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Final Report

September 1, 1994-February 28, 1997 (Extended)

Monitoring and Modeling of Saltwater Intrusion Implemented to Gaza Strip and Morocco

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Accomplishment

The project involves the collaboration of investigators form four countries/entities, Israel, Palestine, Morocco and the US. During the 2 and ½ years project duration, the following objectives have been accomplished:

Technical Accomplishment

- A groundwater database that includes more than a thousand water wells in Gaza Strip has been compiled based on existing data and updated using newly acquired and sampled data. The database includes coordinates of the wells, maps showing their locations, well pumpage, and water quality history in chloride and nitrate concentrations.
- A smaller region surrounding the Khan Yunis area, where the water quality is still good, has been selected to establish a saltwater intrusion monitoring network. Detailed water quality data has been periodically sampled and compiled. Any observation of water quality deterioration will serve as a forewarning of saltwater intrusion.
- The data compiled have been used to calibrate the computer model, and will also be used as the basis of post-validation in the future.
- A dozen or so geological and hydrogeological maps have been acquired, and specially prepared for the purpose using data from Israeli Hydrological Service, and translated into English from Hebrew.
- The geological and hydrogeological information gathered has been used in a synoptic aquifer characteristics study using an advanced technique known as the map theory. The following information has been gathered based on the statistical interpretation of data: geological structure of Gaza Strip, possible tracks of salinization, preferential water flow channels, and heterogeneity in transmissivity distribution.
- Based on data collection and calibration of historical data using computer simulation, detailed hydrological and hydrogeological data have been compiled for a vertical cross-section of the Khan Yunis aquifer.
- The USGS computer program SUTRA is employed to simulate saltwater intrusion in this cross-section. The simulation include both the historical matching by calibration, and future projection by posing various management scenarios.
- To achieve even more accurate result, a separate computer model using the modified Eulerian-Lagrangian methodology has been constructed. Similar simulation are conducted and result compared.

- The computer models have been transferred to the Palestinian team for future planning and management purposes.
- Simultaneously, the Moroccan team has conducted a study in Moroccan aquifers. Following similar steps as in Gaza Strip, hydrological and hydrogeological data have been compiled and manage using a computer software.
- The Chaouia aquifer has been selected as the modeling site. Due to the different geological and hydrogeological conditions from the Gaza Strip case, a different USGS computer model, known as SHARP, is used for the simulation.
- Also, as a separate effort, computer programs based on the boundary element method have been constructed.
- Simulation has been conducted to calibrate the hydrogeological data.
- Projections based on management scenarios have been conducted.
- PC Windows based computer software have been developed.

Collaboration and Technology Transfer Accomplishment

- The project was planned and conducted as team effort. Several meetings involving all team members, and a large number of meeting involving two or more teams took place.
- Particularly, the Israeli and Gaza teams conducted bi-weekly meetings in which team members works hand-in-hand in the same physical location. These meetings continued until border closing affected physical contact. But communication through electronic means (telephone conferencing, Email) continued.
- Water and hydrogeological data are among the most precious and sensitive data in the region. In the past, these data are rarely shared. In this project, all data and all programs are shared by all members.
- The saltwater intrusion monitoring capability, groundwater database, hydrogeological maps, and modeling capability have been transferred to the Gaza Strip team.

Information Dissemination Accomplishment

- Scientific paper are being prepared to be published in international journals.
- Together with saltwater intrusion expert in the world, a first book on saltwater intrusion, entitled "Saltwater Intrusion in Coastal Aquifers, Fundamentals, Theories, and Applications", is being edited by several of the team members. It will contain 22 chapters written by international experts with a planned size of 600 pages. It is schedule for publication around the end of 1997.

Activities

1994 (September-December)

First Planning Meeting

The first planning meeting was held on September 7-9, 1994, at the University of Delaware. Participants included the Principal Investigators:

- Dr. Alexander Cheng, University of Delaware, USA.
- Dr. Shaul Sorek, Ben-Gurion University, Israel.
- Dr. Abraham Melloul, Hydrological Service, Israel.
- Mr. Samir Shaath, Water Resources Consultant, Gaza Strip.
- Dr. Driss Ouazar, Ecole Mohammadia d'Ingenieurs, Morocco.
- Dr. Leonard Konikow, Geological Survey, USA.

sponsoring agency officers:

- Dr. Herbert Blank, Agency for International Development.
- Dr. Edward Rice, Winrock International.

observer from other organization:

- Mr. Andrew Macoun, the World Bank.

and several local participants.

During the meeting, introductions of hydrogeological conditions in the target areas were respectively given by:

- Dr. Melloul, Israeli Coastal Plain Aquifer, Gaza-Israel.
- Mr. Shaath, aquifer in Khan Yunis area, Gaza Strip.
- Dr. Ouazar, Agadir Aquifer, Morocco.

Other presentations included:

- Dr. Sorek, Eulerian-Lagrangian computer modeling of saltwater intrusion.
- Dr. Konikow, USGS computer modeling capabilities.

The division of work was discussed and coordinated. A detailed workplan was drafted and discussed with AID officers.

Contract Negotiation and Fund Transfer

Contract negotiation and international fund transfer has been time consuming. The primary contract between the AID and the University of Delaware was completed around the end of September, 1994. Negotiation of subcontracts with Gaza Strip, Israel, Morocco, and USGS began soon after that. Due to a variety of reasons such as ensuring the consistency of accounting methods, international fund transfer, authorization of advanced payment, permission for equipment purchase abroad, and administrative delays at the University, most of the subcontracts were finally in place around mid-December, 1994.

Preparatory Work

Despite the delay in subcontracts, preparatory work progressed at a slow pace during that period. Regular bi-weekly meetings were held between Israeli and Gaza Principal Investigators and also Dr. Alex Yakirevich, who would be assigned to the Ben-Gurion University team. Meeting summary was forwarded to the Project Coordinator at the University of Delaware. Student training for computer modeling has started in Morocco.

Once the contracts were fully settled, funds transferred to the designated banks, the work pace has hastened. Purchase of one microcomputer for Gaza Strip and one for Morocco has been approved. Office equipment to improve communication with the US has been purchased in Gaza.

Project Meetings

The Israel/Gaza teams held two joint project meeting during this period. The meeting place was at Ben Gurion University in Sede Boker, Israel. Due to the lateness of the fund transfer, the first two meetings are intended to allow all team members to get acquatinted and the set up the logistics of communication, technical exchange, work coordination, etc.

1995 (January-December)

Second Planning Meeting

Following the original plan, the second Planning Meeting took place in Rabat/Marrakech, Morocco. Members arrived in Morocco at different times. The official meeting time was 4/10/95-4/11/95 when all members were present. The Total time covered by all members was 4/5/95-4/20/95. The participants of the meeting were:

- Alexander Cheng (Univ. Delaware, US)
- Leonard Konikow (USGS, US)
- Shaul Sorek (Ben-Gurion Univ., Israel)
- Alex Yakirevich (Ben-Gurion Univ., Israel)
- Abraham Melloul (Israeli Hydrological Service)
- Samir Shaath (Palestinian Authority, Gaza Strip)
- Driss Ouazar (Ecole Mohammadia d'Ingenieurs, Morocco)
- Khalid EL Harrouni (EMI, Morocco)
- Ahmed Naji (EMI, Morocco)

A number of activities took place during this period. They are given here in the form of an itinerary.

- 4/6/95: The Israeli/Palestinian team (Sorek, Melloul, Yakirevich, Shaath) and Ouazar visited AID Mission in Rabat and discussed the project with Dr. Alan Hurdus.
- 4/7/95: The Israeli/Palestinian team and Ouazar visited Dr. Mohammed Ait Kadi, Director of the Administration for Rural Engineering of the Agricultural Ministry. Dr. Ait Kadi expressed his willingness to assist research aimed at agricultural issues from the aspect of water related problems.
- 4/10/95-4/11/95: The project meeting was held in Marrakech. All team members were present. The work of the previous two quarters were reviewed. Arrangement had been made to ensure the smooth transferring of data to Gaza team in the next phase. The Israeli team will try an exciting new technique of Map Theory to map out the hydrogeological characteristics of the Gaza Strip aquifer with focus on the Khan Yunis area.
- 4/11/95: The team visited Marrakech DRH (Division of Water Resources). Director Abdelmajid El Hebil and several of his engineers briefed the team about their effort in modeling the saltwater intrusion in Sahel aquifer near the Atlantic coast. They have completed USGS Modflow modeling and intended to continue on USGS SUTRA modeling. It was apparent that they ran into some technical difficulty. The team provided some advise and offered Dr. Ouazar's researchers at EMI to help. The Director enthusiastically accepted the offer and stated that he would organize a workshop for his engineers. He invited the whole team to come back to lecture. Mr. El Hebil was also to provide the Marrakech hydrogeological data to the Israeli team to generate maps describing the characteristic of the aquifer.
- 4/12/95: Through Dr. Ouazar's arrangement, part of the team visited an AID sponsored agriculture project ORMVAT in Tadla, managed by Chemonics International. We discussed their water quality problem with Mr. Arthur Belsey, Irrigation Engineer, Mr. Ed Ross, Manager, and his Moroccan counter

part, Mr. A. El Antaki. Due to the presence of salt formation in the region, their irrigation water was of poor quality. The agriculture return flow, further contaminated by fertilizer, pesticide, etc., flowed into a reservoir which was the major water supply for the city of Casablanca. They had purchased computer equipment and GIS software in preparation for organizing water quality data and initiating groundwater modeling. The actual work was not started. Dr. Konikow advised them not to carry out a formation capping project (covering with cement/clay) unless a groundwater study was conducted first, as the capping might not be effective. We had agreed that Dr. Ouazar would send one of his researcher to help them organizing their computer effort.

- 4/14/95: Ouazar, Konikow and Cheng visited AID mission in Rabat and met with Dr. Alan Hurdus and Dr. Mohammed Hanafi. We discussed in particular the possibility of studying the Sahel aquifer, rather than the Agadir aquifer. The reason is that the Sahel aquifer data were well organized by the Marrakech DRH such that our modeling effort will be more effective. The Agadir data was not yet organized. Dr. Hurdus stressed that the Agadir aquifer is of more interest, but gave us some flexibility if the data collection effort would turn out to be too difficult. The team later decided that we would adhere to the original plan of modeling the Agadir aquifer and would also model the Sahel aquifer as an extra effort.
- 4/18/95: Cheng gave a two-hour lecture on ``Saltwater intrusion in groundwater aquifers'' to about 20 engineers at ONEP (Office National de L'Eau Potable) in Rabat.
- 4/18/95: Cheng met with Mr. Driss Lahlou, President, Maghreb Agriculture, in charge of an AID agriculture project, in Casablanca. Mr. Lahlou described his problem of losing several fresh water wells in the farm to salt water. Some practical suggestion of using more wells, each pumping at a lower rate was given. He was asked to further contact Dr. Ouazar at EMI for follow-up.

Several other activities took place which were indirectly related to the project:

- 4/17/95: Ouazar and Cheng held a meeting with Dr. Gedeon Dagan, Univ. Tel-Aviv, Israel, to discuss about a separate project sponsored by AID/CDR on stochastic saltwater intrusion modeling in Israel/Morocco/US/Mexico.
- 4/17/95: Ouazar, Dagan and Cheng paid a courtesy call to Dr. Ben Sari, former Director of Moroccan National Research Council, expressing gratitude for his support. Dr. Ben Sari committed continuing support for water resources activities once his new post would be announced.
- 4/18/95: Ouazar and Cheng visited Dr. Mostafa Terrab, Charge de Mission, Cabinet Royal (King's Science Advisor). A preliminary proposal of forming a Water Consortium in the Middle East and North Africa to promote peace and economical development in the region was discussed with Dr. Terrab. Dr.

Terrab expressed Morocco's interest in serving as mediator in the peace process. He also understood the vital importance of water resources in the region. He would help us promote the formation of such a scientific union.

Project Meetings

The third project meeting between the Israel and the Gaza teams was held in Jerusalem on January 13, 1995. The fourth one took place on March 24, 1995 in Beer Sheva. The original team members were:

- Dr. Shaul Sorek, Ben-Gurion University of the Negev
- M.Sc. Samir K. Shaath, Water Resources Consultant, Gaza Strip
- Dr. Abraham Melloul, Israel's Hydrological Service (IHS), Jerusalem
- Dr. Alex Yakirevich, Ben-Gurion University of the Negev

In the third meeting, two new group members were introduced:

- Dr. Anatoly Krupnik—A mathematician who would be involved in interpreting the field data.
- Dr. Viacheslav Borisov—A modeler who would be involved in programming the Modified Eulerian-Lagrangian computer code.

Main project issues were discussed and work assignments were distributed among group members. The fourth meeting was devoted to discussing progress.

From April on, the bi-weekly meetings between the Israel and Gaza Strip team members (Shaul Sorek, Samir K. Shaath, Abraham Melloul, Alex Yakirevich, Anatoly Krupnik, Viacheslav Borisov) continued at Beer Sheva at roughly two to three weeks intervals. However, toward the end of the year, due to the unfortunate incidence of suicide bombing in Israel, the Gaza/Israel border was closed. The bi-weekly meeting between the Israel and Gaza team meetings were disrupted as Mr. Shaath was not able to cross the border, despite the request made by the U.S. Embassy. The work however was not much affected, as both sides have well divided and coordinated the work. Telephone, fax and Email services were not affected, hence communication continues through these channels.

From August to September, 1995, Dr. Driss Ouazar, Morocco Project Director, visited the University of Delaware, as planned. Drs. Ouazar and Cheng worked on the BEM sharp interface saltwater intrusion programs. Computer equipment was ordered for deliver to Morocco. Literature on saltwater intrusion was collected from the University Library and brought back to Morocco. During September, a meeting was held with Dr. Ismael Herrera of Mexico. It was agreed

that a saltwater intrusion book will be edited. The group involved in this project will take the major responsibility of writing the chapters. Other prominent researchers outside the group will also be invited. This book will be the first scientific book focused on this subject. A major publisher will be contacted.

A second meeting took place during October using the opportunity of the CMWR95 (the 3rd International Conference on Computer Methods and Water Resources), of which both Ouazar and Cheng were Chairmen. The conference was held in Lebanon. Drs. Ouazar and El-Harrouni brought further computer work done by the Moroccan group for discussion. Some of these results were presented at the conference.

Dr. Shaul Sorek, Israel Project Director visited the University of Delaware during early December, 1995. The preliminary results on Eulerian-Lagrangian salt transport modeling were discussed with Dr. Cheng. He also brought the maps and computer database prepared by Mr. Samir Shaath, the Gaza Strip Director, for discussion. The contents of the saltwater intrusion book were further refined during his visit.

1996 (January-December)

Third Planning Meeting

As planned, the third project meeting took place in Israel during the last week of March, 1996. Participants of the meeting were:

- Alexander Cheng (Univ. Delaware, US)
- Leonard Konikow (USGS, US)
- Shaul Sorek (Ben-Gurion Univ., Israel)
- Alex Yakirevich (Ben-Gurion Univ., Israel)
- Anatoly Krupnik (Ben-Gurion Univ., Israel)
- Viacheslav Borisov (Ben-Gurion Univ., Israel)
- Abraham Melloul (Israeli Hydrological Service)
- Driss Ouazar (Ecole Mohammadia d'Ingenieurs, Morocco)
- Samir Shaath (Palestinian Authority) (by telephone link-up)

The host was Dr. Shaul Sorek and the meeting was held at Sede Boker Campus of Ben-Gurion University. A number of other activities also took place during this period. An itinerary of these activities is provided below.

- 3/23/96: A preliminary meeting was held at Sede Boker among Sorek, Yakirevich, Ouazar and Cheng, to coordinate the meeting schedule and presentation.
- 3/24/96: Ouazar and Cheng traveled to Tel Aviv to meet with Prof. Gedeon Dagan and Dr. David Zeitoun of Tel Aviv University. Prof. Dagan is an expert in stochastic modeling of saltwater intrusion. The significance of hydrogeological uncertainties in prediction salt/fresh water interface was discussed.
- 3/25/96: Project meeting was held at the Desert Research Institute of Ben Gurion University, at Sede Boker. All members were present, except for Mr. Samir Shaath. Mr. Shaath's presence was prevented by the border closing between Israel and Gaza Strip due to recent terrorist suicide bombing incidents in Israel. Despite the intervention of Dr. David Mulenex, Science Attaché of the US Embassy, Mr. Shaath was unable to cross the border. Luckily, telephone link-up between Israel and Gaza was unaffected. Mr. Shaath stayed in contact and participated through telephone. In the meeting, each team member provided a progress report. Technical difficulties in computer simulation and field data sampling were discussed and suggestions provided by other members. In addition to technical exchanges, two operational resolutions were reached:
    1. Due to the initial 4-month delay in subcontract negotiation and fund transfer, most team members found that it was necessary to request a time extension to complete the project. After consulting with all teams, it was decided that a one-time six-month extension will amply cover the need of all teams. A resolution was passed that a request for a six-month no-cost extension should be submitted to AID as soon as possible.
    2. As the project is nearing its completion, a public presentation for technology transfer should be planned. It was decided that all possible resources within or without the region should be sought for such activities. In particular, a Saltwater Intrusion Workshop would be planned. The Workshop would not only disseminate the practical knowledge gained within the project, but also provide a general training session for key technical personnel in the region. The Workshop will assemble about one dozen lecturers consisting of world renowned experts and members of this team to provide a one-week training and presentation session. To our knowledge, this workshop would be the first one ever assembled on the subject of saltwater intrusion in the region. The Workshop was targeted for November, 1996, in Morocco. Funds would be raised from the Marrakech Provincial Division of Water Resources, the Office of National Potable Water (Morocco), the Middle East and North Africa Economic Summit

Secretariat, and USAID. A proposal to USAID for supplementary funding would be submitted at an appropriate time.

- 3/26/96: A field trip was conducted through the Dead Sea Valley to understand the climate, hydrology, geology and water resources of Israel.
- 3/27/96: A meeting was held with Dr. Mulenex, Science Attaché, at the US Embassy, Tel Aviv. Participants were Sorek, Yakirevich, Ouazar, Konikow, Dagan and Cheng. In addition to the exchange of technical and general information of saltwater and other water resources related issues in Israel, Gaza Strip and West Bank, Dr. Mulenex provided the names of a few key persons in Palestinian Authority to establish contact.
- 3/27/96: Sorek, Yakirevich, Ouazar, Konikow and Cheng then visited the AID Mission at Tel Aviv to hold a meeting with Mr. John Starnes and his colleague. Again, technical and general information was exchanged.
- 3/27/96: Sorek, Yakirevich, Ouazar, Konikow and Cheng visited Technion (Israel Institute of Technology) at Haifa. The Team was hosted by Prof. Jacob Bear, Dean of Civil Engineering, and Prof. Uri Shamir. Issues of regional cooperation in water resources, sharing water data, and the formation of MENA Water Consortium and MENA Waternet were discussed.
- 3/27/96: Ouazar and Cheng continued with a meeting with Prof. Bear on the planning of Saltwater Intrusion Workshop.
- 3/28/96: A field trip was conducted to the pumping station for the National Water Carrier. The trip was extended to the Sea of Galilee, which was used as a fresh water reservoir for water supply in Israel, the Golan Height that served as the watershed of Galilee, and the Yarmouk River basin.
- 3/29/96: Ouazar and Cheng were joined with Dr. Eilon Adar for a field trip to the ancient run-off irrigation system in the Negev dessert and the research project to re-establish such irrigation system for run-off farming.

Project Meetings

The Israel-Gaza team meetings continue to be disrupted by the border crossing. However weekly exchanges are maintained through telecommunication facilities.

During July-August 1996, Dr. Ouazar visited the University of Delaware to conduct the collaborative part of work, which include boundary element sharp interface saltwater intrusion modeling and the windows software development.

In December 1996, Dr. Sorek and Dr. Cheng met at Delft Technical University in the Netherlands where Dr. Sorek was visiting. An project overview was conducted to ensure the on-time delivery of the complete work.

During September-October 1996, The MERC Program commissioned an evaluation team, consisting of Carl Dutto, Kenneth Hollett, Herbert Blank and Dwight Walker, to evaluate the project. The team visited Morocco, Israel and Gaza Strip. A *Final Project Evaluation* was filed at MERC by the evaluation team.

1997 (January-February)

The original project duration was September 1, 1994-August 31, 1996. A six-month extension was sought and granted by MERC. The delayed work was largely completed in a four-month extension period. The final two months in 1997 was used for report writing.

Methods of Work

Water Quality Monitoring

Water quality monitoring was conducted in Khan Yunis City and the surrounding areas. The monitoring serves two purposes: (i) it serves as an early warning system of the deterioration of water quality, and (ii) it is used to calibrate the numerical model which will be used for future planning and management purposes.

The field work included locating water wells (municipal and private), collecting water samples, recording pumpage intensity and frequency, and testing for chloride and nitrate concentration. The wells were selected with the intention to form a dense network for later numerical simulation purposes. Some of these data were tabulated as shown below:

Well Name	Pumpage	Frequency	Chlorides	Nitrates
	m^3/hr	hrs	mg/ℓ	ppm
Al-Amal	90	24	374	203
Al-Saadah	100	24	876	275
Al-Ahraash	80	24	524	227
Al-Jadid	140	24	445	54
Ayah	80	24	624	228

All these wells were municipal wells in or near Khan Yunis City.

For the rest of Gaza Strip, general information and data related to water quantity and quality were searched and collected from various sources at different locations throughout Gaza Strip. Some of the data represented chemical tests conducted in recent years, while other data dated back 8 years. From the information, it was found:

Chlorides

WHO standard for chloride concentration was 250 mg/ℓ. We found a wide range of concentration in Gaza Strip. For example Cℓ was about 50 mg/ℓ to 60 mg/ℓ at Beit Lahia (North of Gaza Strip), and about 1,300 mg/ℓ at both Bani Suhaila and Abasan Al-Kabirah villages (in the vicinity of Khan Yunis). In general, the salinity levels showed dramatic increase in recent years.

Nitrates

The nitrate levels were generally high. In fact there were relatively few wells showed nitrate levels below WHO standard. For example, in some private wells in Khan Yunis, levels as high as 400 ppm were detected.

The monitoring continued through the project. The complete data, which is not proper to be presented here, are organized using a software developed by UNDP, known as Groundwater for Windows. Identical copies of the data are stored with the Gaza, the Israel, and the US teams.

Geological and Hydrogeological Maps

- Prepared four working maps with 1: 20000 scale to mark most of the existing wells.
- Prepared figures of hydrogeological cross-sections.
- Prepared a map of 1: 50000 scale on which we assembled information on the width of lithological layers, location of incoming chlorine fronts and typical hydrogeological sections.
- Prepared maps of lithological variations (sand, clay) which might suggest correlation to the spatial distribution of transmissivities. Later on, with prescribed transmissivities, one could build the correlation function with lithological data which could then be used to reconstruct the spatial distribution of transmissivities.
- Prepared maps showing zones of strong inhomogeneities which might suggest preferential flow paths. This was build on an assortment of different qualitative concepts.
- Prepared diagnostic map describing spatial distributions of local (phreatic and confined) aquifers.
- Prepared maps describing rate variations of chloride concentrations. Such maps might suggest domains with different aquifer recharge ,e.g., natural replenishment through the unsaturated zone or subsurface recharge.
- Prepared map pointing at possible principle axes of transmissivities.

Computer Simulation

Specific Objectives

To achieve the goal of the research we had set ourselves to accomplish the following objectives:

1. Characterization of the Khan Yunis area as part of the Gaza Strip aquifer.
2. Formulation of the saltwater intrusion problem.
   a. 3-D formulation.
   b. Simulations for a vertical cross section.
   c. horizontal plane formulation.
3. The Modified Eulerian Lagrangian (MEL) scheme.
   a. 3-D formulation.
   b. Horizontal plane formulation.
4. Development of the horizontal plane computer code.
5. Performance evaluation by running bench-marks.
6. Sensitivity analysis of the MEL horizontal plane model.
7. Calibration of the MEL horizontal plane model.
8. Simulations of the MEL horizontal plane model for different stress paterns.
9. Possible extension of the MEL horizontal plane code to a 3-D code.

Thus far, during the covered period, we had accomplished the, above mentioned, first seven objectives.

Material and methods employed

Gaza Strip aquifer characterization. The lithologic sequence of the coastal aquifer of the Gaza Strip consists of calcareous sandstone of Pleistocene age, intercalated by silt and clay layers of continental and marine origin, and underlined by the so-called "Saqiye" marl beds of marine origin. As usual, this type of aquifers is highly heterogeneous due to the cooperative influence of the following factors [1] to [3]:

- Lithologic (high spatial variability of the silt, clay and sandstones layers thickness).

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- Diagenesis (cement re-sedimentation, high spatial variability of the secondary porosity).
- Consedimentation tectogenesis that may be reflected in various types of sediments their lithologic composition (high spatial variability of the silt, clay, sandstones and cement matter participation).

These processes form a system of two types of zones:

a. High transmissivity latent drainage system characterized by preferential flow channels with local and regional recharge.

b. Relatively stagnation separated zones with only local recharge.

Preferential flow channels may be presented as high thickness "sandstones tracers", fractured zones, zones of low cement participation. Stagnant zones may be "sealed" by the system of clay layers or high cemented sandstones.

On one hand, these preferential flow channels may be responsible for creation of "inside lateral recharge system". Exhaustion of these channels recharge sources may be responsible for the possible degradation of water quality of Gaza Strip coastal aquifers.

Yet, these channels interconnections with the Mediterranean sea in the west part of aquifer, may be responsible for the creation of "inside lateral salinization system" in the Gaza Strip coastal aquifers. Any action aimed at improving the control over the processes of groundwater flow and pollution requires a better understanding of the system's structure, aquifers subdivision, clay layer development and heterogeneity distributions.

Our objective was to develop a methodology to define qualitatively the.

1. Geological structure of the Gaza Strip coastal aquifer of the investigated area.
2. Possible tracks of salinization.
3. Preferential water flow channels.
4. Heterogeneity distributions.

To do this, we utilize information derived from lithologic data and employ conventional methods implemented in oil fields exploitations [4] to [9].

In hydrogeology practice we usually refer to pumping tests to assess local heterogeneity characteristics, [4] . However, since such tests may show high local transmissivity even in sealed zones, this information may not be representative for sand aquifers.

Due to lack of pumping tests data and high variability of their results in time and space, we suggest instead to apply methods practiced in oil exploitations which are facing analogical situations.

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Heterogeneity of the sedimentation type. For this type of heterogeneity we refer to lithologic based parameters which infer to hydrogeological macro heterogeneity and can be highly correlated with transmissivity values [9]. These parameters are:

I. Parameters associated with clay:

$T_1 \equiv 1/(Number\ of\ Clay\ Layers + 1)$

$T_2 \equiv 1/(Total\ Clay\ Thickness)$

II. Parameter associated with sand:

$T_3 \equiv Effective\ Thickness$

III. Relative parameters:

$T_4 \equiv (Total\ Sand\ Thickness)/(Total\ Clay\ Thickness)$

$T_5 \equiv (Total\ Sand\ Thickness)/(Number\ of\ Clay\ Layers)$

$T_6 \equiv (Total\ Sand\ Thickness)/(Number\ of\ Clay\ Layers + 1)$

IV. Combined parameters:

$T_7 \equiv (Total\ Sand\ Thickness)/(Total\ Clay\ Thickness * Number\ of\ Clay\ Layers)$

$T_8 \equiv 1/(Total\ Clay\ Thickness * Number\ of\ Clay\ Layers)$

These parameters are used to characterize the heterogeneity of geological structures, the location and assessment of flow boundary conditions in saturated aquifers.

Results of implementing some of the methods in the proposed project is exemplified for the Gaza Strip Coastal Aquifer. Lithological profiles for Khan Younis regions were digitized and some of the lithological parameters T_1 to T_3 were mapped.

Figures 1 to 3, describe the contour maps of the parameters, from which we note the heterogeneity at the vicinity of the Khan Younis area. From these figures we note the two ("T" like, NW and NE) anisotropic directions.

Estimation of transmissivity based on lithological data. On the basis of the lithological based parameters using statistical correlations, we may construct the function between transmissivity and thickness, for every sand subaquifers namely,

$$Transmissivity = F\ (SubaquifersThickness)$$

These empirical relationships, utilizes a large amount of core data that was already accumulated during many years of boring and exploitation.

Under conditions of the Khan Yunis scarce core data we applied correlations, created for oil calcareous cemented sandstones aquifers including clay and marl layers. This was done using statistic dependencies created, [13], for groups of oil fields in Bashkiria and Tataria. The result of these estimations are presented in the form of a transmissivity map for the coastal aquifer.

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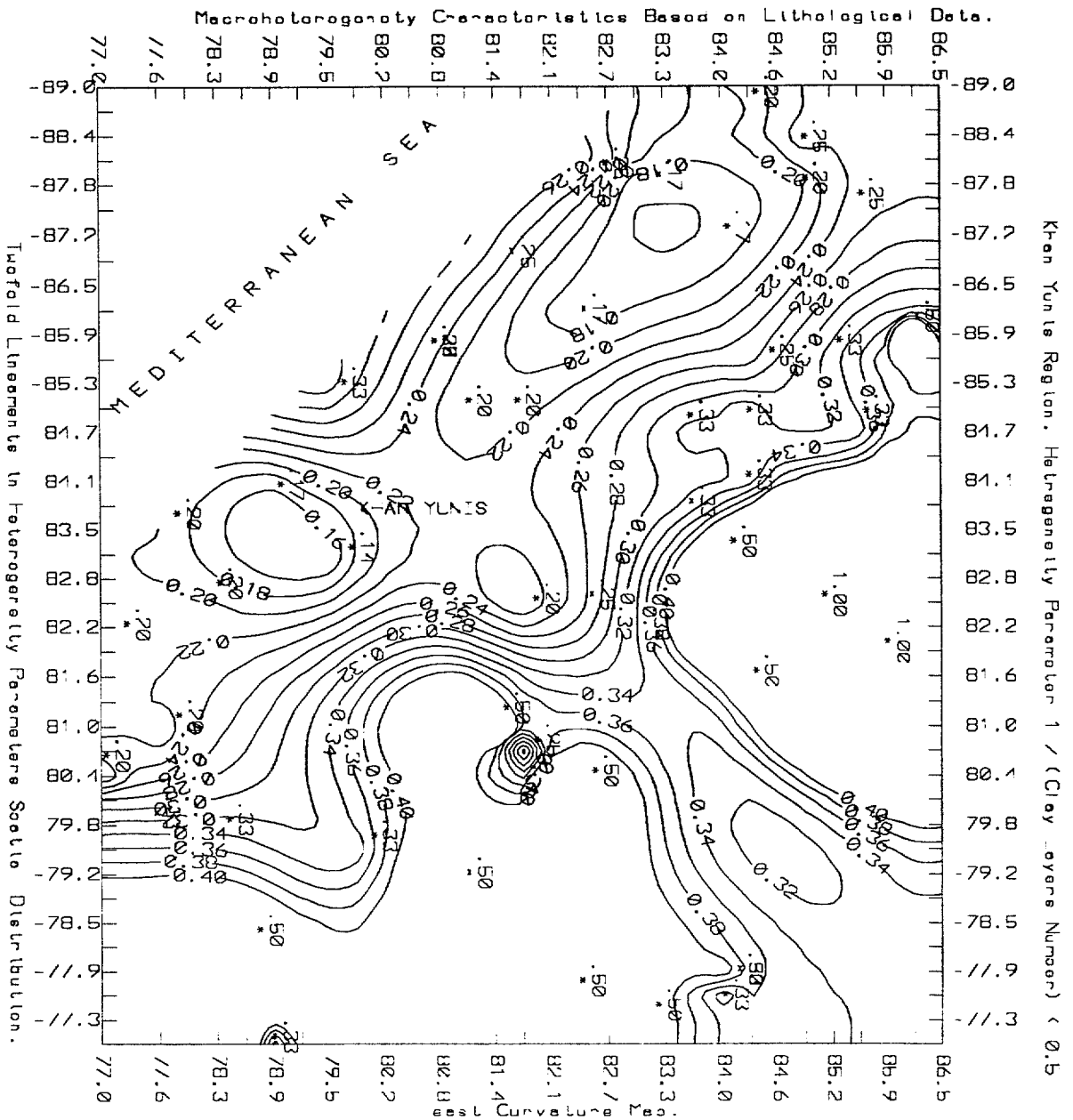


Figure 1: Map of the T_1 heterogeneity parameter

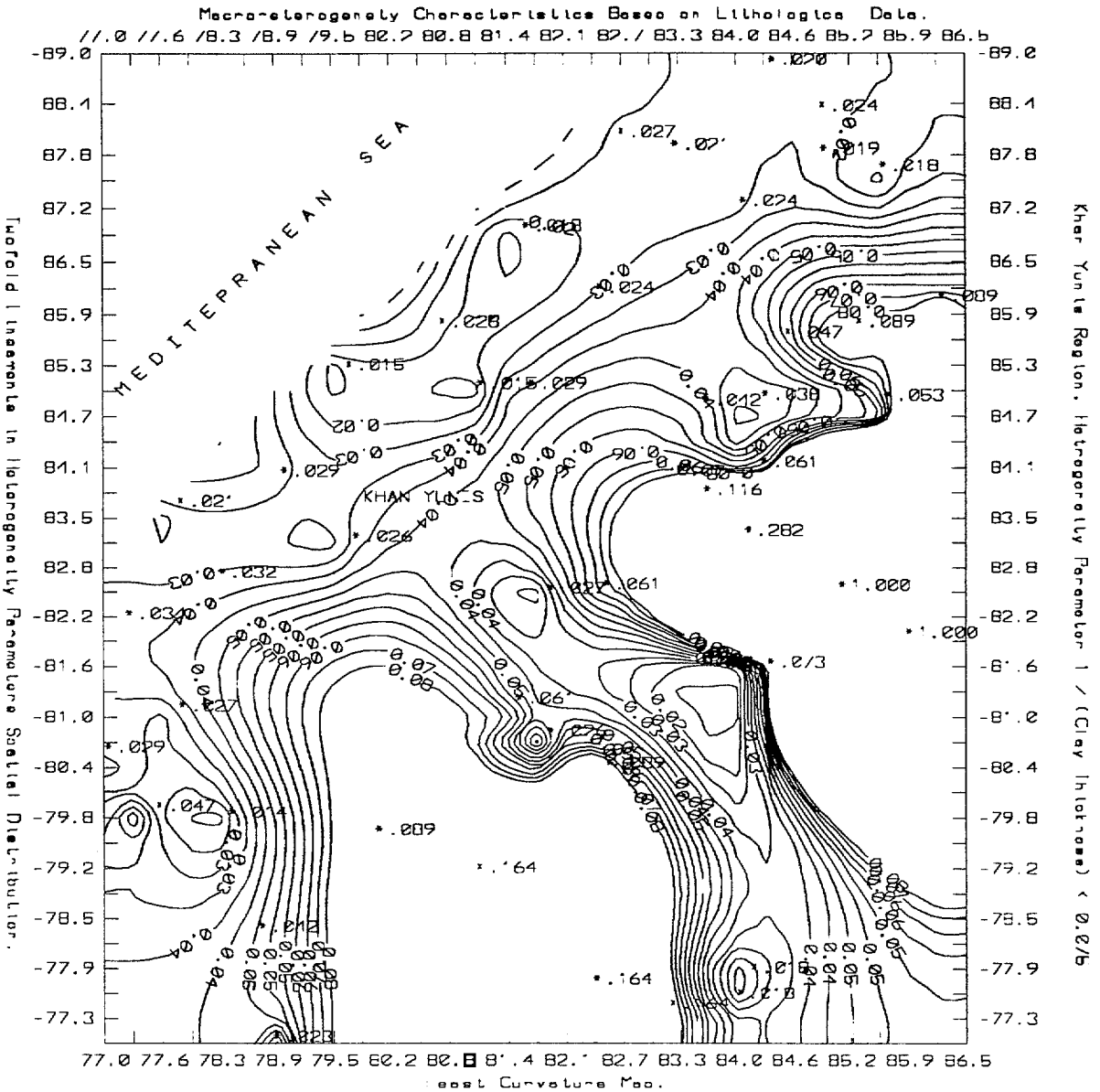


Figure 2: Map of the T_2 heterogeneity parameter

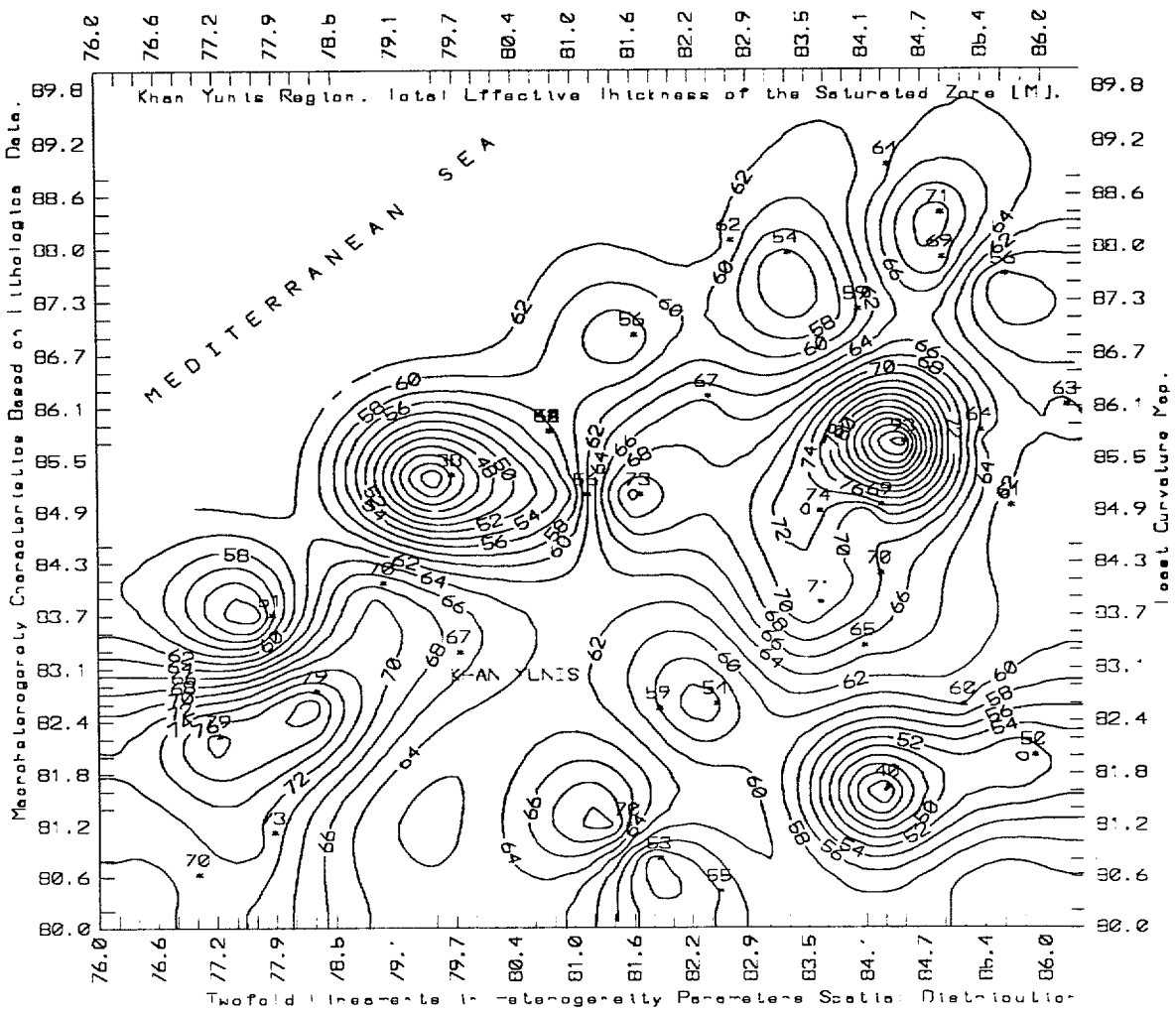


Figure 3: Map of the T_3 heterogeneity parameter

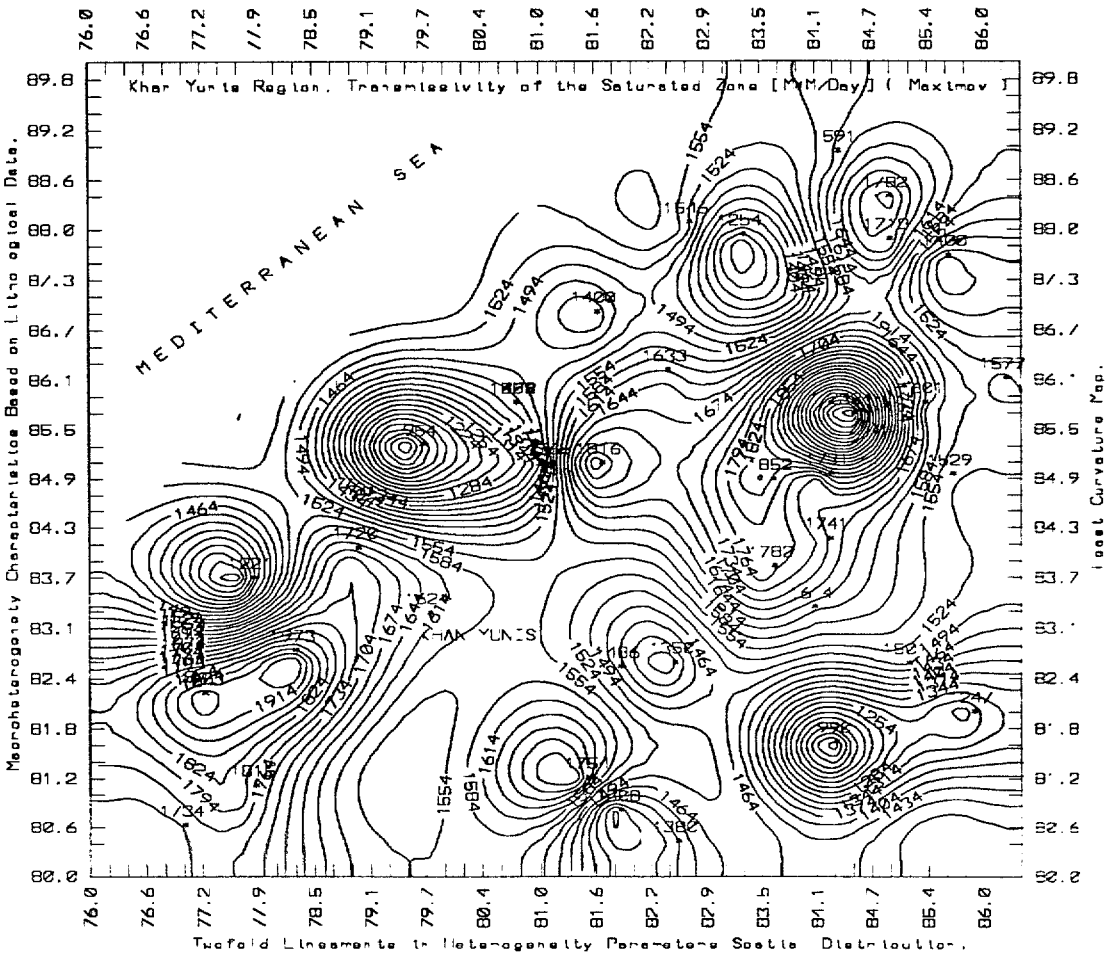


Figure 4: Estimated transmissivities based on lithologic data

For the Khan Yunis region, we estimated and mapped transmissivities, based on lithologic core-data. These results are presented in Table 1 and in Figure 4 which depicts the transmissivity map with "T" like, NW and NE anisotropic directions.

This transmissivity map was created on the basis of the correlation described by Maximov [13], based on huge oil field core data, which is analogous to the Khan Yunis aquifer. This correlation was adapted to the coastal plane aquifer of Israel, and calibrated by accepted typical transmissivity values of Israel's coastal aquifer. Using this correlation for each of the j sands subaquifers, transmissivity was estimated by,

$$T_j = \begin{cases} 39.2\left(.0328 + .0224H_j + .1106H_j^2 - .0049H_j^3\right) & if \quad H_j < 12\,Meter \\ 25H_j & if \quad H_j > 12\,Meter \end{cases}$$

where H_j denotes the saturated thickness of the sands subaquifer.

The transmissivity T of the total thickness of the saturated zone was estimated by,

$$T = \sum_j T_j$$

The Effective Average Permeability K was estimated by,

$$K = \frac{\sum_j T_j}{\sum_j H_j}$$

Table 1: Transmissivity of the Khan Yunis area

East-West x (KM.)	North-South y (KM.)	Saturated Thickness (M.)	Transmissivity ($M.^2/Day$)	Average Permeability (M./Day)
77.05	80.65	70.35	1734	24
78.40	79.85	38.18	937	24
77.60	79.93	70.43	1760	25
78.74	78.46	63.50	1587	25
78.90	77.10	50.58	1245	24
77.28	82.28	78.91	1972	25
78.30	82.80	78.91	1972	25
77.85	81.15	72.62	1815	25
78.40	79.85	40.73	1001	24
80.04	79.64	60.25	1506	25
81.13	79.18	63.59	1589	25
82.40	77.81	42.50	1062	25
83.25	77.50	37.34	933	25
77.84	83.68	50.91	1220	23

East-West x (KM.)	North-South y (KM.)	Saturated Thickness (M.)	Transmissivity ($M.^2/Day$)	Average Permeability (M./Day)
80.75	85.85	63.64	1556	24
79.00	84.05	69.82	1720	24
79.80	83.25	66.95	1624	24
81.56	81.24	70.17	1754	25
81.90	80.84	53.10	1307	24
82.55	80.45	55.19	1379	25
84.15	77.95	6.67	105	15
83.99	77.63	6.70	105	15
79.72	85.33	38.18	954	25
80.75	85.85	40.73	1018	25
81.15	85.10	56.00	1365	24
81.70	85.10	72.57	1815	25
81.90	82.60	59.44	1485	25
82.52	82.65	54.36	1349	24
84.35	81.68	39.60	990	25
84.15	77.95	11.76	294	25
81.65	86.96	56.00	1400	25
80.75	85.85	56.00	1400	25
82.45	86.25	66.72	1633	24
83.63	84.90	74.08	1851	25
84.29	84.97	69.23	1730	25
83.64	83.82	71.27	1781	25
84.28	84.16	69.64	1740	25
84.10	83.32	64.55	1613	25
85.15	82.64	60.06	1501	25
85.88	82.05	49.87	1246	25
80.75	85.85	62.35	1558	25
82.70	88.05	61.83	1545	25
83.30	87.90	54.19	1254	23
84.05	87.25	58.55	1412	24
84.55	85.72	92.95	2323	25
85.34	85.85	64.03	1600	25
86.24	86.15	63.06	1576	25
85.65	84.96	61.16	1529	25
84.95	87.85	68.73	1718	25
84.38	88.93	63.64	1590	25
84.94	88.37	71.27	1781	25
85.60	87.65	56.00	1400	25

Detecting surface water catchement zones for water replenishment into phreatic aquifers. The objective of this methodology is to define infiltration areas recharg-

ing phreatic aquifers, on the basis of topographic information.

As an example in Gaza Strip area, morphostructure includes systems of beach barriers, dry lagoons, channel banks and river beds. These convex and concave topographic elements can be used as hydrogeologic evidence justifying a search for surface catchment of precipitation that will recharge phreatic aquifers. Application of mathematical methods to determine the characteristics of surface water velocities, is employed in aerospace remote sensing practice, [10] and [11]. In what follows we suggest to implement these methods to describe possible zones for surface infiltration.

Construction of parameters to detect infiltration zones. Surface water velocity V can be estimated by,

$$V = C\,R\sqrt{\|\nabla Z\|} \tag{1}$$

where C denotes a compatibility coefficient, R denotes the hydraulic radius and Z denotes the topographic altitude. Zones of stagnant surface water (i.e., catchment zones) can be characterized by low slopes or small norms of the altitude gradient. We can visualize these low contrast zones by contour maps of,

$$S_T \equiv \|\nabla Z\| = [\left(\frac{\partial Z}{\partial x}\right)^2 + \left(\frac{\partial Z}{\partial y}\right)^2]^{1/2} \tag{2}$$

Phreatic aquifer infiltration may be situated in the vincinity of surface concave regions. Such zones for stagnant surface water are associated with.

$$\xi_n \equiv \frac{\partial^2 Z}{\partial \nu^2} > 0 \tag{3}$$

where ν denotes the direction of flow disecting the concave region.

Convex regions may also create aquifer infiltration zones if the surface flow is headed to the direction crossing such a barrier. To describe such a direction, we associate it with.

$$\xi_n \equiv \frac{\partial^2 Z}{\partial \nu^2} < 0 \tag{4}$$

The accumulation of surface water may take place in regions that can be characterized by,

$$\xi \equiv \frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2} > 0 \tag{5}$$

We use the definition in (5) to construct contour maps indicating possible regions for the surface recharge of phreatic aquifers. The surface concave zones (local catchment elements) are depicted in figure 5 (dark areas).

Estimation of the spatial derivatives. We note that in order to construct contour maps of the parameters S_T, ξ_n, ξ and ψ, we need the spatial distribution of Z (topographic altitude) values. Such values may be given only in a sproatic fasion and therefore should be estimated at a prescribed spatial grid. To estimate new Z values from given ones, we refer to geopotential exploration methods described in [13] to [19] and [20] to [22] in which we

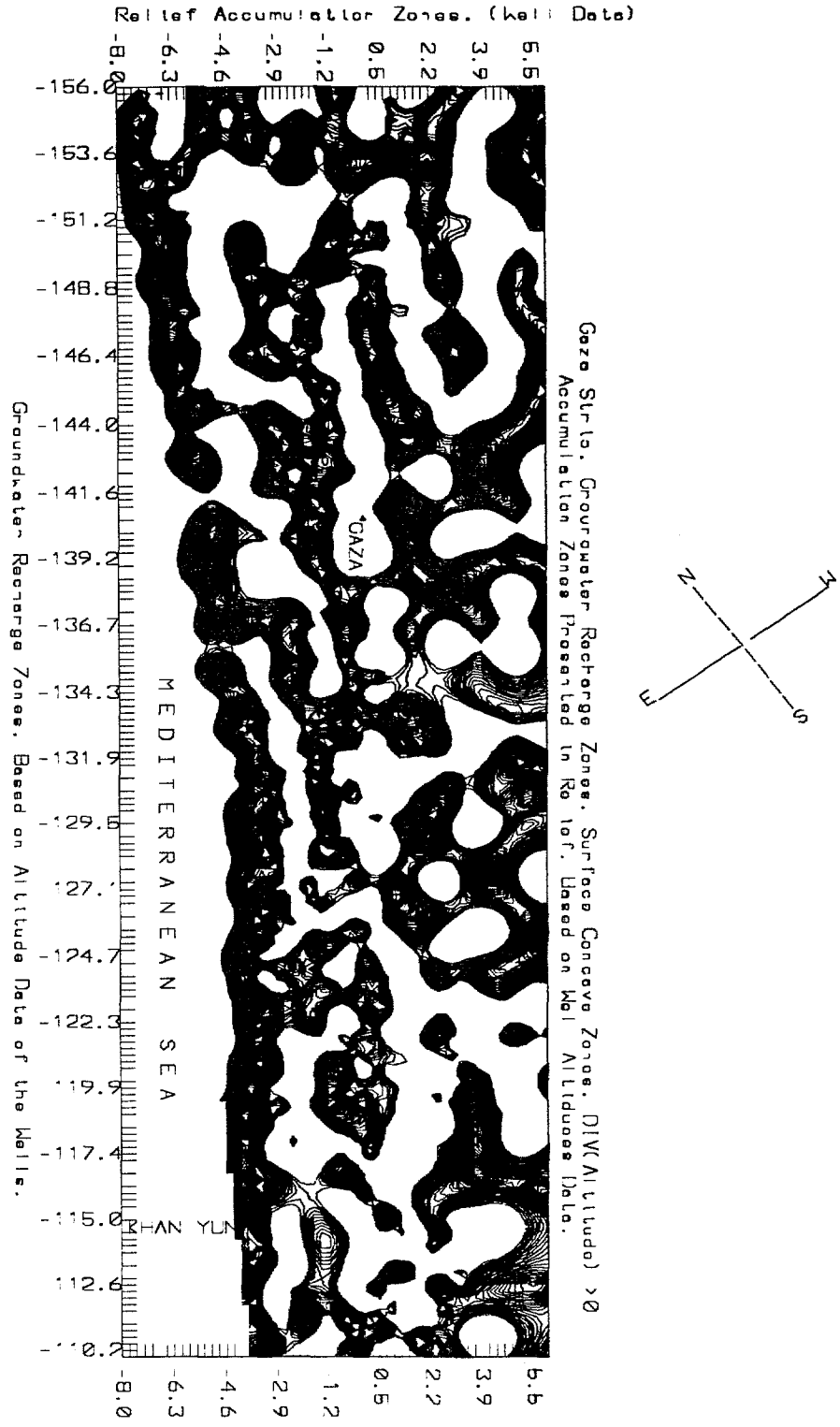


Figure 5: Surface concave and convex elements

apply a variational method of minimizing the average curvature norm of the altitude. This reads,

$$\Omega = \int_S \int \left(\frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2} \right)^2 dx\, dy \rightarrow Min._Z \tag{6}$$

We solve (6) for Z, subject to the conditions that it each nodal i point $Z_i = Z_i^*$ where Z_i^* denotes a prescribed altitude value.

The minimization of Ω describes the solution to Euler's equation given by,

$$\frac{\partial^4 Z}{\partial x^4} + \frac{\partial^4 Z}{\partial y^4} + 2\frac{\partial^4 Z}{\partial^2 x \partial^2 y} = 0 \qquad \text{subject to} \qquad Z_i = Z_i^* \tag{7}$$

Formulation of the saltwater intrusion problem. The mathematical model is based on the balance equations of momentum and mass for the liquid, mass balance equation of a solute in the liquid and on the solid phases, and energy balance equation in the porous media.

a. 3-D Formulation

The Eulerian water flow, solute and heat transport equations are given in the form:

The liquid mass balance equation,

$$\frac{\partial(o\rho)}{\partial t} + \nabla\cdot(\phi\rho\mathbf{V}) = \rho_R Q_R - \rho Q_P \ . \tag{8}$$

where $\phi(p)$ denotes the pressure (p) dependent porosity, $\rho(c,T)$ denotes the liquid density being a function of solute's concentration c (relative to fluid's mass) and fluid's temperature T, and ρ_R denotes the density of a recharged liquid with Q_R as its flux and Q_P denotes a pumpage flux.

Constitutive relations and definitions,

$$\begin{aligned} \rho &= \rho_0 \exp[\chi_c^\rho (c - c_0) + \chi_T^\rho (T - T_0)] \ ; \quad \chi_c^\rho \equiv \frac{1}{\rho}\frac{\partial \rho}{\partial c} \ ; \qquad \chi_T^\rho \equiv \frac{1}{\rho}\frac{\partial \rho}{\partial T} \ , \\ \phi &= 1 - (1 - \phi_0)\exp[\chi_p^\phi (p - p_0)] \ ; \qquad \chi_p^\phi \equiv \frac{1}{1-\phi}\frac{d\phi}{dp} \ , \end{aligned} \tag{9}$$

where ρ_0 , c_0 , T_0 , χ_c^ρ , χ_T^ρ , ϕ_0 and p_0 are prescribed at the same reference.

Liquid's linear (Darcy) momentum,

$$\begin{aligned} \phi\mathbf{V} &= -\frac{\mathbf{k}}{\mu}\cdot(\nabla p - \rho \mathbf{g}) \\ &= -\mathbf{K}\cdot\left(\nabla H + \frac{\rho - \rho_0}{\rho_0}\nabla Z\right) \ , \end{aligned} \tag{10}$$

where $\mathbf{k}$ denotes the intrinsic permeability tensor, $\mathbf{g}$ denotes the vector of gravity acceleration, Z denotes elevation parallel to $\mathbf{g}$. μ denotes a viscosity, $\mathbf{K}$ $(= \mathbf{k}g\rho_0/\mu)$ denotes the hydraulic conductivity and H $(= p/g\rho_0 + Z)$ denotes an hydraulic head with reference to ρ_0.

Assuming decay with η as the decay coefficient, and adsorption (governed by linear equilibrium isotherm) on the solid matrix, we write the

solute mass balance equation for the porous medium,

$$\frac{\partial}{\partial t}[\phi\rho c + (1-\phi)\rho_s c_s] = -\nabla\cdot[\phi\rho(c\mathbf{V} - \mathbf{D}_h\cdot\nabla c)] - \eta\phi\rho c + c_R\rho_R Q_R - c\rho Q_P \ , \qquad (11)$$

in which $\mathbf{D}_h$ denotes the dispersion tensor, c_s $(= \kappa_d \rho c)$ denotes the concentration on the solid matrix, ρ_s denotes the constant solid density, κ_d denotes the *partitioning coefficient* (= volume of fluid per unit mass of solid) and c_R denotes the concentration of a solute associated with an injected liquid. An other form, replacing (11), can be obtained if multiplying (8) by c (for $c \neq 0$) and subtracting this product from (11). We thus obtain,

$$\phi\rho\frac{\partial c}{\partial t} + \frac{\partial}{\partial t}[(1-\phi)\rho_s c_s] = \nabla\cdot(\phi\rho\mathbf{D}_h\cdot\nabla c) - \phi\rho\mathbf{V}\cdot\nabla c - \eta\phi\rho c + (c_R - c)\,\rho_R Q_R \ . \qquad (12)$$

In writing the energy balance equation for the porous medium we assume linear thermodynamics. We assume small deformations so that we neglect the energy associated with heat dissipation and with change of volume. Further more, the liquid specific heat at constant volume, C_f, and the solid specific heat at constant strain, C_s, are assumed constant. We assume that liquid's and solid's temperatures are practically equal, solid's velocity and its dispersive heat flux are much smaller than that of the liquid. Hence, following Bear and Bachmat [24], we write the

porous medium energy balance equation,

$$\begin{aligned}\frac{\partial}{\partial t}([\phi\rho C_f + (1-\phi)\,\rho_s C_s]T) = \ & - \ \nabla\cdot(\phi[(\rho C_f T)\,\mathbf{V} - \mathbf{D}^{*H}\cdot\nabla\,(\rho C_f T) - \boldsymbol{\lambda}^*\cdot\nabla T]) \\ & + \ \rho_R C_f T_R Q_R - \rho C_f T Q_P \ , \qquad (13)\end{aligned}$$

where $\mathbf{D}^{*H}$ denotes the liquid thermal dispersion coefficient as suggested by Nikolaevskij [25] and $\boldsymbol{\lambda}^*$ (for isotropic medium, $\lambda^*_{ij} \equiv \lambda\delta_{ij}$) denotes the thermal conductivity coefficient of the porous medium.

b. Vertical cross section simulations

A general view and a typical hydrogeological cross section of the Gaza strp region is described in Figure 6.

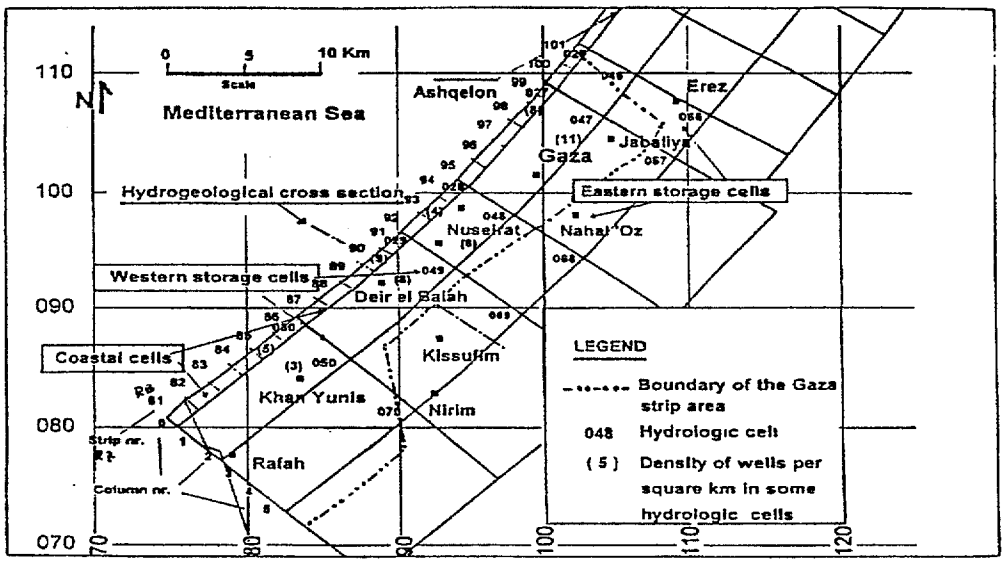
The pumpage at the Khan Yunis area can grossly be considered as being situated along several strips of well batteries (Figure 7.

To estimate the extent of solute migration in depth and time under such stress conditions, we simulated the salt dependent transport problem in vertical cross sections.

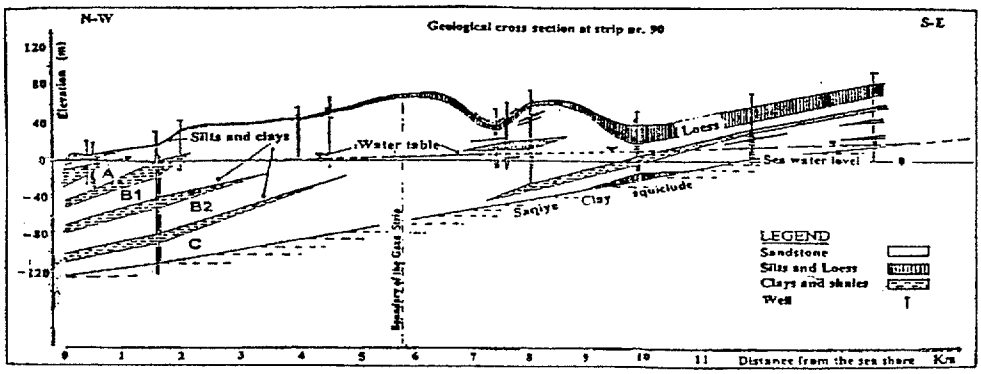
The SUTRA computer code, [26], was applied for simulation of flow and transport in a vertical cross section.

In the two dimensional vertical grid we had introduced the notion of the typical multi-aquifer system (Figure 8).

On the basis of the total pumpage (during the years 1988/1989) along the strip crossing Khan Yunis and the annual population growth (3.8%), we had extrapolated a possible pumpage rate from the years 1850 to 2010 (Figure 9).



Location map.



Hydrogeological cross section of the Gaza Strip region.

Figure 6: General view and a typical hydrogeological cross section

POSITION OF WELLS
(Khan Younis. Gaza strip)

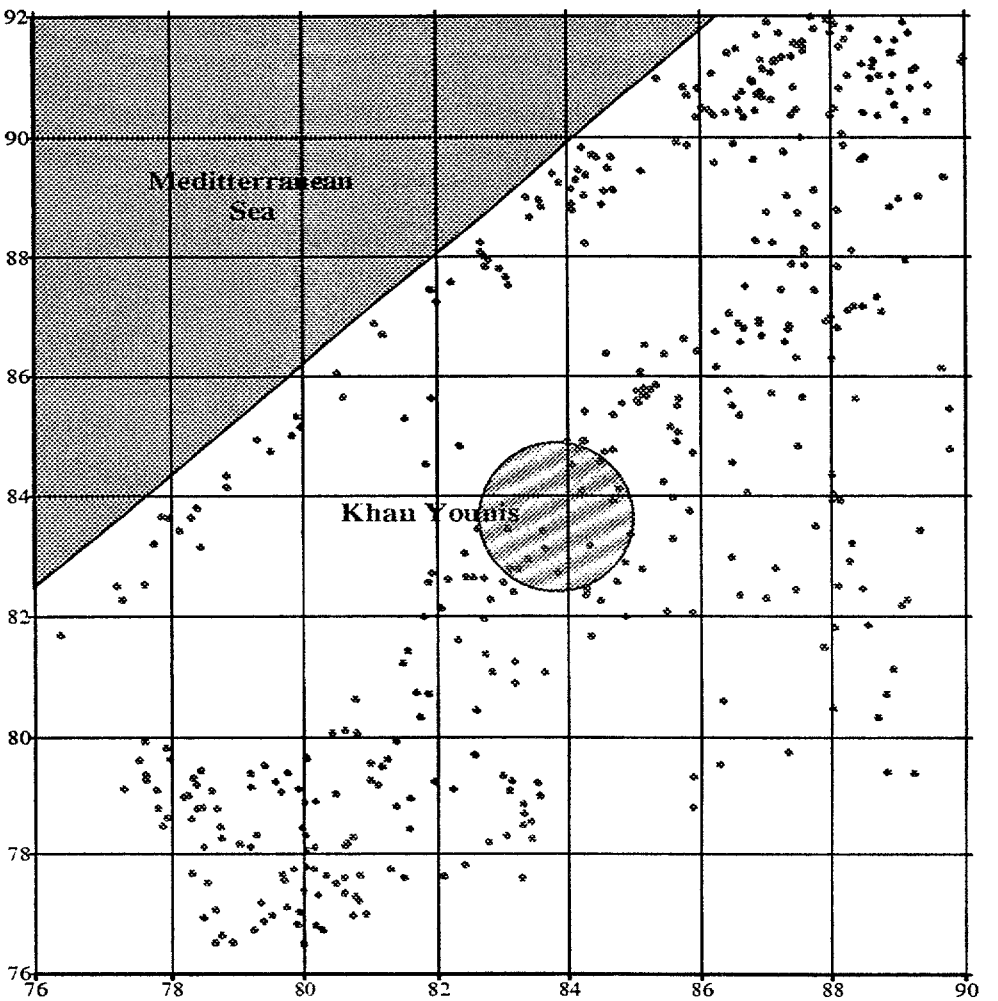


Figure 7: Wells distribution

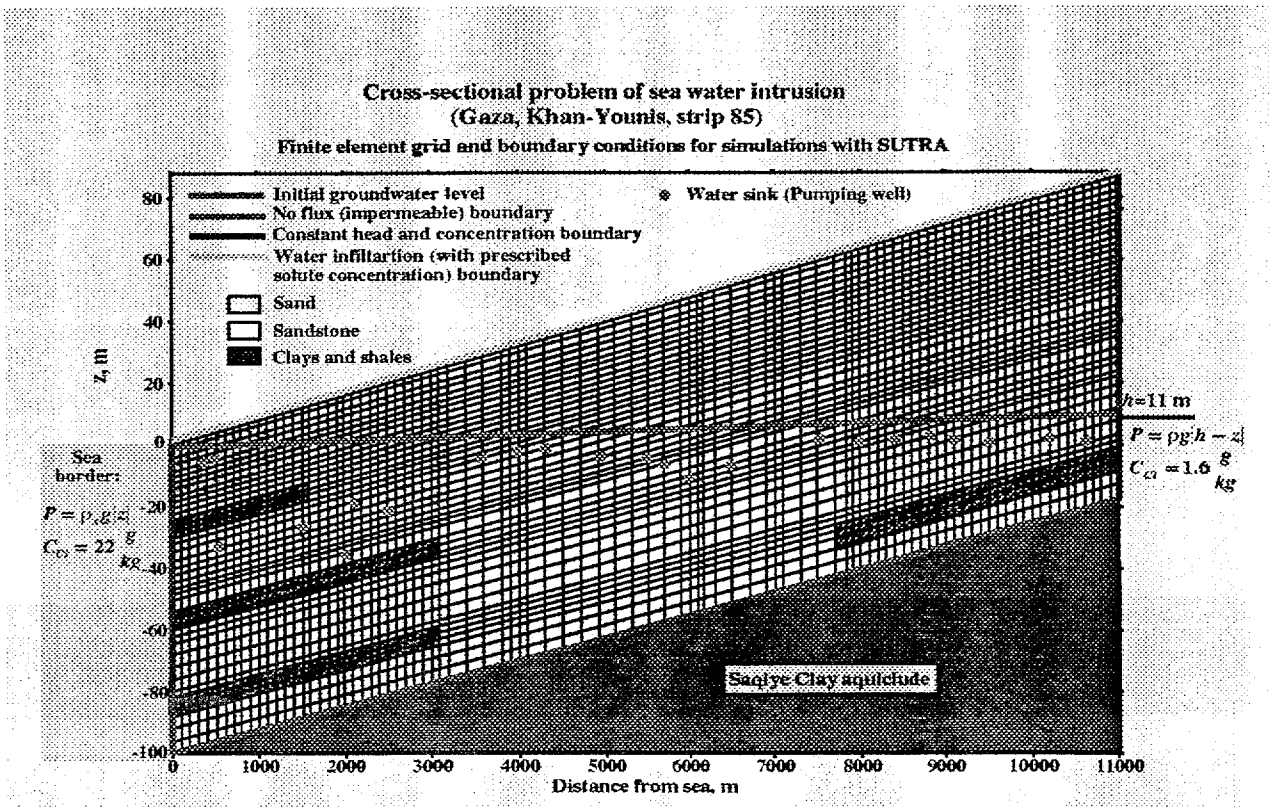


Figure 8: Vertical cross section: Grid and Boundary Conditions

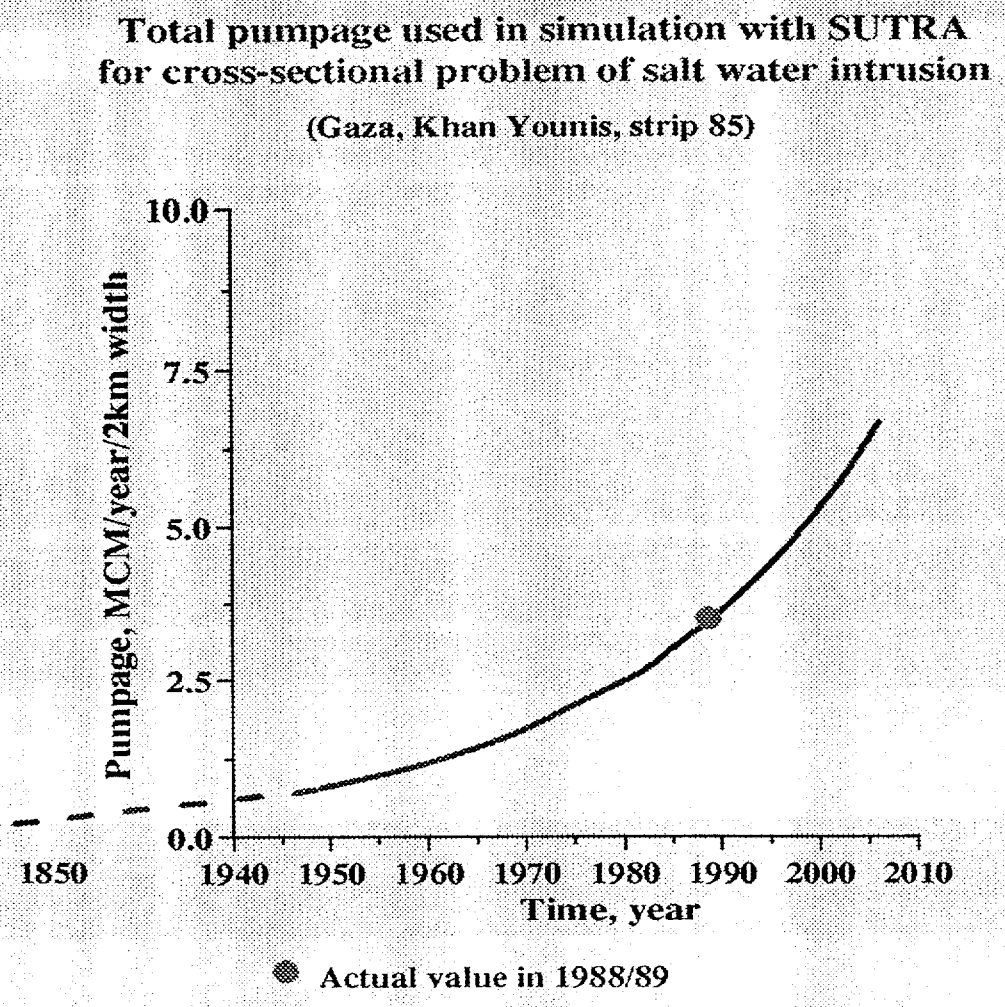


Figure 9: Stipulated pumpage scenario

Boundary conditions are described in Figure 8, initial water level changes linearly between the West and the East borders. Initial chloride concentration was taken as 0.05 g/kg. We started the computation with these conditions to simulate a steady state distribution of heads and concentrations. At this stage the aquifer was not stressed by any pumpage within the domain.

The results of these simulations were used as the initial conditions for the transient simulations through which the aquifer was stressed by pumpage as described in Figure 9. This procedure was carried out for a wide range of aquifer parameters.

A sensitivity study demonstrating the influence of the hydraulic conductivities and dispersivities is presented in Figures 10 to 18.

After having completed the sensitivity analysis, we had attempted to calibrate the model to be consistent with the observed groundwater levels. This enabled us to estimate the flow parameters.

Figure 20, demonstartes the comparisons between the simulated and the observed grounwater levels along the strip crossing Khan Yunis. Based on this, as also shown in Figure 20, we made some predictions as for the groundwater level decrease until the year 2006 if the pumpage pattern will follow the one presented in Figure 9.

Simulations demonstrate the extent of saltwater intrusion as well as the effect of the layers on the migration of the salt plumes.

c. Formulation for a horizontal plane

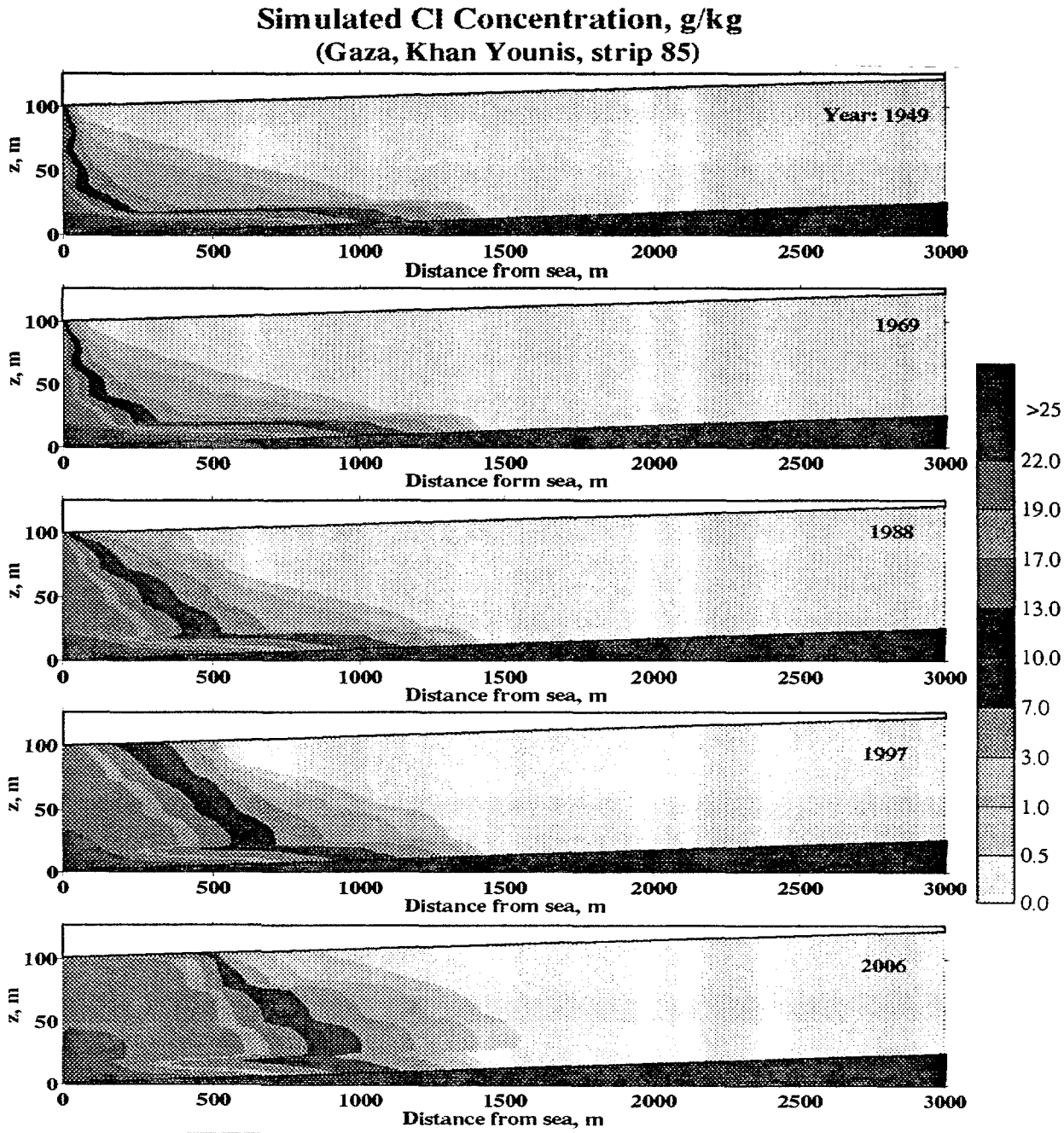
Actually, the 3-D balance equations will describe the saltwater intrusion problem in its full spatial extent. Numerical simulations of this may, however, consume significant computation time. Yet, controlling the migration of a salt plume and studying the effect of different scenarios of stressing the aquifer, can rely on 2-D horizontal plane simulations for regional groundwater management. It is for these above mentioned reasons that we will develop 2-D formulations for the saltwater intrusion problem. In what follows we describe the Eulerian forms of these balance equations.

Consider a *phreatic aquifer* and let h $[= h(x, y, t)$, i.e. function of cartesian plane coordinates and time, respectively] and $b\,[= b\,(x, y)]$, denote the upper (i.e. at the point where $p = 0$) and lower elevations, respectively, of the phreatic aquifer. Flow, transport and heat transfer equations in a 2-D plan space, can be obtained by integrating (from b to h) all of the terms in (8), (10), (11) and (13). A vertical averaged term will thus be in the form

$$\bar{(\ )} \equiv \frac{1}{h-b}\int_b^h (\ )\, dZ\ ,$$

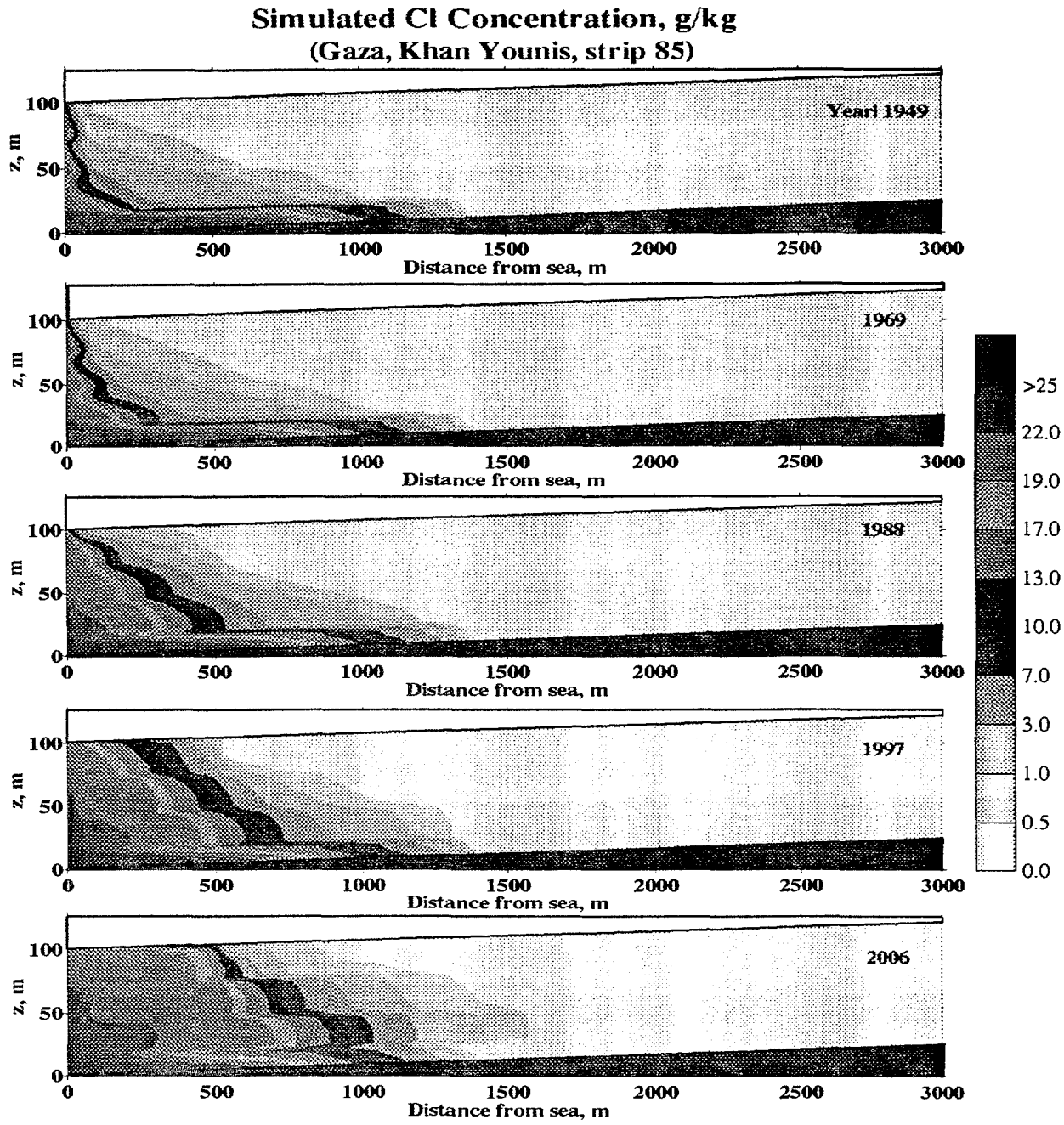
and the average over a product of terms will be assumed to be equal to the product of the averaged terms.

Accounting for the fact that water density is a function of solute concentration, we will also average (10) and assume that pressure in the vertical direction is approximately distributed hydrostatically. Accordingly, using the notion of hydraulic conductivity and head as in (10), we obtain the



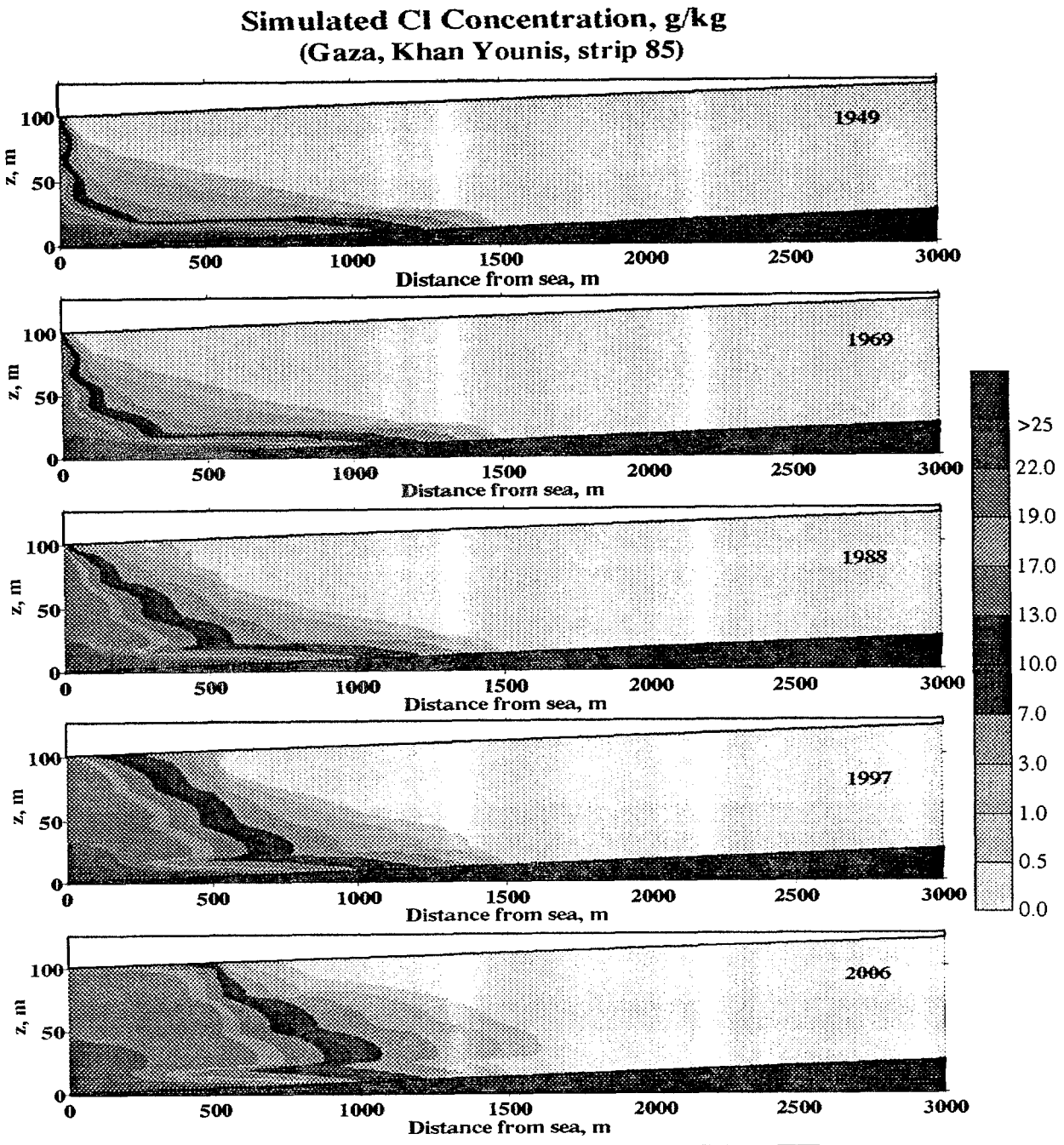
Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.01
Longitudinal dispersivity, m	25.0	12.5	50.0
Transversal dispersivity, m	1.0	0.5	2.0

Figure 10: Predicted evolution of Cℓ concentrations



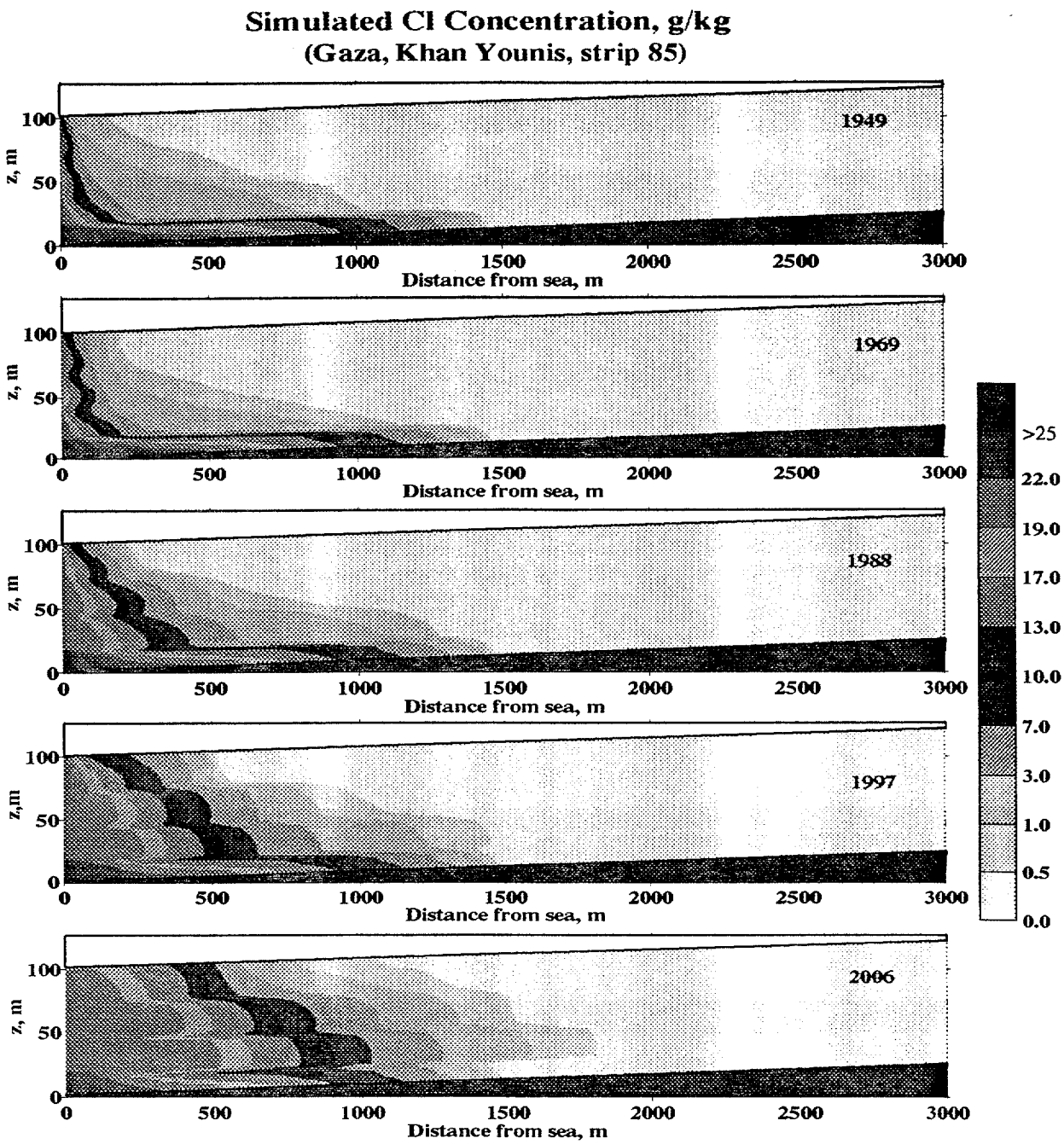
Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.01
Longitudinal dispersivity, m	10.0	5.0	20.0
Transversal dispersivity, m	1.0	0.5	2.0

Figure 11: Predicted evolution of Cℓ concentrations



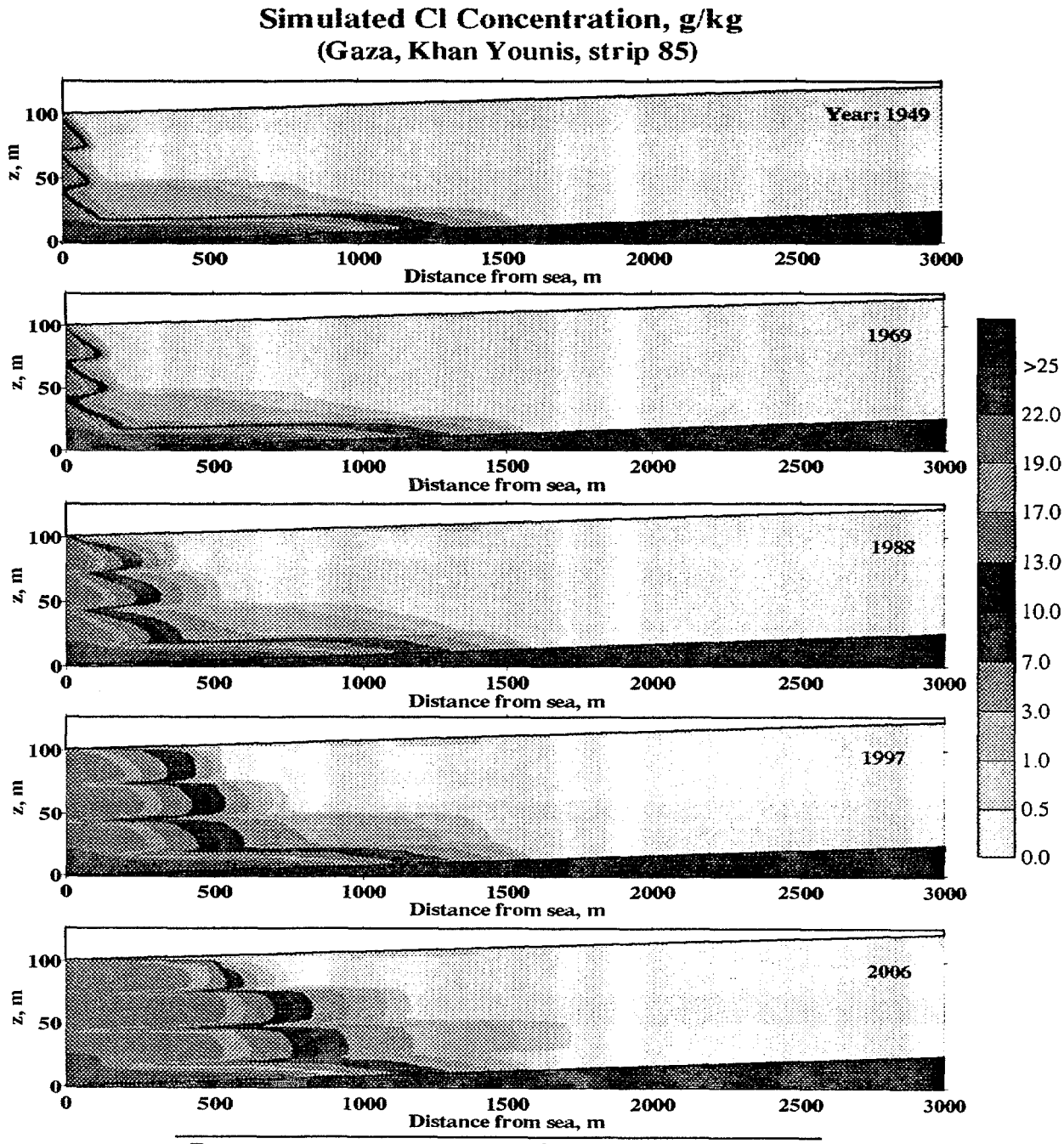
Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.01
Longitudinal dispersivity, m	25.0	12.5	50.0
Transversal dispersivity, m	0.5	0.25	1.0

Figure 12: Predicted evolution of Cℓ concentrations



Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.01
Longitudinal dispersivity, m	50.0	25.0	100.0
Transversal dispersivity, m	1.0	0.5	2.0

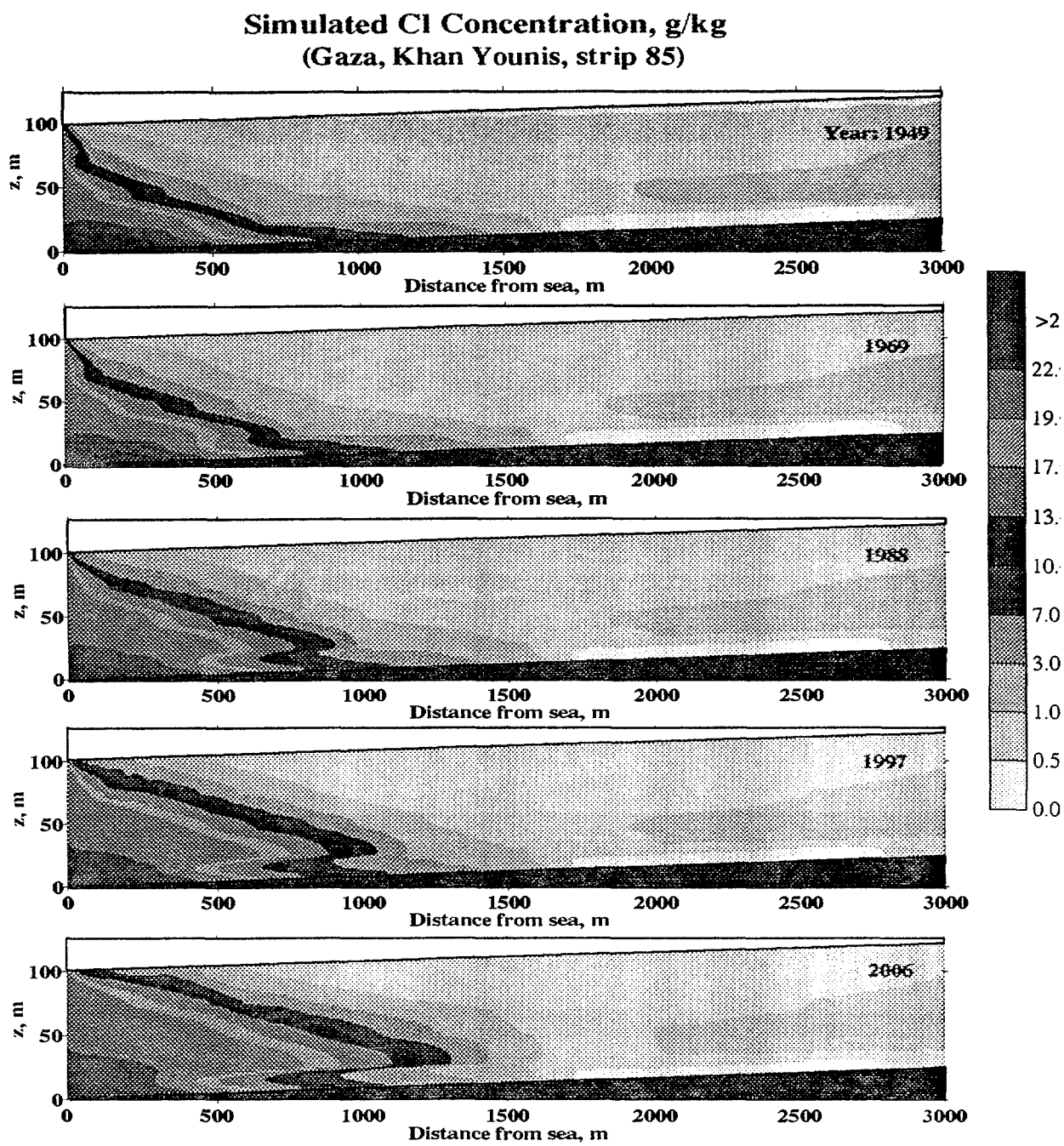
Figure 13: Predicted evolution of Cℓ concentrations



Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.01
Longitudinal dispersivity, m	25.0	12.5	50.0
Transversal dispersivity, m	0.5	0.25	1.0

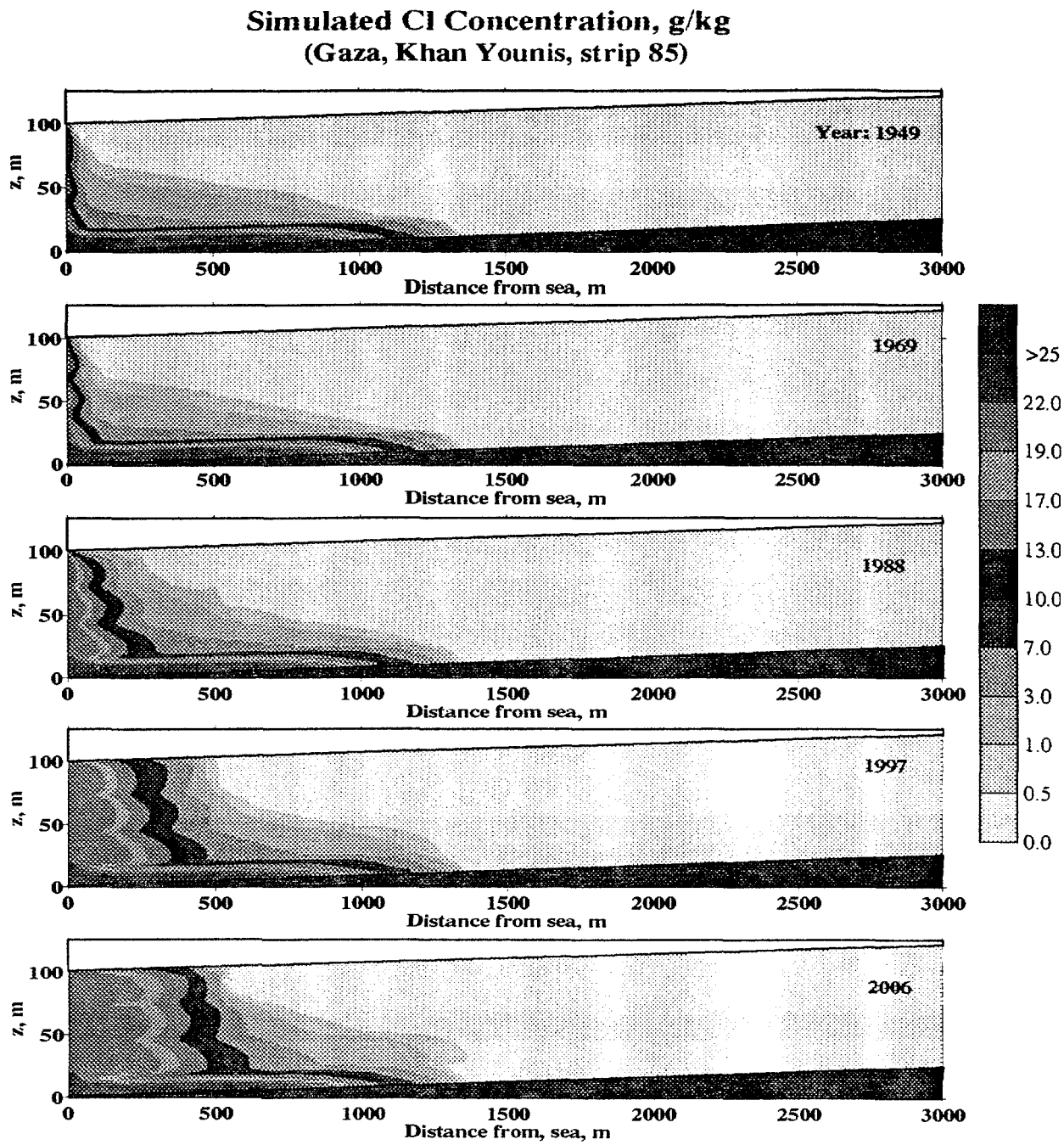
Anysotropy of parameters: horizontal/vertical=10/1

Figure 14: Predicted evolution of Cℓ concentrations



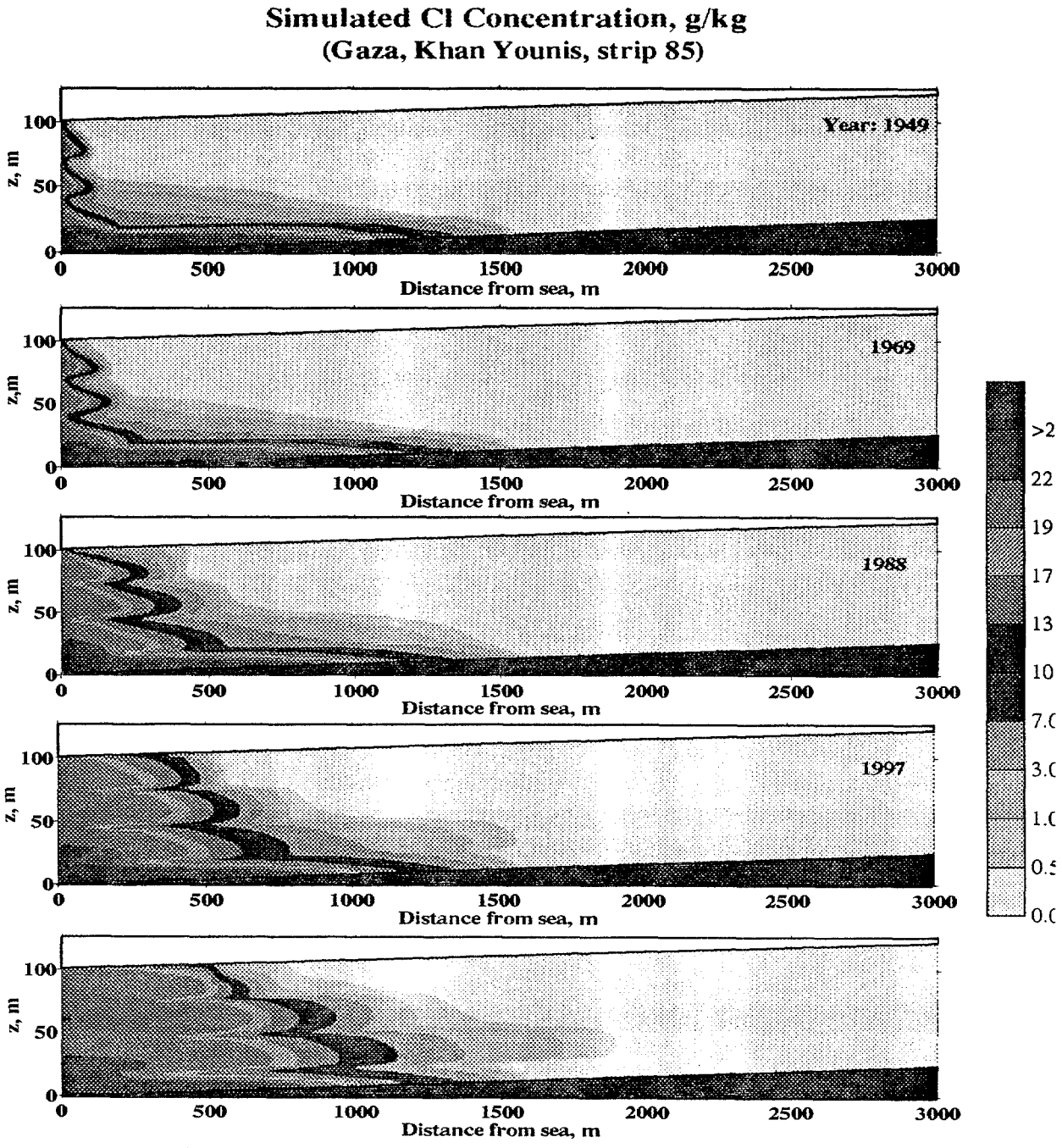
Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	75.0	150.0	0.05
Longitudinal dispersivity, m	25.0	12.5	50.0
Transversal dispersivity, m	0.5	0.25	1.0

Figure 15: Predicted evolution of Cℓ concentrations



Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	5.0	10.0	0.005
Longitudinal dispersivity, m	25.0	12.5	50.0
Transversal dispersivity, m	0.5	0.25	1.0

Figure 16: Predicted evolution of Cℓ concentrations



Parameters:	Sandstone	Sand	Clay
Hydraulic conductivity, m/day	15.0	30.0	0.001
Longitudinal dispersivity, m	10.0	10.0	20.0
Transversal dispersivity, m	0.25	0.25	0.5

Figure 17: Predicted evolution of Cℓ concentrations

Moroccan Aquifer

In the west of Morocco, the coastal CHAOUIA extends from Casablanca to Azemour. The principal activity in this plain is agricultural. Ground water are the only resource available for at fresh water and irrigation. But this water has undergone degradation due to seawater intrusion. Thus, detailed studies must be undertaken to determine the location interface and to predict its spatio-temporal evolution. Studies consist an hydrogeological studies, and a phase of modeling using SHARP model.

The coastal CHAOUIA area lies between latitudes 33°N. and 33°45'N. and longitudes 7°30'W. and 8°30'W. t extends from the Oum Rbia wadi on the West to Casablanca on the East and from Berrechid on the South to the Atlantic ocean on the North. It belongs to the structural domain of the Moroccan coastal Meseta. It represents a littoral band of breadth 15 to 25 km., length 65 km and surface area 1100 square km.

Physiographically, the area presents a monotonous relief as stranded dunes drained by three wadis, among Oum Rbia, is the most important.

The principal hydrogeologic units of interest in the coastal Chaouia are a sandstone and limestone formation of the "Plioquaternaire" and marl-limestone of "Cenomanien" and corrupted schist and fissured quartzite of Paleozoic age.

Ground: is pedological formation which covers the most part of Chaouia's area, it consists of pervious sand and clay.

Plioquaternary formation: consists of marine sandstone and consolidated dune which are an important source of water supply. But its thickness is so thin for having a continuous aquifer.

Cretaceous limestone: localized on the South West of the area.

Paleozoic formations: consists of schists and quartzites with sandstones. Schists are impervious except at surface where its corruption make a circulation of water. Quartzites are also impervious but when they are fissured, they can be natural drains.

The hydrodynamic parameters for which the model will be calibrated are: observed piezometric head, hydraulic conductivities, and specific storage. 147 pumping tests are centered at Bir Jdid. They give data on hydraulic

conductivities for the heterogeneous aquifer (Plioquaternaire and Paleozoic formations.

The effective porosity of all units is estimated as an average of seven values. its indicates a microfissured and pervious media.

The 1995 Geophysical campaign, along plain, give the aquifer bottom and top map which allowed us to draw thickness map. Primary feature is the impervious substratum of the aquifer, its slop increase towards the ocean.

We can subdivide the CHAOUIA region into two parts :

- The North East area from Tnine chtouka to Casa, Plioquaternary formation increase in thickness from Berrechid to Atlantic ocean, and pinches out in the East of the region where the outcrop area is the primary formation. The slope increases at the coast. The depression is filled by plioquaternaires and corrupted schists formations.
- The South West area which the Cenomanien limestone is localized between Plioquaternary and primary formations.

The model SHARP (Essaid, U.S. Geologic Survey,1990) is a quasi-three-dimensional, numerical finite-difference model that simulated freshwater and saltwater flow separated by a sharp interface in layered coastal aquifer systems. The model SHARP was used to simulated the coast CHAOUIA. It facilitates regional simulation of coastal ground-water conditions in layered systems and include the dynamics of both saltwater and freshwater. The model accommodates multiple aquifers, separated by confining units, with spatially variable porous media properties. The modeled area is discretized by square and rectangular grid.

The model is used to estimate freshwater fluxes through the system, to study movement of the freshwater saltwater interface in response to development, and to estimate the current position of the interface.

For each aquifer within a layered coastal system two domains must be considered: freshwater and salt water. The equations used are the equation of continuity vertically integrated. The boundary conditions which are simulated in the model are: prescribed flux boundaries, constant freshwater head and/or constant saltwater head boundaries

In order to implement a numerical model, it is necessary to translate the hydrogeologic conditions of the area into a framework that can be simulated by the model. this is accomplished by defining the geometry, boundary conditions,

and physical parameters of the plain, in a manner that will reproduce the system's behavior, over a discretized grid.

The modeled area of interest (coast CHAOUIA) extends to 1100 square km. Variable grid spacing is used to extend the model to this distance, as well as to allow for finer discretization near the coast. The simulated grid is 30 rows by 15 columns.

We considered the coast CHAOUIA aquifer as a one layer system, indeed, the different formations aquifers (Primary, Cretace and Plioquaternaire) are vertical and lateral hydraulic connection. The Primary feature constitute an impervious substratum for all The coast CHAOUIA.

We distinguished boundaries conditions flowing for this region:

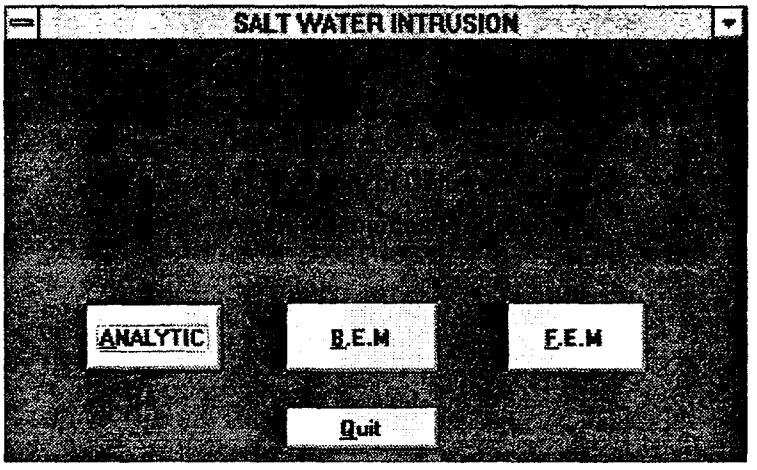
- The prescribe flux boundaries for taking into account, the lateral entry of the coastal CHAOUIA for the water coming from Berrechid plain at the south.
- No-flux boundaries along outcrop line for El Hank quartzites at the east.
- The prescribe flux boundaries at ocean level and at Oum Rbia wadi which constituted the natural principal aquifer outlets .

To resolve flow equations previously described by the model, we needed the aquifers parameters for which the model has been calibrated which are: piezometric head, hydraulic conductivities, specific storage, aquifer thickness, bathymetry, recharge and boundary conditions.

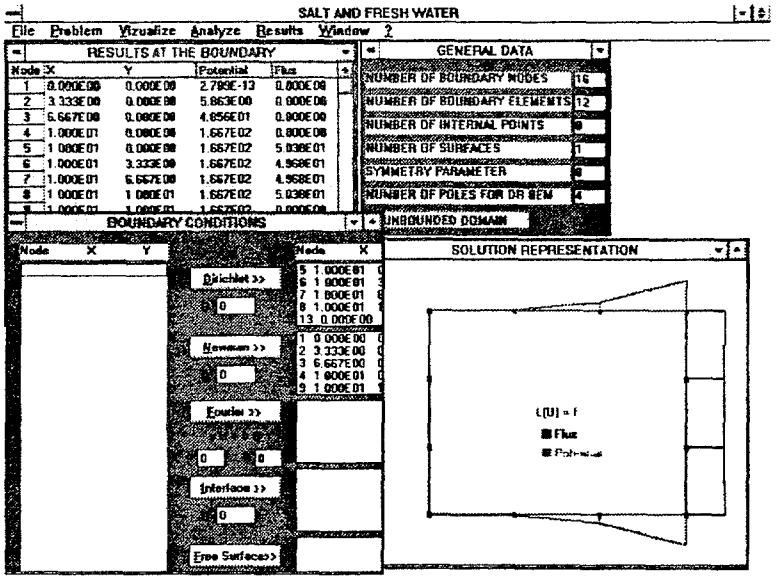
Before using SHARP model, the estimation for parameters at knot by grid in domain, must be made, using available data. The estimation procedure is called kriging.

Computer Software

A software package for sharp interface modeling is accomplished. The figure below shows a selection from the window analytical solution or BEM solution. It also provides a possible linkage with a Finite element solution.



The next figure shows the user-friendly preprocessor for the Boundary Element Method (BEM) which helps the user to generate a mesh for numerical solution. It consists of a spreadsheet for nodal coordinates input, a utility for defining various kind of boundary conditions, and a graphical presentation of the geometry and the final solution.



For the analytical solution capabilities, the following two screen show some sample sessions. The software is free upon request.

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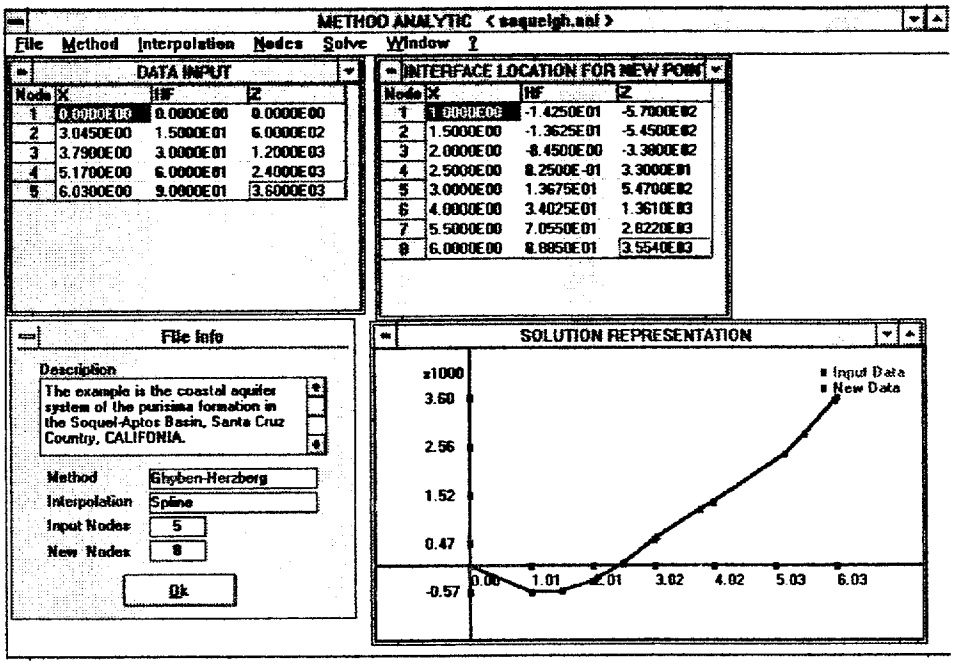
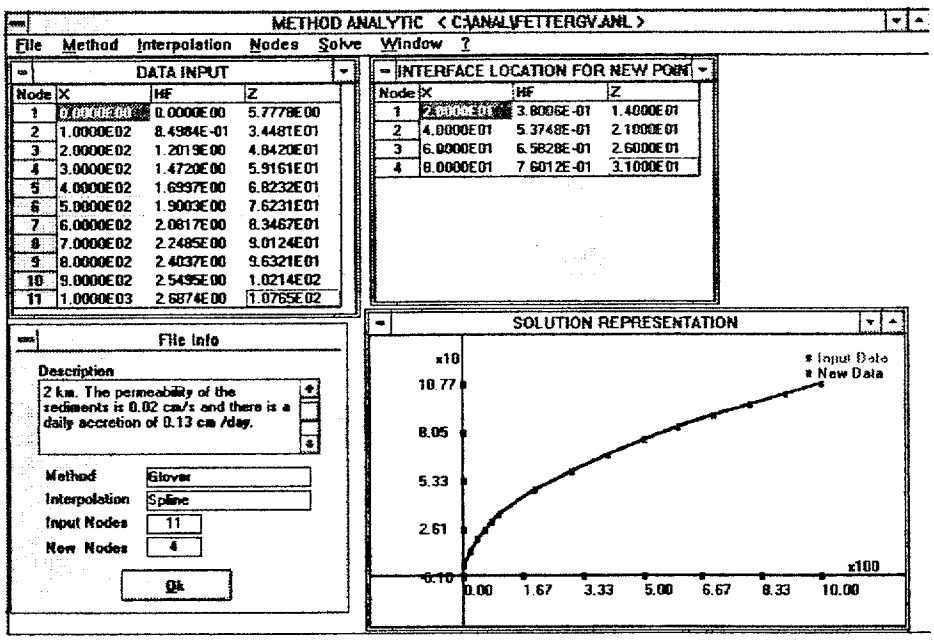
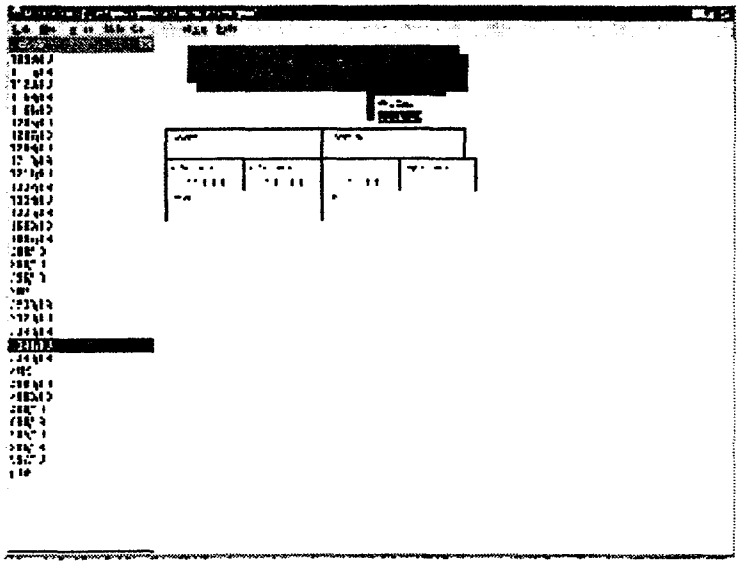


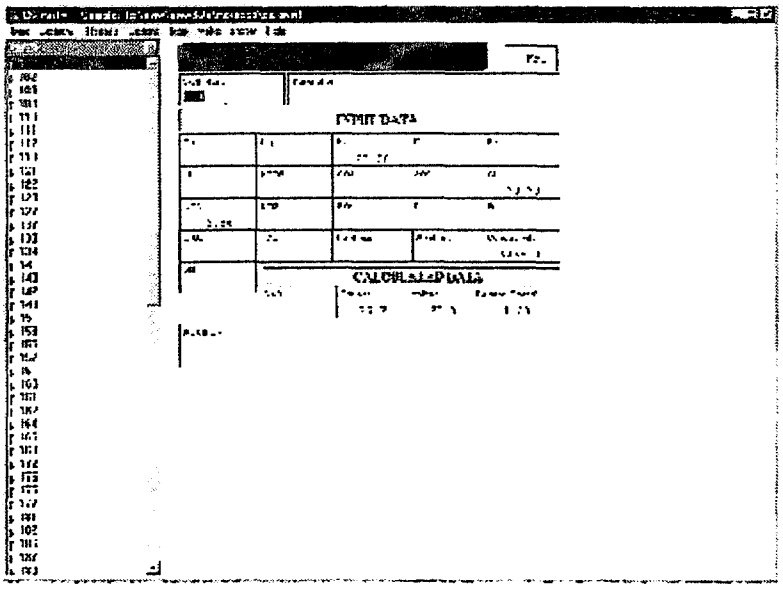


Groundwater Data Management

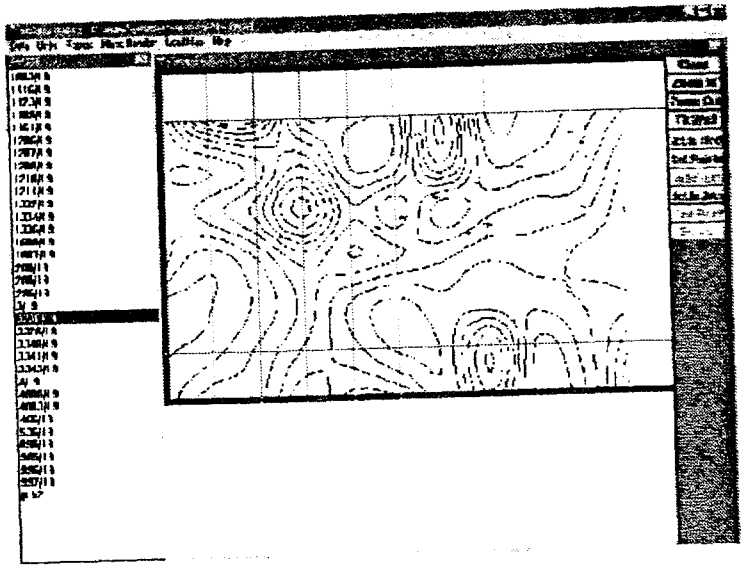
In the Moroccan aquifers, Groundwater for Windows are used to manage coastal aquifer data. A few sample screen is shown below. The first figure shows the management of water quality sampling wells.



The second figure shows the water quality data management in each well.



The third figure shows the water table contour.



Future Recommendations

The following future works to consolidate the gains achieved in this project have been recommended by the AID project review team (see: Final Project Evaluation, by K. J. Hollett, H.G. Blank, C.A. Dutto and D. L. Walker). The team members agree.

- The scope of future work should be expanded to go beyond saltwater intrusion to include general water quality.
- The database and computer models constructed should be used for future planning and management purposes.
- An international seminar/conference should be held to disseminate the lessons learned and information gathered from this project.

Financial Report

Total project budget: $422,857
Total expended: $422,857

Expense Category	Cost
Salaries	
Principal Investigators	$14,708
Graduate Student	$2,500
Staff	$1,000
Miscellaneous wage	$7,193
Fringe Benefit	$5,223
Travel	$28,000
Tuition	$600
Supplies & Expenses	$15,004
Subcontracts	
Israel	$118,150
Gaza Strip	$72,000
Morocco	$25,000
USGS	$24,000
Equipment	$15,000
Total Direct Cost	$328,355
Total Indirect Cost	$94,499
Grad Total	$422,857