/y) decline in overall aquifer storage (using a specific yield of 0.2). In the north, most wells exhibit slower declines than in the south, with partial or complete recovery following the 1991/92 hydrological year (a hydrologically wet year), and influenced by water management practices in Israel (irrigation and artificial recharge).

The ongoing deterioration of the water quality of the Gaza coastal aquifer poses a considerable challenge for water planners. The major documented problems are related to elevated and rising chloride (salinity) and nitrate concentrations. Figure 3 shows chloride and nitrate concentrations in 1998/1999 in municipal supply wells, arranged from north to south. Many supply wells exceed their respective World Health Organization drinking water standards for chloride and nitrate. The extent to which the aquifer may be impacted by other pollutants such as organic chemicals, metals, and pesticides, has not yet been defined.

The replacement of fresh water with brackish and saline water is taking place in many parts of the Gaza Strip. In some cases, documented rates of salinization are nearly 10 mg/L per year. Sources of salinity that have been defined to date with available data are seawater intrusion, lateral inflow of naturally brackish ground water from Israel, and potentially upconing of deep, fossil brines in the southern part of the Gaza Strip. Since the rate of reduction in aquifer storage is estimated to be about 5 Mm^3/y, most of the net 'deficit' described above is inferred to represent deep, regional-scale seawater intrusion.

It is presently estimated that only about 10 percent of the total aquifer volume may be considered ‘fresh,’ meeting the WHO drinking water standard for chloride of 250 mg/L. This corresponds to a total volume of about 450-600 Mm^3. The time frame for depletion of ‘fresh’ groundwater will depend on continued abstraction volumes and patterns. Using an average rate of aquifer depletion of about 25 Mm^3/y over recent years, it can be theoretically calculated that depletion could occur in 20-25 years.

SUMMARY DESCRIPTION OF THE GAZA COASTAL AQUIFER MODEL

The model domain and finite element grid used to simulate ground water flow within the Gaza coastal aquifer are shown in Figure 4. The model encompasses an area of about 2,150 km^2, and contains 3395 nodes and 6686 elements in plan view. The study area encompasses parts of Israel and Egypt since the Gaza coastal aquifer is part of a much larger regional aquifer system and can not be viewed in hydrogeological isolation. The model was also extended approximately 5 km offshore to allow for representation of the ground water interaction with the Mediterranean Sea.

The model was discretized vertically into 11 levels and 10 layers to represent a series of subaquifers and coastal clays near the shore. The coastal aquifer consists of a complex sequence of Pleistocene age sediments (Kurkar Group) that include calcareous and silty sandstones, silts, clays, unconsolidated sands, and conglomerates. The main aquifer unit is subdivided into 3-4 subaquifers (A, B_1, B_2, and C) near the coast by the presence of coastal clays that extend up to 2-5 km inland, as depicted in Figure 5. Towards the east, the clays pinch out and the aquifer system may be regarded as one hydrogeological unit. Within the Gaza Strip, the total thickness of the Kurkar Group is about 100 m at the shore in the south, and about 200 m near Gaza City. The base of the coastal aquifer (a "no-flow" boundary) is marked by the top of the Saqiya Group, a thick sequence of marls, claystones and shales of Neogene age that slopes towards the sea. The Saqiya Group pinches out about 10-15 km from the shore, depending on location, and the coastal aquifer rests directly on Eocene age chalks and limestones.

While there are no stratigraphic data or logs available offshore, the onshore stratigraphy was extrapolated to the offshore boundary of the model.

A specified constant head boundary condition of mean sea level (H=0 mASL) and fixed concentration values equivalent to the TDS of the Mediterranean Sea were assigned to nodes in offshore areas and along the western boundary at all model levels. A reference density of 1.025 g/cm^3 was used for seawater. The numerical code uses this reference value to calculate and adjust fluid densities relative to simulated concentrations of dissolved salts in the model (linear relationship). Because the eastern Mediterranean may have slightly higher TDS than 'typical' seawater, the model was tested by simulating seawater intrusion using a density of 1.028 g/cm^3. Such small changes in density did not significantly affect the calibration or simulated shape and extent of the seawater intrusion wedges).

SUMMARY DESCRIPTION OF MODELING CODE

To simulate variable density effects on ground water flow, the coupled flow and transport code DYNCFT was used. Coupling flow and transport computations allows the effects of fluid density gradients associated with solute concentration gradients to be incorporated into gound water flow simulations (i.e., density-dependent flow). It uses the finite element method of numerical integration to solve fully 3-dimensional confined and unconfined ground water flow under many types of natural and artificial aquifer stresses.

DYNCFT simulates 3-dimensional contaminant transport with dispersion. Constituents that are subject to first-order decay, and/or linear equilibrium adsorption may be simulated, as well as conservative constituents such as salt/chloride. Transport computations are solved based on the Lagrangian approach, and dispersion uses the 'Random Walk" method for a statistically significant number of particles, each particle having an associated weight, decay rate, and retardation. DYNCFT simulates both variable and fixed concentration sources of contamination, which may be specified implicitly or explicitly.

MODEL APPLICATION

Prior to application and simulations of IAMP scenarios, the numerical model was rigorously calibrated and tested against both 'steady-state' and transient data. Approximately 120 calibration target wells were used in the analysis, and the transient calibration period was selected to include the significant hydrological 'wet year' of 1991/92 in the region (this year had 3 times the long-term average rainfall). Examples of the transient calibration results are provided in Figure 6.

Estimated Present Extent of Seawater Intrusion

A major part of the transient calibration was dedicated to achieving a reasonable representation of seawater intrusion, both in terms of geometry and timing. Available field data are not sufficient to estimate the past 'equilibrium', or present location of the transient freshwater/seawater interface. Seawater intrusion is documented only in shallow wells along the coast, and there are currently no deep monitoring wells to verify the extent of intrusion in the deeper part of the aquifer. Therefore, the model was applied to examine how far inland the seawater wedge might have moved since intrusion began.

Based on the history of the Gaza Strip, chloride and water level data for more than 120 wells between 1968-2000, as well as estimates of total aquifer abstraction with time, significant onshore seawater intrusion likely began in the late 1960s/1970. Because there are no data to indicate where the freshwater/seawater interface may have been under 'equilibrium' (pre-development) conditions, initial simulations of intrusion were run with the interface located at the shoreline, and incorporating transient pumping, recharge, and other fluxes. The resulting simulated distribution of salinity was compared against the presumed salinity distribution in the Gaza coastal aquifer from limited available field data, which includes Israeli well measurements from the early 1970s and, primarily, interpretations of surface geophysical measurements (TDEM) carried out in year 2000.

The simulated extent of the present seawater wedge (defined as greater than 60% seawater chloride concentration) is presented in two cross-sections in Figure 7 (Jabalya and Khan Younis, respectively). In Jabalya (north), it is estimated that seawater intrusion may extend about 1.0 km inland in subaquifer B, and up to 3.0 km in subaquifer C. In Khan Younis (south), intrusion is restricted to just over 1 km in subaquifer B_2 and less than 1 km in subaquifer B_1. The salt wedge shown in subaquifer C actually represents concentrations from dense brines that were input in the base levels of the model, and were presumed to extend 3-4 km inland from geophysical survey results. These brines are believed to be trapped in subaquifer C in the south, where the B_2/C clay thickens toward the shore and subaquifer C pinches out (Fink, 1970, Sorek, 1997).

Figure 8 shows a plan view of the present simulated intrusion in the B and C subaquifers in Gaza City, along with locations of municipal wells screened in the B subaquifer (some of the wells also extend into the C subaquifer). Several municipal wells are likely underlain by the deep seawater wedge or in close proximity to it. Continued overpumping of the aquifer will put these wells at risk of significant salt water entrainment. Two municipal wells in Gaza City were already shut down in 1997 due to 'break-through' chloride concentrations.

As a check on model simulations of seawater intrusion, results were compared with geophysical (TDEM) survey results obtained during the CAMP. Experiences from Israel indicate that apparent resistivity values less than 1.9-2.0 ohm-m might be indicative of seawater in the coastal aquifer, and that values less than 0.5 ohm-m may be indicative of the presence of brines.

As an example, Figure 9 shows the simulated extent of the seawater wedge in year 2000 overlain with results of TDEM measurements at a cross-section location near the coast in Rafah. Using this as a basis for interpretations, it can be concluded that present simulations of the extent of seawater intrusion are in reasonable agreement with TDEM data. At this time, without deep confirmatory sampling, it is not possible to conclusively state how the model simulations relate to actual intrusion at every location in the Gaza Strip. While the model provides a reasonable overall representation of intrusion, it may be that the model overpredicts and underpredicts intrusion on a smaller scale.

These modeling results are consistent with significant intrusion beginning around 1970 and with estimated rates of intrusion of about 30-50 m/y. Locally, and with planned expansion of municipal well fields, these rates could be even higher.

MODELING OF THE INTEGRATED AQUIFER MANAGEMENT PLAN

The numerical model of the Gaza coastal aquifer has been applied to test the overall regional impacts on the aquifer of implementation of the Integrated Aquifer Management Plan (IAMP). The IAMP (M&E, 2000) calls for phased construction of major infrastructure facilities and requires the investment of some $1.5 billion in year-2000 US dollars. The IAMP is driven by four principal priorities:

- Ensure supply of water in quantity and of quality to meet the future demands
- Recharge the aquifer by collection, treatment and infiltration of wastewater
- Sustain the aquifer by control and reduction of abstraction for irrigation, and
- Sustain agriculture by supply of treated effluent as the principal source for irrigation (i.e., achieving a reduction in agricultural pumping).

BASIS FOR MODEL SIMULATIONS

For the Gaza Strip, decreased agricultural pumping and increased aquifer recharge (of treated wastewater) are the most obvious and practical methods for stabilization of seawater intrusion, although other techniques and management options are available. In some cases, further seawater intrusion may be acceptable, and the degree of stabilization required is a function of stated objectives in a larger management plan context. Given the reliance of the Gaza Strip on the aquifer as a source of water, and the proximity of the inferred deep seawater to municipal supply wells, one of the stated goals of the IAMP is that stabilization of the seawater wedge should occur "as quickly as possible".

Among the major components of the IAMP that were explicitly or implicitly simulated are:

- Increased municipal demand (i.e., increased pumping), from 50 Mm^3/y in 2000 to 127 Mm^3/y in 2020.
- Provision of 60 Mm^3/y of water into the municipal supply from a proposed new regional desalination plant (and subsequent increases in return flows).
- Reduced agricultural pumping from 90 Mm^3/y in 2000 to 16 Mm^3/y in 2020
- Artificial recharge of 35 Mm^3/y by year 2020.
- Return flows from irrigation (25% of 63 Mm^3/y by year 2020).
- Return flows from wastewater and municipal water supply distribution networks (76 Mm^3/y by 2020).

Most of these components change in time and space over the 20-year planning and simulation period (2000-2020). The complex nature of the IAMP required that some simplifying assumptions be made to the model input. These primarily involve averaging appropriate input data into multi-year ‘stress periods’. Averaging was carried out only as long as the intended spatial distribution of fluxes was not compromised. The selected stress periods were determined from the timing of major IAMP components, such as construction of the regional wastewater treatment plants, construction of artificial recharge basins, and planned delivery of treated effluent directly to farmers in different areas.

Other parameters were not changed temporally, primarily because there is no way to predict how they may change over the next 20 years (e.g., recharge from rainfall, where the estimated long-term average was used).

RESULTS OF MODELING OF THE IAMP

Impacts on Ground Water Levels

Figure 10 illustrates the anticipated improvement in ground water levels in 5-year increments to 2020 following implementation of the IAMP. As expected, the benefits of the IAMP are not visible until a time when large-scale RO is integrated into the municipal supply and significant quantities of treated effluent are made available for aquifer recharge and direct reuse (2005-2010).

Model simulation of the water balance achieved by implementation of the IAMP (and as scheduled) demonstrates that there will be a desired recovery of ground water levels in the aquifer in all areas of the Gaza Strip by year 2020. Initially, head conditions in the aquifer will continue to deteriorate until the required infrastructure can be constructed. The benefits will not be evident until year 2005 in the north and much later in the south. Unfortunately, these effects can not be avoided or remediated sooner unless the timeline of construction of wastewater treatment plants and available recharge are expedited.

Figure 11 shows simulated water levels in a profile through Gaza City (as a function of distance from the coastline) for the period 1936 to 2020. Using anecdotal pumping information for the period 1930 through 1970, and long-term average recharge, a preliminary long-term transient simulation was carried out to examine how regional water levels may have changed from 1935 to present, and how they would be impacted by the IAMP. While significant improvement in head levels will be achieved, water levels do not recover to pre-development conditions of 1935. Significant additional quantities of recharged water, and/or a reduction in overall pumping, would be required.

Impacts on Seawater Intrusion

Impacts on seawater intrusion are expected to be slower than impacts on water levels. Saltwater migration, wedge stabilization, and reversal of intrusion typically work on time scales of decades. In the northern part of the Gaza Strip, the simulated position of the seawater wedge in subaquifer B has more or less stabilized by year 2010, as presented in Figure 12 (cross-section through Jabalya). Inland intrusion in the deepest subaquifer C is predicted to slow considerably between 2010 and 2020. Hence, the impacts of the IAMP in the deepest part of the aquifer are significantly time delayed. This is expected, given the continued heavy reliance on pumping of wells in the future without significant recharge until year 2005 in the north. As demonstrated by Figure 12, seawater intrusion also migrates vertically up towards the municipal wells in the upper part of Subaquifer C. Again, the rate of migration is slowed down by year 2010.

Stabilization of the wedge in the shallower subaquifer B is a result of the increased recharge from the northern WWTP from 2005 through 2015, as well as progressively reduced agricultural pumping in the north.

In the southern part of the Gaza Strip (e.g., Khan Younis), intrusion in subaquifers B_1 and B_2 is predicted to continue over the planning period, but will slow with time as greater quantities of treated effluent are recharged back to the aquifer and agricultural abstraction is reduced. The increased municipal pumping also appears to continue to draw the deep brines upward, although at very slow rates (see Figure 12).

Overall, it is predicted that between years 2000 and 2020, the IAMP will reduce the quantity of seawater intrusion from about 25-30 Mm^3 to about 5-6 Mm^3 along the entire Gaza Strip, respectively under defined 'average' climatic conditions.

SUMMARY OF FINDINGS FROM MODELING

The Gaza coastal aquifer has been overexploited for the past 30-40 years, and current management practices are not sustainable. Drastic and immediate action must begin immediately, and will require significant future investment in national infrastructure ($1.5 billion over the next 20 years, per the IAMP).

Reduction in agricultural pumping, improved management of municipal supply, and recharge of significant quantities of treated effluent to the aquifer system are crucial elements in developing a sustainable water resource in the Gaza Strip. A further requirement is that treated effluent be of sufficient quality such that it meets both agricultural needs and public health criteria. Much of the water that will be recharged will end up back in the municipal supply. The residence time of the reclaimed water therefore has to be maximized. Unfortunately, land ownership issues and the number of new wells that have to be added makes the spacing between recharge basins and municipal wells a considerable challenge. This will have to be closely examined in the future as new wells are installed for municipal supply.

While an aquifer ‘balance’ for years 2000-2020 is presented in the IAMP, it is the spatial distribution of pumping and recharge, as well as implementation schedule of plan components, that will ultimately determine the success of aquifer management.

ROLE OF MODELING IN FUTURE AQUIFER MANAGEMENT

From a hydrogeological point of view, a pro-active management approach is required, whereby the water balance and condition of the aquifer is closely evaluated and monitored on a frequent basis (at least annually). The role of the model will be to simulate the conditions as they are defined in any given season/year. A baseline condition has been established through the CAMP project, and the numerical model can now be used as a primary aquifer management tool.

The model can also be utilized to examine impacts and consequences of not implementing the IAMP. For example, if municipal pumping expands in a manner different from that assumed in the IAMP, and recharge of treated wastewater is not implemented within the schedule defined by the IAMP, what will be the local/regional impacts? Equally importantly, with time, it may be necessary to modify IAMP objectives, and hence management actions. “What-if” scenarios can then be simulated.

Active management and monitoring are closely linked, and evolve in parallel. It is a continuous and live process, and in this process, the model becomes a "living entity" that periodically checks how the aquifer responds to management actions. As such, it is going to be crucial for Palestinian authorities to maintain knowledge of Israeli and Egyptian water management practices. This includes obtaining annual updates on quantities of water pumped or recharged outside the Gaza Strip, as these affect ground water resources of the Gaza coastal aquifer.

Data needs are still many. Since the Gaza coastal aquifer is the single most important source of water for Palestinians in the Gaza Strip, appropriate investments should be made to ensure that each of the major components of the hydrological water budget are adequately quantified, understood, and incorporated into the regional ground water model (and hence, planning). This requires installation of dedicated observation wells (for water levels and water quality), implementation of systematic sampling programs, and careful study of the major factors that influence the ground water regime in the Gaza Strip, including management practices in Israel and Egypt.

FOOTNOTE

The Gaza coastal aquifer is a complex and dynamic 3-dimensional system, with multiple subaquifers and seawater wedges that respond differently to different sets of transient fluxes. Modeling of the Gaza coastal aquifer is therefore also complicated. It involves a tremendous amount of data handling and processing, and consideration of external factors that are beyond the control of Palestinian authorities.

Successful modeling of the Gaza coastal aquifer required a synergistic approach that combined the application of a powerful and tested numerical code with direct linkages to common GIS and data processing tools. As well, development of specialized numerical routines were required to be able to handle large sets of transient data. For example, routines were written specifically to assign pumping from more than 3,300 active wells to appropriate nodes and model levels on a monthly basis, as well as interpret complex and often incomplete sets of pumping records.

With this approach, the work carried out in Gaza CAMP has demonstrated that practical, 3-dimensional modeling of complex, regional and transient coastal aquifer systems is possible. Numerical codes such as DYNCFT, running in transient mode with GIS interfaces, provides the PWA with a set of state-of-the-art tools for managing their critical aquifer resources.

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Keywords:
Integrated aquifer management, modeling of management scenarios, counteracting seawater intrusion

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Figure 1: Location Map of the Gaza Strip

Table 1
Summary of Calibrated 'Steady-State' Water Balance for 1998

Summary 1998 Water Balance (from Model Calibration)

Units: Mm3/y	Model Domain	Gaza Strip
Inflows		
Recharge from Precipitation	95.0	35.0
Return Flows in Gaza	51.6	51.6
Return Flows in Israel	38.3	
Lateral Inflow [1]		36.6
Total Inflow	184.9	123.1
Outflows		
Municipal Abstraction	50.3	50.3
Agricultural Abstraction	90.3	90.3
Settlement Abstraction	5.0	5.0
Israeli & Egyptian Abstraction [2]	53.3	
Natural Ground Water Discharge	21.8	8.5
Total Outflows	220.7	154.1
Net Balance (Deficit)	-35.8	-31.0
Inferred Seawater Intrusion	35.8	31.0

[1] This is not a resource that can be counted on in the Gaza Strip - it is affected by water management practices in Israel and Egypt

[2] Egyptian pumping in model domain is estimated to be very small (2-3 Mm3/y)

Note: Return flows include pipe leakages, wastewater discharges artifical recharge, irrigation returns, etc.

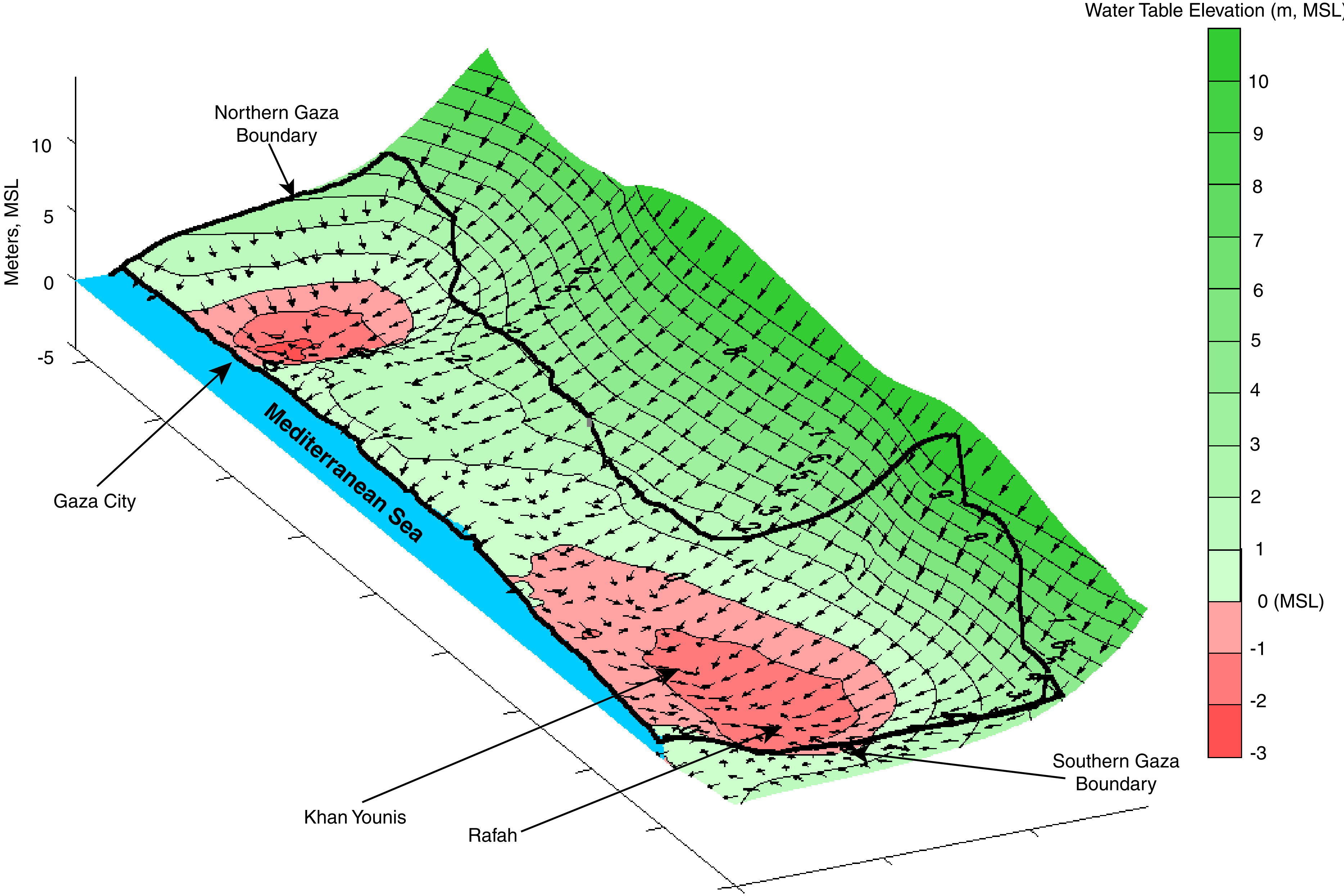


Figure 2: 3-D Representation of Interpreted 1998 Water Table Elevation

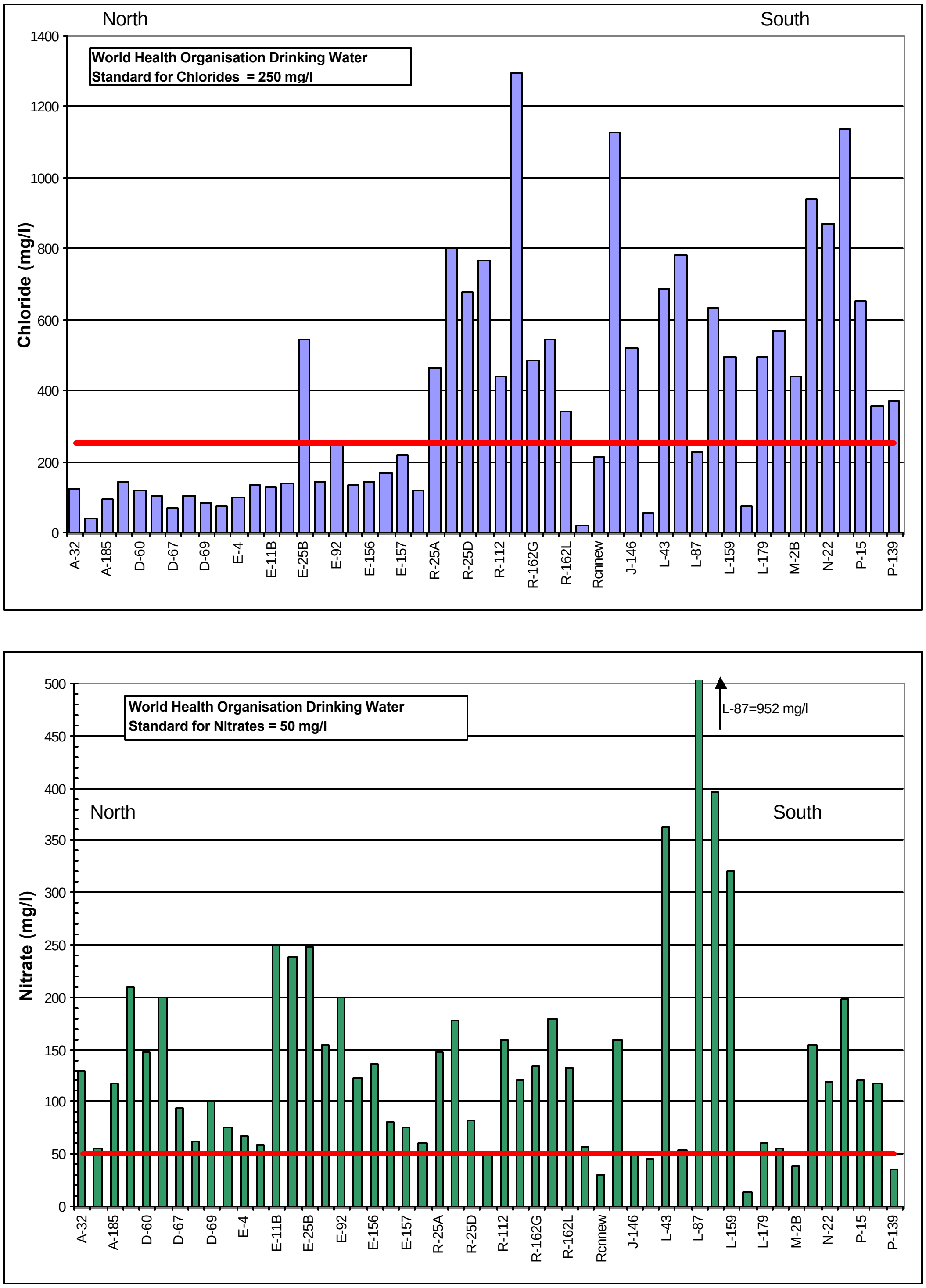


Figure 3: Chloride and Nitrate Concentrations
in Municipal Wells in 1998/1999

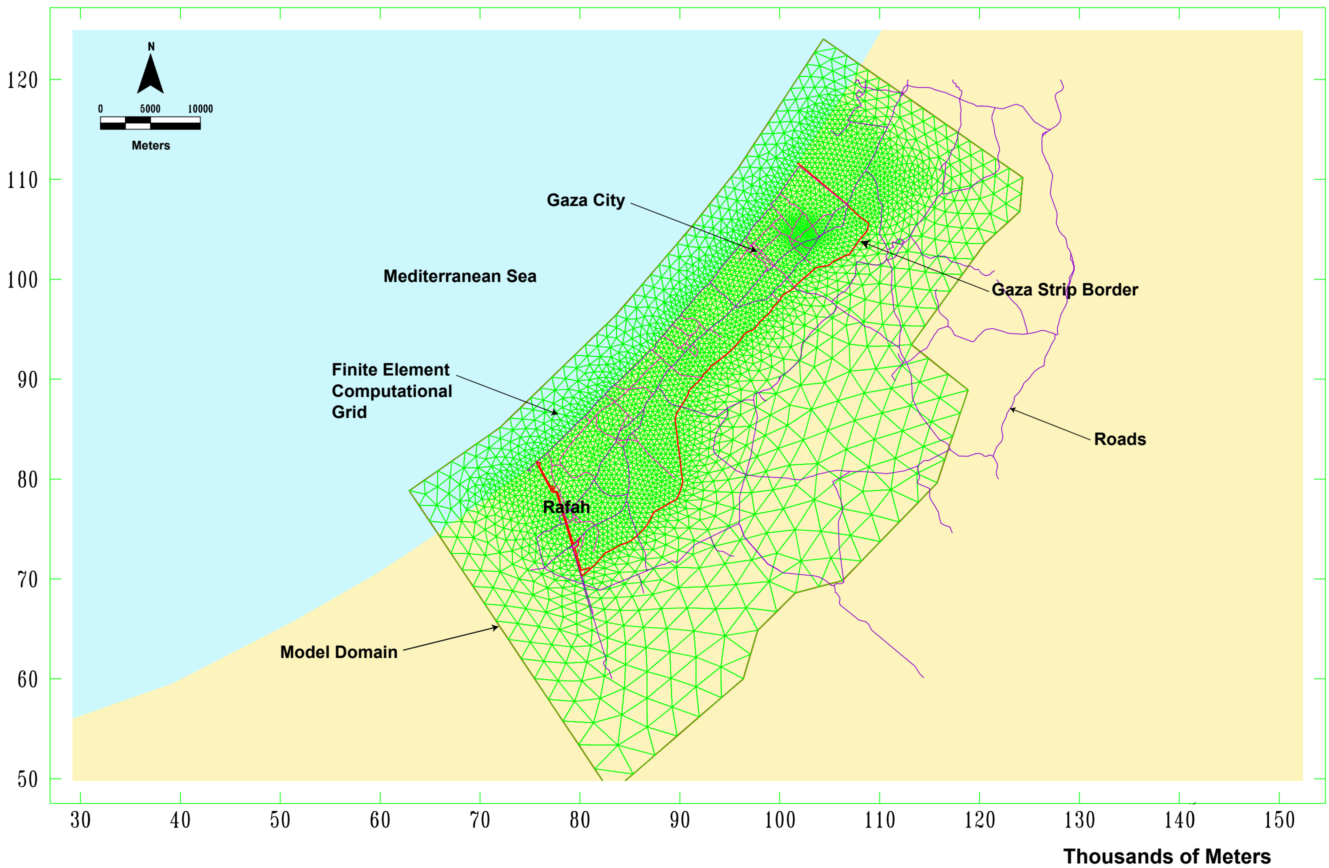


Figure 4: Model Domain and Finite Element Grid

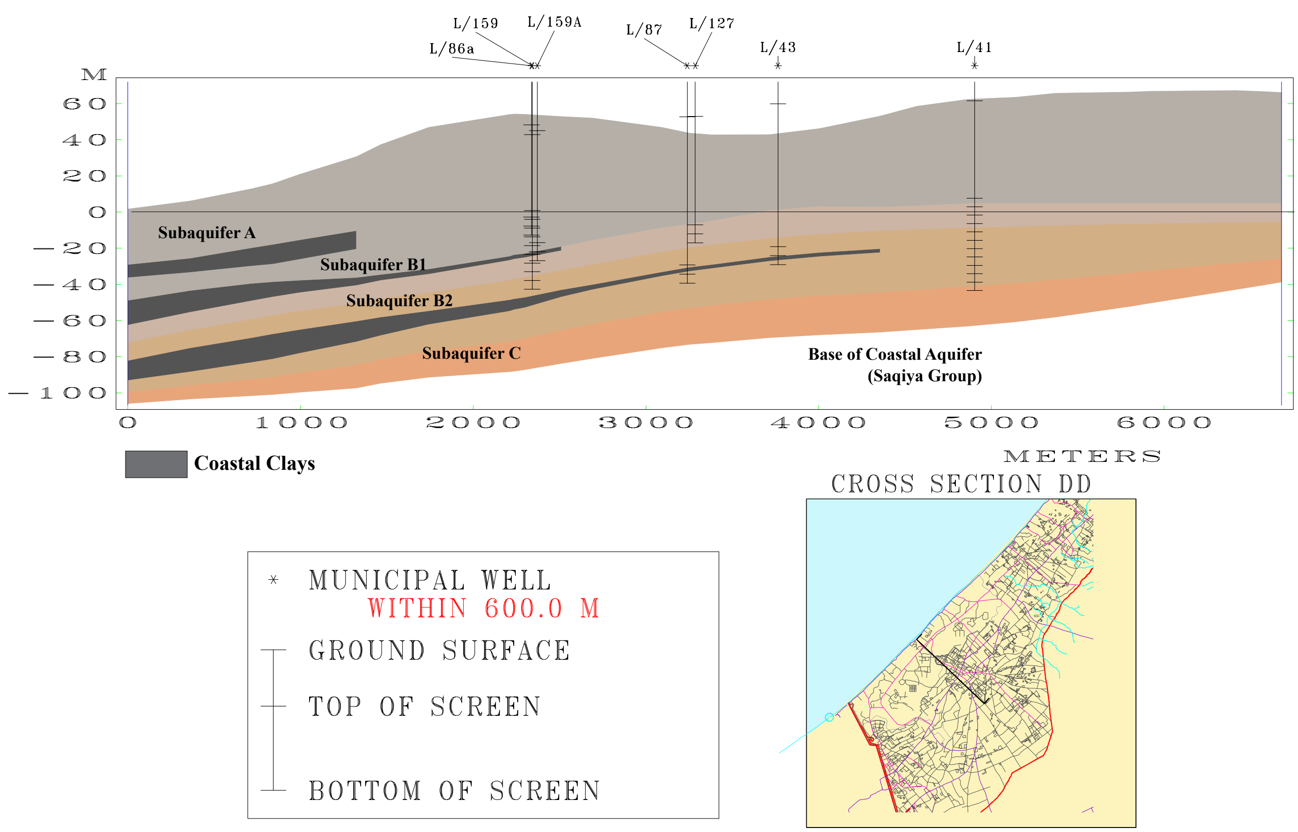


Figure 5: Model Cross-Section (Khan Younis)

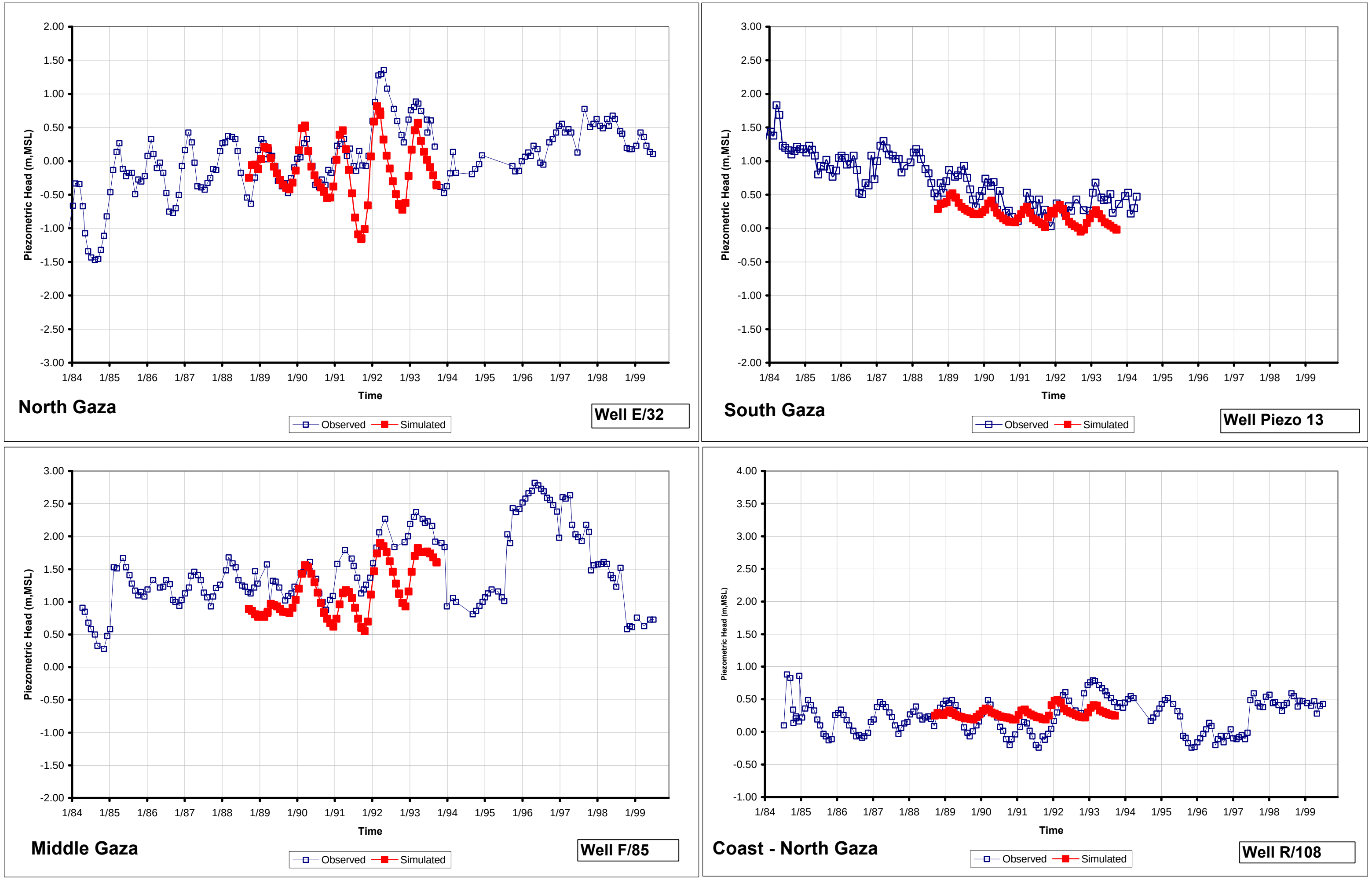


Figure 6:
Comparison of Simulated and Observed Heads
in Example Wells

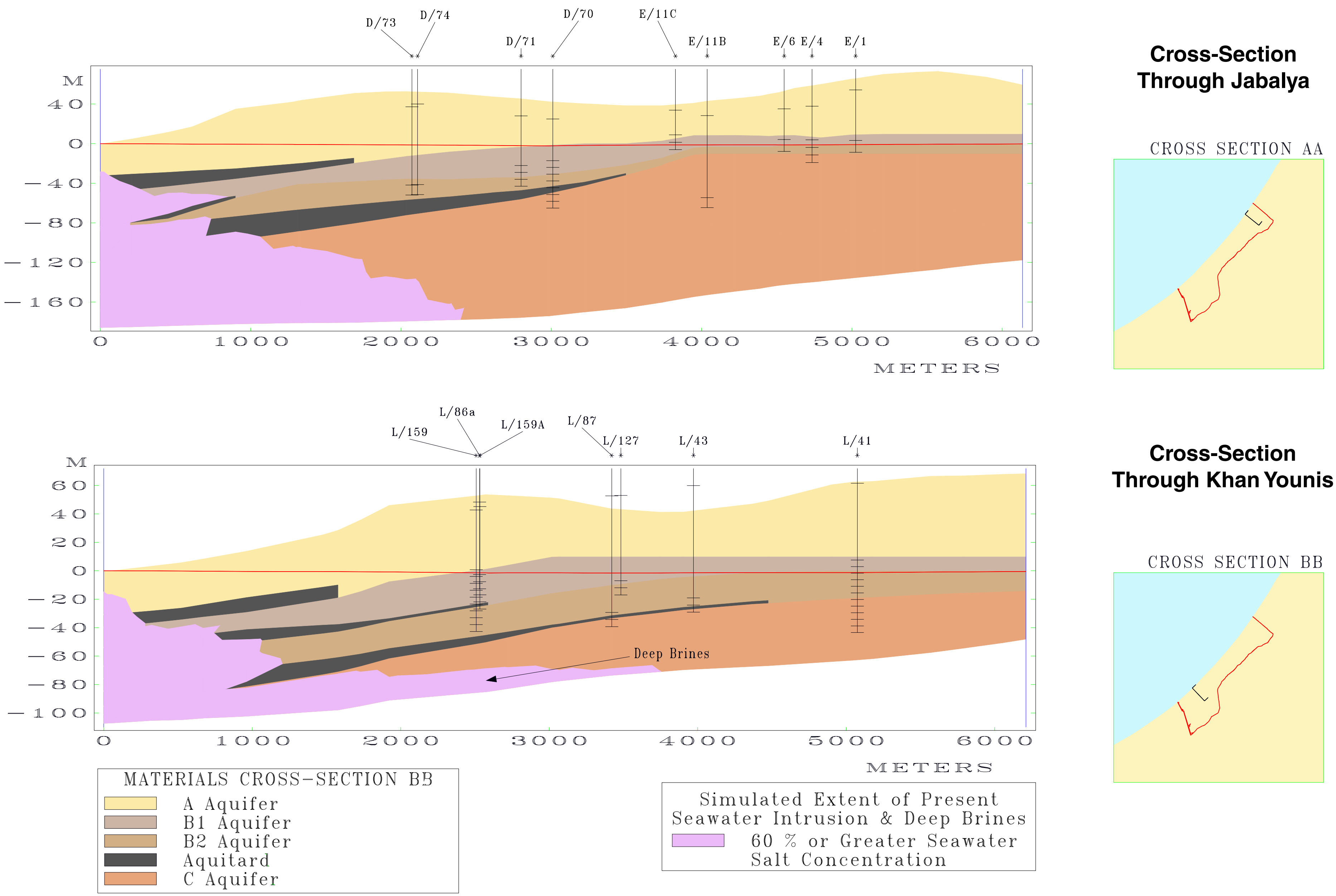


Figure 7: Simulated Extent of Present Seawater Intrusion

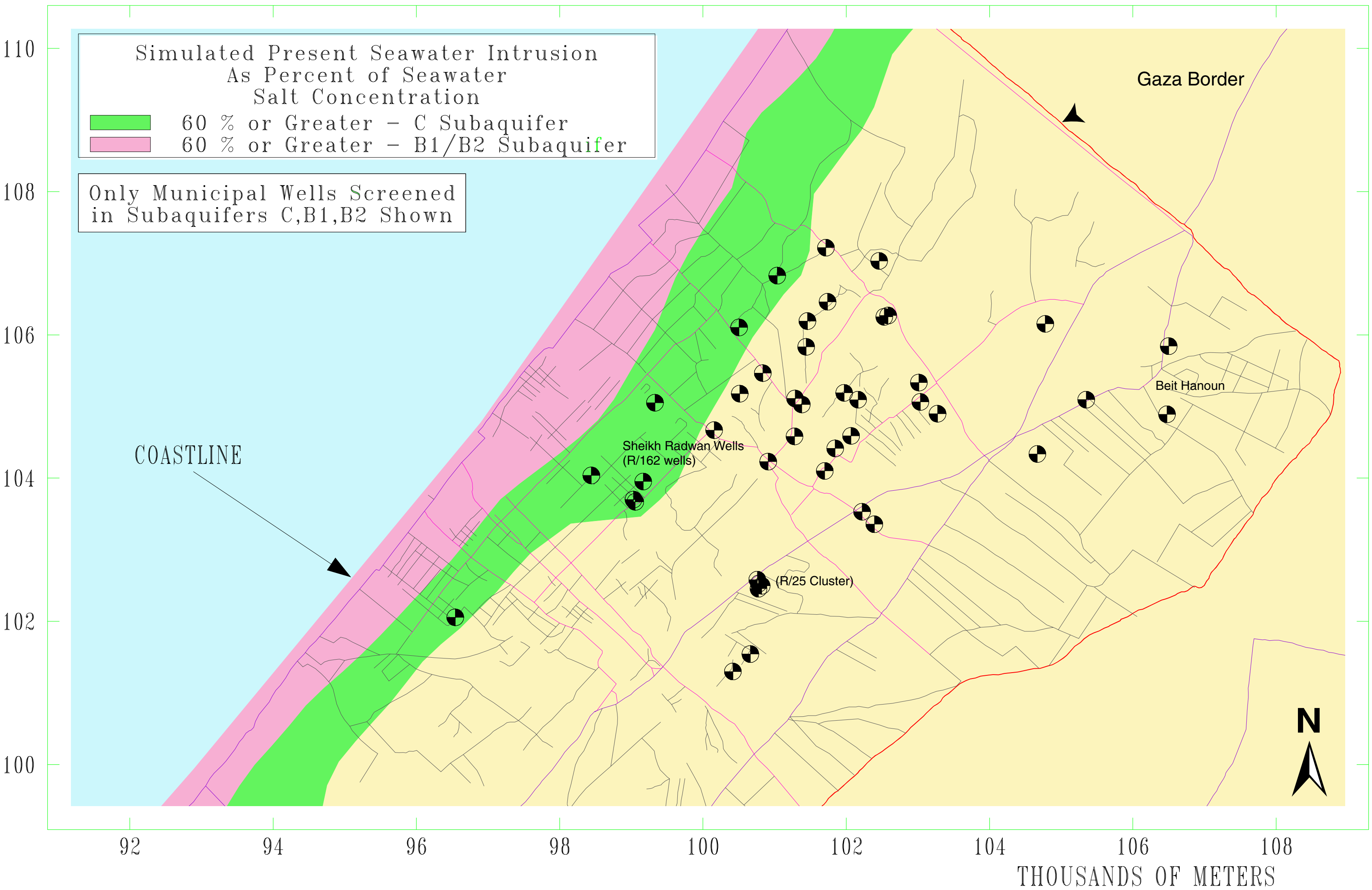


Figure 8: Simulated Extent of Present Seawater Intrusion in Subaquifers B and C (Northern Gaza Strip)

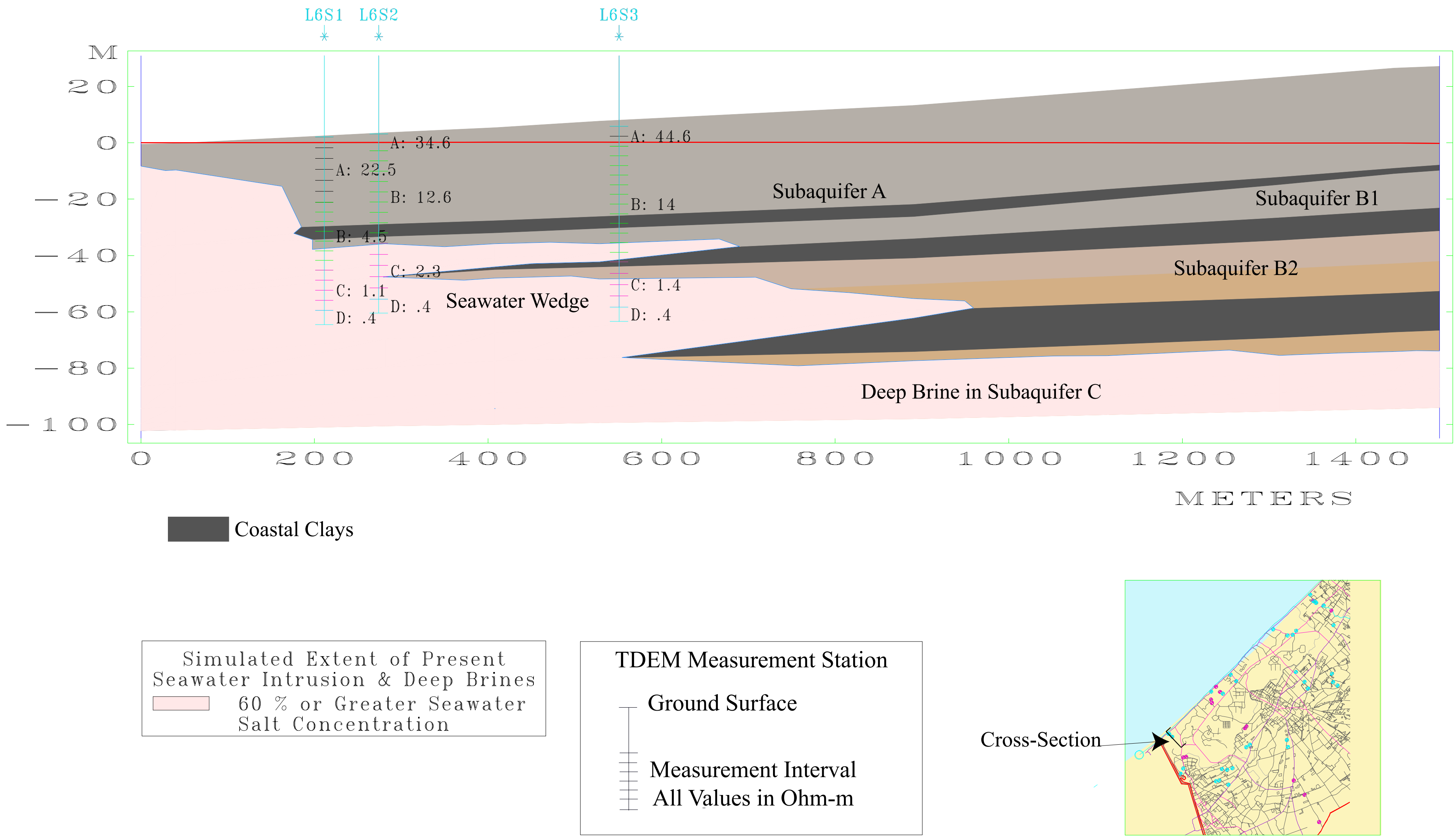
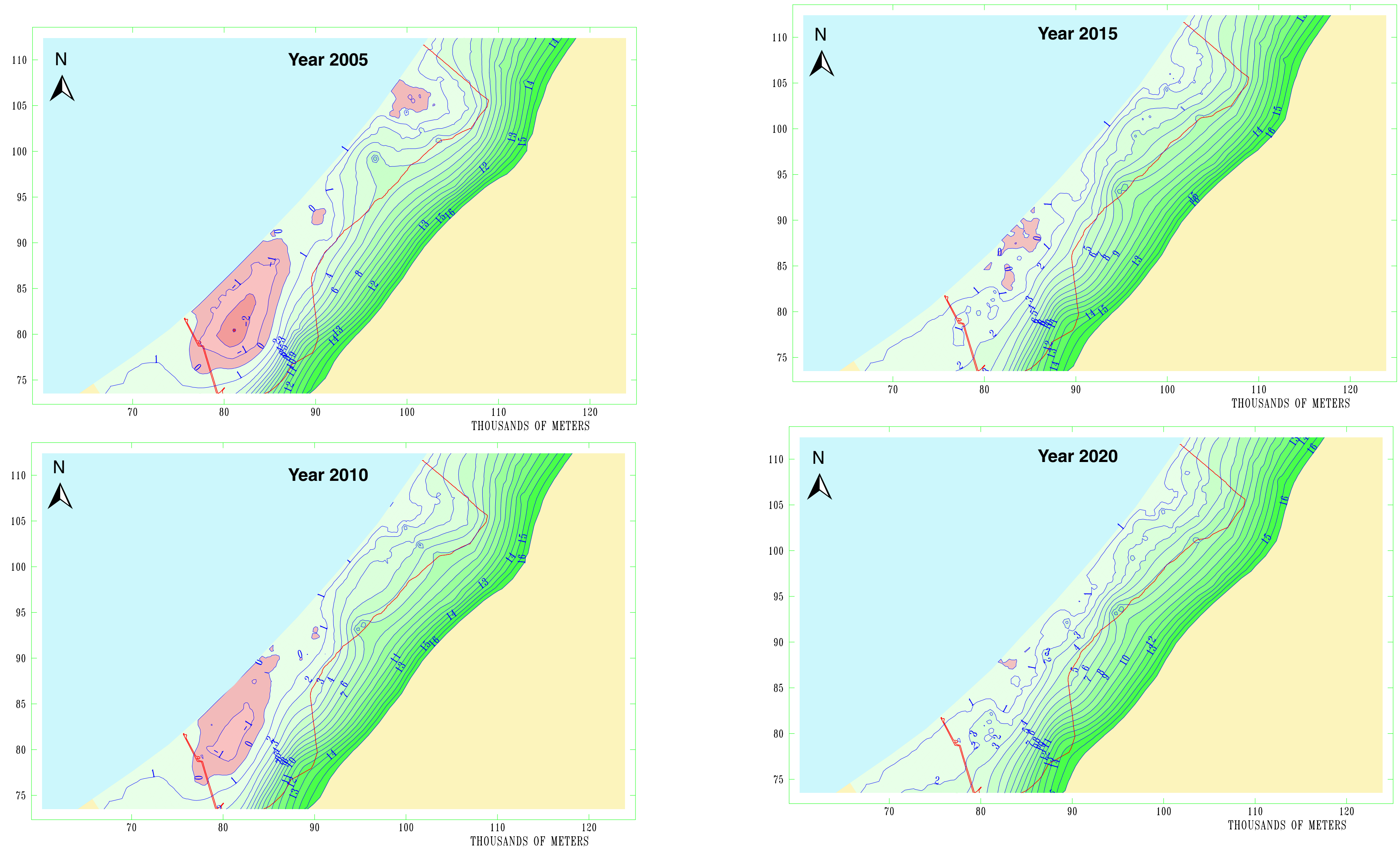


Figure 9: Comparison of TDEM Survey Results and Model-Simulated Extent of Seawater Intrusion Near Coast in Rafah



Note:All contour values are in meters, referenced to mean sea level (m,MSL)

Figure 10: Simulated Water Levels with Implementation of Managment Plan (2000 - 2020)

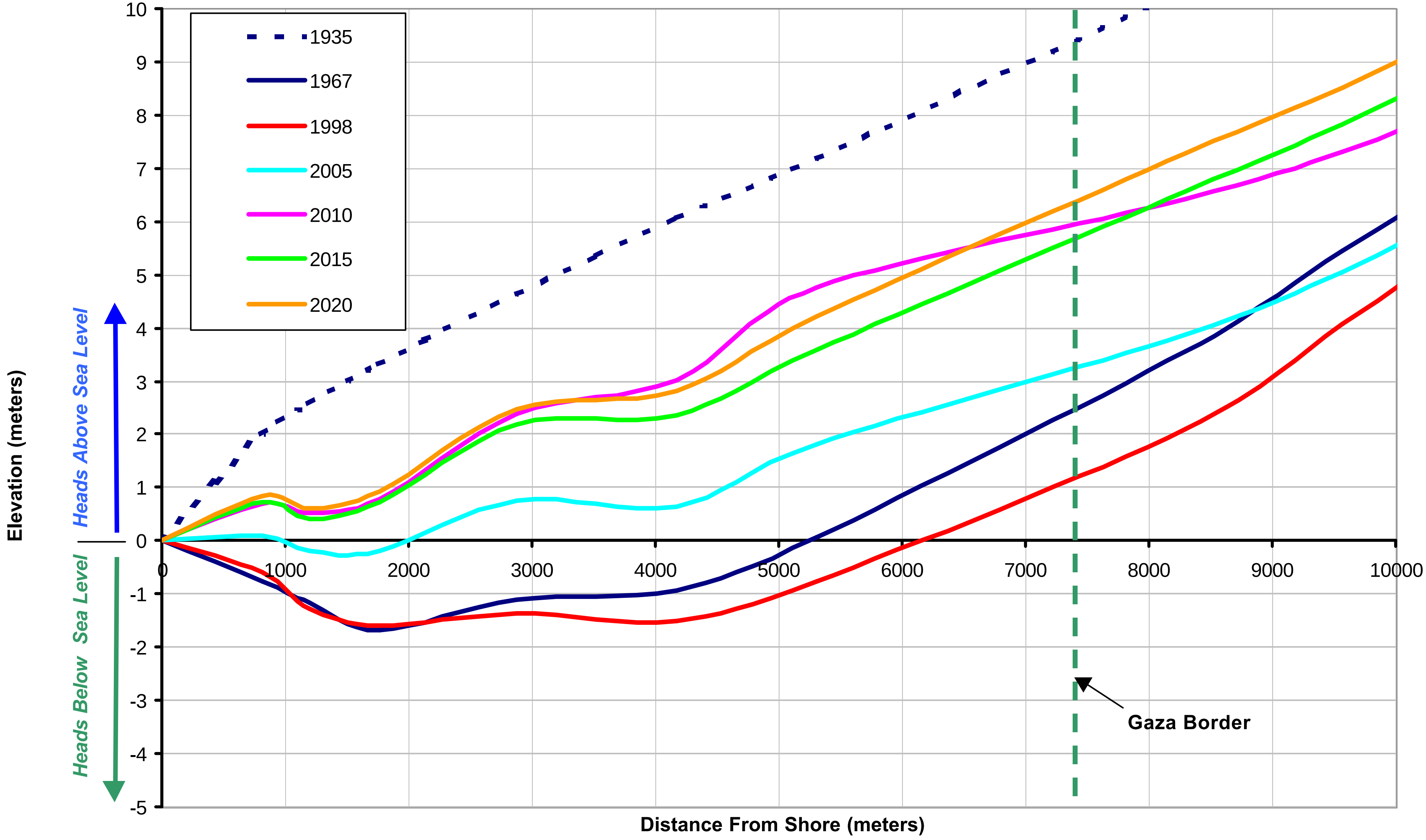


Figure 11:

Simulated Water Table Elevation Through Gaza City: 1935 to 2020

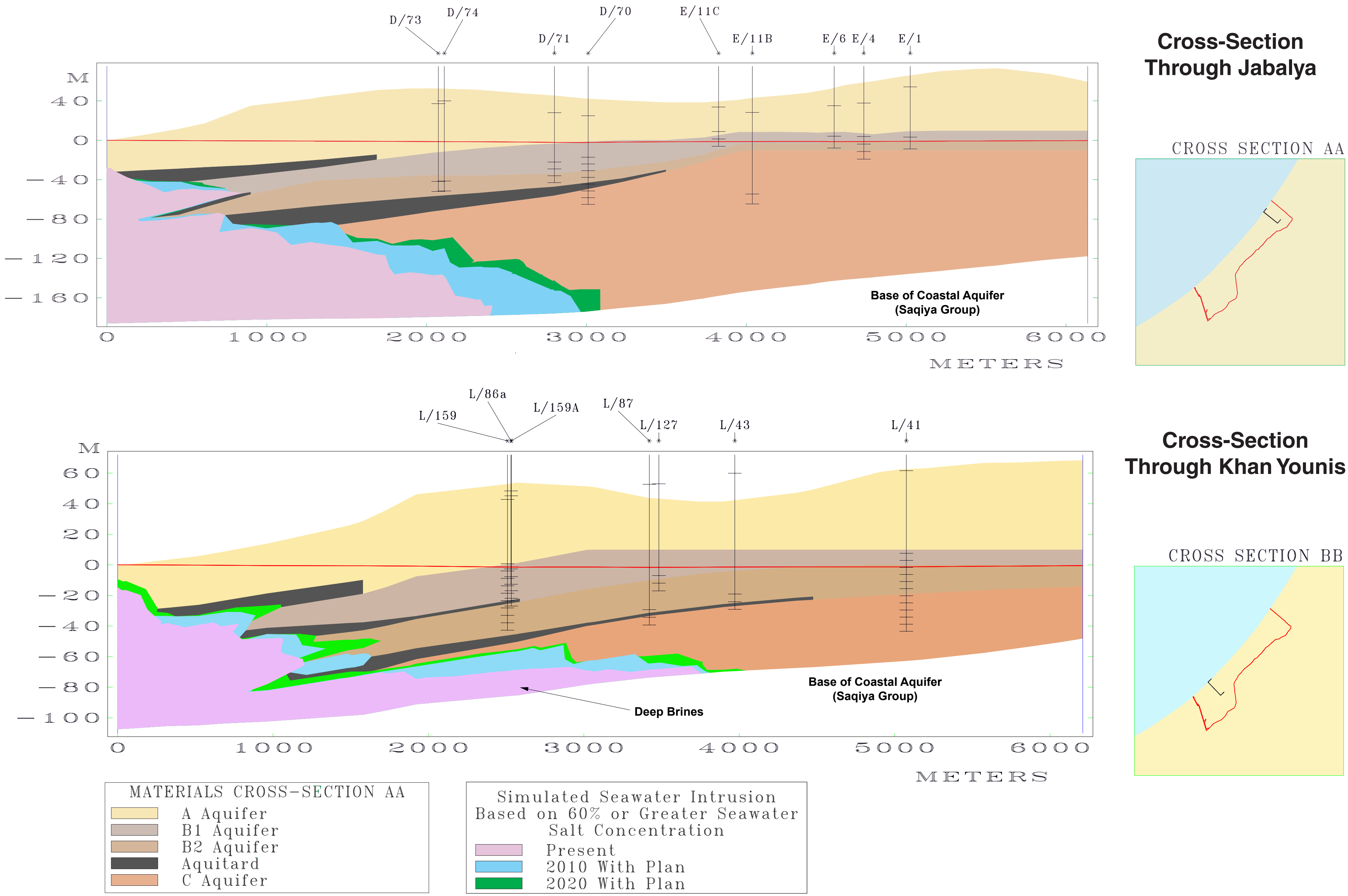


Figure 12: Simulated Seawater Intrusion: Present to 2020 With Implementation of Management Plan