2.3 Model Grid and Boundary Conditions

The finite difference grid design allows selection of graduated grid sizing with the smaller grids providing higher resolution in the zones of greater interest, such as the surface artificial recharge basins area. The ground water flow model grid covers an area of approximately 12 square miles (7,750 acres) with a finite-difference grid consisting of 199 rows in the north to south direction and 278 columns in the west to east direction for a total of 55,322 cells (see Figure 11). The smallest model cells are in the area of the Green Spot site and in map view are squares 20 ft by 20 ft. Model cells at the edges of the model are squares 100 ft by 100 ft.

A boundary condition is an external influence or effect that may act as a source or sink, adding or removing water from the ground water flow system. The boundary conditions used in the model are no-flow, constant head, and a combination of subsurface underflow and mountain front recharge (see Figure 12). The no-flow boundary, in plan view, is depicted as gray on Figure 12. The green cells around the southern portion of the active model area represent the subsurface underflow and mountain front recharge. The brown cells at the northernmost portion of the model represent the constant head boundary.

2.4 Calibration

The Green Spot site ground water model was calibrated for transient conditions from January 1992 through June 2004 using the calibration process described in GEOSCIENCE (2004). Quarterly stress periods (i.e. each stress period is three months) were incorporated into the model for the period January 1992 through December 2003. Semi-monthly stress period were incorporated for the period January 2004 through June 2004. This time period was selected based on the availability of hydrologic data and to include the data collect during the Pilot Scale Artificial Recharge Testing. To facilitate the transient model calibration, a hand-contoured ground water level contour map was constructed from observed January 1992 ground water levels and was used as the starting head for the transient model.

Measured ground water levels for nine transient target wells using 536 ground water level observations between January 1992 and June 2004 are shown on Figure 13 along with model-generated ground water levels. Individual hydrographs for four of the nine target wells used in the transient calibration are also shown on Figure 14. Although there are localized differences between measured and model-generated ground water levels, the model successfully simulates regional changes in ground water levels associated with natural ground water recharge and well pumping across the model area, as well as artificial surface recharge during sub-scale pilot tests.

Results of the transient calibration indicate an acceptable match between model-generated and measured ground water levels as a function of time, particularly the transient response of the ground water mounding generated during the sub-scale pilot artificial surface recharge testing (see Figure 14). The overall model relative error (the standard deviation of the water level residuals divided by the observed head range) is 7.7 percent. Generally accepted model calibration is dictated by a relative error below 10 percent (Spitz and Moreno, 1996; and Environmental Simulations, Inc., 1999).

It should be noted that ongoing ground water exploration and investigation in the Erwin Hydrologic Subunit will yield additional data that can be used to further refine the ground water flow model input parameters and potentially improve the calibration results.

2.5 Sensitivity

A sensitivity analysis was conducted on the transient calibration to assess which model input parameters have the greatest effects on the model's simulation results. For this analysis, the model's sensitivity was evaluated after first increasing the value of model input parameters by 20 percent (relative to the calibrated input value) and then decreasing the value of model input parameters by 20 percent. The following input parameters were varied for this analysis:

- Hydraulic Conductivity,
- Storativity,
- Evapotranspiration Rate,
- Streambed Conductance,
- Spatially Distributed Ground Water Recharge from Precipitation,
- Ground Water Pumping,
- Streamflow, and
- Subsurface Underflow and Ground Water Recharge from Mountain Front Runoff.

The sensitivity analysis indicates that the model is most sensitive to decreases in hydraulic conductivity and increases in subsurface underflow and ground water recharge from mountain front runoff (see Figure 15). Input parameter sensitivity is dictated by the magnitude of impact on ground water level residuals (i.e. the difference between model-generated and measured ground water levels) resulting from increasing or decreasing the value of the input parameter. Thus, a 20 percent decrease in hydraulic conductivity or a 20 percent increase in ground water recharge would have a greater impact on ground water residuals than similar changes in the other input parameters for the model.

2.6 Recharge Water Migration Rate Analysis

To track the temporal and spatial advective subsurface migration of artificial surface recharge water from beneath the Green Spot site to the nearest existing ground water production wells, GEOSCIENCE conducted a particle tracking analysis using the MODFLOW model coupled with MODPATH, a post-processing package used to compute flow paths. MODPATH uses a semi-analytical particle-tracking scheme that provides an analytical expression of the ground water's flow path within each finite-difference grid cell. Flow paths are computed by tracking "particles" of water from a starting cell to the next downgradient cell, and so on, until the particle reaches a boundary, such as a no flow or constant head, or satisfies some other termination criterion. MODPATH does not take into account dispersion or other similar processes. The results of MODPATH, therefore, only provide the direction and rate of advective ground water transport or seepage velocity as defined by:

$$n = \frac{K \frac{dh}{dl}}{q(7.48)}$$

Where:

n = Seepage Velocity, [ft/day]

K = Hydraulic Conductivity, [gpd/ft^2]

$\frac{dh}{dl}$ = Hydraulic Gradient, [ft/ft]

q = Effective Porosity, [fraction]

3.0 DEVELOPMENT OF PREDICTIVE PROJECT OPERATIONAL SCENARIOS

To assess the effects of a full-scale artificial surface recharge program at the Green Spot site on the regional ground water system in the Erwin Hydrologic Subunit, multiple predictive simulations were developed for full-scale operational scenarios using the calibrated ground water flow model. The selected scenarios define the operational inputs to the ground water flow model (i.e. amounts and timing of artificial recharge and ground water pumping) that affect the model's simulation outcome (i.e. changes in ground water levels in response to the artificial recharge and pumping). Predictive scenarios, provided in this report, were developed with input from staff of both the BBDWP and BBCSD based on a strategic knowledge that projected how a full-scale artificial recharge program might be operated in the Erwin Subunit. In the future, additional scenarios can be evaluated using the calibrated ground water flow model as details of the operation of the recharge basins are developed.

A total of nine predictive model scenarios were evaluated with the Green Spot ground water flow model. A summary of operational scenarios applied to the ground water flow model is provided in the following table:

Table 1. Operational Scenarios Applied to the Ground Water Flow Model

Scenario Number	Artificial Surface Recharge Amount [Acre-ft/yr]	Ground Water Extraction "Above Baseline"[1] [Acre-ft/yr]	Number of Extraction Wells Above Baseline Wells[2]
1	0	0	0
2	500	0	0
3	1,000	0	0
4	1,500	0	0
5	2,000	0	0
6	500	500	3
7	1,000	1,000	6
8	1,500	1,500	9
9	2,000	2,000	12

1 Baseline is defined as the "no project" scenario, which is dictated by the annual precipitation and ground water pumping regimes of the transient calibration period between 1992 and 2001.

2 Assume 100 gpm/well

3.1 Assumptions Applicable To All Scenarios

All of the predictive scenarios evaluated included the following basic assumptions:

- The predictive period was 10 years (2005 to 2014) with a monthly stress period. The predictive period is the same amount of time as the transient model calibration (1992 to 2001),
- The predictive period incorporated the precipitation cycles of the transient calibration period (1992 to 2001), which replicated magnitude and timing of precipitation,
- The predictive period assumed the same amount and timing of pumping as the baseline pumping recorded during the transient calibration period (1992 to 2001),

- Artificial surface recharge was simulated in the ground water flow model for a 9-month period (March through November) during each year of the predictive period,

- For simulations that included additional ground water pumping (in addition to the baseline pumping), the pumping was added continuously for 24 hrs/day, seven days a week, twelve months per year,

- Any additional pumping over and above the baseline pumping (see Table 1) was assumed to be from additional wells added to the model, each with a pumping rate of 100 gallons per minute (gpm),

- For simulations that included additional ground water pumping above the baseline, the total annual amount of additional pumping was equal, in each scenario, to the total annual amount of artificial recharge for that scenario (e.g., for the scenario with 500 acre-ft/yr artificial recharge, 500 acre-ft/yr was extracted via the additional pumping wells).

Simulation of the input of artificial recharge into the model was conducted by adding water to model cells located in the 25-acre area of the model representing the potential Green Spot Artificial Surface Recharge area. For the 500 acre-ft/yr scenarios (Scenarios 2 and 6), the water was added to only the model cells in the southern 5 acres of the site. For the 1,000 acre-ft/yr scenarios (Scenarios 3 and 7), water was added to model cells in the southern 5-acre area as well as the eastern 10 acres directly north of it. For the 1,500 and 2,000 acre-ft/yr scenarios (4, 5, 8 and 9), water was added to model cells throughout the 25-acre site.

It should be noted that the artificial recharge added to the Green Spot site for each model scenario is representative of a bulk quantity of water without regard to the source of water. Per California Department of Health Services requirements, it will initially be required to provide a secondary source of water (referred to as “diluent” water) during the artificial recharge process. Potential sources of diluent water could include natural ground water recharge, captured storm water runoff, potable water, or a combination of some or all of these potential sources. Furthermore, some or all of the diluent water may be added on a seasonal basis such that the artificial surface recharge of only recycled water occurs during a portion of the season (e.g. the summer and fall months) and only diluent water is artificially recharged during another portion of the season (e.g. winter and spring months).

The quantities of water used for artificial recharge in the model represent the total quantity of both recycled water and diluent water. Thus, for a 500 acre-ft/yr recharge scenario and assuming a 50 percent recycled water contribution, the 500 acre-ft of recharge represents 250 acre-ft of recycled water and 250 acre-ft of diluent water. It is further assumed that the source of the diluent water does not represent ground water pumped from the Erwin Subunit.

3.2 Description of Operational Full-Scale Model Scenarios

Scenario 1 was a baseline scenario that did not incorporate additional artificial recharge or ground water pumping associated with an artificial recharge project. The purpose of this scenario was to show regional changes in ground water levels resulting from changes in natural recharge (precipitation) and historical ground water pumping. The baseline scenario also provides a reference scenario against which to compare the effects of adding the artificial recharge project.

Scenarios 2 through 5 evaluated potential changes in ground water levels that would result from the artificial recharge of 500, 1,000, 1,500 or 2,000 acre-ft/yr of water with no additional ground water pumping. The purpose of these scenarios was to estimate the maximum amount of water that the aquifers in the Erwin Subunit could accommodate by evaluating potential ground water level rise during artificial recharge operations. The limiting factor for these scenarios was the minimum ground water depth at which liquefaction potential becomes an issue.

Liquefaction is a process whereby shallow saturated unconsolidated sediments lose cohesion during an earthquake. In areas where the soil properties are subject to liquefaction, buildings can be damaged if the magnitude and duration of an earthquake is sufficient to cause a loss of the soil's bearing strength. Saturated sediments less than 30 ft bgs are the most susceptible to liquefaction (Matti and Carson, 1991). However, liquefaction can occur at depths of less than 50 ft bgs (Martin & Lew, 1999). Liquefaction potential was evaluated at the Green Spot site through a detailed borehole drilling and testing program as well as a spectral analysis of surface waves (GEOSCIENCE, 2005). The results of this evaluation showed that the sediments beneath the Green Spot site are not subject to liquefaction. Based on these findings, the 30 ft bgs ground water level criterion is used herein as a basis for maximum artificial recharge receptivity at the Green Spot site.

Scenarios 6 through 9 included the same artificial recharge rates but, in each scenario, an equal amount of ground water was pumped from the model as was artificially recharged. The purpose of these scenarios was to evaluate the potential combined effect of artificial recharge and ground water extraction on ground water levels. Furthermore, they were designed to provide the extreme ranges of potential stresses on the ground water system (both drawdown and recharge mounding) to assess the working bounds within which a full-scale artificial recharge and recovery program would successfully operate. Potential added extraction wells were located in simulation approximately 2,000 ft downgradient of the proposed full-scale Green Spot artificial recharge site. Locations of the six extraction wells simulated for the 1,000 acre-ft/yr scenarios (Scenario 7) are shown on Figure 16.

4.0 RESULTS OF SIMULATION AND ANALYSIS OF OPERATIONAL SCENARIOS

For the purpose of describing the estimated changes in ground water levels across the ground water flow model area resulting from the various artificial recharge and well pumping scenarios described in Section 3.0, ground water level hydrographs for four wells (BBCSD Well No. 2, Vaqueros, etc.) shown on Figure 16 will be discussed in the following sections. These wells include BBARWA monitoring well MW-4 (located on the Green Spot site), BBDWP Lakewood Well No. 5, the BBCSD Vaqueros monitoring well, and BBCSD Well No. 2. The hydrographs for these wells are provided in Appendices A through C.

4.1 The Baseline Scenario (No Artificial Recharge Or Additional Pumping)

The baseline scenario shows ground water fluctuations from natural precipitation/recharge cycles and ground water pumping for municipal supply in the northern Erwin Hydrologic Subunit over the period from 1992 to 2001. As described earlier, this scenario provides a basis against which to compare simulated ground water levels resulting from the introduction of artificial recharge and additional pumping (beyond the baseline) in the model. Baseline ground water level hydrographs for the wells shown on Figure 16 are provided in Appendix A.

Hydrographs from MW-4, located at the Green Spot site, show the widest naturally occurring seasonal fluctuations in ground water levels in the model area. The wide fluctuations correspond to years with above-normal precipitation. The magnitude of the natural seasonal ground water level fluctuations becomes progressively less pronounced with distance away from the Green Spot site to the north (see Appendix A; pgs. A-2 through A-4). Periods of high ground water levels in the Green Spot site area are significant from a site operations standpoint because they may dictate the amount of artificial recharge water that can be stored in the aquifer during those periods of time without additional pumping to lower the ground water table.

The hydrographs show that natural ground water levels in the model area are deepest in the vicinity of the Green Spot site and shallowest in the vicinity of BBCSD Well No. 2. During periods of below-normal precipitation, ground water levels at the Green Spot site are greater than 90 ft bgs. At BBCSD Well No. 2, ground water levels are typically within 10 ft of the land surface. The aquifer system between the Green Spot site and the proposed extraction wells in the Lakewood area would be used to store artificial recharge water.

The water budget for the baseline scenario of the ground water flow model is shown on (Figure 17). Model inflow is shown by the blue and green bars located above the "0" line, which extends horizontally through the center of the chart. As shown, the primary source of water into the model area is underflow from upgradient portions of the Erwin Hydrologic Subunit. Some recharge occurs, primarily during years of high precipitation, from infiltration of running water in ephemeral streams and precipitation falling directly on the land surface. Model outflow, as shown by the colored bars below the "0" line on the chart, include ground water pumping, evapotranspiration, streamflow out of the model area, and underflow out of the model area (see Figure 17).

4.2 Scenarios 2 Through 5 (Artificial Recharge With No Additional Pumping)

Scenarios 2 through 5 evaluated potential changes in ground water levels that would result from the artificial recharge of 500, 1,000, 1,500 and 2,000 acre-ft/yr of water, respectively but without additional ground water pumping. The purpose of these scenarios was to assess the limits of the holding capacity of the aquifer system in the northern Erwin Hydrologic Subunit.

4.2.1 Impacts of Artificial Recharge on Ground Water Levels

Hydrographs from Scenarios 2 through 5 (see Appendix B) show a predictable increase in ground water levels with increasing amounts of artificial recharge applied to the Green Spot Site.

Ground water levels beneath the Green Spot Site, as shown from the model-generated hydrograph of MW-4, show the greatest increases during artificial recharge but also show rapid declines during the 3-month period of each year that artificial recharge is not conducted. During dry climatic periods, ground water levels remain below approximately 15 ft bgs for artificial recharge amounts of 1,000 acre-ft/yr or less. For Scenario 4 (1,500 acre-ft/yr artificial recharge scenario), maximum ground water level rises are at the land surface during dry climatic periods and rise above the land surface during wet climatic periods. Maximum ground water level rise is above the land surface during dry and wet climatic cycles for Scenario 5 (2,000 acre-ft/yr artificial recharge scenario).

At downgradient Lakewood Well No. 5, ground water levels rise between approximately 6 ft (Scenario 2; 500 acre-ft/yr artificial recharge) and 20 ft (Scenario 5; 2,000 acre-ft/yr artificial recharge). The magnitude of ground water level rise is greater during dry climatic periods. At the furthest downgradient well (BBCSD Well No. 2), ground water levels, which naturally rise to within a few feet of the land surface during climatically wet periods, rise above the land surface during the same time periods for Scenarios 2 through 5.

4.2.2 Impacts of Artificial Recharge on the Hydrologic Budget

The model analysis of Scenarios 2 through 5 show that increasing amounts of artificial recharge, when not pumped, result in increasing amounts of evapotranspiration and streamflow out of the model in the Shay Meadow area. Water budget diagrams for Scenarios 2 through 5 are provided in Appendix D. Underflow out of the model, which conceptually would flow into the aquifer system beneath Baldwin Lake, does not substantially increase as a result of increasing artificial recharge at the Green Spot Site.

4.2.3 Recharge Water Migration Rate Analysis

To evaluate the potential migration rate of water artificially recharged at the Green Spot site, a particle-tracking analysis was conducted using MODPATH as described in Section 2.6. Results of the analysis show that the time required for water artificially recharged at the Green Spot site to reach BBDWP's Lakewood well field ranges from approximately 1 year (Scenario 5; 2,000 acre-ft/yr artificial recharge) to approximately 2 years (Scenario 2; 500 acre-ft/yr artificial recharge).

4.3 Scenarios 6 Through 9 (Artificial Recharge with Additional Pumping)

Scenarios 6 through 9 were analyzed to evaluate potential changes in ground water levels that would result from the artificial recharge of 500, 1,000, 1,500 and 2,000 acre-ft/yr of water, respectively while pumping a like amount of ground water from downgradient wells. The purpose of these scenarios was to assess the combined impact of artificial recharge and ground water pumping on ground water levels and artificial recharge water migration rates. Although details of the amounts and timing of future recharge and recovery operations for the artificial recharge basins at the Green Spot site will be determined in the future, Scenarios 6 through 9 more realistically simulate how the artificial recharge and recovery operation might work because they include extraction of the stored water.

4.3.1 Impacts of Artificial Recharge on Ground Water Levels

Hydrographs from Scenarios 6 through 9 (see Appendix C) show rising ground water levels in the vicinity of the Green Spot site but the magnitude of the rise is not as great as in previous scenarios that did not include additional pumping. In addition, changes in ground water levels downgradient of the production well field are minor. The comparatively lower ground water levels are a result of pumping within the hypothetical well field described in Section 3.2. During dry climatic periods, ground water levels are as low as 30 ft bgs for artificial recharge amounts of 1,000 acre-ft/yr or less and 50 ft bgs for artificial recharge amounts of 500 acre-ft/yr or less. For Scenario 5 (2,000 acre-ft/yr artificial recharge scenario), maximum ground water level rises are above the land surface during dry and wet climatic periods.

At downgradient Lakewood Well No. 5, ground water levels are typically lower relative to the baseline ground water level due to the increased pumping levels from the extraction well field. Ground water levels are higher than the baseline period during climatically wet periods, presumably due to decreased pumping from the Lakewood well field.

At the furthest downgradient well (BBCSD Well No. 2), ground water levels are lower than the baseline period during the first year of pumping/recharge but return to levels that closely match the baseline ground water level. The initial drop in ground water levels is due to the startup of the extraction well field.

4.3.2 Impacts of Additional Ground Water Pumping on Private Wells

There are 74 private wells within the active model area (see Table 2). A range of potential ground water level impacts on these wells from pumping associated with the Green Spot artificial recharge project were evaluated using the model output of Scenario 6 (500 acre-ft/yr recharge and recovery) and Scenario 7 (1,000 acre-ft/yr recharge and recovery). For Scenario 6, model results show that the maximum additional ground water drawdown (i.e. pumping interference) from extraction well pumping did not exceed approximately six feet in any wells and interference in excess of five feet was restricted to wells that were located within 500 ft of the proposed well field. For Scenario 7, the maximum pumping interference was approximately 13 ft in two wells located approximately 240 to 280 ft from proposed extraction wells. However, additional drawdown did not exceed approximately 11 ft in wells located more than 500 ft from the extraction wells.

It should be noted that the potential well impacts described above are based on scenarios that were designed to maximize potential ground water level impacts, thereby presenting a "worst case" scenario. In reality, artificial recharge and corresponding extraction can be planned to minimize ground water level impacts to private wells. Furthermore, the locations of the private wells are approximate because they are based on California Department of Water Resources driller's logs, which provide only a general location of the wells. Finally, the actual locations of extraction wells have not been determined but may be located to avoid private wells. With all of these considerations in mind, the above ground water level impacts are approximate but are considered to be the maximum that would be expected from the project.

4.3.3 Impacts of Artificial Recharge and Ground Water Pumping on the Hydrologic Budget

The model analysis of Scenarios 6 through 9 show that the artificially recharged water is almost completely recovered with the extraction wells with little additional evapotranspiration and streamflow (relative to the baseline scenario) out of the model in the Shay Meadow area. Water budget diagrams for Scenarios 6 through 9 are provided in Appendix E.

4.3.4 Recharge Water Migration Rate Analysis

Results of the particle tracking analysis for Scenarios 6 through 9 show that the time required for water artificially recharged at the Green Spot site to reach BBDWP's Lakewood well field ranges from approximately 1 year (Scenario 9; 2,000 acre-ft/yr artificial recharge) to approximately 2 years (Scenario 6; 500 acre-ft/yr artificial recharge). In all scenarios evaluated, the minimum recharge water residence time specified by the California Department of Health Services (DHS) for recycled water recharge projects (6 months) was met.