Groundwater Flow between Basins
Mojave River Basin

Oeste – Alto Hydrologic Subareas
Groundwater Flow Between Basins Report
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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

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

Nicholas R. Napoli, MSc.
Graduate Student
California State University, Fullerton
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Appendix A – Procedural Methodology
Flow between Basins Report
Oeste – 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 Oeste to Alto and LA County! Based on the judgment Oeste subarea is responsible for 800 acre-ft/year of flow to Alto subarea.

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 Oeste-Alto Hydrologic subarea boundary region. Oeste subarea was further divided into an upper and lower aquifer system [Smith and Pimentel, 2000]. This became important to separate out the two aquifers to determine if any changes in groundwater gradients are taking place. 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. Due to the flow direction not being directly across the boundary between the two adjudicated basins, only one gradient line is used for the actual
flow across the basin divide (gradient line C) (see Figures 6a, 7a and 8a). This was also accounted for in the USGS Mojave River groundwater model, where they simulated a no-flow boundary at the Oeste-Alto boundary [Stamos, et. al., 2001 and Hardt, 1971]. The other gradient lines (gradient lines A & B) are therefore used for analysis of change within Oeste subarea alone. The average of the three calculated 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:

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

The cross-sectional area \( (A) \) was based on a range of aquifer thicknesses at the Oeste-Alto Hydrologic Subarea boundary. The aquifer thickness varied from a minimum of a few hundreds of feet to a maximum of over 2,500 feet [Horne, 1989]. The minimum is based on the deepest depth of groundwater wells within the study area.

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, Heath, 1987 and Driscoll, 1986] (Table 2). These constitute the range of expected hydraulic conductivity values for undifferentiated alluvium [Stamos, et. al., 2001] or semi-cemented sandstone to weathered fractured gravelly sandstones. Based on interpretive geologic cross-sections through the area [Stamos, et. al., 2001 and Horne, 1989] this seems reasonable.
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-Oeste 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.
Figure 2: Location map of wells used in this study.
4.0 Data

A total of 187 groundwater wells were available for this study (152 wells in Oeste and 35 wells in Alto), and are shown in Figure 2. Data for all 187 wells resides in the NWIS or DWR databases (see methods). Records from these wells represent 1,624 individual data points from 1916 through 2005. Groundwater elevation ranged from a low of 1922.8 feet above mean sea level (AMSL) to a high of 4,692 AMSL (Figure 3a).

5.0 Results/Discussion

The results of this study are listed in three parts: hydrograph analysis, gradient analysis and flow analysis. The hydrograph analysis consisted of visually inspecting the respective hydrographs for trends across the period of entire length of record. The gradient analysis was conducted for specific individual time-steps; winter 1956-57, spring 2000, 2002 and 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 187 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 (Oeste 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 8 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 suggests that groundwater levels remained relatively constant throughout the boundary between Alto and Oeste Subareas.
Figure 3a: Oeste-Alto groundwater hydrographs from 1915 to present.
Legend for Oeste-Alto groundwater hydrographs from 1915 to present.
Figure 3b: Alto groundwater hydrographs from 1915 to present.
Figure 3c: Oeste groundwater hydrographs from 1915 to present.
Legend for Oeste groundwater hydrographs from 1915 to present.
Groundwater Elevation (Feet) (AMSL)

Figure 4a: Oeste-Alto groundwater hydrographs from 1990 to present.
Figure 4b: Alto groundwater hydrographs from 1990 to present.
Figure 4c: Oeste 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 2000, 2002 and 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 period of 2000 and 2004 was chosen to capture changes, if any, in gradient that have taken place during the adjudicated period. Figures 5a - 8b show the results of the groundwater level contour analysis for both the upper and lower aquifer systems. It should be noted that the contour intervals for 1956-57 had little coverage of the lower aquifer while recent contour intervals have a great deal of data in the lower aquifer. Figures 9a-9c show groundwater level profiles based on the computer interpolated elevations from the GIS contour analysis.
Figure 5a: Lower aquifer groundwater elevation contour map for 1956 to 1957.
Figure 5b: Upper aquifer groundwater elevation contour map for 1956 to 1957.
Figure 6a: Lower aquifer groundwater elevation contour map for Spring 2000.
Figure 6b: Upper aquifer groundwater elevation contour map for Spring 2000.
Figure 7a: Lower aquifer groundwater elevation contour map for Spring 2002.
Figure 7b: Upper aquifer groundwater elevation contour map for Spring 2002.
Figure 8a: Lower aquifer groundwater elevation contour map for Spring 2004.
Figure 8b: Upper aquifer groundwater elevation contour map for Spring 2004.
The gradient shows that changes have taken place across the study area. However, these changes are primarily only within the Oeste subarea. Gradient line C, the only gradient line that crosses the subarea boundaries, shows a slight decrease (0.0048 to 0.0043 ft/ft) in gradient between 2000 and 2004, but within the error (± 0.0005 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 ± 10 feet of elevation change over the study region. Over the study area this equates to a gradient variation (potential error) of ± 0.0005 ft/ft.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Calculated from contour map (ft/ft)</td>
<td>0.0056</td>
<td>0.0060</td>
<td>0.0083</td>
<td><strong>0.0038</strong></td>
<td>0.0068</td>
<td>0.0075</td>
<td><strong>0.0033</strong></td>
<td>0.0051</td>
<td>0.0069</td>
<td><strong>0.0038</strong></td>
</tr>
<tr>
<td>GIS Groundwater cross-section tool (ft/ft)</td>
<td>0.0053</td>
<td>0.0074</td>
<td>0.0101</td>
<td><strong>0.0039</strong></td>
<td>0.0074</td>
<td>0.0085</td>
<td><strong>0.0035</strong></td>
<td>0.0073</td>
<td>0.0091</td>
<td><strong>0.0042</strong></td>
</tr>
<tr>
<td>Vector Analysis (ft/ft)</td>
<td>0.0049</td>
<td>0.0067</td>
<td>0.0067</td>
<td><strong>0.0067</strong></td>
<td>0.0061</td>
<td>0.0061</td>
<td><strong>0.0061</strong></td>
<td>0.0048</td>
<td>0.0048</td>
<td><strong>0.0048</strong></td>
</tr>
<tr>
<td>Average of all three techniques (ft/ft)</td>
<td>0.0053</td>
<td>0.0067</td>
<td>0.0084</td>
<td><strong>0.0048</strong></td>
<td>0.0068</td>
<td>0.0074</td>
<td><strong>0.0043</strong></td>
<td>0.0057</td>
<td>0.0048</td>
<td><strong>0.0043</strong></td>
</tr>
</tbody>
</table>

**Note:** Vector Analysis is calculated across the entire area not a single gradient line. Please refer to Figures 5a, 6a, 7a and 8a for gradient transect lines A, B and C.

* Gradient line C is the only transect which crosses the Oeste/Alto subarea boundary.

Table 2: Gradient Calculations for individual time-steps.
Groundwater Elevation (Feet) (AMSL)

Profiles of interpolated groundwater elevation grid

Linear regression of profiles

Gradient
2000 = 0.0074 ft/ft
2002 = 0.0074 ft/ft
2004 = 0.0073 ft/ft

Figure 9a: Profile of interpolated lower aquifer groundwater elevation grid of gradient line A.
Figure 9b: Profile of interpolated lower aquifer groundwater elevation grid of gradient line B.
Groundwater Elevation (Feet) (AMSL)

Figure 9c: Profile of interpolated lower aquifer groundwater elevation grid of gradient line
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 (ft$^3$/day) across the subarea boundary for each time-step.

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft$^3$/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>0.003 0.5 12 300</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>240 40,300 970,000 24,192,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>560 94,000 2,250,000 56,500,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>2000 336,000 8,000,000 201,600,000</td>
</tr>
</tbody>
</table>

Table 3: Spring 2000 Flow Calculations (ft$^3$/day) (Gradient 0.0048 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft$^3$/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>0.003 0.5 12 300</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>220 36,000 1,800,000 21,700,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>500 84,250 2,000,000 50,500,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>1,800 300,000 15,050,000 180,600,000</td>
</tr>
</tbody>
</table>

Table 4: Spring 2002 Flow Calculations (ft$^3$/day) (Gradient 0.0043 ft/ft).

<table>
<thead>
<tr>
<th>Thickness (b) (ft)</th>
<th>Discharge (Q) (ft$^3$/day)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>0.003 0.5 12 300</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>220 36,000 1,800,000 21,700,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>500 84,250 2,000,000 50,500,000</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>1,800 300,000 15,050,000 180,600,000</td>
</tr>
</tbody>
</table>

Table 5: Spring 2004 Flow Calculations (ft$^3$/day) (Gradient 0.0043 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 boundary.

<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></td>
<td>0.003</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.01</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>700</td>
<td>&lt; 0.02</td>
<td>2</td>
</tr>
<tr>
<td>2,500</td>
<td>&lt; 0.1</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 6: Spring 2000 Flow Calculations (acre-ft/day) (Gradient 0.0048 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></td>
<td>0.003</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.01</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>700</td>
<td>&lt; 0.02</td>
<td>2</td>
</tr>
<tr>
<td>2,500</td>
<td>&lt; 0.1</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 7: Spring 2002 Flow Calculations (acre-ft/day) (Gradient 0.0043 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></td>
<td>0.003</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 0.01</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>700</td>
<td>&lt; 0.02</td>
<td>2</td>
</tr>
<tr>
<td>2,500</td>
<td>&lt; 0.1</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 8: Spring 2004 Flow Calculations (acre-ft/day) (Gradient 0.0043 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 0.5 and 12 ft/day is more realistic. Typical well depths range between 300 and 700 ft, thus a yearly discharge range of at least 300 – 19,000 acre-ft per year seems to be the most reasonable. Based on the Judgment, the Oeste subarea is responsible for 800 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>Thickness (b) (ft)</th>
<th>Discharge (Q) (acre-ft/year)</th>
<th>Hydraulic Conductivity (K) (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.003</td>
<td>0.5</td>
</tr>
<tr>
<td>300</td>
<td>&lt; 2</td>
<td>300 - 350</td>
</tr>
<tr>
<td>700</td>
<td>&lt; 5</td>
<td>700 - 790</td>
</tr>
<tr>
<td>2,500</td>
<td>&lt; 16</td>
<td>2,500 – 2,800</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 the proximal portion of Sheep Wash fan in the south to the northern central portion of Oeste subarea. However, due to the fan morphology a portion of flow exits Oeste subarea and flows into Alto 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, concluding that there has been little increase or decrease in flow between the Oeste and Alto Subareas. The gradients have however increased towards the central portion of Oeste subarea. This appears to be due to the increased pumping of groundwater in this area creating a large cone of depression.

The groundwater gradient between Oeste and Alto Hydrologic Sub-basins is small, less than 0.0043 ft/ft. Using three different time-steps (1956-57, spring 2000, 2002 and 2004) within the 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 0.0043 ft/ft in spring 2002 and 2004 to a high of 0.0048 ft/ft in spring 2000. 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 300 feet to a maximum of 2,500 feet [Horne, 1989]. The ranges in hydraulic conductivities used in this study came from a variety of sources [Stamos, et. al. 2001, Fetter 2001, Heath, 1987 and Driscoll, 1986]. These constitute the range of expected hydraulic conductivity values for undifferentiated alluvium [Stamos, et. al., 2001] or semi-cemented sandstone to weathered fractured gravely sandstones.
Based on the depth to water and gradient calculations, the flow across the Alto/Oeste Subarea boundary appears to have been maintained throughout the past 10+ years. A range of discharge was calculated to be between 300 and 19,000 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/).


Mojave Basin Area Adjudication, 1996. Judgment After Trial: Riverside County Superior Court Case No. 208568.


Appendix A – Procedural Methodology
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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 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) (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/). 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 nnnlnnlnlnnn, where n = number and l = letter. DWR uses the format nlnnnlnnnnn. **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: \{groundwater elevation = ground surface elevation – 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 (Δh) by the distance (Δx) 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):

\[ Q = KiA \]  

where:

- \( Q \) = discharge in ft\(^3\)/d
- \( K \) = hydraulic conductivity (see Figure 4) in ft/d
- \( i \) = gradient or slope (Step 8) in ft/ft
- \( A \) = cross sectional area in ft\(^2\)
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 then 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:


\[
\begin{align*}
1954: & \quad 40 \text{ ft/day} \times 0.005 \times 5,000,000 \text{ ft}^2 = 1,000,000 \text{ ft}^3/\text{day} \\
1972: & \quad 40 \text{ ft/day} \times 0.003 \times 5,000,000 \text{ ft}^2 = 600,000 \text{ ft}^3/\text{day} \\
1989: & \quad 40 \text{ ft/day} \times 0.002 \times 5,000,000 \text{ ft}^2 = 400,000 \text{ ft}^3/\text{day} \\
1994: & \quad 40 \text{ ft/day} \times 0.0007 \times 5,000,000 \text{ ft}^2 = 140,000 \text{ ft}^3/\text{day} \\
2005: & \quad 40 \text{ ft/day} \times 0.0001 \times 5,000,000 \text{ ft}^2 = 20,000 \text{ ft}^3/\text{day}
\end{align*}
\]

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

\[
\begin{align*}
[(1,000,000 \text{ ft}^3/\text{day} + 600,000 \text{ ft}^3/\text{day})/2] \times (1972-1954) & = 12,800,000 \text{ ft}^3 \\
[(600,000 \text{ ft}^3/\text{day} + 400,000 \text{ ft}^3/\text{day})/2] \times (1989-1972) & = 8,500,000 \text{ ft}^3 \\
[(400,000 \text{ ft}^3/\text{day} + 140,000 \text{ ft}^3/\text{day})/2] \times (1994-1989) & = 1,350,000 \text{ ft}^3 \\
[(140,000 \text{ ft}^3/\text{day} + 20,000 \text{ ft}^3/\text{day})/2] \times (2005-1994) & = 880,000 \text{ ft}^3
\end{align*}
\]

C) Sum all discharge values

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