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THE EVALUATION OF WATER STORAGE IN DEATH VALLEY USING GRACE SATELLITE DATA

by

Maile J. Sweigart

Bachelor of Science in Geology
University of Nevada, Las Vegas
2011

A thesis presented in partial fulfillment
of the requirements for the

Master of Science in Geoscience

Department of Geoscience
College of Sciences
The Graduate College

University of Nevada, Las Vegas
May 2013

THE GRADUATE COLLEGE

We recommend the thesis prepared under our supervision by

Maile Sweigart

entitled

The Evaluation of Water Storage in Death Valley Using Grace Satellite Data

be accepted in partial fulfillment of the requirements for the degree of

Master of Science in Geoscience
Department of Geoscience

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May 2013

ABSTRACT

THE EVALUATION OF WATER STORAGE IN DEATH VALLEY USING GRACE SATELLITE DATA

By

Maile J. Sweigart

Dr. Zhongbo Yu, Examination Committee Chair
Professor of Hydrogeology and Hydrology
University of Nevada, Las Vegas

As drought conditions spread across the United States, concerns over water supplies, water use, and water management policies are growing and possible contributing environmental factors are continually being scrutinized. This thesis examines Death Valley as an analog for Southern Nevada and utilizes NASA EOS data, combined with ancillary climate data, to assess the effect of decadal climate variability on groundwater storage in the Death Valley area. Historical climate data, combined with satellite imagery observations, were compiled and calculated for analyses. Conclusions derived from statistical analyses infer trends between GRACE (Gravity Recovery and Climate Experiment) satellite data and fluctuating levels of recharge and groundwater storage, as well as climatic changes in temperature and rainfall. The observations show seasonal variations in ground water thickness of up to 10 cm from the mean, correlated directly to seasonal temperature variability. Connections were also observed between temperature and precipitation with a correlation factor of -0.5. The relationship between precipitation and groundwater thickness change is also evident, with a correlation factor of 0.4 where evaporation and delayed aquifer response are likely impacting direct correlation.

The research illustrates how and which environmental factors are impacting the groundwater storage in Death Valley. Due to the similarity of climates between Death Valley and Southern Nevada, this research may be used as an analogy illustrating the impact of climate variability in Southern Nevada. The research, combining GRACE satellite observations and downscaled historical climate data will show any adverse effects that climate variability may be having on the area, including the impact it has on aquifers, and the impact it has on Death Valley's water supply in general.

Acknowledgements

I'd like to start off by thanking NASA for funding my education, as well as all of the faculty members who served on my committee for their enthusiastic support: Dr. Zhongbo Yu, Dr. Ganqing Jiang, Dr. Scott Nowicki, and Dr. Zhonghai Ding. I especially want to thank Dr. Yu, who not only was a great advisor, but who also kept me motivated and inspired throughout the project. I also want to thank John Mejia Ph.D. and KC King from Desert Research Institute, for their collaboration and support. I'd be remiss if I didn't thank Victor Zlotnicki Ph.D. from JPL, for his guidance, as well as for being approachable and available, despite his busy schedule.

I would not have gotten to this point without the inspiration of two professors from the University of South Alabama: Dr. James Connors and Dr. Lary Dilsaver. It was in Dr. Dilsaver's World Regions Geography class where he taught the issues with and the value of water as a resource worldwide that initially sparked my interest in the hydrogeology field. Dr. Connors, my undergraduate advisor, taught me the real-world applications of hydrogeology in industry, and he has been an inspiration and continues to support and be a mentor to me.

Finally, I would like to thank my husband, Ryan Sweigart, for his unconditional love and support, and without whom I could have done none of this.

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Chapter 1 Introduction

Southern Nevada experienced a period of historic drought throughout the first decade of the 21st century. Lake Mead was at its lowest levels since the Hoover Dam was completed and the lake created during the 1930s (McKinnon, 2010). The depleted Lake Mead and declining aquifer water levels in the surrounding areas are issues of great concern for Southern Nevada. A recent new article reported 2012 as being the warmest year on record for the United States, and that 2/3rds of the country had experienced drought that year. Even though there had been some relief to the drought at the end of summer 2012, the National Drought Mitigation Center reported that there was still a lingering drought in water stored underground (2012).

Water storage decrease in Southern Nevada, or any region, can be attributed to many factors, a few of which include anthropogenic-related activities, an increase in area population, and natural environmental factors, such as changing rainfall patterns and evaporation. Changes in water storage, regardless of its nature, have an impact on a desert's fragile eco-biological system. Further development of water resources in an area will put additional strain on the system, which could be detrimental to the entire health of the area's ecosystem. To better understand groundwater activity in the southern Nevada area, this study uses Death Valley as an analog, and examines gravimetric data from NASA and climate data from numerous other agencies, downscaled by Desert Research Institute (DRI), for hydrogeological comparisons and calculations in an attempt to assess which kinds of changes have impacted groundwater storage in the Death Valley area. Death Valley was selected due to the fact that there is only one groundwater flow terminus or a closed basin. In doing so, this study looks at whether or not GRACE satellite observations are of sufficient resolution to measure groundwater storage levels, show discernible trends, and reveal short-term consistencies or fluctuations for Death Valley, and whether or not decadal climatic variation is decreasing the groundwater storage in Death Valley.

Background

GRACE Satellite Mission

The Gravity Recovery and Climate Experiment (GRACE) mission is a joint venture between NASA and the German Space Agency. GRACE consists of not one satellite, but twin satellites that orbit 220 km apart and 500 km above the earth (NASA, 2011). Utilizing the Global Position System (GPS) and a microwave ranging system, the satellites map the gravity fields in the Earth, which after many processes and calculations have been applied, can measure the runoff and groundwater storage within continental land mass (NASA, 2011).

Monthly GRACE gravimetric data is made available by NASA’s Jet Propulsion Laboratory, where a hydrologic signal has already been applied to pull out areas where a change in land mass equals a change in groundwater storage. The raw data is reported in grids measuring one degree latitude by one degree longitude (a 1 degree bin). This raw data requires scaling by the user, based on its’ position on the Earth, to reestablish energy removed from filters made to land grids. The data for each 1 degree bin is then averaged over the observed time period. Deviation from the mean for each month is calculated, to show the monthly equivalent water thickness change in centimeters for each 1 degree bin.

Analyzing the remote sensing data that GRACE provides becomes a viable means for estimating total basin water storage. This remote sensing tool is useful for drought studies, as can be seen in as the 2005 study of the Amazon River basin (Chen, 2009). In 2005, the Amazon River basin experienced an extreme drought which was deemed a ‘public calamity’ by Eduardo Braga, governor of Amazonas State. Total Water Storage (TWS) analysis was conducted to understand the event and to gauge the accuracy of current modeling systems against the more insightful GRACE satellite groundwater observations. The results revealed that GRACE observations showed a much more dramatic change in TWS for the summer of 2005, the specifics of which were validated against the collected precipitation and river gauge data, which provides a more accurate picture of the drought. The National Centers for Environmental Prediction (NCEP) results showed almost no change from the mean, and while the Global Land Data Assimilation System (GLDAS) results demonstrated a decrease in TWS, the estimated change is significantly smaller than the GRACE observations. The results reveal that current modeling systems are limited due to their lack of a groundwater component, and indicate the level of improved accuracy that can be gained in calculating groundwater storage and its’ variations throughout the year if GRACE data is used to enhance the capability of existing models.

In a preliminary study conducted on the Las Vegas Valley area, the results showed little correlation between the change in Lake Mead water levels and the change in groundwater storage revealed by GRACE gravimetric observations. From this study, it is presumed that there needs to be a minimum amount of surface water in arid areas or a minimum amount of surface water across a large grid cell to affect total water storage, and therefore surface processes were not included as part of this study.

Objectives

Objectives for this research are to: (1) compare and analyze GRACE data from NASA for the Death Valley region for the period of 2003 (first calendar year after mission inception) to 2011, (2) compile gravity changes over time and correlate to groundwater storage amounts, (3) analyze downscaled historical precipitation, temperature, and specific humidity data to show trending of groundwater recharge, and (4) provide trending and use data to forecast future groundwater storage levels.

Chapter 2 Methodology

Problem Description

Terrestrial water storage (TWS) change is a very important part of understanding the hydrologic cycle. It quantifies the amount of water stored in soil, snow and ice, groundwater reservoirs, and surface waters in a defined area or basin. It can also be used to measure the effect of anomalies, such as a drought, which can be used to make decisions concerning water distribution changes for human needs, including water for agricultural, industrial and domestic uses. Although there is not a lot of knowledge about the variability of water storage on a global scale, the information is important for understanding the global hydrologic cycle. Estimating TWS change is often limited to simple observations of certain elements, such as of groundwater reservoirs, precipitation, etc., due to the lack of a sufficient monitoring network.

To enhance our TWS knowledge, GRACE data was obtained for the Death Valley region. Scaling and calculations were made to measure groundwater storage changes over time. The gravimetric data shows changes in water storage near the surface, as well as underground, which can be used to understand runoff. The gravimetric data was analyzed and compared to the DRI downscaled historical precipitation, temperature, and air moisture data. This analysis reveals trends in groundwater recharge to the Death Valley region.

Death Valley

Death Valley lies within the Mojave Desert, covers approximately 4.4 million acres, and exhibits basin and range topography. The rocks that can be found in this area range from intrusive to extrusive, and include igneous, sedimentary and metamorphic rocks which have experienced compressional and extensional deformations over long periods of time (D'Agnese, 1996). According to Davey (2007), the climate of the northern portions of the valley is considered to be "high desert" or cold desert, while the southern portion is considered to be a hot desert environment. The Sierra Nevada and Transverse Ranges of California create a rain shadow, which is the basis, or stimulus, of the dry conditions of the area. Death Valley itself was formed between the Armagosa and Pinamint ranges, two major block-faulted mountain ranges (NPS, 2001). Elevations range from 282 feet below sea level at Badwater Basin salt pan (the lowest point in the western hemisphere), to 11,049 feet above sea level at Telescope Peak.

Looking at the climate history of the region, the Mojave has exhibited a warming trend over the past century, with Death Valley holding the record for the world's highest temperature at 134℉ (NPS, 2012). The Western Regional Climate Center (WRCC) compiled data from April of 1961 to August of 2012 as part of the climate data they collected for global models. According to the WRCC, Death Valley's average annual maximum temperatures range from 65.1℉ in December to 116℉ in July (2012). The WRCC also reports that average annual minimum temperature ranges from 38.3℉ in December to 87.6℉ in July.

The Death Valley groundwater flow system represents areas in which groundwater flows toward Death Valley. Nevada supplies much of the groundwater in the lower portion of the flow system (Pal, 1995), while areas in California adjacent to the valley also supply some of the flow (NPS, 2001). The current use of groundwater in the flow system is deemed to already be fully appropriated, and any additional groundwater withdrawal could negatively impact Death Valley’s water resources.

A closer look at the valley floor reveals the fact that it receives the least amount of precipitation in the United States. The area itself has an annual average rainfall of approximately 55 mm/yr. (Davey, 2007). There have been years with no recorded rainfall, as well. Overall, most precipitation occurs during the winter months.

A recent hydrogeological study of Gold Valley, an intermountain basin within Death Valley, was conducted by Abdulaziz et al. in 2012, and sheds more light on the groundwater activity in the region. In their study, they concluded that groundwater recharge mainly takes place at elevations > 1100 m during the winter months (averaging 1.78 mm/yr.). In their research, they used the theory postulated by Flint et al. (2002), suggesting that decadal climate cycles need to be considered in order to understand recharge for large basins. To better understand these cycles, downscaled climate data from Desert Research Institute (DRI) from 1980-2009 was analyzed for climate trends.

In order to understand the change in groundwater in Death Valley, GRACE data was taken over 105 months, from January of 2003 to December of

2011. Three months of data are missing in this period (June, 2003, January 2011, and June 2011), due to mandatory eclipsing of the GRACE satellites, to preserve battery life. To define the area of interest, the Death Valley boundary created by D'Agnese et al. (1997) for the U. S. Geological Survey (USGS) was utilized (Fig. 2-3). The GRACE data was taken from 7 points that cover this area. The latitude, longitude coordinates of the centers of each of these points are as follows: 35.5, -116.5; 36.5, -115.5; 36.5, -116.5; 36.5, -117.5; 37.5, -115.5; 37.5, -116.5; and 37.5, -117.5 (see Fig. 2-3). GRACE points were selected based on whether there was Death Valley coverage of 15% or more within a data point. The data results were filtered in a time series showing surface mass variations calculated to centimeters of water. In Death Valley, any changes in surface mass are dominantly due to the change in groundwater storage. Any errors from the GRACE time series are due to attenuation from filtering, lingering atmospheric signals, calculation limits and/or GRACE measurement errors (Chen, 2009).

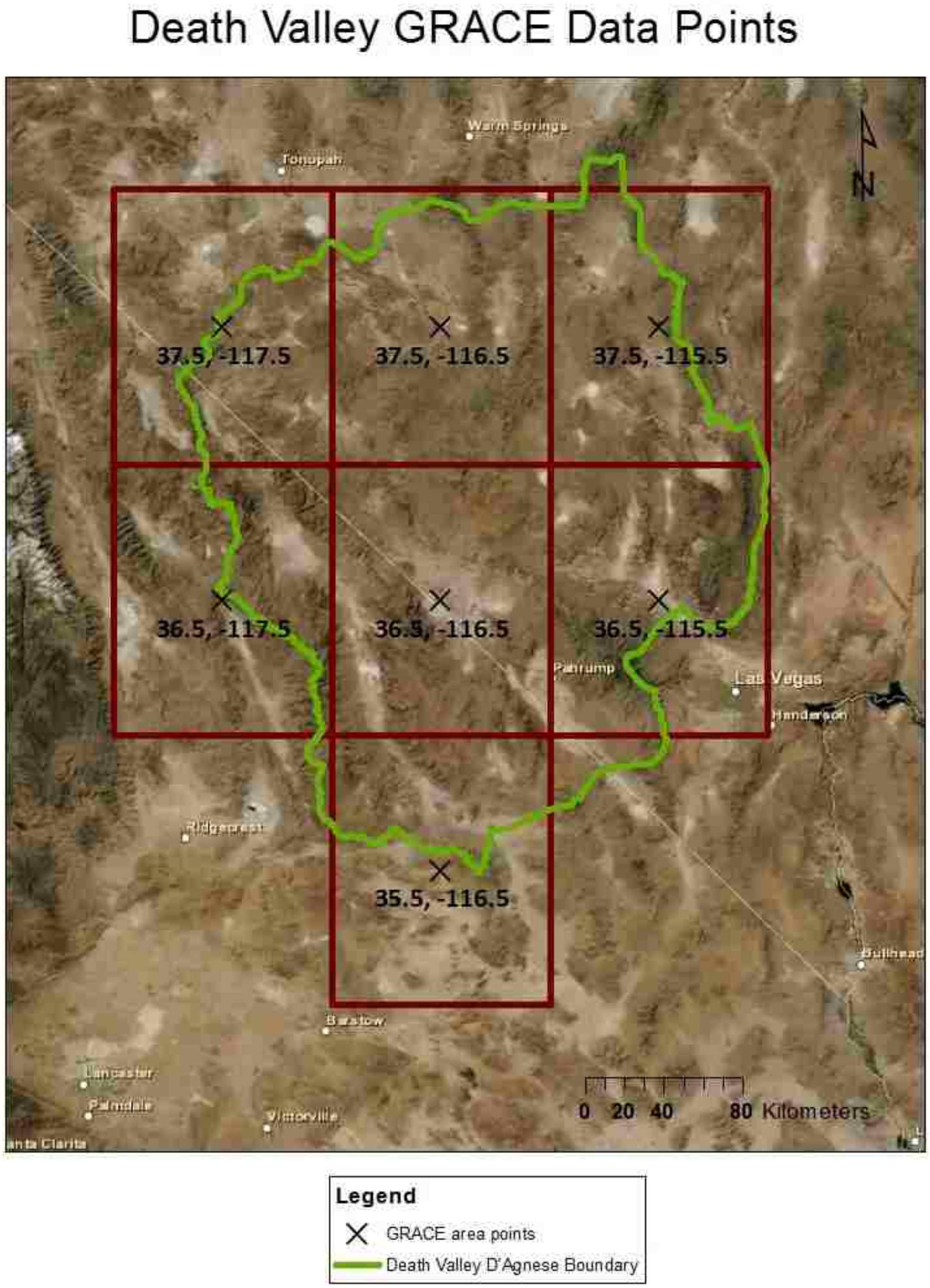


Figure 2-1. Research area - D'Agnese Death Valley boundary and GRACE data area locations.

Historical climatic data was collected for the Death Valley area to show the relationship of changing climate variables with changing groundwater storage, which include NCEP/NCAR (National Center for Atmospheric Research) modeled precipitation, temperature, and air moisture data that have been modeled and downscaled at Desert Research Institute (DRI). The climate data for the area was taken from 40 climate points within the area of interest (see Fig. 2-3). Each point represents a 36 km^2 area. The climate data was taken over 360 months, from January of 1980, to December of 2009, to better understand decadal trends. Downscaling improves regional climate models' results, to achieve a more accurate picture of climate trends in Nevada versus what is reported by using Global Climate Models (GCMs).

To select the appropriate DRI downscaled climate data points, all of the data was loaded into ArcGIS. The points that were within 10 kilometers of D'Agenese's Death Valley boundary, as well as everything within the boundary, were then selected. This resulted in 40 climate points that were identified. These points were then intersected with the seven GRACE points to identify which of the downscaled DRI climate points laid within the individual GRACE data points (Fig. 2-4). The correlation of the DRI climate points to GRACE data points were charted, showing their elevations for purposes of identifying potential recharge areas (Fig. 2-5). Areas with elevations less than 1100 m were highlighted to show where recharge would not occur in the valley.

When viewed in terms of the GRACE data points, the entire area within point 35.5, -116.5 (the southernmost point) is below 1100 m, and half of the data points 36.5, -116.5 (center point) and 36.5, -117.5 (west center point) are below 1100 m. In these cases, areas that fell below 1100 m were given a precipitation value of “0”, when averaging the overall precipitation within a GRACE data point area, since there would be no precipitation contributing to recharge.

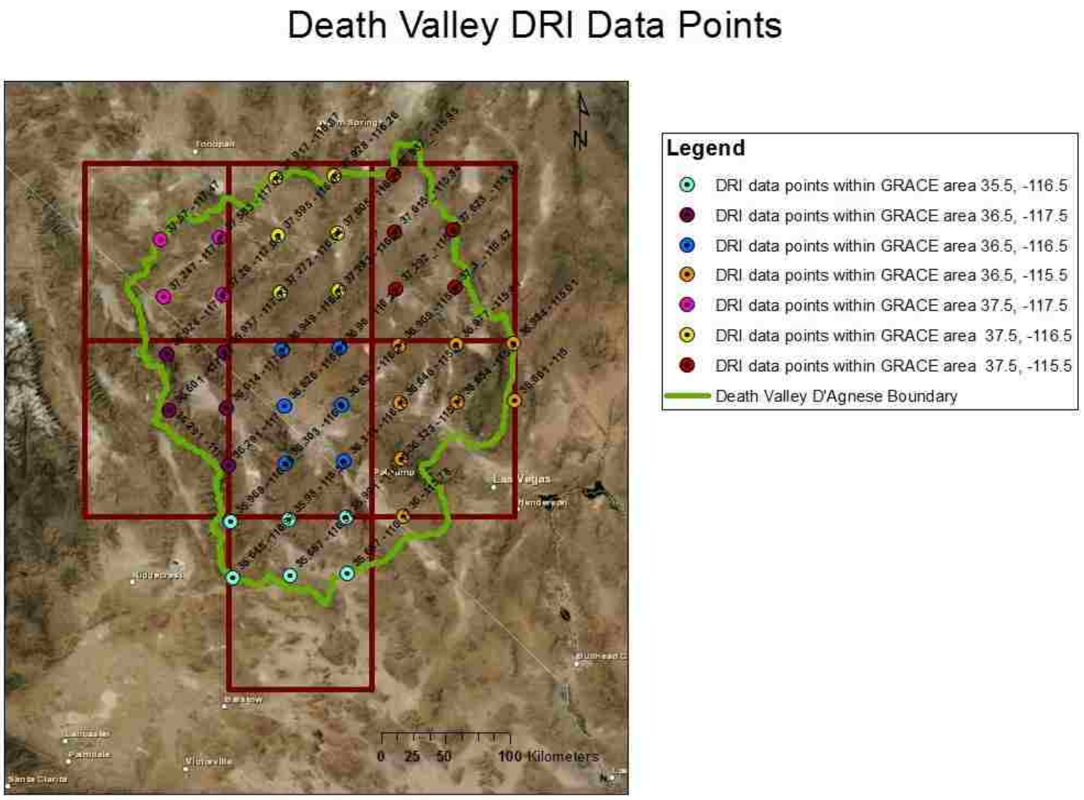


Figure 2-2. DRI climate data point locations.

GRACE Data Point Center	DRI Downscaled Climate Data Point Center	Elevation (m)
35.5, -116.5	▨ 35.968 -116.98	908.5
	▨ 35.98 -116.58	731.33
	▨ 35.991 -116.18	811.39
	▨ 35.645 -116.97	882.17
	▨ 35.657 -116.57	676.46
	▨ 35.667 -116.17	662.23
36.5, -115.5	36.969 -115.81	1368.1
	36.977 -115.41	1331.6
	36.984 -115.01	1229.1
	36.646 -115.8	1332.7
	36.654 -115.4	1381.5
	36.661 -115	1122.9
	36.323 -115.79	1423.4
	36 -115.78	1174.1
36.5, -116.5	36.949 -116.62	1310.8
	36.96 -116.22	1399.4
	▨ 36.626 -116.61	869.84
	36.637 -116.21	1099.6
	▨ 36.291 -117	823.83
	▨ 36.303 -116.6	760.12
	▨ 36.314 -116.19	1004
36.5, -117.5	▨ 36.291 -117	823.83
	▨ 36.601 -117.41	1045.5
	▨ 36.614 -117.01	807.93
	36.924 -117.43	1243.9
	36.937 -117.03	1214.7
37.5, -115.5	37.937 -115.85	1784.9
	37.615 -115.84	1742.6
	37.623 -115.43	1628.6
	37.292 -115.83	1608.2
	37.3 -115.42	1450.2
37.5, -116.5	37.928 -116.26	1847.6
	37.917 -116.67	1808.1
	37.595 -116.65	1726.2
	37.605 -116.24	1834.7
	37.272 -116.64	1647.4
	37.283 -116.23	1731
37.5, -117.5	37.57 -117.47	1691.7
	37.583 -117.06	1618
	37.247 -117.45	1540
	37.26 -117.04	1532.4
	▨ Elevation < 1100m	

Figure 2-3. GRACE and DRI data point correlation chart.

The water balance for the region can be determined using the equation

Equation 2-1. $dS/dt = P - E - Q$

(Famiglietti et al., 2011) where dS/dt represents the change in groundwater storage over time, P = Precipitation, E = Evapotranspiration, and Q = streamflow (negligible for the study area). Since the traditional Maxey-Eakin evapotranspiration estimation method cannot be used for the area due to the low precipitation accumulation amounts, precipitation in areas above 1100 m was used as indicators for groundwater recharge. These results were compared to the GRACE observations and were used as an additional method to verify results.

Changes to the monthly average minimum, mean, and maximum temperatures for the area were also graphed, analyzed and compared with the groundwater change, precipitation, and specific humidity results to identify similar or inverse trends and relationships between each of the variables. The equation for specific humidity is as follows:

Equation 2-2. $q=m_v/(m_v + m_d)$

where q = specific humidity, m_v = mass of water vapor (kg), and m_d = mass of dry air (kg). Correlation coefficients were used to show the degree of the relationship between the variables, as well as to show the magnitude of change when variables are combined. When comparing the results, similar trending declines in yearly precipitation accumulation, combined with increase in temperatures and specific humidity observed in the area, may be indicators of drought affecting groundwater recharge in Death Valley.

Chapter 3 GRACE Groundwater Change Results for Death Valley Compared with DRI Downscaled Historical Climate Data Observations and Trends

The results of the GRACE gravimetric observations show a decreasing trend in groundwater storage over time, averaging approximately 0.348 cm of loss over the entire Death Valley area, per year. The results are confirmed by the additional historical data collected, showing an overall trending decline from downscaled precipitation observations, as well as an increase in maximum, mean, and minimum temperatures, and a slight increase in specific humidity measured for the valley. To show the correlation between the gravimetric and climate observations, the data was charted and a number of linear and regressional trendlines were created, over the time period studied, showing the correlation between the decrease in groundwater recharge and storage to the area. To further illustrate how different areas of the valley are affected by changes in climate conditions, maps were created for showing the variable groundwater storage changes within Death Valley. Maps illustrating precipitation above 1100 m were also created to compare and contrast with the gravimetric maps.

Death Valley Groundwater Decline from 2003-2011 GRACE Observations

In the Death Valley area, data from 7 GRACE data points were taken from January of 2003 to December of 2011. The data was scaled, surface mass variations were calculated in the unit of cm and monthly deviations from the mean were calculated, and then graphed. Statistical analysis of the Death Valley

GRACE gravitational results revealed a trending decline of groundwater storage, with a loss of approximately 0.348 centimeters a year (-0.029 cm/month), for the entire Death Valley region (Fig. 3-1). Based on an area of approximately 75,000 km^2 for a 1 degree bin at 30°, the volume of water loss per year for Death Valley is approximately 0.26 km^3 per year.

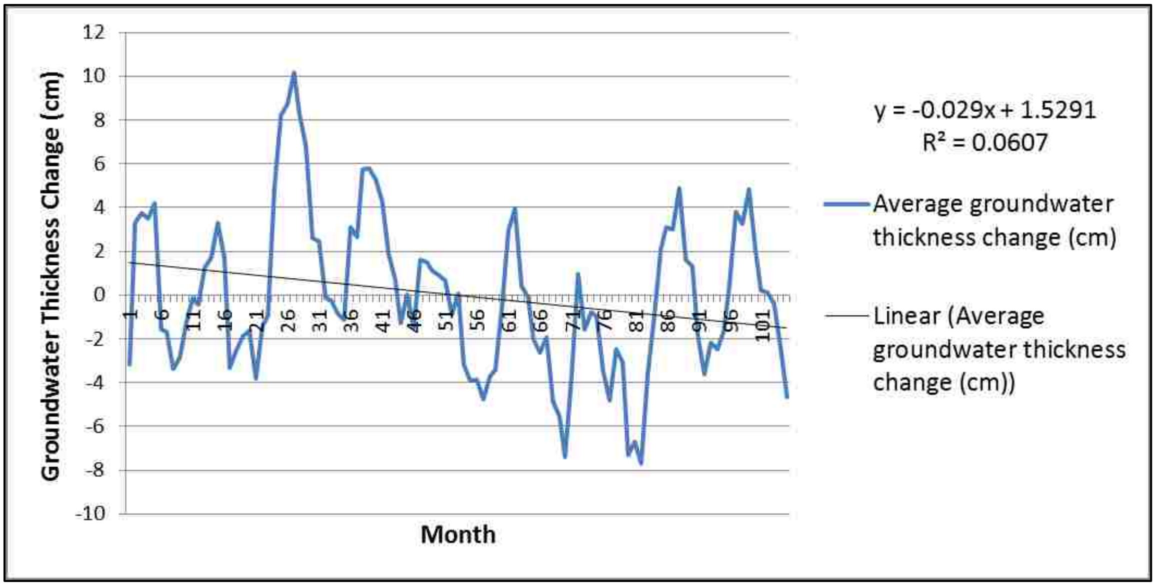


Figure 3-1. GRACE Death Valley groundwater thickness change 2003-2011.

To obtain a better look at how groundwater changed for each of the GRACE point locations, the data from each point was graphed against each other, as seen in Figure 3-2. The results show that all the points follow the same general trend, with the southeast point 36.5, -115.5 showing a greater amount of change and northwest point 37.5, -117.5 showing the least amount of change throughout the time period. When looking at all the points individually, the northwest area of Death Valley is shown to have less variation in groundwater levels than the rest of the area, in general, while the southeast is the most affected. Trending groundwater loss for each individual 1 x 1 degree bin can be viewed in the appendix.

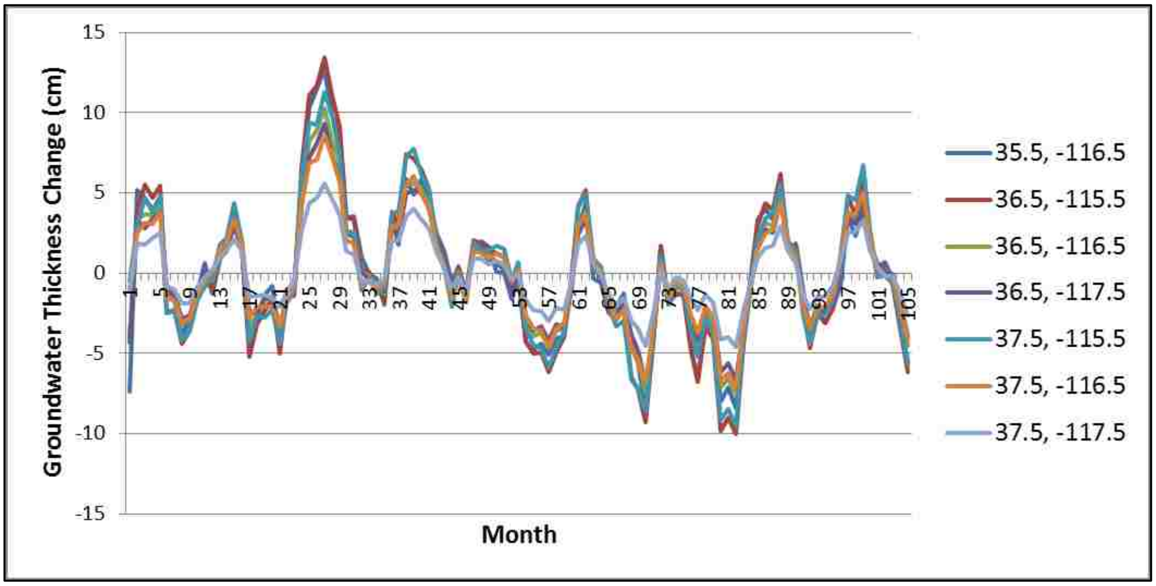


Figure 3-2. GRACE Death Valley groundwater change by area.

To illustrate the seasonal change in groundwater thickness over time in the Death Valley area, winter and summer results were calculated and mapped. The winter results represent the calculated groundwater thickness change average of the three months of the year where groundwater storage is observed to be at its highest: March, April, and May. The summer results represent the calculated groundwater thickness change average of the three months of the year where groundwater storage is observed to be at its lowest: September, October, and November. The graphed results for both winter and summer seasons clearly record the drought experienced in 2009 throughout the valley, with the rebound experienced in 2010 and 2011 (see Figures 3-3 through 3-7). In these results, like the previous one, the northwest part of the valley experiences the most resilience to groundwater storage changes.

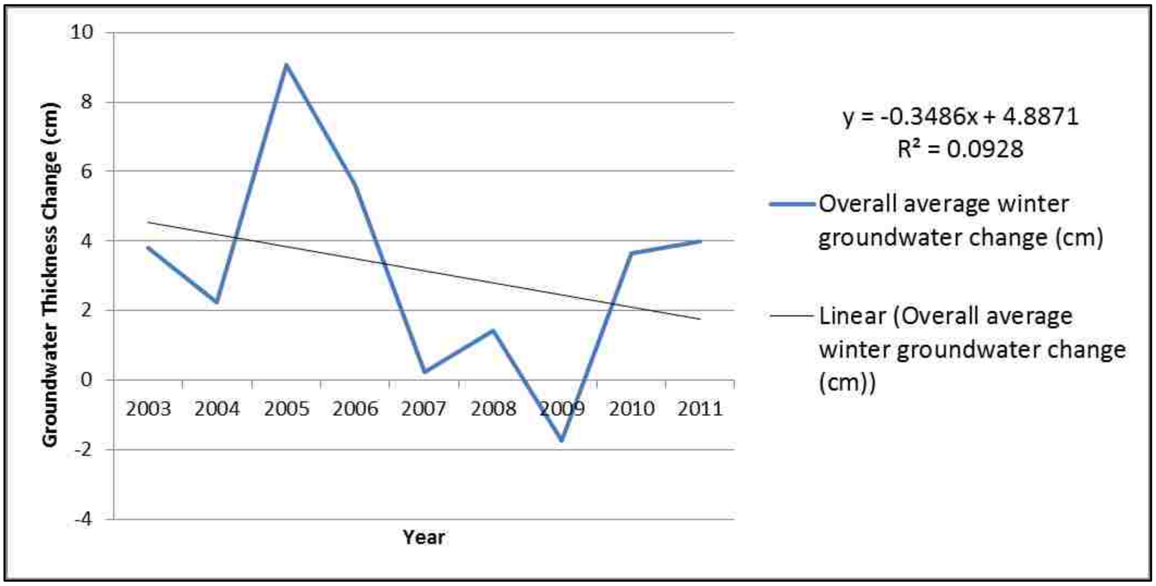


Figure 3-3. GRACE average winter monthly groundwater thickness change (Average of March, April, and May).

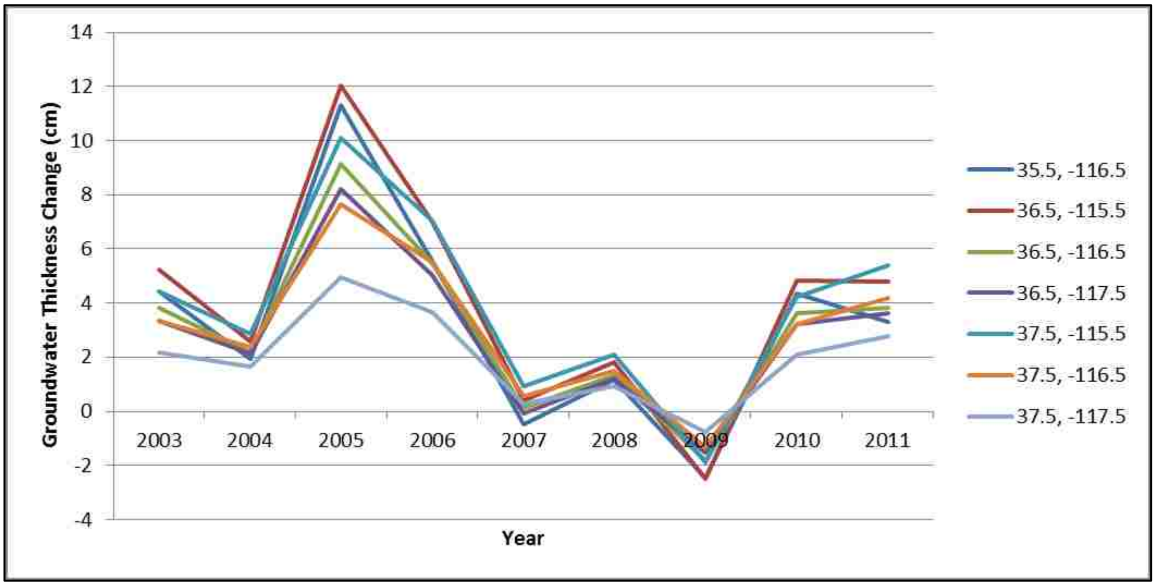


Figure 3-4. GRACE average winter monthly groundwater thickness change by data point.

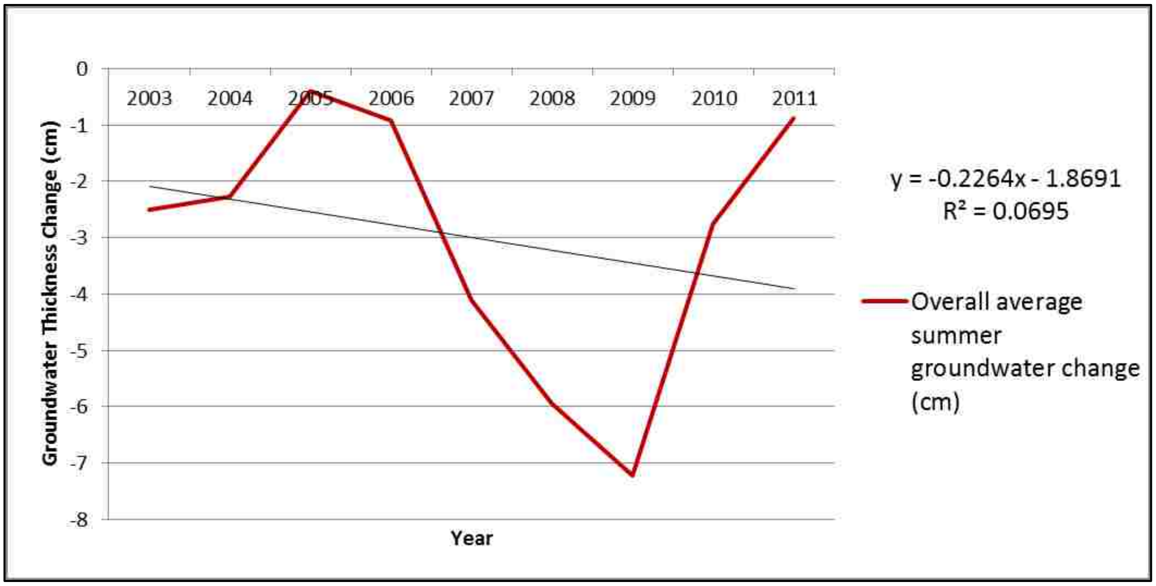


Figure 3-5. GRACE average summer monthly groundwater thickness change (average of September, October, and November).

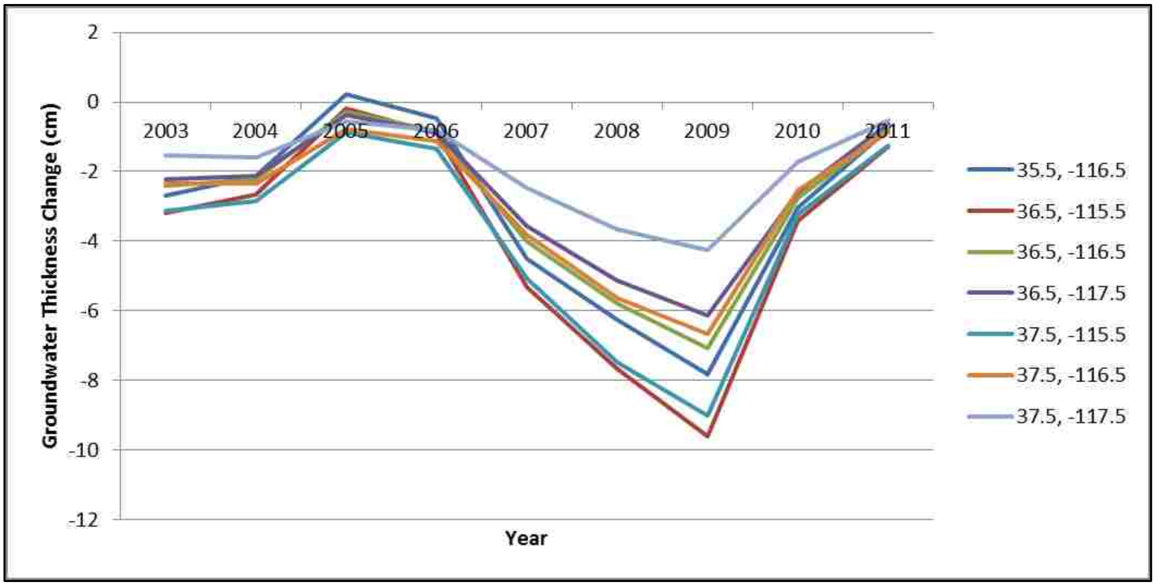


Figure 3-6. GRACE average summer monthly groundwater thickness change by data point.

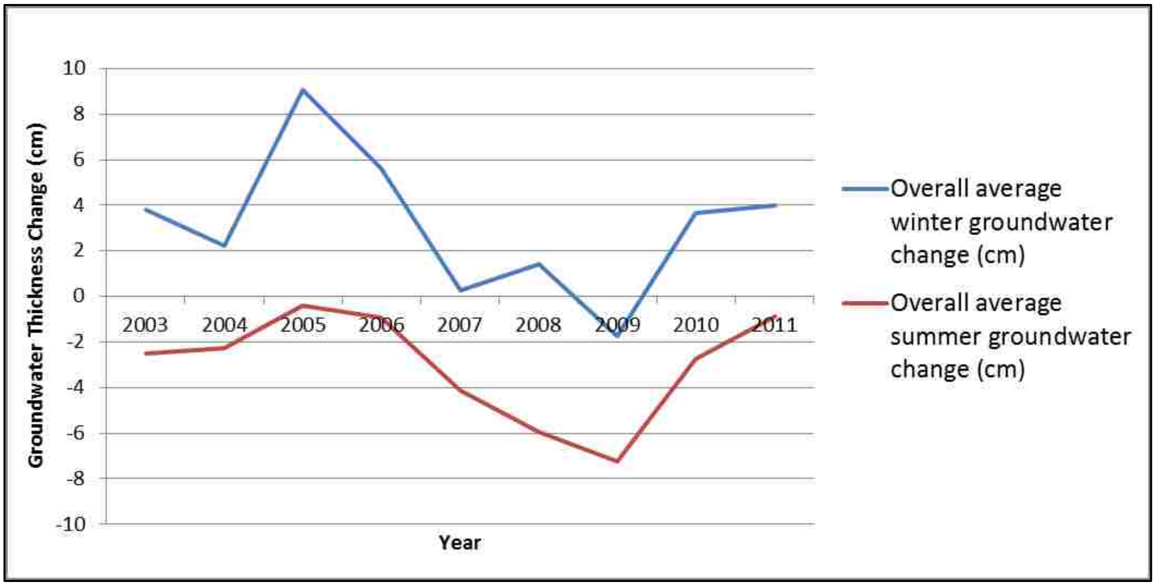


Figure 3-7. Combined GRACE seasonal average monthly groundwater thickness change (cm).

Groundwater change for both winter and summer seasons was mapped individually, and then placed together to show the similarities and differences between the seasons in the years observed. When the winter maps are viewed alongside each other, it is evident that 2005 and 2006 were much wetter years, when the positive groundwater change is evident throughout the valley (Fig. 3-8). Even in the wettest years, the northwest data point (37.5, -117.5) shows the least amount of change. The map of 2009 shows an obviously much drier year than the others, displaying a groundwater level that represents the mean observed to a slight negative groundwater change, in what should be a time of surplus or increase.

For the summer season, the maps reveal 2008 and 2009 to be much drier than average years, displaying a higher than average negative groundwater change. Even in what was recorded to be a period of drought, the northwest data area of the valley shows its resistance toward a change in groundwater levels (Fig. 3-9).

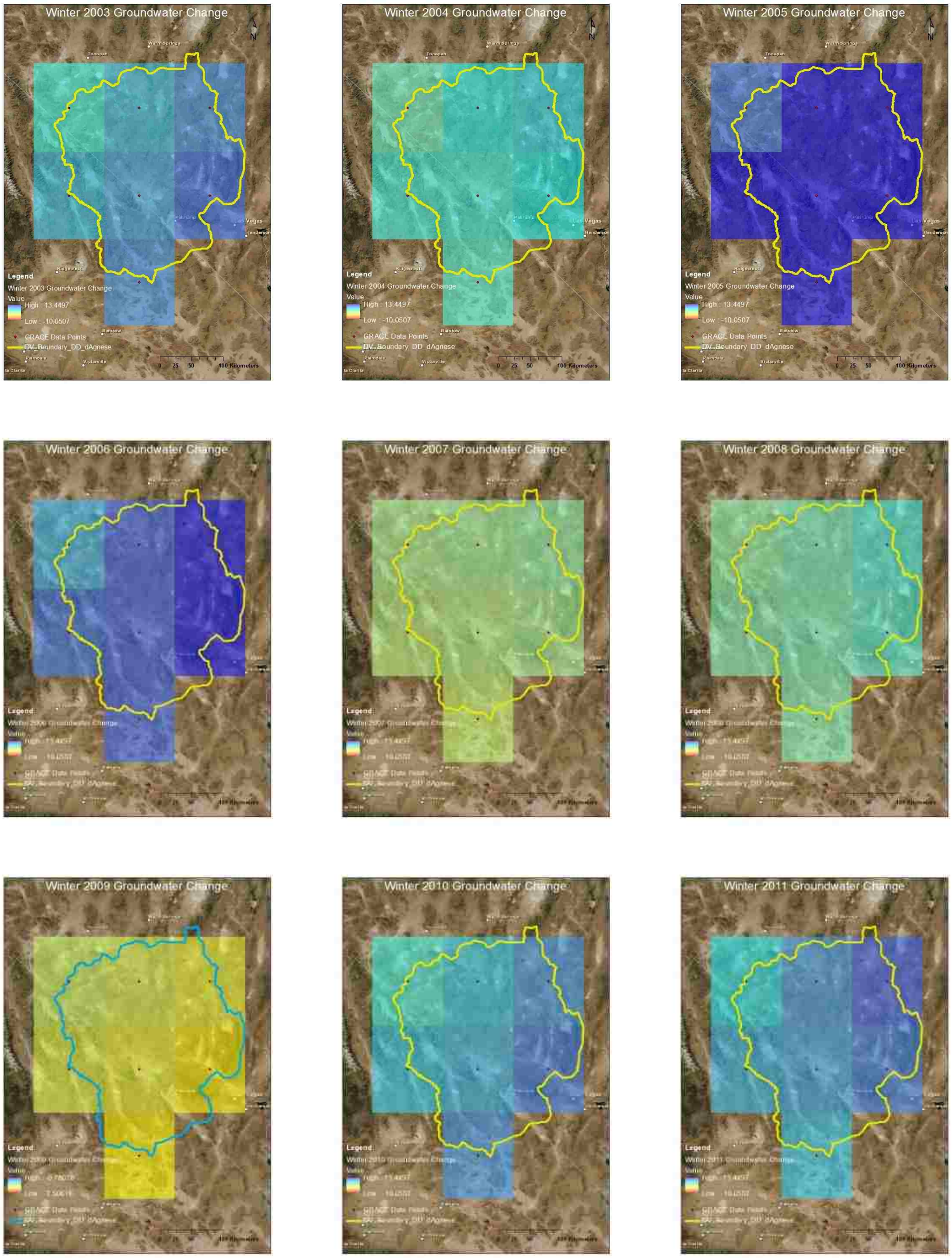


Figure 3-8. Winter groundwater change 2003-2011. See Appendix for full size figures.

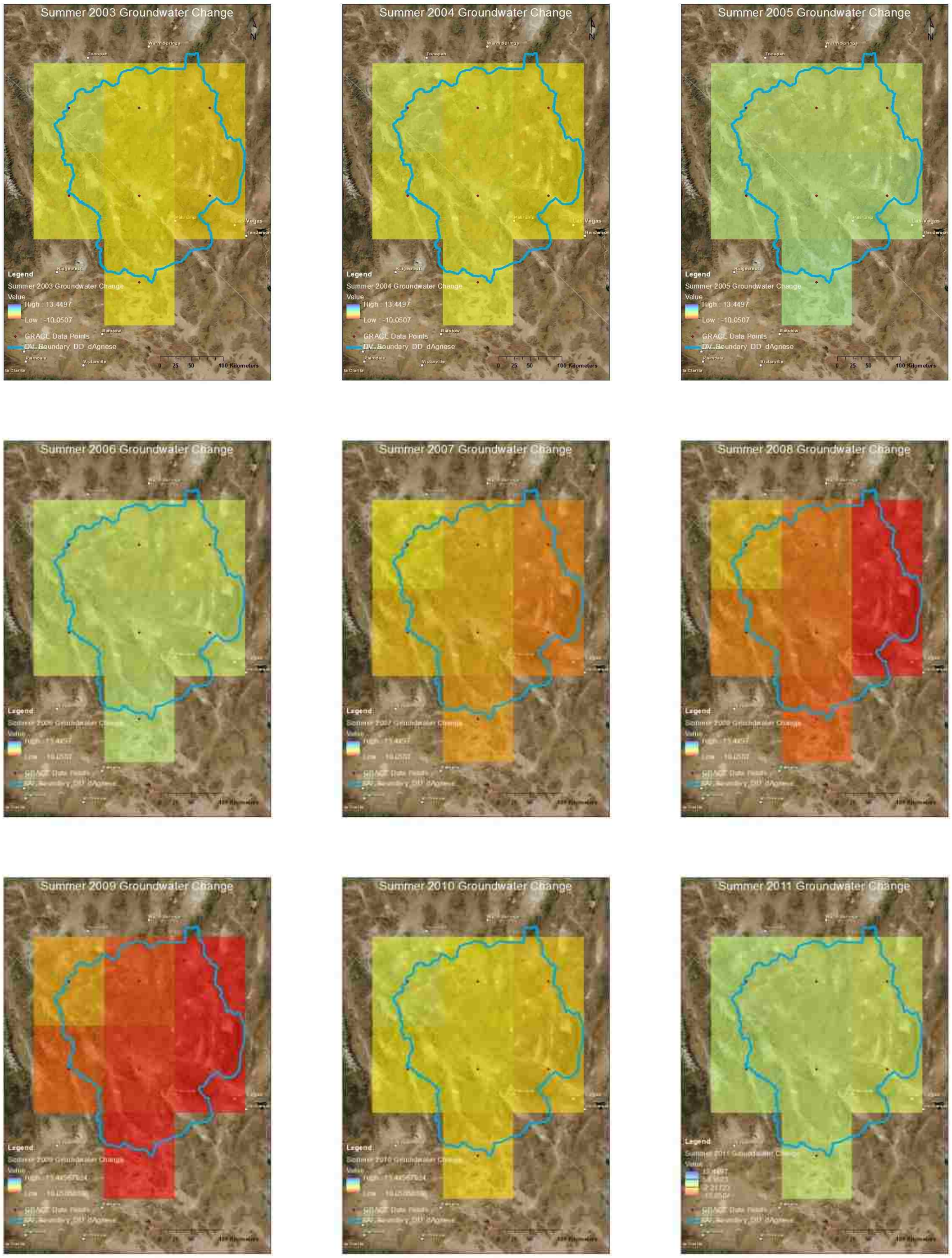


Figure 3-9. Summer groundwater change 2003-2011. See Appendix for full size figures.

DRI Downscaled Observations: Precipitation Decrease, Temperature and Specific Humidity Increase

Climate observation data for the Death Valley area spanned 30 years, from 1980-2009. Precipitation for the entire time period was analyzed and graphed to identify any possible long term trending that may be occurring in the area. The results show an average of 0.19 mm/yr. precipitation loss across the entire valley over the 30 year period (Fig. 3-12). If the areas located above 1100 meters are graphed, the results show an average of 0.13 mm/yr. precipitation loss (Fig. 3-13). The latter results take into consideration only the areas that would theoretically contribute to groundwater recharge.

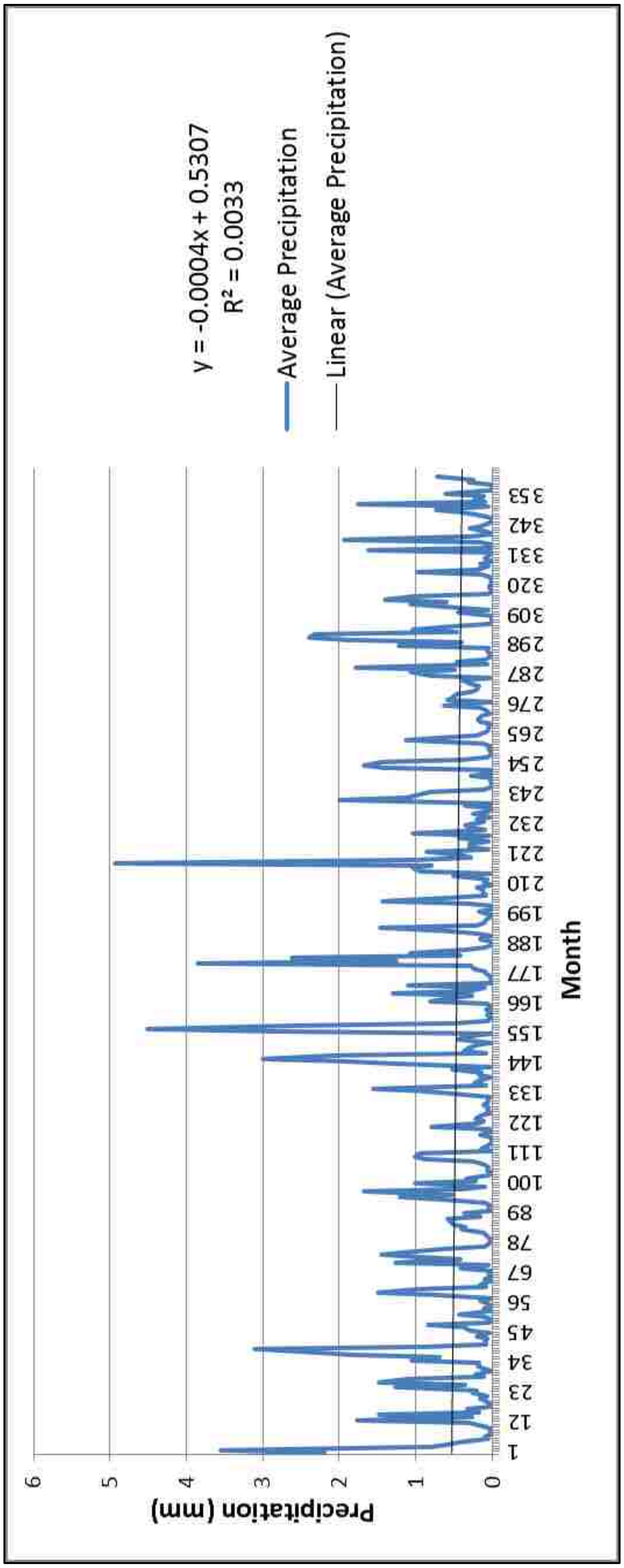


Figure 3-10. Death Valley average monthly precipitation 1980-2009.

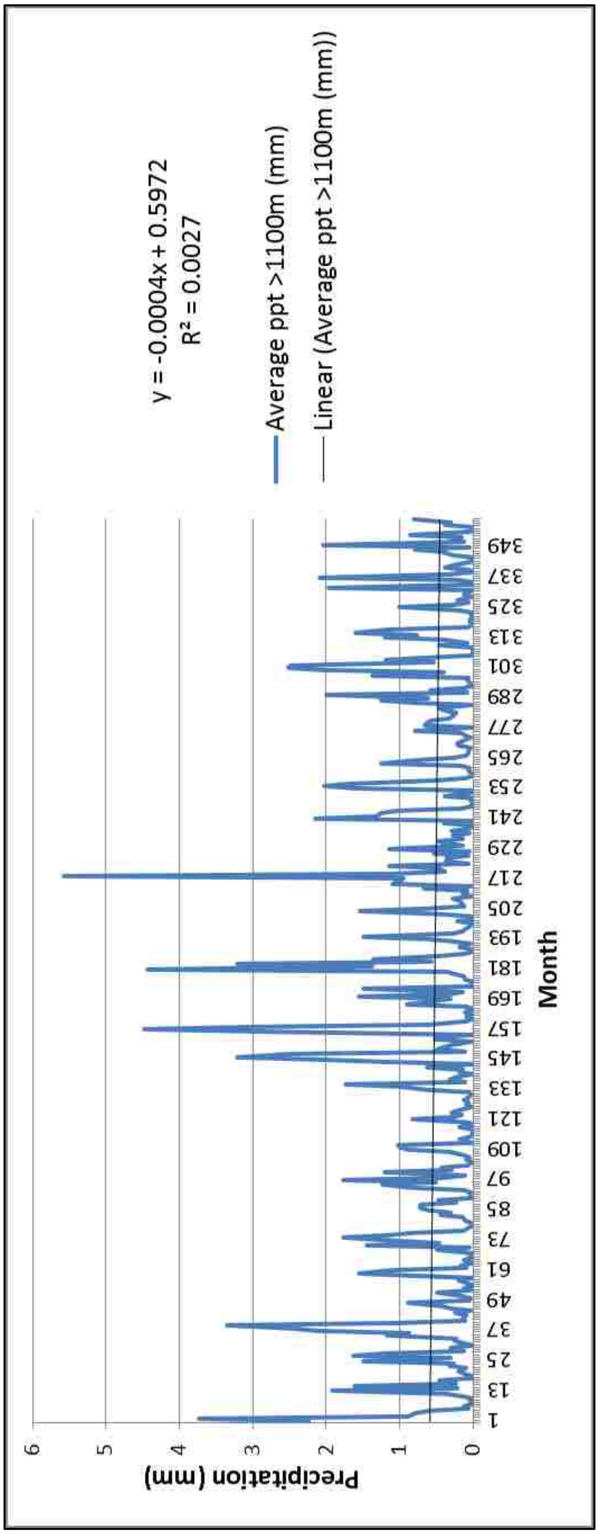


Figure 3-11. Death Valley average monthly precipitation 1980-2009, for areas above 1100 meters.

Each of the three decades spanning 1980 through 2009 was graphed individually, to examine the decadal trending (see Appendix for detailed results). Results show a trending decrease in precipitation, not only from month to month within each decade, but from decade to decade, down 0.07 mm from 1980 to 1990, and down 0.11 mm from 1990 to 2000. When viewed together (Fig. 3-12) the results reveal the wet and dry trends of each decade. From this data the drought of the 1980s is apparent, as well as a much wetter decade of the 1990’s. The last decade (2000-2009) shows a drier precipitation trend similar to what was seen in the 1980s. The tracking of these results quantify drought conditions during these time periods, and can be used for additional analysis when comparing it with other factors involved.

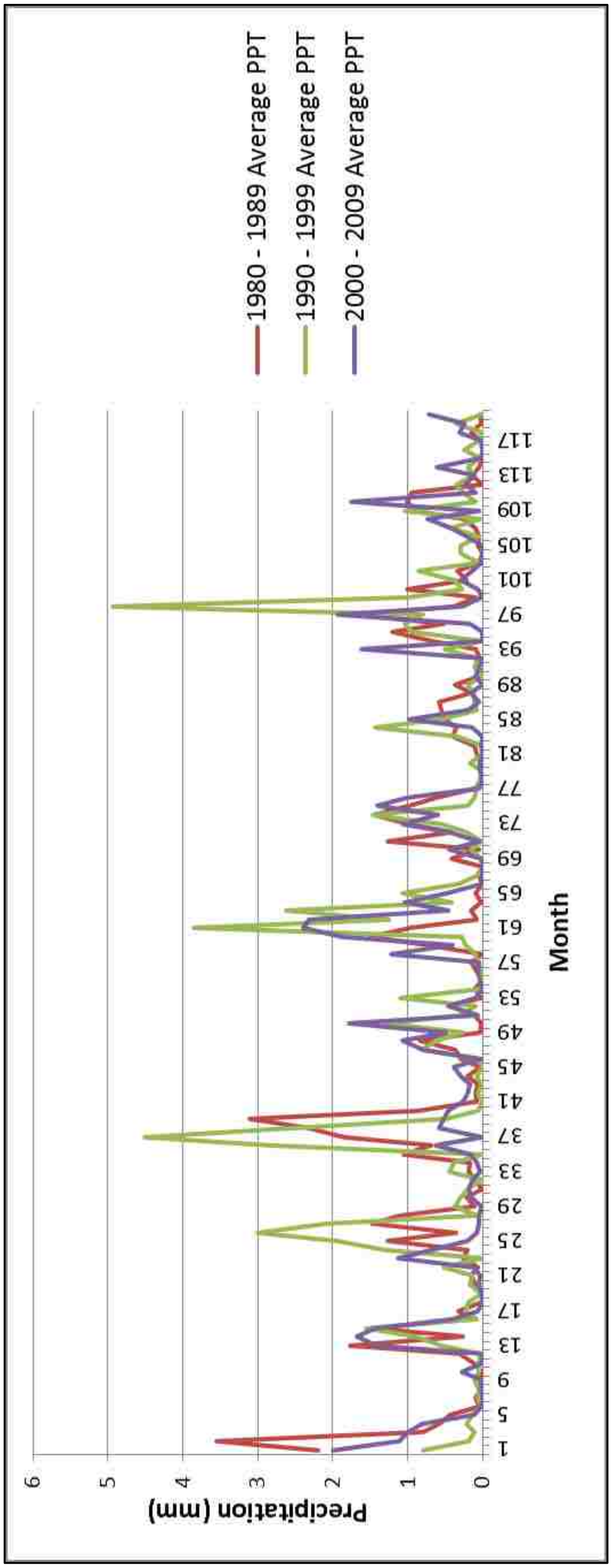


Figure 3-12. Death Valley decadal precipitation comparison.

To illustrate the seasonal changes in precipitation within the overlapping time period with GRACE data in the Death Valley area, winter and summer results were calculated and mapped. The winter results represent the calculated precipitation average of the three observed wettest months of the year: December, January, and February. The summer results represent the calculated precipitation average of the three driest months of the year: June, July, and August.

The results clearly show anomalies in the winter of 2005 (see Fig. 3-13), as well as in the summers of 2003 and 2009 (see Fig. 3-14). The winter results also show that the center of the western side of the valley, represented by precipitation within GRACE point 36.5, -117.5, receives the least amount of precipitation in the valley. The southeast area of the valley, representing precipitation within GRACE point 36.5, -115.5, receives the most winter precipitation. The summer results show a clear anomaly in 2008 for the northeast part of the valley for precipitation within GRACE point 37.5, -115.5. During this year, that area did not see a decrease in precipitation from the year before, but rather an increase that continued on into 2009. The results show how different areas of Death Valley are affected by climate conditions due to their elevation and distinct geological conditions. By understanding how geological conditions within the same valley can have different sensitivities, the information can be used to better predict future changes to groundwater based on current climate conditions in the future.

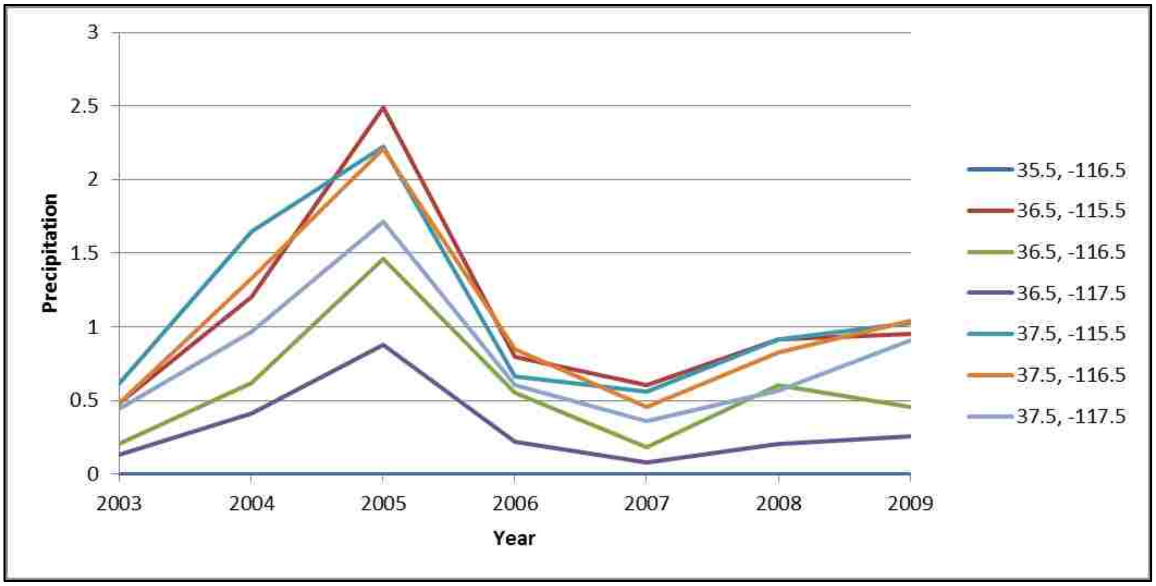


Figure 3-13. Average winter monthly precipitation within GRACE data points (average of March, April, and May).

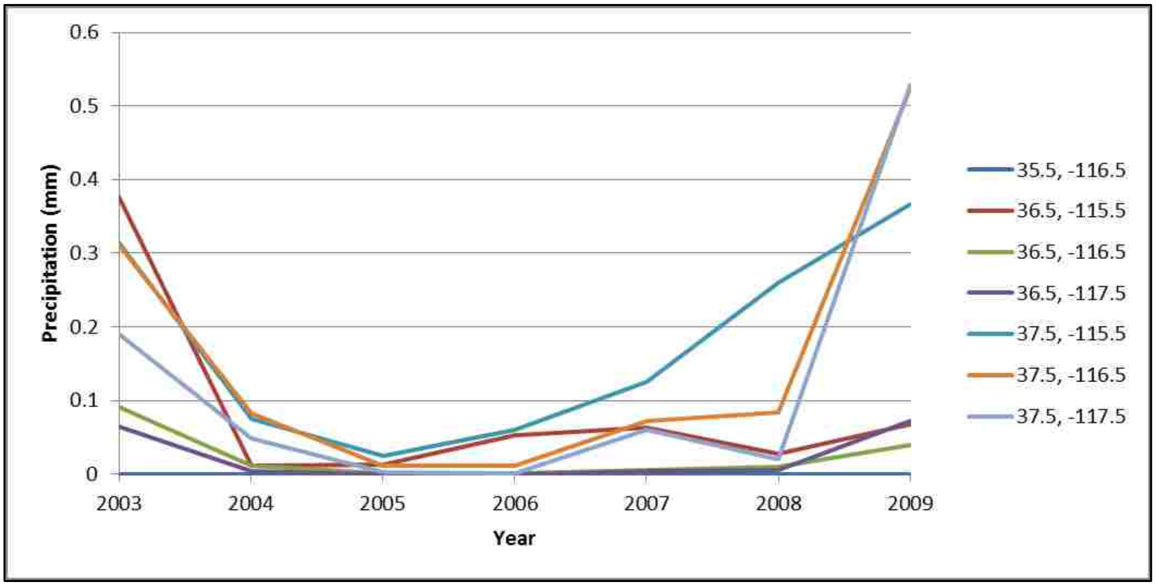


Figure 3-14. Average summer monthly precipitation within GRACE data points (average of June, July, and August).

Precipitation for both winter and summer seasons were mapped for 2003 to 2009 (years that coincided with the GRACE data). They were then placed together to show the similarities and differences between the years observed. When the winter maps are viewed alongside each other (Fig. 3-15), it becomes evident that 2004 and 2005 were wetter years, compared to the rest, receiving more precipitation on average throughout the valley. The winter maps of 2003 and 2007 are shown to be drier years than the others, displaying a marked decrease in precipitation in certain areas. The summer maps reveal consistent dry conditions (Fig. 3-16), with an anomaly in 2007, which displays greater precipitation than normal in the northeast areas of the valley.

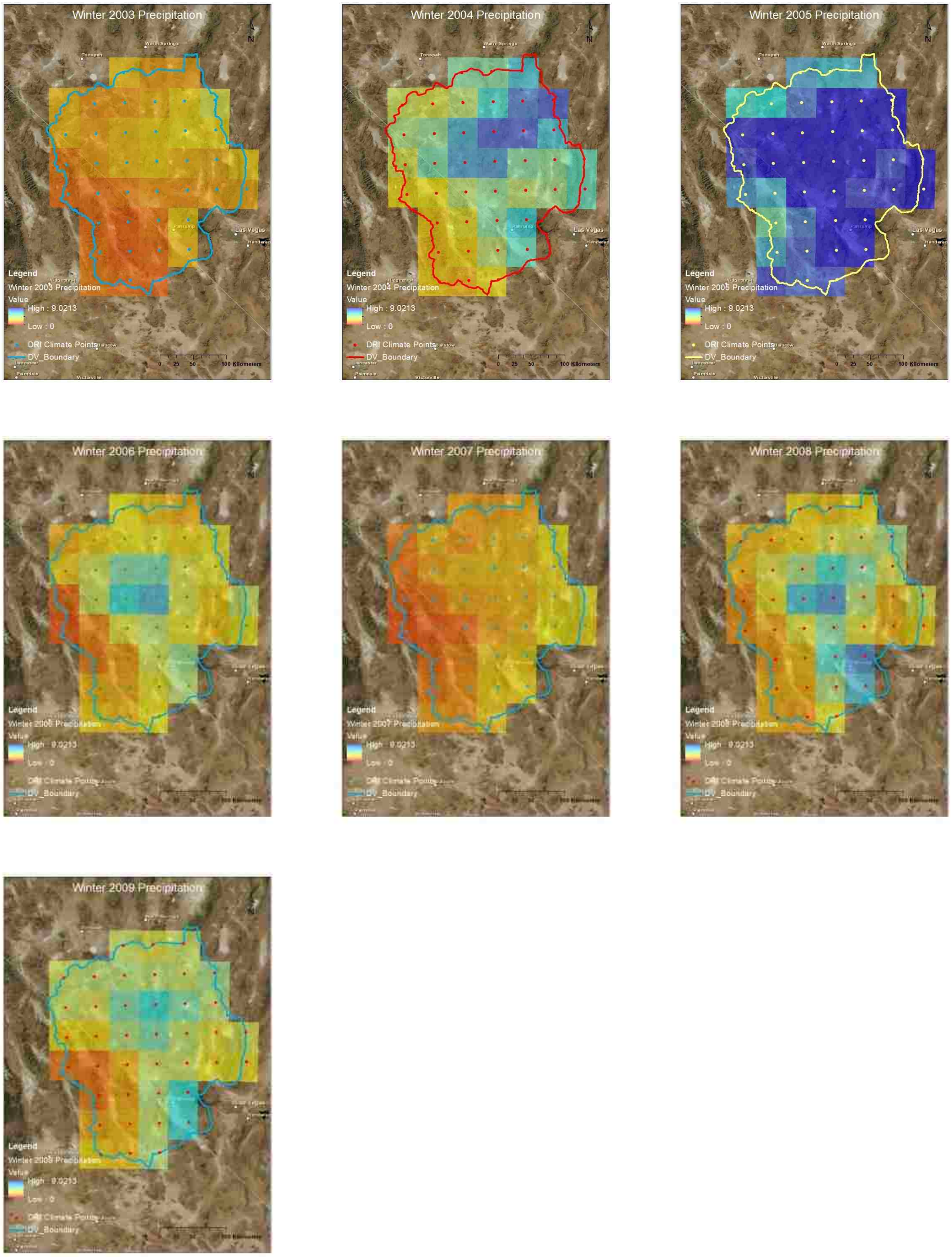


Figure 3-15. Winter precipitation 2003-2009.

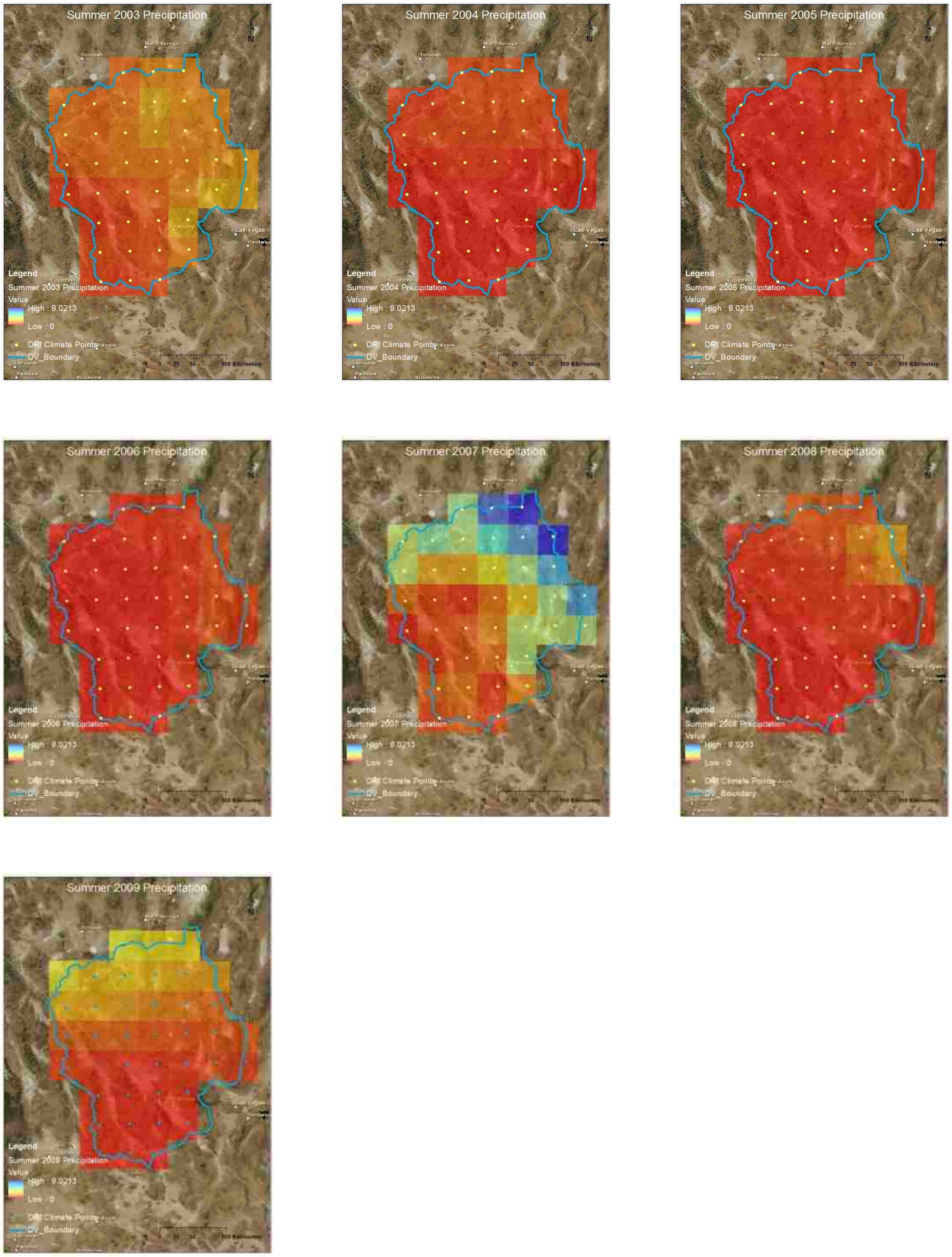


Figure 3-16. Summer precipitation 2003-2009.

Average minimum, mean, and maximum temperature data was also acquired for the 30 year period and graphed for comparison and trending. The results show that the average minimum temperature slightly increases at a rate of 0.018 °F/yr., the average mean temperature is also slightly increasing at 0.035 °F/yr., and the average maximum temperature is slightly increasing at 0.052 °F/yr. (see Appendix for detailed figures). When decadal comparisons were analyzed overall (Figs. 3-17 through 3-19), each decade shows a slight increase in average temperature that trends upward with each consecutive decade. There was one exception for trending of the average minimum temperature for 2000-2009, which is showing a slight decreasing trend. This exception could be an indicator for continued decrease in minimum temperatures to be continued into the next decade. Additional graphs showing the temperature spans by decadal time periods can be viewed in the appendix.

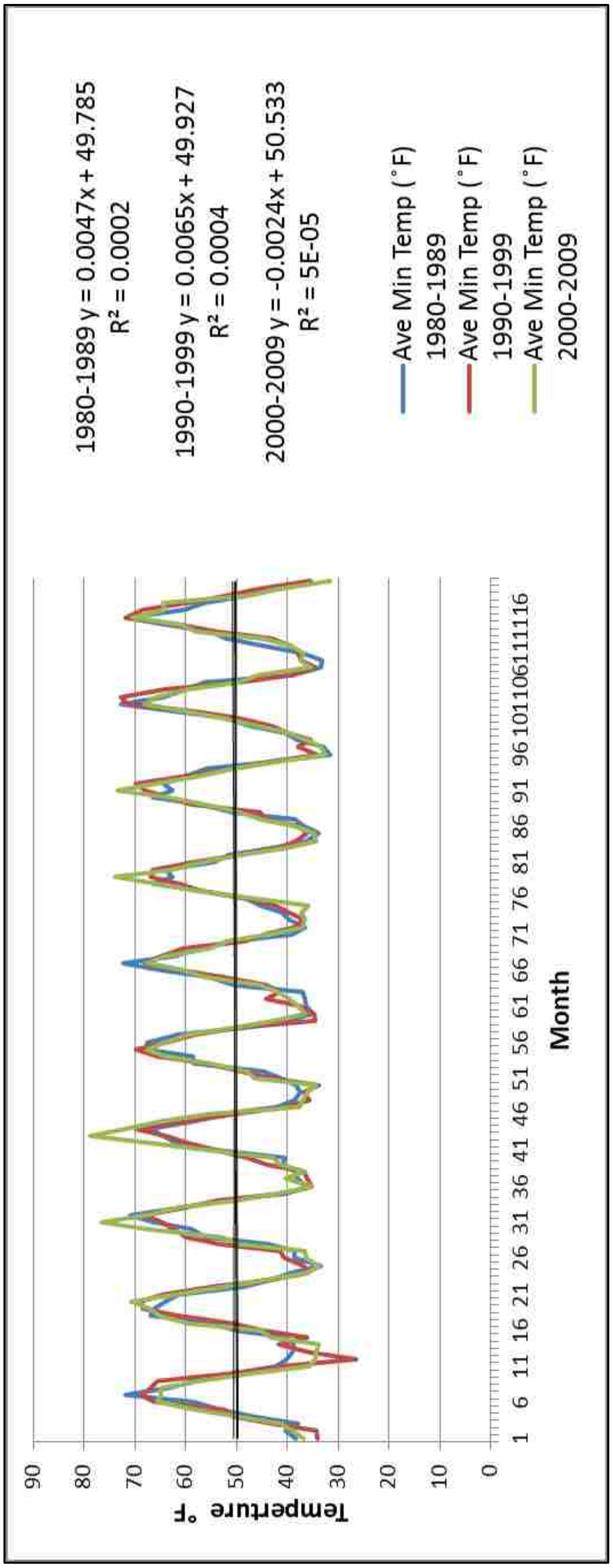


Figure 3-17. Death Valley average minimum temperature decadal comparison.

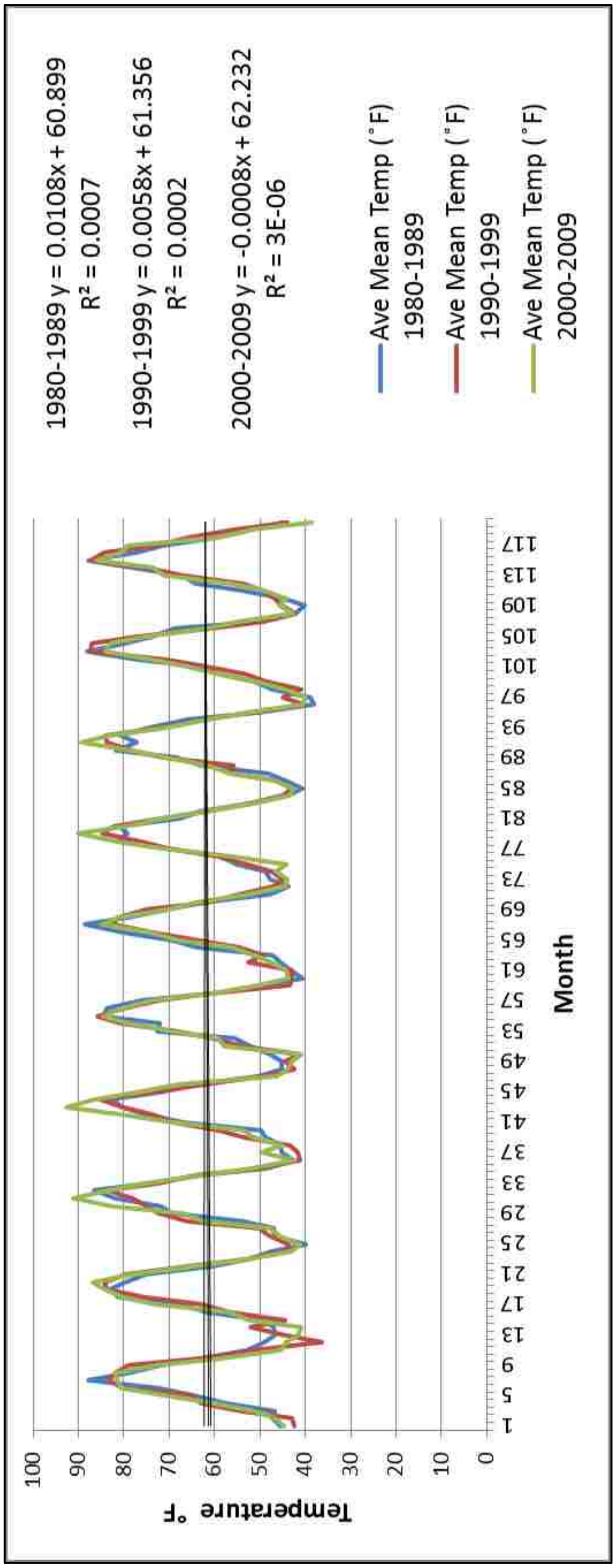


Figure 3-18. Death Valley average mean temperature decadal comparison.

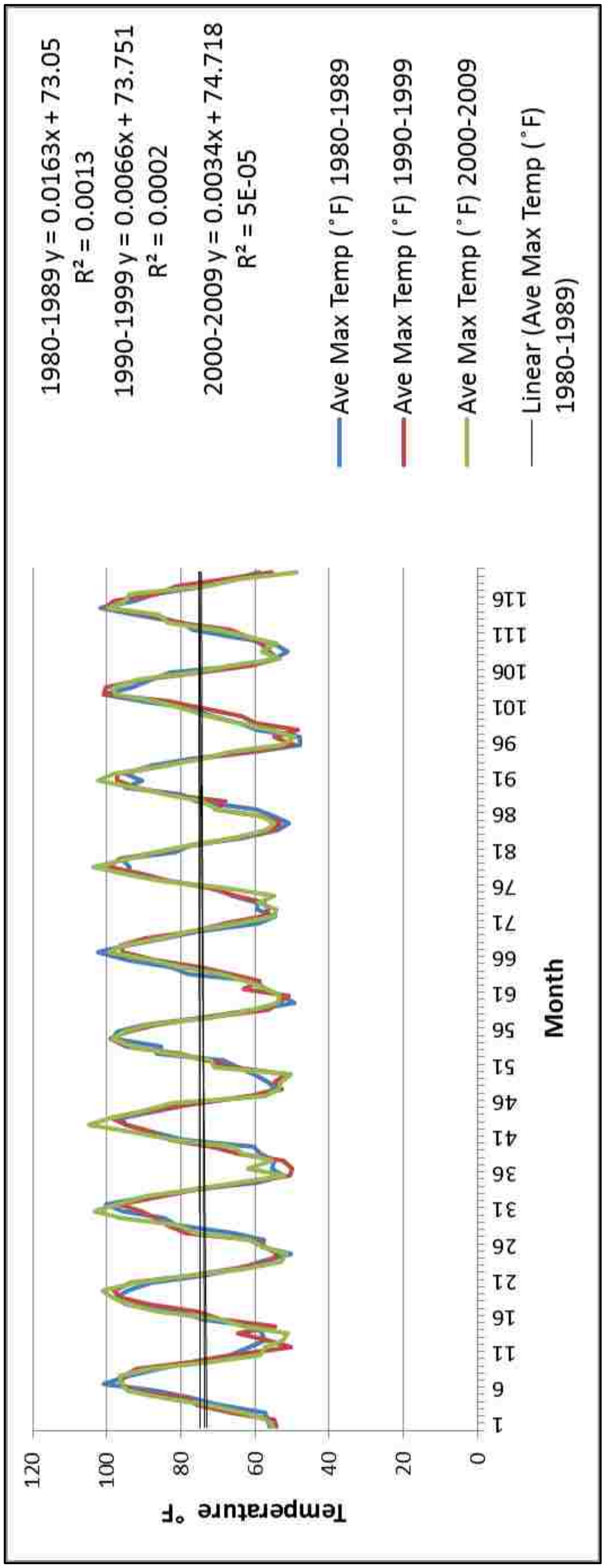


Figure 3-19. Death Valley average maximum temperature decadal comparison.

An additional climate detail analyzed for the Death Valley area was specific humidity. As would be expected given the slight decline in precipitation (Fig. 3-20) of the 30 year trend, a slight decline in specific humidity also is revealed. Looking at decadal trends, the total amount of humidity is also slightly decreasing with each subsequent decade (Fig. 3-21). These results further illustrate the increasing dryness of the valley over the time period observed.

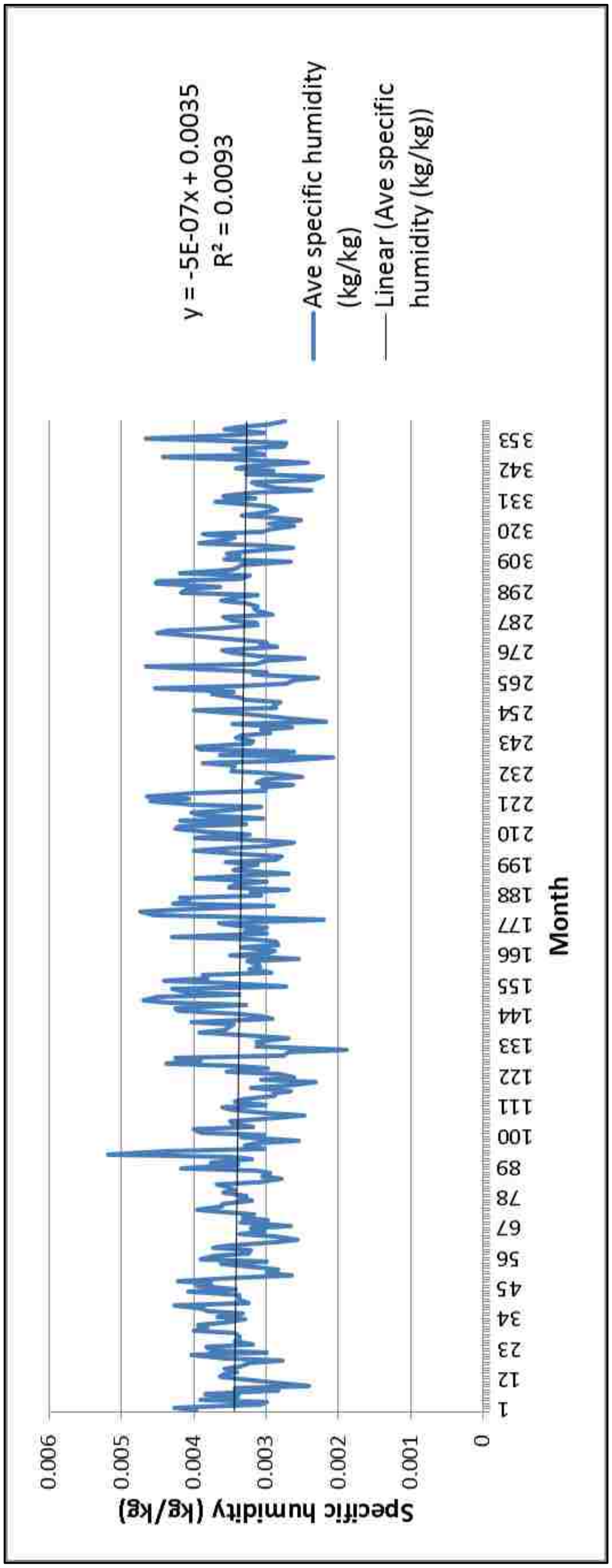


Figure 3-20. Death Valley specific humidity 1980-2009.

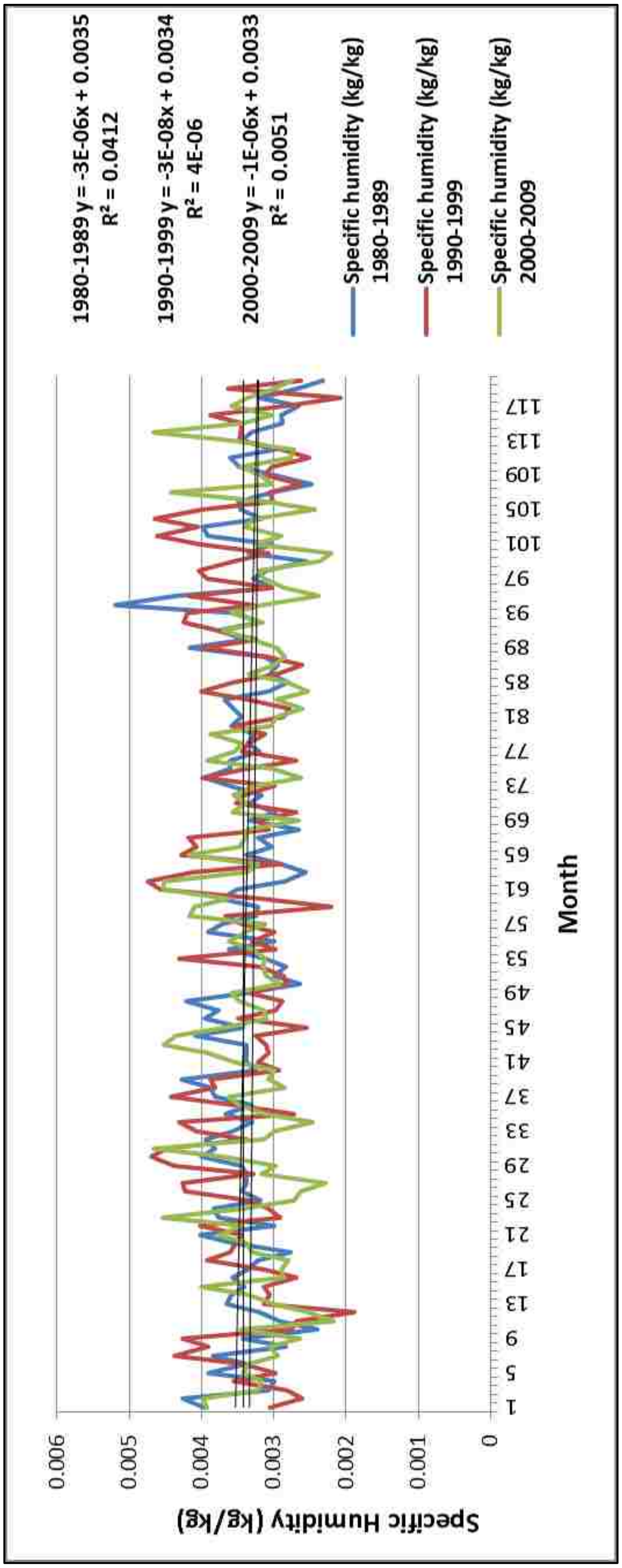


Figure 3-21. Death Valley specific humidity decadal comparison.

GRACE and DRI Downscaled Climate Data Correlations

The precipitation results from the downscaled DRI data points were combined and graphed against the GRACE data points that they correlate to, in their overlapping time scale (January 2003 – December 2009). Since the study by Abdulaziz et al. (2012) concluded that recharge mainly takes place in areas above 1100 meters during winter, both the total precipitation and the precipitation data from areas exclusively above 1100 meters were graphed. It is assumed that any areas below 1100 meters did not result in any recharge to the area. The entire area encompassed by the southernmost GRACE data point (35.5, -116.5) was entirely below 1100 meters, so it is presumed that no recharge occurs here from precipitation. To show correlation between the GRACE and DRI data, the results were graphed together, with and without the precipitation below 1100 meters (Figs. 3-22 through 3-28). The results show a correlation coefficient that ranges from 0.43-0.46 (in a range of +1 to -1) for areas with precipitation above 1100 m. When the area that is completely below 1100 m is thrown in, the average correlation coefficient is 0.40. This shows that on average, the two results are 20-25% out of sync, or, in terms of time, approximately 3 months apart. This is the equal amount of time observed as a gap between the wet and dry precipitation seasons and the high and low groundwater change levels.

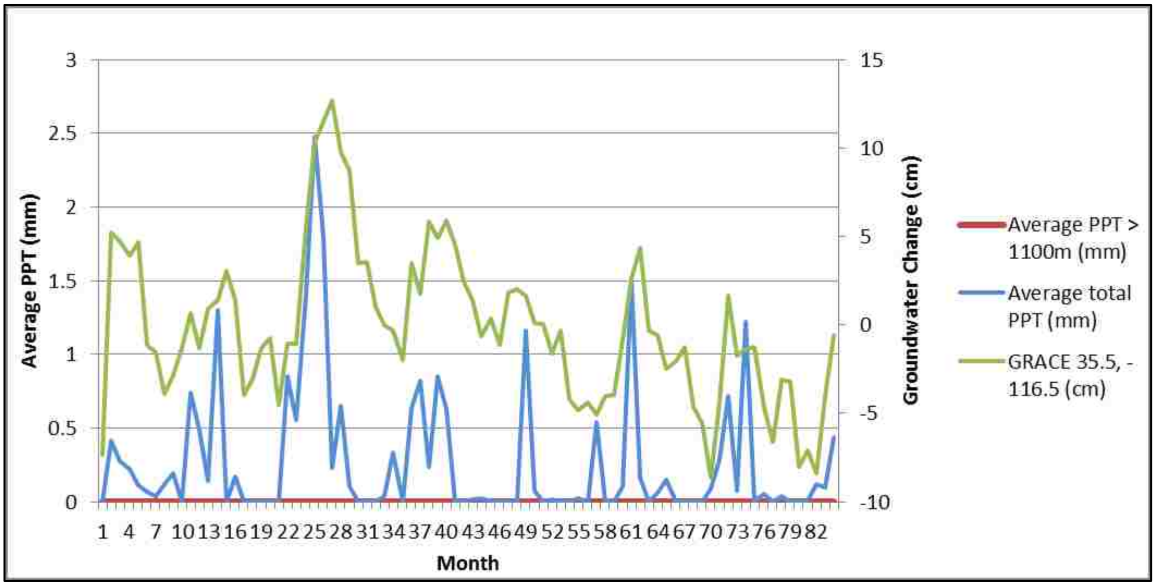


Figure 3-22. 2003-2009 GRACE Data Point 35.5, -116.5 and corresponding DRI downscaled precipitation data. Correlation coefficient = N/A (all areas below 1100 meters).

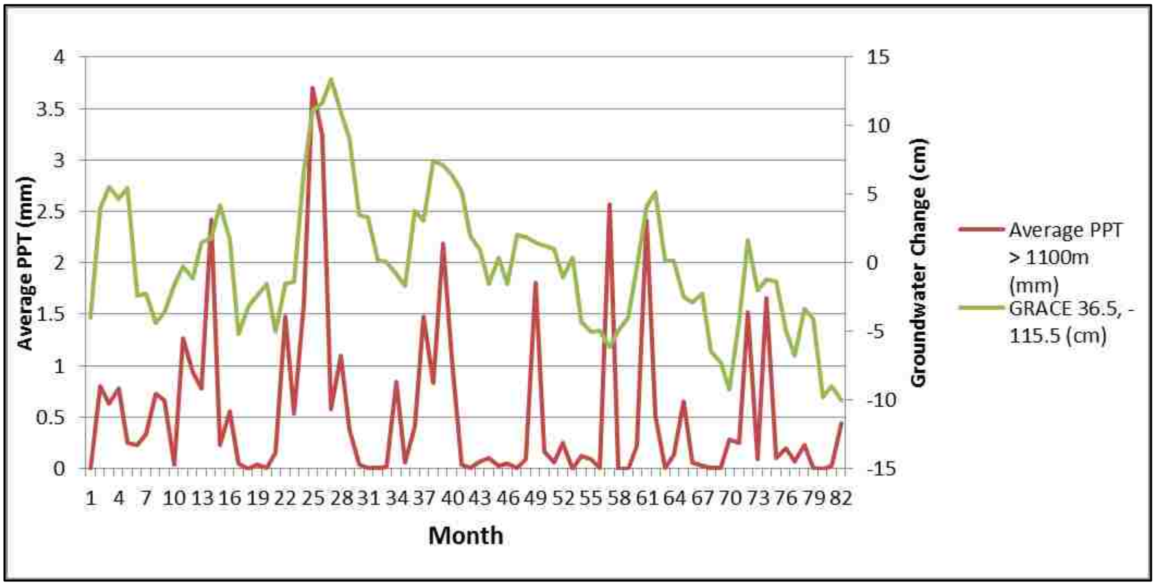


Figure 3-23. 2003-2009 GRACE data point 36.5, -115.5 and corresponding DRI downscaled precipitation data for areas > 1100m (all areas above 1100 meters). Correlation coefficient = 0.46.

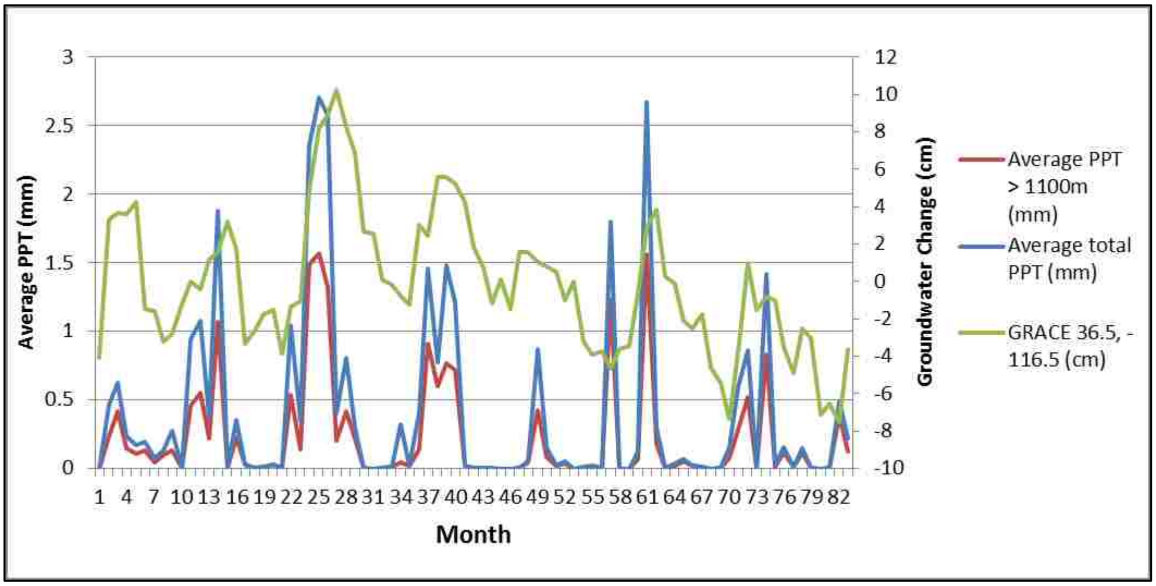


Figure 3-24. 2003-2009 GRACE data point 36.5, -116.5 and corresponding DRI downscaled precipitation data. Correlation coefficient = 0.46.

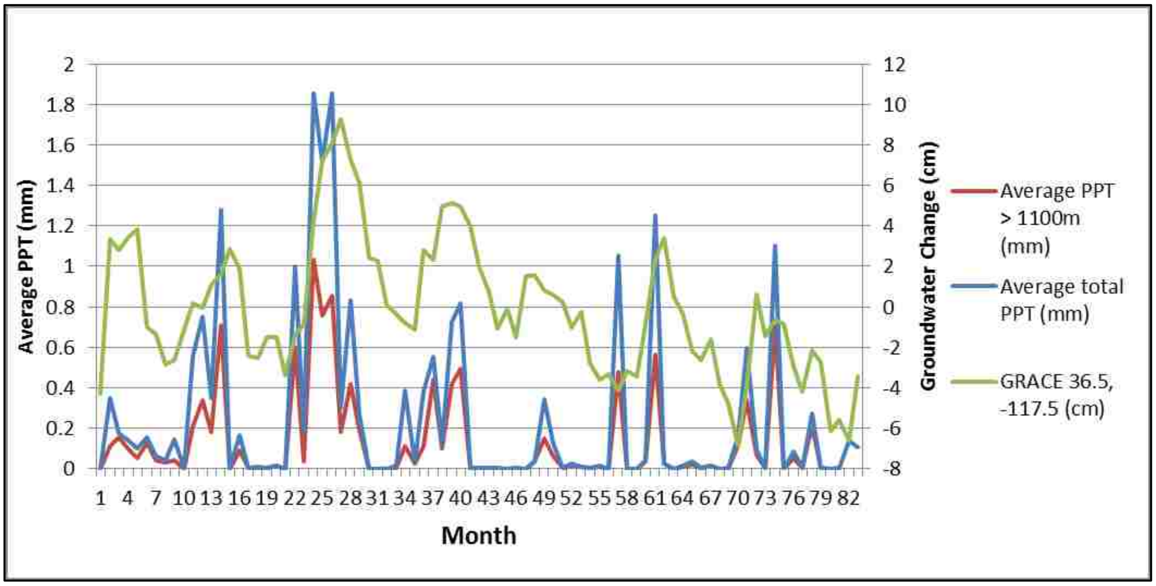


Figure 3-25. 2003-2009 GRACE data point 36.5, -117.5 and corresponding DRI downscaled precipitation data. Correlation coefficient = 0.44.

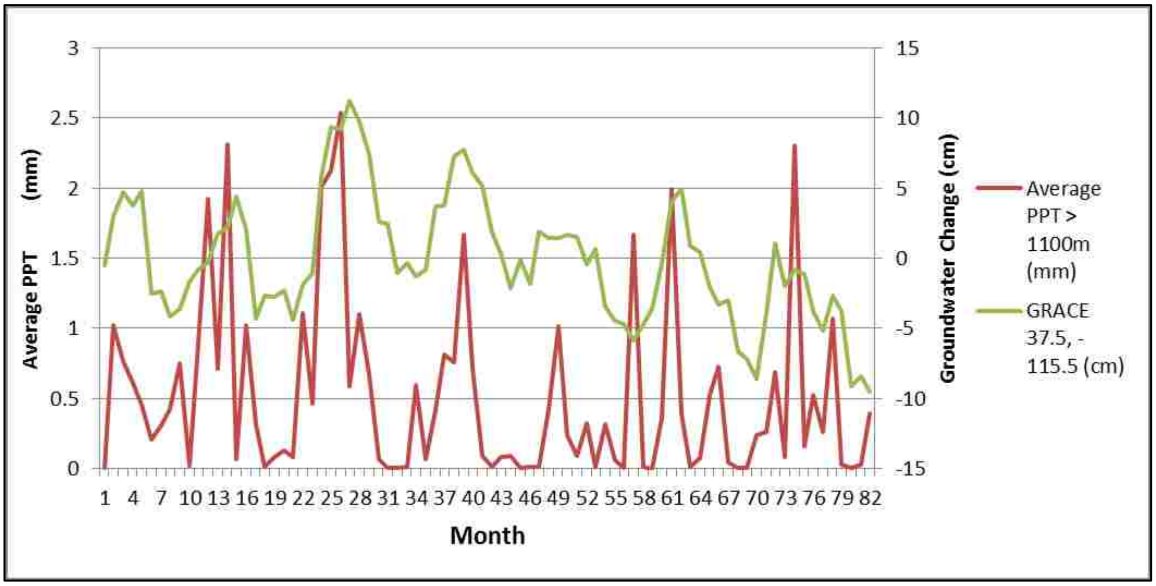


Figure 3-26. 2003-2009 GRACE data point 37.5, -115.5 and corresponding DRI downscaled precipitation data (all areas above 1100 meters). Correlation coefficient = 0.43.

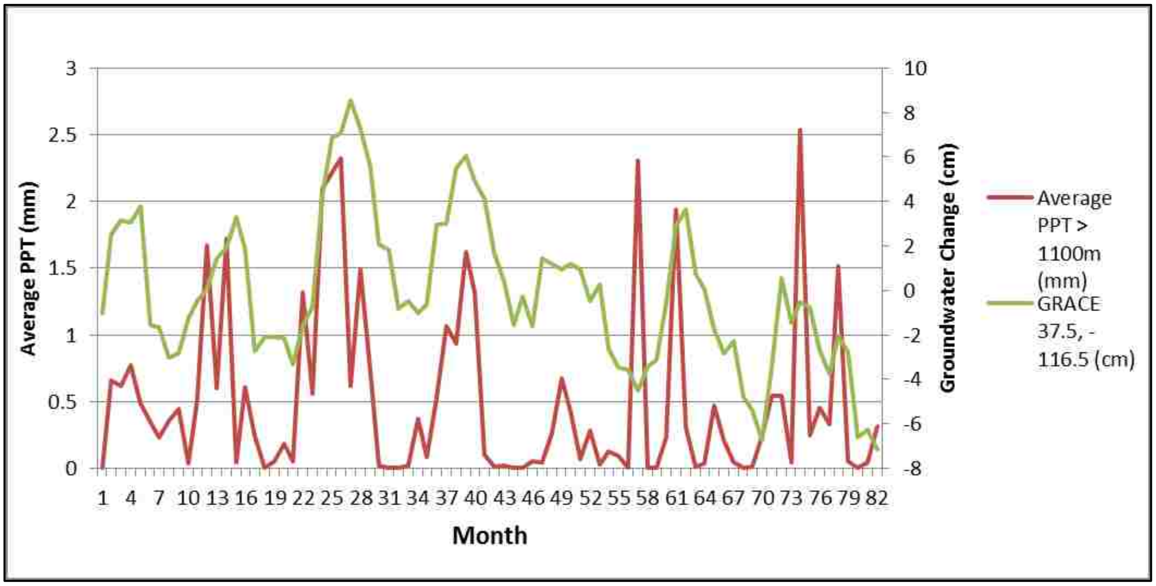


Figure 3-27. 2003-2009 GRACE data point 37.5, -116.5 and corresponding DRI downscaled precipitation data (all areas above 1100 meters). Correlation coefficient = 0.44.

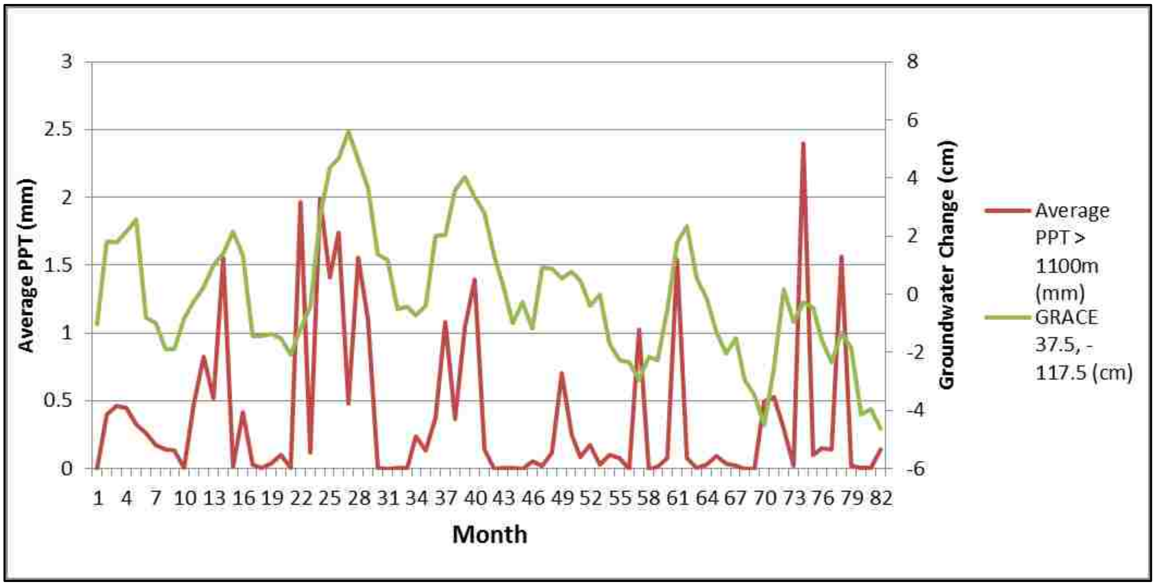


Figure 3-28. 2003-2009 GRACE data point 37.5, -117.5 and corresponding DRI downscaled precipitation data (all areas above 1100 meters). Correlation coefficient = 0.43.

The maps of the downscaled DRI precipitation and the GRACE groundwater change results were compared together, to show trends for both the summer and winter seasons (Figs. 3-29 through 3-42). Anomalies in the results include the winter of 2005 showing an above average precipitation season, which is reflected in the groundwater change results (Fig. 3-33). The above average precipitation seems to offset the drier than average summer of 2005 (Fig. 3-34), where the groundwater change is not as negative relative to the below average precipitation observed for the season. The same pattern can be seen going from the winter of 2006 (Fig. 3-35) to the summer of 2006 (Fig. 3-36). Likewise, since the winter of 2007 was unusually dry (Fig. 3-37), the effects are seen in the low groundwater during the summer of 2007 (Fig. 3-38). These maps show that the effects of different climate conditions persist for months in order to have an effect on groundwater change in an area. Consequently, in order to completely understand the nature of groundwater change to an area, both the current and previous season’s climate variables need to be taken into account.

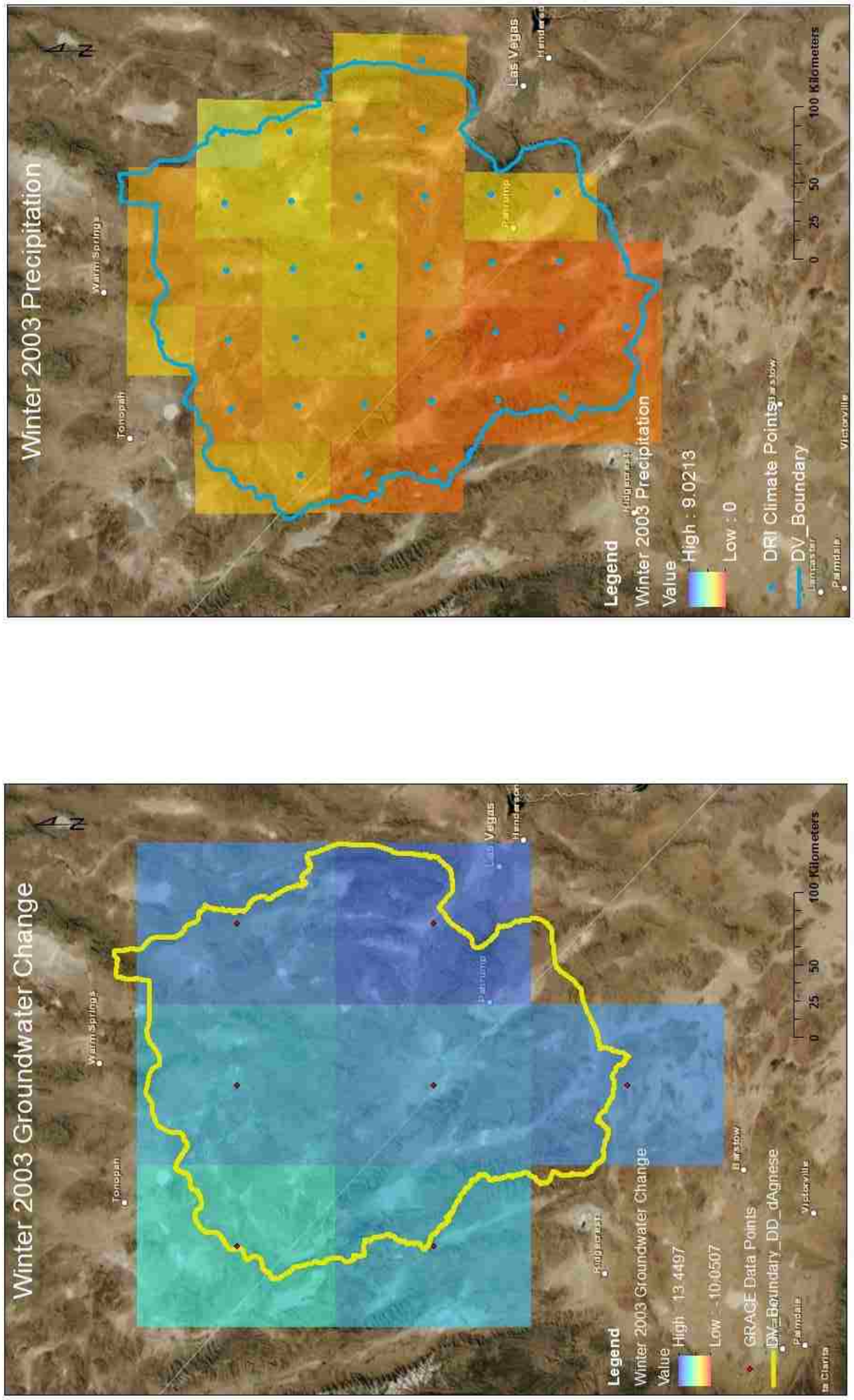


Figure 3-29. Winter 2003 groundwater change vs. precipitation.

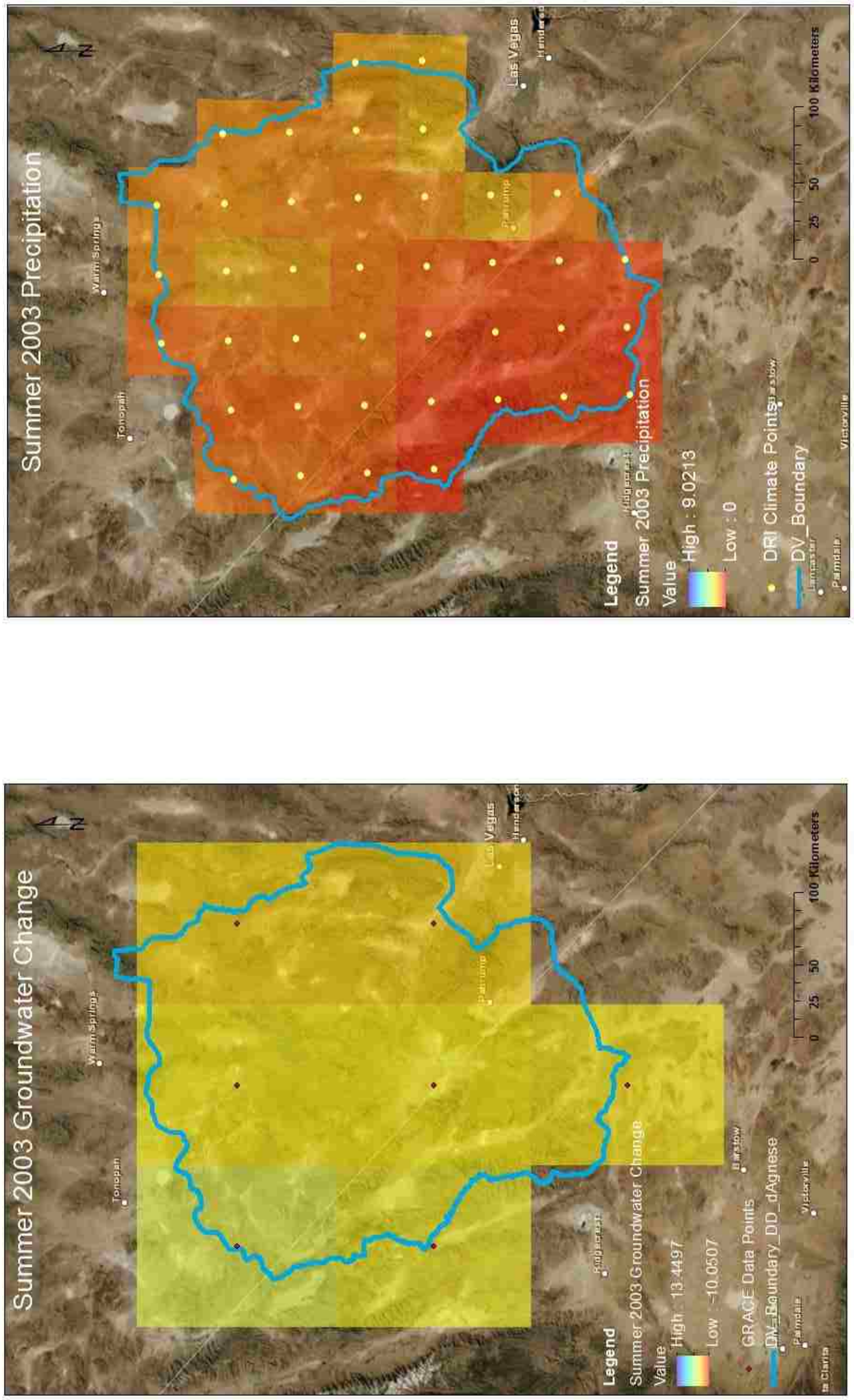
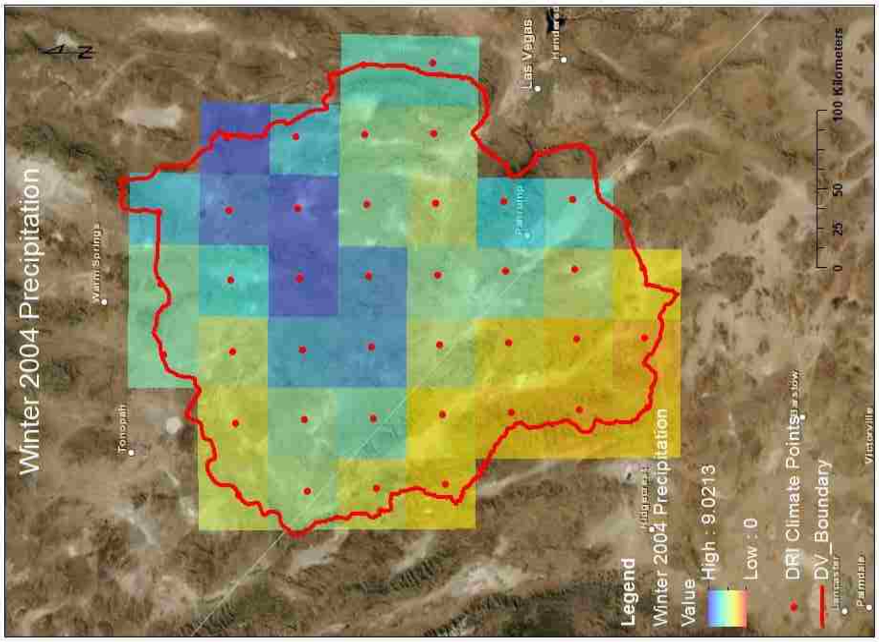


Figure 3-30. Summer 2003 groundwater change vs. precipitation.



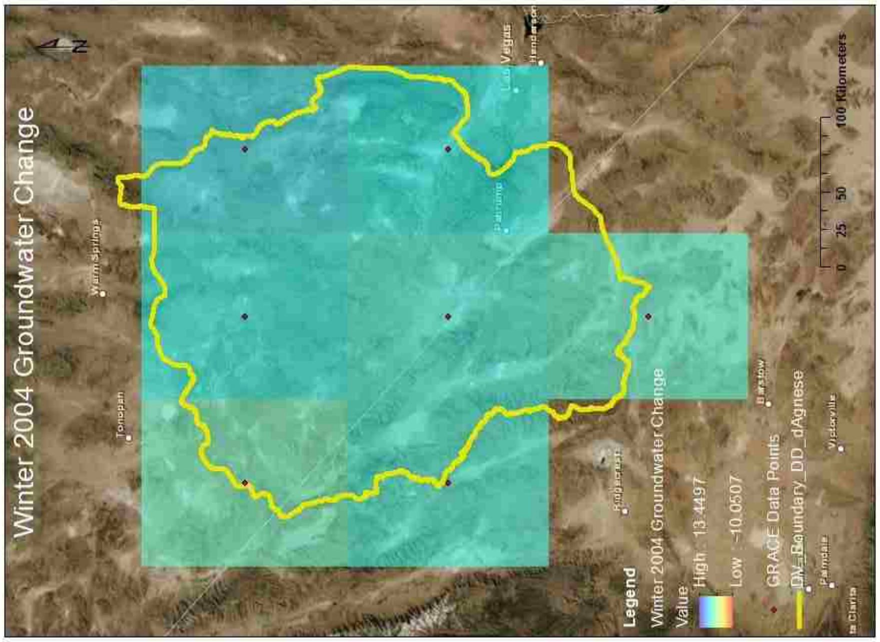


Figure 3-31. Winter 2004 groundwater change vs. precipitation.

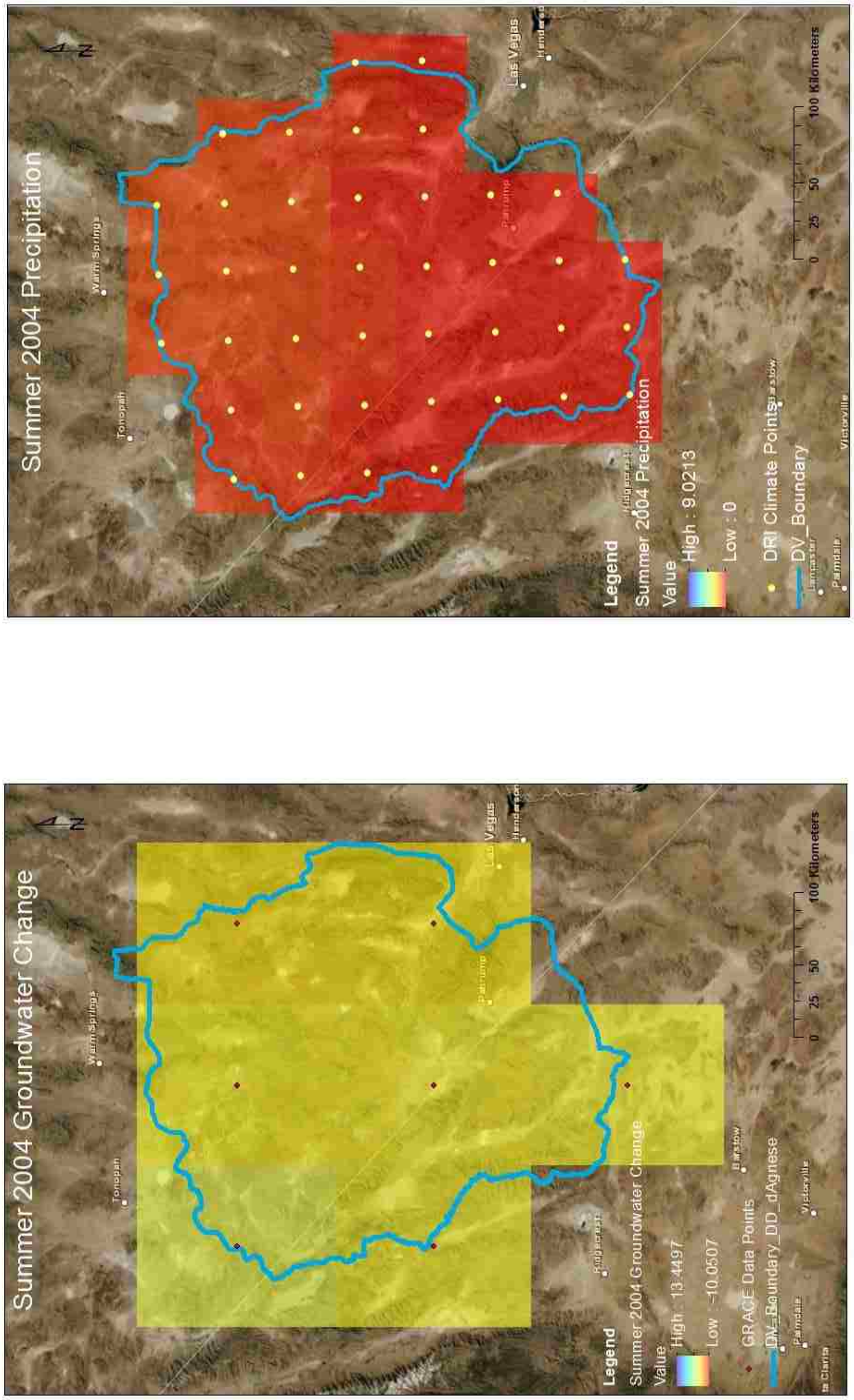


Figure 3-32. Summer 2004 groundwater change vs. precipitation.

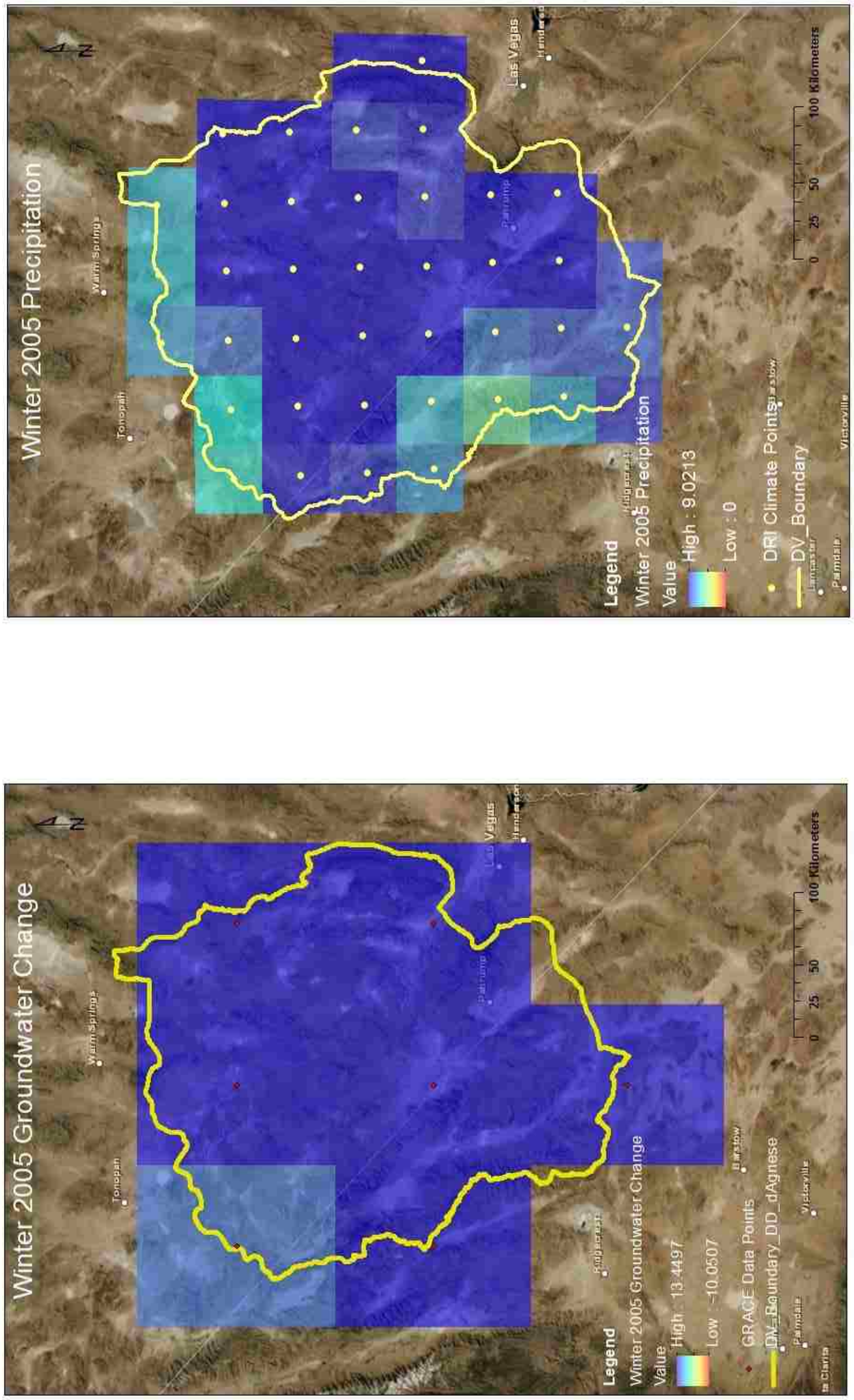


Figure 3-33. Winter 2005 groundwater change vs. precipitation.

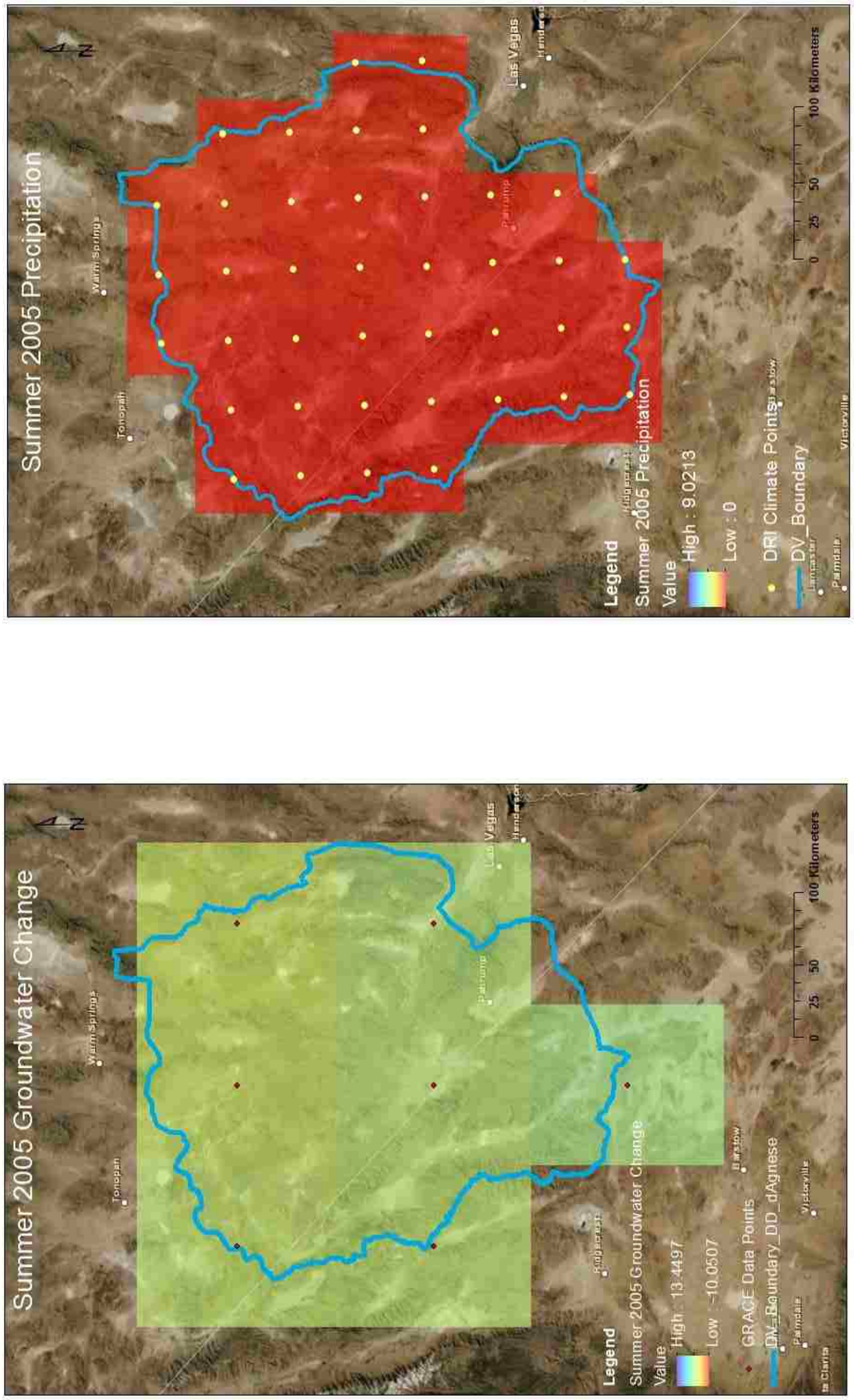


Figure 3-34. Summer 2005 groundwater change vs. precipitation.

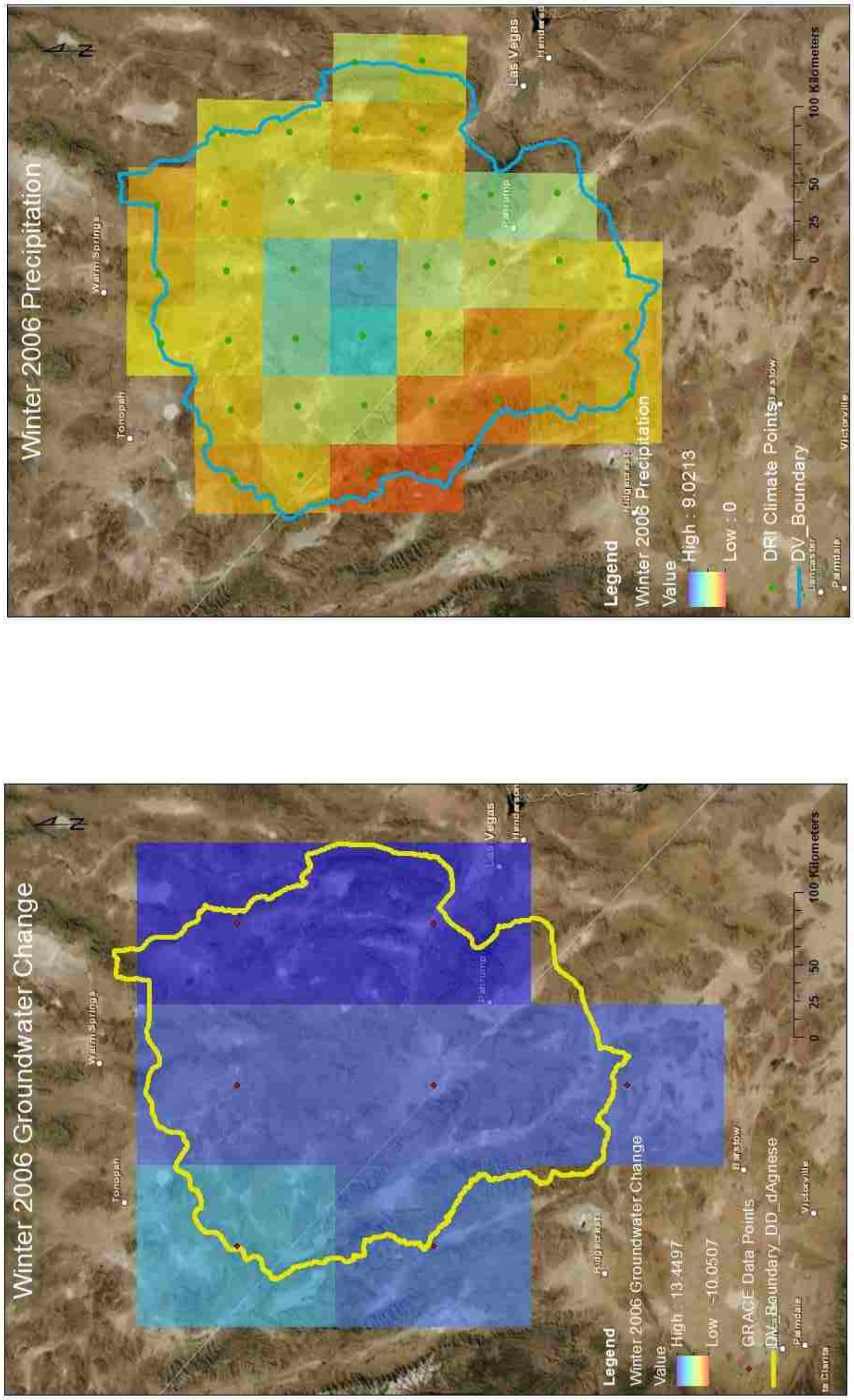
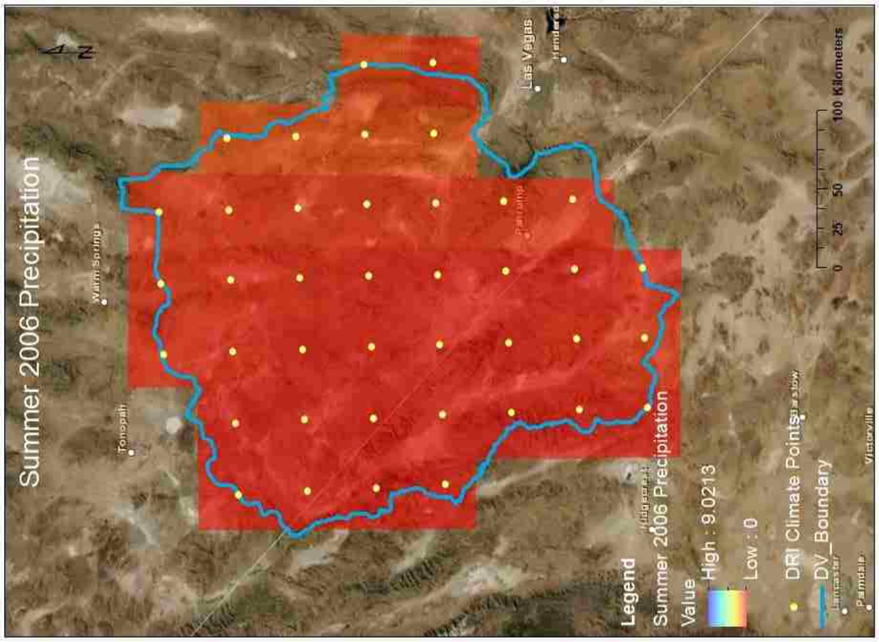


Figure 3-35. Winter 2006 groundwater change vs. precipitation.



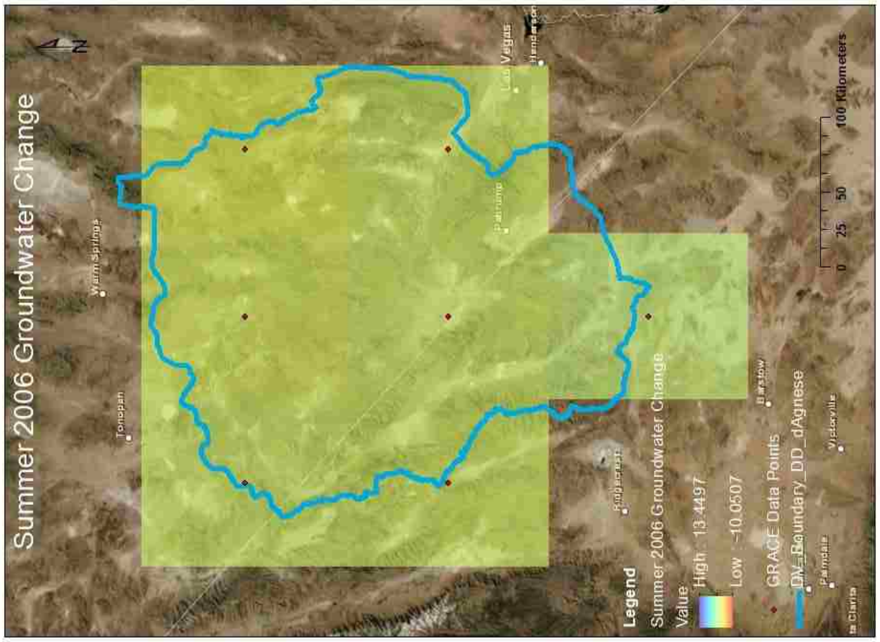
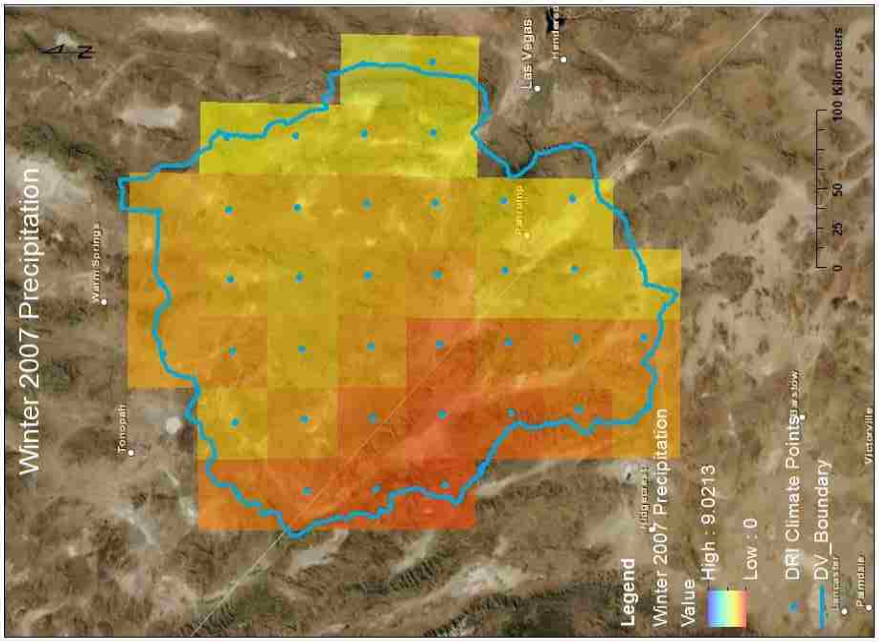


Figure 3-36. Summer 2006 groundwater change vs. precipitation.



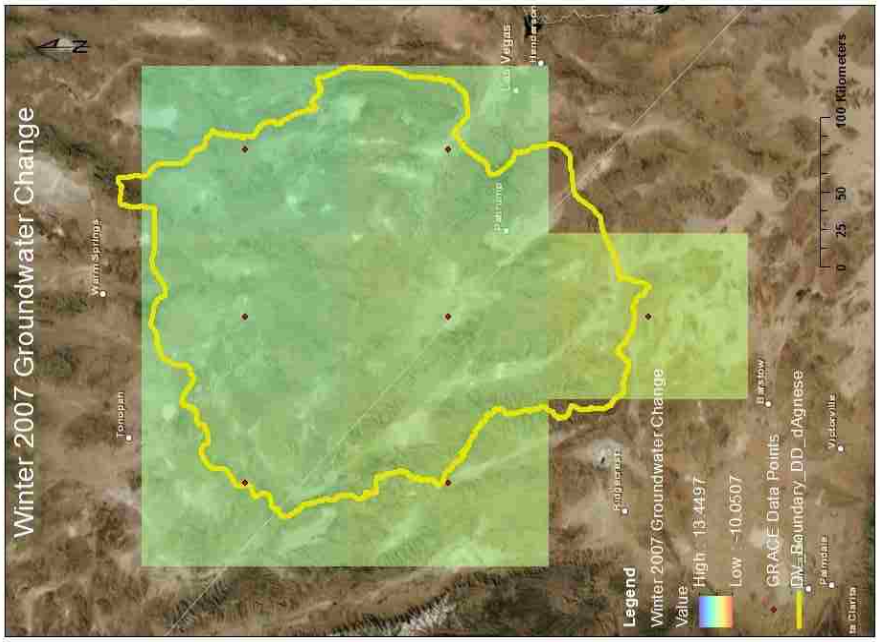
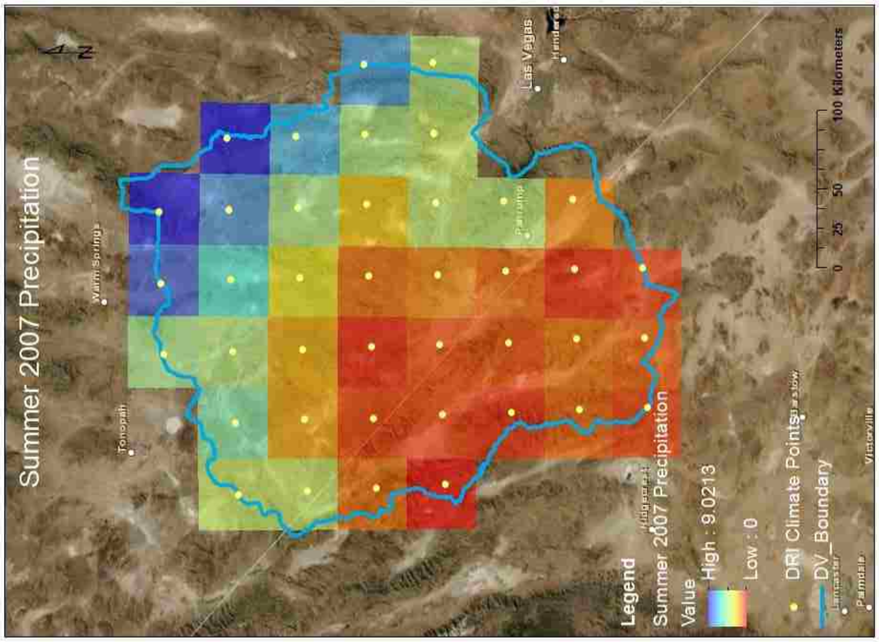


Figure 3-37. Winter 2007 groundwater change vs. precipitation.



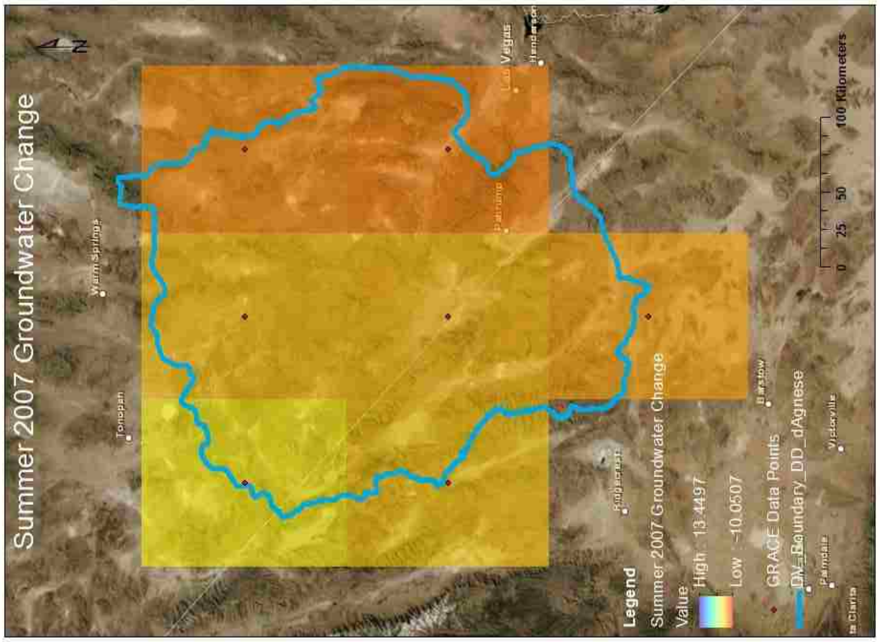


Figure 3-38. Summer 2007 groundwater change vs. precipitation.

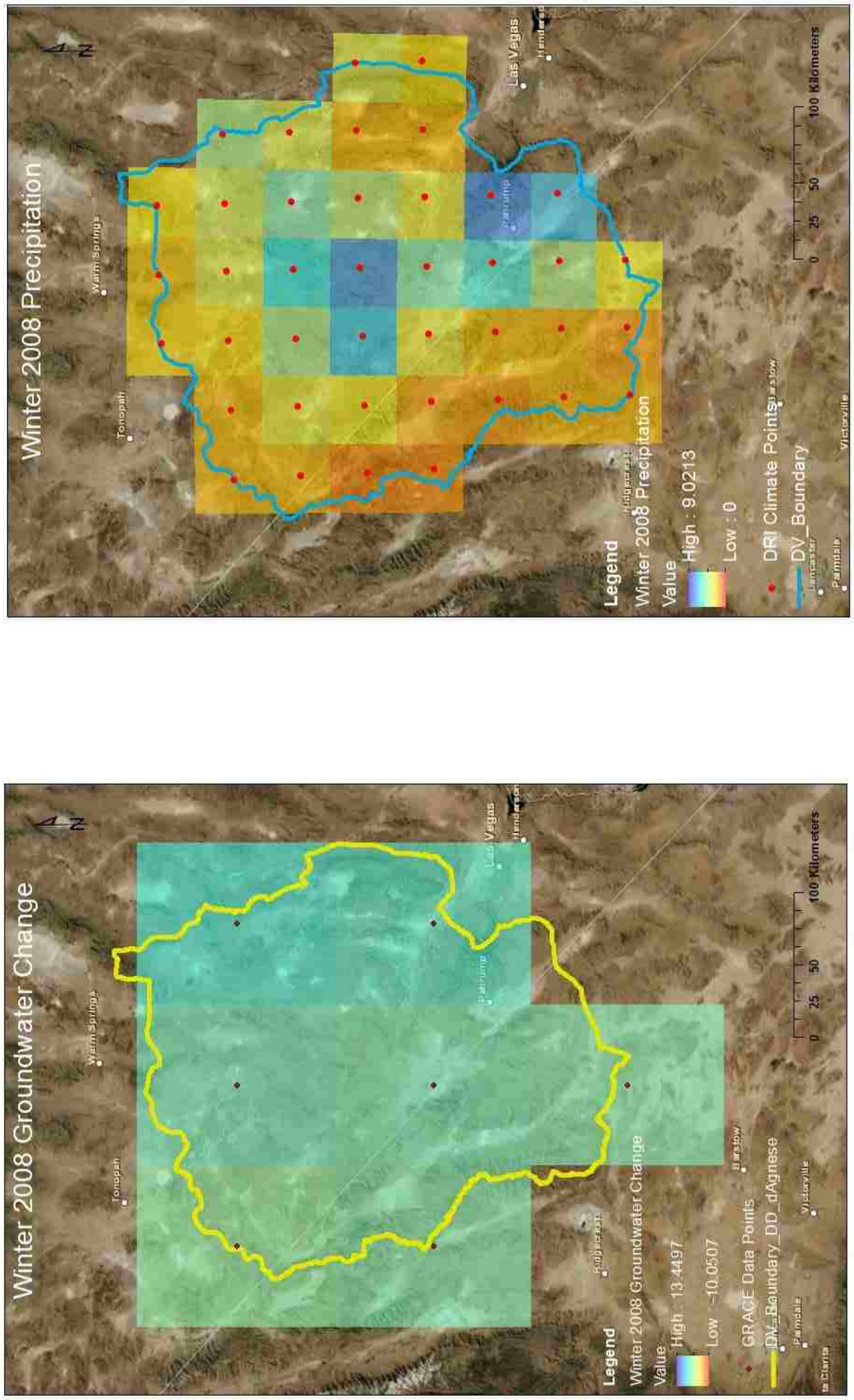


Figure 3-39. Winter 2008 groundwater change vs. precipitation.

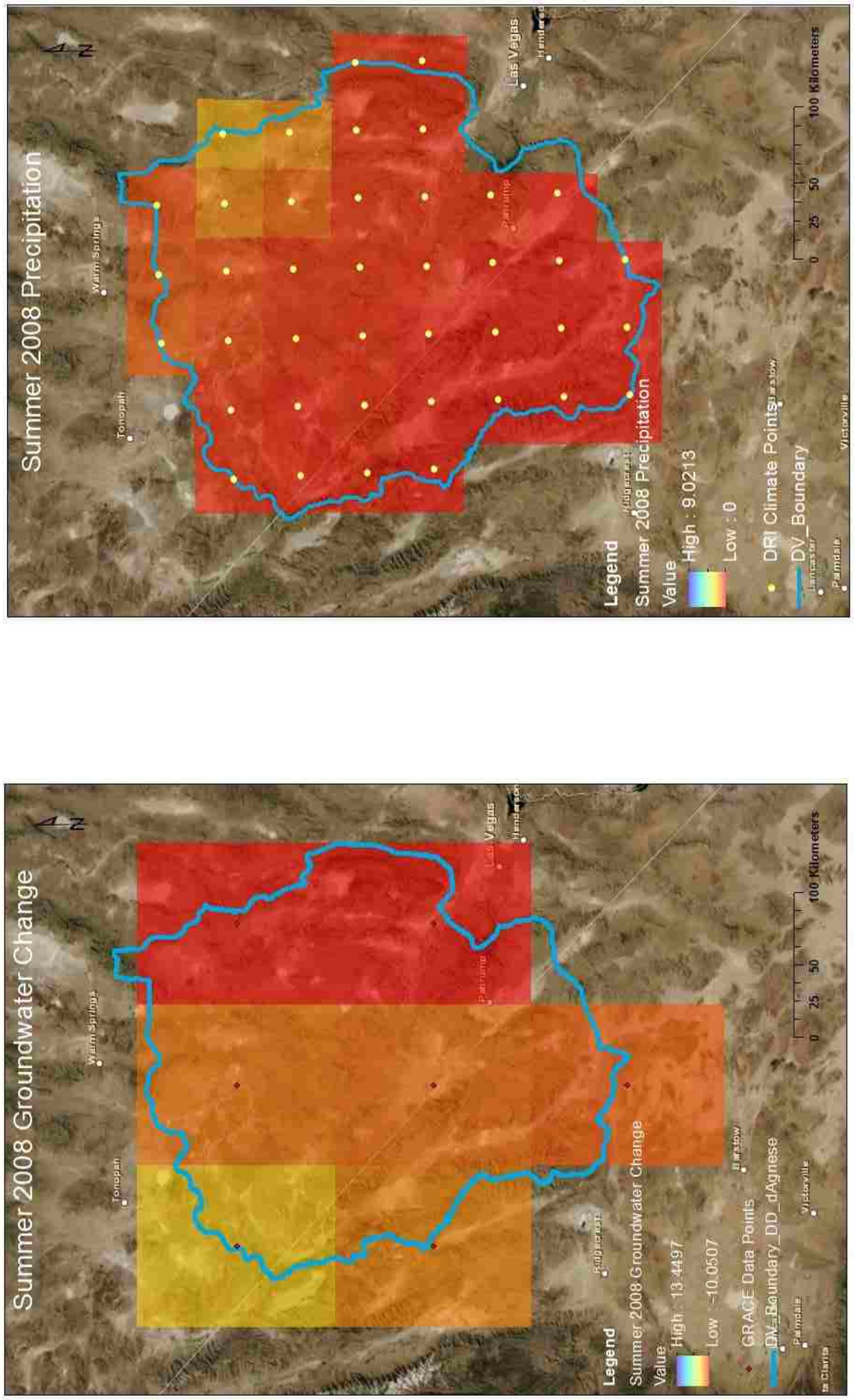
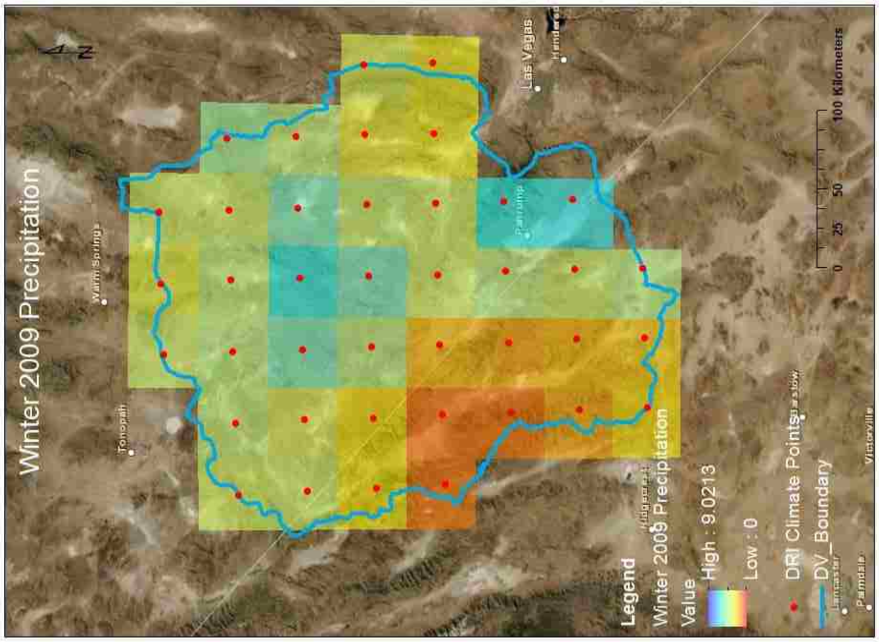


Figure 3-40. Summer 2008 groundwater change vs. precipitation.



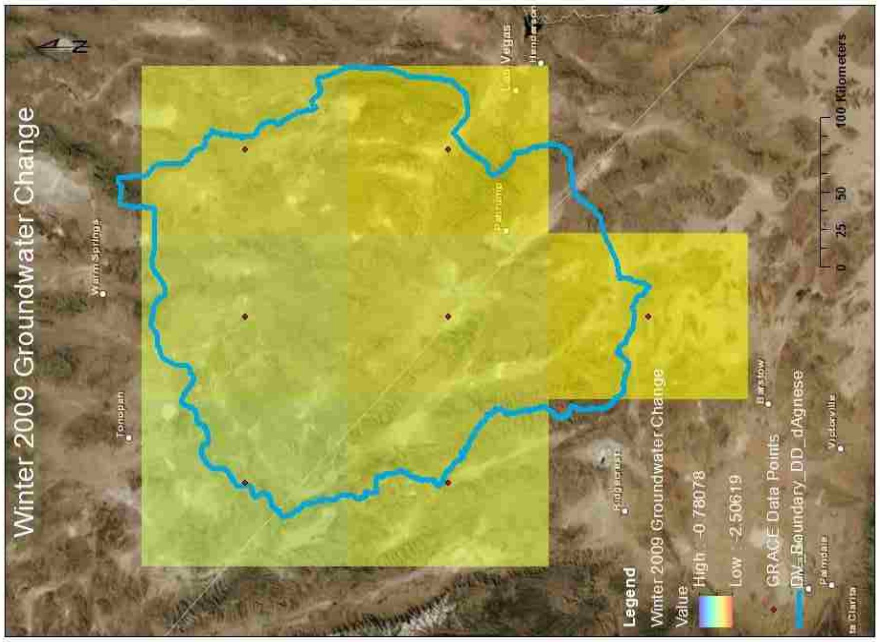


Figure 3-41. Winter 2009 groundwater change vs. precipitation.

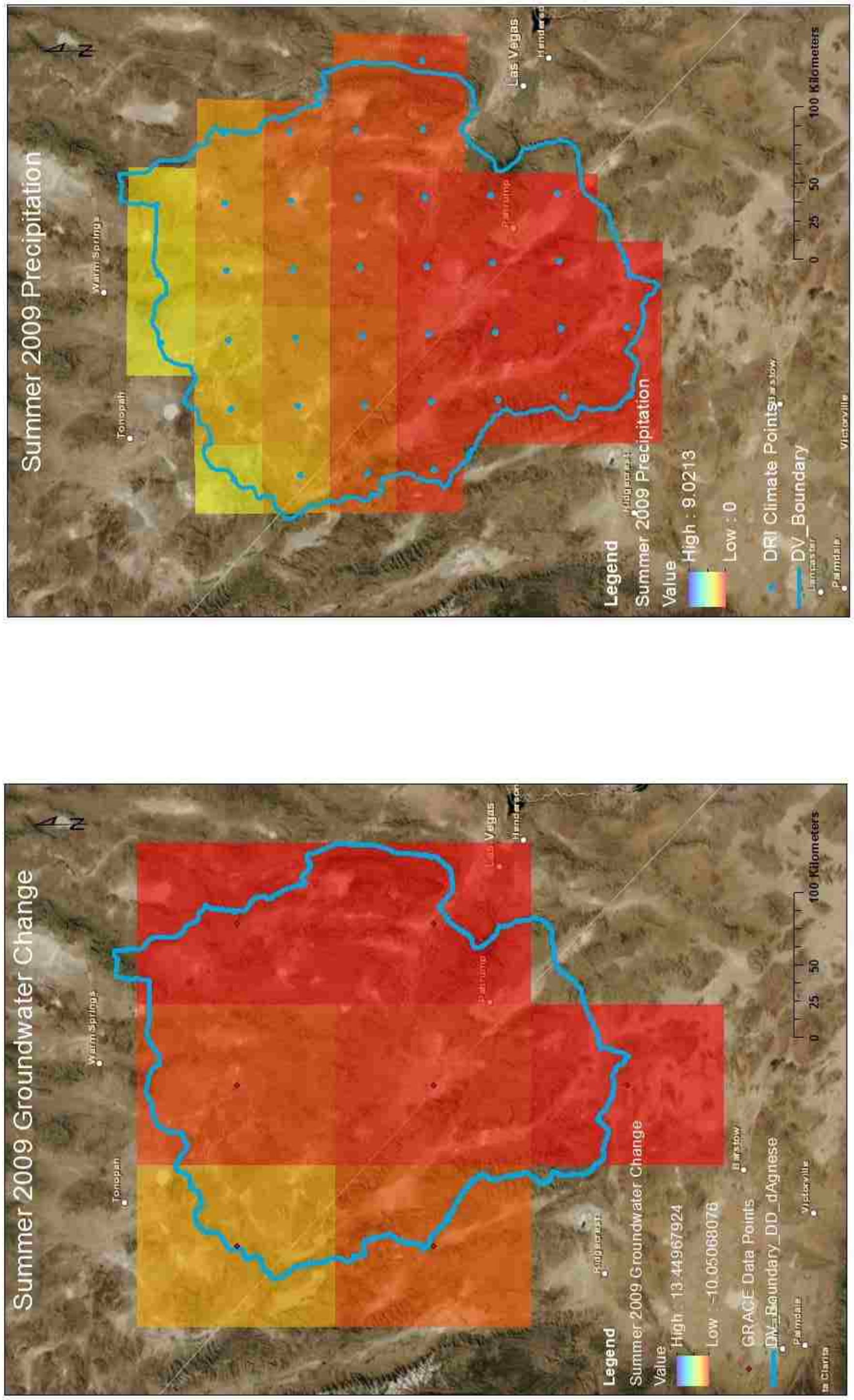


Figure 3-42. Summer 2009 groundwater change vs. precipitation.

The seasonal precipitation results were summed and averaged, and the deviation from the mean was calculated, so it could be graphed against the GRACE groundwater change results for 2003-2009 (shared observational years). The graphed results (Fig. 3-43) confirm that precipitation from both current and the previous seasons contribute to the current groundwater level.

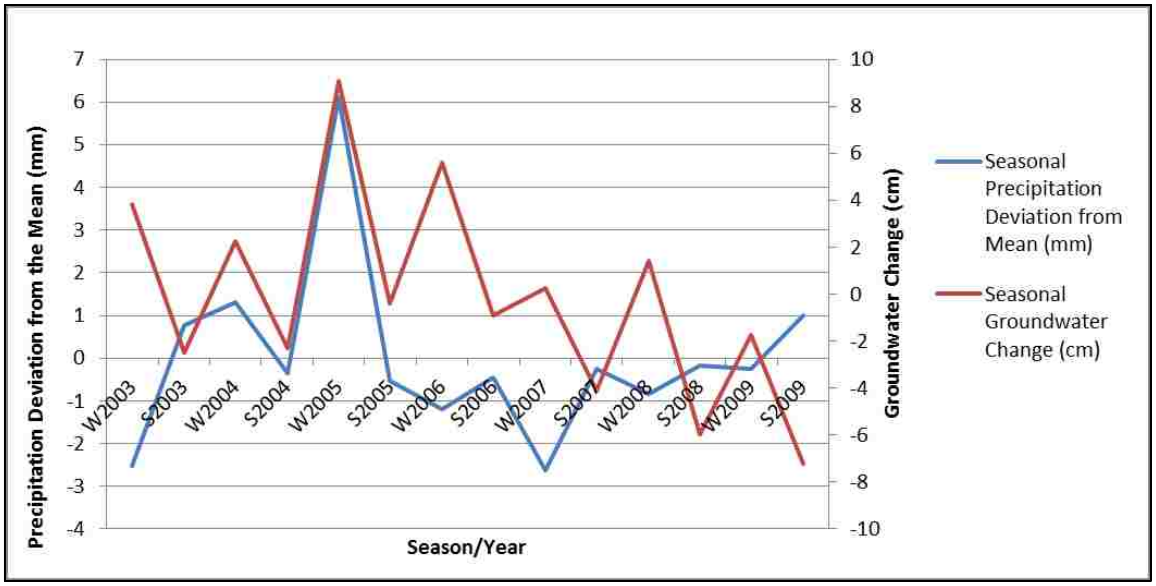


Figure 3-43. Seasonal groundwater change vs. precipitation deviation from the mean (2003-2009).

To show how change in temperature and specific humidity, combined with precipitation, affects groundwater recharge, these three variables were combined together to show their relative and inverse relationship (Figs. 3-44 through 3-46). In addition, the graphs show the complicated relationships between the different climate variables and how they contribute to groundwater change. For the period of 2003 to 2009, the significant correlation coefficients between the variables are as follows:

- GRACE and precipitation: 0.40
- GRACE and average mean temperature: -0.19
- Precipitation and average mean temperature: -0.47
- Specific humidity and temperature: 0.25

Correlation coefficients range from +1 to -1; therefore, the more negative the number, the more adverse the effect is on a variable. From these statistics, we see that temperature has the most negative effect on precipitation in the area. The trend of the average maximum, mean, and minimum temperatures in the area increasing over the 30-year historical period reviewed inversely correlates with the trend of decreasing groundwater levels seen in the GRACE results. When multiple variables are combined, for example, high temperatures, high humidity and no rainfall, the groundwater change is significant in the negative direction.

Chapter 4 Conclusions

Diminishing water storage in Southern Nevada is an ever-increasing concern as drought spreads throughout the country. It can be attributed to many factors, both anthropogenic-related, as well as environmental. Changes in water storage, regardless of the nature, have an impact on the desert's fragile eco-biological system. The purpose of this study was to better understand groundwater change in the Death Valley area, and to use it as an analog for Southern Nevada. By examining new technological data from NASA and DRI, the results can be used to assess what kinds of changes can be seen on groundwater storage in the Death Valley area, and to predict changes in other areas like it in the future.

GRACE gravimetric data were filtered to show results in a time series that shows surface mass variations that could be calculated in the unit of centimeters of water. Historical climate data was downscaled at DRI to improve regional climate models' results, in order to achieve a more accurate picture of climate trends in Nevada. The results from both GRACE and the downscaled DRI data were graphed, analyzed, and combined, to show the relationships between the different variables and the effect the climate variables have on groundwater change.

The results show that between 2003 and 2011, groundwater storage for the Death Valley area is decreasing at a rate of 0.348 cm/yr., the volume of which is approximately 0.26 km^3/yr. over an area of almost 75,000 km^2. While this is only 0.8% of the volume of Lake Mead, Death Valley has a very delicate ecosystem which relies on what little water it gets to survive.

In reviewing the decadal trending precipitation patterns from 1980 to 2009, the lower levels of precipitation in the 2000's fall in line with what was observed in the 1980s, a decade which experienced drought. The overall precipitation trend shows a decrease of 0.19 mm/yr. throughout the entire valley, 0.13 mm/yr. decrease in areas above 1100 m. Due to the minimal precipitation already received in the area, even subtle decreases can adversely affect the ecology of the area.

Overall temperature and specific humidity trends over the 30 year period show a gradual increase. When changes in temperature and humidity are graphed against the changes in groundwater thickness over the area, they show an indirect correlation between the events. When these variables are combined with the peaks and valleys of monthly precipitation, the results are compounded and can be seen in groundwater change 3 months later, on average. The correlation coefficients between the variables quantify the effects that each climate variable has on groundwater change, and can be used to better understand the connections between them.

The results reveal the complicated relationships between groundwater and many climate and geographical variables, including elevation, precipitation, humidity, and temperature. The results show that although there is recharge generated from precipitation at higher elevations, this cannot be the only source of groundwater recharge for the Death Valley area. The study by Abdulaziz et. al.

(2012), attempted to verify the ability of local recharge to support the high flowing springs in Death Valley National Park. In doing so, they looked at two paradigms, one of which supported local recharge to feed the springs (Pistrang and Kunkel, 1964; Nelson et al. 2004; Anderson et al. 2006). The second paradigm alternatively supported the concept of interbasin flow as the main contributor (Winograd and Eakin 1965; Belcher and Sweetkind 2010). Abdulaziz et al (2012) concluded that there was no possible way for the local recharge to have supplied the amount of water observed discharging from the springs. The GRACE and downscaled DRI data provided here support Abdulaziz et al.'s findings, and lean toward the second concept mentioned above, of interbasin flow between the funeral mountains and Death Valley contributing to the groundwater in the Death Valley area.

Overall, the GRACE gravimetric data is of sufficient resolution to be able to measure groundwater storage levels, showing short-term fluctuations and similar patterns to and effects from the cyclical precipitation, temperature, and humidity changes. The data reveals the fact that the groundwater storage levels are decreasing in the Death Valley area, as well as the average monthly decrease rate. This data can not only be used for looking into the rate at which the aquifers in Death Valley are recharged or depleted, but can also confirm that these variables are not the only source for groundwater change in the area. Since the amount of change revealed by the GRACE satellites cannot solely be accounted for by local precipitation accumulation at elevations above 1100 m, then the rest must come from interbasin groundwater flow.

The results of this research will help predict upcoming fluctuations in the aquifer water levels in future studies. The relationships between the variables can help identify any adverse effects that drought may be having on the area, as well as help predict future groundwater changes based on current climate conditions. The analyzed hydrogeological data reveals the impact of varying precipitation, temperature, and specific humidity levels on the Death Valley area, all of which can stand in as an analog for the effects on the water supply for Southern Nevada, and the potential impact it may have on Southern Nevada's population. Since the amount of groundwater change cannot be accounted for solely on precipitation, the results gathered can also help determine the amount of interbasin groundwater exchange that is occurring between the Funeral Mountains, or other areas, into Death Valley. Due to the fact that current climate models lack a groundwater component, the results of this study can be used to adjust existing models and make them more accurate going forward.

This research is an environmental impact assessment of climate variation on Death Valley, using NASA satellite technology, which will aid in future water resource planning and management. This falls in line with NASA's vision of revealing the unknown and using what is learned to benefit humankind. The GRACE mission is under the NASA Earth System Science Pathfinder (ESSP) program. Climate variability and change, which includes drought, are one of the six focus areas under the program's Science Mission Directorate (SMD) for 2011. A decreasing water supply affects the health of all living things. It is therefore, extremely important that we continue to collect and analyze water resource data, as well as monitor current conditions, to better understand the impact that drought and other climate variations are having on local areas such as Death Valley and southern Nevada. It is with these crucial pieces of scientific evidence that we are able to identify and understand the impact of global changes on these areas, so that strategic planning can take place and preventative measures may be carried out. If we are able to turn data into a viable action plan, we can certainly avoid predicaments that stem from water shortage, and resolve issues before they become serious problems.

Recommendations for Future Work

Recommendations for future work include expanding the areas/points of coverage of the Gravity Recovery and Climate Experiment (GRACE) studies to understand the subsurface change in aquifers adjacent to the area. As we have determined that Death Valley area is reliant on groundwater flow from other basins, the changes in those areas need to be taken into consideration as well, and only then can we possibly understand the full scope of hydrogeological events taking place. Research to correlate the increased Las Vegas Valley groundwater usage with changes in surrounding water basins, other than Death Valley, is also suggested, to understand the impact to surrounding areas.

Additional research to understand how GRACE groundwater change results relate to snowpack, soil moisture, and topography is recommended, as well as figuring out a way to downscale the GRACE results to a smaller scale, so that they can be applied to a wider variety of research.

Lastly, it is recommended that GRACE be used to measure areas where no direct groundwater monitoring is available. The GRACE measurements can then be used to enhance existing global climate models that currently have no groundwater component. In areas where well measurements are available, future studies can augment existing direct groundwater level measurements with GRACE data.

Appendix

The following graphs and maps provide additional detail and larger views of the data analyzed in this study. Some graphs are broken down to provide a more detailed understanding of results by each section of the Death Valley area, and to provide additional insight into how each part of the valley may be affected differently by climate variables and groundwater change.

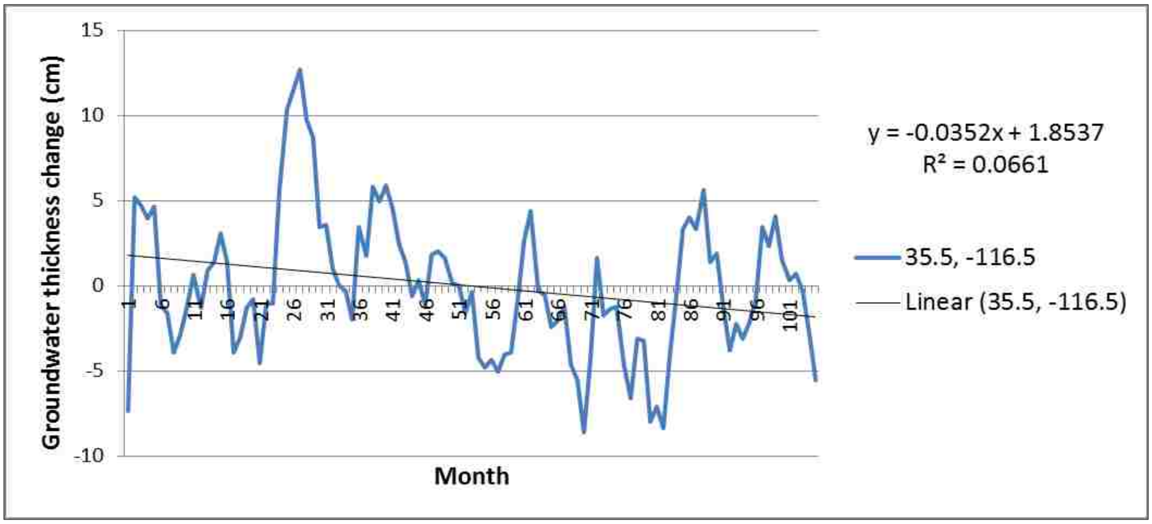


Figure A-1. 35.5, -116.5 bin. 0.42cm/yr. loss.

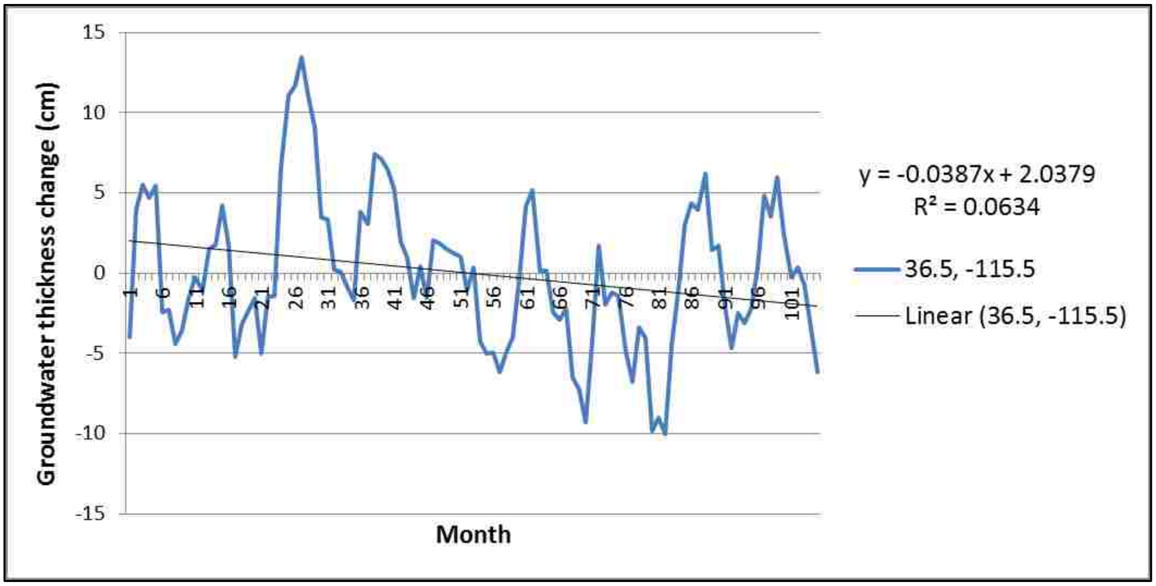


Figure A-2. 36.5, -116.5 bin: 0.46 cm/yr. loss.

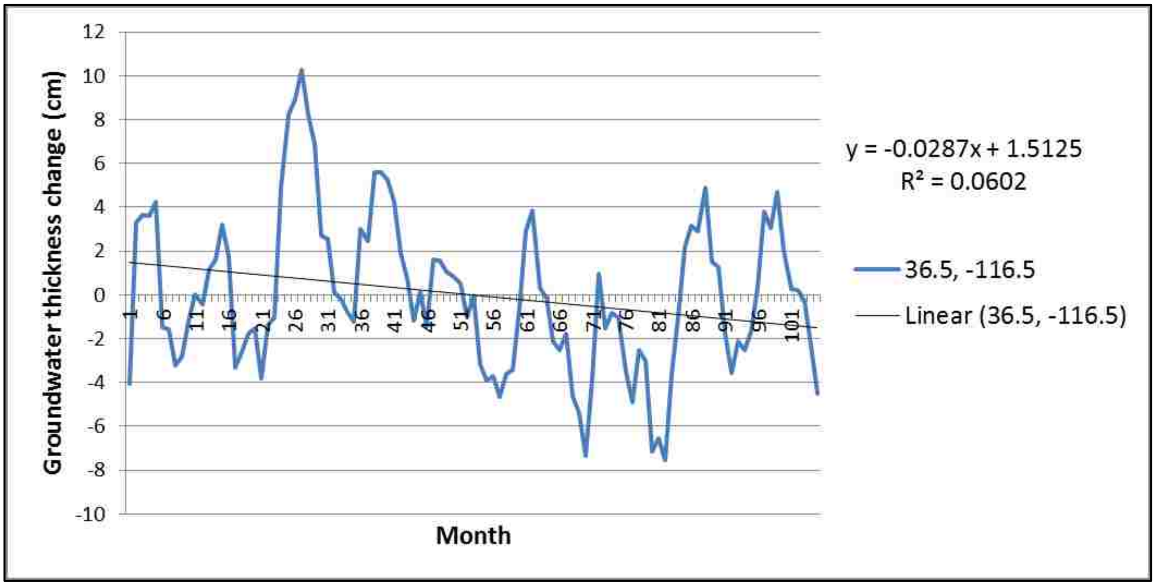


Figure A-3. 36.5, -116.5 bin: 0.34 cm/yr. loss.

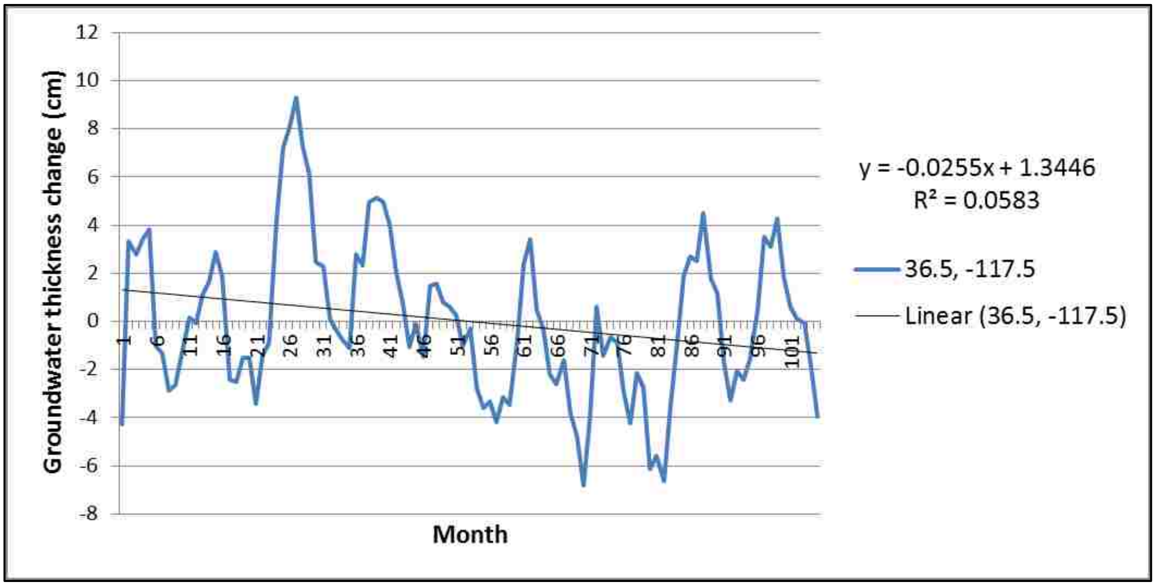


Figure A-4. 36.5, -117.5 bin: 0.31 cm/yr. loss.

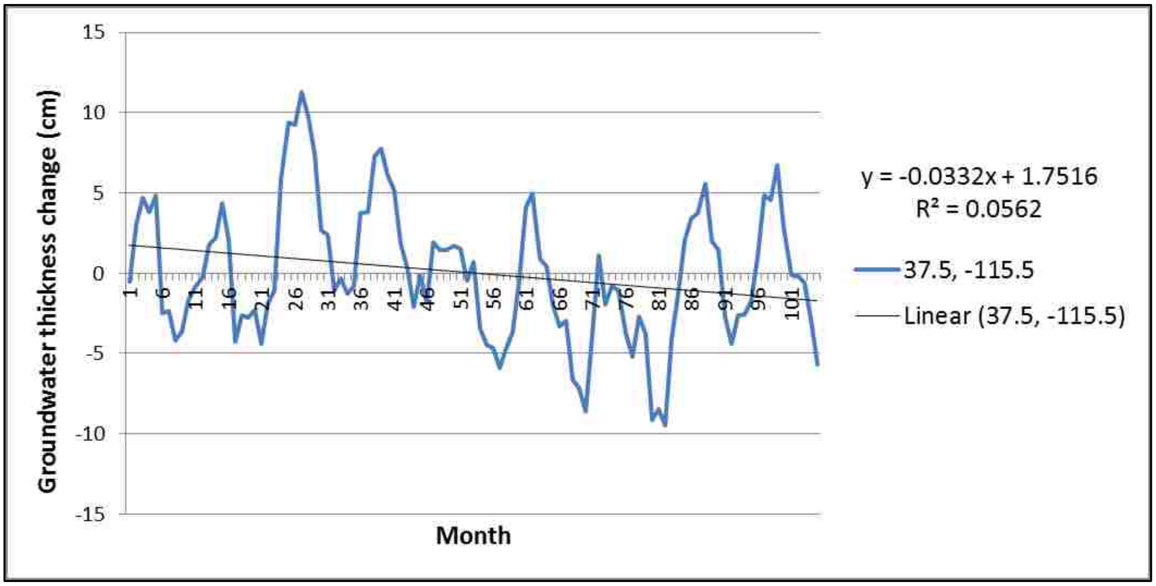


Figure A-5. 37.5, -115.5 bin: 0.40 cm/yr. loss.

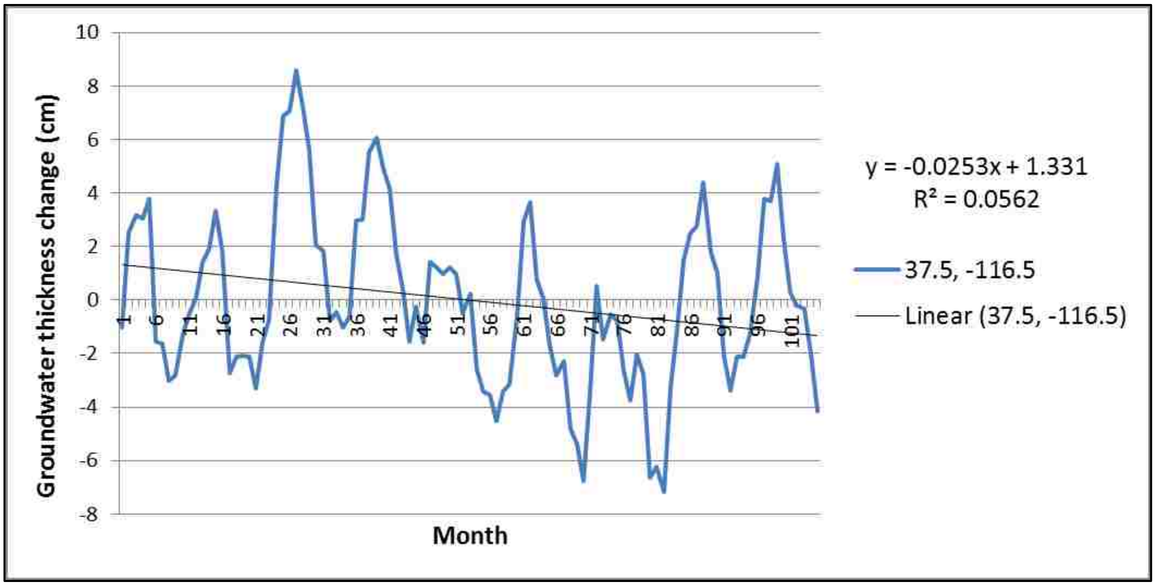


Figure A-6. 37.5, -116.5 bin: 0.30 cm/yr. loss.

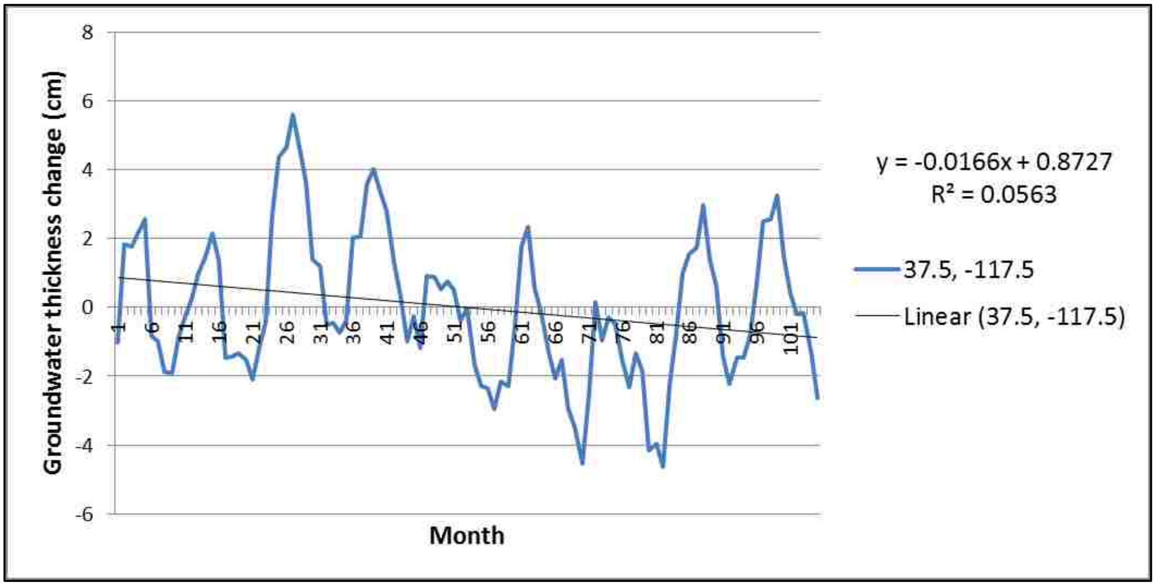


Figure A-7. 37.5, -117.5 bin: 0.20 cm/yr. loss.

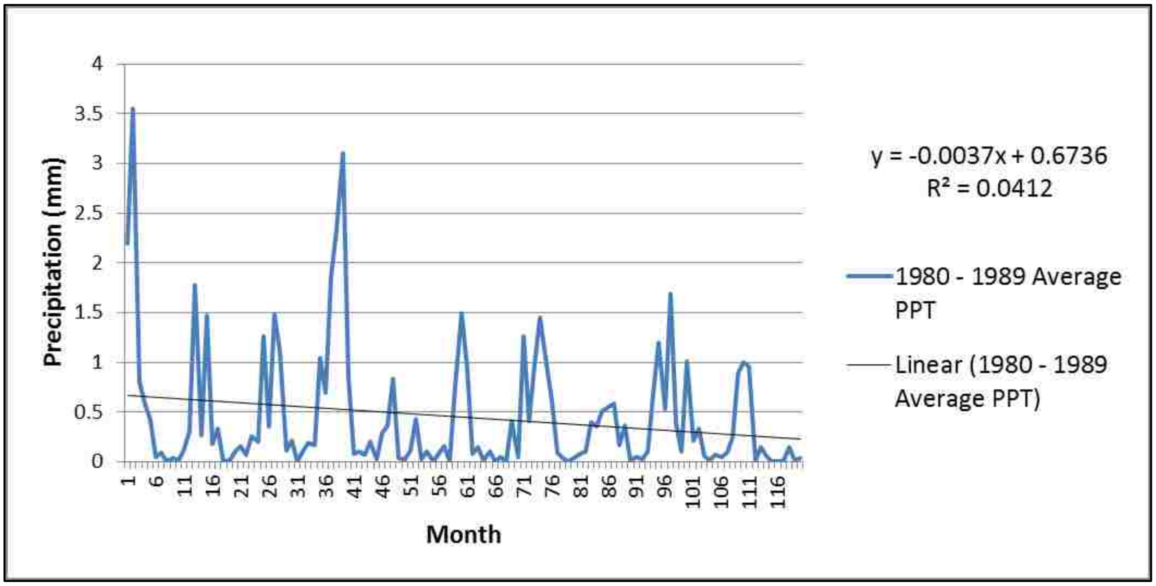


Figure A-8. Death Valley Average Monthly Precipitation 1980-1989.

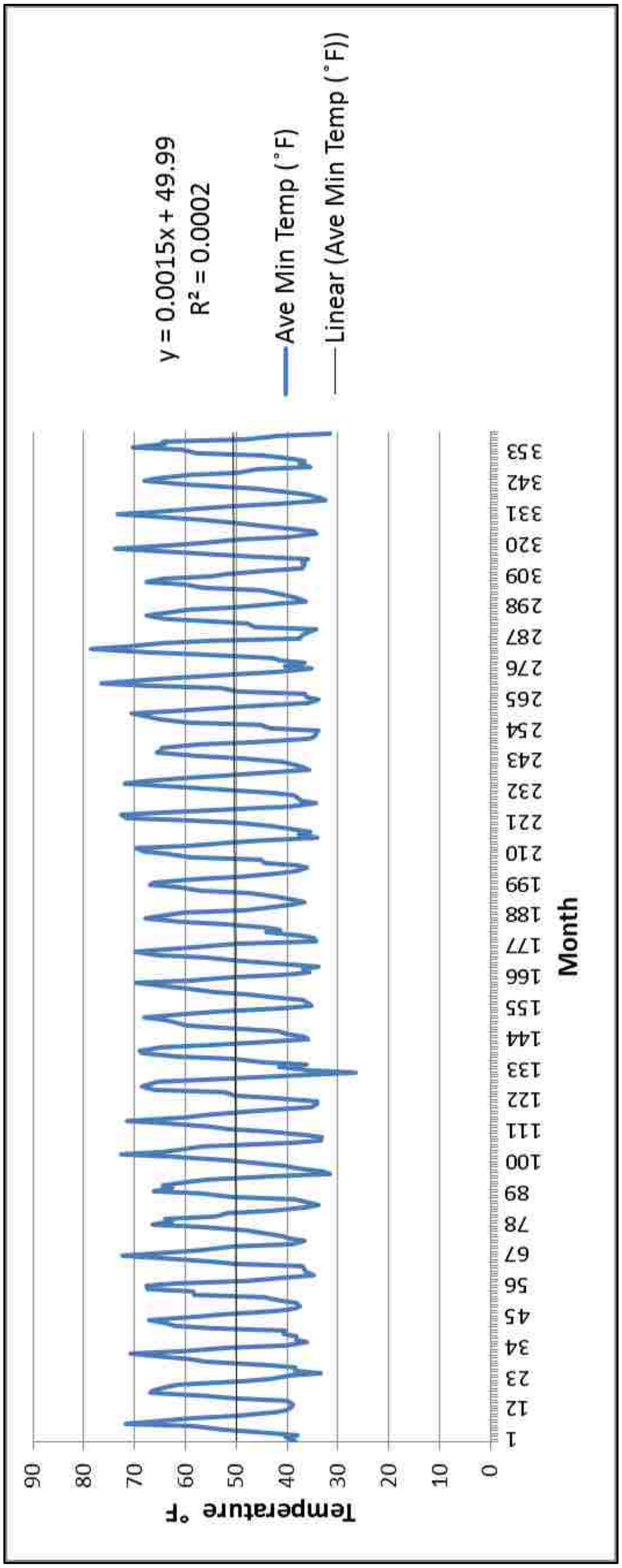


Figure A-9. Death Valley average minimum temperature 1980-2009.

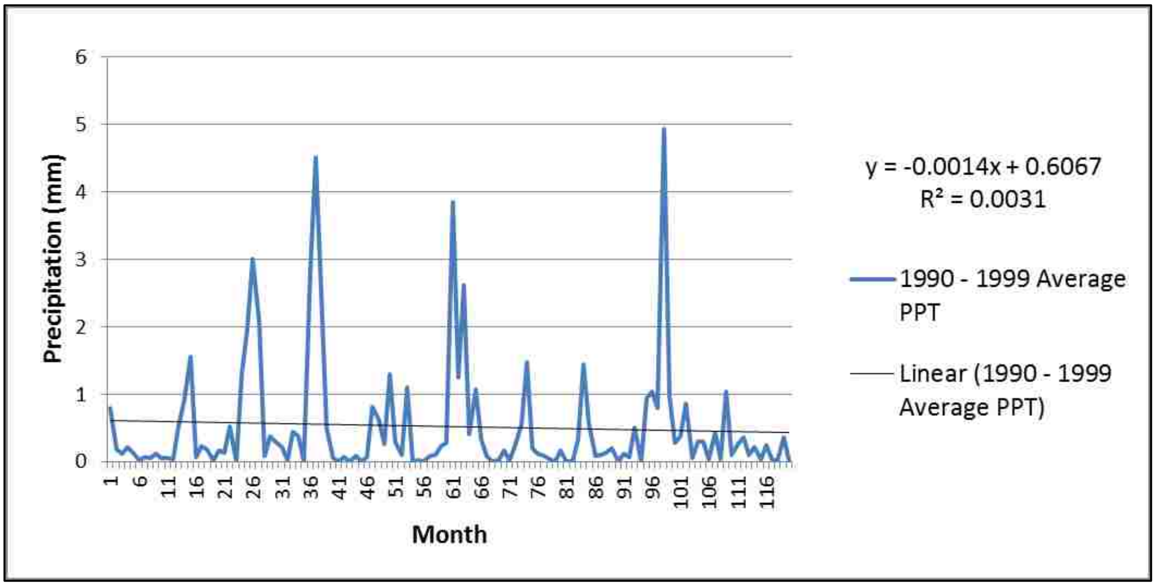


Figure A-10. Death Valley average monthly precipitation 1990-1999.

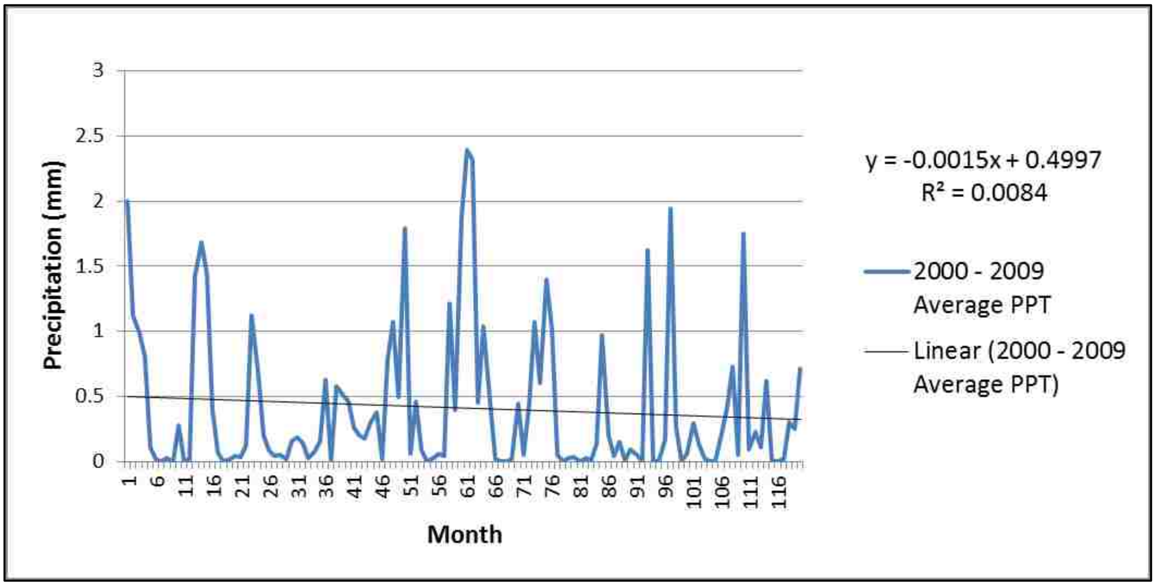


Figure A-11. Death Valley average monthly precipitation 2000-2009.

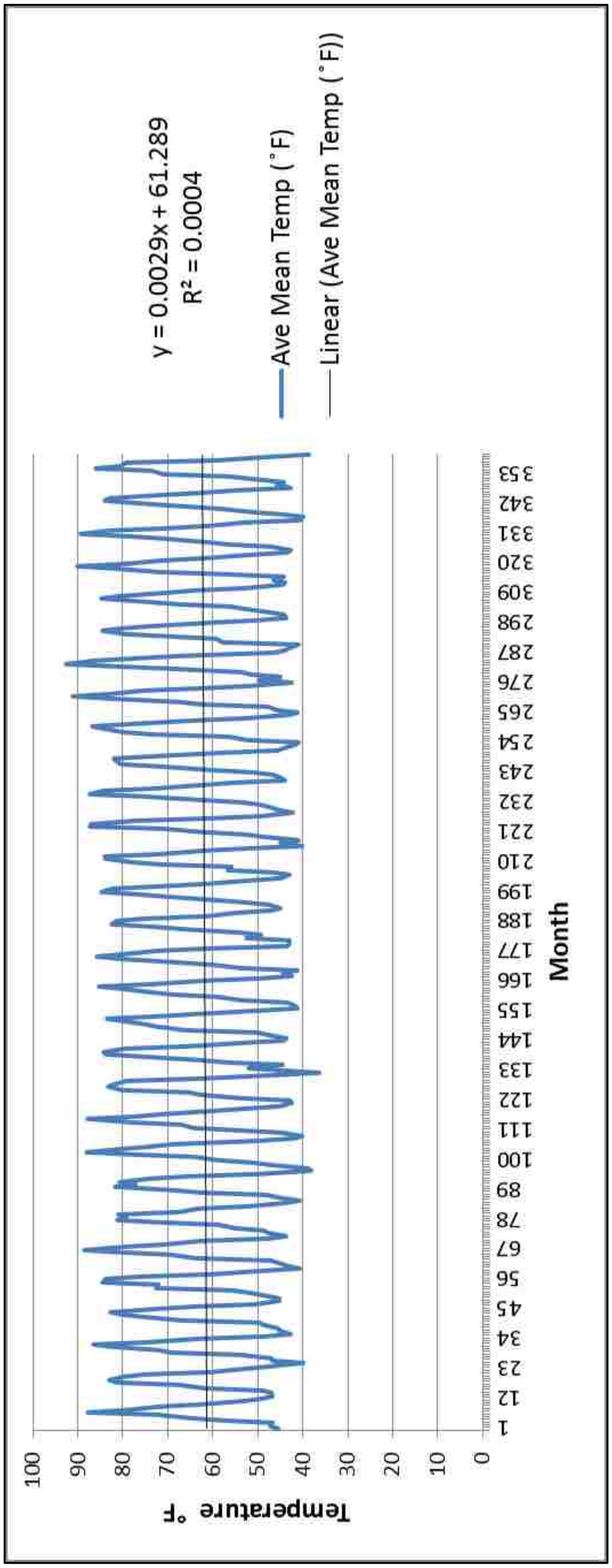


Figure A-12. Death Valley average mean temperature 1980-2009.

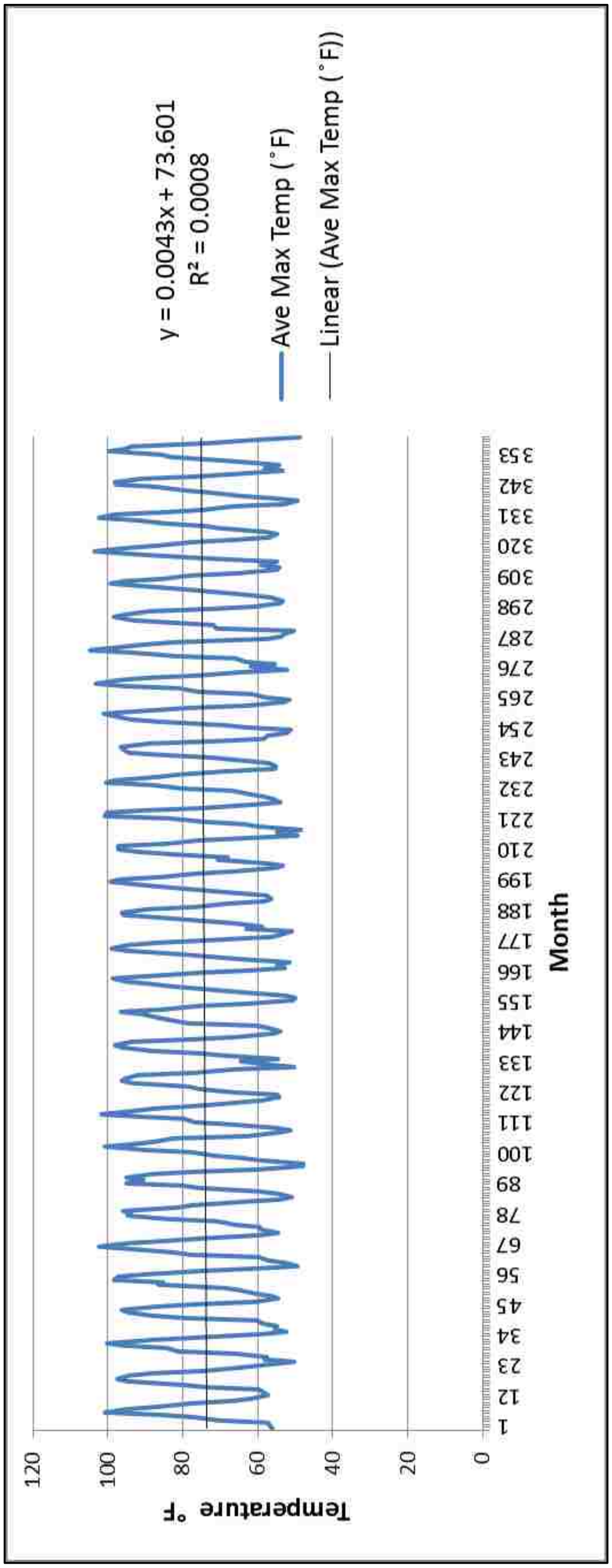


Figure A-13. Death Valley average maximum temperature 1980-2009.

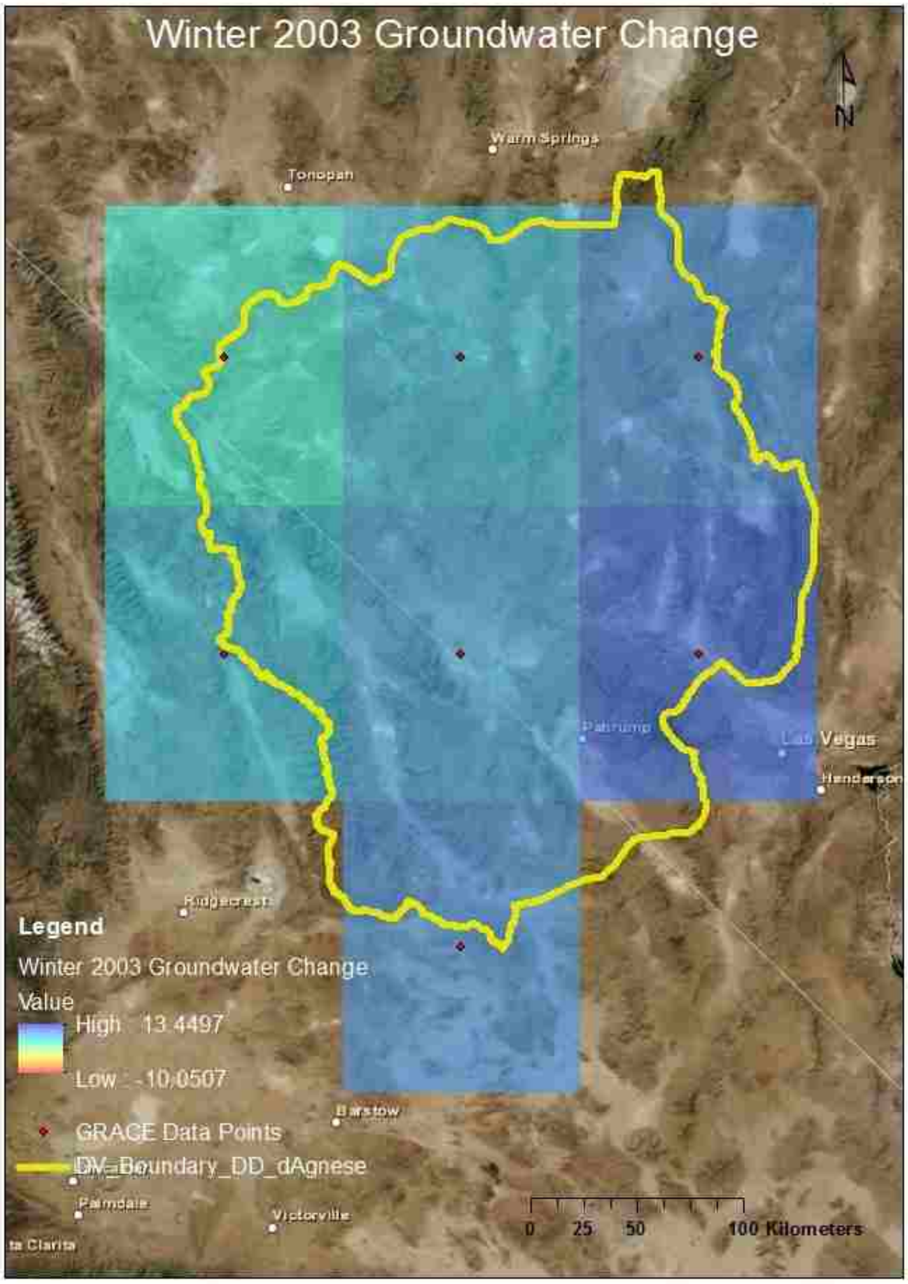


Figure A-14. Winter 2003 groundwater change.

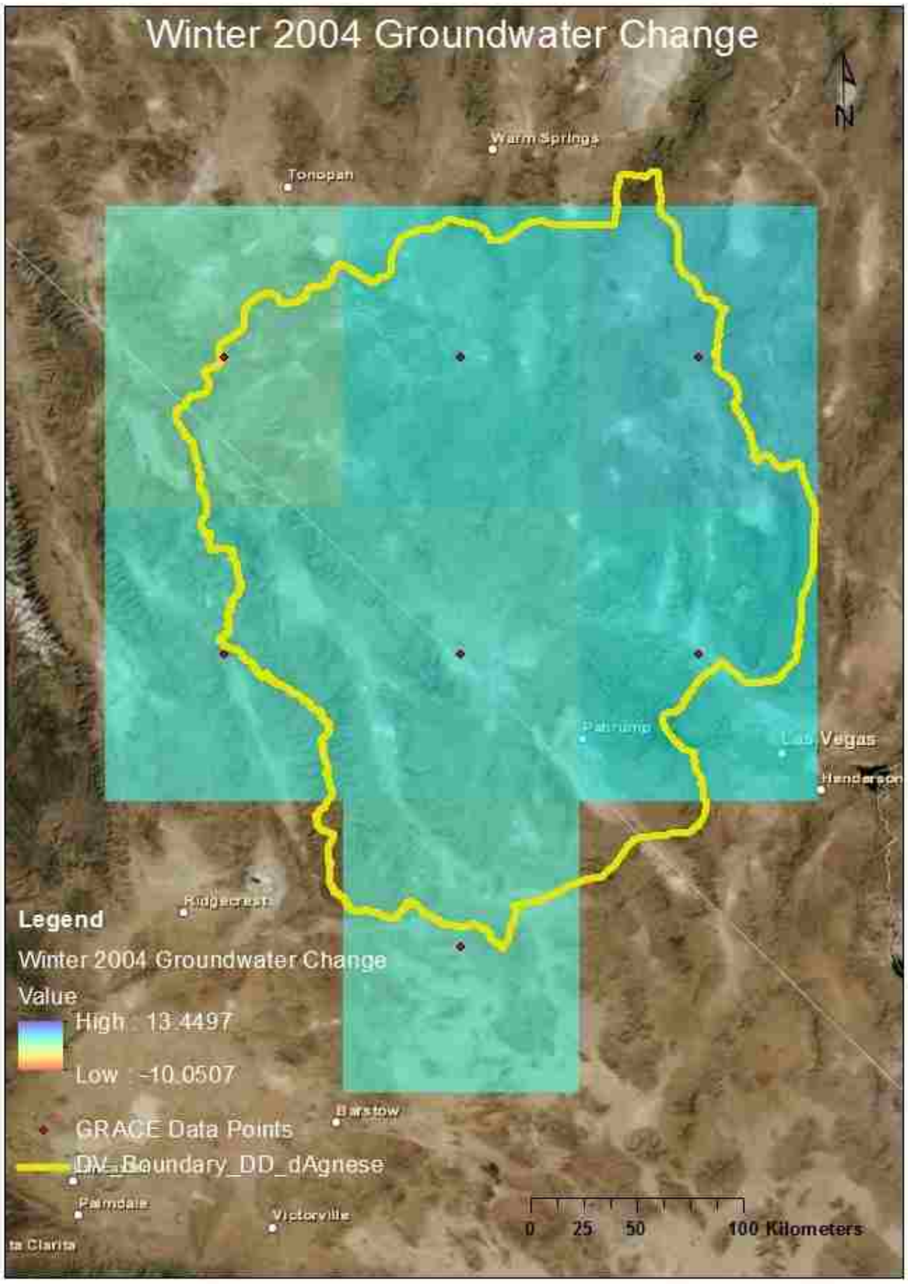


Figure A-15. Winter 2004 groundwater change.

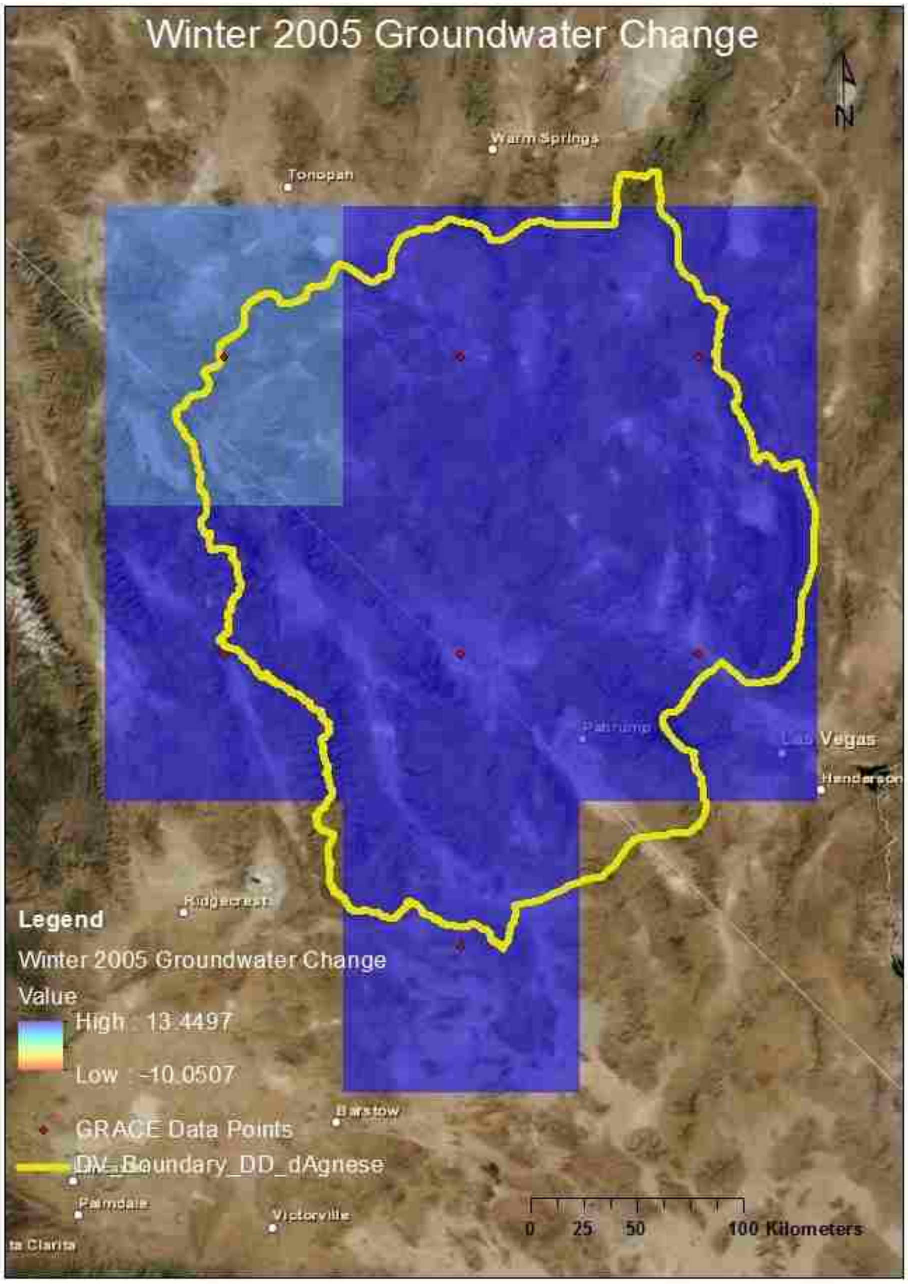


Figure A-16. Winter 2005 groundwater change.

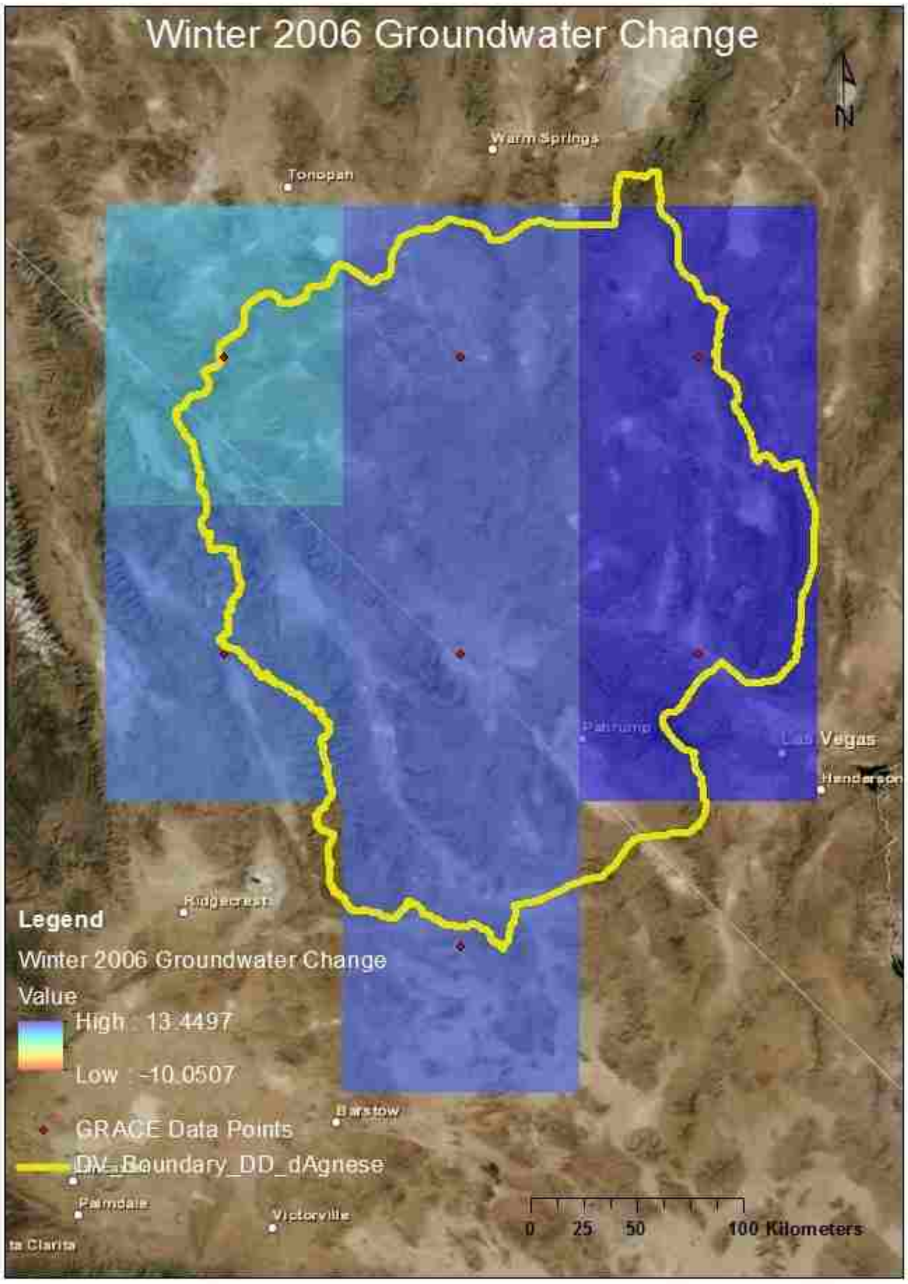


Figure A-17. Winter 2006 groundwater change.

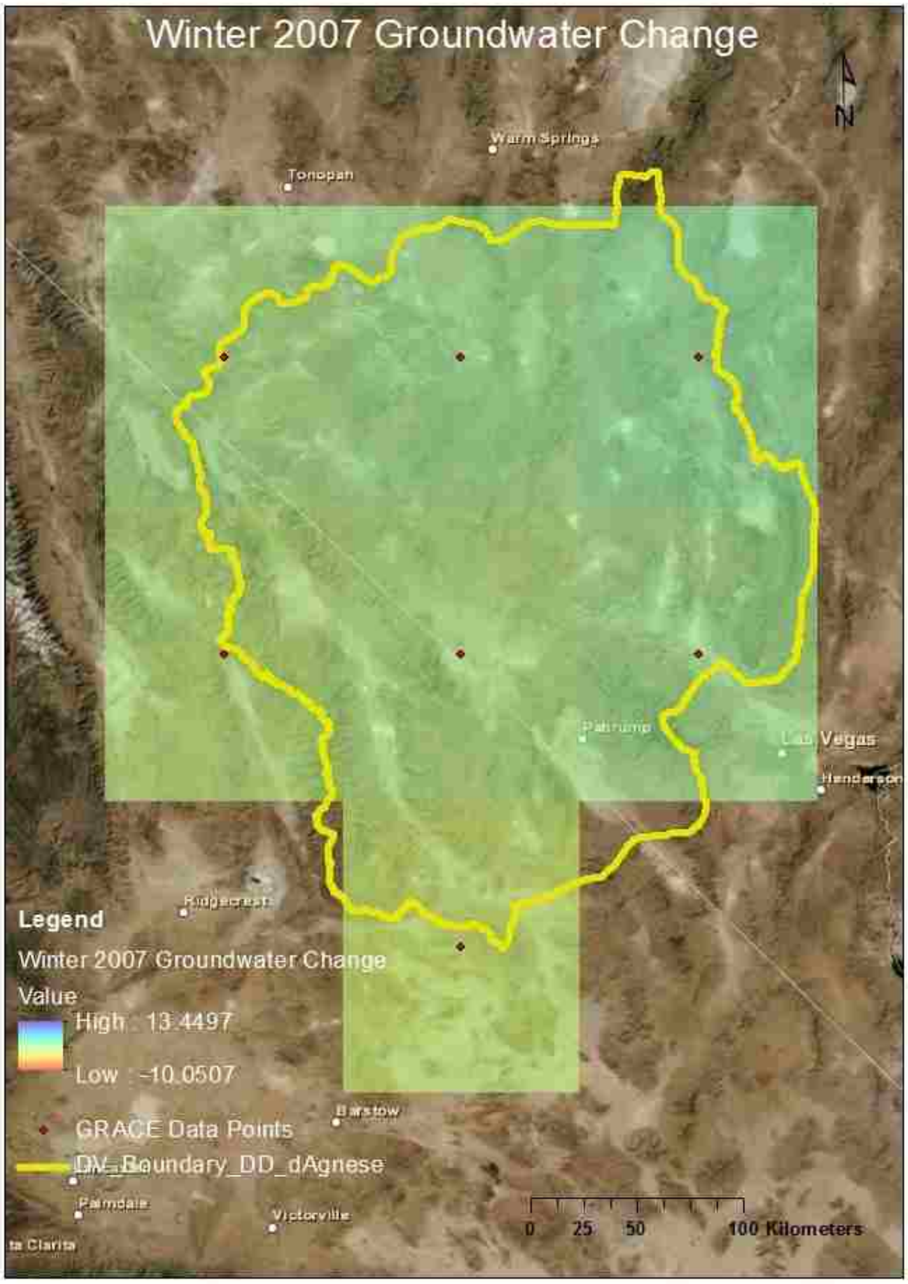


Figure A-18. Winter 2007 groundwater change.

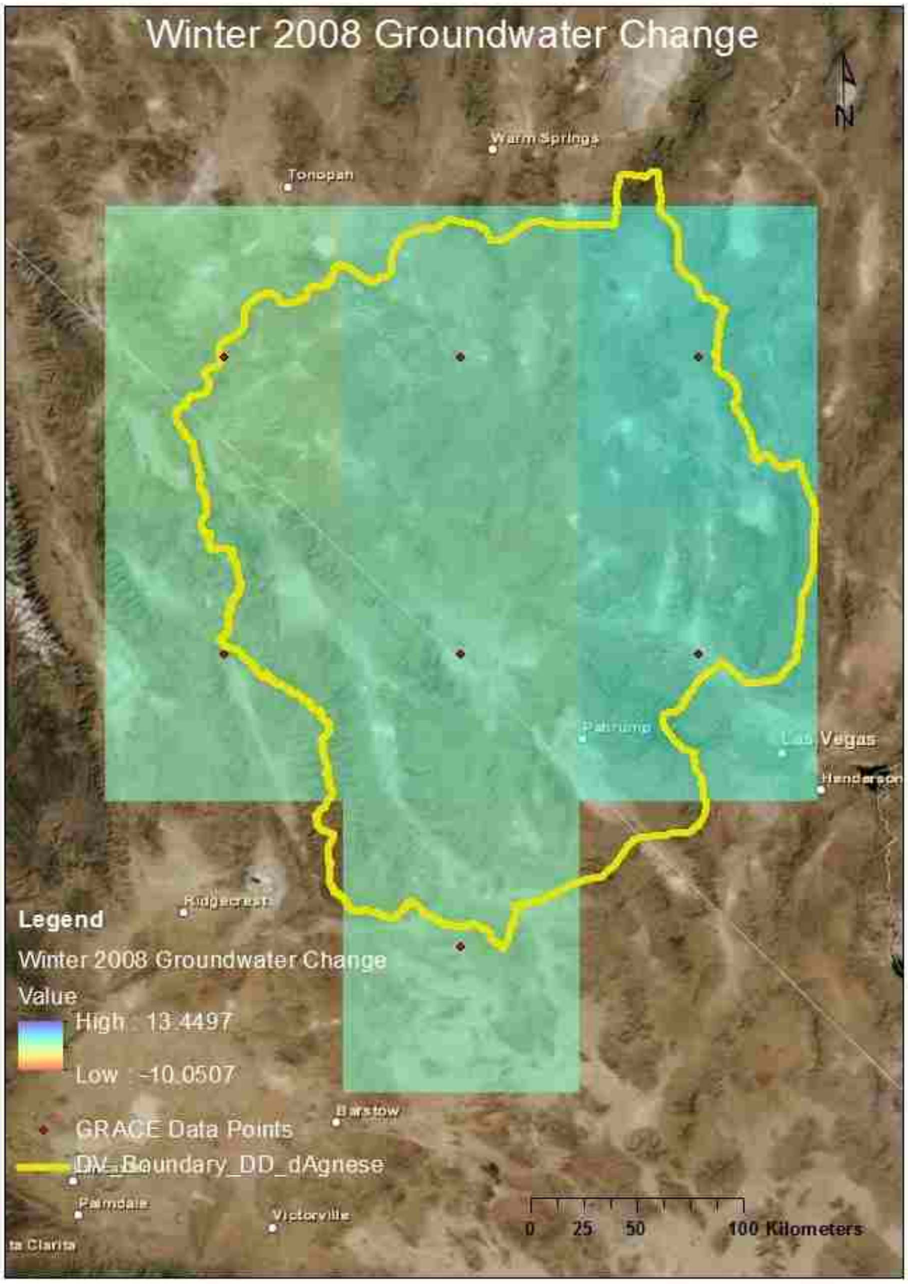


Figure A-19. Winter 2008 groundwater change.

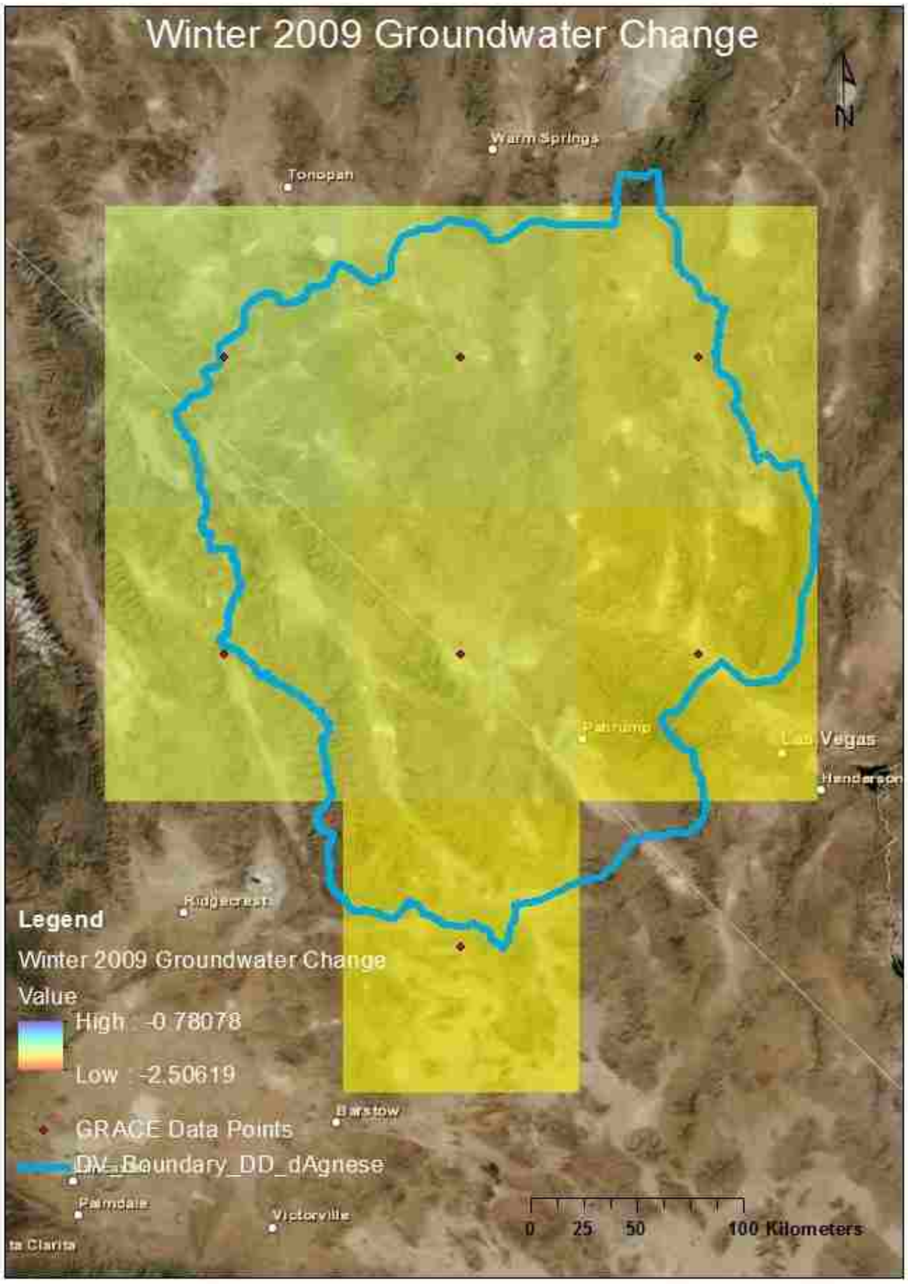


Figure A-20. Winter 2009 groundwater change.

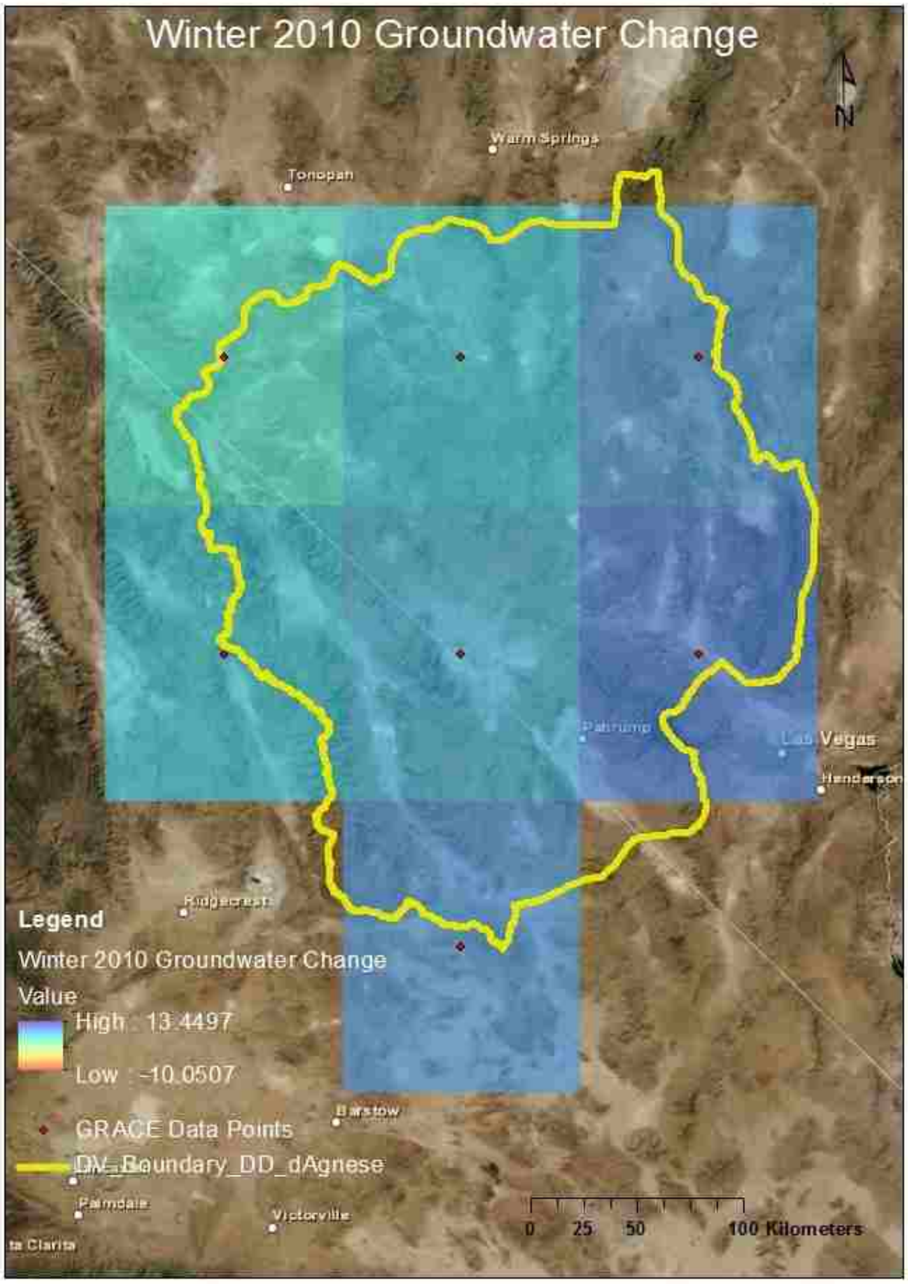


Figure A-21. Winter 2010 groundwater change.

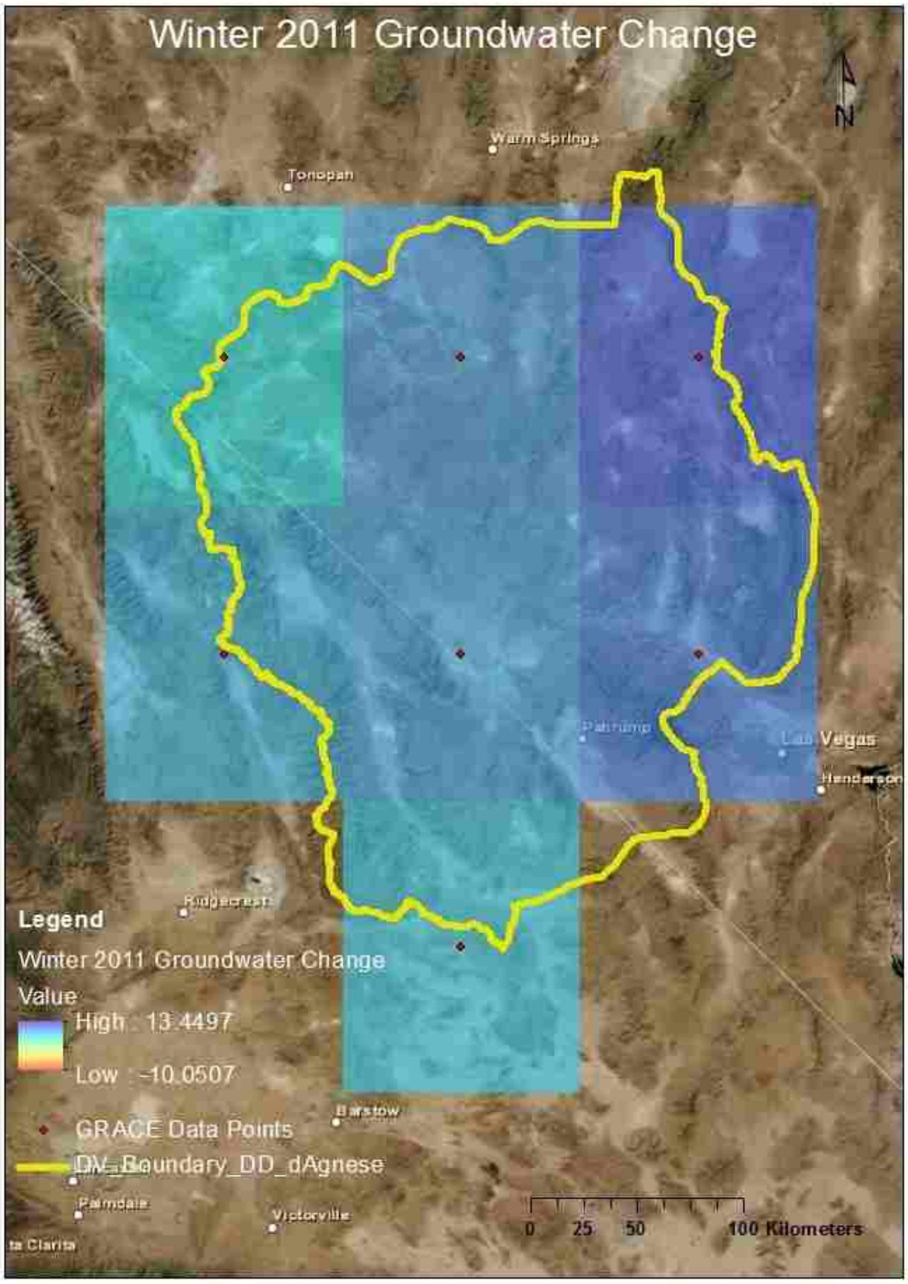


Figure A-22. Winter 2011 groundwater change.

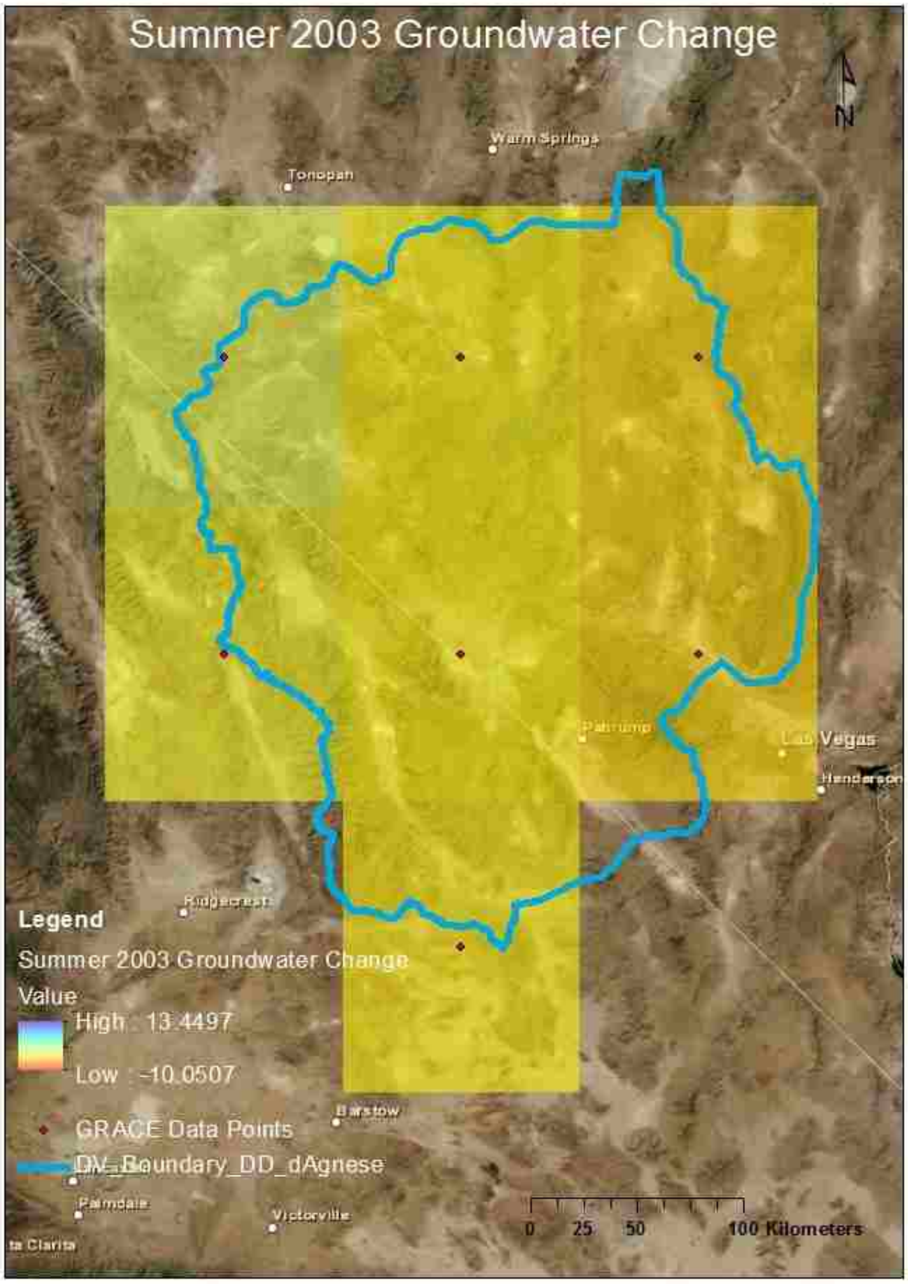


Figure A-23. Summer 2003 groundwater change.

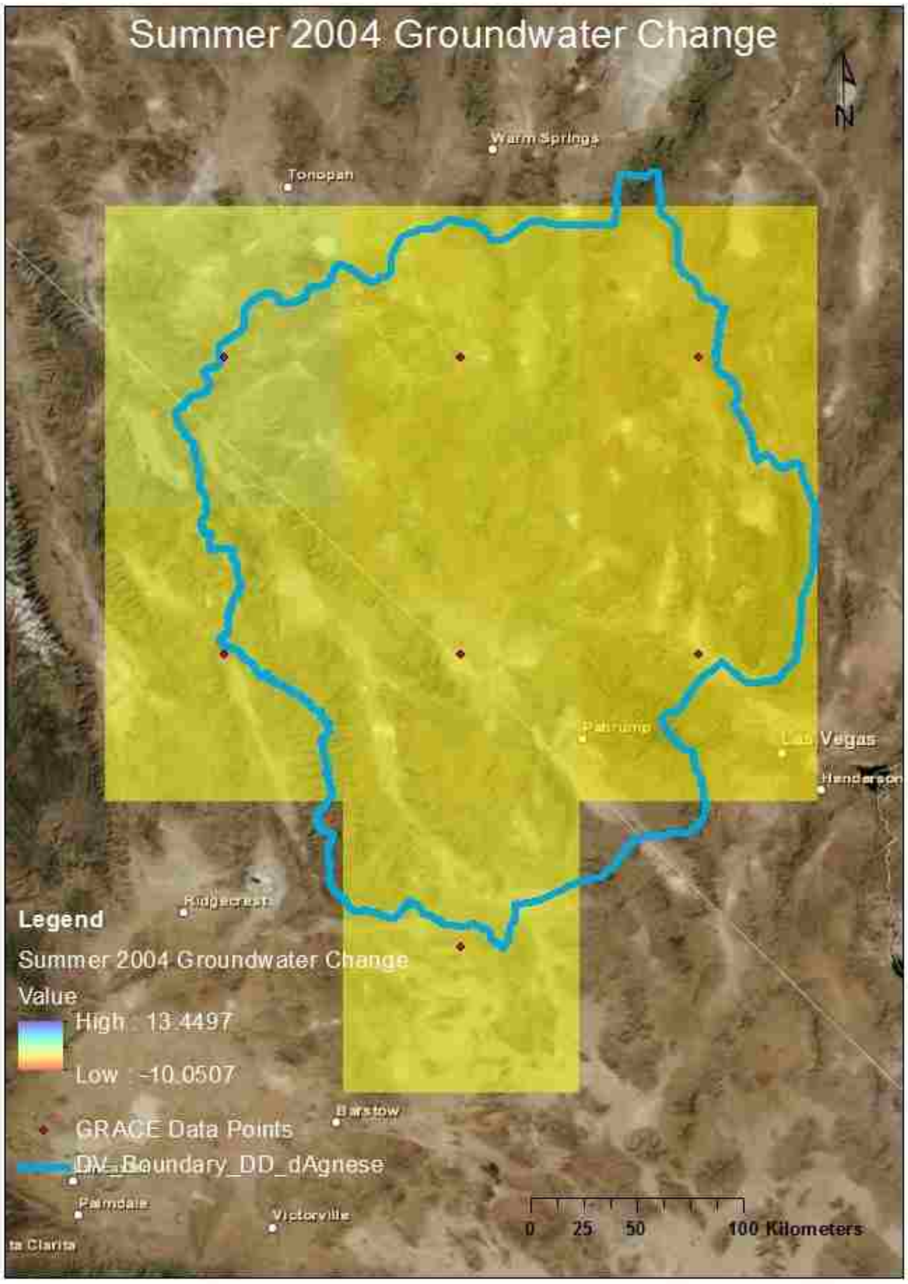


Figure A-24. Summer 2004 groundwater change.

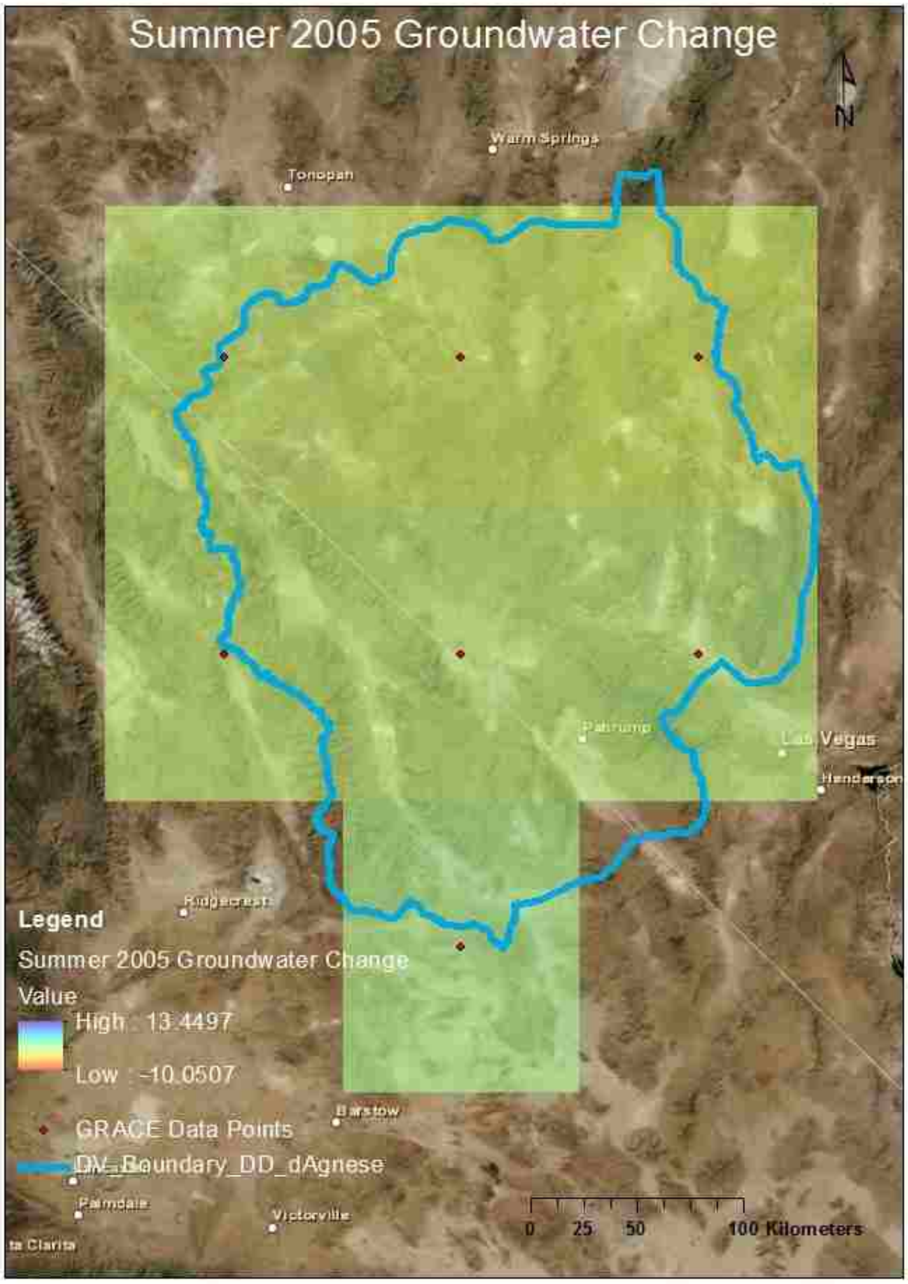
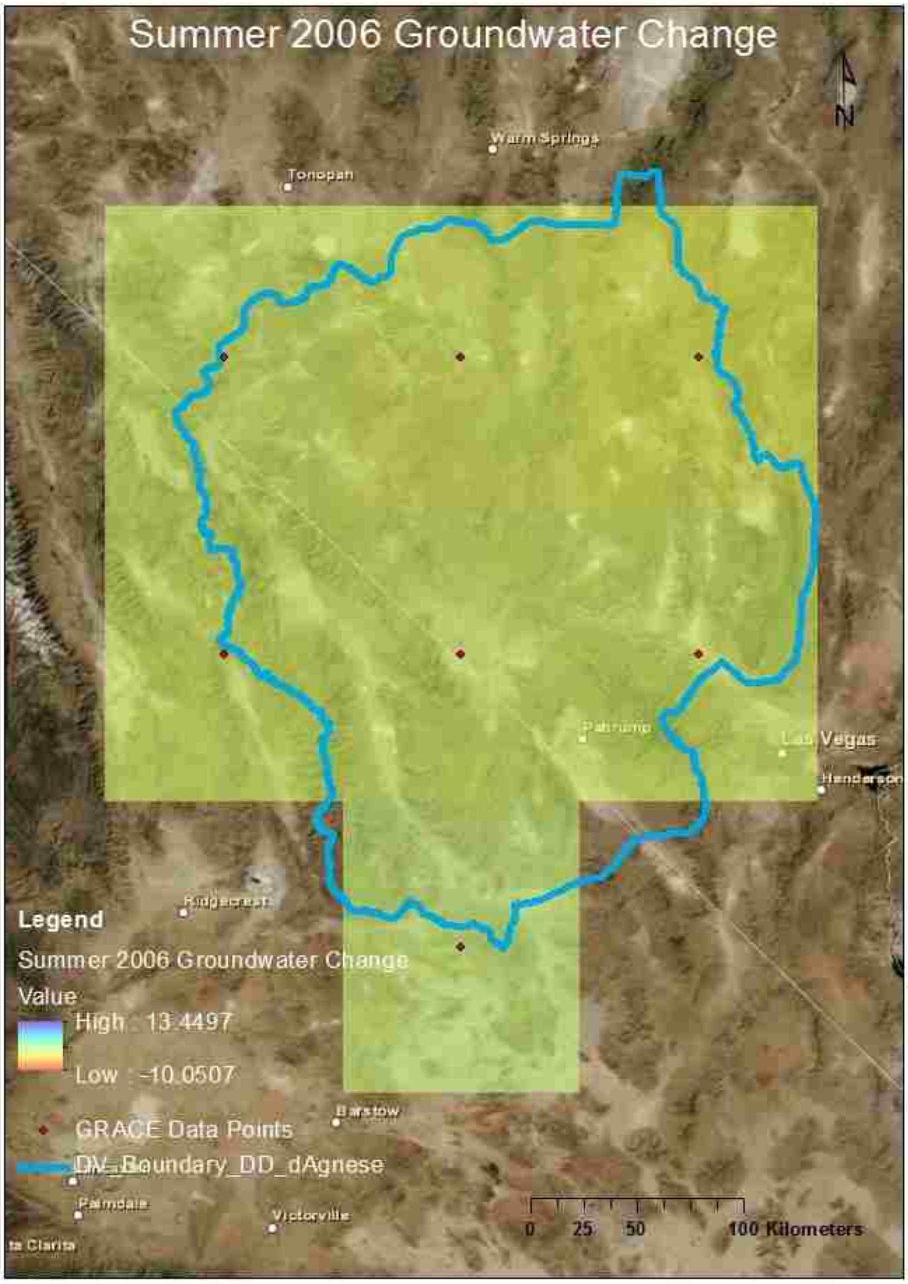


Figure A-25. Summer 2005 groundwater change.



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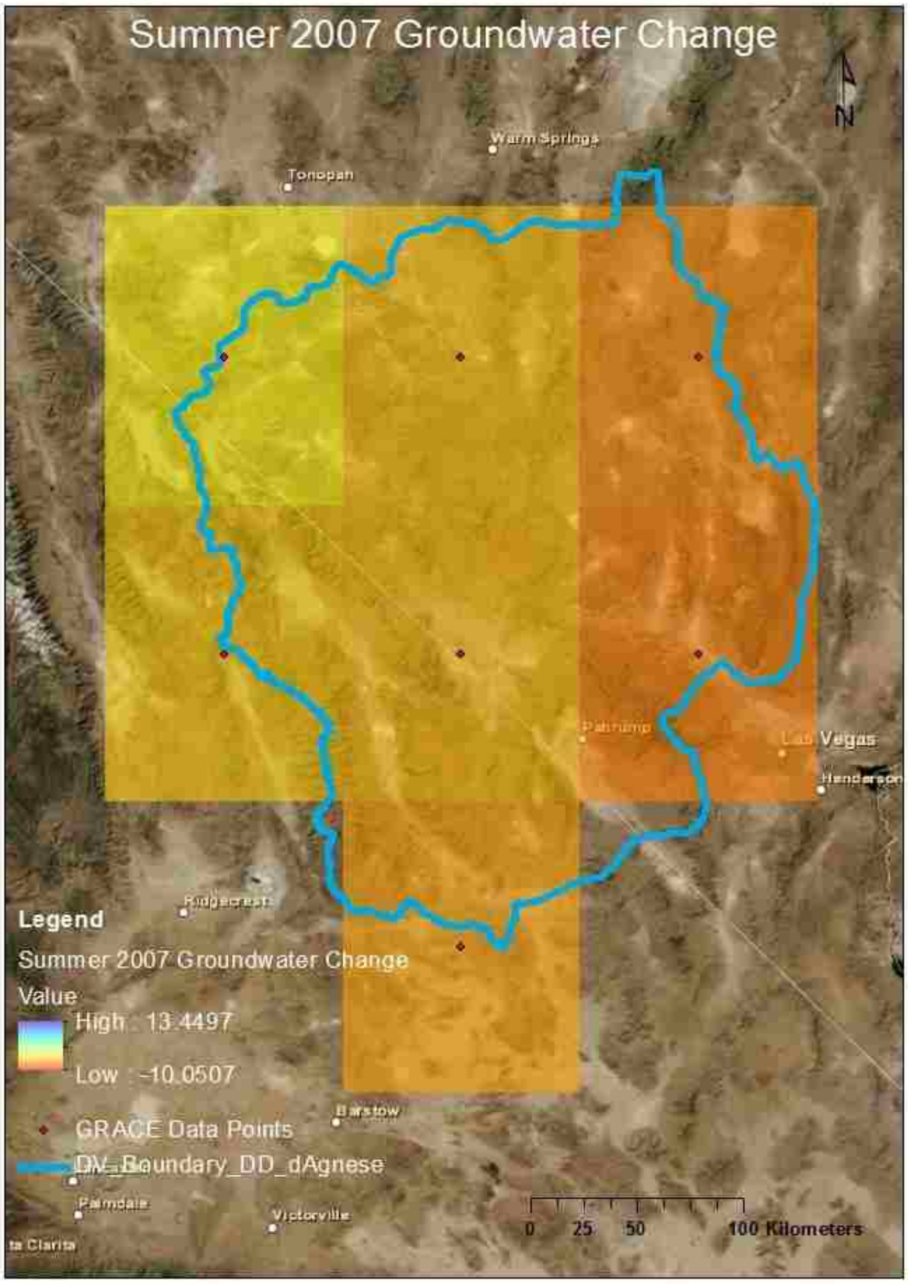


Figure A-27. Summer 2007 groundwater change.

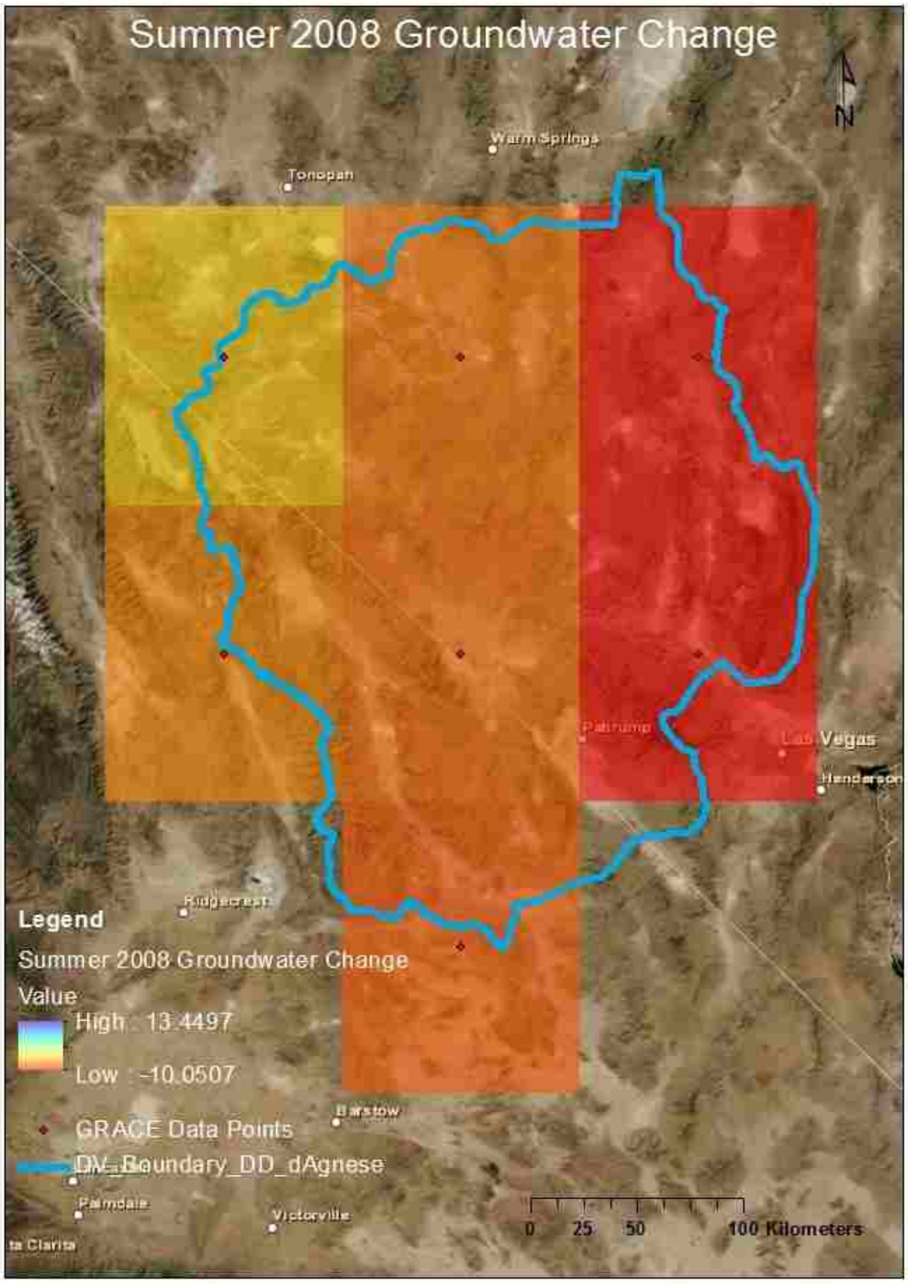


Figure A-28. Summer 2008 groundwater change.

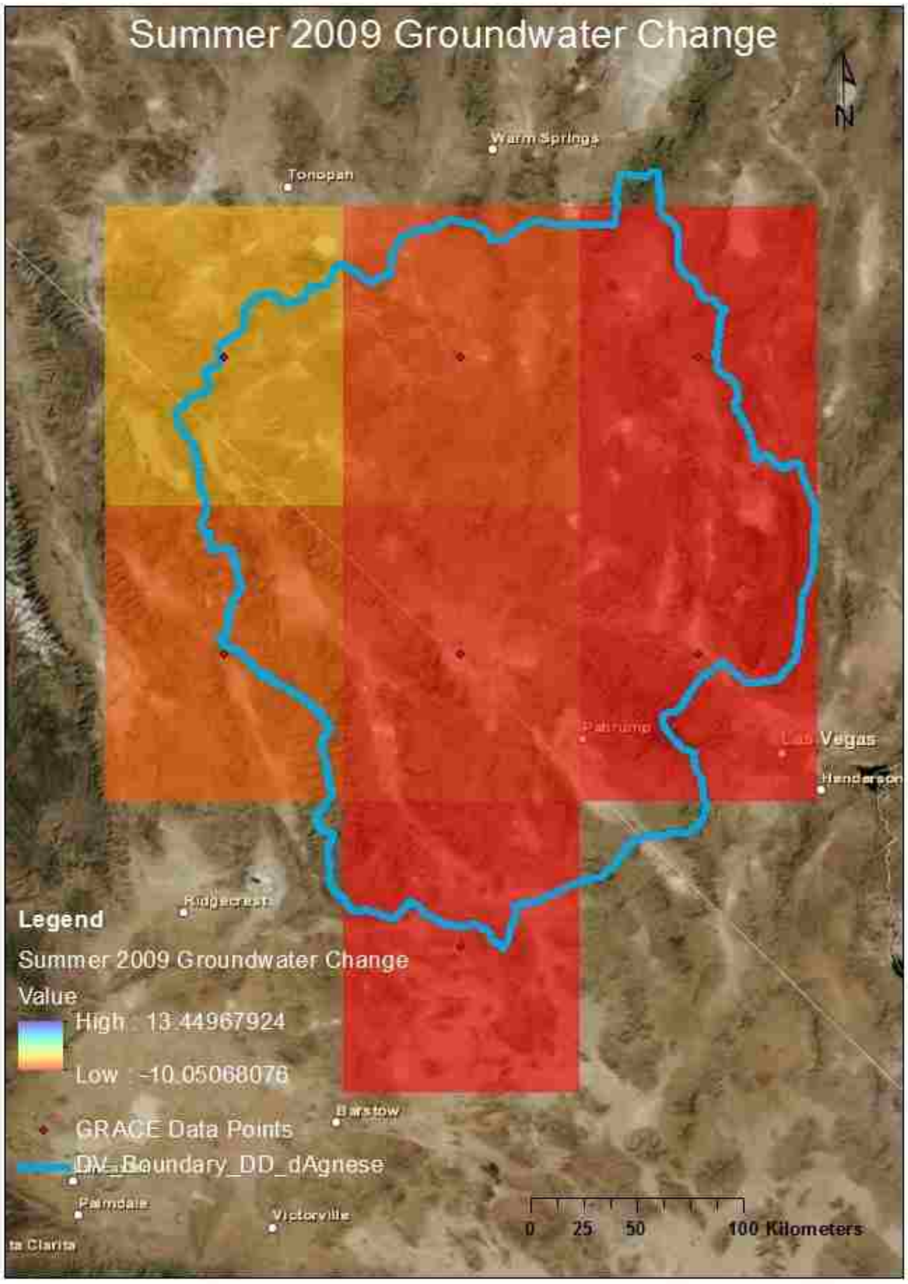
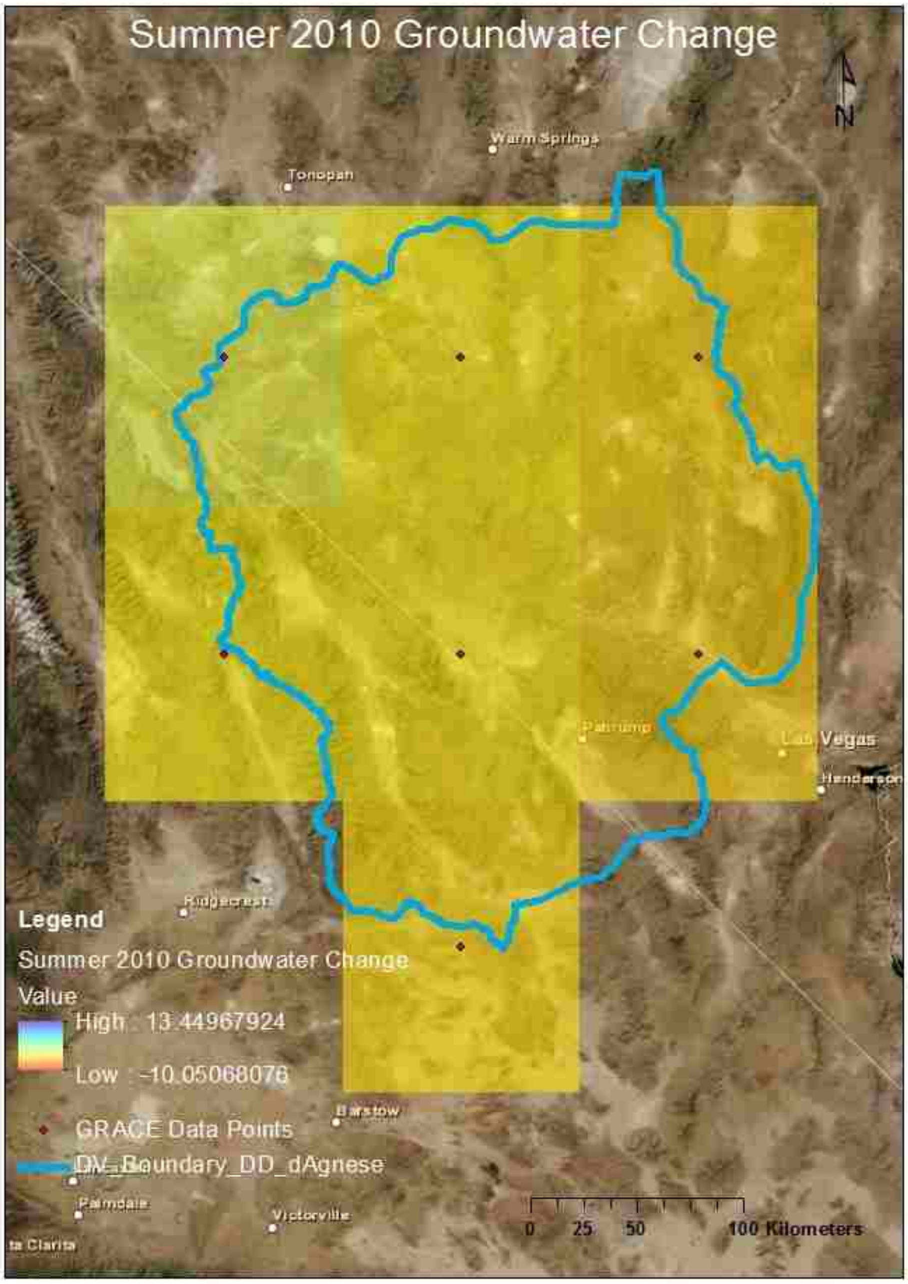


Figure A-29. Summer 2009 groundwater change.



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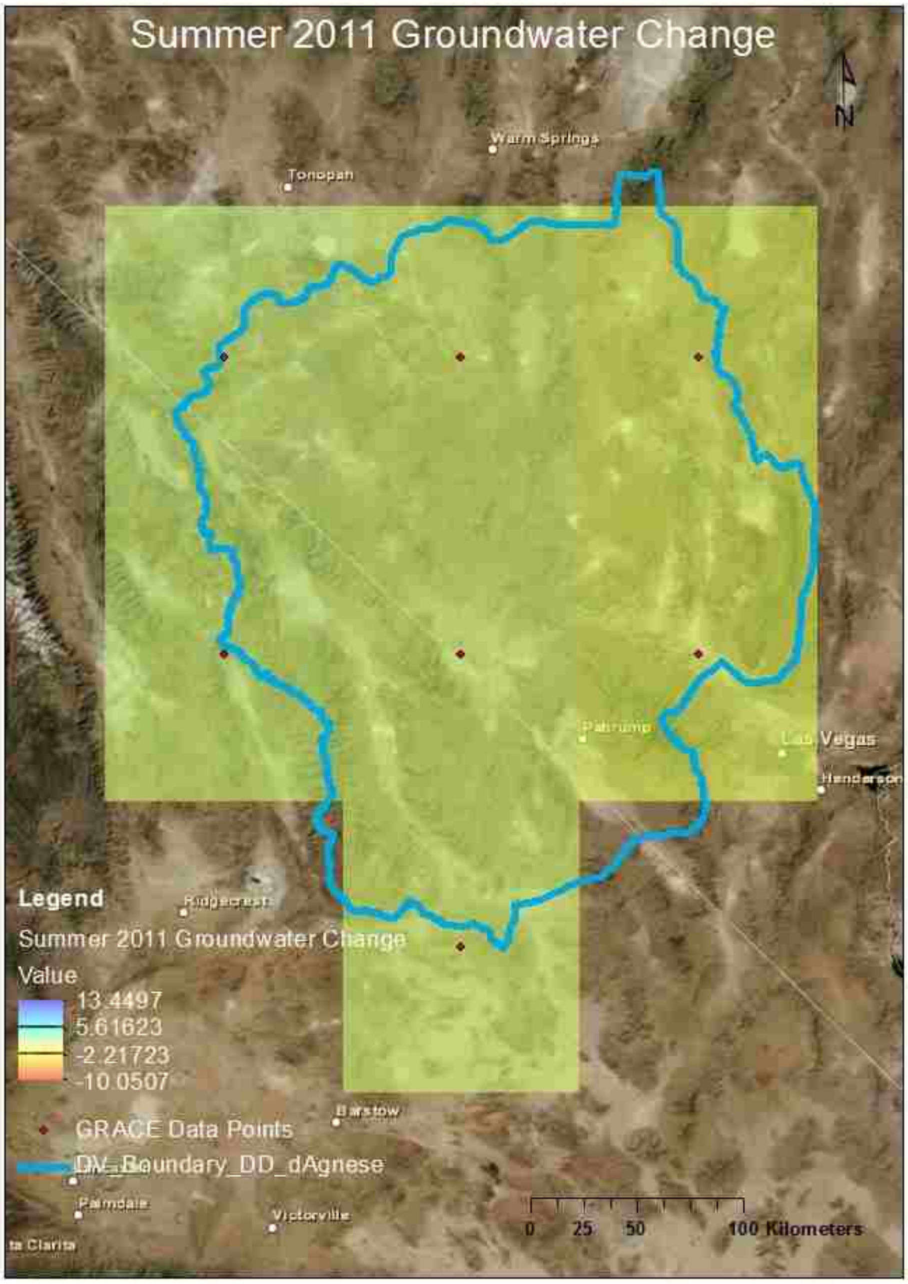


Figure A-31. Summer 2011 groundwater change.

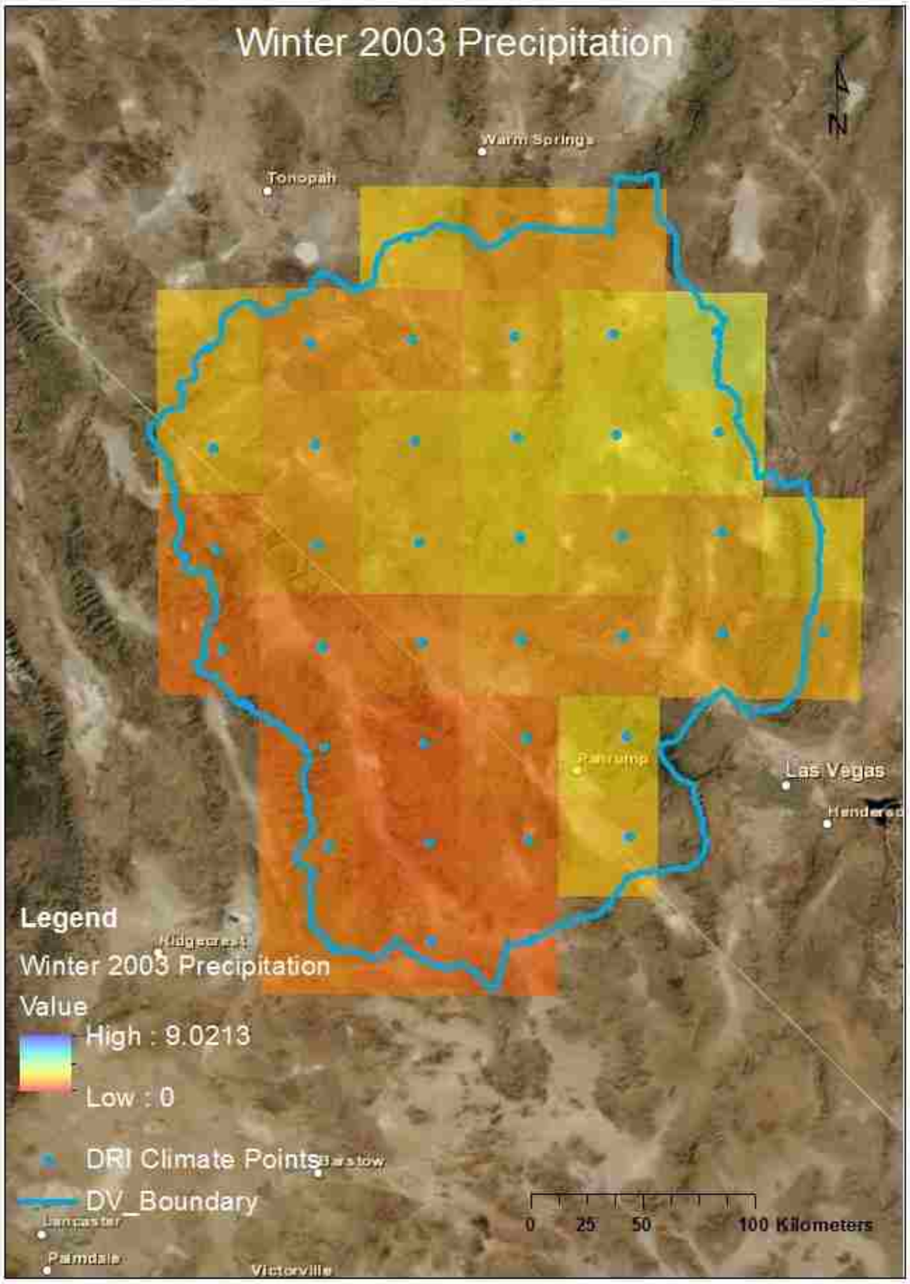


Figure A-32. Winter 2003 precipitation.

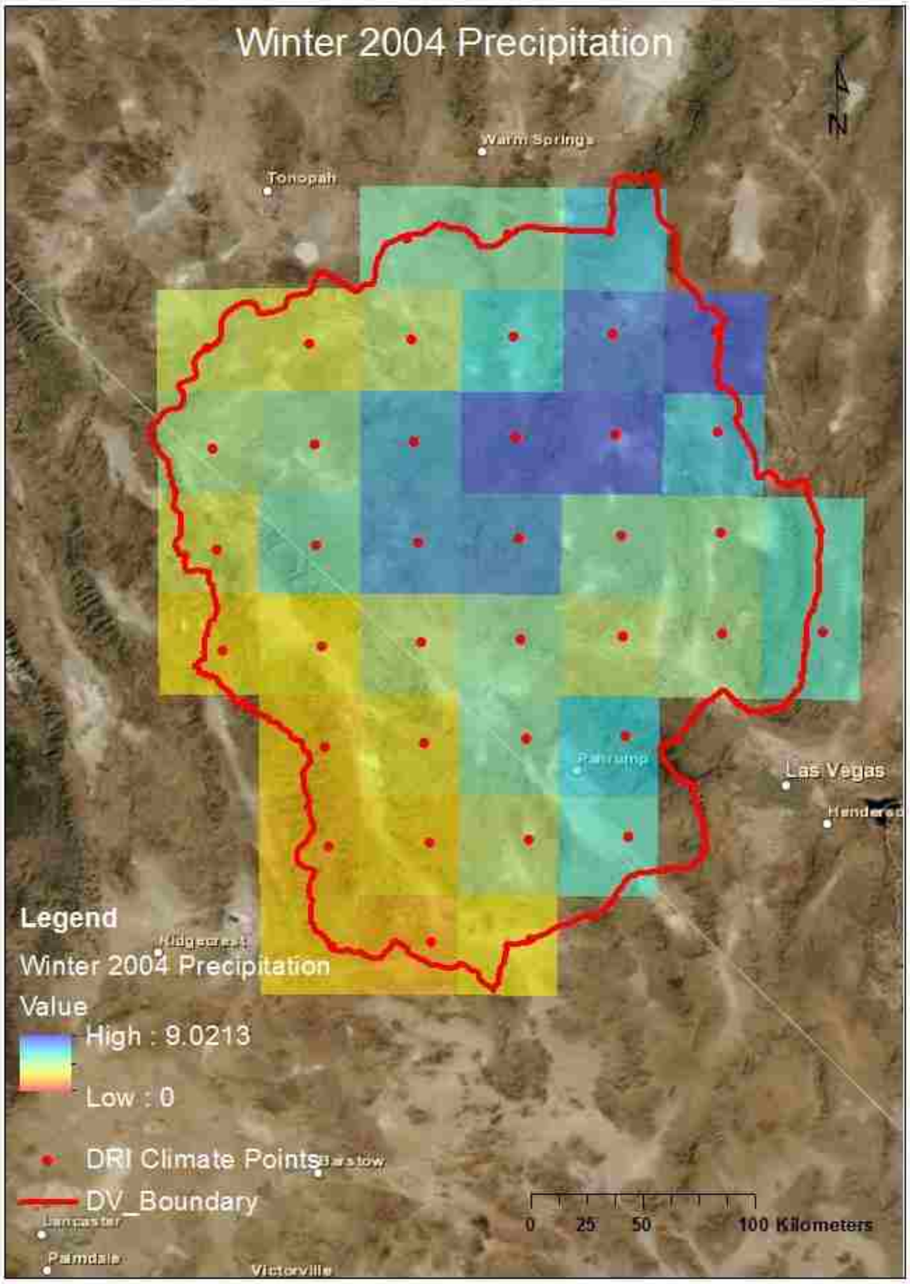


Figure A-33. Winter 2004 precipitation.

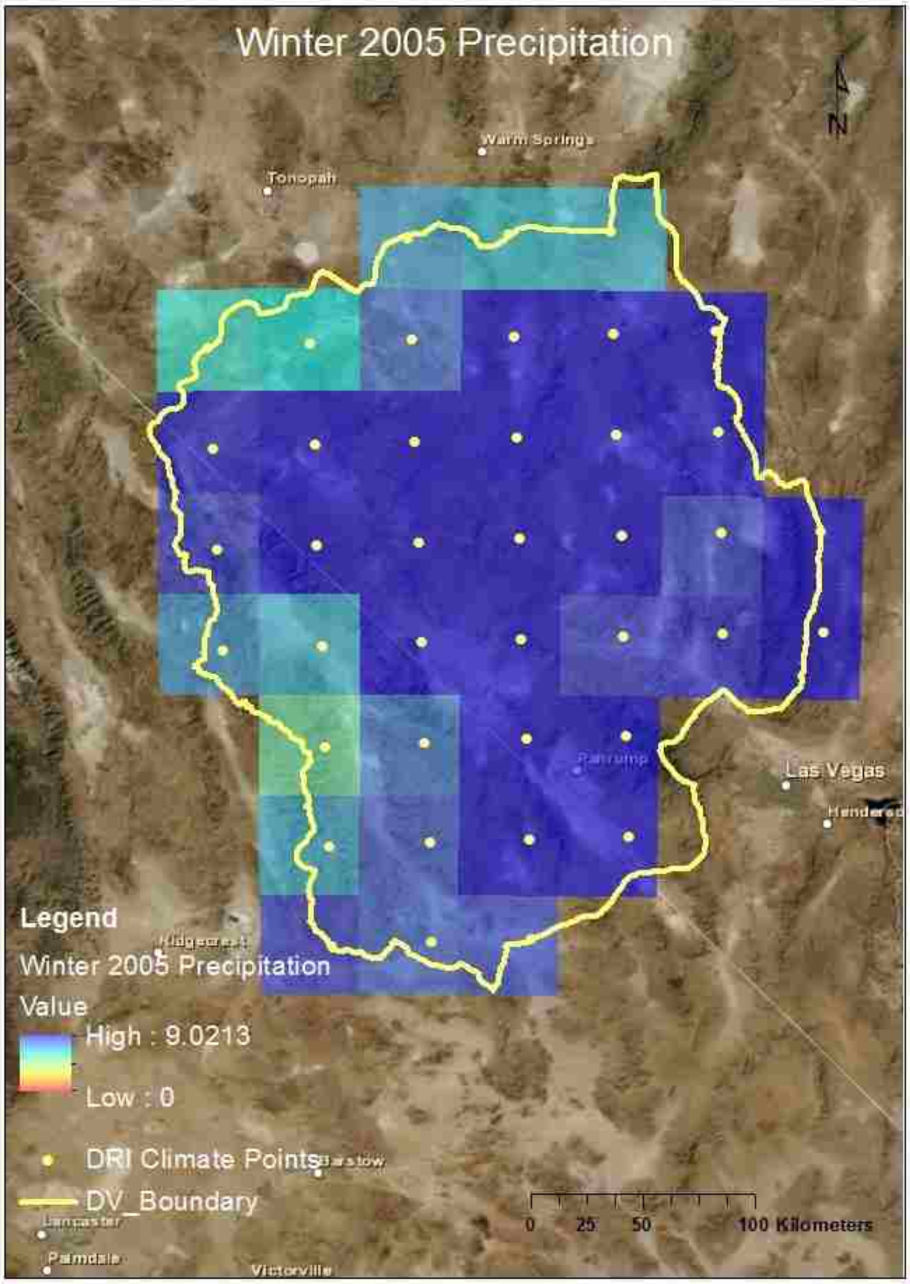
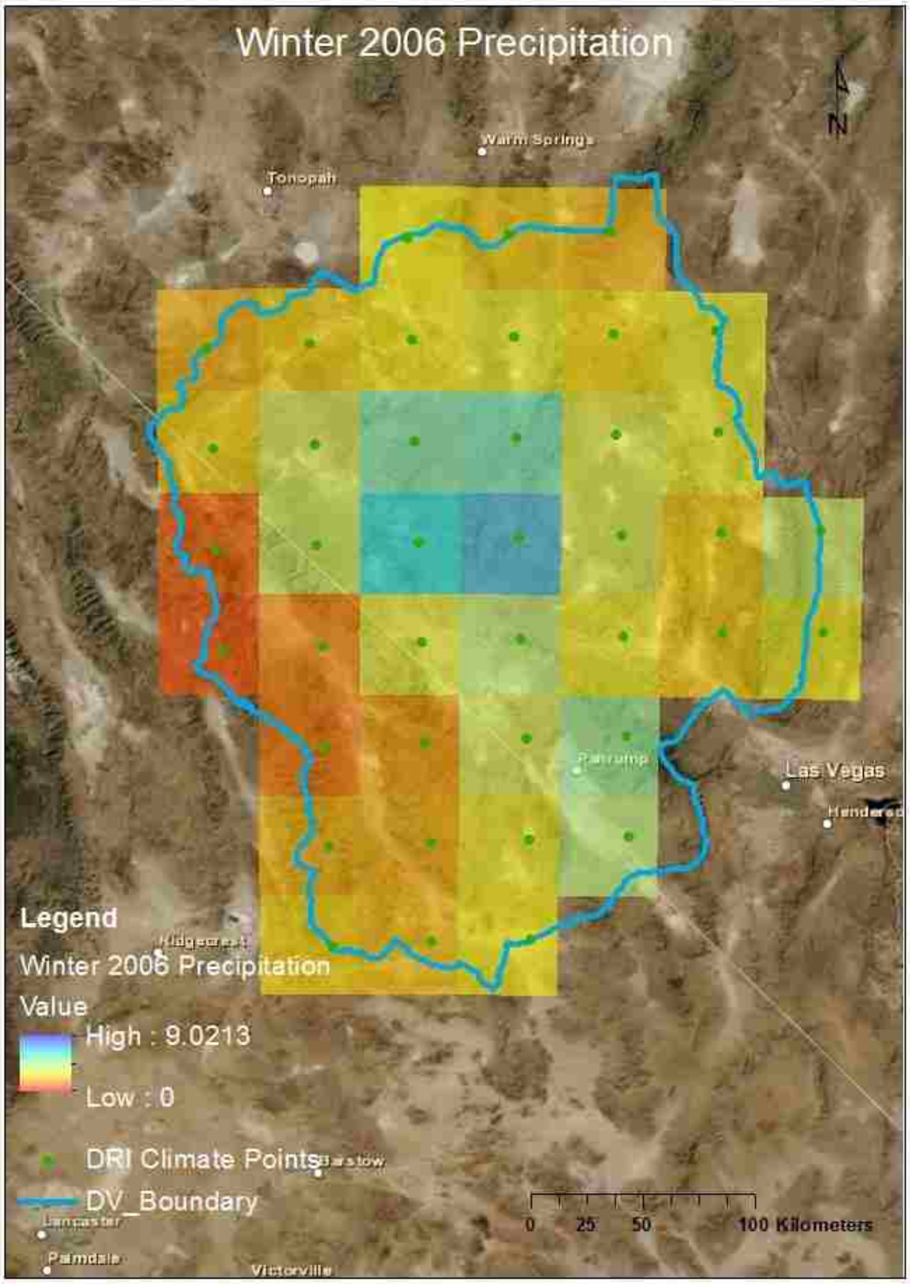


Figure A-34. Winter 2005 precipitation.



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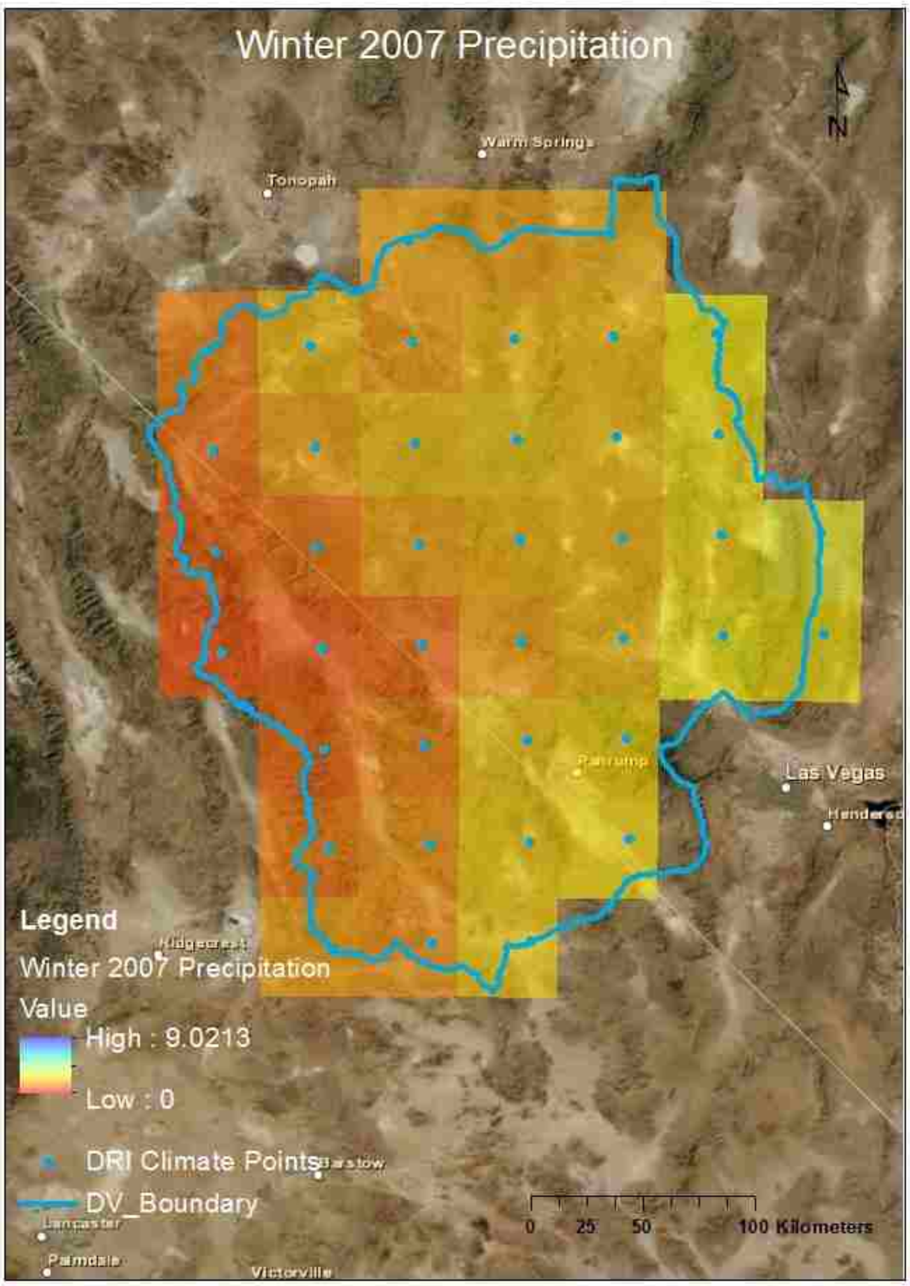


Figure A-36. Winter 2007 precipitation.

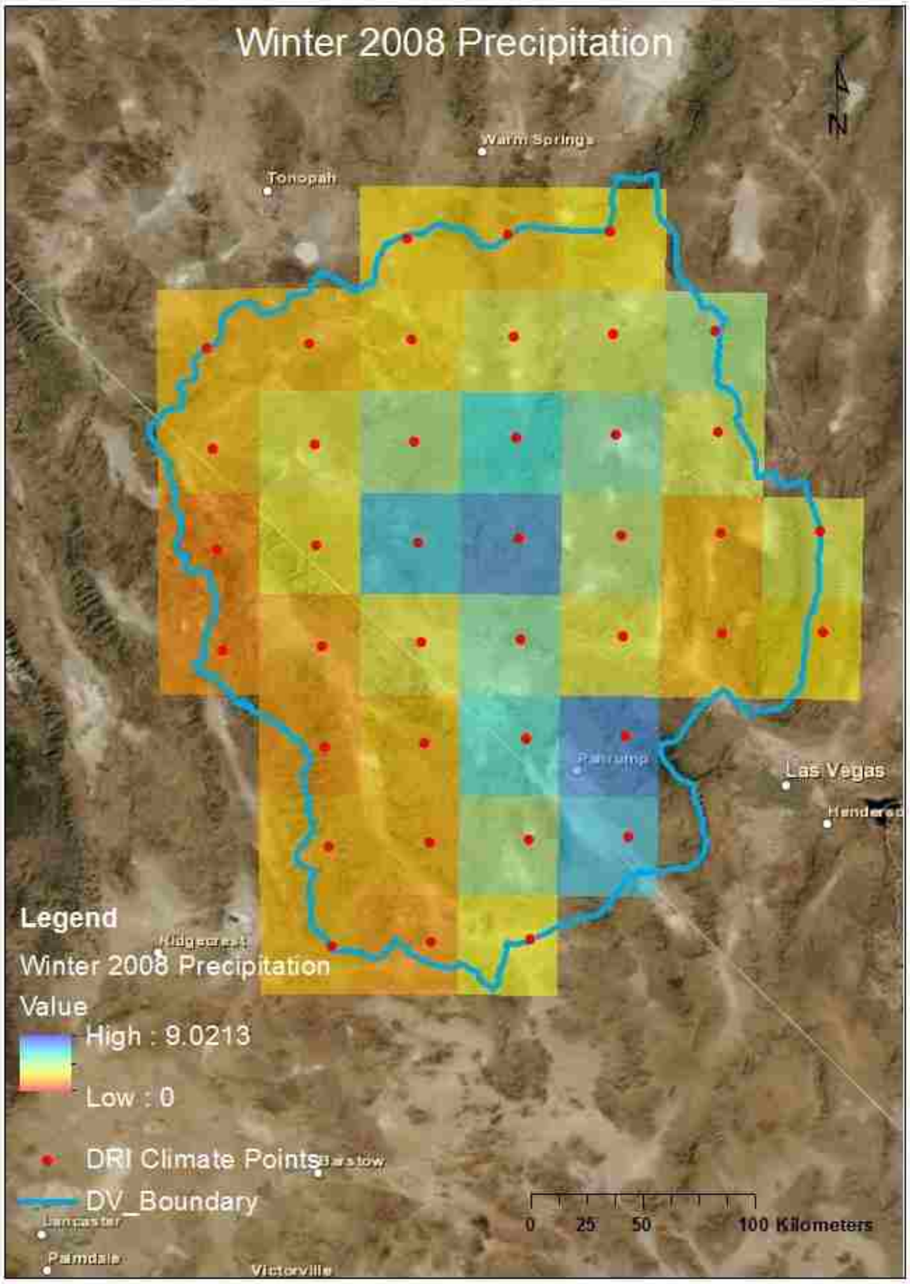


Figure A-37. Winter 2008 precipitation.

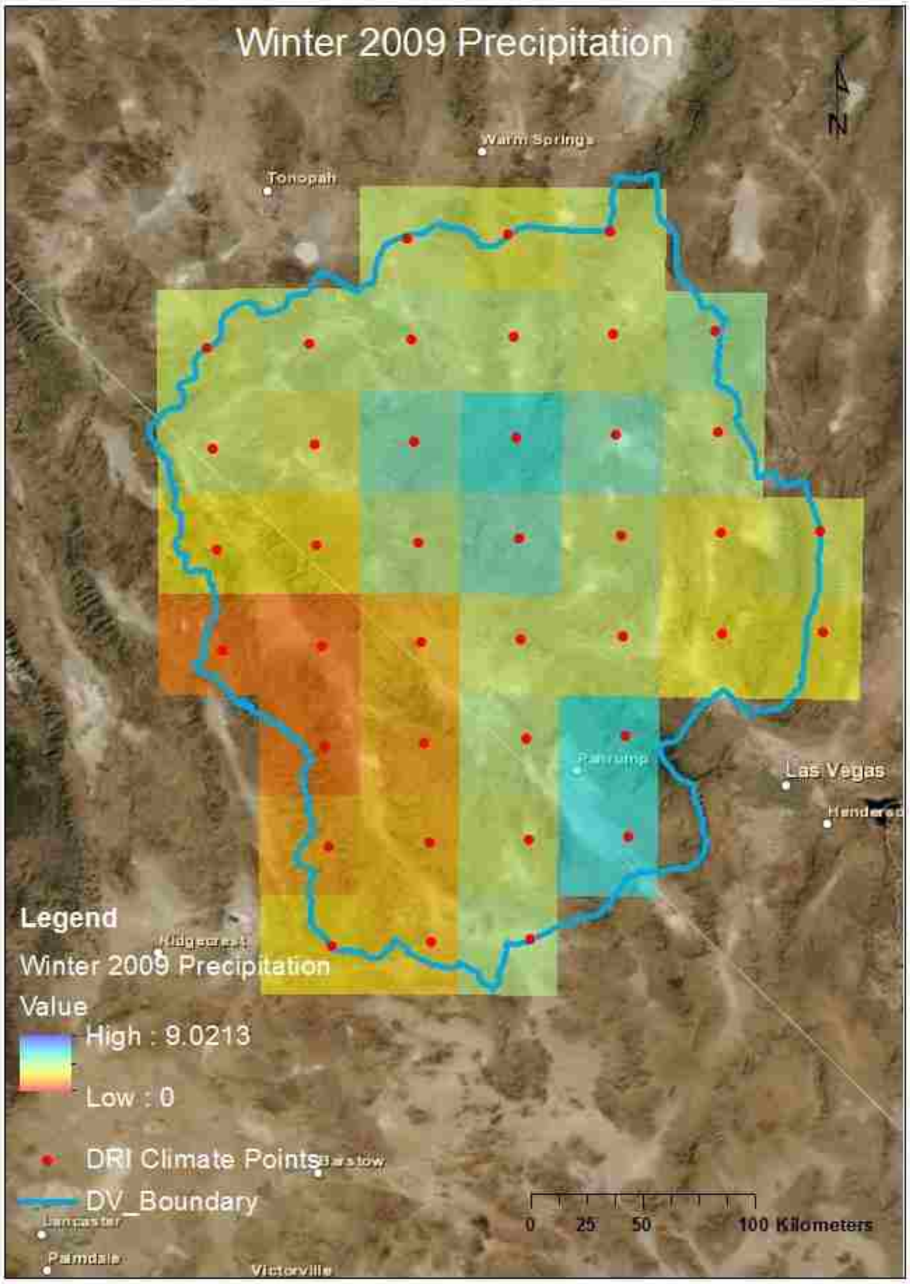
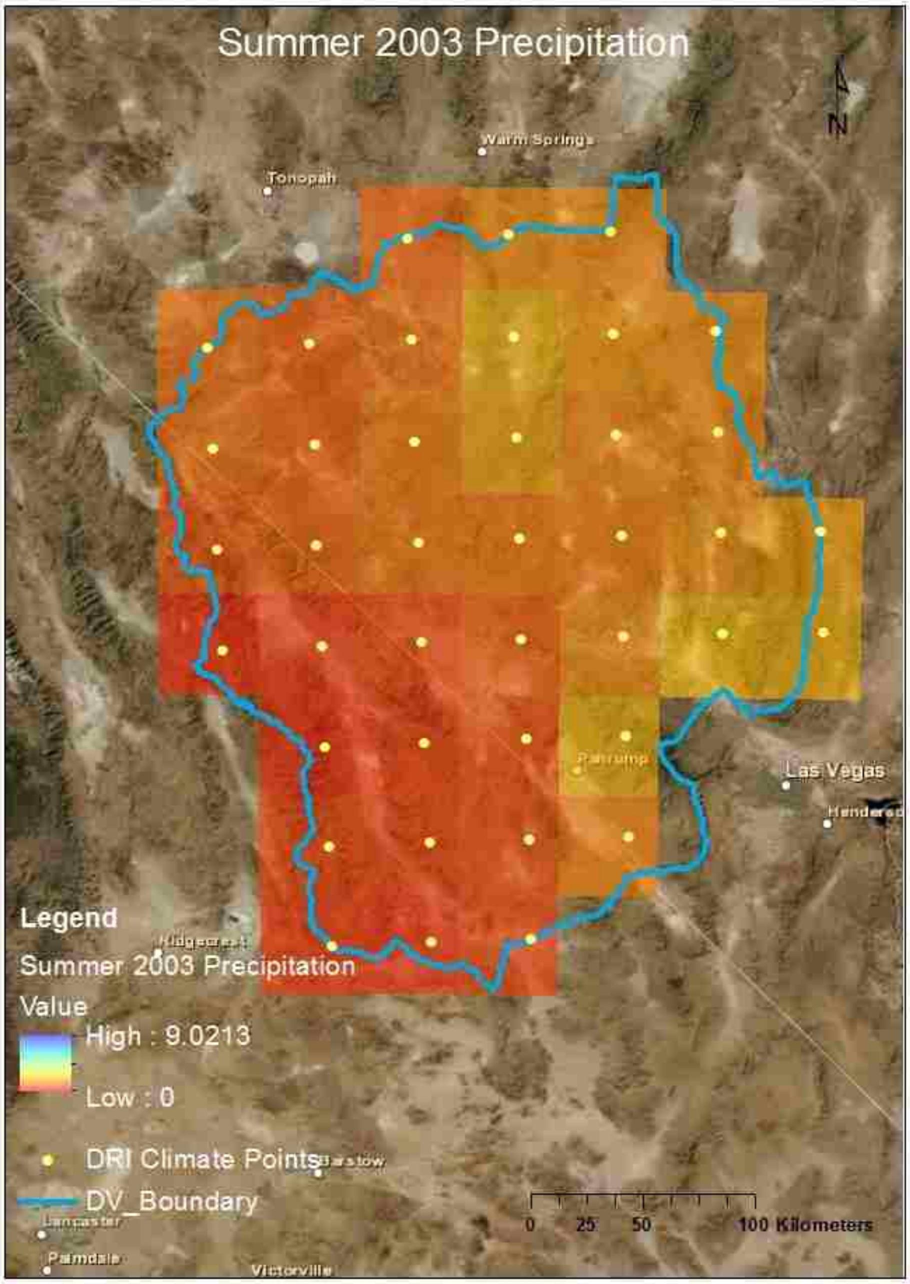


Figure A-38. Winter 2009 precipitation.



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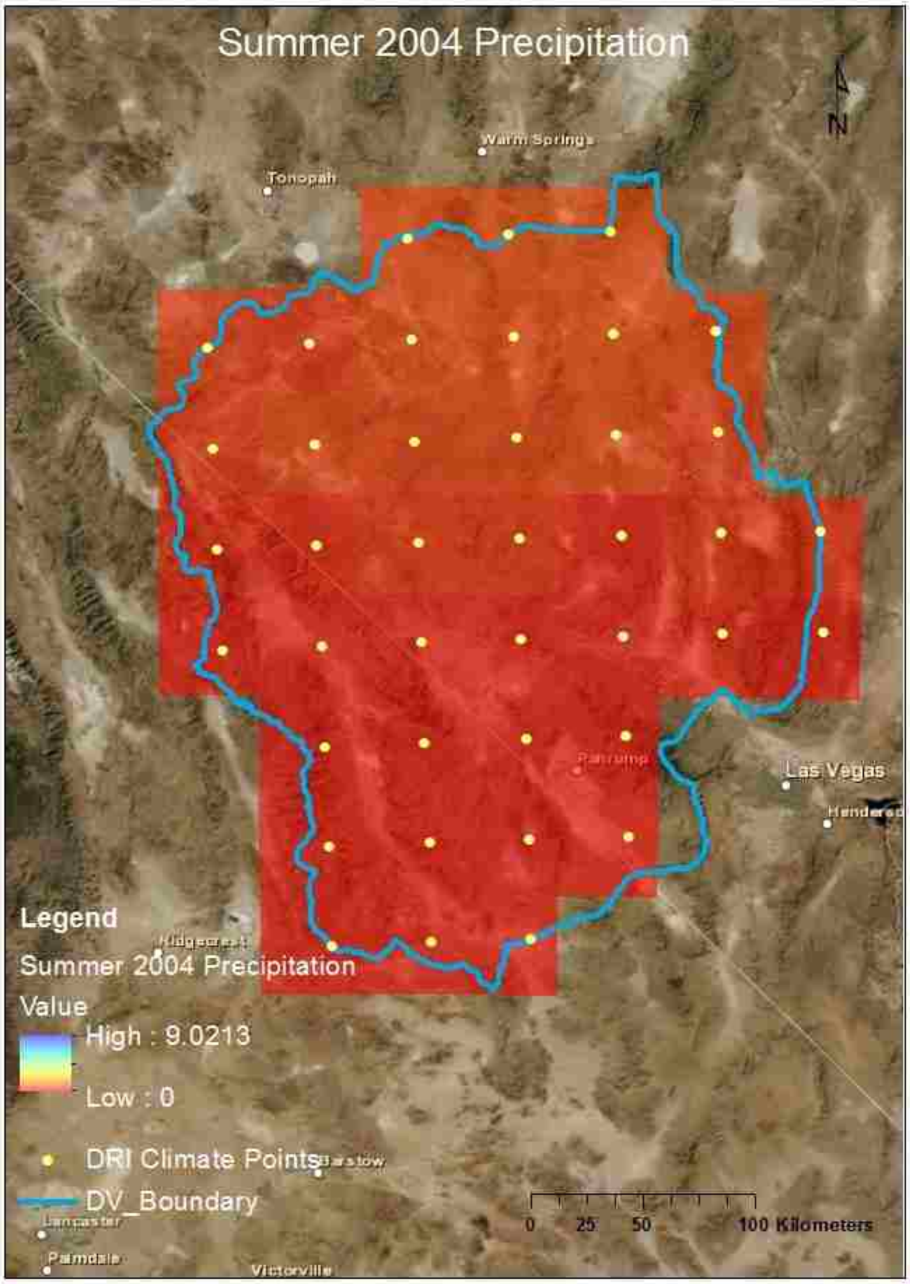


Figure A-40. Summer 2004 precipitation.

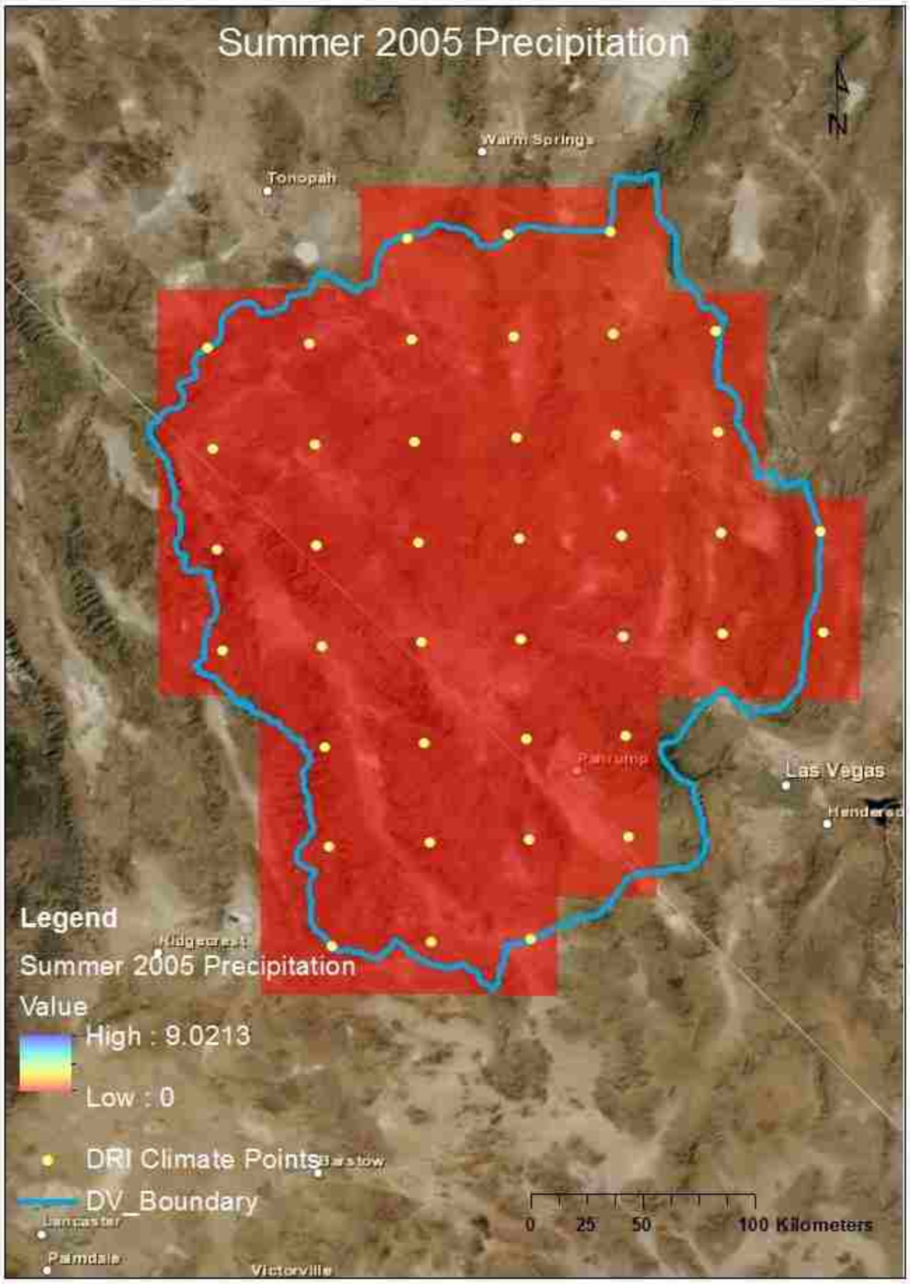


Figure A-41. Summer 2005 precipitation.

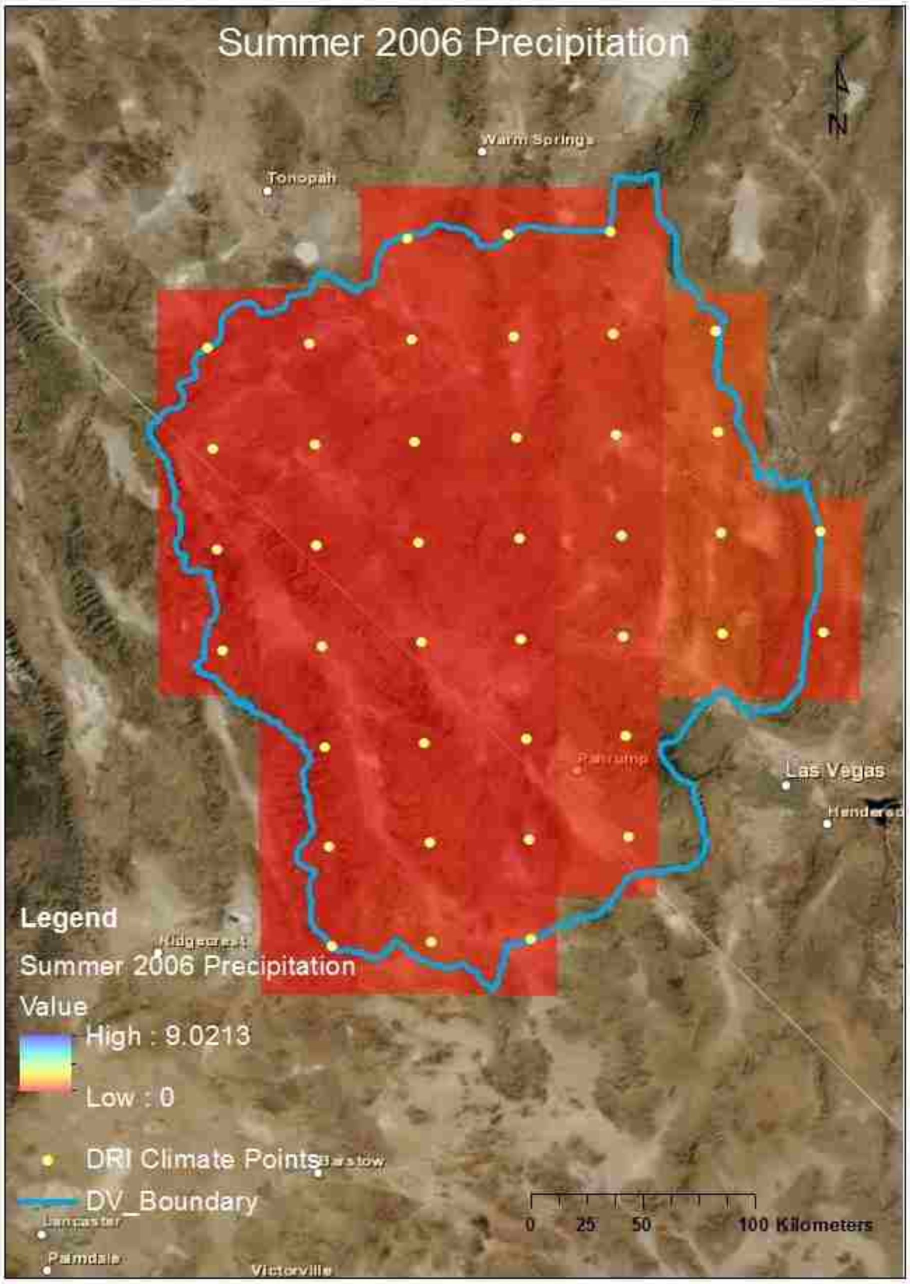


Figure A-42. Summer 2006 precipitation.

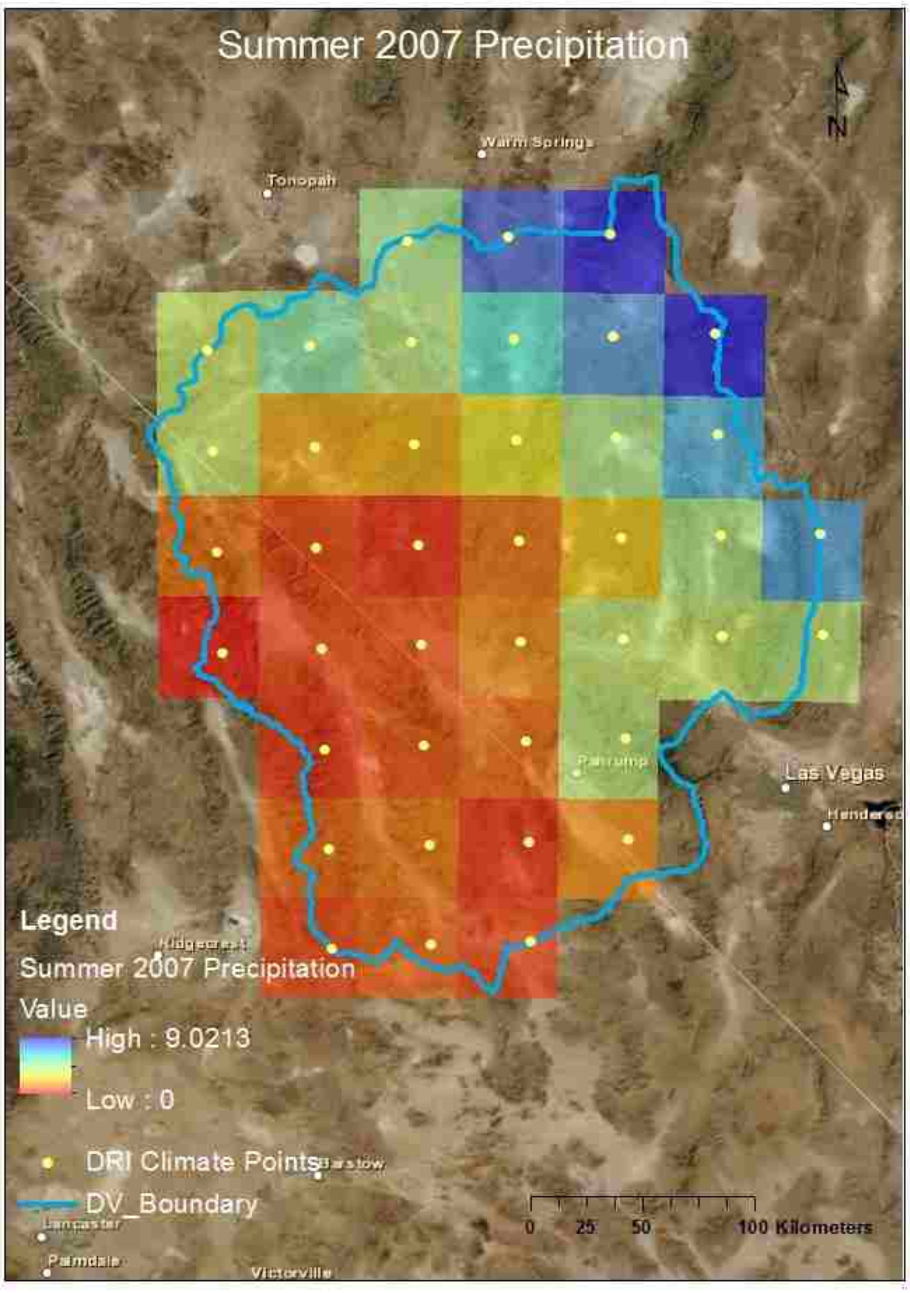
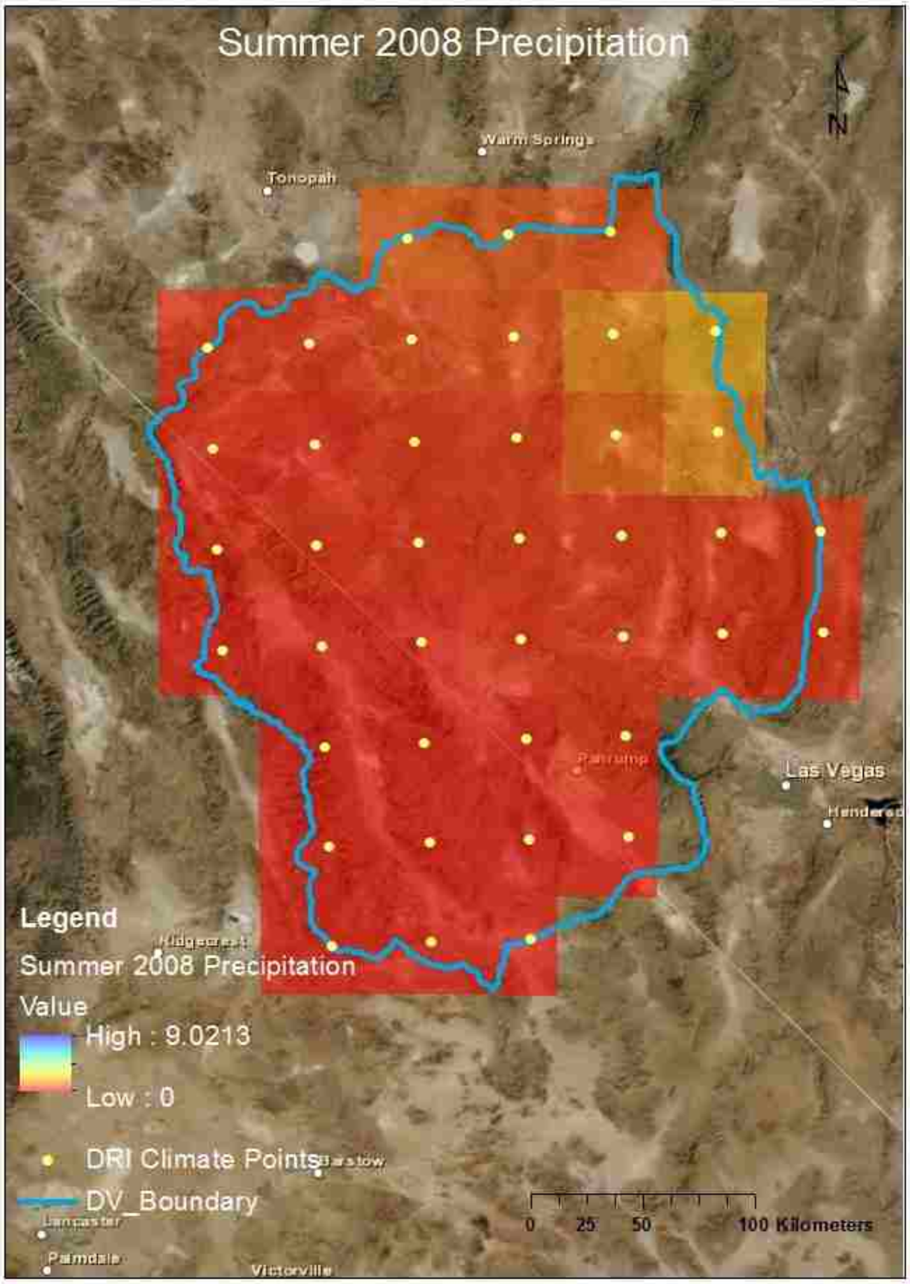


Figure A-43. Summer 2007 precipitation.



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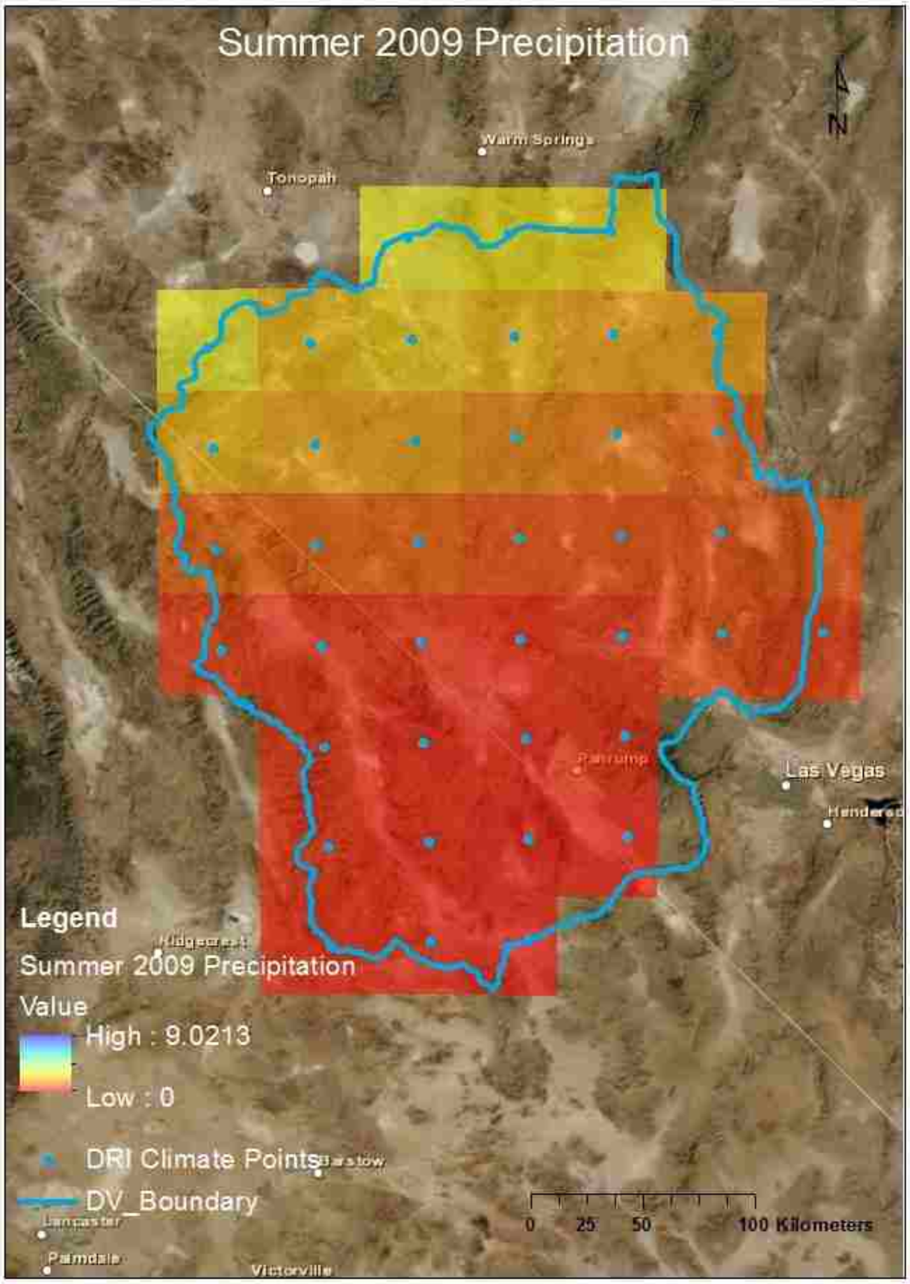

Figure A-45. Summer 2009 precipitation.

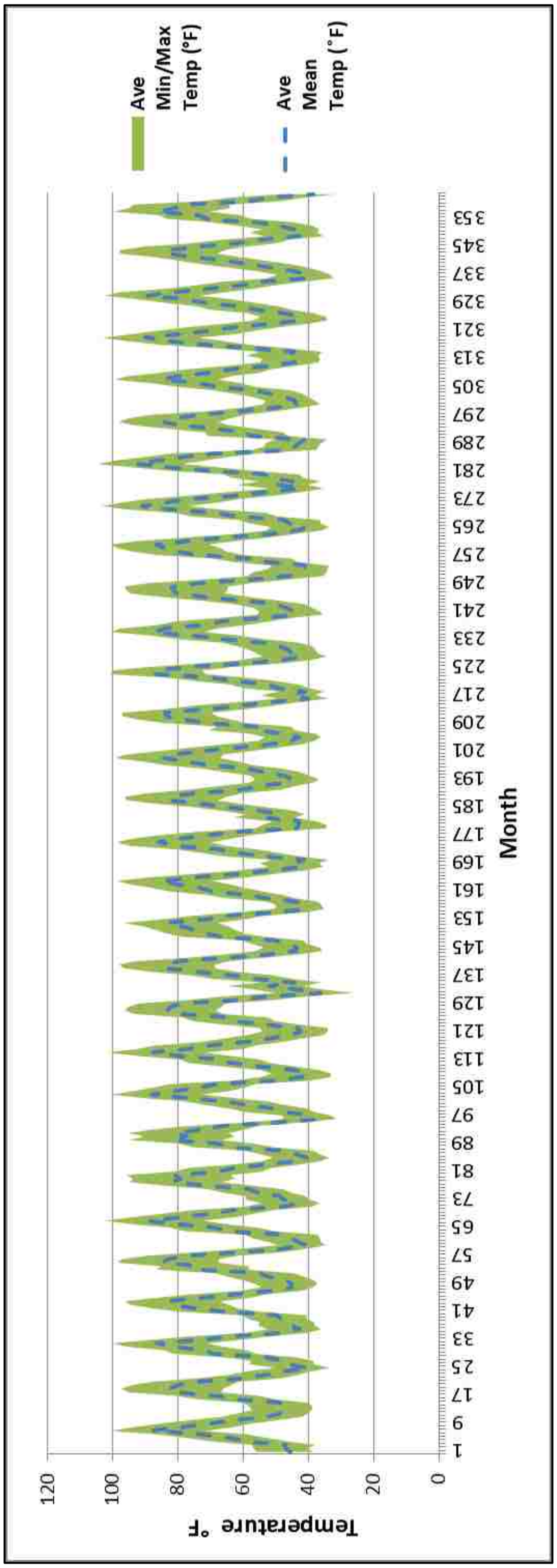

Figure A-46. Overview of Death Valley average temperatures.

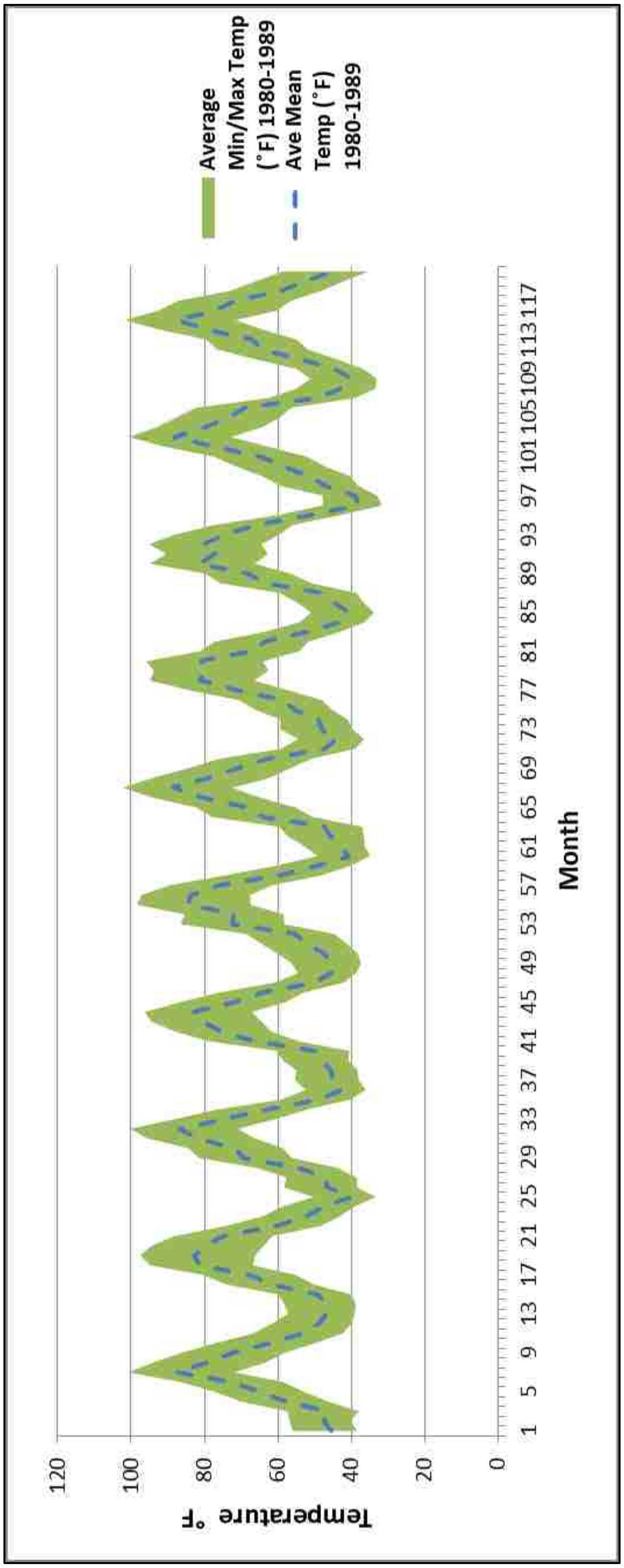

Figure A-47. Death Valley average temperatures 1980-1989.

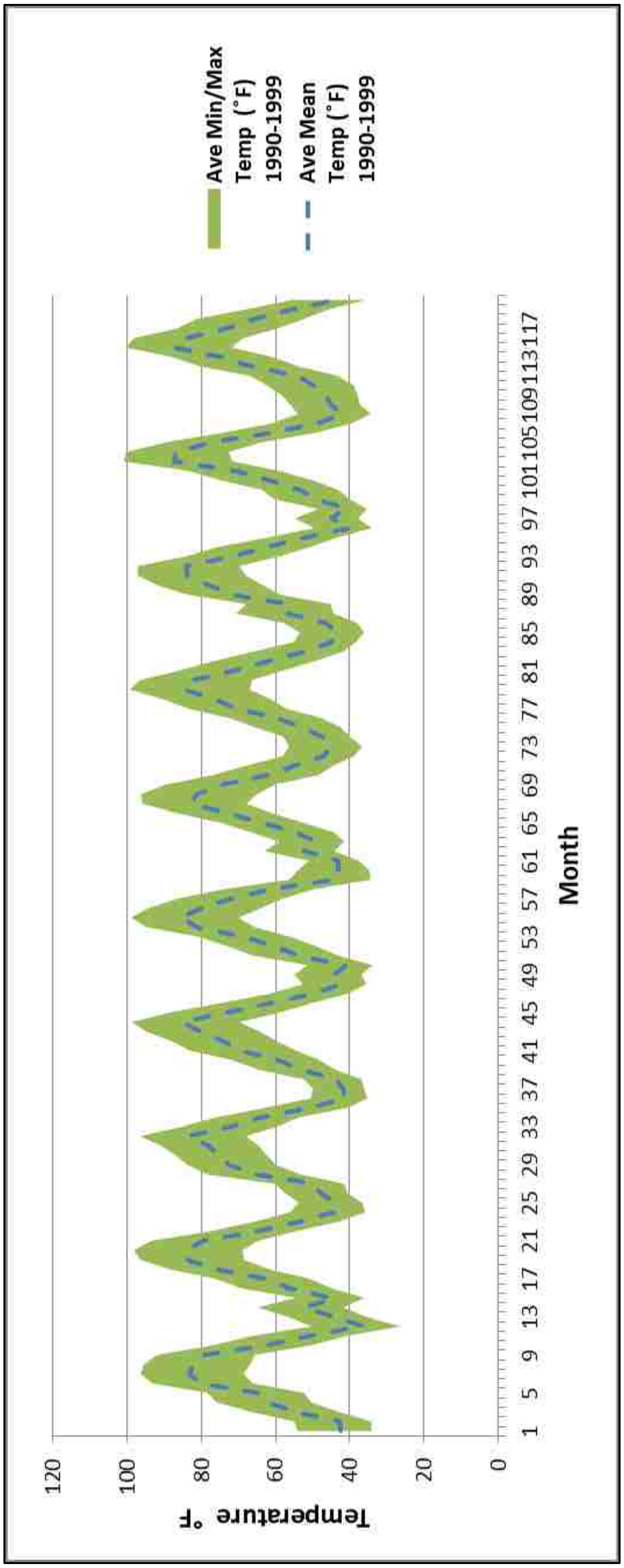

Figure A-48. Death Valley average temperatures 1990-1999.

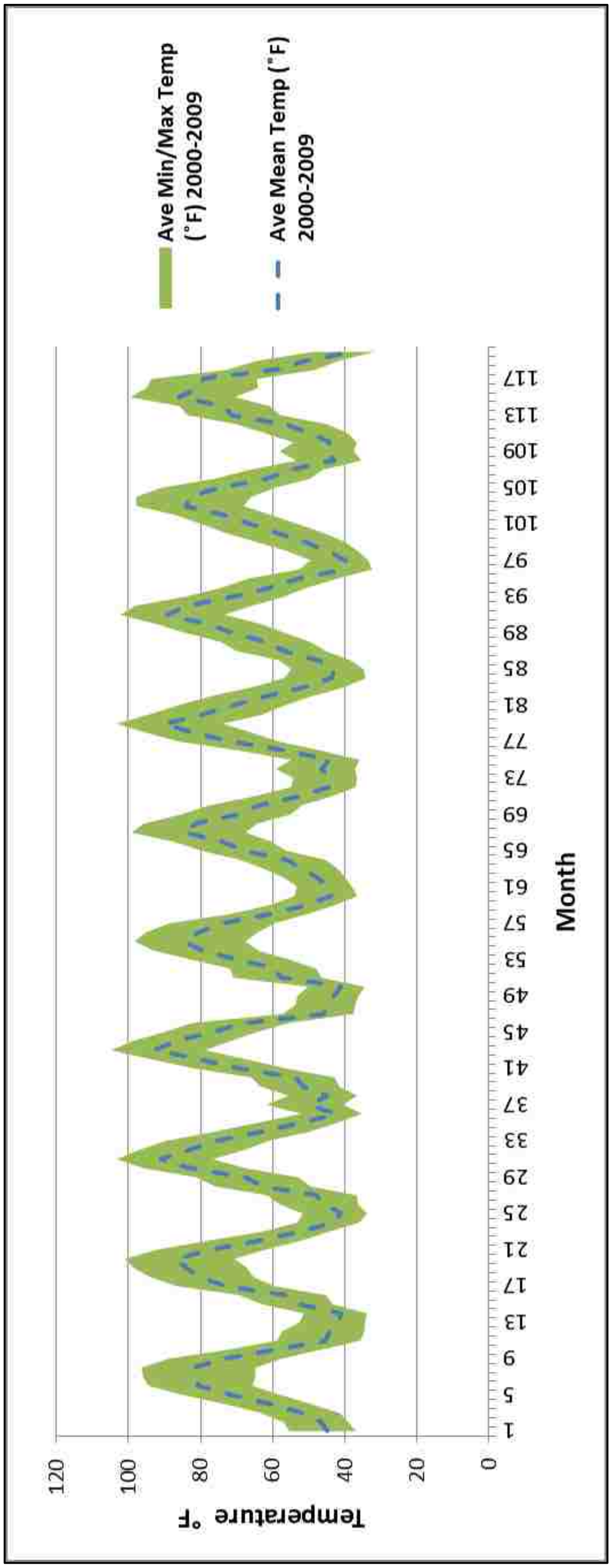

Figure A-49. Death Valley average temperatures 2000-2009.

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EDUCATION

8/2011 – 5/2013
University of Nevada, Las Vegas, Department of Geoscience,
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M.S. - Geoscience, Hydrogeology emphasis
Cumulative GPA: 3.94/4.0
Thesis: The Evaluation of Water Storage In Death Valley Using GRACE Satellite Data

8/2010 – 5/2011
University of Nevada, Las Vegas, Department of Geoscience,
Las Vegas, NV
B.S. - Geology
Cumulative GPA: 3.96/4.0

1/2009 – 6/2010
University of South Alabama, Department of Geoscience,
Mobile, AL
Cumulative GPA: 4.0/4.0

6/2005 – 9/2006
Western International University
Phoenix, AZ
A.A. – Business
Cumulative GPA: 4.0/4.0

POSITIONS

5/2012 – 9/2012
ExxonMobil, Houston, TX
Cross Discipline Technology Intern

Internship at ExxonMobil, tasked to research the capabilities of LiDAR data for geological use within the organization. Responsibilities included working with the Upstream Research Company to visualize terrestrial LiDAR data sets in ArcGIS 10.1. This visualization will aid in creating more accurate geological models for an upcoming Kearl Oil Sands mining project in Canada. Canada's oils sands are one of the largest energy resources in the world. According to ExxonMobil's 2012 Outlook on Energy, "By 2040, oil sands will account for 25% of total liquids supply for North and South America." Presented results and recommendations for future LiDAR use to numerous groups at various levels of the ExxonMobil organization. Research will serve as the basis for future LiDAR utilization throughout the company.

Also tasked with coordinating the ArcGIS 10.1 rollout, including: developing test cases, testing, documenting bugs, and managing issue resolution with ESRI.

Key Contributions:

- Incorporated LiDAR data into ArcGIS 10.1 for geological interpretation
- Proposed expanding the use of LiDAR data for other key company initiatives

6/2010 – 6/2010 **University of South Alabama**, Mobile, AL

Drill Site Participant

Participated in the drilling of a monitoring well. Experienced the process of drilling a well, classifying soil cores with the Unified Soil Classification System, developing the well and taking water samples. Calculated groundwater flow rate and mapped direction through the area using measurements from five separate monitoring wells.

1/2010 – 4/2010 **NASA DEVELOP**, Mobile, AL

Intern

Recruited to work with a seasoned team of Geologists and other professionals to provide guidance for upcoming U.S. Environmental Protection Agency (EPA) regulation changes. Analyzed satellite imagery (remote sensing), ground-level ozone, census data, and daily vehicle miles travelled. Correlated land use/land change and the increase of urban development with the change in ground-level ozone readings collected from an ozone monitoring station.

Key Contribution:

- Results of completed analysis were published and presented to local county administrators

10/2000 – 4/2007 **Sprint/Nextel Partners Inc.**, Panama City Beach, FL

Systems Analyst

Performed business systems analysis and management of the complete lifecycle of enterprise-wide projects in billing, business process automation, and other critical initiatives. Staff development including the implementation of an enterprise-wide e-learning solution. Vendor liaison, managing production launches, transaction volume projections, and issues management. Developed and managed 5-week Customer Care new-hire training program, training employees on software applications, customer service skills, and sales, for class sizes ranging between 15-70 students.

Planned and coordinated motivational and community service efforts as Spirit Committee Manager. Events included onsite and offsite activities, charity events, and fundraising. Planned and executed the company’s annual Holiday Party.

Key Contributions:

- Served as Enterprise Application Integration Chair, implementing automation projects reducing annual operating expenses by over $25 million
- Streamlined new-hire system training to reduce training time from 6 weeks to 4, expediting on boarding and reducing training expenses by 1/3
    - Implemented further curriculum enhancements to allow for doubling classroom headcount, while maintaining effectiveness.
- Twice awarded the *Circle of Excellence* award for superior performance

PRESENTATIONS:

Sweigart, M.J. Drought in the Las Vegas Valley. Keynote speaker at the 1st annual Festival of Communities Undergraduate Research Symposium, Las Vegas, NV. 16 Apr 2011.

MEDIA APPEARANCES HIGHLIGHTING RESEARCH:

2011. Interview for Festival of Communities keynote presentation “Drought in the Las Vegas Valley” on local ABC morning news program “The Morning Blend”. 25 Mar 2011. http://www.vegasmorningblend.com/videos/118098344.html

PROFESSIONAL HONORS:

- 7th Annual UNLV GeoSymposium Most Outstanding Graduate Poster Award (2012)
- NASA Space Grant Consortium Fellowship (2011-2012)
- Keynote Presenter, 2011 Nevada Undergraduate Research and Creative Activities Symposium (2011)
- 6th Annual UNLV GeoSymposium Most Outstanding Undergraduate Poster/Presentation Award (2011)
- Association of Environmental and Engineering Geologists Student Presentation Award (2011)
- Nevada NASA Space Grant Consortium Scholarship (2011)
- Nevada National Science Foundation Experimental Program to Stimulate Competitive Research Scholarship (2010-2011)
- University of South Alabama Geological Hammer Award (2009)

PAST/CURRENT MEMBERSHIPS:

- Geological Society of America (GSA)
- Association of Environmental and Engineering Geologists (AEG)
- National Ground Water Association (NGWA)
- American Association of Petroleum Geologists (AAPG)
- American Geophysical Union (AGU)
- Association for Women Geoscientists (AWG)
- The Paleontological Society
- Society of Vertebrate Paleontology (SVP)
- Society for Sedimentary Geology (SEPM)
- Sigma Gamma Epsilon Honor Society
- Golden Key International Honour Society