Table of Contents

1.0 Introduction ..........................................................................................................1
  1.1 Purpose and scope of report ..............................................................................1
  1.2 Description of study area ..................................................................................1
    1.2.1 Physiographic features ...........................................................................1
    1.2.2 Hydrogeologic features ...........................................................................2
    1.2.3 Basin boundary ......................................................................................3
    1.2.4 Cultural features ...................................................................................4
    1.2.5 Water use ..............................................................................................5
    1.2.6 Groundwater conditions .......................................................................5
  1.3 Model code used ................................................................................................6

2.0 Data used .............................................................................................................9
  2.1 Previous work ...................................................................................................9
  2.2 Hydrogeologic information .............................................................................9
  2.3 Well inventory ..............................................................................................10
  2.4 Groundwater levels ......................................................................................11
  2.5 Groundwater pumping .................................................................................11
  2.6 Groundwater recharge ..................................................................................11
    2.6.1 Prior investigations ...............................................................................11
    2.6.2 Satellite-image analysis ........................................................................12

3.0 Model development ...............................................................................................15
  3.1 Model assembly .............................................................................................15
    3.1.1 Finite-element mesh .............................................................................15
    3.1.2 Time step, simulation periods, and unit dimensions .........................16
    3.1.3 Recharge volumetric and solute fluxes ...............................................17
    3.1.4 Pumping volumetric and solute fluxes ...............................................18
    3.1.5 Boundary conditions ..........................................................................19
    3.1.6 Initial conditions ..................................................................................21
  3.2 Aquifer-parameter identification ...................................................................22
    3.2.1 Identification approach ........................................................................22
    3.2.2 Calibration results ...............................................................................25

4.0 Model simulations of future conditions ...............................................................27

5.0 Conclusions .......................................................................................................28

6.0 References cites ................................................................................................29
## List of Figures

| Figure 1.1 | Map showing location of Seaside groundwater basin. |
| Figure 1.2 | Map showing physiographic and cultural features. |
| Figure 1.3 | Map showing hydrogeology. |
| Figure 1.4 | Diagrams showing cross sections through Seaside groundwater basin:  
  a. Northeast to southwest section.  
  b. Northwest to southeast section. |
| Figure 1.5 | Maps showing base altitudes of hydrogeologic units:  
  a. Santa Margarita Formation.  
  b. Purisima Formation.  
  c. Paso Robles Formation.  
  d. Surficial deposits.  
  e. Salinas Valley clay |
| Figure 1.6 | Map showing model boundary and alternative groundwater-basin boundaries. |
| Figure 1.7 | Map showing satellite image of groundwater basin, March 2000. |
| Figure 1.8 | Maps showing groundwater levels for Fall 2002:  
  a. Paso Robles Formation.  
  b. Santa Margarita Formation. |
| Figure 1.9 | Maps showing extent of seawater intrusion:  
  a. Salinas Valley 180-foot aquifer.  
  b. Salinas Valley 400-foot aquifer. |
| Figure 2.1 | Map showing locations for production wells. |
| Figure 2.2 | Map showing locations for monitoring wells. |
| Figure 2.3 | Maps showing geographic distribution of NDVI*:  
  e. October, 1993.  
| Figure 2.4 | Map showing location of CIMIS sites. |
| Figure 3.1 | Diagram showing element types used to construct finite-element mesh. |
| Figure 3.2 | Map showing finite-element mesh. |
| Figure 3.3 | Diagram showing oblique view of finite-element mesh. |
| Figure 3.4 | Diagrams showing cross sections through finite-element mesh:  
  a. Northeast to southwest section.  
  b. Northwest to southeast section. |
| Figure 3.5 | Diagram showing contraction of element column. |
| Figure 3.6 | Diagram showing horizontal weighting of pumping from a well to a node. |
| Figure 3.7 | Diagram showing vertical weighting of pumping from a well to a node. |
| Figure 3.8 | Map showing location of specified-head boundaries |
| Figure 3.9 | Graph showing specified heads along Reliz Fault. |
Figure 3.10  Maps showing initial heads assigned to model:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 3.11  Maps showing initial salinity assigned to model:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 3.12  Graphs comparing computed heads and measured groundwater levels:
   a. Unweighted residuals.
   b. Weighted residuals.

Figure 3.13  Maps showing computed heads for 2002:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 3.14  Maps showing computed salinity for 2002:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 4.1  Maps showing computed heads for 2002 with continued pumping:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 4.2  Maps showing computed salinity for 2002 with continued pumping:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 4.3  Maps showing computed heads for 2002 with relocated pumping:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.

Figure 4.4  Maps showing computed salinity for 2002 with relocated pumping:
   a. Paso Robles Formation.
   b. Santa Margarita Formation.
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Location and construction of production wells.</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Location and construction of monitoring wells.</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Measured groundwater levels in wells.</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Annual pumping from production wells.</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Attributes of CIMIS stations.</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>ET corresponding to 1993 satellite images.</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Hydraulic and transport parameters assigned to model.</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Groundwater budget for 2002.</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Groundwater budget for 2015 with continued pumping.</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Groundwater budget for 2015 with relocated pumping.</td>
</tr>
</tbody>
</table>
1.0 Introduction

1.1 Purpose and Scope of Report

The Seaside groundwater basin, which is located adjacent to and beneath Monterey Bay (Figure 1.1), has been the subject of an ongoing adjudication. Groundwater pumping exceeds the natural and secondary recharge, groundwater levels have been declining, and the adjudication has focused on the corresponding threat of seawater intrusion. While seawater intrusion has not been detected, except near Marina, the parties to the adjudication recognized the inevitability of eventual seawater intrusion were existing conditions to continue. However, the parties did dispute the best approach to addressing the threat, with respect to both the institutional setting and the physical solution.

A trial was held during late 2005 in the Monterey County Superior Court to adjudicate the disputed issues. The outcome was that the Court ordered the creation of a Watermaster, which was to be comprised of a collective of water users. The Watermaster was directed to monitor groundwater conditions, develop a physical solution, and implement the solution. The Court directed that the Watermaster report periodically to the Court on progress toward meeting it obligations.

An obligation of the Watermaster is to develop a groundwater model. During the trial, the testimony for the California-American Water Co. included the description of a groundwater model, which was used to evaluate the threat of seawater intrusion. In its post-trial decision, the Court ordered the creation of a groundwater model. Subsequently, the Watermaster decided the groundwater model developed for California American Water could meet the current basin-management needs. That model includes both groundwater flow and solute transport components. The trial testimony did not include written documentation of the model, which the Watermaster needs in order to use the model.

This report represents the needed documentation. The objective of the report is to describe the available data, the use of the data to develop the model, the predictive simulations, and the structure of the model input files. The documented model is the same as that presented to the court during the trial.

1.2 Description of Study Area

1.2.1 Physiographic Features

The Seaside groundwater basin underlies the hills and coastal plane at the northern end of the Sierra de Salinas (Figure 1.2). The principal drainages are Arroyo del Rey and El Toro Creek. Arroyo del Rey is a northwestward flowing tributary to Monterey Bay. El Toro Creek is a northeastward flowing tributary to the Salinas River.
While Arroyo del Rey and El Toro Creek drain mostly the upland areas overlying the groundwater basin, smaller streams drain the coastal plane toward Monterey Bay.

Yates and others (2005) examine the possible contributions of these streams to groundwater recharge. They concluded that El Toro Creek and Arroyo del Rey contribute insignificantly to groundwater recharge. Along limited reaches, these streams gain streamflow from groundwater discharge. However, the stream-aquifer exchanges are not important to either the groundwater budget or the response of the groundwater basin to pumping. Yates and others (2005) also concluded the smaller streams contribute insignificantly to groundwater recharge.

1.2.2 Hydrogeologic Features

The Seaside groundwater basin is underlain by six hydrogeologic units ranging from Miocene to Holocene age. From oldest to youngest, these units include the Monterey Formation of Miocene age, the Santa Margarita Formation of Miocene to Pliocene age, the Purisima Formation of Miocene to Pliocene age, the Paso Robles Formation of Pliocene to Pleistocene age, the Aromas Formation of Pleistocene Age, and surficial deposits of Pleistocene to Holocene age (Greene, 1970; Greene, 1977; Logan, 1982; Muir, 1982; Clark and others, 1997; Saucedo and others, 2000; Feeney and Rosenberg, 2002; Wagner and others, 2002). Figure 1.3 shows the surficial occurrences of these units, and Figures 1.4a-b show generalized cross sections through the groundwater basin. The map and cross sections represent generalizations derived for CH2M/Hill (2005) and Yates and others (2005).

While the Monterey Formation is essentially non-water-bearing, the younger units contain the active groundwater system. The Monterey Formation consists of low-permeability marine shale and mudstone, and locally is as much as 3,000 ft in thickness. The overlying Santa Margarita Formation consists of moderately-permeable sandstone, and locally is as much as 400 ft in thickness. The overlying Purisima Formation consists of poorly-permeable to moderately-permeable gravels to silty clays, which typically are poorly consolidated. The formation locally is as much as 1,000 ft in thickness. The overlying Paso Robles Formation consists of moderately-permeable to highly permeable gravels to silts, which typically are moderately consolidated. The formation locally is as much as 700 ft in thickness. The overlying Aromas Formation consists of highly-permeable sands deposited by wind and waves, and locally is as much a 200 ft in thickness. The contemporaneous and overlying surficial deposits consist of moderately-permeable to highly-permeably alluvial and other clastic deposits, and locally may be as much as 200 ft in thickness.

Figure 1.5a shows the extents and base altitudes of the Santa Margarita, Purisima, and Paso Robles formations. It shows also the extents and base altitudes of the surficial deposits and Salinas Valley clay. The Santa Margarita Formation underlies most of the landward part of the groundwater basin and the eastern seaward part (Figure 1.5a). The Purisima Formation underlies the northern landward part of the groundwater basin and eastern seaward part (Figure 1.5b). The Paso Robles Formation underlies all of the...
landward part of the groundwater basin and the eastern seaward part (Figure 1.5c). The surficial deposits underlie the central part of the groundwater basin (Figure 1.5d). The Salinas Valley clay underlies a small area along the northern landward boundary of the groundwater basin (Figure 1.5e).

The base altitudes shown on Figures 1.5a-e were developed from various sources. For the landward part of the groundwater basin, the altitude contours represent extrapolations from the cross sections developed by CH2M/Hill (2005) and Yates and others (2005). For the seaward part of the groundwater basin, the contours represent a generalization and extrapolation from Greene (1970) and Greene (1977).

The top of the Monterey Formation represents the stratigraphic base of the groundwater basin, and the active groundwater system is limited to the overlying more-permeable formations. The altitude ranges from 1,800 ft below sea level to 1,600 ft above sea level. However, within much of the geographic area where the Monterey Formation is overlain, the base of the groundwater system is below sea level. Within most of the landward part of the groundwater basin, the Monterey Formation is overlain immediately by the Santa Margarita Formation, and the lowest interval of the groundwater system is contained in that formation. Along the eastern margin of the basin, the Monterey Formations is overlain immediately by the Paso Robles Formation, and there the lowest interval of the groundwater system is contained in that formation. Within the western seaward part of the groundwater basin, the Monterey Formation is overlain immediately by the Purisima Formation, and the lowest interval of the groundwater system is contained in that formation.

The groundwater basin is intersected by several significant northwest-trending faults as shown on Figure 1.3. The Chupines Fault is the most southerly. The Monterey Formation is displaced downward on the northeast side by about 100 ft. The Seaside Fault is located about 2,000 ft northeast of the Chupines Fault. There, the Monterey Formation is displaced downward on the northeast side by about 200 ft. The Ord Terrace Fault is located about 6,000 ft northeast of the Seaside Fault. There, the Monterey Formation is displaced downward on the northeast side by about 50 ft. The Reliz Fault is located near the Salinas River about 30,000 ft northeast of the Ord Terrace Fault. There, the Monterey Formation is displaced downward on the northeast side by as much as 1,000 ft.

While the vertical displacement along faults impact the geometry of the groundwater basin, they do not appear to have much influence on groundwater flow. However, the Ord Terrace Fault may represent an exception. Within the southeastern part of the groundwater basin, the Ord Terrace Fault appears to be responsible for abruptly lower groundwater levels on its north side relative to its south side, at least as interpreted by Yates and others (2005). However, the supporting water-level data are so sparse that the actual influence of the Ord Terrace Fault is uncertain.

1.2.3 Basin Boundary
Various investigators have variously delineated the boundary of the Seaside groundwater basin. The California Department of Water Resources (2003) defines two subbasins of the Salinas Valley groundwater basin within the Seaside area (Figure 1.6). The Seaside Area Subbasin extends along the Monterey Bay coastal plane from the Chupines Fault to the Reliz Fault, and it includes the communities of both Seaside and Marina. The Corral de Terra Area Subbasin comprises the upland areas east of the coastal plane. CH2M/Hill (2005) defined the Seaside groundwater basin (Figure 1.6) as consisting only of the southern one-half of the area defined by the California Department of Water Resources (2003) as the Seaside Area Subbasin. Yates and others (2005) similarly defines the Seaside groundwater basin (Figure 1.6), except that the northern boundary of his delineation is about 4,000 ft south of the CH2M/Hill (2005) boundary. Both CH2M/Hill and Yates located the northern boundary based not on a hydrologic feature but on the assumed occurrence of a groundwater divide. While such a divide would represent a no-flow boundary, CH2M/Hill (2005) and Yates and others (2005) both inconsistently ascribe northward groundwater flow across the boundary.

For the development of the groundwater model, the Seaside groundwater basin (Figure 1.6) includes both Seaside Area Subbasin and Corral de Terra Area Subbasins as generally described by the California Department of Water Resources (2003). The southwestern boundary is represented by segments of the Chupines, Seaside, and Ord Terrace faults, the northeastern boundary is the Reliz Fault, the southeastern boundary is the surface contact between the Monterey Formation and the overlying formations, and the offshore boundary is the subsea contact between the Monterey Formation and the overlying formations (Greene, 1970; Greene, 19977). Except at the Reliz Fault, the boundaries are no-flow boundaries because the Monterey Formation impedes cross-boundary groundwater flow. However, cross-boundary flow occurs between the Seaside basin and 180/400-Foot aquifer sub-basin of the Salinas Valley groundwater basin (California Department of Water Resources, 2003). Within the boundaries of the Seaside basin, groundwater flows in response to recharge, pumping, and the hydraulic interactions with Monterey Bay, including groundwater flow across the northern boundaries defined by CH2M/Hill (2005) and Yates and others (2005).

The groundwater divide used by CH2M/Hill (2005) and Yates and others (2005) is not used as a boundary for the development of the groundwater model. This is the case firstly because neither CH2M/Hill (2005) nor Yates and others (2005) considered it to be a no-flow boundary, because both quantify northward groundwater flow across the divide. This is the case secondly because the divide is not a stationary hydrologic boundary. Even if the divide were to be a no-flow boundary, such a no-flow boundary would tend to move in response to groundwater pumping. Correspondingly, the northern model boundary is the Reliz Fault. Even though that is not a hydrologic boundary, the Reliz Fault is sufficiently distant from the principal groundwater pumping that its actual characteristic is not important.

The boundary used for the model development is not the adjudication boundary. The adjudication boundary encloses a smaller geographic area than the model boundary, and the adjudication boundary is mostly contained within the model boundary.
1.2.4 Cultural Features

The communities of Seaside, Del Ray Oaks, and Marina overlie the basin. However, the majority of the groundwater basin is overlain by mostly undeveloped land. That land represents native vegetation and minor residential development. Figure 1.7 is a 2000 false-color infrared satellite image on which the communities and undeveloped land can be identified. The developed areas appear as light blue on the image, and the undeveloped areas appear as pink to red. The more reddish areas correspond to more verdant vegetation.

1.2.5 Water Use

Groundwater is the water supply for communities within the Seaside groundwater basin. However, groundwater pumping can be different than the water use because the regional water-distribution system has interconnections that cross the southeastern basin boundary. Water can be conveyed through the interconnections from or to the Seaside basin to or from the areas otherwise served from the Carmel River basin, and the net transfers in recent years have been from the Seaside basin to the areas otherwise served from the Carmel River basin. Considering just basin boundaries defined by CH2M/Hill (2005), the water use within the Seaside groundwater basin was 6,000 acre-ft (CH2M/Hill, 2005, Terry Foreman, written communication). However, the groundwater pumping was about 6,200 acre-ft (CH2M/Hill, 2005), which suggests a net transfer of 200 acre-ft. The groundwater pumping within the Seaside basin is supported by annual natural recharge of about 4,200 acre-ft and secondary recharge of about 400 acre-ft (CH2M/Hill 2005), which suggests that the 2002 pumping exceeded the natural and secondary recharge by about 1,800 acre-ft.

Little agricultural water use occurs within the Seaside groundwater basin. Some agricultural water use occurs immediately adjacent to the northern basin boundary. However, the groundwater pumping for that water use has essentially no impact on the Seaside groundwater basin with respect to the adjudicated area.

1.2.6 Groundwater Conditions

Groundwater flows northwestward and northward within the Seaside basin, and this pattern occurs within both the Paso Robles and Santa Margarita formations. This is expressed in the groundwater-level contours shown on Figures 1.8a-b, where the contours are modified from Yates and others (2005, Figures 13 and 15). Within both the Paso Robles and Santa Margarita formations, groundwater levels within the southeast corner of the Seaside basin have an altitude of about 180 ft, and groundwater flows radially from that corner toward Monterey Bay and the Salinas Valley. The pattern of radial groundwater flow results from the boundary effects produced by the hydraulic interactions between the Seaside basin, Monterey Bay, and the Salinas Valley.
However, pumping from wells within Seaside and Marina has produced local groundwater levels lower than sea level. Within the Paso Robles Formation, groundwater levels are below sea level underlying Seaside, where groundwater levels are as much as 30 ft below sea level. Groundwater levels are below sea level within a roughly circular area that is about 7,000 ft in diameter and is located entirely landward of Monterey Bay. Within the Santa Margarita Formation, groundwater levels are below sea level underlying both Seaside and Marina, where groundwater levels respectively are as much as 40 ft and 50 ft below sea level. Underlying Seaside, groundwater levels are below sea level within an area that is about 10,000 ft in diameter and is located partly beneath Monterey Bay. Underlying Marina, groundwater levels are below sea level within an area that is about 4,000 ft in diameter and is located entirely landward of Monterey Bay.

Little groundwater-level data are available for the Purisima Formation. Similarly, little data are available for the surficial deposits, except adjacent to the northern boundary of the Seaside basin. However, the groundwater conditions within the Purisima Formation and surficial deposits most likely are similar to the corresponding local conditions within the Santa Margarita and Paso Robles formations.

Except for areas underlying Marina, seawater intrusions has not been detected within the Seaside groundwater basin. The impacted area as reported by the Monterey County Water Resources Agency (2001) are shown on Figures 1.8a-b, which delineate the extent of intrusion within both 180-Foot and 400-Foot aquifers. The maximum southward extent is about 6,000 ft from the Reliz Fault, where the extent represents areas with chloride greater than 500 mg/L.

1.3 Model Code Used

The groundwater model was developed using a modified version of the U. S. Geological Survey computer program \textit{FEMFLOW3D}, Version 1.0 (Durbin and Bond, 1998), which is referred to as \textit{FEMFLOW3D}, Version 3.0, (Durbin, 2007) \textit{FEMFLOW3D} is a program for simulating three-dimensional groundwater systems using the finite-element method. \textit{FEMFLOW3D} includes a module for vertically expanding or contracting the model grid to follow a fluctuating groundwater table as described by Durbin and Berenbrock (1985), which is a feature not included within \textit{FEMFLOW3D}, Version 1.0. With respect to groundwater flow, the mathematical basis and source code of \textit{FEMFLOW3D}, Version 3.0 is the same as described by Durbin and Bond (1998) and Durbin and Berenbrock (1985). The simulation of groundwater flow is based on the governing equation

\[
\frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial h}{\partial x_j} \right) + W = S_v \frac{\partial h}{\partial t} \tag{1.1a}
\]

with the free-surface boundary condition
\[
K_{ij} \frac{\partial h}{\partial x_j} n_i = -S_y \frac{\partial h_f}{\partial t} n_i
\]  

(1.1b)

for

\[
i = 1, 2, 3 \quad j = 1, 2, 3
\]

where \(h\) is the hydraulic head (ft), \(h_f\) is the water-table altitude (ft) \(K_{ij}\) is a component of the hydraulic conductivity tensor (ft), \(W\) is the source injection rate per unit volume (1/d), \(S_i\) is the specific storage (1/ft), \(n_i\) is component of the outward normal on the water-table surface, \(S_y\) is the specific yield (ft\(^0\)), \(x_i\) is an axis of a right-hand Cartesian coordinate system (ft), and \(t\) is time (d).

However, with respect to solute transport, new modules have been added with a mathematical basis as described by Pinder and Gray (1977). The modules allow the simulation of a non-reacting solute with linear sorption and decay according to the governing equation

\[
\phi\left(1 + \frac{\rho_h K_s}{\phi}\right) \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i}\left(\phi D_{ij} \frac{\partial c}{\partial x_j}\right) + \frac{\partial}{\partial x_j} (q_j c) + \phi W c^* - \phi \lambda c
\]  

(1.2)

for

\[
i = 1, 2, 3 \quad j = 1, 2, 3
\]

where \(c\) is the solute concentration (mg/ft\(^3\)), \(\phi\) is the effective porosity (ft\(^0\)), \(D_{ij}\) is a component of the dispersion tensor (ft\(^2\)/d), \(q_j\) is a component of the groundwater flux (ft/d), \(c^*\) is the concentration of injected water (mg/ft\(^3\)), \(\rho_h\) is the aquifer bulk density (mg/ft\(^3\)), \(K_s\) is the partitioning coefficient (ft\(^3\)/mg), and \(\lambda\) is the decay coefficient (1/d).

Equations 1.1 and 1.2 are solved within FEMFLOW3D using the finite-element method (Pinder and Gray, 1977; Wang and Anderson, 1995; Huyakorn and Pinder, 1983). The solution uses linear four-node tetrahedral elements (Huyakorn and Pinder, 1983, p. 88-91). However, a mesh is input to FEMFLOW3D using three-dimensional wedge elements that subsequently are decomposed into tetrahedrons within FEMFLOW3D. The mathematics of the solution are identical to those described by Pinder and Gray (1977, pp.126-199). The shape functions for the tetrahedral elements were derived from Zienkiewicz and Taylor (1989, pp. 135-139).

FEMFLOW3D, Version 3.0 is described in a user’s manual (Durbin, 2007). The manual describes the mathematical bases and input formats for simulating groundwater
flow and solute transport. Additionally, the manual describes the application of 
FEMFLOW3D to test problems for which the solution is known.

The transport and ground-water flow simulations do not account for the density
effects normally associated with seawater intrusion. Those effects were not included
because they were assumed to be unimportant to the simulation of potential landward
seawater intrusion into the Seaside groundwater basin. This assumption is based on
simulations that were made with the computer program FEMWATER (U.S. Army, 1995),
which simulates density-dependent groundwater flow. FEMWATER was used to
simulate two-dimensional groundwater flow in a generalized cross section. The section
was perpendicular to the Monterey Bay shore and extended beneath the bay. The
simulation results were that the seaward part of the groundwater basin contains only
dilute seawater, except for the immediately contact zone between Monterey Bay and the
underlying groundwater system. Therefore, the potential for seawater intrusion can be
simulated without considering density aspects.
2.0 Data Used

2.1 Previous Work

A large number of reports have been prepared on the geology and water resources of the Seaside groundwater basin and adjacent areas, and selected reports were obtained and reviewed during the development of the groundwater model. The reviewed materials include reports on geologic and hydrogeologic investigations by Wagner and others (2002), Clark and others (1997), Greene (1970 and 1977), Stall, Gardner & Dunn (1987, 1988, 1990a, and 1990b), Logan (1982). They include reports on water-resource investigations by CH2M/Hill (2005), Yates and others (2002 and 2005), Yates and Rosenberg (2005), Hanson and others (2002), Yates and others (2002), Yates (1988), Durbin and others (1978), and Muir (1982). Additionally, geospatial information was obtained from the California Geological Survey, California Spatial Information Library, California Department of Water Resources, and U. S. Geological Survey.

However, the development of the groundwater model relied mostly on the reports by CH2M/Hill (2005) and Yates and others (2005).

The report “Hydrogeologic Assessment of the Seaside Groundwater Basin” was prepared by CH2M/Hill (2005) for the California-American Water Co. The report was prepared to facilitate the development of a groundwater management strategy for the Seaside groundwater basin. The report contains a compilation of hydrogeologic information, including maps and cross sections. The report describes the groundwater levels and quality within the Seaside basin. Finally, the report describes the quantification of natural recharge, groundwater pumping, and secondary recharge. Much of this information was incorporated into the model. CH2M/Hill provided data used in preparing the report but not tabulated in the report (CH2M/Hill, Terry Forman, written communication, 2005), including the computational details of the recharge estimates.

The report “Seaside Groundwater Basin: Update on Water Resource Conditions” was prepared by Yates and others (2005) for the Monterey Peninsula Water Management District. The report was prepared to assist the District in developing a comprehensive groundwater-management plan of the Seaside groundwater basin, implementing management actions, and securing grant funding. The report is similar to the CH2M/Hill (2005) report in that it: contains a compilation of hydrogeologic information, including maps and cross sections; describes the groundwater levels and quality within the Seaside basin; and describes the quantification of natural recharge, groundwater pumping, and secondary recharge. Much of this information was incorporated into the model or otherwise significantly influenced the model development.

2.2 Hydrogeologic Information

To develop a hydrogeologic model for the groundwater model, hydrogeologic information was extracted from CH2M/Hill (2005), Yates and others (2005), Greene
(1977), Greene (1970). Within the CH2M/Hill (2005) report: Figure 3-5 shows fault locations, except for the Reliz Fault; Figures 3-6 through 3-11 show geologic cross sections; and Figure 3-12 and 3-13 respectively show the regional and surficial geology. Within the Yates and others (2005) report: Figure 3 shows the regional geology and the location of the Reliz Fault; and Figures 3 and 4 show geologic cross sections. This information was supplemented with topographic and bathymetric information downloaded from the U. S. Geological Survey as DEMs (digital elevation model). Additionally, geologic information was downloaded from the U. S. Geological Survey as isopach maps representing the offshore geology (Wong and Eittreim, 2001).

The hydrogeologic model incorporated within the groundwater model was constructed from Figures 1.5a-e, which show the base altitude for each of the hydrogeologic units represented in the model. Contours of base altitude were developed from extrapolations of the cross sections constructed by CH2M/Hill (2005) and Yates and others (2005). They also were developed from the geologic descriptions of Greene (1970) and Greene (1977), and Wong and Eittreim (2001). To translate Figures 1.5a-e into the model mesh, the contours were converted to raster grid files using the 3D Analyst and Spatial Analysis extensions of ArcGIS.

Aquifer-parameter information has been compiled by CH2M/Hill (2005) and Yates and others (2005). The compiled aquifer-test data suggest an average hydraulic conductivities of 100 ft/day for the Paso Robles Formation and 130 ft/day for the Santa Margarita Formation. However, because wells tend to be screened in the more conductive intervals of a formation, the aquifer-test results likewise tend to overstate the depth-averaged conductivity for the entire formation thickness. Accordingly, Yates and others (2005) derived hydraulic conductivities of 2 ft/day for the Paso Robles Formation and about 4 ft/day for the Santa Margarita Formation, based on the calibration of a groundwater model, where these conductivities represent the entire thicknesses of the respective formations. Yates and others (2005) also derived from the model calibration a specific yield of 0.08 and specific storages in the range $10^{-5}$ to $10^{-6}$ ft$^{-1}$.

### 2.3 Well Inventory

To define the monitoring and production locations within the Seaside groundwater basin, a well inventory was compiled. CH2M/Hill (Terry Foreman, 2005, written communication) provided information on the location and construction of monitoring and production wells within the Seaside groundwater basin. The provided information was supplemented with data extracted from Yates and others (2005, Appendix C). Table 2.1 lists the information compiled on the monitoring wells actually used in developing the model, and Figure 2.1 shows the well locations. Table 2.2 lists the information compiled on production wells, and Figure 2.2 shows the well locations. Additionally, Tables 2.1 and 2.2 identify the hydrogeologic units within the screened interval of the monitoring or projection well. As shown on Figures 2.1 and 2.2, the well inventory included wells outside the study areas used by CH2M/Hill (2005) and Yates and others (2005).
2.4 Groundwater Levels

To calibrate the groundwater model, data on groundwater levels were compiled. CH2M/Hill (Terry Foreman, 2005, written communication) provided water level measurements representing 1952-2004. Table 2.3 lists the measurements actually used in developing the model, which includes those measurements made during 1995 and later, and Figure 2.2 identifies the well locations. The model development was based only on the later measurements because they were considered to be the most reliable.

2.5 Groundwater Pumping

To specify the pumping rates to be assigned within the model, data on groundwater production was compiled. CH2M/Hill (Terry Forman, 2005, written communication) provided information on annual groundwater production from individual wells. The production from the California American Water Co., City of Seaside, County of Monterey, and private wells was provided for 1956-2002. The production from Marina Coast Water District wells was provided for 1993-2002. Table 2.4 lists the compiled production and identifies the well owners, and Figure 2.1 shows well locations. As shown on Figure 2.1, groundwater pumping outside the study areas by CH2M/Hill (2005) and Yates and others (2005) was incorporated into the model.

2.6 Groundwater Recharge

2.6.1 Prior Investigations

To specify the natural and secondary recharge rates to be assigned within the model, prior estimates of recharge were compiled. Both CH2M/Hill (2005) and Yates and others (2005) estimated the recharge to the Seaside groundwater basin. To estimate precipitation recharge, they used similar approaches, and they obtained similar results. They both used a soil-water budget approach. The approach involved simulating the inflow and outflow to the vegetative root zone. The inflow to the root zone is the precipitation infiltration, and the outflows are evapotranspiration and deep percolation. CH2M/Hill (2005) used a monthly time step to simulate these processes, and Yates and others (2005) used a daily time step. To estimate the secondary recharge from landscape irrigation, septic tanks, leaking pipes, and other sources, CH2M/Hill (2005) and Yates and others (2005) based their estimates on different approaches and data but produced similar estimates.

CH2M/Hill (2005) and Yates and others (2005) use slightly different study-area boundaries, and their respective recharge estimates differ in part due to that. The study area used by CH2M/Hill contains 12,600 acres, and the study area used by Yates and others contains 12,300 acres. Nevertheless, when the respective recharge rates are expressed in terms of the average rate per unit area, the separate recharge estimates are nearly identical. The average rate for CH2M/Hill is 0.35 ft/yr, and the average rate for Yates and Others is 0.32 ft/yr. However, the recharge rate estimated by CH2M/Hill (2005) was used in the model.
The natural recharge rates estimated by either CH2M/Hill (2005) or Yates and others (2005) are based on their estimates of the potential evapotranspiration within their respective study areas. Presumably, CH2M/Hill (2005) and Yates and others (2005) considered the dual effects of distance from Monterey Bay and altitude in characterizing the evapotranspiration over their study areas. Nevertheless, the region representing the groundwater model contains more coastal area and more higher-altitude area than within the CH2M/Hill (2005) or Yates and others (2005) study areas. These characteristics of the model area are counter balancing with respect to potential evapotranspiration. Therefore, the average natural recharge within the model area probably is similar to the average natural recharge estimated by either CH2M/Hill (2005) or Yates and others (2005).

Likewise, the secondary recharge rates estimated by either CH2M/Hill (2005) or Yates and others (2005) is based on the extent of the urbanized area within their respective study areas. The region representing the groundwater model is larger, but the proportion of urbanized area is not greatly different than within the study area used by CH2M/Hill (2005) or Yates and others (2005). Therefore, the average secondary recharge within the model area probably is similar to the average secondary recharge estimated by either CH2M/Hill (2005) or Yates and others (2005).

### 2.6.2 Satellite-Image Analysis

As preparation for 2005 trial on the Seaside basin adjudication, Timothy Durbin, Inc. (2005, written communication) evaluated the water-budget approach used by CH2M/Hill (2005) and Yates and others (2005). The approached used by them equates the precipitation recharge to the precipitation minus the evapotranspiration. Satellite imagery was analyzed by Durbin to estimate the consumptive use of the native vegetation, and a satellite analysis was used to evaluate the reasonableness of the prior recharge estimates.

Satellite imagery for the Seaside groundwater basin was related to consumptive use through the \( NDVI \) (Normalized Difference Vegetation Index) index (Gates, 1980). This index in turn is related to reflectances measurements acquired in the red and near-infrared spectral regions by the expression (Sellers, 1985; Myneni and others, 1995)

\[
NDVI = \frac{\rho_{\text{NIR}} - \rho_R}{\rho_{\text{NIR}} + \rho_R}
\]

(2.1)

where \( \rho_R \) is the red reflectance and \( \rho_{\text{NIR}} \) is the near-infrared reflectance. Work by Sellers (1985) and Myneni and others (1995) has shown the \( NDVI \) is related directly to the energy adsorption of plant canopies and hence to transpiration.

By design, \( NDVI \) values range from +1 (when \( \rho_R = 0 \)) to -1 (when \( \rho_{\text{NIR}} = 0 \)). However, the \( NDVI \) calculated from a particular satellite image and for a particular
vegetative condition depends on the atmospheric opacity when the image was acquired. The $NDVI^*$ index corrects for the atmospheric and other factors (Huete and Liu, 1994; Liu and Huete, 1995), which has the form

$$NDVI^* = \frac{NDVI - NDVI_0}{NDVI_S - NDVI_0}$$

where $NDVI_0$ is the $NDVI$ representing bare soil and $NDVI_S$ is the $NDVI$ representing saturation. Saturation occurs in areas with the most verdant vegetation, such as irrigated crops. The $NDVI^*$ index has a range of 0 (for bare soil) to 1 (for verdant vegetation), and it enables the comparison of $NDVI$ measured at different times with different atmospheric opacities.

The $NDVI^*$ index is related to actual evapotranspiration of the vegetative canopy by the relation (Baugh and Groeneveld, 2006)

$$ET = NDVI^* \cdot ET_0$$

where $ET$ is the actual evapotranspiration and $ET_0$ is the reference evapotranspiration. Equation 2.3 has the same form as the reference-crop equation used to compute crop consumption, where $NDVI^*$ is the crop coefficient. Equation 2.3 can be applied monthly, given a set of monthly satellite images and monthly $ET_0$ values.

Calendar year 1993 was selected for an analysis of evapotranspiration based on Equation 2.3. This year was selected because the annual precipitation was near normal and satellite images were readily available. Six 30-meter LANDSAT TM images, representing August, December, January, March, June, and October were used because these comprised the available cloud-free images. $NDVI$ was calculated for each image using the Leica image-analysis extension for ArcGIS, and the $NDVI$ values representing bare soil and verdant vegetation were extracted. The $NDVI^*$ index was then calculated using the map-calculator function within ArcGIS. Figures 2.3a-f show the resulting geographic distribution of $NDVI^*$ within the Seaside basin for the selected months.

The reference evapotranspiration within the Seaside basin decreases with increasing altitude and distance inland from Monterey Bay. Monthly $ET_0$ values are available from the California Irrigation Management Information System for three sites near Salinas, which have altitudes ranging from 9 to 146 ft, distances inland from Monterey Bay ranging from 4,800 to 107,000 ft, and annual $ET_0$ ranging from 36 to 46 inches. Figure 2.4 shows the site locations. Table 2.5 lists the station attributes, and Figure 2.4 shows the station locations.

The actual evapotranspiration was obtained by combining the geographic distribution of $NDVI^*$ (Figures 2.3a-f) with the respective $ET_0$ for the months represented by the satellite images. The geographic distribution of $ET$ was calculated from Equation 2.3 using the map-calculator function within ArcGIS. The resulting $ET$ for each satellite image is listed in Table 2.6, along with the corresponding annual $ET$. The resulting
annual ET for 1993 is 1.5 ft, within the study area used by CH2M/Hill (2005). Based on the precipitation, runoff, and irrigation for 1993 (CH2M/Hill, 2005; Yates and others, 2005), the corresponding recharge is 0.46 ft. The average annual recharge estimated by CH2M/Hill (2005) for that study area is 0.32 ft, and the average annual recharge estimated by Yates and others (2005) for that study area is 0.35 ft. The recharge derived from the satellite-image analysis is similar, after accounting for the above average precipitation during 1993. Correspondingly, the average recharge estimated by CH2M/Hill (2005) was used in the model.
3.0 Model Development

The development of the groundwater model involved the steps of assembling and then calibrating the model. The assembly of the model involved firstly constructing a finite-element mesh and secondly assigning recharge, pumping, boundary conditions, and initial conditions to the mesh. The calibration of the model involved identifying the hydraulic conductivity, specific storage, and specific yield for the hydrogeologic units that comprise the groundwater system. These steps were applied to a model with a geographic extent congruent with the areas defined by the California Department of Water Resources (2003) for the Seaside and Corral de Tierra groundwater basins. These basins collectively are referred to in this report as the Seaside groundwater basin.

3.1 Model Assembly

3.1.1 Finite-Element Mesh

The computer program FEMFLOW3D uses a finite-element mesh to model the hydrogeologic conditions within a groundwater basin. The mesh is used to represent the geographic extent of a groundwater system and the thickness of the geologic units that comprise the system. Additionally, the mesh is used to specify the hydraulic properties, pumping, and recharge. The mesh for a groundwater model based on FEMFLOW3D is constructed by assembling a wire-frame mesh using wedge-shaped elements. The individual elements are oriented as shown on Figure 3.1, such that the triangular faces of the wedge are parallel (or sub parallel) with a horizontal plane. They are oriented additionally such that the rectangular (or trapezoidal) faces are parallel with a vertical plane. The results of this orientation are that an element appears as a triangle when viewed from above and as a rectangle (or trapezoid) when viewed from the side.

A wedge-shaped element has six vertices, which in the vernacular of groundwater modeling, are referred to as nodes (Figure 3.1). An individual element is located geographically and vertically by specifying the three-dimensional coordinates for each node. A mesh is constructed by creating an assemblage of nodes and by identifying which nodes define which elements.

Modified forms of the wedge-shaped elements also are used in the construction of the finite-element mesh. These forms are used where a hydrogeologic unit pinches out. Pinch-outs occur where the thickness of a hydrogeologic unit tapers to a zero-thickness along a boundary of the unit. Correspondingly, a wedge-shaped element adjacent to such a boundary would have a zero-height at the nodes located on the boundary. If a wedge-shaped element is oriented such that one node is located in a pinch-out boundary, the six-node wedged-shaped element is replaced with a five-node pyramid-shaped element as shown on Figure 3.1. If a wedge-shaped element is oriented such that two nodes are located in a pinch-out boundary, the six-node wedge-shaped element is replaced with a four-node tetrahedral-shaped element as shown on Figure 3.1.
The finite-element mesh is depicted in Figure 3.2 (map view), Figure 3.3 (perspective view), and Figures 3.4a-b (cross-sections through the mesh interior). The top surface of the mesh is the land surface, and the subsurface structure of the mesh corresponds to the hydrogeologic units that comprise the groundwater system. The mesh depicts the Santa Margarita, Purisima, Paso Robles, and Aromas formations, where the representation of the Aromas Formation includes the surficial deposits. The base elevations for these formations, as shown on Figures 1.5a-e, define the layers within the mesh. The mesh also portrays the Salinas Valley clay, which occurs within the upper part of the surficial deposits.

Node elevations for the base of each hydrogeologic unit were derived from Figures 1.5a-e, which shows contours of the base altitude for each hydrogeologic unit represented in the model. The contours firstly were translated into raster grids by using the 3D Analyst and Spatial Analyst extensions to ArcGIS. The nodal elevation secondly were interpolated from this raster grid by using the Spatial Analyst extension.

The only fault represented explicitly within this model is the Ord Terrace Fault. That fault dissects the landward part of the Seaside basin and the near-shore seaward part. The fault is represented in the model mesh as a narrow band of elements that extend vertically through the overall thickness of the groundwater system.

The mesh contains 30,361 nodes and 56,503 elements. To accommodate numerical requirements for the transport simulations, the horizontal nodal spacing is generally about 500 ft, and the vertical nodal spacing is generally about 50 ft. The number of element layers at a particular location depends on the number of hydrogeologic units occurring in the subsurface at the location and the number of element layers comprising the respective hydrogeologic units. The Santa Margarita Formation is represented in the model mesh with six element layers, the Purisima Formation is represented with six layers, the Paso Robles Formation is represented with 10 layers, and the Aromas Formation and surficial deposits are represented with six layers. At the locations where the mesh has the most layers, 34 layers occur.

\[ FEMFLOW3D \] simulates changing groundwater-table conditions by adjusting the altitudes of mesh nodes. The mesh is expanded upward or collapsed downward such that the altitudes of the nodes representing the top surface of the model mesh equal the local altitude of the simulated groundwater table. However, the altitude adjustments typically involve more than just the top nodes. If a downward adjustment is large with respect to the thickness of an element layer, the bottom nodes for the element layer also are moved downward. Figure 3.5 shows the collapse of a element column due a water-table decline during time step \( t \), where \( \Delta h \) is the water-table decline, \( z_{t-1} \) is the element height after time step \( t-1 \), \( z_t \) is the element height after time step \( t \), and \( z_{\text{min}} \) is the specified minimum spacing between nodes. The quantity \( z_{\text{min}} \) is specified to flatten an element to effectively remove it from the hydraulics of the groundwater system but to maintain an element aspect ratio (horizontal to vertical dimensions) not larger than about 200.
3.1.2 Time Step, Simulation Periods, and Unit Dimensions

The model was developed based on annual time steps. Furthermore, the computational time step is annual, where $\Delta t = 365$ days for each step. The period used in the model calibration is the 47-year period 1956-2002, and the period used for future projections was the 13-year period 2003-2015. Correspondingly, $t = 0$ is the start of 1956, $t = 365$ days (time step 1) is the end of 1956, $t = 17,155$ days (time step 47) is the end of 2002, and $t = 21,900$ days (time step 60) is 2015.

The 47-year period 1956-2002 was used in the model development in part because of data availability. More importantly, that period was used because the Seaside basin most likely was in a steady-state condition. The groundwater development was minimal with respect to the natural recharge, and in 1956 groundwater pumping most likely had not impacted groundwater levels. That steady-state condition was used as the initial condition for the model simulations. Data do not exist for describing an initial condition for the model (in 1956 or any other time), but an initial condition can be constructed by computing steady-state heads. The computed initial condition represents the start of 1956.

The model inputs and simulation outputs are in a consistent set of unit dimensions. Length is in feet, and time is in days. Concentrations are expressed in terms of the dimensionless equivalent seawater proportion. Correspondingly, the dimensionless concentration $c = 1$ is equivalent to a mass concentration of 35,000 mg/L, $c = 0.1$ is equivalent to 3,500 mg/L, and $c = 0.01$ is equivalent to 350 mg/L.

3.1.3 Recharge Volumetric and Solute Fluxes

Both recharge rates and salinity were assigned to the model. The recharge rate represents a water flux into the groundwater basin. When combined with water flux, the assignment of a recharge salinity represents a solute flux into the groundwater basin.

Groundwater Flow

Recharge was assigned to the model by specifying water fluxes to the top nodes within the model mesh. A geographically uniform recharge rate was applied to the model. Even though the rate for a particular year is variable, the average annual rate was applied to each time step within a simulation. The average annual rate is 11,900 ft/yr. This recharge rate is substantial larger than reported by either CH2M/Hill (2005) or Yates and others (2005) because the model areas is much larger then their study areas. Nevertheless, recharge rate per unit area used in the model is the same as that estimated by CH2M/Hill (2005), or 0.35 acre-ft/yr per acre.

While the average annual recharge corresponds to a volume per unit area of 0.35 acre-ft/yr per acre (ft/d), the nodal model inputs must be expressed the volumetric flux
The volumetric rate for a particular top node within the model mesh is given by the expression

\[ R_{i,t} = \frac{1}{3} \sum_{e \in \{i\}} A_e r_t \]  

(3.1)

where \( R_{i,t} \) is the volumetric flux assigned to node \( i \) for year \( t \), \( A_e \) is the area of element \( e \) projected onto a horizontal plane, \( r_t \) is the recharge per unit area in year \( t \) and \( \{i\} \) is the set of all elements that share node \( i \).

**Solute Transport**

Recharge salinity was assigned to the model by specifying a salinity corresponding to the water fluxes at each node. However, the assigned salinity equals zero for all landward top nodes and all times. Even though the recharge water has some salinity, the salinity equals essentially zero relative to seawater.

#### 3.1.4 Pumping Volumetric and Solute Fluxes

Pumping rates were assigned to the model, but the pumping salinity is not a model input.

**Groundwater Flow**

Pumping represents a water flux from the groundwater basin. Pumping was assigned to the model by specifying fluxes to nodes within the model mesh. Annual pumping was assigned based on the well locations and constructions listed in Table 2.1 and the pumping rates listed in Table 2.4, except for the pumping for Marina. The Marina pumping is not included in the model because the wells are located very near the Reliz Fault, which as described later is represented in the model as a specified-head boundary. Whether the Marina pumping is or is not represented in the model, the boundary condition overrides the potential pumping effects.

Each production well was assigned to a collection of nodes corresponding to its well location and screened interval. The flux assigned to a particular node in the collection is a proportion of the total well pumping based on horizontal and vertical weightings. The horizontal weighting is based on the geographic location of the well within an element as shown on Figure 3.6, which shows the triangular top face of an element that is penetrated by a well. The vertices are labeled \( A \), \( B \), and \( C \) counterclockwise around the triangle. The horizontal weighting for node \( A \) is the perpendicular distance from the well to the line \( BC \) (quantity \( a \) on Figure 3.6) divided by the perpendicular distance from node \( A \) to the line \( BC \) (quantity \( b \) on Figure 3.6), the weighting for node \( B \) is the distance from the well to the line \( CA \) divided by the perpendicular distance from node \( B \) to the line \( CA \), and the weighting for node \( C \) is the distance from the well to line \( AB \) divided by the perpendicular distance from node \( C \) to the line \( AB \). The horizontal weights have the property that
\[ \sum_{i=1}^{3} W_{hi} = 1 \]  

(3.2)

where \( W_{hi} \) is the horizontal weight for node \( i \). This property and the weighting scheme itself follow directly from the mathematical formulation of the finite-element method (Pinder and Gray, 1977).

The vertical weighting is based on the screen lengths within the elements penetrated by the well as shown on Figure 3.7, which shows the trapezoidal side faces for a stack of elements penetrated by a well. For nodes in the top face of element \( e \), the vertical weight is given by the relation

\[
W_{vi} = \left( \frac{L_e}{L} \right) \left( \frac{b_e}{\Delta z_e} \right) 
\]

(3.3a)

where \( W_{vi} \) is the vertical weight for node \( i \), \( L \) is the total screen length for the well, \( L_e \) is the length of the screen segment within the element \( e \), \( \Delta z_e \) is the vertical distance between the top and bottom faces of element \( e \) at the well location, and \( b_e \) is the distance from the bottom face of element \( e \) to the middle of the screen segment within the element. Likewise, for nodes in the bottom face of element \( e \), the vertical weight is given by the relation

\[
W_{vi} = \left( \frac{L_e}{L} \right) \left( 1 - \frac{b_e}{\Delta z_e} \right) 
\]

(3.3b)

Finally, the vertical weight for a node with a contribution from screen segments within two vertically adjacent elements is the sum of the individual elemental contributions. As for the horizontal weighting scheme, the vertical weighting scheme follows from the mathematical formulation of the finite-element method (Pinder and Gray, 1977)

The proportion of the pumping from the well assigned to a node is the product of the vertical and horizontal weights for the node, or

\[ p_i = W_{hi} \cdot W_{vi} \]  

(3.4)

where \( p_i \) is the proportion of the total pumping from the well assigned to the node \( i \).

**Solute Transport**

The salinity of pumped groundwater is not a model input. The combination of the pumping rate and the salinity of the pumped water represent a solute flux from the
groundwater basin. However, the pumpage salinity is identical to the local groundwater salinity, but the groundwater salinity is a calculated quantity.

### 3.1.5 Boundary Conditions

Boundary conditions were assigned to the model domain for both groundwater flow and solute transport. Boundary surfaces were assigned specified heads and specified fluxes to specify groundwater-flow conditions. Additionally, boundary surfaces were assigned specified fluxes to specify solute-transport conditions.

#### Groundwater Flow

For groundwater-flow, a specified-head boundary condition was applied to the bathymetric surface representing the bottom of Monterey Bay and the vertical surface representing the boundary between the Seaside groundwater basin and the Salinas Valley basin. The groundwater-flow simulations are configured in terms of fresh water, and the specified head for Monterey Bay corresponding are expressed as equivalent freshwater heads. The relation for translating from seawater to freshwater heads is

\[
h_f = d_s \left( \frac{\rho_s}{\rho_f} - 1 \right)
\]

where \(h_f\) is the equivalent freshwater head, \(d_s\) is the seawater depth, \(\rho_s\) is the density of seawater, \(\rho_f\) is the density of freshwater. Based on a seawater density of 1,035 g/L and a freshwater density of 1,000 g/L, the freshwater head equals the seawater depth multiplied by 0.035. The heads derived from that relation were assigned to the model as temporally invariant heads over the Monterey Bay region shown on Figure 3.8.

The boundary between the Seaside groundwater basin and the Salinas Valley basin is the Reliz Fault, and specified heads were assigned to the fault plane from 5,000 ft offshore to where the eastern boundary of the Seaside basin intersects the Reliz Fault. Along that fault segment, which is identified on Figure 3.8, a specified-head boundary was assigned over the full thickness of the Seaside basin. While the assigned heads vary along the fault trace, they do not vary with depth at a particular location. The assigned heads represent the groundwater conditions on the north side of the Reliz Fault, where the heads were derived from a composite of the groundwater-level contour maps produced by Yates (1988) and Yates and others (2005). The derived heads were assigned to the model as temporally invariant specified heads as shown on Figure 3.9. The representation of the Reliz Fault as a specified head boundary allow unimpeded groundwater exchanges between the Seaside and Salinas Valley groundwater basins.

The remainder of the boundary surfaces are specified-flux boundaries. The boundary condition on the top surface of the landward part of the model domain is the precipitation and secondary recharge into the groundwater system, which was described previously. The boundary condition on bottom surface of the landward and seaward parts
of the model domain also is a no-flow boundary. Likewise, the boundary conditions on the landward and seaward vertical surfaces of the model domain, except for the segment of the Reliz Fault described above, are no-flow boundaries.

The leakances for the specified-head boundaries were assigned so as to produce a computed head almost identical to the specified head. Accordingly, the leakances were set to a somewhat arbitrary large value. The leakances were set sufficiently large to produce nearly identical specified and computed heads, but they were set also such that the difference between the specified and computed heads was with the precision of the computer.

**Solute Transport**

Where water crosses boundary surfaces as inward flows, due either to the assignment of specified-head or non-zero specified-flux groundwater-flow boundaries, the salinity of the inward flow is assigned. However, except for the boundary surface representing the bottom of Monterey Bay, the specified salinity equals zero. For the Monterey Bay surface, the specified salinity equals unity, which is the dimensionless concentration equivalent to seawater.

### 3.1.6 Initial Conditions

The groundwater-flow and solute-transport initial conditions is an assumed steady-state condition at the end of 1955. The groundwater development at the time was minimal at that time relative to precipitation recharge, and initial conditions were simulated based on the assumed steady state.

**Groundwater Flow**

The initial heads for groundwater flow are the calculated steady-state heads representing the long-term average annual recharge, the 1956 groundwater pumping, and the boundary conditions described above. *FEMFLOW3D* can calculate steady-state initial heads within a transient-state simulation, and that facility was used to specify the initial heads for the Seaside groundwater basin. The resulting steady-state groundwater levels are shown on Figures 3.10a-b. Because the steady-state heads depend on the hydraulic parameters assigned to the hydrogeologic units represented in the model, Figures 3.10a-b are derived from the model calibration, which is described later.

**Solute Transport**

The initial salinity for solute transport are the calculated nearly steady-state salinity again representing the long-term average annual recharge, the 1956 groundwater pumping, and the boundary conditions described above. By this construction of initial conditions, the seawater intrusion in the seaward part of the Seaside basin is assumed to be in equilibrium with the 1956 steady-state groundwater flow. Calculating steady-state solute-transport with *FEMFLOW3D* is not as convenient as for calculating steady-state
heads. The approach was to make a long-term simulation of solute transport based on the steady-state heads. A simulation period was selected such that near steady-state transport conditions occurred at the end of the simulation. This was achieved with a simulation period of 10,000 years. The resulting steady-state salinities are shown on Figures 3.11a-b. Because the steady-state salinities depend on the hydraulic and transport parameters assigned to the hydrogeologic units represented in the model, Figures 3.11a-b are derived from the model calibration, which is described next.

3.2 Aquifer-Parameter Identification

Aquifer-parameters for groundwater flow and solute transport were assigned to the model. The hydraulic parameters for groundwater flow include the hydraulic conductivity, specific storage, and specific yield for each hydrogeologic unit represented in the model. Likewise, the transport parameters include the effective porosity and dispersivity.

3.2.1 Identification Approach

Different approaches were used for the identification of the hydraulic and transport parameters. Groundwater-level data are available for the Seaside basin, and hydraulic parameters were identified by calibrating the model to groundwater-level measurements. The basin has been impacted little by seawater intrusion, and no basis exists for identifying the transport parameters by calibration. Correspondingly, transport parameters were assigned based on the textural characteristics of the individual hydrogeologic units.

Groundwater Flow

Two data sources were used in the identification of hydraulic parameters. With respect to the first data source, parameters were identified by formally calibrating the model to the groundwater levels listed in Table 2.3, which represent measurement is made within the wells listed in Table 2.2. The simulated head for a well follows from the assignment of mesh nodes to each monitoring well, and the simulated head is a weighted sum of the simulated heads for the assigned nodes. The weights are derived exactly as described in Section 3.1.4 for the assignment of well pumping to nodes. With respect to the second data source, parameters were identified by subjectively calibrating the model to qualitative characteristics of the groundwater-level contour maps produced by Yates and others (2005, Figures 12 through 15). Those maps show groundwater levels for Spring and Fall 2002 and respectively for the Paso Robles and Santa Margarita formations. Immediately landward from Monterey Bay and north of the Ord Terrace Fault, the maps show roughly circular areas where groundwater levels are below sea level. Within the Paso Robles Formation, the area is about 5,000 ft in diameter, and the area is contained entirely within the landward part of the groundwater basin, as shown on Figure 1.18a. Within the Santa Margarita Formation, the area is about 12,000 ft in diameter, and the area extends partly into the seaward part of the groundwater system, as
shown on Figure 1.18b. The model was calibrated in part to simulate similar areas where groundwater levels are below sea level.

Hydraulic parameters were identified from a weighted least-squares fit of the computed heads to the measured groundwater levels. The computer program PEST (Watermark Numerical Computing, 2002) was used to perform the calibration. PEST identifies parameter values such that the model fit minimizes the objective function

\[ S = \sum_{i=1}^{n} [w_i (h_{ci} - h_{mi})]^2 \]  \hspace{1cm} (3.6)

where \( S \) is the sum of weighted squared residuals, \( h_{ci} \) is the computed head for a particular well and time, \( h_{mi} \) is the measured groundwater level for the particular well and time, \( w_i \) is the weight assigned to the measured groundwater level, and \( n \) is the number of measured groundwater levels. The weight assigned to a measurement is related to the uncertainty in the measurement according to the relation

\[ w_i = \frac{1}{\sigma_i^2} \]  \hspace{1cm} (3.7)

where \( \sigma_i \) is the standard error of the uncertainty in the measurement.

All groundwater-level measurements are uncertain, and the uncertainty has at least two sources. Firstly, uncertainty arises in measuring or recording groundwater depths and in measuring, estimating, or recording measuring-point altitudes. Additionally, uncertainty arises in the documentation of the location and construction of wells. However, for the Seaside groundwater basin, this uncertainty type most likely is small. Secondly, uncertainty arises because groundwater-level measurements represent spatial and temporal point processes, but the computed heads represent spatially and temporally average processes (Anderson and Woessner, 2002, pp.229-230, Gelhar, 1986), where the averaging depends on the effective spatial and temporal scales represented in the model. This uncertainty increases significantly with lower-permeability groundwater systems and with more heterogeneous and anisotropic groundwater systems. Because the Seaside groundwater basin can be characterized as a highly heterogeneous, highly anisotropic, and moderately permeable groundwater system, and because the effective model spatial and temporal scales are large, the second uncertainty type is large.

Within the groundwater-level data for the Seaside groundwater basin, the standard error for the combined effects of the two uncertainty types is about 16 ft. The first uncertainty type has a standard of perhaps 5 ft or less, the second error type has a standard error of most likely 15 ft or more. These combine according to the relation

\[ \sigma_i = \sqrt{\sigma_{ui}^2 + \sigma_{2i}^2} \]  \hspace{1cm} (3.8)
where $\sigma_{ij}$ is the combined standard error, $\sigma_{1i}$ is the standard error for the first uncertainty type, $\sigma_{2i}$ is the standard error for the second uncertainty type. The effect of the combined error is that, even if the parameter values assigned to the model exactly match the actual characteristics of the groundwater system at the effective model scales, the fit of the model to the measured groundwater levels would have an expected standard error of 16 ft, which is the expected standard deviation of the residuals between the computed heads and measured groundwater levels.

The formal calibration was configured to identify for each hydrogeologic unit represented in the model the basin-wide average horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield. However, calibration involved identifying parameter values for just the Paso Robles Formation, because the parameter values for the other hydrogeologic units were assigned a fixed proportional relation to the Paso Robles Formation. For each of the other units, the horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield respectively are assigned a fixed ratio between the parameter value for the unit and the corresponding parameter value for the Paso Robles Formation. The assigned ratios are listed in Table 3.1. The ratios were assigned based on the review of aquifer properties compiled by CH2M/Hill (2005), Yates and others (2005), Davis (1969), Anderson (1984), Johnson (1967), Shepherd (1989), Morris and Johnson (1967), Lohman (1972), and others sources.

**Solute Transport**

The transport parameters for the model were selected from values published for similar aquifer parameters. The parameters include effective porosity, horizontal longitudinal dispersivity, horizontal transverse dispersivity, and vertical transverse dispersivity, where the dispersivities are related to the dispersion tensor in Equation 1.2 by the relations (Hydrogeologic, Inc., 1996)

\[
D_{xx} = \alpha_{Lh} \frac{v_x^2}{v} + \alpha_{Th} \frac{v_y^2}{v} + \alpha_{Tv} \frac{v_z^2}{v}
\]

\[
D_{yy} = \alpha_{Th} \frac{v_y^2}{v} + \alpha_{Lh} \frac{v_x^2}{v} + \alpha_{Tv} \frac{v_z^2}{v}
\]

\[
D_{zz} = \alpha_{Tv} \frac{v_z^2}{v} + \alpha_{Tv} \frac{v_y^2}{v} + \alpha_{Lh} \frac{v_x^2}{v}
\]

\[
D_{xy} = D_{yx} = (\alpha_{Lh} - \alpha_{Th}) \frac{v_x v_y}{v}
\]
\[ D_{x_1} = D_{x_2} = (\alpha_{L_h} - \alpha_{T_h}) \frac{v_x v_z}{|v|} \]  
\tag{3.9e}

and

\[ D_{y_2} = D_{y_3} = (\alpha_{L_h} - \alpha_{T_h}) \frac{v_y v_z}{|v|} \]  
\tag{3.9f}

where

\[ v_i = \frac{q_i}{\phi} \]  
\tag{3.10}

for

\[ i = 1, 2, 3 \]

and

\[ |v| = \sqrt{v_x^2 + v_y^2 + v_z^2} \]  
\tag{3.11}

and where \( D_{ij} \) is a component of the dispersion tensor, \( \alpha_{L_h} \) is the horizontal longitudinal dispersivity, \( \alpha_{T_v} \) is the vertical longitudinal dispersivity, \( \alpha_{T_h} \) is the horizontal transverse dispersivity, \( \alpha_{T_v} \) is the vertical transverse dispersivity, \( \phi \) is the effective porosity, and \( q_i \) is a component of the groundwater-flux vector.

The dispersivities and porosity were assigned to each hydrogeologic unit represented in the model from a review of the parameter compilations by Davis (1969), Anderson (1984), Morris and Johnson (1967), and others sources. The resulting values are listed in Table 3.1.

### 3.2.2 Calibration Results

The calibration results are listed Table 3.1 and are shown on Figures 3.12a-b through 3.14a-b. Table 3.1 lists the hydraulic and transport parameters for the model. Figures 3.12a-b compare the computed heads and measured groundwater levels. Figure 3.13a shows the simulated heads within the Paso Robles Formation for 2002, and Figure 3.13b shows the simulated heads within the Santa Margarita Formation. Figure 3.14a shows the simulated salinity within the Paso Robles Formation for 2002, and Figure 3.14b shows the simulated salinity within the Santa Margarita Formation.

The hydraulic parameters derived from the calibration are mostly consistent with prior work. CH2M/Hill (2005) and Yates and others (2005) compiled aquifer-test data that suggests an average hydraulic conductivities of 110 ft/d for the Paso Robles Formation and 130 ft/day for the Santa Margarita Formation, but the variance of the
Aquifer-test data would suggest no actual difference between the formations. Nevertheless, the aquifer-test values are larger than identified for the model. However, because wells tend to be screened in the more conductive intervals of a formation, the aquifer-test results likewise tend to overstate the depth-averaged conductivity for the entire formation thickness. Correspondingly, Yates and others (2005) derived hydraulic conductivities of 2 ft/d for the Paso Robles Formation and about 4 ft/d for the Santa Margarita Formation, based on the calibration of a groundwater model for the southern part of the Seaside groundwater basin, where these conductivities represent the entire thicknesses of the respective formations. Yates and others (2005) also derived from the model calibration a specific yield of 0.08 and specific storages in the range $10^{-5}$ to $10^{-6}$ ft$^{-1}$, which is similar to the storage properties listed in Table 3.1.

The work of Yates and others (2005) suggests a lower conductivity for the Paso Robles Formation than for the Santa Margarita Formation. However, such a discrimination probably cannot be identified from a model calibration. While the available data allow the identification of the overall transmissivity of the groundwater-water system, the data do not allow the identification of conductivities for individual formations.

The model fit to groundwater levels is reasonable, given the high uncertainty in the measured groundwater levels. Figure 3.12b shows a scatter diagram comparing the weighted computed heads to the corresponding weighted measured groundwater levels, where the weighting corresponds to Equation 3.7. The coefficient of determination ($r^2$) is 0.92, and the correlation coefficient ($r$) is 0.96. Likewise for the unweighted statistics, the coefficient of determination ($r^2$) is 0.92, and the correlation coefficient ($r$) is 0.96, which corresponds to Figure 3.12a. Hill (1998) suggests that the correlation coefficient should be greater than 0.9 for the model fit to be acceptable, which is the case for both the weighted and unweighted statistics. Hill (1998) further suggest not using weighting when the observation uncertainties are identical, but doing so results in incorrect assessments of some calibration statistics. In particular, while the standard error of the estimate for the unweighted observations is 29 ft, the standard error for the weighted observations is 0.13. Such differences occur furthermore with respect to the parameter and predictive statistics. Correspondingly, calibration statistics based on the weighted observations better characterize the model calibration than those based on the unweighted observations.

The contours of computed heads correspond to the geographic pattern identified by Yates and others (2005, Figures 13 and 15) and shown here on Figures 1.8a-b. For the Paso Robles Formation, Figure 3.13a shows an area underlying Seaside that has computed heads below sea level. The area is similar in size to that shown on Figure 1.8a, and the lowest groundwater levels are similar. For the Santa Margarita Formation, Figure 3.13b shows areas underlying Seaside has computed heads below sea level. The area is similar in size to those shown on Figure 1.8b, and the lowest groundwater levels are similar.

The contours of computed salinity correspond to the seawater intrusion shown on Figures 1.9a-b, which indicates the absence of observed intrusion within the Seaside area.
As shown on Figures 3.14a-b, simulated seawater-intrusion impacts are absent within the Seaside area. However, the seaward parts of the Seaside groundwater basin show seawater intrusion, but the simulated salinity tends to be limited to the upper depth intervals of the groundwater system.
4.0 Model Simulations of Future Conditions

To assess the potential for future seawater intrusion within the Seaside area, the model was used to simulate groundwater conditions in 2015. For this simulation, the annual groundwater pumping during 13-year period 2003-2015 was set equal to the 2002 pumping from the Seaside groundwater basin. The groundwater recharge was set equal to the 1956-2002 average annual rate. The 2002 pumping is 6,300 acre-ft/yr, and the average annual recharge is 11,900 acre-ft/yr.

The simulation indicates that groundwater levels will decline within the Seaside area but seawater intrusion will not occur. Figures 4.1a-b show contours of computed heads within Paso Robles and Santa Margarita formations for 2015. The computed heads are as much as 5 ft lower in the Paso Robles Formation than in 2002, and they are as much as 10 ft lower in the Santa Margarita Formation. However, sizes of the regions within the Paso Robles and Santa Margarita formations with groundwater levels below sea level increase from 2002 to 2015. Figures 4.2a-b shows contours of computed salinity within the Paso Robles and Santa Margarita formations for 2015. For both the Paso Robles and Santa Margarita formations, the computed salinity is similar to that simulated for 2002. The water budget for the simulation is listed in Table 4.1.

To evaluate the potential benefits of relocating some of the pumping, the model was used to simulate the groundwater conditions with relocated pumping. The basic configuration of the simulation was the same as for the first. However, the pumping from the Paralta well (Table 2.1) was transferred to a new well located 10,000 ft northeast from the Paralta well. The relocated pumping represented a pumping rate of 2,000 acre-ft/yr.

The simulation indicates that groundwater levels will recover within the Seaside area and seawater intrusion will not occur. Figures 4.3a-b show contours of computed heads within Paso Robles and Santa Margarita formations for 2015. Within the vicinity of the Paralta well, the computed heads are as much as 20 ft higher in the Paso Robles Formation than in 2002, and they are as much as 30 ft higher in the Santa Margarita Formation. Figures 4.4a-b show contours of computed salinity within the Paso Robles and Santa Margarita formations for 2015. For both the Paso Robles and Santa Margarita formations, the computed salinity is similar to that simulated for 2002. The water budget for the simulation is listed in Table 4.2.
5.0 Conclusions

A groundwater model has been constructed for the Seaside groundwater basin, using the basin boundaries as defined by the California Department of Water Resources (2003). The model simulates groundwater flow and solute transport using the groundwater-modeling software *FEMFLOW3D*, which is a variant of the modeling software *FEMFLOW3D* (Durbin and Bond, 1998). The development of the model for the Seaside basin is based mostly on the hydrogeologic interpretation and data tabulations developed by CH2M/Hill (2005). The resulting model is a generalized representation of the groundwater system. Simulation results derived from the model can be interpreted to phenomena with spatial scales several thousand feet or more and temporal scale of a year or more.

The model was used to make two simulation scenarios involving future conditions. The first scenario assumes that the 2002 pumping would be continued until 2015, and the second scenario assumes that the pumping from the Paralta well would be relocated inland. For the first scenario, the simulation results are that groundwater levels will decline relative to the 2002 conditions, but seawater intrusion will not occur within the landward part of the Seaside basin. For the second scenario, the simulation results are that groundwater levels near Monterey Bay will increase, and seawater intrusion will not occur within the landward part of the Seaside basin.
6.0 References Cited


Hydrogeologic, Inc., 1996, MODFLOW-SURFACT software documentation—Volume II, Transport modules:


Monterey County Water Resources Agency, 2001, Water quality data:


Saucedo, G. J., Bedford, D. R., Raines, R. J., and Wentworth, C. M., 2000, GIS Data for the geologic map of California: California Division of Mines and Geology CD 2000-007


Tables
### Table 2.1 Location and Construction of Production Wells

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\(^1\)California State Spatial Library Albers projection.
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Table 3.2 Groundwater Budget for 2002
(acre-feet per year)

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Table 4.1 Groundwater Budget for 2015
With Continued Pumping
(acre-feet per year)

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Figures
Figure 1.1 Location of Seaside Groundwater Basin
Figure 1.2  Physiographic and Cultural Features
Figure 1.3 Hydrogeology of Study Area
Figure 1.4a  Northeast-Southwest Cross-Section of Seaside Groundwater Basin
Figure 1.4b  Northwest-Southwest Cross-Section of Seaside Groundwater Basin
Figure 1.5a  Base Elevation of Santa Margarita Formation
Figure 1.5b  Base Elevation of Purisima Formation
Figure 1.5c Base Elevation of Pasa Robles Formation

Monterey Bay

Model Boundary
Paso Robles Formation
Pasa Robles Formation Elevations
Figure 1.5d  Base Elevation of Surficial Deposits
Figure 1.5e  Base Elevation of Salinas Valley Clay
Figure 1.6  Model and Alternative Groundwater Boundaries

- Monterey Bay
- Model Boundary
- DWR Basins
- CH2M Hill Model Boundary
- Yates Model Boundary
Monterey Bay

Figure 1.7  Satellite Image of Groundwater Basin, March 2000
Figure 1.8a  Groundwater Levels for Fall 2002, Paso Robles Formation
Figure 1.8b Groundwater Levels for Fall 2002, Santa Margarita Formation
Figure 1.9b  Extent of Seawater Intrusion for 2001, Salinas Valley 400-Foot Aquifer
Figure 2.1  Production Wells in Model Area

- Model Boundary
- Production Wells in Model Area
- City of Marina
- City of Seaside
Figure 2.2 Monitoring Wells in Model Area
Figure 2.3a Geographic Distribution of NDVI*, January 1993
Monterey Bay

Figure 2.3b Geographic Distribution of NDVI*, March 1993

Model Boundary

NDVI*

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0.8

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Figure 2.3b Geographic Distribution of NDVI*, March 1993
Figure 2.3c Geographic Distribution of NDVI*, June 1993
Figure 2.3d  Geographic Distribution of NDVI*, August 1993

NdV*I®

Model Boundary

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0.6

0.8

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Monterey Bay
Figure 2.3e Geographic Distribution of NDVI*, October 1993
Figure 2.3f  Geographic Distribution of NDVI*, December 1993
Figure 2.4 Location of CIMIS Sites
Figure 3.1: Element Types Used to Construct Finite-Element Mesh

- Node
- Tetrahedral-Shaped Element
- Pyramid-Shaped Element
- Wedge-Shaped Element
Figure 3.2 Finite-element Mesh
Figure 3.3 Oblique View of Finite-Element Mesh
Figure 3.4a  South-North Cross-Section of Finite-Element Mesh
Figure 3.4b Northwest-Southeast Cross-Section of Finite-Element Mesh
Figure 3.5 Contraction of Element Column
Figure 3.6 Horizontal Weighting of Pumping From a Well to a Node
Figure 3.7 Vertical Weighting of Pumping From a Well to a Node
Figure 3.8  Location of Specified-Head Boundaries

- Model Boundary
- Reliz Fault
- Monterey Bay Bottom

Monterey Bay
Figure 3.9 Specified Heads Along Reliz Fault
Figure 3.10a  Initial Heads Assigned to Model, Paso Robles Formation
Figure 3.10b Initial Heads Assigned to Model, Santa Margarita Formation
Figure 3.11a Initial Salinity Assigned to Model, Paso Robles Formation
Figure 3.11b Initial Salinity Assigned to Model, Santa Margarita Formation
Figure 3-12a Comparison of Computed Heads and Measured Groundwater Levels, Unweighted Residuals
Figure 3-12b  Comparison of Computed Heads and Measured Groundwater Levels, Weighted Residuals
Figure 3.13a Computed Heads for 2002, Paso Robles Formation
Figure 3.13b  Computed Heads for 2002, Santa Margarita Formation
Figure 3.14b Computed Salinity for 2002, Santa Margarita Formation
Figure 4.1a Computed Heads for 2015 with Continued Pumping, Paso Robles Formation
Figure 4.1b Computed Heads for 2015 with Continued Pumping, Santa Margarita Formation
Figure 4.2a Computed Salinity for 2015 with Continued Pumping, Paso Robles Formation
Figure 4.2b Computed Salinity for 2015 with Continued Pumping, Santa Margarita Formation
Figure 4.3a Computed Heads for 2015 with Relocated Pumping, Paso Robles Formation
Figure 4.3b  Computed Heads for 2015
with Relocated Pumping, Santa Margarita Formation
Figure 4.4a Computed Salinity for 2015 with Relocated Pumping, Paso Robles Formation
Figure 4.4b Computed Salinity for 2015 with Relocated Pumping, Santa Margarita Formation