First International Conference on Saltwater Intrusion and Coastal Aquifers—
Monitoring, Modeling, and Management. Essaouira, Morocco, April 23–25, 2001

An Integrated Set of Modeling Codes to Support a Variety of Coastal Aquifer Modeling Approaches

Robert Fitzgerald, P.E., Peter Riordan, P.E., Brendan Harley, ScD, C.Eng.

Camp Dresser & McKee Inc., Cambridge, MA, USA

ABSTRACT

An integrated set of modeling codes is introduced which can support a variety of modeling approaches used to address coastal aquifer issues. This set of tools includes groundwater flow, solute transport, 2-phase sharp interface and coupled flow-transport modeling codes. All of the codes are fully 3-dimensional and linked by a common model database (input/output files), input command structure and graphical pre/post processor. The linkages between codes expedite application of multiple approaches to a problem and a logical sequencing of model development. Further, linkage of all codes to a dedicated graphical pre/post processor and related modeling and GIS tools such as GMS, ArcView GIS, Argus ONE, AutoCAD and EVS enhances modeling efficiency and graphical presentation.

Example applications of these codes are briefly presented which illustrate different approaches appropriate to addressing different coastal aquifer modeling issues. These include:

- Groundwater flow and particle tracking simulations to assess the effectiveness of alternative groundwater management strategies to retard the intrusion of saline water into a Central Valley, California aquifer
- 2-dimensional and 3-dimensional sharp interface modeling of potential groundwater impacts resulting from a proposed development in Hawaii. Potential pitfalls of applying 2-dimensional areal models in coastal aquifers are also highlighted.
- coupled flow-transport simulations of sea water intrusion in Gaza.
- simulations using single phase (non-density-dependent) groundwater flow and transport models to assess the effectiveness of injection barriers used to inhibit salt water intrusion in Southern California
- 3-dimensional sharp interface simulations of seawater intrusion on Long Island, New York
- Sharp interface and solute transport modeling applied to water supply development study on the Gulf Coast of Florida

INTRODUCTION

This paper presents the development and examples of applications of a comprehensive set of model codes which have been developed at Camp Dresser & McKee (CDM), with emphasis placed on the study of coastal aquifers. The groundwater modeling group at CDM in Boston has been developing codes for the modeling of groundwater systems for more than 20 years, and the DYNSystem series of codes represents the evolution of their development efforts.

The codes are built around a command driven, user-focused, interface structure, which has continually evolved to allow users to quickly and efficiently address the modeling issues which arise in any real-world application of codes to 3-dimensional flow systems.

CDM has been modeling complex coastal aquifer systems since the early 1980s, and our experience during that period have confirmed that the modeler needs to have a number of simulation tools available to address the issues that can arise in evaluating the behavior of coastal systems and developing management schemes.

Figure 1 illustrates the DYNSystem set of codes that are described in this paper to address coastal aquifer issues. The core of the system is the fully 3-dimensional flow code, DYNFLOW, which evolved from the MIT-developed AQUIFEM code in the 1970s. DYNFLOW is a comprehensive finite element code, proven during hundreds of practical applications. DYNFLOW simulates fully 3-D multi-layer aquifer systems and allows a wide range of stresses and boundary conditions to be applied. The basic flow model also includes the ability to incorporate interaction with surface water systems (DYNRIVER), and users can include the impact of agricultural activities on recharge or extraction from the aquifer (DYNAG, DYNSOIL). Application of DYNFLOW is supported by various visualization programs; Figure 2 shows a 3-D of the multi-layer Gaza coastal aquifer, and Figure 3 illustrates a DYNFLOW grid for the Long Island, New York, aquifer system.

The companion DYNTRACK code is a random-walk based mass-transport code used to simulate the migration of dissolved contaminants. DYNTRACK is also fully 3-dimensional and simulates advection, dispersion, retardation, and decay. It is fully integrated with DYNFLOW, and has been applied by CDM and the authors at numerous hazardous waste sites, and for studies of development and protection of groundwater resources. Figures 4 and 5 show examples of output from DYNTRACK with multiple "plumes" from a site presented in plan and cross-section (using the DYNPLOT Graphical User Interface (GUI)).

Variable density flow regimes can be simulated using DYNCFT which is a coupled flow and transport code. It is a linkage of DYNFLOW and DYNTRACK, and incorporates the many years of practical experience with both of these codes. DYNCFT is fully 3-dimensional, and can address multiple intrusion zones. It has been in use for the past two years, and is the principal simulation code for the Gaza coastal aquifer management study presented at this conference.

The authors' experiences are that in situations where density effects are not significant, and this is often the case in coastal aquifers where production of potable water is still possible, the combination of DYNFLOW and DYNTRACK run in an "uncoupled" mode has proven to be very effective and cost-efficient in assessing aquifer conditions and management strategies. There may not be a need to apply the more complex density-dependent codes for such studies.

To address regional-scale sea-water intrusion, another code, DYNSWIM, may also be appropriate. This is a sharp-interface code, developed directly from DYNFLOW. The code is also fully 3-dimensional and can evaluate the potential migration of sharp intrusion zones into a complex aquifer system. The migration of the intrusion can be thus vertical (such as through "holes" in clay layers) as well as horizontal. DYNSWIM can also be applied in localized areas where DYNFLOW is being used for overall aquifer evaluation. An example of this situation is on Long Island, New York, where this joint use of the codes has been ongoing for the past decade (and presented elsewhere at this conference.) In practice, DYNSWIM has been found exceptionally useful in evaluating potential intrusion into over-stressed aquifer systems, and has clearly indicted the root causes of several unexplained seawater impacts on near-coast well fields.

The authors' experience is that each of the codes (DYNFLOW, DYNTRACK, DYNSWIM and DYNCFT) plays a role in the detailed assessment of coastal aquifer systems. No single code is "right" for every problem, and the effective modeler needs to have a suite of codes available. Each of these codes is described in more detail later in this paper.

Supporting these codes are links to ever-evolving GIS and database systems (see Figure 1). Rather than build such capabilities directly into DYNSystem, or have the DYN computational modules as sub-sets of a GIS system, we have elected to permit ready import of data from such industry standards as ArcView, Access and Excel to DYNSystem, and also have DYNSystem modules write output files which are in an open format read by those systems. DYN users can also apply data processing software such as Argus ONE and ArcView to build DYN grids, stratigraphy, and property files, and results from DYN can be visualized using tools such as GMS, EVS, Surfer etc. CDM has also developed standard routines which permit MODFLOW model files to be read into or from DYN data files. While these external graphical or data base capabilities are available, the indigenous DYNPLOT GUI remains the principal mechanism by which the modeler can fully interact with results from any DYN simulation run, and display results (in plan or cross-section) of various runs (from any of the DYNSystem codes) overlain on each other or on field data.

DYNFLOW – Groundwater Flow Model

DYNFLOW simulates 3-dimensional groundwater flow. It uses the Galerkin finite element formulation, and is coded in the FORTRAN computer language. The DYNFLOW code was developed for applications including coal strip-mine dewatering projects, regional groundwater supply studies and hazardous waste remediation studies. It has since been applied in a number of coastal aquifer management and salt water intrusion studies.

Based on the conventional equations of flow in porous media, DYNFLOW can be used to simulate equilibrium or transient responses of groundwater flow systems to several types of natural and artificial stresses. These include induced infiltration from streams, artificial and natural recharge or discharge, pumping, and evapotranspiration.

The program employs linear finite elements and solves both linear (confined) and non-linear (unconfined) aquifer flow equations, including special routines to handle a change in status from a confined to unconfined situation. The program uses a trapezoidal time stepping scheme with both lumped and distributed storage term options. The program has a "rising water" scheme to allow drainage to local streams if the piezometric head in a phreatic aquifer rises to the elevation of the streambed. DYNFLOW can treat the problem of multi-level pumpage using one-dimensional elements, and can treat general anisotropy in hydraulic conductivity, and stress dependent hydraulic conductivity and specific storativity.

The DYNFLOW structure can utilize four different types of elements, with a combination of any of the four types in a given simulation. The element types are:

Element Type	Purpose
Three-dimensional (3-D)	Flow in all three spatial directions.
One-dimensional (1-D)	Multi-aquifer wells; underdrains; and fractured rock interconnections.
Two dimensional (2-D)	Vertical barriers such as faults and slurry walls.
Pond	Surface water bodies.

In general, a porous medium will be represented by three-dimensional elements. In DYNFLOW, the basic working element in three dimensions is a vertical triangular prism with six nodes. Using methods presented by Huang, et al. [1974], the working element is subdivided into three tetrahedral elements. The coefficient matrix for each tetrahedron is then computed, and assembled into the global matrix. DYNFLOW uses the same properties within each element of the triangular prism except for the non-linear case where the phreatic surface spans two working elements in the vertical direction. For this case, averaging of properties for each tetrahedron is done based on the relative portion of the tetrahedron in each originally defined working element.

Types of boundary conditions accepted by DYNFLOW include:

- Specified head boundaries (where the piezometric head is known, such as at streams, lakes or other points of known head)
- Specified flux boundaries (such as rainfall infiltration, well pumping, and no-flow “streamline” boundaries
- Rising water boundaries; these are conditional boundaries (specified head or flux boundary) depending on the system status at any given time
- Head-dependent flux (3rd type) boundaries including “River” and “General Head” boundary conditions.

Boundary conditions can be changed during transient simulations, and output can be created in any of a number of formats to be compatible with GIS/visualization systems or other modeling codes.

The intent, in developing DYNFLOW, was to create not only a versatile, three-dimensional groundwater flow code, but also a simple and flexible data entry and data management capability, which would be more intuitive and more understandable to the typical user than simply inputting a long series of numbers. The development of a graphical user interface and linkages with GIS, database and mesh creation packages has further expedited user interaction.

The code has been applied at hundreds of aquifer evaluations directly by CDM, by independent users, and by academic institutions. Since its original development, continued extensions and improvements to the code have been made. Many of these were in the area of more simplified and powerful input structure, and extensive graphical pre- and post-processing. The graphical capabilities are implemented in the companion code DYNPLOT.

Recent additions to DYNFLOW include the following capabilities:

- Routines for computing agricultural water demands and associated groundwater pumping and recharge
- Soil and unsaturated zone computations
- Stream flow rate and depth computations
- Enhanced data processing capabilities to expedite input of transient pumping, recharge and boundary conditions

The code has proved to be a versatile and flexible code in applications to both simple and complex problems in groundwater hydrology. It is the basis for a whole range of additional DYNSYSTEM codes which can be applied to a site model as developed for DYNFLOW.

DYNTRACK – Solute Transport Model

DYNTRACK simulates three-dimensional contaminant transport in the saturated zone. DYNTRACK uses the same three-dimensional finite element grid representation of aquifer geometry, flow field, and stratigraphy used for a corresponding DYNFLOW model.

DYNTRACK can perform either simple, single-particle tracking along advective flowpaths or can model contaminant transport with particle clouds incorporating three-dimensional dispersion. Chemical constituents may be modeled as either conservative or subject to first-order decay. A special version of DYNTRACK, called DYNBIO models constituent degradation using Monod kinetics. DYNTRACK can also be used to model adsorption. Typically, linear, equilibrium adsorption is simulated. However, capabilities for representing non-linear, non-equilibrium adsorption have also been developed.

Single-particle tracking is typically used to follow the expected advective path of a conservative constituent, to determine an expected location of the center of mass of contamination after a specified time interval, to evaluate capture zones, and to estimate time of constituent travel. It may be used where the effects of dispersion are secondary to a thorough understanding of the groundwater flow field. Commonly, multiple individual particles are simulated with single-particle tracks in a simulation. Special routines have been incorporated into DYNTRACK and DYNPLOT to expedite the application of particle tracking to delineate hydraulic capture zones of wells or other points of discharge. Particle tracks may also be run in a backward mode to help identify potential source locations and source timing for observed groundwater contamination.

The contaminant dispersion section of the code uses the random walk method for a statistically significant number of particles. Each particle is assigned a representative weight. The constituent concentration at each model node is computed from the particle distribution at any time by dividing the total particle weight of all particles within a specific distance from the node by the water volume associated with the node. DYNTRACK simulates dispersion in each time step by imparting a random deflection to the average groundwater velocity in the model element for each particle within that element, given an underlying probability density function. If desired, DYNTRACK simulates contaminant decay by reducing each particle's representative weight according to a first-order decay function. In a simulation with a continuing source, the particles may have a variety of representative weights. Retardation is modeled by adjusting the rate of particle movement and the dissolved concentration associated with a given particle mass.

A solute source can be represented in DYNTRACK as an instantaneous input of solute mass (represented by a fixed number of particles), as a continuous source for which particles are input at a constant rate, or as a specified concentration at a node. Particles are automatically removed at points of discharge such as pumping wells, streams and model boundaries. The discharge mass and concentration is computed and recorded for each node.

Random Walk Method

The fundamental basis of the random walk method is well established in mathematical physics beginning with the early works of Einstein [1905, 1906] on Brownian motion, and Taylor (1921) on turbulent diffusion. This material is discussed in textbooks on diffusion and mixing [e.g. Csanady, 1973, Chap. 2; Fischer et al., 1979, Chap. 2]; applications to porous media are discussed in detail in Bear [1972, Section 10.3.2]. These analyses establish, via the central limit theorem, the normality of the particle distribution after a large number of steps, and the equivalence of the result to the classical diffusive transport equation. In fact, from one point of view, the random walk model can be considered to be the basis for the classical diffusive transport equation. The review article by Weiss [1983] illustrates the broad application of random walk models in many scientific disciplines.

As a practical matter, refinement of numerical solution techniques, whether based on the random walk approach or the classical discrete approximation of partial differential equations, does not necessarily lead to improved engineering solutions. The field data are subject to observational error and natural variability and, in spite of what is commonly presumed, the classical solute transport equation is itself only an approximation of nature. Nevertheless, the random walk method does offer some significant computational advantages; e.g., it inherently conserves mass, is stable, and is not subject to cumulative numerical dispersion.

In more than 15 years of experience with DYNTRACK, in a wide variety of applications, the random walk method has generally proven to be reliable and practical tool for simulating ground water contamination.

DYNSWIM – Sharp Interface Two-Phase Flow Model

DYNSWIM is an extension of DYNFLOW to account for the interaction of salt water and fresh water flow systems. It computes the location of the interface between the two fluids, as well as the pressures and fluxes within each fluid system. DYNSWIM is a fully 3-dimensional model capable of simulating intervening wedges of fresh and salt water, including multiple transitions between two fluids in a vertical column.

DYNSWIM is designed for regional salt water intrusion. Because it is a sharp interface model, it is not suitable for predicting chloride levels in individual wells. The model provides information on the location, thickness, and rate of movement of intruding salt water. It simulates intrusion due to excessive pumping, and the retreat of a salt water front resulting from reduced pumping and higher fresh water heads. The model will also simulate upconing of salt water beneath a pumping center. The model can be utilized to test the effects of groundwater extraction on intrusion, to evaluate the susceptibility of proposed public water supply well locations to salt water intrusion, and to develop and design ways of halting or reversing intrusion using hydraulic barriers through recharge or pumping.

In general terms, DYNSWIM can be thought of as solving two distinct, but linked, flow systems, one for each fluid. Within each system, the computations are the same as DYNFLOW. DYNSWIM links the two systems at the interface on the basis of the following relationships:

- The pressures are equal on each side of the interface.
- For transient simulations, any movement of the interface location is accompanied by an increase in the volume of one fluid system and a decrease of an equal volume from the other fluid system.

For any computational element which includes only one fluid, the hydraulic equations constructed are identical to DYNFLOW. An element which includes both fluids, i.e., the interface exists in the element, is divided into separate sub-layers for each fluid. Temporary nodes are added above and below the interface as part of each computational iteration. Thus, since temporary computational nodes are automatically added at the interface elevation, the precision of the defined interface location is not constrained by the vertical discretization of the model grid.

Hydraulic equations are developed for each sub-element as for any DYNFLOW element with respect to both the temporary interface nodes and the permanent nodes. The local equations for both sub-elements are assembled into the system matrix for simultaneous solution.

For transient simulations, it is necessary to account for water added to storage or removed from storage due to interface movement. That is, when the interface moves, a certain volume of one fluid must be removed and an equal volume of the other fluid added. This constraint tends to damp interface movement. The volume of fluid interchange associated with a unit movement of the interface is proportional to the specific yield specified for the aquifer unit. This is reasonable since interface movement is analogous to phreatic surface movement.

Similar to a phreatic surface, assumed values of interface location are estimated to preserve the linearity of the system equations. After each solution of the system equations, a new estimate of interface location is defined based on the newly computed heads. In DYNSWIM, solution iterations are required even for fully confined aquifer systems.

Since DYNSWIM and DYNFLOW share the same database, input conventions, and output formats, data developed for a single phase flow model are easily transferred to DYNSWIM, including model geometry, hydraulic properties, fluxes and boundary conditions.

Prior to making a simulation with DYNSWIM, a working fresh water model of the area of interest is typically developed. The onshore or fresh water portion of the model is then typically calibrated using DYNFLOW in conjunction with a suitable set of boundary conditions at the shoreline before starting the salt water simulations. The additional input requirements for DYNSWIM beyond the requirements for a DYNFLOW simulation are minimal. These include an initial position of the salt water system, fluid densities and viscosities, and computational parameters.

DYNCFT - Coupled Flow-Transport Model

DYNFLOW and DYNTRACK have been combined into a single code capable of simulating coupled flow and transport. Coupling flow and transport computations allows the effect on groundwater flow of fluid density gradients associated with solute concentration gradients to be incorporated into model simulations. The main application will be in studies of seawater intrusion where dispersion of salt into the fresh water zone needs to be quantified and mapped.

The flow and transport computations in DYNCFT are loosely coupled. At each time step, the flow computations are completed first, holding densities constant, then the transport computations are completed. The flow computations are identical to DYNFLOW with the following exceptions.

- Preceding the flow computations, fluid density at each node is computed based on the current simulated concentration.
- The flow computations are revised to account for fluid density. This includes converting head values to equivalent fresh water head, and adding terms in the matrix assembly which incorporate density and elevation.

Transport computations for the current time step are performed immediately after the flow computations, using updated values of computed head. The groundwater flow velocity computations are revised to account for fluid density. Otherwise, the transport computations are the same as DYNTRACK.

Since flow and transport computations are loosely coupled, the computational time step must be selected carefully. This may involve some sensitivity testing.

All DYNFLOW and DYNTRACK commands work the same in DYNCFT. Also, any data files created by or for DYNFLOW or DYNTRACK may be read and processed by DYNCFT, and vice versa. Thus, the same modeling database is shared among these programs.

It is sometimes useful to incorporate the hydraulic influence of a salt water wedge without doing transport computations to simulate movement of the wedge. Using DYNCFT it is possible, for example, to perform "steady-state" flow simulations incorporating density effects in a situation where the wedge is not necessarily stable over the long term. The advantage is that the effects of a dense saline plume on nearby fresh water flow may be accounted for in relatively quick, simple simulations. In this case the user inputs values of density at selected nodes to represent sea water, and suppresses transport computations.

EXAMPLE APPLICATIONS

Following are some brief examples of different ways DYN programs have been applied to address coastal and salt water intrusion issues.

Central Valley, CA

An ongoing groundwater management study is assessing strategies to alleviate the existing depressed water levels in the vicinity of Stockton, CA. Alternatives being considered include proposed groundwater recharge projects, as well as converting agricultural and municipal water supplies from groundwater to surface water.

The modeling includes potential changes in land use and agricultural practices. For this purpose, DYNFLOW modules for processing monthly water consumption for different crops and estimating agricultural pumping and irrigation return flows are being applied. Linkages between DYNFLOW and GIS transfer land use and crop data directly to the model. Figure 6 is an ArcView plot illustrating the assignment of land use categories to model elements.

Transient groundwater flow simulations incorporating alternative management scenarios have been made using DYNFLOW. These DYNFLOW simulations include surface water flow and depth (in the river) as well as groundwater flow. Quantifying changes in groundwater-surface water interaction as well as the effects on stream flow of increased water supply diversions is an important aspect of this study.

One of the most significant impacts of the Stockton cone of depression is the induced intrusion of high salt content water towards Stockton from saline aquifers to the west. Particle track simulations using DYNTRACK have been used to estimate changes in the rate of intrusion resulting from different management options. Since measured chloride concentrations are typically less than 1,000 ppm, particle tracking in conjunction with single-phase flow modeling is considered to be reasonably representative of relative migration rates. Such particle tracking is a much quicker and simpler process than transport modeling, and for this study provides a valuable indication of the relative effectiveness of various management alternatives. Figure 7 illustrates simulated particle tracks superimposed on simulated groundwater head contours.

Ewa Plain, Hawaii

Sharp-interface seawater intrusion and groundwater flow modeling was conducted using DYNSWIM to estimate potential impacts of excavation for a proposed marina on the shallow Caprock aquifer in the Ewa Plain on Oahu. In this instance, single-phase flow modeling was not appropriate because the intruding sea water wedge has a significant effect on near-shore groundwater flow. Since the study focussed on potential changes in head and shifts in the saltwater-fresh water interface due to construction, DYNSWIM was selected as an appropriate tool. Also, available field data indicated a limited zone of transition from sea water to relatively fresh water, and thus the assumption of a sharp interface was reasonable for the purposes of this study.

Based on previous 2-dimensional (plan view) groundwater modeling, it had been erroneously concluded that a band of relatively impermeable limestone existed near the shore, and that breaching this low permeability formation by marina construction might significantly reduce heads and increase seawater intrusion in the aquifer. However, further studies and DYNSWIM modeling indicated that the relative relatively sharp head gradients observed near the shoreline were better explained by vertical to horizontal anisotropy of aquifer hydraulic conductivity. Because the previous modeling was 2-dimensional (plan view), the significant vertical component of fresh water flow as it moves over the intruding seawater wedge near the shoreline was neglected. The much greater resistance to vertical flow compared to horizontal flow typical in this type of aquifer causes the sharp head gradients at the fresh water discharge zone near the shoreline.

Part of the model calibration and verification process for this study included transient simulation of the water level response to tidal fluctuations measured at a line of monitoring wells extending nearly 4,000 feet from the shoreline. For this purpose, a 2-dimensional, cross-section model of the Caprock aquifer was created using DYNSWIM. The model represented a strip of aquifer perpendicular to the shore, extending 10,000 feet onshore and 4,000 feet offshore. The tidal signal was defined by adjusting specified water levels at model nodes representing the seabed during the course of the simulation according to measured tidal fluctuations, and recording the time history of simulated heads at nodes representing the monitoring well locations. Figure 8 shows simulated water level time histories at various distances from the shoreline, as well as the input tidal signal. The attenuation and lag of the tidal fluctuations with distance from the shore is evident in Figure 8.

Figure 9 shows contours of the simulated freshwater-salt water interface prior to construction. The modeling indicated that head and seawater intrusion impacts due to construction would be limited; moreover, the modeling indicated that the pending cessation of sugar cane farming on the plain, supported in part by irrigation using imported water, would likely have a more far reaching impact on the aquifer conditions.

While 2-dimensional modeling was suitable for simulating tidal response in the aquifer with no marina, potential convergence of flow towards the marina required that 3-dimensional modeling be applied to estimate construction impacts.

Integrated Aquifer Management Plan, Gaza

Mitigating salt water intrusion in a coastal aquifer subject to significant over-development is one of the primary objectives of an integrated aquifer management plan recently developed for the Gaza Strip. Figure 2 shows a perspective view of the Gaza model (using GMS to display DYN stratigraphy). For this project, links from DYNCFT to GMS were utilized to create such perspective views and also to create an animated presentation of modeling results. The application of coupled flow-transport modeling using DYNCFT is described in another paper presented at this conference. One aspect of model application for this project is briefly described below.

Initial flow model calibration for the coastal aquifer was conducted using DYNFLOW. Because DYNFLOW is a single-phase flow modeling code, density effects of salt water offshore and near shore were not explicitly accounted for. In such cases, density effects are typically approximated by specifying and fixing equivalent fluid heads at the offshore boundary. However, for the Gaza situation reliable flow model calibration could not be achieved without a better representation of salt water density effects.

This created a potential difficulty because, for recent calibration periods, it was not possible to make reasonable steady-state coupled flow-transport simulations. The equilibrium seawater position for recent (late 1990’s) pumping and recharge conditions envelops a number of major production wells and is not representative of actual conditions which have not yet reached equilibrium. At the same time, it was not practical to conduct initial flow model calibration in transient mode, since the initial calibration process would be unduly slowed by the significantly greater data handling and computational burden required by long term transient simulations. (Long term transient calibration simulations were conducted after completion of the initial steady state calibration simulations had significantly narrowed the feasible range of a number of model parameters.)

The solution adopted was to run DYNCFT in a steady state “flow-only” mode, with seawater fluid density specified at offshore and near-shore model nodes. In this simulation mode, no transport computations were performed and assigned fluid density values at model nodes were not changed. However, the groundwater flow computations did explicitly include the effect of the specified fluid density distribution on flow and head. Using this approximation during the calibration stage provided a much better initial calibration than using a single-phase model and setting equivalent fluid heads offshore, and it was much more efficient than processing and analyzing long term transients.

Long Island, New York

DYNSWIM has been applied over the past 10 years in regional and sub-regional applications to investigate past and future seawater intrusion at both the North and South

Shores of the Island. The model is also used to assess groundwater management strategies for mitigating potential salt contamination problems in the multi-layer aquifer system which provides the only source of fresh water to most of Long Island. A perspective view of the Nassau County, Long Island regional groundwater model is shown in Figure 3. The application of DYNSWIM and DYNFLOW has allowed development of a detailed assessment of aquifer conditions, and development of an effective long term management plan for sustainable utilization of this coastal resource.

A number of detailed, local-scale models have been developed for site specific studies using the regional Long Island models as a basis. The local models were "telescoped" from a regional model using automated data conversion and interpolation routines provided in DYNPLOT. For example, detailed DYNFLOW, DYNTRACK and DYNSWIM modeling of a shallow well field near the South Shore was completed to assess different possible sources and pathways for salt contamination to reach the well field, and estimate the potential for future water quality deterioration due to salt water intrusion.

Seawater intrusion modeling for the Eastern Forks of Long Island using DYNSWIM and DYNCFT is currently underway.

Los Angeles Basin, California

DYNFLOW and DYNTRACK models were applied to evaluate the effectiveness of an injection well barrier operated to inhibit seawater intrusion in the West Coast Basin of Los Angeles. The injection barrier consists of 144 wells extending over a distance of approximately 8 miles, injecting an average of approximately 25,000 acre-feet (30 million cubic meters) of water per year. An 8-layer model was developed to represent the complex stratigraphy. The model was used to project future migration and impact of remnant salt plumes which exist shoreward of the barriers, as well as to evaluate strategies for enhancing barrier effectiveness. Alternative management approaches simulated included modifying barrier injection rates, constructing new injection wells, constructing new wells to extract brackish water, reducing water supply withdrawals from the basin and relocating existing water supply wells. A similar modeling study was subsequently conducted for the Dominguez Gap area of the Central Basin.

Gulf Coast, Florida

DYNSWIM modeling was conducted to estimate potential seawater intrusion impacts in the Floridan aquifer due to operation of a proposed new well field. This work was required to obtain a permit for the new well field.

Alternatives to developing the new well field that were considered included constructing a new deep water supply well at the shoreline, and using reverse osmosis to desalinate brackish water pumped from this well. DYNSWIM and DYNTRACK modeling was used to estimate future salt concentrations at the proposed new deep well. Based on this analysis, it was concluded that rapid degradation of the water quality at the well site could occur once production pumping was applied. Under these conditions, desalination of brackish water from this well was no longer considered the most economical option available to the water purveyor. During the studies, the modeling work also clarified the rate at which other near-shore production wells might be expected to reach salinity levels above drinking water limits.

SUMMARY

This paper has presented a series of inter-related codes that together can address the issues related to effective management of coastal aquifer systems. Fully 3-dimensional groundwater flow in multi-aquifer systems can be simulated. Management practices such as Aquifer Storage and Retrieval (ASR), injection barrier wells, optimization of pumping locations and depths, can be evaluated. The codes represent two decades of development, refinement, and application and have proven themselves in practice. The authors suggest that future evolution will be to continue to enhance the computational capabilities of existing mature codes while adding linkages to widely used graphical, GIS, and support programs.

REFERENCES

Bear, J. Dynamics of Fluids in Porous Media. American Elsevier. 1972.

Csandy, G.T. Turbulent Diffusion in the Environment. D. Riedel Pub. Co. 1973

Einstein, A. "Uber die von der Molekular-kinetischen Theorie der Warme gerfordete Bewegung von in ruhenden Flussigkeiten suspendierten Teilchen." Ann. Der Physik. 17:154-60. 1905.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, N.H. Brooks. Mixing in Inland and Coastal Waters. Academic Press, 1979.

Huang, Y.H., S.J. Wu. "Analysis of Unsteady Flow Toward Artesian Wells by Three-Dimensional Elements." Research Report No. 75, University of Kentucky, Water Resources Research Institute. Lexington, Kentucky. 1974.

Taylor, G.L. "Diffusion by Continuous Movements." Proc. Lond. Math. Soc. 20:196-212. 1921-22.

Weiss, G.H. "Random Walks and Their Applications." American Scientist. Pp. 65-71. Jan.-Feb. 1983.

Keywords: groundwater models, salt water intrusion, water supply planning, coastal aquifer management, sharp interface models, coupled flow-transport models

Corresponding Author: Robert Fitzgerald, Camp Dresser & McKee Inc., 50 Hampshire Street, Cambridge, MA 02139, USA. E-mail: FitzgeraldRH@CDM.COM

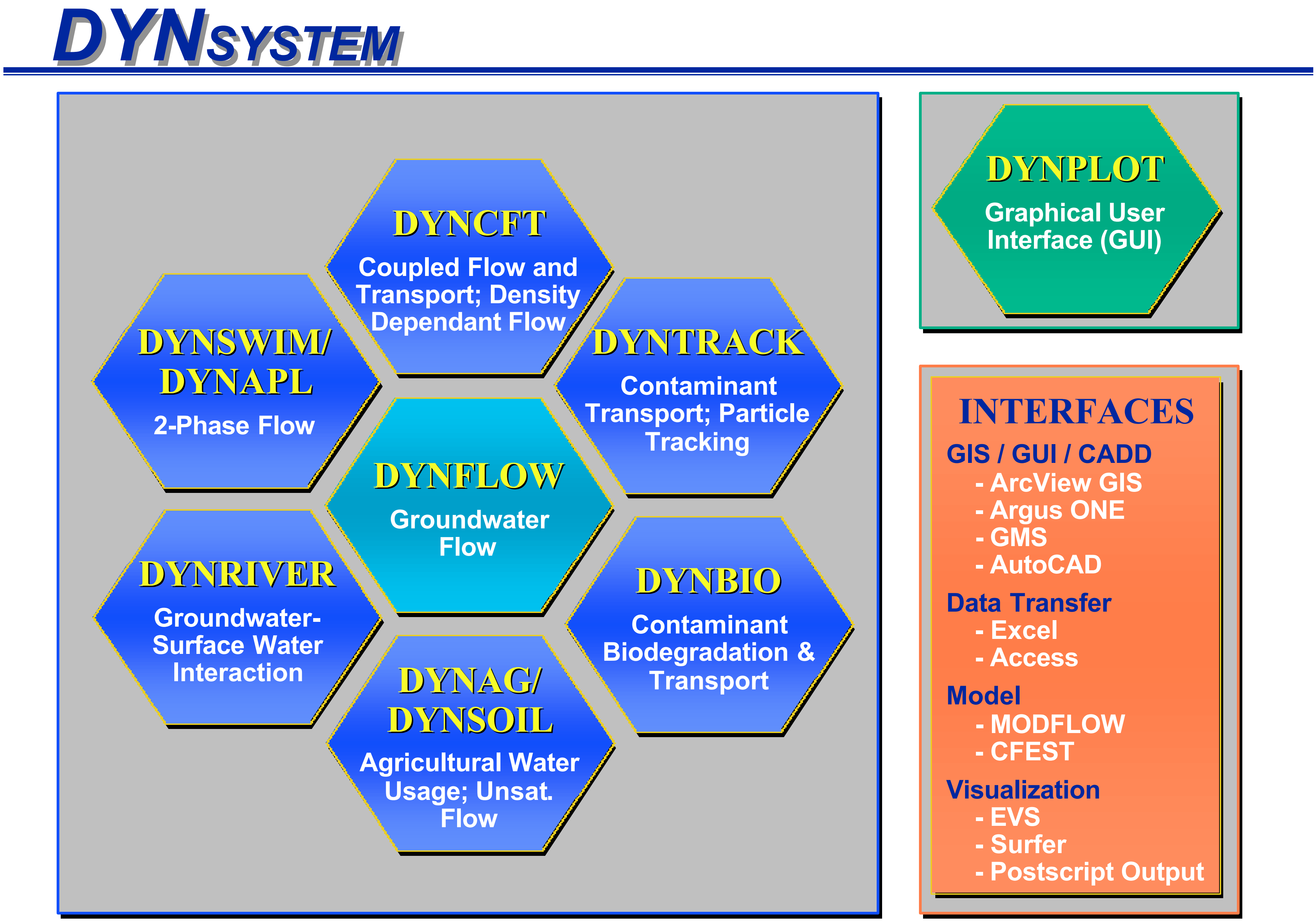

Figure 1: DYNSYSTEM Functionality

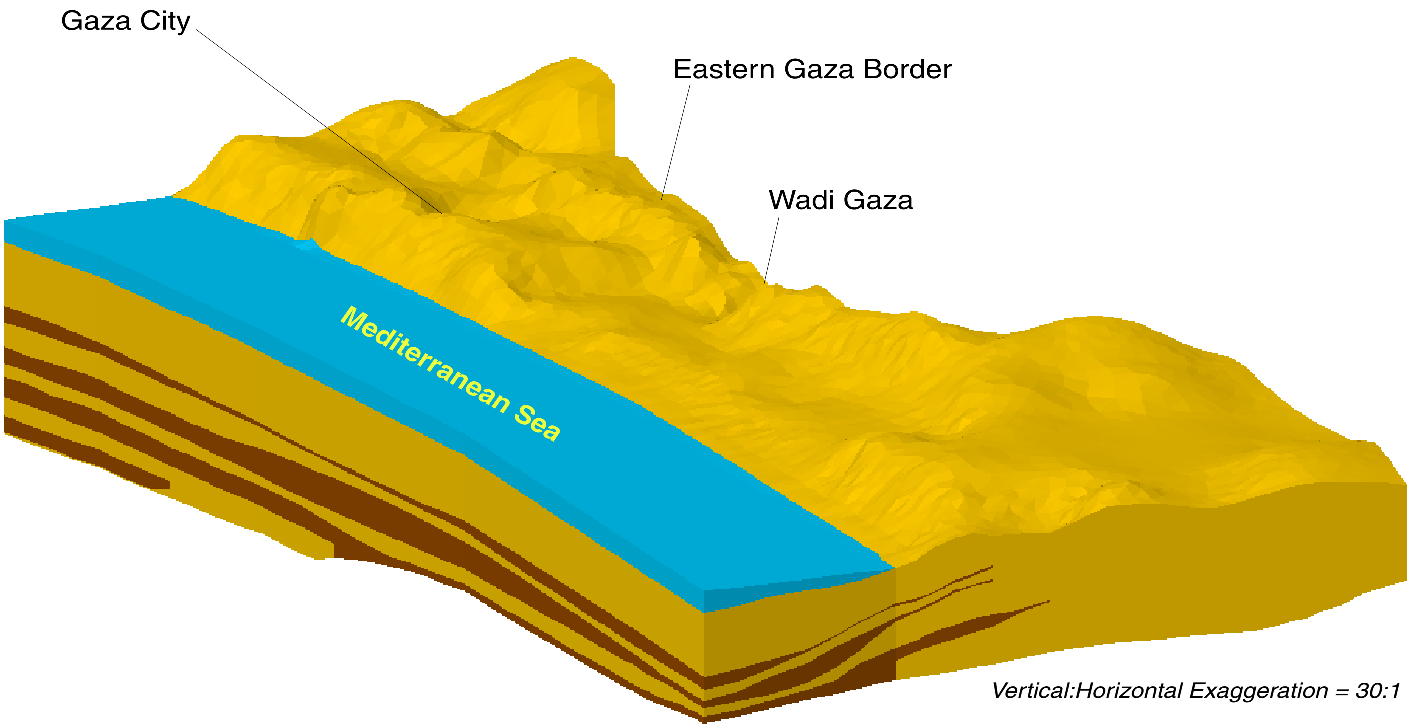

Figure 2: Model Topography and 3-D View of Stratigraphy, Gaza Strip

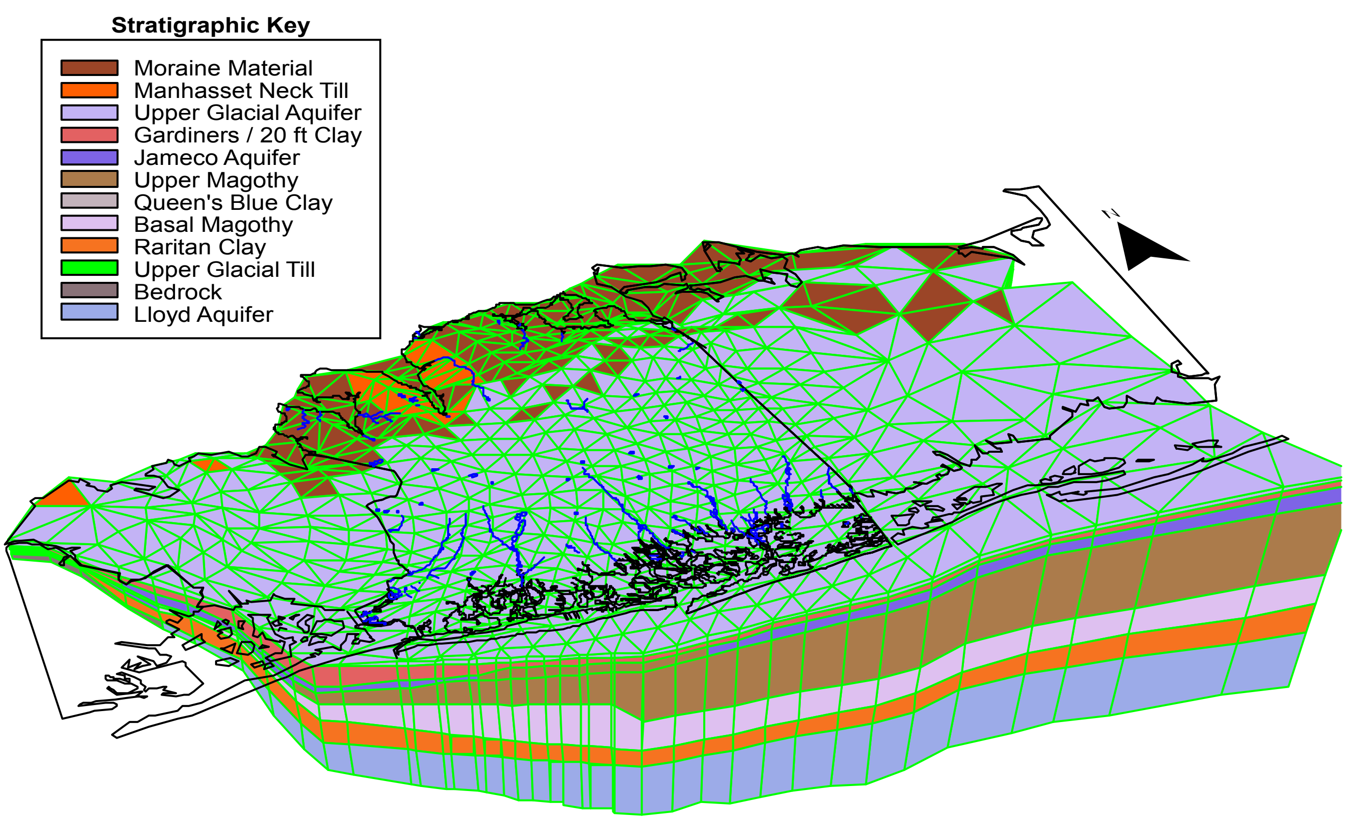

Figure 3: 3-D View of Model Grid and Stratigraphy, Long Island, NY

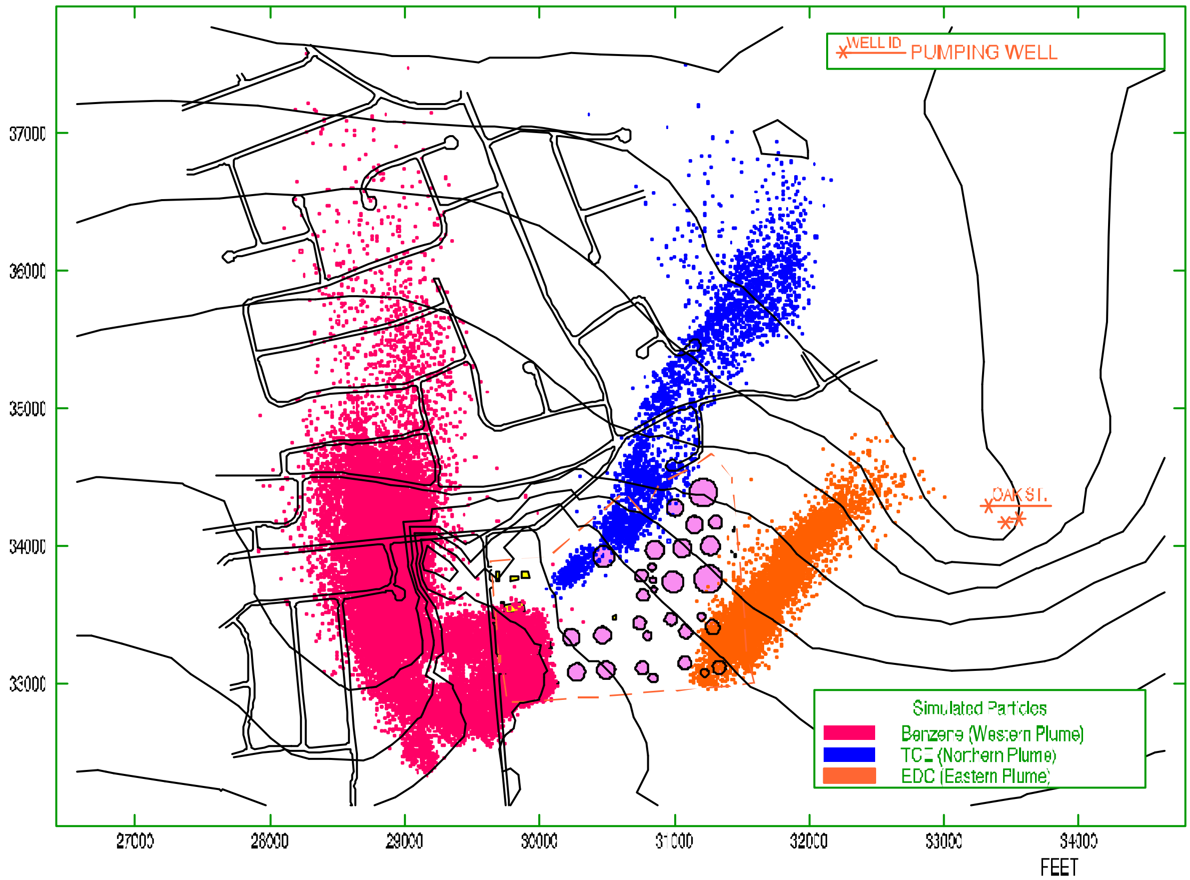

Figure 4: Simulated Multiple Constituent Particle Clouds

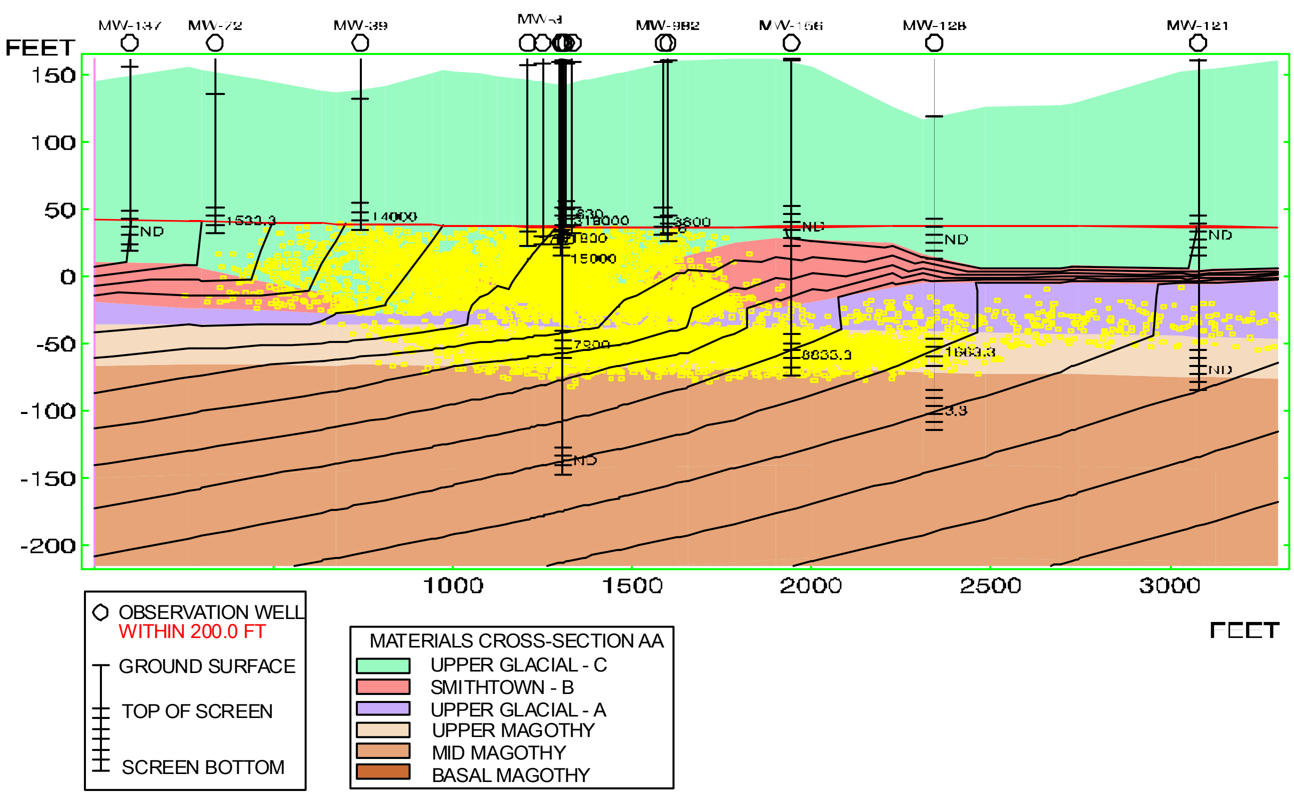

Figure 5: Simulated Particle Cloud and Observed Concentrations

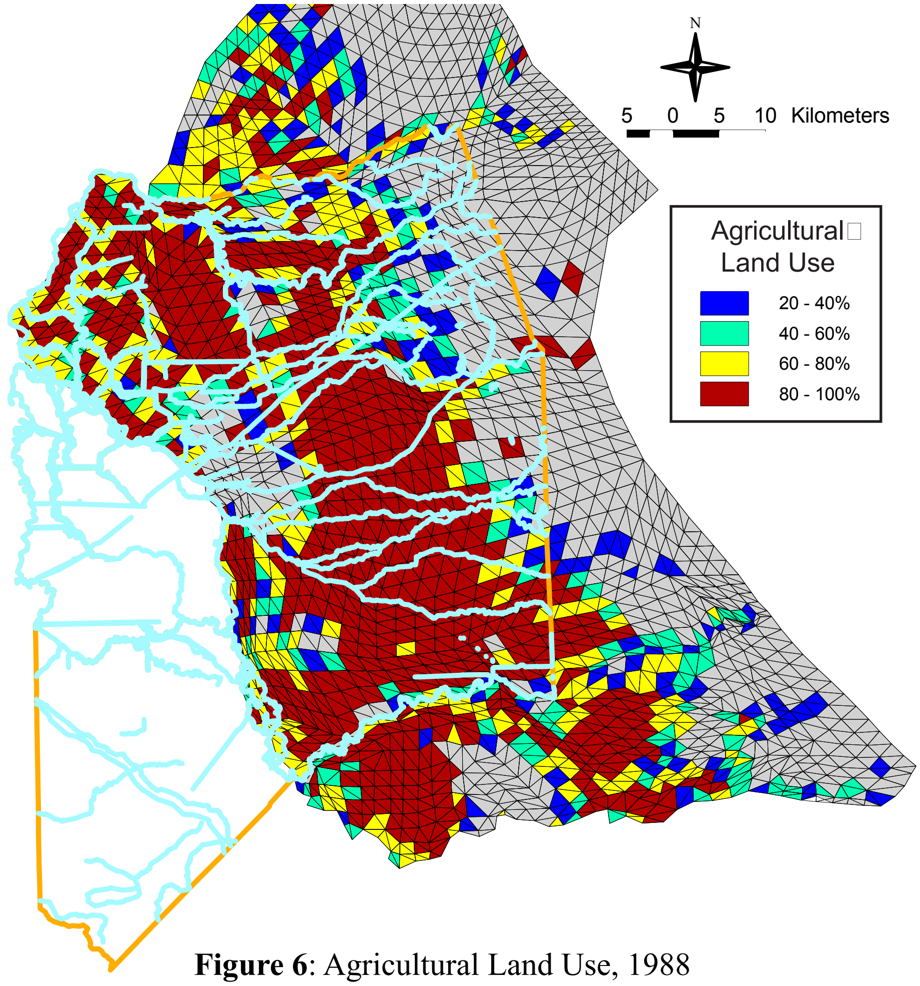

Figure 6: Agricultural Land Use, 1988
Central Valley, California

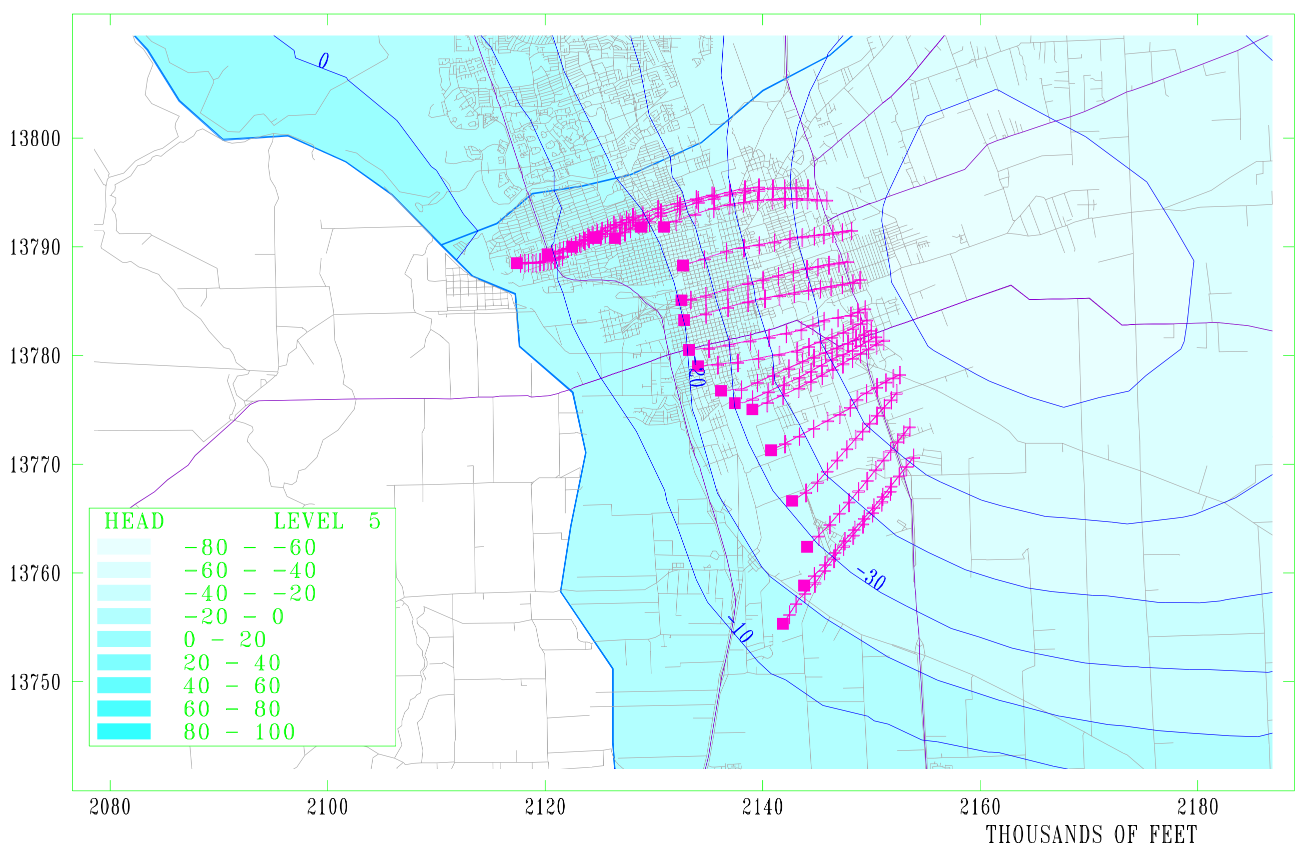

Figure 7: Simulated Particle Tracks (60 Years, 5 Year Intervals)
Based on Estimated Location of Saline Front
Central Valley, California

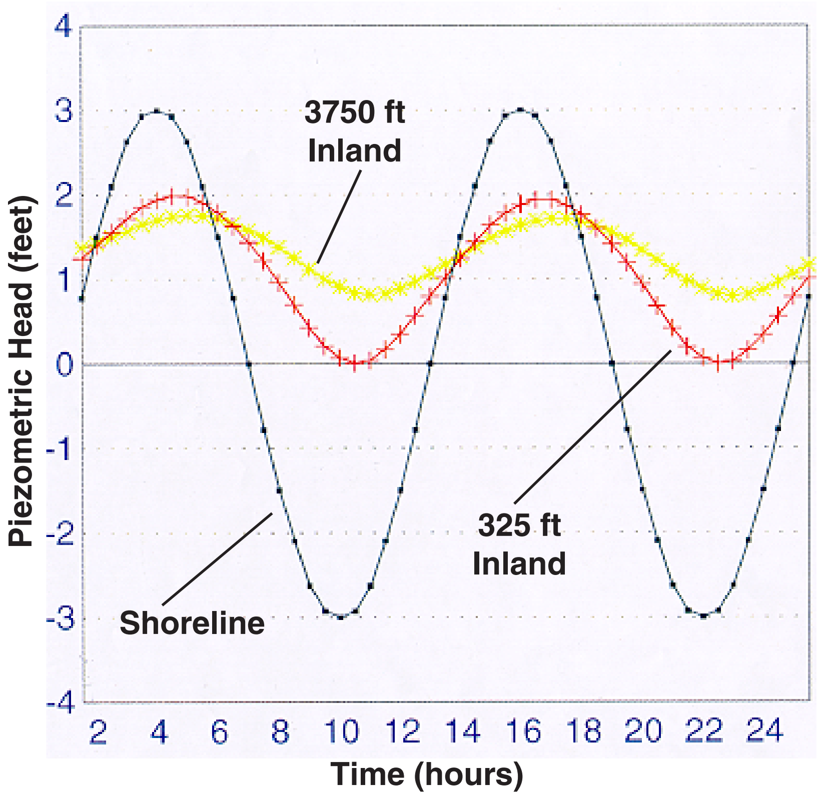

Figure 8: Simulated Tidal Response
Ewa Plain, Hawaii

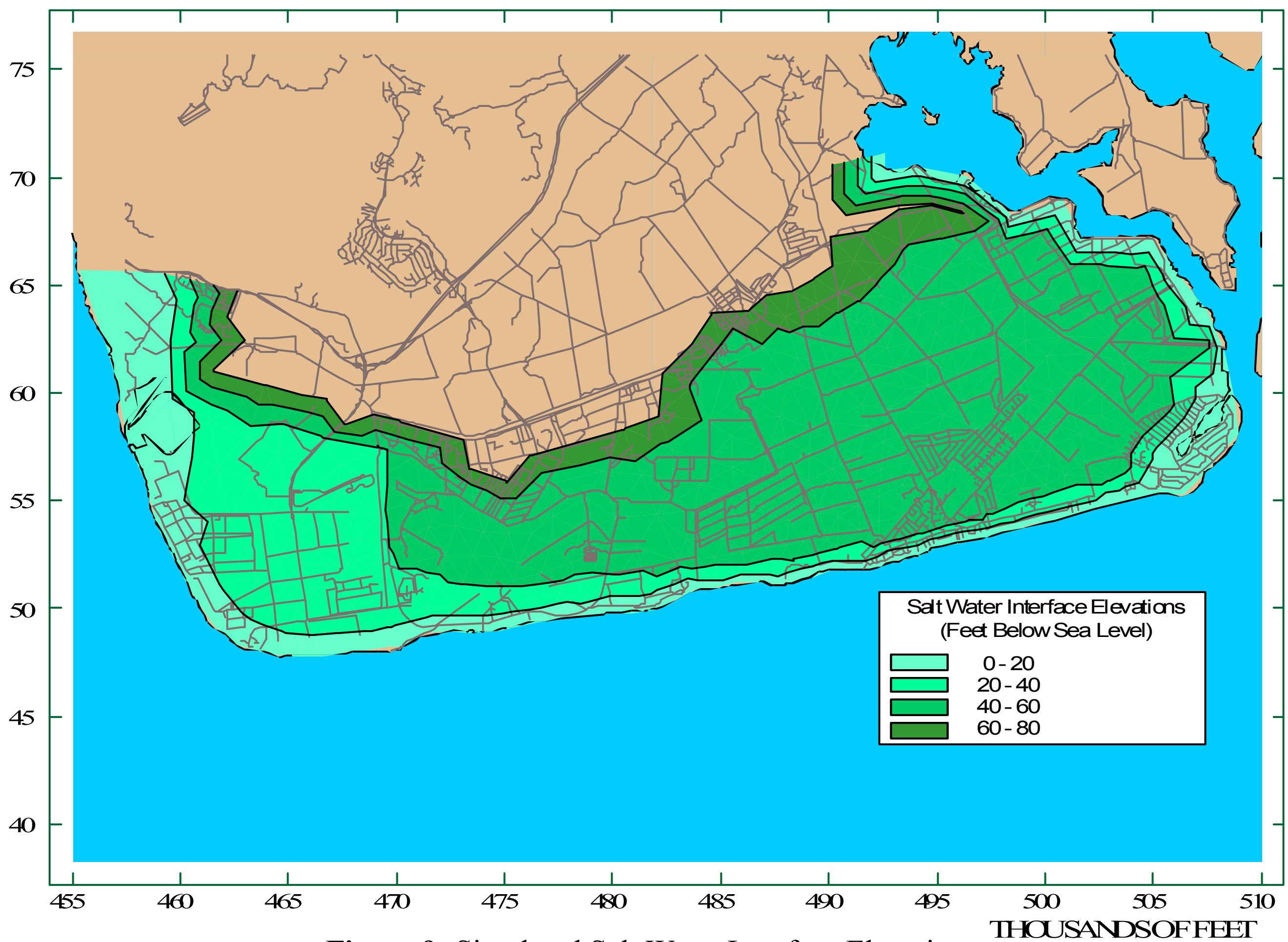

Figure 9: Simulated Salt Water Interface Elevations
Ewa Plain, Hawaii