Groundwater Flow between Basins
Mojave River Basin

Este – Alto Hydrologic Subareas

California State University, Fullerton
Department of Geological Sciences
Groundwater flow between Basins Report
Mojave River Basin
Este – Alto Hydrologic Subareas

Authored by

Nicholas Napoli
W. Richard Laton, Ph.D., PG, CPG

Prepared in Cooperation with and

Submitted to

Mojave Water Agency

October 2005

California State University, Fullerton
Department of Geological Sciences
Groundwater Flow Between Basins Report
Mojave River Basin
Este – Alto Hydrologic Subareas

This report has been prepared by California State University, Fullerton; Department of Geological Sciences for the exclusive use of the Mojave Water Agency. The procedures and interpretations described in this report have been prepared in accordance with practices generally accepted by other academic institutions, engineers, geologists, hydrogeologists, environmental engineers, and environmental scientists practicing in this field. No other warranty, either expressed or implied, is made.

REPORT PREPARED BY: ___________________
W. Richard Laton, Ph.D., PG, CPG
Assistant Professor of Hydrogeology
California State University, Fullerton

REPORT PREPARED BY: ___________________
Nicholas R. Napoli, MSc.
Graduate Student
California State University, Fullerton

UNDER THE PRIMARY REVIEW OF: ___________________
Lance Eckhart, PG, CHG
Senior Hydrogeologist
Mojave Water Agency
List of Tables:

Table 1: Source and Information on Varying Hydraulic Conductivity Values.
Table 2: Gradient Calculations for individual time-steps.
Table 3: Winter 1956-57 Flow Calculations (ft³/day).
Table 4: Spring 1994 Flow Calculations (ft³/day).
Table 5: Spring 2004 Flow Calculations (ft³/day).
Table 6: Winter 1956-57 Flow Calculations (acre-ft/day).
Table 7: Spring 1994 Flow Calculations (acre-ft/day).
Table 8: Spring 2004 Flow Calculations (acre-ft/day).
Table 9: Range of yearly discharge values (acre-ft/year).

List of Figures:

Figure 1: Location map of study area.
Figure 2: Location map of wells used in this study.
Figure 3a: Este-Alto groundwater hydrographs from 1915 to present.
Figure 3b: Alto groundwater hydrographs from 1915 to present.
Figure 3c: Este groundwater hydrographs from 1915 to present.
Figure 4a: Este-Alto groundwater hydrographs from 1990 to present.
Figure 4b: Alto groundwater hydrographs from 1990 to present.
Figure 4c: Este groundwater hydrographs from 1990 to present.
Figure 5a: Groundwater elevation contour map for Winter 1956-1957.
Figure 5b: Groundwater elevation contour map for Spring 1994.
Figure 5c: Groundwater elevation contour map for Spring 2004.
Figure 6: Profile of interpolated groundwater elevation grid.

Appendices:

Appendix A – Procedural Methodology
Flow between Basins Report
Este – Alto Hydrologic Subareas

1.0 Introduction

The following report represents the work efforts between California State University, Fullerton – Department of Geological Sciences and the Mojave Water Agency (MWA) Water Resources Department on determining the groundwater flow across sub-basin boundaries. In order to determine what, if any, groundwater flow exists at these boundaries, a series of investigative tests were run. These tests examined the change(s) in groundwater gradients across these boundaries through a comparison of historical water level records for the region in question (Figure 1). The following discussion outlines the procedures and protocols followed in order to make these determinations.

2.0 Background

Flow is from Este to Alto!
I need to insert a little background regarding the Judgment and obligations of the MWA to quantify Subarea flow. I will work with Bob Wagner on this section and this can be inserted later. A little emphasis will be made regarding focus of quantifying change in flow from ~1994 to present rather than quantifying the actual amount of flow between areas with little data regarding several key variables. ADD THAT JUDGMENT STATES ESTE IS OBLIGATED TO PROVIDE MINIMUM ANNUAL SUBSURFACE FLOW OF 200 AFY TO FLOW INTO ALTO

3.0 Methods

Water level data from the United States Geological Survey’s (USGS) National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis) and the California’s Department of Water Resources (DWR) (http://wdl.water.ca.gov/) were compiled to create a groundwater level database for the Este-Alto Hydrologic subarea boundary region. This database was then spatially mapped to determine a definitive boundary for the study area. Once this boundary was identified, the groundwater level data inside the boundary was used to create a series of hydrographs. The hydrographs were then used to determine which multiple time-steps contained enough spatially diverse data to create reasonable groundwater elevation contour maps for individual periods of time. Groundwater gradients are then calculated using three different methods: (1) electronically (by computer), (2) manually (by hand) from the groundwater elevation contour maps, and (3) using a gradient vector analysis. The average of the three gradients is considered the actual gradient value, and is used to calculate the change in gradient during the interval between time-steps. At the boundary between the two basins, a cross-section is drawn perpendicular to the gradient, and cross-sectional area is calculated. Using Darcy’s Law (Equation 1) discharge per day is calculated for the individual time-
periods. Flow and discharge are used interchangeably in this report. Flow is then calculated by multiplying discharge per day by days in a given time-period.

Darcy’s Law

\[ Q = KiA \]

where:

\[ Q = \text{discharge in ft}^3/\text{day} \]
\[ K = \text{hydraulic conductivity in ft/day} \]
\[ i = \text{gradient or slope in ft/ft} \]
\[ A = \text{cross sectional area in ft}^2 \]

The cross-sectional area (A) was based on a range of aquifer thicknesses at the Este-Alto Hydrologic Subarea boundary. The aquifer thickness varied from a minimum of 100 feet to a maximum of 1,000 feet. The minimum was based on Stamos, et al. [2004], whereas, the 300 foot thickness of the aquifer is based on the deepest depth of groundwater wells within the study area. The maximum was based on oil and gas well logs near the boundary, but within the Este Hydrologic Subarea.

Due to the lack of depth and discrete information on both basin geometry and aquifer properties, a range of values is used. This range of values was based on previous regional and local studies and estimates using available data. The ranges in hydraulic conductivities come from a variety of sources [Stamos et al, 2001, Fetter 2001, Geosciences Support, 1992, Barto, 1990, Heath, 1987 and Driscoll, 1986] (Table 1). These constitute the range of expected hydraulic conductivity values for semi-cemented sandstone to weathered fractured gravelly sandstones. Based on interpretive geologic cross-sections through the area [Laton, et. al., 2005 and Stamos et al., 2001] this seems reasonable.

<table>
<thead>
<tr>
<th>Source</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
<th>Aquifer Thickness (ft)</th>
<th>Notes on source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Sources</td>
<td>0.003</td>
<td></td>
<td>General References</td>
</tr>
<tr>
<td>Stamos et al, 2001</td>
<td>0.25</td>
<td>100</td>
<td>2001 USGS calibrated groundwater model</td>
</tr>
<tr>
<td>GeoSciences Support, 1992</td>
<td>47.9</td>
<td></td>
<td>Aquifer test conducted at Old Women Springs Ranch</td>
</tr>
<tr>
<td>Laton et. al., 2005</td>
<td></td>
<td>300 – 1,000</td>
<td>Este Hydrologic Sub-basin Report</td>
</tr>
<tr>
<td>Barto, 1990</td>
<td>56.2</td>
<td></td>
<td>Aquifer test conducted at Mr. Harry Abdul’s ranch located in the Este Hydrologic subarea.</td>
</tr>
<tr>
<td>Multiple Sources</td>
<td>300</td>
<td></td>
<td>General References</td>
</tr>
</tbody>
</table>

Table 1: Source and Information on Varying Hydraulic Conductivity Values.
Although flow between subareas can be calculated, many assumptions have to be made regarding basin geometry and the hydraulic conductivity of the aquifer material(s) through which the groundwater is flowing. Therefore, a range of values have been calculated for flow across the Alto-Este Subarea. Data associated with depth to groundwater and groundwater gradients have been collected by the MWA and others for several decades and are readily available. These data can be used to accurately determine if:

1. Regional groundwater levels have materially changed historically and within the onset of the Judgment and
2. Regional groundwater gradients, which control the speed at which groundwater flows, have changed historically and within the onset of the Judgment.

Pursuant to the subsurface flow between subareas, the only dynamic variables which can control flow are changes in water levels and changes in hydraulic gradient. Basin geometry and the hydraulic conductivity of the aquifer materials are not prone to change. Therefore, this study will focus on changes in groundwater levels and changes in hydraulic gradient. Both of these variables can be altered via groundwater pumping and historical data exists to verify these changes, if any.
Figure 1: Location map of study area.
4.0 Data

A total of 83 groundwater wells were available for this study (28 wells in Este and 55 wells in Alto), and are shown in Figure 2. Data for all 83 wells resides in the NWIS or DWR databases (see methods). Records from these wells represent 784 individual data points from 1917 through 2004. Groundwater elevation ranged from a low of 2,770 feet above mean sea level (AMSL) to a high of 3,050 AMSL (Figure 3a).

5.0 Results/Discussion

The results of this study are listed in three parts: hydrographs analysis, gradient analysis and flow analysis. The hydrograph analysis consisted of visually inspecting the respective hydrographs for trends across the period of record. The gradient analysis was conducted for specific individual time-steps; winter 1956-57, spring 1994 and spring 2004. The change in gradient was derived from the differences calculated between these three time-steps. The flow analysis determines if the change(s) in gradient constitute a significant change in flow (Q) across the subarea boundary.

5.1 Hydrograph Analysis

Groundwater hydrographs were created for all 83 wells within the study area (see Figure 2). Figure 3a shows that over the long-term there has been little variation in groundwater levels with only minor fluctuations attributed to seasonal effects. Figures 3b and 3c, separate the data by basin (Este and Alto) respectively, also suggesting minor fluctuation and relative stability conditions.

Figures 4a-c provides a record of recent water levels from 1990 to present, of which 11 wells contain records from 1994 to present (the period of the last 10 years since formal adjudication). From these figures it can be shown that water levels have been stable with only minor (less than 10 feet) fluctuation over the past 15 years. This confirms that water levels have not experienced any increase or decrease over the past 15 years. This suggests that groundwater levels remained relatively constant throughout the boundary between Alto and Este Subareas.
Figure 3a: Este-Alto groundwater hydrographs from 1915 to present.
Figure 3b: Alto groundwater hydrographs from 1915 to present.
Figure 3c: Este groundwater hydrographs from 1915 to present.
Figure 4a: Este-Alto groundwater hydrographs from 1990 to present.
Figure 4b: Alto groundwater hydrographs from 1990 to present.
Figure 4c: Este groundwater hydrographs from 1990 to present.
5.2 Gradient Analysis

In order to determine changes in the groundwater gradient (slope of the water table), three time-steps within the database containing the most abundant and spatially diverse data were chosen: winter 1956-57, spring 1994 and spring 2004. In order to avoid outlying data, wells not within the contour boundary in Figure 2 were omitted from these time-step analyses. Each time-step had sufficient data to contour across the study area. The periods of 1994 and 2004 were chosen to capture the onset of the adjudication to the present. Figures 5a-c show the results of the groundwater level contour analysis while Figure 6 shows the groundwater level profile based on the computer interpolated elevations from the GIS contour analysis.
Figure 5a: Groundwater elevation contour map for Winter 1956-1957.
Figure 5b: Groundwater elevation contour map for Spring 1994.
Figure 5c: Groundwater elevation contour map for Spring 2004.
Gradient

Winter 1956-57 (0.0021 ft/ft)
Spring 1994 (0.0027 ft/ft)
Spring 2004 (0.0026 ft/ft)
The gradient shows an increase from 1956, 0.0021 to 0.0025 ft/ft in 2004. This change in gradient is within the error (± 0.0004 ft/ft) of the analysis. The error is based on the variation in surface elevation. Surface elevations have been calculated by a comparison of the USGS topographic map and USGS digital elevation map. The variation in these measurements is ± 8 feet of elevation over the study region. Over the study area this equates to a gradient variation (potential error) of ± 0.0004 ft/ft.

<table>
<thead>
<tr>
<th>Method / Period</th>
<th>1956</th>
<th>1994</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Calculated from contour map (ft/ft)</td>
<td>0.0024</td>
<td>0.0029</td>
<td>0.0024</td>
</tr>
<tr>
<td>GIS Groundwater cross-section tool (ft/ft)</td>
<td>0.0021</td>
<td>0.0027</td>
<td>0.0026</td>
</tr>
<tr>
<td>Vector Analysis (ft/ft)</td>
<td>0.0019</td>
<td>0.0024</td>
<td>0.0025</td>
</tr>
<tr>
<td><strong>Average of all three techniques (ft/ft)</strong></td>
<td><strong>0.0021</strong></td>
<td><strong>0.0027</strong></td>
<td><strong>0.0025</strong></td>
</tr>
</tbody>
</table>

Table 2: Gradient Calculations for individual time-steps.
### 5.3 Flow Analysis

Flow is defined as the discharge (Q) across the boundary in question. Using the ranges in values and the calculated time-step gradients as discussed earlier, the following tables represent the range in discharge or flow (ft³/day) across the subarea boundary for each time-step.

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft³/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td>118</td>
</tr>
</tbody>
</table>

Table 3: Winter 1956-57 Flow Calculations (ft³/day) (Gradient of 0.0021 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft³/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td>149</td>
</tr>
</tbody>
</table>

Table 4: Spring 1994 Flow Calculations (ft³/day) (Gradient of 0.0027 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft³/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td>140</td>
</tr>
</tbody>
</table>

Table 5: Spring 2004 Flow Calculations (ft³/day) (Gradient of 0.0025 ft/ft).
Using the same ranges in hydraulic conductivity and time-step gradients, the following tables represent the discharge or flow (acre-ft/day) across the subarea boundary for each time step.

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (acre-ft/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.003</td>
<td>0.25</td>
</tr>
<tr>
<td>100</td>
<td>&lt; 0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>1,000</td>
<td>&lt; 0.02</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 6: Winter 1956-57 Flow Calculations (acre-ft/day) (Gradient of 0.0021 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (acre-ft/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.003</td>
<td>0.25</td>
</tr>
<tr>
<td>100</td>
<td>&lt; 0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>1,000</td>
<td>&lt; 0.02</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 7: Spring 1994 Flow Calculations (acre-ft/day) (Gradient of 0.0027 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (acre-ft/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.003</td>
<td>0.25</td>
</tr>
<tr>
<td>100</td>
<td>&lt; 0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>1,000</td>
<td>&lt; 0.02</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 8: Spring 2004 Flow Calculations (acre-ft/day) (Gradient of 0.0025 ft/ft).
Converting Tables 3 thru 8 from acre-ft/day to yearly discharge (acre-ft/year) a range in values between time steps is shown in Table 9. Regional geology based on drilling logs suggests that the lower (0.003 ft/day) and higher (300 ft/day) hydraulic conductivity values are unreasonable for study area. A range of hydraulic conductivity between 0.25 and 56.2 ft/day is more realistic. Typical well depths range between 200 and 300 ft, thus a yearly discharge range of at least 25 – 7,000 acre-ft per year seems to be the most reasonable. Based on the Judgment, the Este subarea is responsible for 200 acre-ft/year of flow to Alto subarea [Mojave Basin Area Adjudication, 1996]. Future work will be needed in order to define these values further.

<table>
<thead>
<tr>
<th>Discharge (Q) (acre-ft/year)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
<th>0.003</th>
<th>0.25</th>
<th>56.2</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>&lt; 7</td>
<td>7 - 11</td>
<td>1,800 – 2,400</td>
<td>9,900 – 12,500</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>&lt; 7</td>
<td>25 - 33</td>
<td>5,500 – 7,000</td>
<td>30,000 – 37,500</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>&lt; 7</td>
<td>84 - 102</td>
<td>18,400 – 23,600</td>
<td>99,000 – 125,000</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Range of yearly discharge values (acre-ft/year).
6.0 Conclusions

Historical groundwater flow direction for the study area is from Este Hydrologic Subarea to Alto Hydrological Subarea. Groundwater levels have been stable across this area with only minor fluctuations over the past 15 years (since 1990). This demonstrates that water levels have not experienced any significant increase or decrease over the past 15 years.

The groundwater gradient between Este and Alto Hydrologic Sub-basins is small, less than 0.003 ft/ft. Using three different time-steps (winter 1956-57, spring 1994 and spring 2004) within a 48 year record of water levels, we were able to evaluate the change, if any, in groundwater gradient across the boundary between the subareas. Each time-step was evaluated using three separate techniques: hand calculated from a contour map, GIS cross-section tool, and vector analysis. Even though each of these analyses looked at the same data, each applied a different approach.

The range in gradients was from a low of 0.0021 ft/ft in winter 1956-57 to a high of 0.0027 ft/ft in spring 1994. From spring 1994 to spring 2004 a slight drop in gradient is observed (0.0025 from 0.0027 ft/ft), but is within the calculated error of the analysis (± 0.0004 ft/ft). Overall, the change in gradient from 1956-57 to 2004 is negligible, thus no major change in gradient magnitude or direction is observed.

At the boundary between the two basins, a cross-section was drawn perpendicular to the gradient, and cross-sectional area was calculated. Using Darcy’s Law discharge per day is calculated for the individual time-periods. Flow was then calculated by multiplying discharge per day by days in a given time-period.

Darcy’s Law: \( Q = K i A \)

where:

- \( Q \) = discharge in \( ft^3/day \)
- \( K \) = hydraulic conductivity in \( ft/day \)
- \( i \) = gradient or slope in \( ft/ft \)
- \( A \) = cross sectional area in \( ft^2 \)

The cross-sectional area \( A \) was based on a range of aquifer thicknesses at the Este-Alto Hydrologic Subarea boundary. The aquifer thickness varied from a minimum of 100 feet to a maximum of 1,000 feet. The ranges in hydraulic conductivities used in this study came from a variety of sources [Stamos, 2004, Fetter 2001, Geosciences Support, 1992, Barto, 1990, Heath, 1987 and Driscoll, 1986]. These constitute the range of expected hydraulic conductivity values for semi-cemented sandstone to weathered fractured gravely sandstones.

Based on the depth to water and gradient calculations, the flow across the Alto/Este Subarea boundary appears to have been maintained throughout the past 10+ years. A range of discharge was calculated to be between 25 and 7,000 acre-ft per year. The quantifiable amount of flow across this boundary is questionable, due to the lack of
specific basin geometry and aquifer properties, but the data indicate that the flow between these adjoining subareas does not appear to have changed since the onset of the Adjudication.

To determine the actual amount of subsurface flow between subareas calculations must be used which rely on significant assumptions that cannot be further quantified without additional field investigations and years of continued consistent monitoring. The only dynamic variables which control flow are changes in water levels and changes in hydraulic gradient. Basin geometry and the hydraulic conductivity of the aquifer materials are not prone to change. Therefore, more emphasis should be towards quantifying any material change in groundwater gradients and depth to groundwater since the onset of the Adjudication to present. Future research should focus on defining the basin geometry, aquifer properties and water levels throughout the area of study. This can be accomplished with the addition of several new nested monitoring wells, aquifer testing and geophysics.
7.0 References


California’s Department of Water Resources (DWR) (http://wdl.water.ca.gov/).


Appendix A – Procedural Methodology
# Table of Contents

1.0 Procedure for Determining Groundwater Flow between Basins ........................................ 3  
   Step 1: Determine the Area to be Analyzed ........................................................................ 3  
   Step 2: Acquiring the Data .................................................................................................. 3  
   Step 3: Organizing the Data .............................................................................................. 4  
   Step 4: Basic Analysis ........................................................................................................ 4  
   Step 5: Creating Contour Maps .......................................................................................... 5  
      Figure 1: Contour map with Gradient ......................................................................... 6  
   Step 6: Analysis of Contour Maps ..................................................................................... 7  
      Figure 2: Two contour maps on top of one another with a third on below  
                  representing the change map .............................................................................. 8  
   Step 7: Vector Analysis ...................................................................................................... 9  
      Figure 3: Vector Analysis .............................................................................................. 10  
   Step 8: Statistical Analysis ................................................................................................ 11  
   Step 9: Calculating Discharge ........................................................................................... 11  
      Figure 4: USGS Hydraulic Conductivity Ranges .......................................................... 12  
   Step 10: Change in Discharge .......................................................................................... 13  
      Figure 5: Cross-sectional Area Diagram ....................................................................... 13
1.0 Procedure for Determining Groundwater Flow between Basins

Step 1: Determine the Area to be Analyzed

The amount of available data plays a central role in determining the size of the study boundaries. Questions to keep in mind when determining the area boundaries may include:

1. How much data is exists in both quantity and length of record?
2. How spatially separated is the data (wells)?
3. Is the data spatially separated to sufficiently and accurately define the change in conditions across the area of interest?

Once the above points and questions are addressed, one can begin to establish the limits of the study and the potential accuracy of the results.

Step 2: Acquiring the Data

Groundwater elevation data and well location is available from several sources, including:

- The Mojave Water Agency (MWA) internal database (wells monitored specifically by MWA).
- United States Geological Survey (USGS) National Water Information System (NWIS) database ([http://waterdata.usgs.gov/nwis](http://waterdata.usgs.gov/nwis)) (up to date). Information from this source is only available for download by individual wells.
- California Department of Water Resources (DWR)* ([http://wdl.water.ca.gov/](http://wdl.water.ca.gov/)). Data from this source can be downloaded through a township and range search. DWR data is not as current as NWIS data.

Data may also be available from other sources such as a county office, but it should be noted NWIS and DWR contain a wealth of well data.

*The DWR database generally contains the same data as the NWIS database. Both databases however, have some records not found in the other.
Step 3: Organizing the Data

This step is primarily concerned with creating a working database from multiple data sources. Once the desired data sets have been acquired, the data needs to be formatted into a workable database and all duplicate records must be filtered out and deleted.

Problems with multiple data sources may include:

1. Formatting of the State Well Number (SWN). NWIS uses the format nnnlnnnlnnnlnnn, where n = number and l = letter. DWR uses the format nlnnlnnnlnnn. Solution: Use “find” and “replace” in Microsoft Excel or Access to conform to one format or the other.

2. Latitude (lat) and longitude (long) are accurate up to four decimal places in the DWR database. The NWIS database calculates latitude and longitude in decimal degrees. Solution: Use the “round” function in Microsoft Excel or Access to round to the nearest four decimal places.

3. Well location data from the DWR database comes in two files: one with water level data and one with location data. These files need to be merged using a database program such as Microsoft Access.

4. Determining groundwater elevation requires ground surface elevation and depth to water. Solution: Use the calculation: \[ \text{groundwater elevation} = \text{ground surface elevation} - \text{depth to water} \]. In some cases the data will contain the above ground surface height of the casing (stick-up) and above ground surface height must be subtracted from depth to water. Both calculations can be performed in Microsoft Excel or Access.

Once the data is organized into one complete database and any discrepancies are addressed, the database is then ready for analysis.

Step 4: Basic Analysis

Creating a complete set of hydrographs for the given well database is the next step. This provides a visual observation of groundwater level changes through time, but not space, to be analyzed. This analysis is usually done in Microsoft Excel. To examine water level changes spatially over time, contour maps should be created (Step 5). This step requires datasets to be analyzed for the most spatially complete time periods.

Groundwater levels fluctuate throughout the year as the aquifer responds to seasonal variation in precipitation and recharge and thusly, timescale may become important. For example, analyzing change in storage over a three year period should not be calculated from January to March in one period, and from August to October in another period. The
overall groundwater level change may be overestimated or underestimated due to seasonal groundwater oscillation within the aquifer system. Therefore, it is recommended that for short-term (< 5 years) analysis groundwater level data should be compared during the same yearly time periods. Additionally, where a well is sampled two or more times in a period, the conservative or lowest groundwater elevation value is used. For consistency, conventions should be applied to all periods of the analysis, not just one. Once two or more periods have been determined, contour maps can be created.

Step 5: Creating Contour Maps

Groundwater elevation contour maps can be created from time periods, as described in Step 4. Contour maps can be created in two ways: (1) manually (by hand) or (2) by the appropriate computer program. Computer programs, such as most GIS based programs, allows for rapid calculation of change in storage while creating multiple contour maps quickly. Contour maps can be created by hand, but this is labor intensive and may not be as accurate as computer based contour modeling.
Figure 1: Contour map with Gradient.
Step 6: Analysis of Contour Maps

Once groundwater contour maps have been created, difference maps or groundwater elevation maps can be completed. These refer to the groundwater elevation differences between two maps. The differences between these two maps represent a change in storage and/or change in gradient. Groundwater gradients can be determined by dividing the change in groundwater elevation ($\Delta h$) by the distance ($\Delta x$) between two wells or contour lines (GIS based programs will provide the fastest and more accurate results than manual operations).

Once a gradient is calculated between two wells in the same location, but, of different time periods, the change in gradient can be calculated by subtracting the older of the two gradients from the younger. To calculate storage, subtract the volume under the older contour map from that of the younger contour map. This step can only be done within the intersected area of the two contour maps.
Figure 2: Two contour maps on top of one another with a third on below representing the change map.
Step 7: Vector Analysis

Vector analysis consists of measuring the distance and elevation change mathematically between individual wells. Distances between wells can be calculated using Latitude and Longitude of the wells under investigation. Once all the distances have been calculated and the change in elevation between the two points determined, a gradient was calculated by dividing the elevation change by the distance. If more than one method (manual, computer program, or vector analysis) was applied to determine the gradient, an average gradient must be calculated.
Figure 3: Vector Analysis
Step 8: Statistical Analysis

Statistical analysis consists of using the calculated values from steps 1 through 7 to determine if a significant correlation exists. The calculated gradients from the individual time-steps and the values from the three methods should be similar. A good result will typically be within one standard deviation of one another. If there is a glaring statistically difference, additional steps may be required to find any miscalculations, etc.

Step 9: Calculating Discharge

Flow or discharge (Q) can be calculated for different gradients using Darcy’s Law (Equation 1):

\[ Q = K i A \]  

(1)

where:

- **Q** = discharge in ft³/d
- **K** = hydraulic conductivity (see Figure 4) in ft/d
- **i** = gradient or slope (Step 8) in ft/ft
- **A** = cross sectional area in ft²

Hydraulic conductivity can have a wide range of values. Figure 4, from the USGS provides ranges of hydraulic conductivity for a variety of sediments and rocks.
Figure 4: USGS Hydraulic Conductivity Ranges.
Step 10: Change in Discharge

Once $Q$ has been calculated for two or more periods, change in $Q$ can be calculated by subtracting the younger value from the older value ($\Delta Q$). Total discharge can be calculated by multiplying the average $Q$ for two consecutive periods by the time between those periods. If more than two $Q$ values have been calculated within the study area, treat each consecutive time period independently and add the discharge values together as the final step.

Cross-sectional area is calculated by the distance of the boundary in feet times the average depth across the boundary (see figure 5). This assumes a rectangular shape which in most basins is not exact. However, for the purpose of general flow calculations this assumption is used until such time that better cross-sectional profiles of the aquifer system are determined.

Figure 5: Cross-sectional Area Diagram.

Cross sectional Area
Area (feet$^2$) = ($x$ feet) x ($z$ feet)
Example Calculations

Example:

Calculate the flow between basin A to basin B between spring 1954 spring 2005; given the gradients in spring 1954, 1972, 1989, 1994, and 2005 are 0.005, 0.003, 0.002, 0.0007, and 0.0001, respectively. Hydraulic conductivity (K) is 40 ft/day and the cross-sectional area is 5,000,000 ft².

Solution:


1954: $40 \text{ ft/day} \times 0.005 \times 5,000,000 \text{ ft}^2 = 1,000,000 \text{ ft}^3/\text{day}$

1972: $40 \text{ ft/day} \times 0.003 \times 5,000,000 \text{ ft}^2 = 600,000 \text{ ft}^3/\text{day}$

1989: $40 \text{ ft/day} \times 0.002 \times 5,000,000 \text{ ft}^2 = 400,000 \text{ ft}^3/\text{day}$

1994: $40 \text{ ft/day} \times 0.0007 \times 5,000,000 \text{ ft}^2 = 140,000 \text{ ft}^3/\text{day}$

2005: $40 \text{ ft/day} \times 0.0001 \times 5,000,000 \text{ ft}^2 = 20,000 \text{ ft}^3/\text{day}$

B) Use the average between two consecutive time steps multiplied by the time between periods

$[(1,000,000 \text{ ft}^3/\text{day} + 600,000 \text{ ft}^3/\text{day})/2] \times (1972-1954) = 12,800,000 \text{ ft}^3$

$[(600,000 \text{ ft}^3/\text{day} + 400,000 \text{ ft}^3/\text{day})/2] \times (1989-1972) = 8,500,000 \text{ ft}^3$

$[(400,000 \text{ ft}^3/\text{day} + 140,000 \text{ ft}^3/\text{day})/2] \times (1994-1989) = 1,350,000 \text{ ft}^3$

$[(140,000 \text{ ft}^3/\text{day} + 20,000 \text{ ft}^3/\text{day})/2] \times (2005-1994) = 880,000 \text{ ft}^3$

C) Sum all discharge values

$12,800,000 \text{ ft}^3 + 8,500,000 \text{ ft}^3 + 1,350,000 \text{ ft}^3 + 880,000 \text{ ft}^3 = 23,530,000 \text{ ft}^3$