NRCE

ZUNI INDIAN RESERVATION
REVIEW OF AND REBUTTAL TO EXPERT REPORTS
FOR
PAST AND PRESENT IRRIGATED LANDS
SERVED BY
PERMANENT IRRIGATION WORKS

In the matter of
United States v. A&R Productions
Case # 07cv06811-BB

Prepared for:
Bureau of Indian Affairs
And
United States Department of Justice

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1 INTRODUCTION

1.1 Overview

This report addresses technical issues in expert reports prepared by the expert consultants for the State of New Mexico (State) and the Navajo Nation involved in the United States v. A&R Productions, Zuni River Basin Water Rights Adjudication, Subproceeding 1 (Case No. 07cv06811-BB) regarding the identified lands and crop water requirement analyses performed by Natural Resources Consulting Engineers, Inc. (NRCE) in the November 2008 report, *Identification of Lands and Estimation of Water Requirements for Past and Present Lands Served by Permanent Irrigation Works* (NRCE, 2008) and supplemented by the June 2009 report *Corrections and Clarifications to the 2008 Report* (NRCE, 2009). The State's expert reports include Longworth (2010), Franzoy (2010), Samani (2010), Brengosz (2010), Petronis (2010) and Wear (2010). The other report reviewed is by Dr. James T. McCord the expert for the Navajo Nation (Amec, 2010).

1.2 Summary of Differences

The most significant differences between the consultants for the State and NRCE for the United States are 1) the acreage of past and present irrigated lands used to calculate irrigation diversion and depletion quantities, and 2) methodology used to calculate the consumptive irrigation requirements. Other differences in methodology or analysis result in only small differences in diversion and depletion amounts.

1.2.1 *Past and Present Irrigated Lands*

In Wear (2010), Mr. Wear states "[t]he mapping from NRCE was based primarily on aerial photography, and although the delineated areas appear to indicate lands that are irrigable and may have been irrigated in the past, there is no data to suggest that all of the acreage mapped was ever irrigated in any one year." Thus, the major differences between Wear's approach and NRCE's concerns the definition of past and present irrigated lands, not the fact that the Zuni have irrigated the lands in question. Mr. Wear also states that the maximum acreage under irrigation in any one year is 2,904 acres based on Bureau of Indian Affairs (BIA) crop reports for 1949. NRCE identified a cumulative total of 7,018 acres of past and present irrigated lands served by permanent irrigation works. NRCE did not estimate the maximum acreage irrigated in a single year.

The most obvious differences between Wear's and NRCE's methodology is that NRCE identifies all past and present irrigated lands served by permanent irrigation works and

Wear makes an estimate of maximum acreage in a single year. Another State expert, Longworth (2010), uses of 2,572.6 acres, which is the average of BIA reported irrigated acreage for years 1947 through 1950, when computing irrigation requirements. The irrigated acreages are summarized below.

Irrigated Acreage

Wear 2010 – 2,904 acres described as maximum irrigated acreage in a single year (1949) based on the years 1947-1950.

Longworth 2010 – 2,572.6 acres described as the average irrigated acreage for 1947-1950.

United States – 7,018 acres described as past and present irrigated land served by permanent irrigation works (Allen, 2008).

Since the completion of NRCE's report in 2008, an additional field investigation, information from meetings with Tribal members, and aerial photo interpretation have provided NRCE data for making some changes to the originally surveyed acreage, which is detailed within this report. The revised area served by permanent irrigation works is 6,892.7 acres.

1.2.2 *Calculation of Consumptive Irrigation Requirement*

Longworth (2010) concluded that a historic water use estimate utilizing the Modified Blaney-Criddle method adjusted for alfalfa yield is reasonable. NRCE uses the American Society of Civil Engineers (ASCE) Standardized Reference Evapotranspiration Equation Penman-Monteith method to calculate reference crop evapotranspiration and crop water requirements (ASCE, 2005). NRCE's results differ from Longworth's result due to this difference in methodology and other considerations used to calculate crop water requirements. Longworth adjusted the water requirement based on reported alfalfa yield for 1947 through 1950; NRCE did not use yield to estimate irrigation requirement. Longworth based effective precipitation on average precipitation; NRCE used 80 percent exceedance precipitation (data for 1948 through 2004). Longworth also used different cropping patterns than NRCE. Based on these major differences and other minor differences Longworth's estimation of consumptive irrigation requirement is 1.1 acre-feet per acre, roughly half the amount estimated by NRCE. The values are listed below.

Source	Consumptive Irrigation Requirement (ac-ft/ac)	Diversion Requirement (ac-ft/ac)	Depletion (ac-ft/ac)
NRCE (weighted average for all agricultural units)	2.01	4.52	2.51
Longworth (2010)	1.1	2.56	1.1

For computing consumptive irrigation requirements, NRCE adopts the FAO-56 definition for crop evapotranspiration of "evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions" (FAO, 1998). By incorporating yields into his methodology, Longworth (2010) is not calculating a consumptive irrigation requirement, but is attempting to estimate actual historical water use. In this report, "consumptive irrigation requirement" in quotes references Longworth's description of consumptive irrigation requirement.

Method Used to Calculate Crop Water Requirement - The Modified Blaney-Criddle method used by Longworth is an outdated method that only considers average monthly temperature and the percent of annual daylight in each month (based on latitude). In general, the Blaney-Criddle method results in calculation of crop water requirements that are less precise when compared to field measurements and results in lower estimates in arid climates, as discussed in detail in Section 3.2 of this report. NRCE uses the ASCE Penman-Monteith method (ASCE P-M), with the Hargreaves-Samani method as a check to validate the results. Currently, the American Society of Civil Engineers, the Food and Agriculture Organization of the United Nations, and the United States Soil Conservation Service (now named the Natural Resources Conservation Service) recommend the Penman-Monteith method over the modified Blaney-Criddle method. A recent journal article by Dr. Theodore W. Sammis, et al. (2011) states that "the empirical relationship and the originally derived coefficients [of the Blaney-Criddle method] are outdated and invalid for today's agriculture production systems and should be replaced with the Penman-Monteith equation when adjudicating water rights".

Water Requirement Adjustment for Alfalfa Yield – As explained in Section 3.3 of this report, it is NRCE's opinion that the reported alfalfa yield and yield-evapotranspiration (ET) relationship is not an appropriate element to calculate crop water requirements. If properly applied, the alfalfa yield and ET relationship can predict yield based on precipitation and irrigation, or estimate water use by crops when accurate yields are available. By definition, Longworth's results are different from crop water requirements. Water use quantified based upon the consumptive irrigation requirement allows farmers to produce crops at the optimal production level when water is available.

Effective Precipitation – Both Longworth (2010) and NRCE apply the method developed by the USDA Soil Conservation Service for calculating effective precipitation on a monthly basis. The primary difference is that Longworth uses average monthly precipitation to calculate effective precipitation while NRCE uses the 80 percent exceedance precipitation. The problem with using average precipitation is that for approximately half of the years, the effective precipitation calculated in this manner is higher than the actual effective precipitation and, therefore, decreases the calculated consumptive irrigation requirement below what the crops require for healthy growth. In contrast, the use of 80 percent exceedance precipitation results in a consumptive irrigation requirement value that is adequate in 80 percent of the years.

Cropping Pattern – The primary difference in the cropping pattern developed by the State's experts concerns the percentage of irrigated pasture. Longworth (2010) uses two percent while NRCE estimates 20 percent irrigated pasture in addition to the other crops reported in each of the project areas. NRCE's assessed water use is for past and present irrigated lands served by permanent irrigation works. It is not entirely clear as to what extent the historic BIA crop reports account for (or do not account for) irrigated pasture. In addition, the majority of the acreage is currently pasture based upon observations during field visits and supported by New Mexico Agricultural Statistics Service county crop reports. Accordingly, NRCE's crop mix better reflects the existing practice on the Zuni Reservation.

1.3 Summary of Opinions

1. Using the ASCE P-M method to determine evapotranspiration and the methods specified by NRCE to compensate for climate data limitations are acceptable approaches that provide good estimates of crop water requirements.

2. The method NRCE uses to fill and extend temperature and precipitation data produces similar results to the analysis performed by the State's experts.

3. The weather stations at the Gallup Airport and Albuquerque International Airport show sufficient correlation to fill and extend the climate data (wind, solar radiation, and dew point temperature) record at Gallup. Furthermore, comparisons of Gallup weather data with

Remote Automated Weather Stations in the basin show that the climate at Gallup is similar to the basin for these parameters.

4. Appropriate adjustments to climate data from "non-reference" weather stations allow for the use of the data in the ASCE 2005 Penman-Monteith ET equation.

5. The Penman-Monteith is the method NRCE prefers to calculate evapotranspiration when adequate climate data is available or when methods can estimate such data. Research has shown the Penman-Monteith method to be more accurate than other methods of calculating ET.

6. The State's expert, Longworth (2010), estimates "consumptive irrigation requirements" based upon historical crop yields, which results in lower estimated water requirements than what is calculated using any evapotranspiration equation. Using historical yields does not adequately determine crop water requirements.

7. The accuracy of the crop yield data used by the State's expert is questionable. There are various reasons recorded crop yields are lower than potential yields, not all of which relate to crop water use. These reasons include:

    - Yields over a long period cannot be directly related to water use because yields have improved over time due to harvest efficiencies, crop varieties, and improvements in fertility and crop management.

    - The historical reported yields are subject to inaccuracies and inconsistencies. The fact that the reported yields are all rounded-off values in the BIA crop reports indicates that not all yields are measured.

    - Historical yield data is vulnerable to environmental factors and management practices that impact the accuracy of the ET and crop yield relationship. The State's expert, Longworth, uses equations that researchers developed under research conditions using modern crop varieties. These equations have not been, and cannot be, verified for application to historical yield data derived from uncontrolled conditions, unknown management practices, and unspecified crop varieties.

- Weather conditions such as late or early frosts, and/or damage by disease, insects, rodents, or wildlife will result in lower yields per acre without lowering water use.

- Crop damage and grazing can alter the amount of acreage harvested, further decreasing yield and skewing the relationship between yield and water use.

8. Using average (which is approximately the median) rainfall for computing effective precipitation overstates the historical precipitation component in half of the years. Using 80 percent exceedance rainfall for estimating the irrigation requirements is a more appropriate basis for determining irrigation water requirements.

9. On-farm and conveyance efficiencies used by the State's experts (Franzoy, 2010, and Longworth, 2010) are similar to values used by NRCE. The efficiencies are not measured, but are estimates based upon on-farm irrigation methods and irrigation conveyance systems.

10. Depletion consists of consumptive irrigation requirement plus consumptive losses in delivery and drainage systems. For irrigation conditions on the Zuni Reservation NRCE estimates consumptive losses (in addition to crop ET) to be 9.2 to 11.6 percent of irrigation diversions depending on the irrigation conveyance system.

11. The irrigated acreage presented by NRCE is a composite acreage and does not purport to represent land that the Zuni have irrigated in any single year.

12. Wear (2010) disagrees with three of the 293 ditches that are mapped by NRCE. While these ditches are included in the survey maps, NRCE acknowledges they do not directly irrigate any acreage. Two collect runoff at Pescado and the other one delivers water to a stock pond, most likely for livestock use, in Ojo Caliente.

13. The BIA developed the 1956 maps to estimate the agricultural diversion requirements for the Zuni Reservation for purposes of the *Arizona v. California* case. NRCE received the accompanying engineering study report (Exhibit #36 from the AZ v. CA case) after the submission of the November 2008 expert report. These maps generally support the irrigated areas as mapped by NRCE. However, some differences between these maps and NRCE's work are to be expected.

14. NRCE did not base its work on the available water supply at each agricultural area. The analysis presented concerns those areas evidencing past and present irrigation by permanent irrigation works and the determination of consumptive irrigation requirements. In the Zuni River Basin, as in most places in New Mexico and throughout the southwestern United States, irrigation shortages have occurred and will continue to occur in the future.

2 CLIMATE ANALYSIS

This section pertains to the climatological analysis required for the various evapotranspiration (ET) methods used by NRCE, the State, and Amec in this adjudication. This section addresses questions from the State's consultants concerning the appropriateness and accuracy of NRCE's methods used to fill and extend missing data at weather stations and whether or not the weather stations used in NRCE's analysis are representative of conditions on the Zuni Reservation. Table 2-1 is a comparison of the annual average of climate data computed by NRCE for the United States and Brengosz (2010) for the State.

Apparently, Brengosz did not adjust the maximum and minimum air temperatures for aridity effects (whereas NRCE follows procedures in FAO-56 that include such adjustments) because for the common period (1991-2004) the reference ET she calculated is higher than that calculated by NRCE. Brengosz also does not use dew point temperatures recorded at Gallup, but rather estimates it from the minimum temperature using equation E.1 in ASCE (2005). The average wind speed used by Brengosz is the same as that used by NRCE. The average solar radiation used by Brengosz is lower than that used by NRCE and would decrease reference ET. Therefore the higher reference ET calculated by Brengosz must be due to higher temperatures resulting from not adjusting observed temperatures for weather station aridity. This difference is greater during the summer irrigation months when the effects of weather station aridity have a much larger impact on evapotranspiration estimates due to higher air temperatures. Section 2.3 of this report further explains this correction of air temperatures for non-reference conditions.

Table 2-1: Comparison of NRCE's and the State's Zuni Climate Parameters (1991-2004 Averages)

	NRCE Data from Weather Stations	NRCE Data Adjusted for Non-Reference Conditions	Brengosz (2010)
Reference ET (in)	Not Computed	53.7	56.9
Max Temperature (F)	69.8	68.0	69.9
Min Temperature (F)	33.8	32.0	33.8
Precipitation (in)	12.3		12.2
Wind (mph)	5.0		5.0
Solar (MJ/m^2)	19.0		18.4
Dew Point Temp (F)	27.3	29.8	29.6

2.1 Selection of Weather Stations and Filling of Missing Data

NRCE, the State's consultants, and Amec use daily temperature and precipitation records that are available from several weather stations within the Zuni river basin. These stations include Zuni (#9897), Black Rock (#1018), McGaffey 5 SE (#5560), El Morro National Monument (#2785), and Fence Lake (#3180). Additional data such as dew point temperature, wind speed, and percent sky cover is from the Gallup Airport (#23081) and Albuquerque International Airport (#23050), which are located outside of the Zuni basin. The ASCE 2005 Penman-Monteith procedure used by NRCE requires dew point, wind, and sky cover (used to calculate solar radiation). Longworth (2010), on page 22 of his report, expresses concern that the filling procedures used by NRCE to estimate missing data are not representative of the climate in the Zuni basin. This section presents analysis that shows a high degree of correlation between these weather stations, indicating that they are adequate for data filling and extension for the purposes of estimating average annual irrigation requirements.

2.1.1 *Temperature*

NRCE agrees with Brengosz's assessment that the temperature records for the weather stations within the Zuni basin are generally complete for the length of record available. Therefore, the stations within the basin are adequate to fill all missing temperature data as done by NRCE and the State. There is, however, a potential issue regarding the missing temperature record filling procedure used by Brengosz. Brengosz (2010) states that:

> The Zuni, Black Rock and El Morro stations were used for data replacements for each other when data were available and surrounding days were similar and Gallup was used for data replacements at Zuni after 1973.

It is not clear if Brengosz fills missing temperature data at a station by directly substituting data from one station to another or if the State used an appropriate statistical analysis, such as linear regression as described in FAO-56 Annex 4 (FAO, 1998). While the differences between observed temperatures at each station are minimal, filling procedures that consider the statistical relationship between stations are more appropriate. It is also not clear how Brengosz selected the "filling station. " Is the nearest station used? Is the station with the highest correlation used? Is the station with the most complete record used? Additionally, the State uses the same temperature estimates for each agricultural area, which does not consider the effect that the elevation differences of each of the agricultural units has on temperature.

The primary stations relied upon by NRCE for developing the temperature inputs are the Zuni (#9897) and McGaffey (#5560) stations for the period 1948 through 2004. NRCE selected the McGaffey station, in addition to the Zuni station, due to its close proximity to the irrigation project at Nutria. Longworth (2010), on page 21 of the State report, notes that the Black Rock station (#1018) can be used to extend the Zuni station's period of record to include several earlier years. NRCE did not include these additional years because the analysis using Zuni and McGaffey weather stations needed a common period of record. NRCE's analysis uses the longest period of record in common between the Zuni and McGaffey stations, which is years 1948 through 2004 (at the time NRCE conducted the analysis). This ensures that the averages computed at each station consider the same period.

2.1.2 *Precipitation*

There is a high degree of spatial and temporal variability between precipitation events. NRCE's approach (NRCE, 2008) included statistical analysis of several weather stations within and in close proximity to the basin. While this method increases the complexity of NRCE's precipitation analysis, as discussed by Longworth (2010) on pages 22-23 of his report, the monthly and annual precipitation is very similar to values resulting from the State's analysis. Brengosz's methodology found that the average annual precipitation at the Zuni weather station for the period 1949-2008 is 11.98 inches (Brengosz, 2010) whereas NRCE's methodology found that the average precipitation at the same station for the period 1948 through 2004 is 11.73 inches (NRCE, 2008). Despite using different methods and using a slightly different period of record, this difference has a minimal impact on the consumptive irrigation requirements.

There is a potential issue regarding the missing precipitation record filling procedure used by Brengosz. Brengosz (2010) states that:

> Missing precipitation data were generally replaced with an average of the nearby stations for the day, and "accumulated" readings noted in the data were distributed to the preceding days based on the relative amount of precipitation at the nearby stations.

As with the procedure used to fill missing temperature data by the State, it is not clear what methods Brengosz used to fill missing precipitation data. The term "replaced" would imply that the State used direct data substitution instead of an appropriate statistical filling method. The State's experts use the same precipitation estimates for each agricultural area, which does not consider the effect that elevation has on precipitation (refer to Section 2.4).

2.2 Additional Parameters Required by Penman-Monteith Method

The ASCE Standardized Reference Evapotranspiration Equation Penman-Monteith method requires additional climate parameters not recorded by weather stations in the Zuni basin, such as daily dew point temperature, wind speed, and solar radiation. FAO-56 (FAO, 1998) provides procedures for evaluating if data from one station provides an acceptable statistical relationship to fill missing data at nearby stations. The temperature-based Blaney-Criddle or Hargreaves-Samani methods do not require these additional parameters. The nearest station with substantial records for dew point, wind, and percent sky cover is located at the Gallup Airport. Albuquerque International Airport provides several additional years of record, which NRCE uses to fill and extend missing data for Gallup.

Remote Automated Weather Stations (RAWS) collect humidity, wind, and solar radiation data within the Zuni River basin. The data is for limited periods and is not suitable for developing long-term averages. However, even when considering the limited RAWS data available, no major variations of climate between the locations are apparent. The average wind speeds during the irrigation season at Gallup is about 1 percent higher than the average wind speed for the irrigation season for the average of Zuni Buttes, Zuni, and Ramah RAWS sites. The differences in the measured solar radiation among the sites are likely a result of sensor calibration or maintenance as discussed by Brengosz (2010). As a result, evapotranspiration calculated using data from Gallup (and filled from Albuquerque) is expected to be similar to ET calculated using data collected within the Zuni Basin. Amec (2010) calculates ET using gridded climate models, which predict climate data at each agricultural location within the Zuni Reservation. Amec's (2010) calculated ET is very similar to NRCE's ET, despite using a different method to predict climatic conditions within the Zuni basin, and thus confirming that NRCE's methodology is acceptable for estimating ET within the basin.

Longworth (2010), on page 21 of his report, expresses concern that the distance between Gallup, Albuquerque, and the Zuni Reservation is too large to use climate data from these locations. Analysis by NRCE shows that the high correlation between the data at Gallup and the data at Albuquerque meet the FAO-56 criteria for filling missing days at Gallup using the procedure described in NRCE's report (NRCE, 2008). This is especially appropriate for developing annual average evapotranspiration, where daily and monthly fluctuations of climate parameters have minimal impact on averages.

FAO-56 evaluates the potential of a station to replace missing data at another based upon the coefficient of determination (r^2) and the regression coefficient (b) between the data at two stations. FAO calculates these parameters as follows:

$$r = \frac{\text{cov}_{xy}}{s_x s_y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2\right)^{1/2}}$$

$$b = \frac{\text{cov}_{xy}}{s_x^2} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Where x represents data on a given day at the filling station and y represents data for the same day at the station being filled. Variables r and b are empirical regression constants, and cov_{xy} is the covariance between X_i and Y_i. For the following analysis of data at the Gallup and Albuquerque weather stations, Gallup is the filled station, “y”, and Albuquerque is the filling station, “x”. FAO states:

> [b]oth a high r^2 ($r^2 \geq 0.7$) and a value for b that is within the range ($0.7 \leq b \leq 1.3$) indicate good conditions and perhaps sufficient homogeneity for replacing missing data in the incomplete data series. These parameters r^2 and b can be used as criteria for selecting the best nearby station (FAO, 1998).

NRCE considers averaged daily values in this analysis because the daily variations between data have a minimal impact when estimating the average evapotranspiration on an annual basis.

2.2.1 *Dew Point Temperature*

The correlations between data at the Gallup and Albuquerque stations are quite high, showing that the relationship between the two stations is adequate for filling dew point temperatures at Gallup. Figure 1 is a plot of the average daily dew point temperature for Gallup and Albuquerque. This shows very similar daily averages computed from overlapping period of record between the two weather stations. This overlapping period of record exists from 1973-2004.

Figure 2 is a plot of the daily dew point temperatures observed at Gallup and Albuquerque on the same day for the overlapping period of record. For these data sets $r^2 = 0.97$ and $b = 0.88$ for the overlapping period of record. Both values of r^2 and b satisfy the criteria in FAO-56. The excellent correlation of the average daily dew point temperatures indicates that the data sets provide good long-term average estimates for use in the ASCE P-M standardized equation to estimate average annual evapotranspiration.

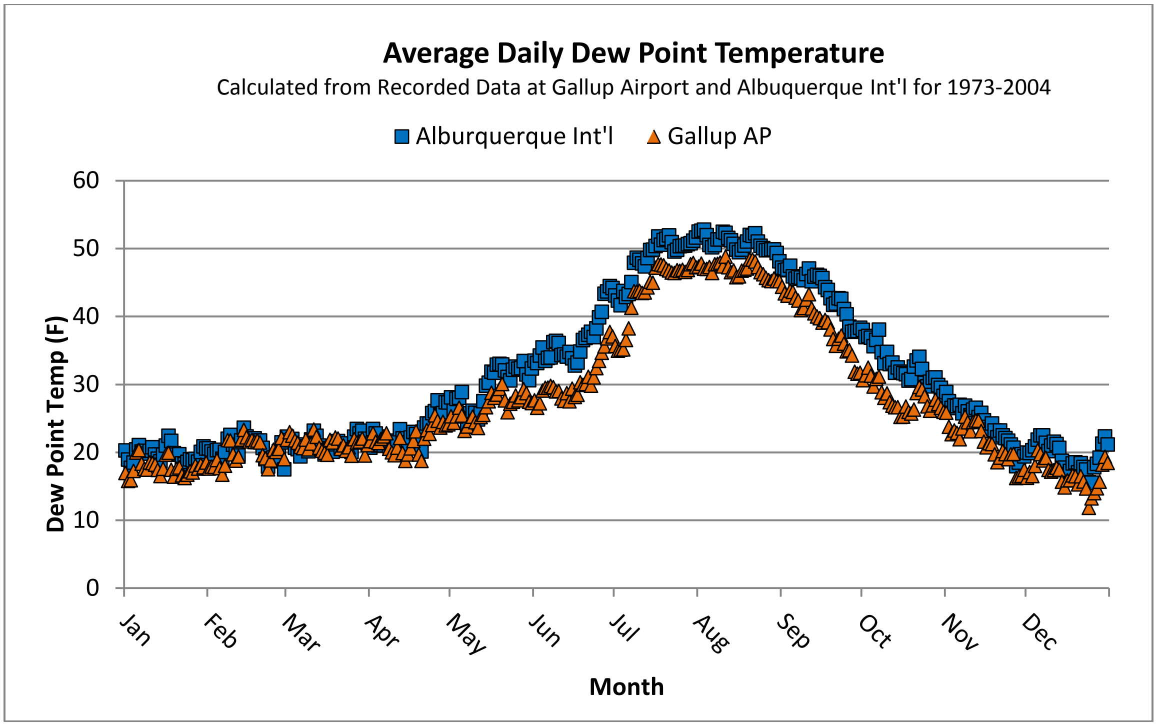

Figure 1 – Average Daily Dew Point Temperature (T_{dew}) at Gallup and Albuquerque

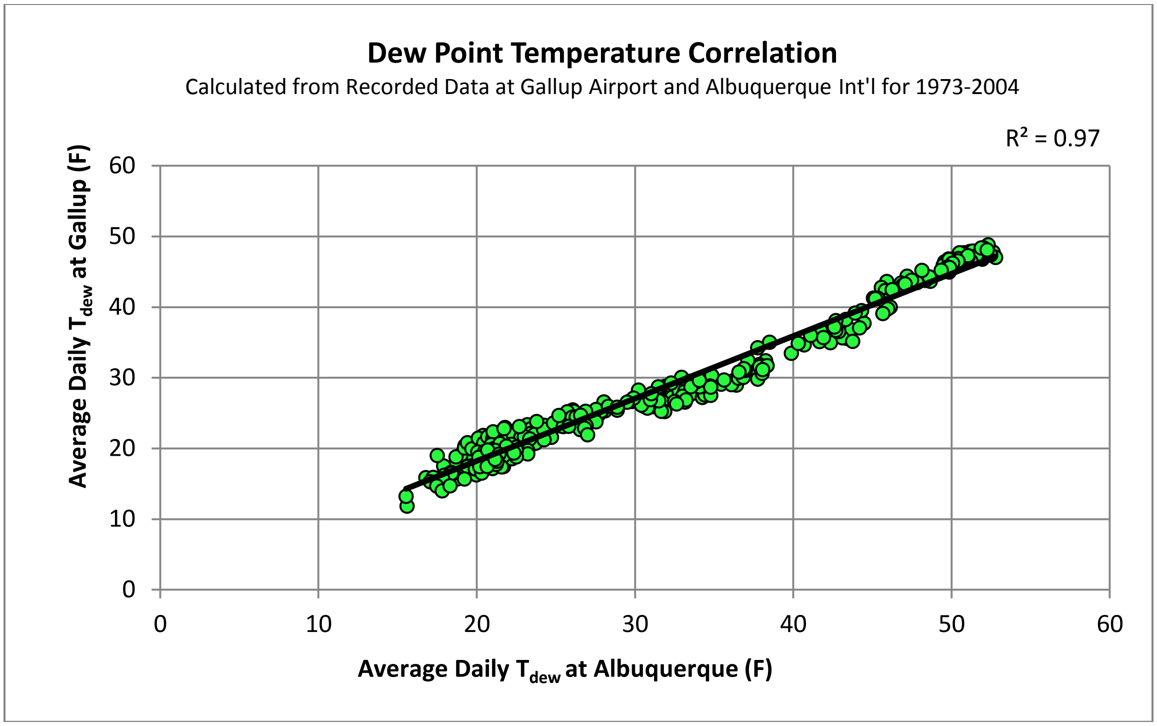

Figure 2 - Average Daily Dew Point Temperature (T_{dew}) Correlation between Gallup and Albuquerque

2.2.2 *Wind Speed*

In a similar fashion as dew point temperature (see section 2.2.1), the wind speeds between the Gallup and Albuquerque Airports can be compared. Hourly and daily wind speeds can vary a great deal between nearby stations, but these variations become smaller by averaging the wind speeds over longer periods (ASCE, 2005). The average daily wind speeds for the overlapping period of record between the two stations shown in Figure 3 show relatively similar seasonal wind patterns. Figure 4 shows the correlation between these daily averages. For these data sets r^2 = 0.77 and b=1.09 for the overlapping period of record. The good correlation of the average daily wind speed indicates that the filling of wind speed at Gallup from Albuquerque data provide good long-term average estimates for use in the ASCE P-M equation.

The average wind speeds recorded at Albuquerque International Airport are higher than speeds at Gallup. The filling methods as described by NRCE (2008) use the ratio of the monthly means between the stations to account for this effect.

The wind speeds shown in Figure 3 and Figure 4 are at an assumed anemometer height of 10 meters, which is a common height at airport weather stations. For input in to the

ASCE P-M Equation, NRCE (2008) adjusted wind measurements to a height of 2 meters using the logarithmic wind profile equation given in the ASCE text.

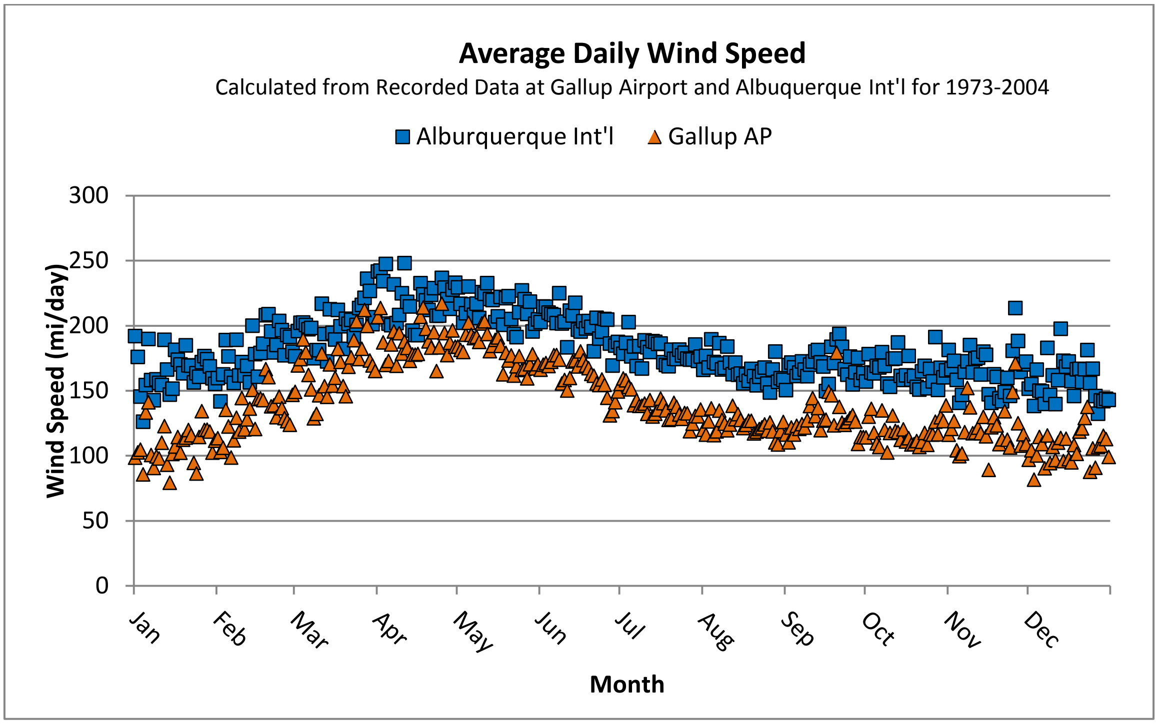

Figure 3 - Average Daily Wind Speed at Gallup and Albuquerque

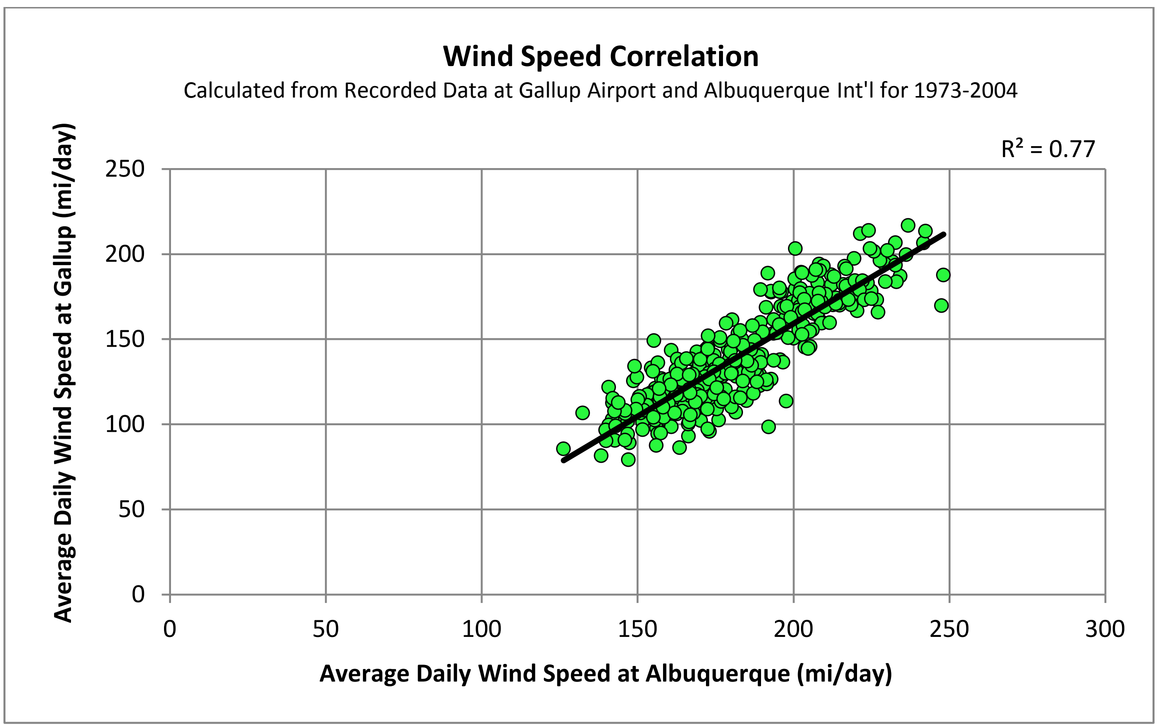

Figure 4 - Average Daily Wind Speed Correlation between Gallup and Albuquerque

Brengosz (2010) found that the anemometer at Albuquerque has had past heights of 7.01, 10, and 14.63 meters. NRCE (2008) assumes a 10 meter height for the entire period. The result of under or over estimating anemometer heights by these magnitudes have a very minor impact on the calculation of annual crop irrigation requirements. For example, using the anemometer heights of 7.01, 10, and 14.63 meters and corresponding periods given in Brengosz (2010), the average wind speed reduction factor to adjust measured wind speeds to 2 meter wind speeds (using the ASCE 2005 wind profile equation) is 0.767 for 1948 through 2004. The factor computed assuming a 10 meter height for the entire period of 1948 through 2004 from NRCE (2008) is 0.748. This difference is 2.5 percent, which would not significantly influence ET results.

2.2.3 *Solar Radiation*

NRCE (2008) estimates solar radiation from the percent sky cover at Gallup and Albuquerque. Figure 5 and Figure 6 are plots of the average daily observed sky cover and global solar radiation calculated from the sky cover data at each of the stations for the overlapping period of record. Both figures show strong seasonal correlations at each site. Figure 7 is a plot of the daily solar radiation observed at Gallup and Albuquerque on the same day for the overlapping period of record. For these data sets the $r^2 = 0.98$ and $b = 0.99$ for the overlapping period of record. Both values satisfy the criteria for r^2 and b given in FAO-56. The excellent correlation of the average daily solar radiation indicates that the data sets provide good long-term average estimates for use in the ASCE P-M equation to estimate average annual evapotranspiration.

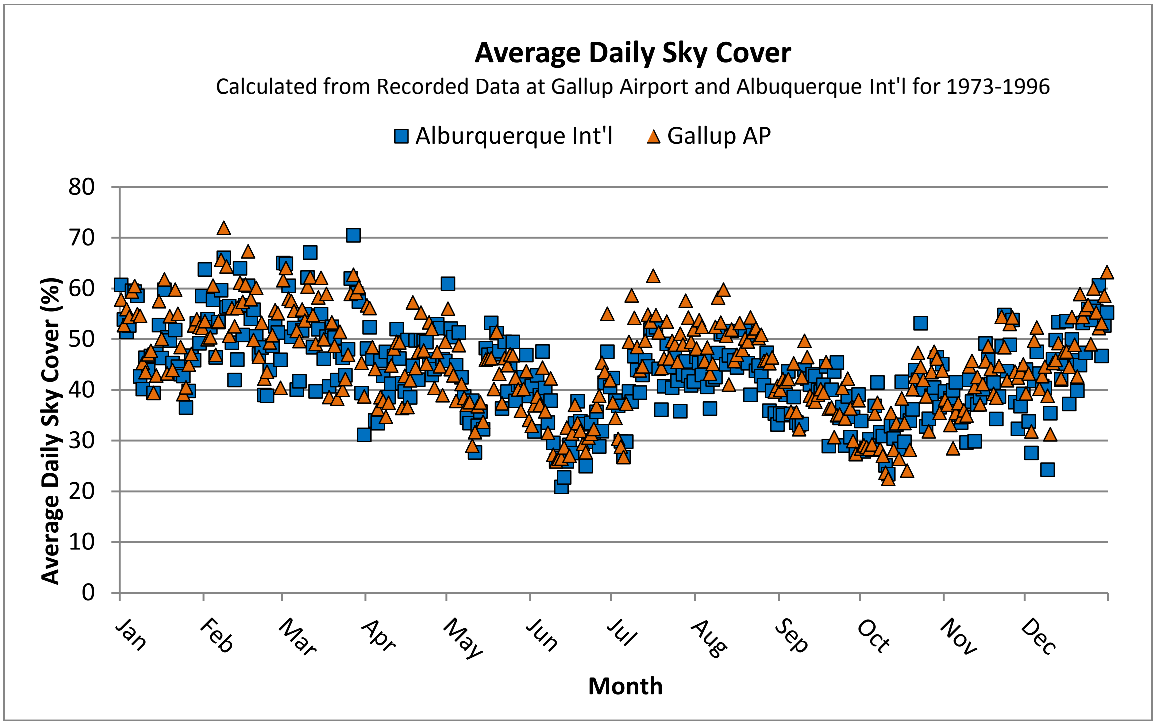

Figure 5 - Average Daily Sky Cover at Gallup and Albuquerque 1973-1996

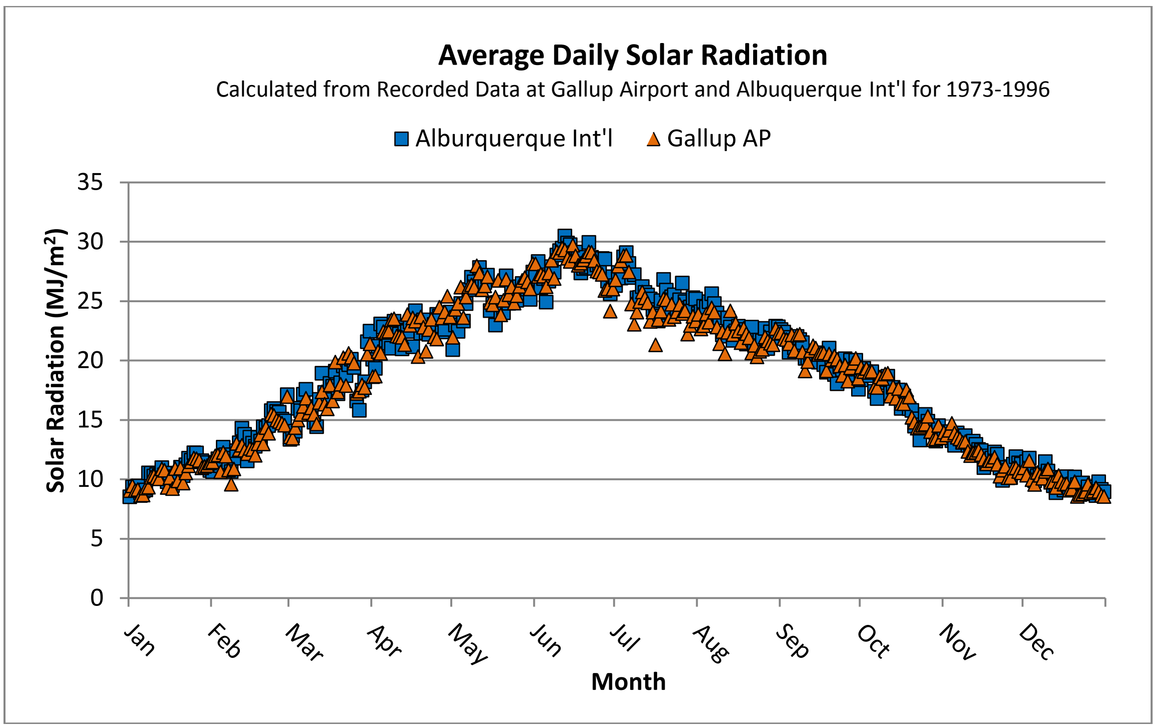

Figure 6 - Average Daily Solar Radiation at Gallup and Albuquerque 1973-1996

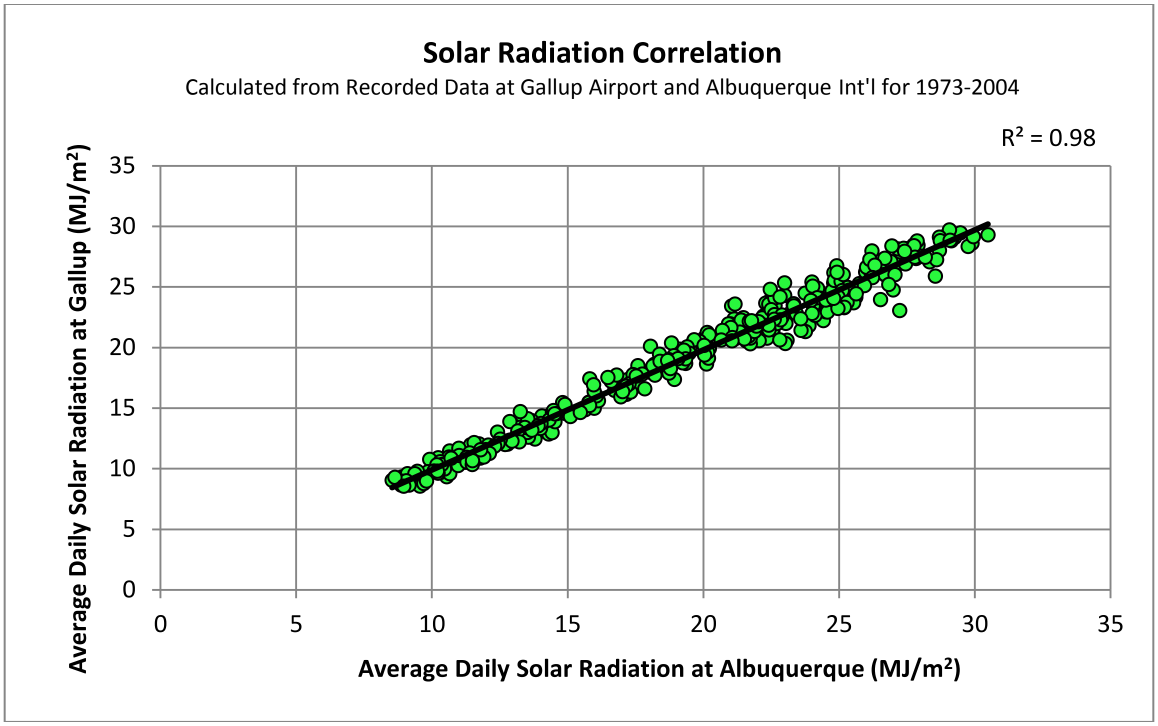

Figure 7 - Average Daily Solar Radiation Correlation between Gallup and Albuquerque

NRCE's (2008) procedure for estimating incoming solar radiation uses measured sky cover at Gallup. This procedure reduces the global clear-sky solar radiation by computing a "cloud factor" (f_{cloud}) from sky cover data. This method uses an empirical relationship developed by the Tennessee Valley Authority (TVA).

The experts for the State question the validity of using the TVA relationship in the state of New Mexico (Longworth, 2010). A comparison of NRCE's solar radiation to the State's analysis shows that the TVA procedure is valid. Brengosz (2010) uses solar radiation from the National Solar Radiation Data Base (NSRDB), which is a nation-wide solar radiation dataset developed by the National Renewable Energy Laboratory under the U.S. Department of Energy. The NSRDB uses solar radiation measurements from the National Climatic Data Center. Figure 8 compares the monthly solar radiation at Gallup, averaged for the years 1991-2005 for the NSRDB and 1991-2004 for NRCE (NRCE's analysis did not include years after 2004). The monthly NSRDB values shown in this figure are from the appendix of Brengosz's report. The values calculated by NRCE closely agree with those presented by Brengosz (2010) from the NSRDB. This close agreement shows that NRCE's use of this TVA equation has not resulted in any significant disagreement with the solar radiation analysis performed by the State's expert.

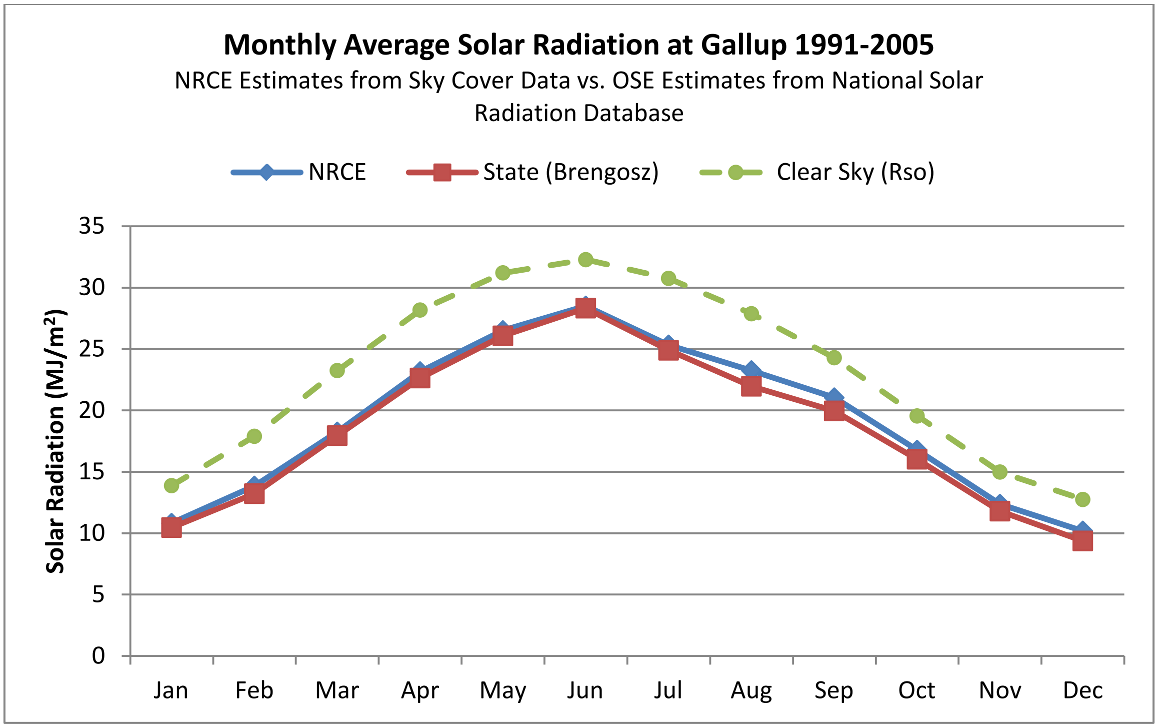

Figure 8 - Monthly Solar Radiation at Gallup, Estimates from NRCE's Sky Cover Data vs. Brengosz (2010)'s Radiation Estimates from NSRDB

2.3 Aridity Adjustments

Longworth and Brengosz questioned the validity of data for use in the ASCE P-M equation because the settings of the weather stations are in "non-standard" conditions. The State's consultants have made the following statements regarding this issue:

> The idealized approach proposed by the experts for the United States is complicated by the fact that they must obtain significant amounts of data from non-standard conditions (Longworth, 2010).
>
> Arid conditions at the weather station can cause overestimation of reference ET (Brengosz, 2010).

ASCE describes the preferred setting of a weather station as having "low growing, well-watered vegetation in the immediate and near vicinity of the weather station (~50 m) and mostly the same or other well-watered vegetation for a few hundred meters beyond that" (ASCE, 2005). NRCE, as well as the State's experts, observe that the weather stations within the Zuni basin do not meet these criteria. However, this does not mean that the Penman-Monteith equation is not valid. The following citation is from ASCE (2005):

> Failure of a weather station site to meet the definition of a reference condition described above does not preclude use of the data for estimation of ET_o. However, data from such a station should be examined carefully before use, and may, in some cases, require adjustment to make the data more representative of reference conditions.

FAO-56, in Annex 6, (FAO, 1998) contains specific procedures to adjust air and dew point temperatures observed at a site whose setting is in a non-standard condition for use in the Penman-Monteith equation. NRCE applied these adjustments to the climate parameters following this methodology. NRCE's report (2008) describes this procedure in detail on page F1.

2.4 Lapse Rates

The irrigated agricultural areas on the Zuni Reservation are located at various elevations. However, none of the experts for the State considered this in their analysis. The NRCE (2008) report shows that there is a strong correlation between annual temperature and precipitation with elevation in the region. An annual lapse rate can be determined using several weather stations at various elevations (NRCE, 2008).

2.4.1 *Application of Lapse Rates*

Longworth (2010), on pages 21 and 23 of his report, argues that elevation adjustments to temperature and precipitation are not necessary. NRCE has found that these elevation differences result in crop water use that varies from area to area. For example, these elevation differences account for approximately three inches of reference ET (48.56 inches at Nutria vs. 51.55 inches at Zuni (NRCE, 2008)) or two inches of crop irrigation requirement (22.79 inches at Nutria vs. 24.86 inches at Zuni (NRCE, (2008)). The weather stations within the Zuni Basin are also not at the same elevations, which influences the measured precipitation. For example, the McGaffey station at 8,000 feet receives an annual average total of 19.1 inches of precipitation and has an average daily temperature of 43.1°F. In contrast, the Zuni station at 6,300 feet receives an annual average total of 12 inches of precipitation and has an average daily temperature of 50.7°F.

The use of lapse rates in NRCE's 2008 analysis is consistent with methodology used to adjust temperature and precipitation due to elevation. The PRISM Climate Model (PRISM, 2011) and the US Geological Survey (USGS, 2005) both use this methodology to generate temperature and precipitation maps. Temperature lapse rates result from the adiabatic process in which the temperature of a mass of air increases as it compresses due to the increased atmospheric pressure at lower elevations and decreases at higher elevations due to expansion at lower atmospheric pressure.

Brengosz (2010) uses climate data from the Zuni weather station (#9897) for temperature and precipitation, which is located at an elevation of 6,300 feet. The approximate elevations of the irrigated areas range from approximately 6,200 feet in the Zuni, Tekapo, and Ojo Caliente areas to 6,800 feet at the Nutria project (NRCE, 2008). The result of not including elevation adjustments leads to an overestimate of ET at elevations above the weather station and an underestimate of ET at elevations below the weather station. Inversely, precipitation is higher at elevations above the station and less at elevations below the station. A further explanation of these relationships is in the NRCE (2008) report.

NRCE included the McGaffey station due its close proximity to the Nutria agricultural project. The Nutria project exists 18 to 20 miles from the Zuni weather station (#9897) and only seven to ten miles from the McGaffey weather station (#5560). Therefore, NRCE uses the McGaffey station (with elevation adjustments) to determine the climate at Nutria. Longworth (2010), on page 23 of his report, points out that the McGaffey 5 SE (#5560) weather station used in NRCE's analysis is at an elevation of 8,000 feet, which is well above the Nutria agricultural site of 6,800 feet. Because of the elevation difference, NRCE applied the elevation adjustments. Using un-adjusted data, the ET calculated for Nutria would be erroneously low because the temperatures recorded at McGaffey are much lower than the temperatures at Nutria.

2.4.2 *Use of Annual Lapse Rates*

Longworth (2010) questions the appropriateness of applying the annual average lapse rate to daily data. The purpose of the NRCE 2008 analysis is to estimate average annual evapotranspiration, not daily evapotranspiration. Because NRCE's analysis determines the average annual crop water requirements, annual lapse rates are adequate.

2.4.3 *Changes in Solar Radiation due to Elevation*

Longworth (2010), on page 22 of his report, makes the following comments regarding elevation adjustments to the solar radiation estimates:

> Allen did not adjust the sky cover for elevation. He did adjust dew point temperatures, used in the solar radiation equations, for the elevation bands, and this appeared to result in small changes in solar radiation for the 600-foot elevation change in the elevation bands. However, the dew point temperatures were derived from the Gallup and Albuquerque airports and data were not available at other weather stations to investigate the validity of the adjustments.

Sky cover depends on atmospheric conditions resulting in clear or cloudy days. The sky cover has little correlation with changes in elevation of 600 or 700 feet; accordingly, there is no reason to adjust sky cover for elevation. In the equations used by NRCE (2008), the slight changes in radiation due to elevation are from the lapse rate impact on the dew point temperature. In a basin such as the Zuni River basin, higher elevations result in lower air and dew point temperatures, due to temperature lapse rates. The ASCE (2005) recommended method to calculate clear-sky short wave solar radiation includes the atmospheric pressure, which is a function of elevation; higher incoming radiation occurs at higher elevations. Section 2.2 of this report discusses the validity of using the Gallup and Albuquerque airport data in analysis.

2.5 Filling Solar Radiation

2.5.1 *Filling Missing Solar Radiation Data*

NRCE found that various methods to estimate missing solar radiation data are necessary. The three situations encountered by NRCE when filling the solar radiation data were: (1) the extension of the record at Gallup before the year 1973 where data from Albuquerque is available, (2) the estimation of missing data for very short periods of time, and (3) the filling of missing data at Gallup when Albuquerque is also missing data for the overlapping periods where lack of data makes linear regression unavailable. Discussions of these filling methods are in the appendix of the NRCE report (NRCE, 2008) and summarized in Table 2-2 below.

Table 2-2: Methods Used by NRCE to Fill Solar Radiation Data

Situation	Filling Method	Years Applied	Comments
Missing sky cover data at Gallup	Linear Regression	1948-1973	The data at Gallup are extended using linear regression from the records at Albuquerque International Airport.
	Linear Interpolation	Various	4 days of data were filled by linear interpolation of the days before and after the missing date. The more complex methods are not necessary to fill only 4 days of data.
Missing sky cover data at ABQ and Gallup	Thornton and Running (1999)	1996-2000 & 2001-2004	Without any sky cover data available from either Gallup or Albuquerque, a method was selected to estimate the f_{cloud} parameter for these dates.

2.5.2 *QA/QC Check of Solar Radiation against Clear-Sky Radiation*

In the ASCE Standardized Reference Evapotranspiration Equation manual (ASCE, 2005), a quality control check of solar radiation data is presented that involves comparing measured radiation (R_s) values to the clear-sky solar radiation (R_{so}) curve. The daily measured R_s should “bump up” against the R_{so} curve on clear sky days and R_s should not be consistently above or below the R_{so} estimation. Longworth (2010) questions whether NRCE compared the estimated solar radiation with the theoretical clear sky-solar radiation.

The quality check that Longworth refers to does not apply to NRCE’s analysis because the analysis does not include any measured R_s data. The weather station records from Gallup and Albuquerque are percent sky cover due to clouds. As described in the equations in the NRCE (2008) report, R_s is determined as a fraction of R_{so} by multiplying the R_{so} by a “cloud factor” (f_{cloud}). Therefore, the R_s values will always bump-up against the R_{so} curve on cloudless days and R_s would never be consistently above or below the clear sky curve.

2.6 PRISM Gridded Climate Model

Amec (2010) utilized data from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) gridded climate model for maximum and minimum temperatures, dew point temperature, and precipitation on both monthly and annual bases (PRISM Climate Group, 2011). The figures below compare the results from the PRISM model to results calculated by NRCE (2008 and 2009) from National Climatic Data Center datasets (NCDC, 2002). Figure 9 through Figure 12 show general agreement between the climatic parameters from these two sources. Figure 9 through Figure 12 include elevation adjustments to the PRISM data to the same elevations used by NRCE for each area.

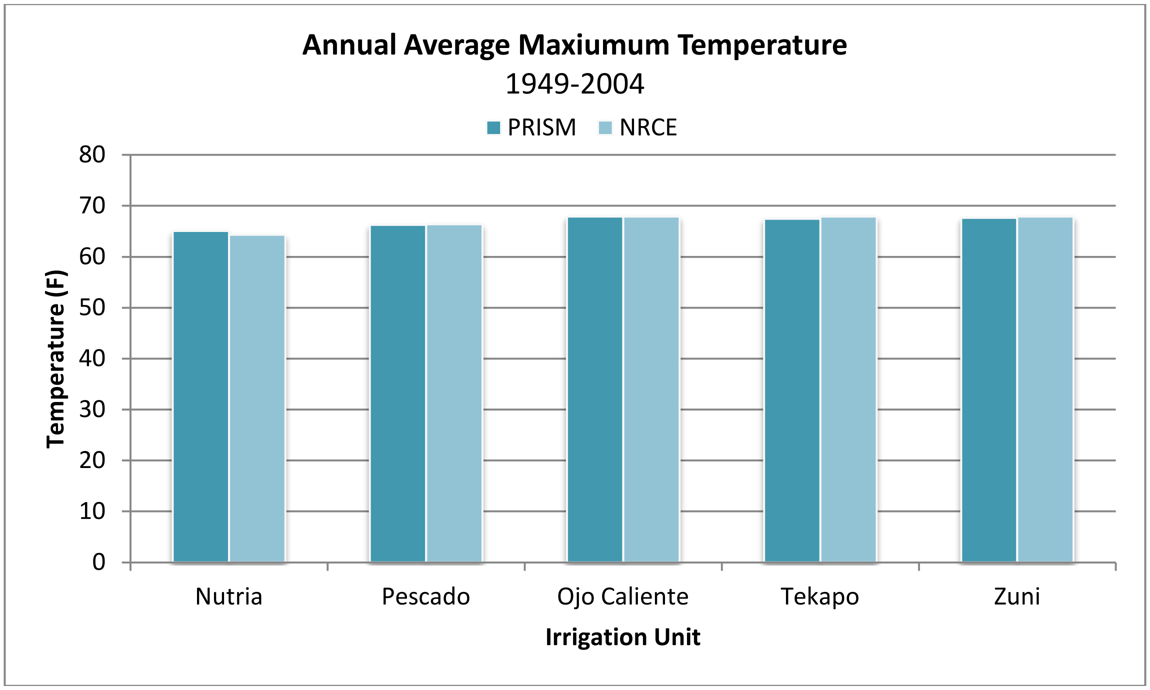

Figure 9 - PRISM vs. NRCE Analysis for Maximum Temperature

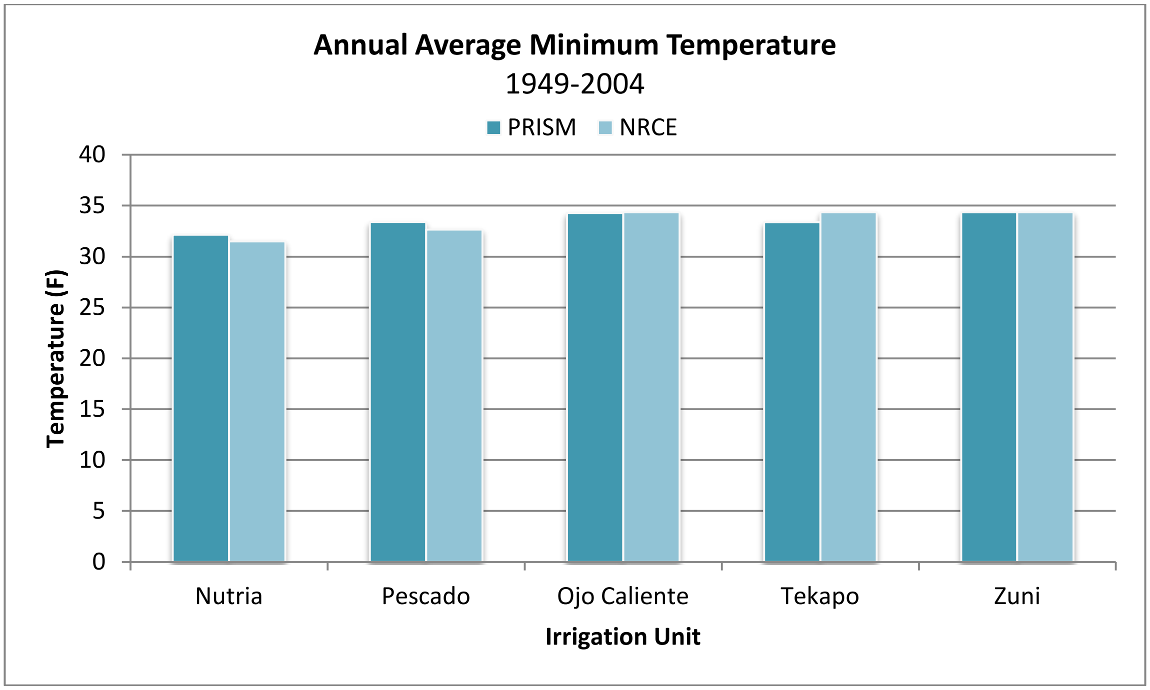

Figure 10 - PRISM vs. NRCE Analysis for Minimum Temperature

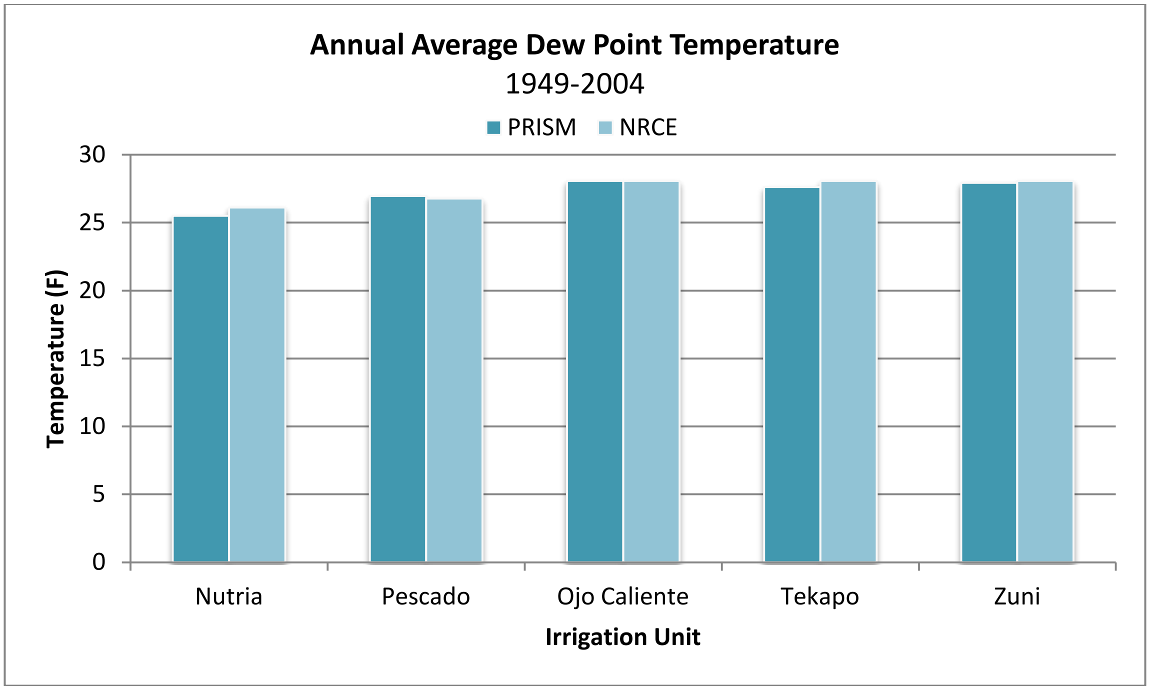

Figure 11 - PRISM vs. NRCE Analysis for Dew Point Temperature

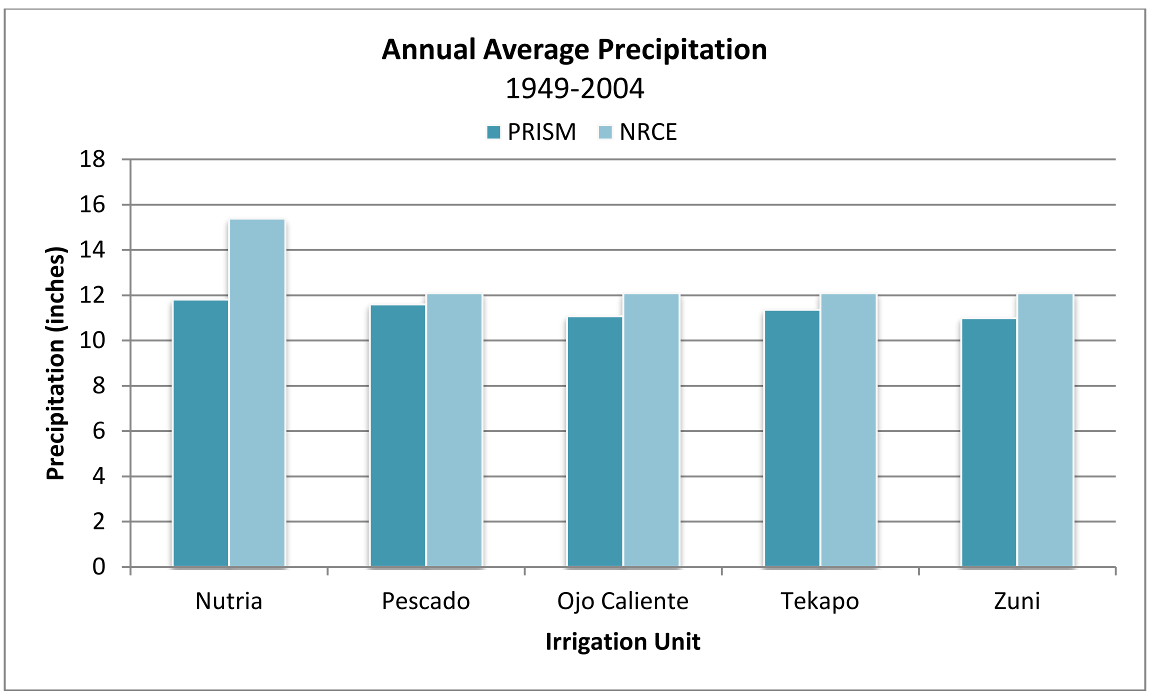

Figure 12 - PRISM vs. NRCE Analysis for Average Annual Precipitation

NRCE's analysis predicts slightly higher precipitation for the agricultural areas than the PRISM model does, particularly for the Nutria area. Analyses of the monthly precipitation totals show that the differences between NRCE and PRISM are smaller during the irrigation season than during the off-season months. The consequences of the differences in precipitation are less when considering the 80 percent exceedance precipitation during the irrigation season (see Figure 13). Furthermore, these differences have even less of an impact on the net irrigation requirement when the effective precipitation is calculated. Considering Amec's (2010) calculated evapotranspiration using PRISM, the impact of any differences between PRISM and NRCE's climate analysis is rather small (see Section 3.1).

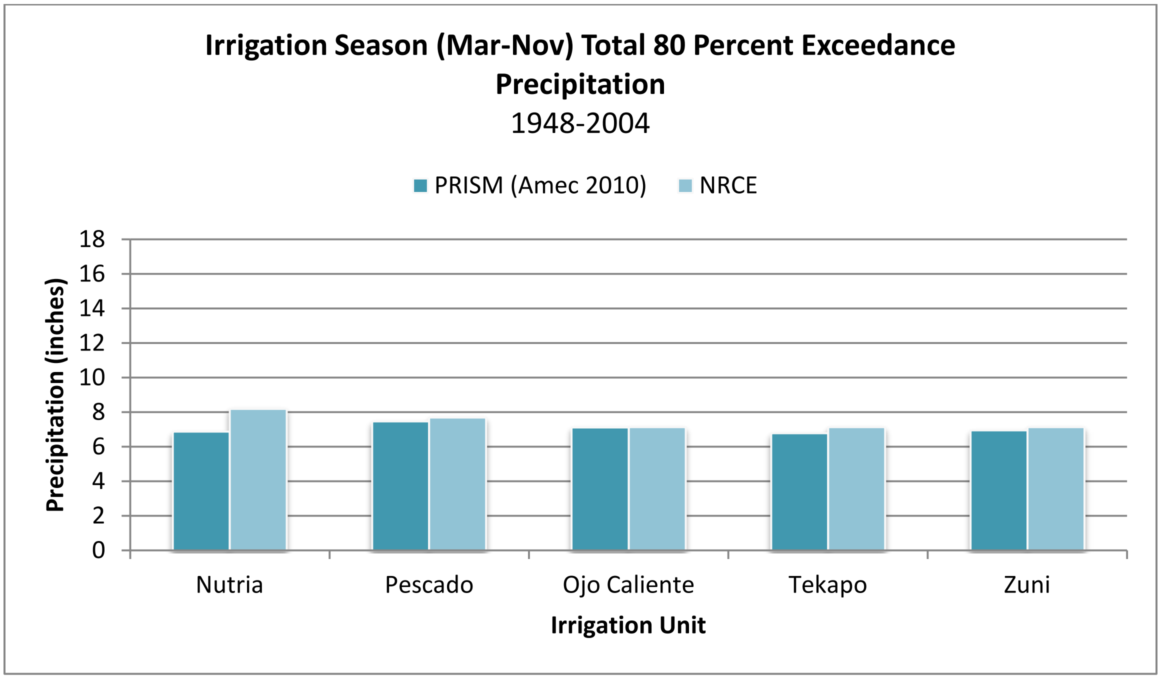

Figure 13 - PRISM vs. NRCE Analysis for 80 Precent Exceedance Annual Precipitation

3 REFERENCE EVAPOTRANSPIRATION

This section discusses the various methodologies used by NRCE, the experts for the State, and experts for Navajo Nation to calculate reference evapotranspiration (ET_o) on the Zuni Reservation.

3.1 Comparison of Experts' Analyses

Table 3-1 and Figure 14 illustrate the various results of reference evapotranspiration (ET_o) calculations on the Zuni reservation. Due to the significant differences in the development and application of the Blaney-Criddle formula (such as crop coefficients exclusive to the method), it is not included in this comparison. For comparison purposes with Brengosz's results, the reference ET listed in the table from NRCE and Amec are for the Zuni agricultural unit. The monthly ET_o amounts generally follow the same trend, with larger differences seen during the summer months.

Table 3-1: Comparison of Experts' Reference ET Estimates for Zuni

Source	Reference ET (inches)	Method	Period of Analysis
Brengosz (2010)	53.1	Hargreaves-Samani (1985)	1948-2008
Brengosz (2010)	56.41	Hargreaves-Samani (1985)	1991-2008
Brengosz (2010)	57.39	ASCE P-M	1991-2008
NRCE (2008)	51.55	ASCE P-M	1948-2004
NRCE (2008)	50.07	Hargreaves-Samani (1985)	1948-2004
Amec (2010)	51.95	ASCE P-M, using weather station data	1948-2004
Amec (2010)	50.93	ASCE P-M, using climate data inputs from gridded climate models	1948-2004

Note: ET_o for NRCE and Amec are for the Zuni unit

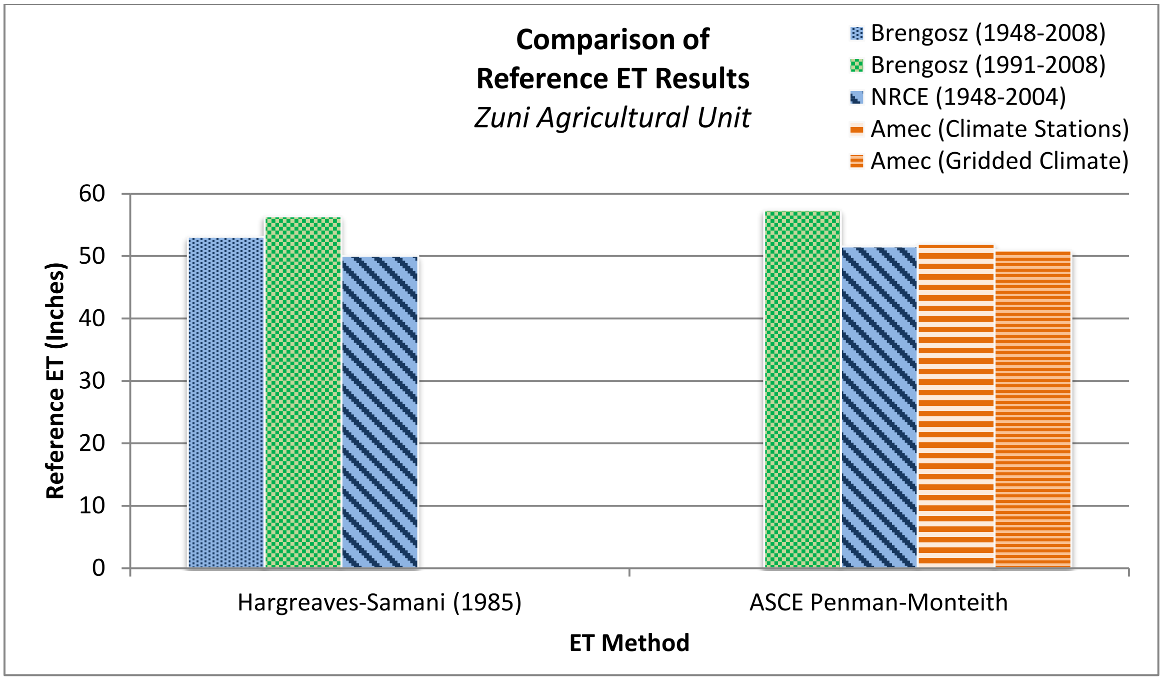

Figure 14 - Comparison of Experts' Reference ET Estimates for Zuni

Brengosz (2010) obtained higher estimates than both NRCE and Amec for evapotranspiration using the ASCE P-M method. The higher reference ET obtained by the State's expert appears to be the result of not adjusting the observed maximum and minimum temperature data to reference conditions as well as considering years with higher than average temperatures (1991-2008) when compared to the average computed from a longer period of record. NRCE (2008), Brengosz (2010), and Longworth (2010) note that the weather stations where daily maximum and minimum temperature data is collected are not located at a site that would represent reference conditions as defined in ASCE (2005). Therefore, it would also be appropriate to adjust the observed daily temperatures to account for non-reference conditions as described in Annex 6 of FAO-56 (FAO, 1998) before being input into the Penman-Monteith equations. These adjustments would decrease daily temperatures and consequently lower the estimated reference ET. Experts for the State did not present crop ET or irrigation requirements estimated from reference ET calculated using the Penman-Monteith method.

As shown in Figure 14, both Brengosz (2010) and NRCE (2008) found that the results of the ASCE P-M and Hargreaves-Samani methods of calculating reference ET yield very similar results when using the same set of climate data input.

3.2 Selection of an Evapotranspiration Equation

In addition to the ASCE P-M method, Brengosz and Longworth select the Blaney-Criddle and Hargreaves-Samani methods for their analysis. The final "consumptive irrigation requirement", on-farm requirements, and diversion requirements presented by Longworth (2010) is calculated using the modified Blaney-Criddle method with considerations for historical crop yield. By incorporating yields into his methodology, Longworth (2010) is no longer calculating a consumptive irrigation requirement that is consistent with standard definitions such as given in FAO-56 (FAO, 1998) and ASCE No. 70 (Jensen, et al., 1990). The general definition of consumptive or net irrigation requirements is; ET, leaching, and miscellaneous water requirements not provided by precipitation.

Longworth (2010) selected the Blaney-Criddle equation because it requires relatively simple climatic data, and claims that it is consistent with previous water right adjudications in the State of New Mexico. However, this method does not consider additional environmental variables that affect evapotranspiration, such as wind, actual solar radiation, and humidity. The ASCE P-M equation incorporates these parameters and is the preferred method by the American Society of Civil Engineers (ASCE, 2005), the Food and Agriculture Organization of the United Nations (FAO, 1998), and U.S. Department of Agriculture Soil Conservation Service (SCS, 1993) where such data is available or where methods can reliably estimate such data. The advancement of evapotranspiration research has developed better methods of calculating ET than the Blaney-Criddle method.

FAO (1998) recommends the use of the FAO Penman-Monteith method, which is essentially identical to the ASCE P-M method used by NRCE. FAO (1998) states, "[t]he use of older FAO or other reference evapotranspiration methods is no longer encouraged." Additionally, FAO presents the use of the Hargreaves equation as an alternative method to Penman-Monteith if solar radiation, humidity, and/or wind speed data are missing or cannot be adequately estimated (FAO, 1998). NRCE determined that both the Hargreaves and the ASCE P-M methods produce the same results and both are acceptable.

Longworth (2010) calculates the "consumptive irrigation requirement" using combinations of the Modified Blaney-Criddle method, Hargreaves-Samani method adjusted for yield using the FAO-33 method (1986) for corn, the Smeal (1995) yield vs. ET relationship for alfalfa, and the SCS TR-21 method (1970) to estimate effective precipitation. Longworth's concludes that using the Modified Blaney-Criddle method and the Smeal (1995) yield vs. ET method for alfalfa is reasonable. This results in an irrigation "requirement" that is less than both the Penman-Monteith and Hargreaves-Samani equations. Jensen, et al. (1990) is one of the most comprehensive comparisons of ET calculation methods. This ASCE publication by Jensen compares various methods of calculating ET to measured ET from lysimeters. One of the findings was that the SCS modified Blaney-Criddle method performed rather poorly compared to other monthly methods and underestimated ET in arid climates. As discussed by Jensen (1990), the modified Blaney-Criddle equation does not always adequately account for the total energy available to the plant; this is because air temperature lags behind solar radiation as an estimate of available energy.

In addition to the Blaney-Criddle methods, Longworth also presents the Hargreaves-Samani equation to calculate reference ET. In the 1990 ASCE report on ET methods (Jensen, et al., 1990), the Hargreaves-Samani equation performed reasonably well with other monthly ET calculation methods. The highest ranked method in the ASCE report is the Penman-Monteith method, which Jensen (1990) found to underestimate ET in arid climates by only one percent. Figure 15 shows plots of how well the estimated ET correlates to the lysimeter measurements at various locations for each of these ET methods. Note that the Penman-Monteith method provided the best correlation between estimated and actual evapotranspiration in these studies.

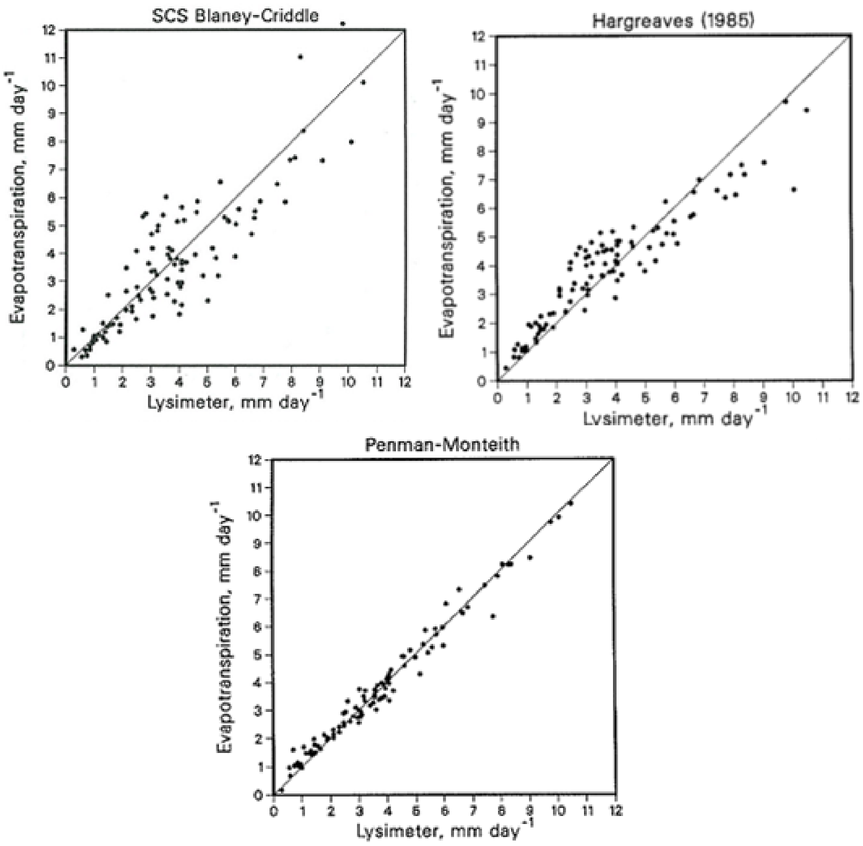

Figure 15 - Estimated ET verses Measured ET (lysimeter) for Blaney-Criddle, Hargreaves, and Penman-Monteith Methods at 11 Locations (Jensen, et al., 1990)

The following excerpt from the ASCE Manual No. 70 (Evapotranspiration and Irrigation Water Requirements) describes the importance of utilizing the best scientific practices when calculating crop water requirements, supporting the use of the more advanced Penman-Monteith method over that of other methods.

> The science of evapotranspiration has been advanced greatly during the past three decades, and is still evolving. Engineers need to adapt relationships that are based on sound physical laws and principles. Future estimates of consumptive use will need to be more accurate than in the past as the value of water increases. The legal system involved in water rights transfer can no longer justify "simple" estimating procedures if more accurate methods are available (Jensen, et al., 1990).

Over 20 years after ASCE Manual No. 70 on ET and irrigation water requirements the conclusion regarding ET methodology remains the same. In regards to the application of these ET methods to water right adjudications, Sammis, et al. (2011) states:

> State judicial courts are reluctant to use the modern methods and crop coefficients to calculate water rights because of previous court case precedents, but the Blaney-Criddle formula and the originally derived coefficients are outdated and invalid for today's agriculture production system and should be replaced with the Penman-Monteith equation when adjudicating water rights.

A technical manual prepared jointly by FAO and the International Institute for Land Reclamation and Improvement states:

> … [The Blaney-Criddle] method is not very accurate; it provides a rough estimate or "order of magnitude" only. Especially under "extreme" climatic conditions, the Blaney-Criddle method is inaccurate: in windy, dry, sunny areas, the ETo is underestimated (up to some 60 percent), while in calm, humid, clouded areas, the ETo is overestimated (up to some 40 percent) (Brouwer and Heibloem, 1986).

The USDA Natural Resource Conservation Service (formally Soil Conservation Service) has recommended the use of the Penman-Monteith method for reference evapotranspiration since 1993 (SCS, 1993). Chapter 2 (Irrigation Water Requirements) of the SCS National Engineering Handbook states:

> Because of its accuracy, the Penman-Monteith method is recommended when air temperature, relative humidity, wind speed, and solar radiation data are available or can be reliably estimated. The method can also be adjusted to the physical features of the local weather station (SCS, 1993).

Both the Hargreaves-Samani and Penman-Monteith methods are common methods for estimating crop water requirements. One advantage in using the Hargreaves-Samani method is that it requires minimal climate data. NRCE supports the use of the ASCE Penman-Monteith equation when adequate climate data is either available or can be reliably estimated. As demonstrated by both NRCE and Brengosz (2010), the Hargreaves-Samani equation produces similar reference evapotranspiration results as the Penman-Monteith, despite requiring considerably less climate data. Considering both methods yield very similar results, NRCE is confident that the ASCE Penman-Monteith equation calculates crop water requirements in the Zuni River Basin successfully.

NRCE's 2008 report includes a brief comparison between the results of the Penman-Monteith and Hargreaves-Samani methods, showing close agreement of calculated reference evapotranspiration. In the NRCE report, two Hargreaves-Samani equations are given. Dr. Samani correctly identifies that these two equations are the same except for the units (Longworth, 2010). The reason that these two equations have slightly different results in the 2008 report is due to the method used by NRCE to convert the units of ET in one equation (referred to as the Hargreaves-Samani 1982 equation in NRCE, 2008) from MJ/m^2 per day to inches of water per day. The 'latent heat of vaporization' parameter is required for this unit conversion. This term remains relatively constant throughout the irrigation season, which is constant at 2.45 MJ/kg in the ASCE text (ASCE, 2005). It is also appropriate to calculate this term using the average daily temperature as done by NRCE in the 2008 report (see section 3.4.1 for further explanation). Both Hargreaves-Samani equations presented by NRCE (2008) give identical results when using the same equation for the latent heat of vaporization.

3.3 ET Based Upon Crop Yields

The historical water use in the Longworth report relies upon studies that have determined a relationship between the seasonal yield of a crop and the evapotranspiration (ET) of the crop. In general, as the crop ET increases, the yield of that crop also increases as seen in Figure 16. As used by Longworth, the Smeal (1995) ET vs. yield relationship provides a methodology for calculating the water use of a crop based upon historical crop yield data. However, crop water use calculated in this manner is significantly less than the crop irrigation requirement estimated from various evapotranspiration methods. This is because there are numerous environmental factors other than water use that influence crop yields. Irrigation use as calculated from average yield is not a basis for determination of crop irrigation requirement and irrigation diversion requirement.

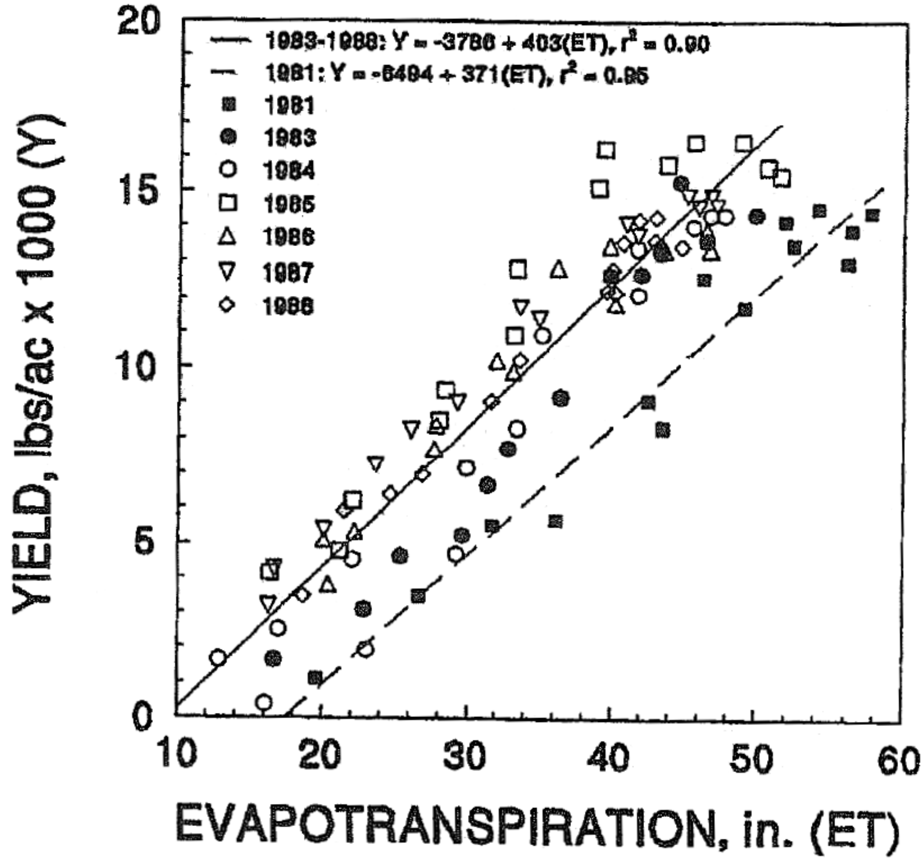

Figure 16 - Crop production function for alfalfa (Smeal, 1995)

Longworth (2010) applies the crop yield function from Smeal (1995) to estimate the consumptive irrigation requirement for alfalfa. By definition, consumptive irrigation requirement is the potential use and therefore not based upon historical yields. Consumptive irrigation requirements are computed from crop evapotranspiration, which is defined by FAO (1998) as the "evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions." Longworth estimates the consumptive irrigation requirement for the other crops in the mix using the Modified Blaney-Criddle method. Additionally, the Figure 16 shows a range of water use from about 12 inches to 58 inches during Smeal's research at Farmington, NM. The climate at Farmington is only slightly warmer than in the Zuni Basin.

Under ideal conditions yield vs. ET relationships can provide an approximation of water use, but not a quantification of water requirements. In addition to being an inappropriate method to quantify consumptive irrigation requirements, yield vs. ET has numerous other limitations. There are unavoidable uncertainties when using such yield data.

- The efficiency of crop water use per unit of water function has increased with time due to improved varieties of alfalfa that can produce higher yields with per unit water use (Jensen, et al., 1990).
- The historical reported yields are subject to inaccuracies and inconsistencies. The fact that the reported yields are all rounded-off values in the BIA crop reports indicates that not all yields are measured.
- Weather conditions such as late or early frosts, and/or damage by disease, insects, rodents, or wildlife will result in lower yields even if the crops received adequate irrigation.
- Crop damage and grazing can alter harvested acreage, decreasing yield and skewing the relationship between yield and water use.

Smeal established the crop yield vs. ET relationship in a research rather than field setting. Smeal states:

> It should be noted that this study was conducted in small plots where potential yield-limiting factors other than water (i.e., weeds, soil fertility, gopher mounds) could be carefully controlled. Under actual field conditions where management of these factors may be difficult, potential yields can be substantially reduced. Additionally, different alfalfa varieties, plant stands older than 8 years, or effects of high groundwater tables have not been considered in this analysis (Smeal, et al., 1995).

Due to these factors, the yields reported by Smeal, unlike historical yields, come close to reflecting the effect of water availability alone. Thus, while the Smeal equation can estimate the amount of water used to produce a certain yield under controlled conditions, it inevitably understates, to an unknown extent, the amount of water used to produce historic yields grown under actual field conditions. Accordingly, even if one presumes the historical reported yields to be accurate, there is no scientific basis for using the Smeal equation to determine the quantity of water beneficially used to produce those yields. It is inappropriate to use the Smeal equation to calculate irrigation requirements.

New Mexico Water Use by Categories 2005 (Longworth, 2008) provides procedures for calibrating consumptive use for alfalfa using research conducted at New Mexico State

University. This research (conducted by Sammis) is similar to Smeal's research as discussed above where a linear relationship between alfalfa yield and crop ET is developed. Longworth (2008) states that:

> If the ET predicted by [the Sammis alfalfa crop production function] was higher than the value obtained using the [Original Blaney-Criddle] method, then the predicted ET was used in determining the consumptive irrigation requirement. Using this method results in a higher estimate of water use and was only done in cases where sufficient water was available to meet irrigation demand.

Contrary to the above quotation, Longworth (2010) applies an alfalfa production function to the Zuni Basin despite the fact that this lowers the predicted ET from the Original Blaney-Criddle method. Furthermore, neither county where the Zuni Reservation exists are among the counties where Longworth (2008) applies the Sammis alfalfa production function in New Mexico Water Use By Categories 2005. It is also not clear why Longworth selects the Smeal equation over the Sammis equation for computations on the Zuni Reservation.

To calculate the historic ET of other crops (not alfalfa), Longworth (2010) applies a "stress factor" which reduces the consumptive irrigation requirement. Longworth calculates this factor from recorded crop yields following methods in FAO-56 (equation 103). However, this equation is only valid for water shortages up to 50 percent as discussed in FAO-33 (1986). Longworth (2010), on page 19, implicitly acknowledges this, stating that:

> The actual ET in this analysis using the FAO-33 method for adjusting yields was limited to no lower than 50 percent of the maximum crop ET, since the estimated actual ET values calculated with the actual yield data were substantially lower than the 50 percent amount.

This quotation suggests that the low crop yields used by Longworth for this analysis are not valid input for the FAO equation. The act of limiting any deficits to a maximum of 50 percent also means that Longworth is not actually using the yield data, but rather simply reduces the ET by half.

Furthermore, limiting a water right to a quantity based on average yields would not supply adequate irrigation for the years of higher than average yield, for example, those obtained by the Zuni Tribe in recent years, as shown in Figure 17 for alfalfa. Additional complications arise with this method because Longworth uses an average yield that is even lower than the average for the entire period of crop reports, considering only the years 1947-1950 in his analysis.

The State's consultants did not provide the crop yield data used in their reports, but it appears to average approximately 1.5 tons per acre, based on the 12 inches of so called "consumptive irrigation requirement" given in Longworth's report and about 5 inches effective precipitation presented in Brengosz's report. As indicated in Figure 17, there are years with a reported yield of 4 tons per acres which, applying Longworth's method, would imply a water use of about 30 inches per year (roughly what would result from a consumptive irrigation requirement of 24 inches per year). The "consumptive irrigation requirement" amount estimated and stated as reasonable by Longworth is only approximately half of what his own methodology calculates as the water actually used by the crops in the years with 4 ton per acre yields. Again, Longworth's assumption is that the reported yields are accurate and that average yields are a suitable basis for crop water requirements.

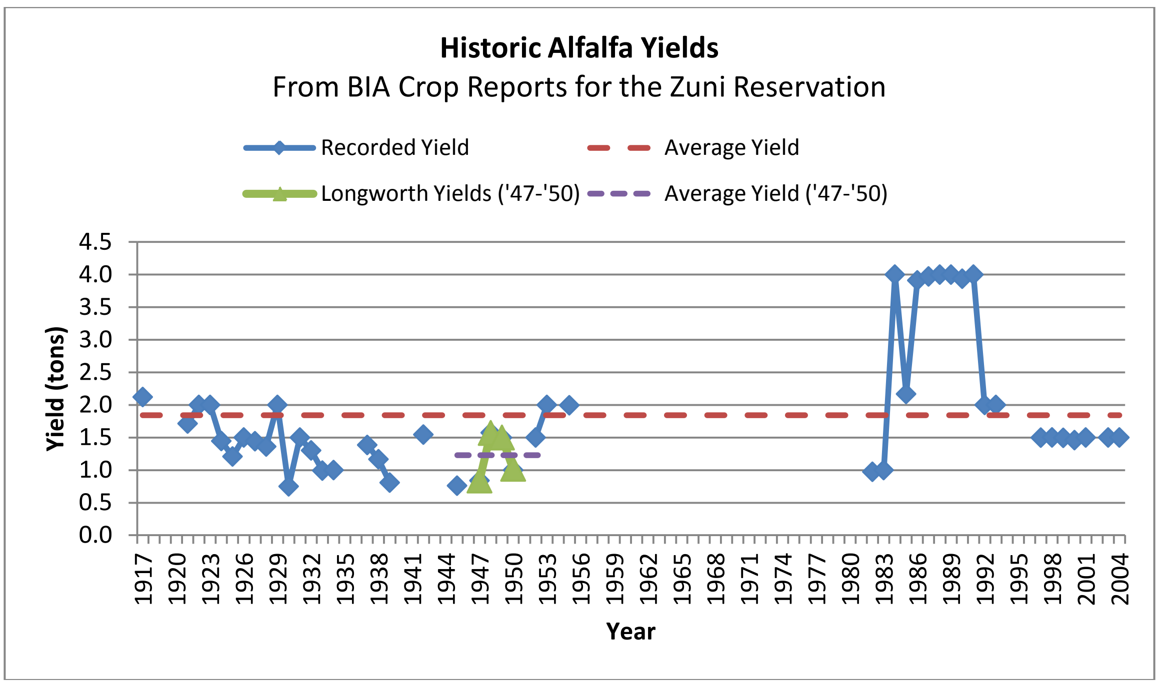

Figure 17 - Historic Alfalfa Yields 1917-2004 (BIA Crop Reports), Zuni Indian Reservation

From work for one of the parties in the Jemez River Adjudication, NRCE is familiar with the definition of consumptive irrigation requirement adopted by the Court in that case. The Jemez River Addendum to Partial Final Judgment on Non-Pueblo, Non-Federal Proprietary Rights defines the consumptive irrigation requirement (CIR) as the "maximum consumptive irrigation requirement expressed in acre-feet per acre per year for irrigation." (U.S.v. Abousleman,Civil Case Number 83-1041 JC, filed December 1, 2000, Book 1, page iv). The approach to determining consumptive irrigation requirements taken by the State's experts for the Zuni Tribe is not consistent with the definition in the Jemez River Adjudication.

3.4 Equations used by NRCE

The experts for the State of New Mexico have expressed concern because some of the equations used by NRCE deviate from the equations given in the ASCE 2005 Standardized Reference Evapotranspiration Equation manual. Longworth (2010) identifies the equations used by NRCE for the 'latent heat of vaporization' and the 'psychrometric constant' as being inconsistent with those in the ASCE manual. The following sections explain why NRCE uses different forms of these equations.

3.4.1 *Latent Heat of Vaporization*

The latent heat of vaporization, lambda (λ), is the amount of energy required to evaporate a mass of water and depends upon the ambient temperature of the air. Less energy is required for evaporation to occur when air temperatures are higher than at lower temperatures. The formula shown in Appendix F of the NRCE report (NRCE, 2008) is described in FAO-56, Annex 3 (FAO, 1998), and treats this parameter as a function of the daily average temperature (T_{avg}):

$$\lambda = 2.501 - 0.00236T_{avg} \quad \text{MJ/kg} \qquad \text{(used by NRCE, 2008)}$$

The ASCE manual simplifies the latent heat of vaporization equation as the following constant:

$$\lambda = 2.45 \quad \text{MJ/kg} \qquad \text{(from ASCE, 2005)}$$

The ASCE (2005) manual states that the value of lambda "varies only slightly over the ranges of air temperatures that occur in agricultural or hydrologic systems." ASCE assumes a constant average temperature of 20 degrees Celsius (68°F), which reduces the equation used by NRCE to the constant 2.45 MJ/kg. Thus, the formulas are essentially the same and NRCE's use of the FAO-56 version caused no significant difference in the results.

3.4.2 *Psychrometric Parameter*

The psychrometric parameter, gamma (γ), is calculated by NRCE in a manner that considers variations in daily air temperature. The formula as shown in Appendix F of the NRCE report (NRCE, 2008) is described in FAO-56, Annex 3 (FAO, 1998), and treats this parameter as a function of the latent heat of vaporization (λ) as described previously in section 3.4.1. The equation used by NRCE is:

$$\gamma = CP/(0.622\ \lambda) \qquad \text{(used by NRCE, 2008)}$$

Where C = 0.001013

The ASCE manual simplifies the psychrometric parameter equation as the "psychrometric constant":

$$\gamma = 0.000665P \qquad \text{(from ASCE, 2005)}$$

If lambda is taken as the ASCE constant (λ = 2.45 MJ/kg), then the equation that is used by NRCE reduces to the equation shown in the ASCE manual. Again, NRCE's use of the FAO-56 version is not a material difference.

3.4.3 *Solar Radiation*

As discussed in NRCE's report (2008), NRCE selected a method of computing solar radiation based upon the ability to define a value for the albedo (reflection coefficient of incoming solar radiation) explicitly. The ASCE standardized equation uses a fixed albedo of 0.23 for the standard reference surfaces and therefore the user cannot change the value.

In the solar radiation equations by Dingman (1994), the user has the ability to change the albedo. The in-house climate data analysis and filling software used by NRCE provides input for several models, some of which need the ability to change the albedo value. For example, the ability to define separate albedos for vegetation cover, snow cover, or water surfaces is useful when developing hydrologic models. Longworth (2010), on page 22 of his report, states that, "[s]now cover is typically not present in the growing season in New Mexico." NRCE agrees with Longworth's observation, which is why the NRCE used the albedo recommended by ASCE of 0.23 (ASCE, 2005) in the 2008 calculation of irrigation requirements for the agricultural units on the Zuni Reservation.

The results for these alternative equations used by NRCE closely agree with ASCE and FAO methods for an albedo of 0.23 (NRCE, 2008).

Table 3-2 and Figure 18 are comparisons of average monthly solar radiation calculated using the equations selected by NRCE and the methods presented in the ASCE 2005 Standardized Reference Evapotranspiration Equation (ASCE, 2005). Note that for comparison purposes, the simple transmissivity equations from ASCE are used and Dingman results assume a clear atmosphere.

Table 3-2: Comparison of Monthly Global Solar Radiation (R_s, MJ/m2/day) at Gallup Airport

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dingman 1994	10.81	13.91	18.42	23.47	26.94	29.01	25.80	23.63	21.29	16.89	12.38	10.16
ASCE 2005	11.06	13.93	18.21	23.20	26.76	29.00	26.41	24.23	21.37	16.66	12.35	10.40
Difference Percentage	2.31	0.17	-1.13	-1.19	-0.67	-0.06	2.36	2.57	0.37	-1.34	-0.25	2.39

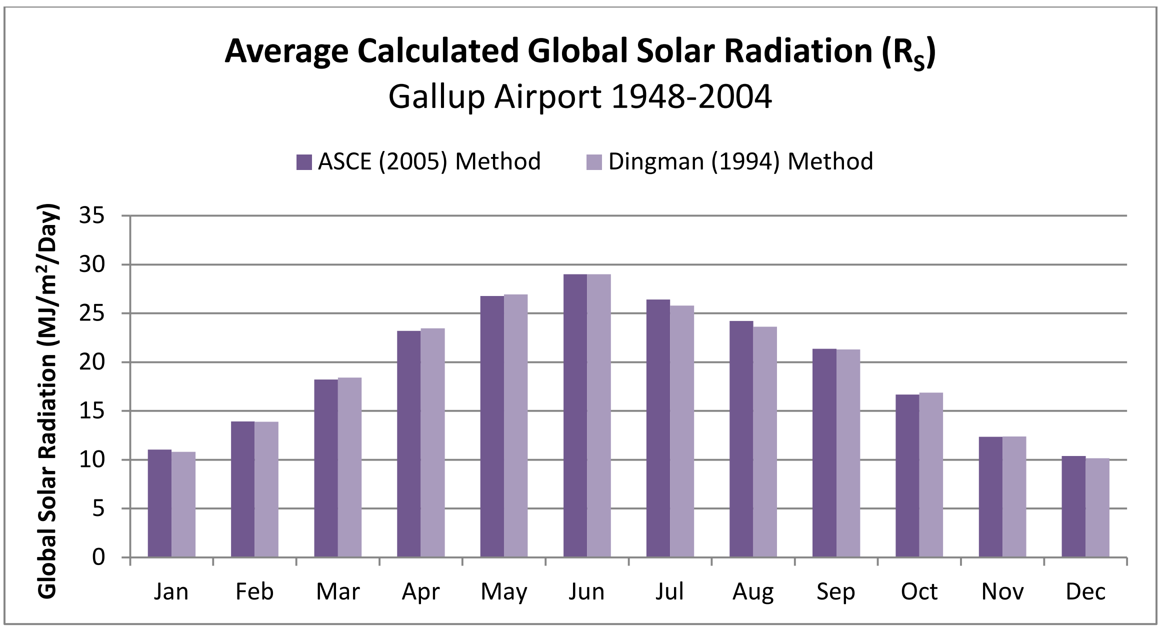

Figure 18 – Comparison of Global Solar Radiation at Gallup Airport (1948-2004) Calculated with Dingman (1994) and ASCE (2005) Equations, filled from Albuquerque Int'l as described in section 2.5.1

3.4.4 Atmospheric Transmissivity

The ASCE (2005) manual, in Appendix D, includes modifications to the clear-sky solar radiation equations to account for the effect of atmospheric impurities on solar radiation.

In a similar fashion, Dingman's equations for calculating solar radiation also include methods to account for the effects of water vapor and other particulate matter on atmospheric transmissivity. The equations in Dingman (1994) account for this variable as the "attenuation due to dust, or γ_{dust}." Longworth (2010) questions the selection of the value of this parameter by NRCE. Table 3-3 lists the criteria and ranges of this parameter from Dingman (1994).

Table 3-3: Attenuation Due to Dust, γ_{dust}, from Dingman (1994)

Range for γ_{dust}	Location
0.00 – 0.05	Remote Areas
0.03 – 0.10	Medium Cities
> 0.13	Large Metro Areas

NRCE selected the value of 0.03 for γ_{dust} due to the remote locations (in comparison to medium cities) of the historical irrigated acreage.

4 IRRIGATION AND DIVERSION REQUIREMENTS

This section discusses the various methods for calculating crop evapotranspiration used by experts to estimate water requirements on the Zuni Reservation.

4.1 Comparison of Experts' Analyses

The methods used by experts to calculate the water requirements are ASCE Penman-Monteith (P-M), Original Blaney-Criddle (OBC), Modified Blaney-Criddle (MBC), and Hargreaves-Samani (HS). Figure 19 compares weighted irrigation requirements on the Zuni reservation from the various experts. The weighted consumptive irrigation requirements from the State (Longworth Tables 3, 5, and 7) is calculated using a crop mix from years 1947-1950, climate data period of 1914-2008, and do not include the adjustments for crop yields. The final "consumptive irrigation requirements" presented by Longworth are lower than what Figure 19 shows when he makes adjustments based on crop yield. The two Blaney-Criddle analyses reported in Longworth (2010) result in much lower irrigation requirements than other methods. Despite calculating a reference evapotranspiration using the ASCE P-M method (in Brengosz, 2010), the State's experts do not ultimately calculate any consumptive irrigation requirements using this method. Therefore, there are no irrigation requirements to compare from their Penman-Monteith analysis.

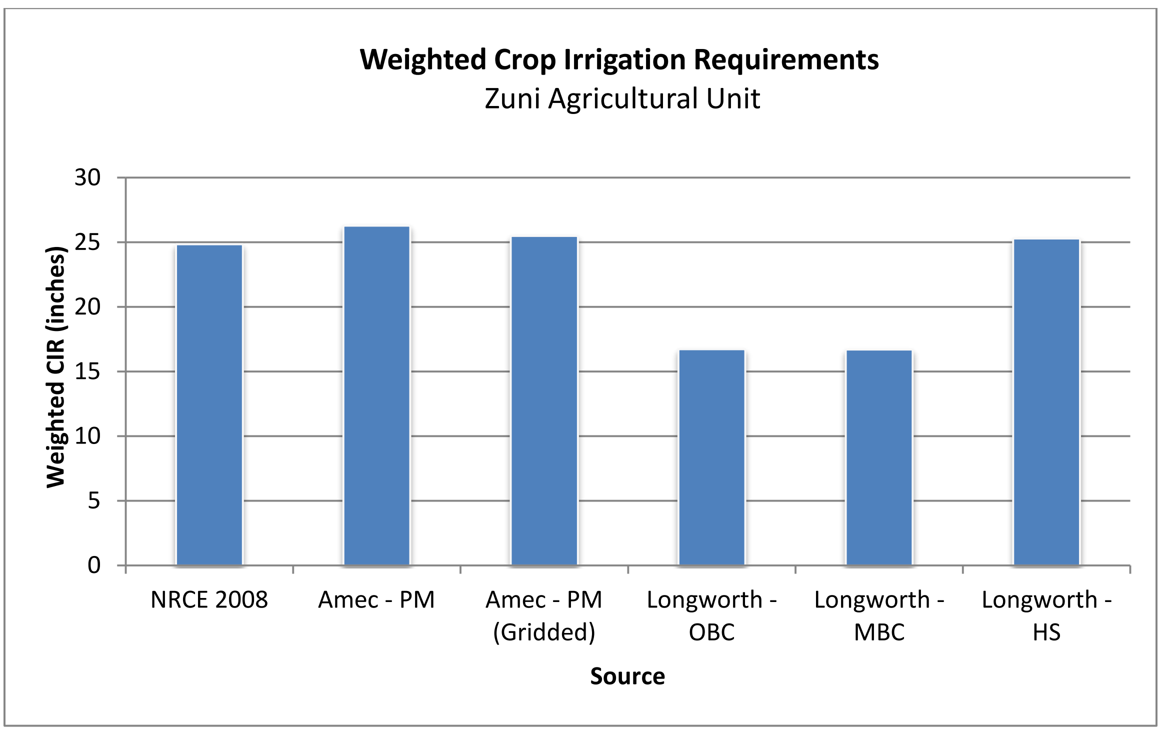

Figure 19 - Weighted Consumptive Irrigation Requirements from Various Experts

4.2 Crop Mix

The selected crop mix has a relatively small impact on the final weighted consumptive irrigation requirement. Figure 20 shows the different crop mixes used by the experts. Longworth (2010) considers only 4 years (1947-1950), out of over 50 years of crop reports listed in the report, in developing the mix, and therefore is expectedly quite different from NRCE's mix. The greatest difference in cropping patterns is the percent of crop that is small grains. In recent decades, the amount of small grains planted is much lower than some historical periods.

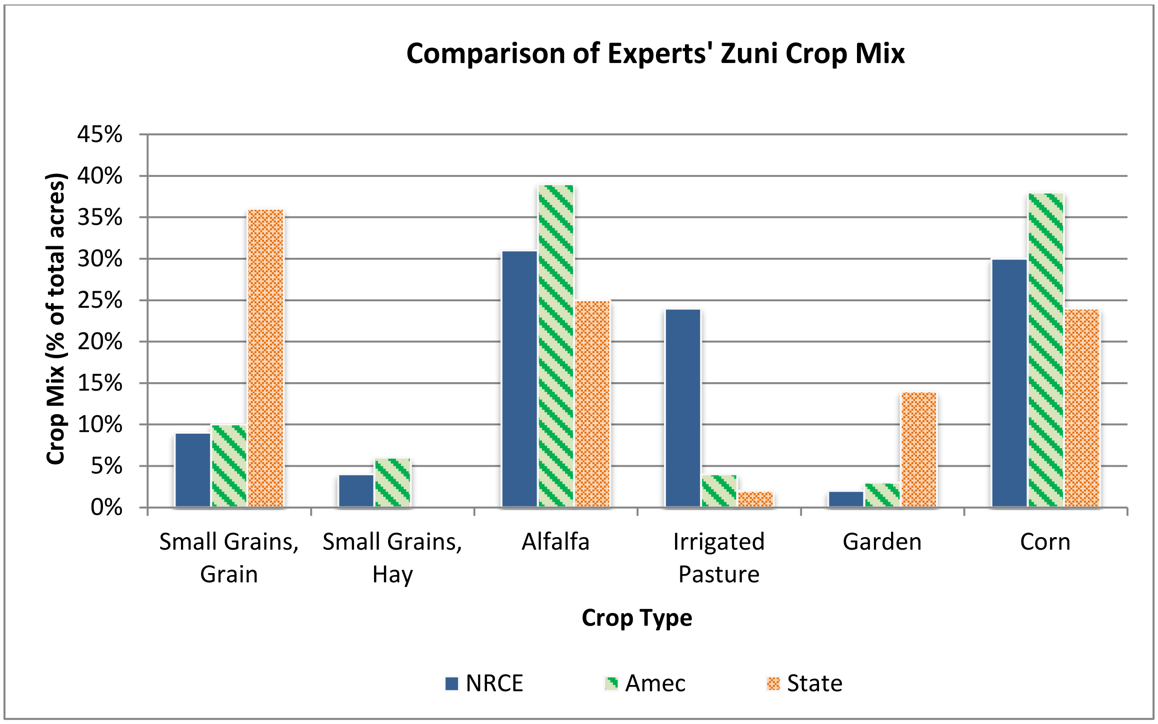

Figure 20 - Crop Mix Comparison from Various Experts

4.2.1 *Additional Pasture*

Longworth (2010), on page 20 of his report, questions the inclusion of additional pasture by NRCE. The BIA crop reporting methods for pasture appear to be inconsistent from year to year. This inconsistency between years probably depends on who compiled the report and the methods used to account for irrigated pasture, or if it was accounted for at all. Currently much of the irrigated Zuni project areas exist as pasture, as observed by NRCE during field visits. Additionally, New Mexico Agricultural Statistics Service county cropping records support the observation that pasture is higher in more recent years than reported in historical BIA data as discussed in NRCE (2008). Based on this information, NRCE used 20 percent as an estimate of irrigated pasture (NRCE, 2008). NRCE adjusted the average crop mix from all years reported by the BIA to include 20 percent additional pasture. All irrigated non-crops reported by BIA (approximately 4 percent of the mix) are included to achieve a final “irrigated pasture” percentage of 24 percent. If the consumptive irrigation requirement analysis ignores this 20 percent additional pasture, the weighted consumptive irrigation requirement decreases by less than one inch. Despite the small impact of including additional pasture, NRCE believes that pasture is a significant part of the current cropping pattern and therefore accounts for this. Based upon observations during recent field visits by NRCE, the majority of the agricultural areas under permanent works on the Zuni reservation currently exist as pasture. The irrigated pasture is for livestock grazing and harvested for hay.

4.2.2 *Crop Reports*

Longworth (2010) considered crop reports from the BIA for the years 1947-1950 in his analysis whereas NRCE considered many more years of crop data. In the 2008 report, NRCE used crop reports for years 1934, 1952, 1981-1993, 1997-2001, and 2003-2004 (NRCE, 2008). After the completion of the 2008 report, NRCE obtained more BIA crop reports for 28 years between 1917 and 1955. Table 4-1 compares the weighted annual consumptive irrigation requirement as calculated by NRCE from the 2008 NRCE report with the weighted consumptive irrigation requirement calculated from using only the years 1947-1950 and from including the all additional years of cropping reports .

Table 4-1: Comparison of BIA Crop Reports and Effects on Annual Consumptive Irrigation Requirement for Zuni Agricultural Unit

Crop	[1]CIR from NRCE Report (inches)	Mix from NRCE 2008	Mix For Years 1947-1950	Mix For Years 1917-2004
Corn	19.89	30%	17%	18%
Small Grains, Hay	16.21	4%	11%	4%
Small Grains, Grain	19.29	9%	19%	22%
Alfalfa	30.36	31%	19%	28%
Garden	19.84	2%	11%	5%
[2]Irrigated Pasture	27.88	24%	23%	23%
Weighted CIR (inches)		**24.85**	**23.19**	**24.38**

[1] *CIR- Consumptive Irrigation Requirement for the Zuni Agricultural Unit (NRCE, 2008)*

[2] *Irrigated pasture includes 20 percent additional pasture as discussed in Section 4.2.1.*

The weighted annual consumptive irrigation requirement calculated by NRCE (2008) declines by 1.66 inches using the same years of crop reports as Longworth (adjusted for additional pasture). In addition, NRCE’s (2008) weighted consumptive irrigation requirement declines by approximately half an inch when considering the additional years of BIA crop reports dating back to 1917.

However, including these earlier crop reports would not necessarily increase the accuracy or completeness of NRCE's analysis. Crop reports from the earlier years (pre-1930s) are of questionable usefulness. Many of the reports for these years contain only reservation wide totals or totals only for the Zuni Unit (this distinction is not entirely clear, but it appears to be reservation-wide based on the magnitude of the acreages). Additionally, notes on the reports for some of these years indicate that they may include acreage for both irrigated and dry-farmed crops.

4.3 Period of Record

As previously explained in Section 4.2.2, Longworth uses a crop mix and yield data from records for years 1947-1950 for the results shown in Table 11 of Longworth (2010). Longworth also only considers climate data for these same four years to calculate evapotranspiration. An analysis using only four years of data, when records exist for over 60 years in the Zuni basin, results in computed average annual irrigation requirements that are not representative of the entire period. It is also not clear if all of the experts for the State are in agreement with this period in their own analyses. For example, Brengosz (2010) uses all data available at each weather station in her analysis and Samani (2010) does not appear to limit his calculations to this period either. Longworth also does not state whether his growing season calculations consider only these years as well.

In the context of the available data, four years of climate and crop data does not provide "a reasonable basis to estimate historical water use and a long-term idealized consumptive irrigation requirement estimate" (from Longworth, 2010, page 11).

4.4 Growing Seasons

Longworth (2010) requested clarification on what temperature data and elevations NRCE uses to determine the growing seasons. The criteria used are on page 3-4 of the NRCE (2008) report. As discussed previously (see Section 2), the agricultural areas on the Zuni reservation exist at different elevations and therefore have slight variations in temperatures. It is for this reason that NRCE developed the growing seasons based upon the fully filled/extended and elevation adjusted temperature records.

The dates selected by the State's experts for the growing seasons (Longworth, 2010 and Samani, 2010) are generally similar to those dates selected by NRCE. The State's experts use different criteria for selecting the growing season dates for the Hargreaves-Samani method than for the Blaney-Criddle methods. There is no explanation of this difference or a recommendation what growing season criteria to use. However, slight variations in estimating growing season criteria are common between sources and these differences generally have relatively small effects on annual irrigation requirements. Figure 21 is a comparison of the growing seasons used by NRCE and the State's experts.

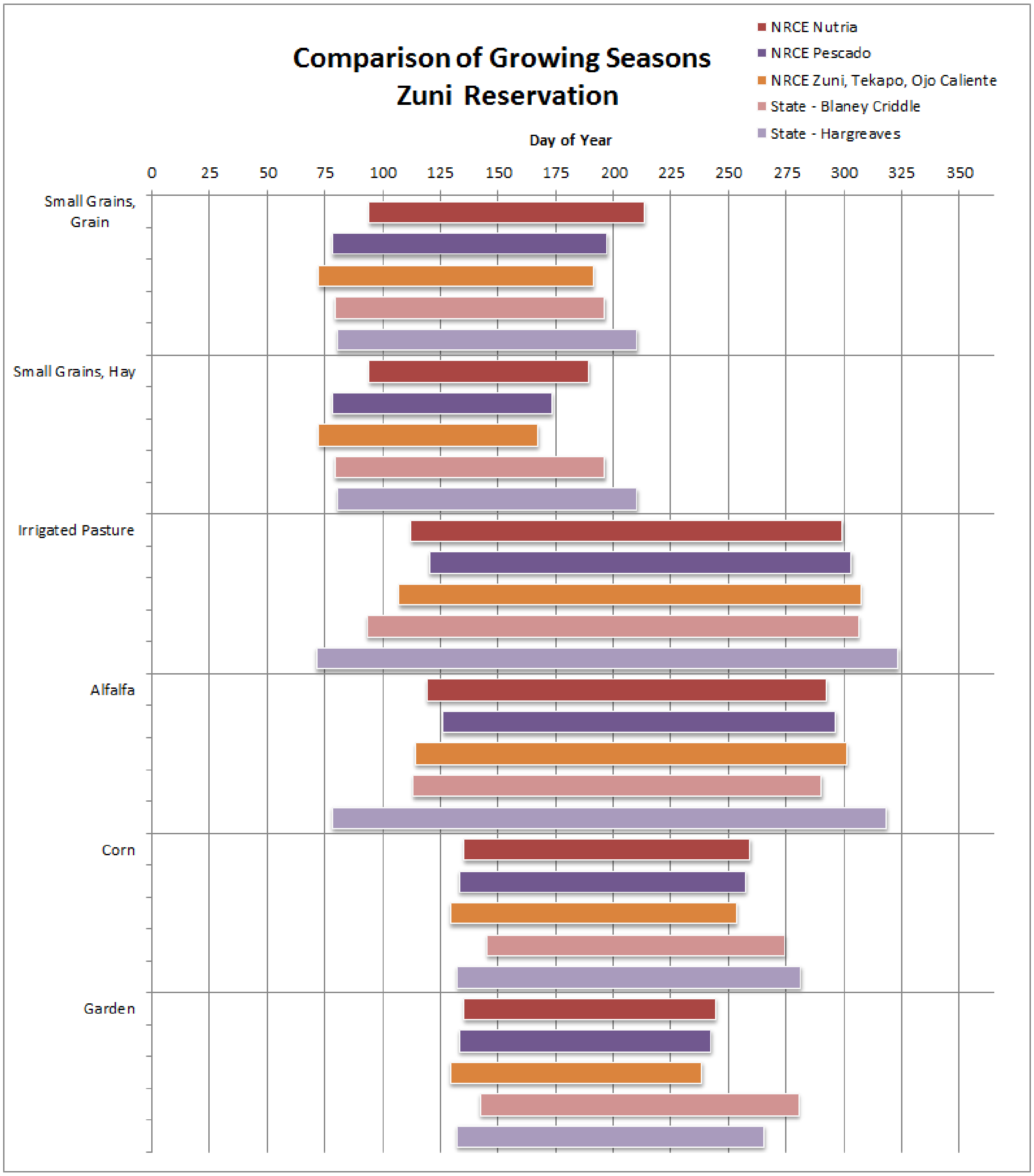

Figure 21 - Comparison of Growing Seasons used by experts for Zuni Reservation

4.5 Wet Soil Evaporation

NRCE (2008) applied a wet soil evaporation factor (K_w) to the crop coefficient to account for early and later season water evaporation from partially exposed soil. This is an additional refinement to the model made after completion of the initial report for Zuni. NRCE's 2008 report describes this procedure in appendix F.

4.5.1 *Soil Types*

The State experts requested clarification regarding the soil types used in NRCE's analysis. The majority of the soil at the Zuni agricultural areas consists of a range between clay and sandy loam. Soil maps developed by the Natural Resources Conservation Service (NRCS) and data available on the NRCS soils website support NRCE's analysis. To calculate an annual average crop irrigation requirement, NRCE estimated the irrigation frequencies assuming an approximate soil composition of clay loam and sandy loam when selecting the "average wet soil evaporation factor (A_f)" from Table 2-30 in the National Engineering Handbook (SCS, 1993). NRCE's decision not to complete a more detailed soil analysis beyond review of NRCS soil maps would not have a significant impact on annual irrigation requirements.

4.5.2 *Irrigation Frequency*

NRCE estimates an average irrigation frequency to account for how soils respond to wetting events. Particularly, recently wetted soils exhibit a higher evaporation rate than dryer soils. The soil moisture content and physical properties of the soil determine this evaporation rate. The assumed irrigation frequencies are 14 days for small grain hay and garden crops and 21 days for grains, corn, alfalfa, and pasture (NRCE, 2008). The basis of these frequencies is the amount of water that can be stored in the soil that is available to the crops between irrigation events during times of peak water consumption. It is important to understand that NRCE calculates these average and approximate irrigation frequencies in order to determine the annual crop water requirements. Accurate irrigation scheduling requires a more detailed procedure and may vary significantly from year to year. As such, irrigation scheduling is not a component of NRCE's analysis of crop water requirements.

Longworth (2010) estimates a minimum irrigation frequency during peak periods at 21 days assuming a 4 foot root depth for all crops. The actual crops within the mix range from a 2 to 5 foot root depth with a weighted average of 3 to 4 feet (Franzoy, 2010). A shorter irrigation interval (i.e., more frequent irrigation) than what Longworth suggests is necessary for crops that have a shallower root depth and access to less soil moisture. Longworth (2010) also states that for early and late season irrigation when ET is less, the irrigation interval may be 30 or 50 days between events stating "[u]sing an average irrigation interval of 21 days would inadvertently result in a higher Kc, and higher ET."

While crops in the early growing stage have lower ET, the root zone depths of annual crops are also shallower during this period. There are also significant losses to evaporation during the early growth period of annual crops. Early irrigation may be more frequent than what Longworth is suggesting due to the young crop's shallow root zone. For example, the root depth for corn does not fully develop to the 4 foot depth until approximately two months after emergence (Kranz, et. al., 2008). Additionally, in areas with limited water storage available, such as the Pescado or Nutria units, the irrigations occur regularly, even in the early growing periods to utilize the water supply to replenish the soil water.

4.6 Effective Precipitation

NRCE uses the 80th percentile exceedance precipitation when calculating the effective precipitation using the equations in the SCS (1993) manual. Longworth (2010), for the State, calculates the effective precipitation using the mean monthly rainfall. Longworth (2010) states, "the 80 percent exceedance rainfall is more appropriately used for irrigation system design and is not typically used for estimating historical actual use". The NRCE (2008) report calculates the irrigation requirements and not historical use. NRCE considers the following citation from the SCS (1993) National Engineering Handbook:

> Crop evapotranspiration depends upon a number of climatic factors that vary from year to year. The variation of these factors is normally less than that in precipitation. Accordingly, the net irrigation requirement varies widely from year to year in response to changes in effective precipitation. Because of this variation in net irrigation requirements, the development of an irrigation water supply cannot be based on average conditions.

A reasonable interpretation of the above citation is that monthly mean or average rainfall, such as used by Longworth (2010), is not an adequate basis for estimating consumptive irrigation requirements. Using mean or average annual rainfall results in a precipitation shortage (the rainfall is less than the mean) approximately half of the time, because the mean and median annual rainfall are about the same. Using 80 percent exceedance rainfall results in a precipitation shortage in only one of every 5 years. For this reason, calculating effective precipitation using the average rainfall does not represent actual agricultural practice. Analysis shows that by using the average instead of the 80 percent exceedance precipitation for this calculation, NRCE's weighted annual irrigation requirement would decrease by approximately 1.5 inches.

The manner in which Longworth applies the effective precipitation to the ET adjusted for yields is questionable. The SCS effective precipitation methodology, used by Longworth, assumes a full or typical irrigation requirement. A water-stressed crop growing in deficit irrigation conditions would generally utilize more precipitation than a fully irrigated crop and therefore the effective precipitation should increase, not decrease as it does in Longworth's analysis. Using the mean precipitation will also underestimate the historical precipitation approximately half of the time. However, this consideration is overshadowed by the inappropriateness of using historical yields to determine consumptive irrigation water requirement.

4.7 On-Farm and Conveyance Efficiencies

Franzoy (2010) estimates the on-farm and conveyance efficiencies. Generally, the on-farm efficiencies are similar to those used by NRCE (2008) for each of the agricultural units. The conveyance efficiencies for pipes and canals estimated by Franzoy are similar or somewhat lower than estimates by NRCE. Without any measurements or data collection to show otherwise, the irrigation efficiency estimates prepared by Franzoy appear reasonable.

4.8 Depletion

Depletion is the amount of diverted water that does not return to the hydrologic system of the Zuni River basin. NRCE (2008) estimates depletion as the sum of the consumptive irrigation requirement plus 20 percent of the losses due to conveyance inefficiency. Longworth (2010), on page 24 of his report, did not find an explanation of the basis of the 20 percent additional depletion. The total depletion presented by Longworth (in Table 11 of his report) only includes depletion by the crops. It appears that his total depletion does not include depletions from the inefficiencies in the irrigation conveyance system and on-farm irrigation system.

Depletion includes both consumptive use by crops and additional consumptive uses from other non-crop plants in or along ditches, drains, wetlands, vegetated areas receiving water from irrigation, evaporation from open channels, and evaporation operational losses. NRCE estimates these additional depletions to range between 9.2 and 12.6 percent of the diversions, based on 20 percent of diversion not used for crop ET. The following equation describes the calculation of the total depletion amount:

Depletion = CIR + (20 percent)(Irrigation losses)*

Where: *CIR* = water consumed by crops (consumptive irrigation requirement).
Irrigation losses = the difference between total water diverted and consumptive irrigation requirement is the irrigation losses (water not available to crops) due to conveyance and on-farm irrigation efficiencies.
20 percent = fraction of the water that is diverted but not consumed by crops that is otherwise consumed and does not ultimately return to the hydrologic system of the Zuni River basin.

4.9 Justification for Retaining Claimed Irrigation Requirements

Longworth (2010), on page 25 of his report, has expressed concern regarding differences of results presented by NRCE in 2008 when compared to the irrigation requirements that are in the document titled "*United States' Subproceeding Complaint and Statement of Claims for Water Rights on Behalf of, and for the Benefit of, the Zuni Indian Tribe and Zuni Allottees*" submitted May 11, 2009. NRCE discusses these differences in Appendix H of the NRCE 2008 report.

It is not the intention of NRCE to indicate that the wet soil evaporation or wind speed modifications have a negligible effect on the irrigation requirements. It was found that the *net result* due to the modifications by NRCE were minor. The adjustments made to NRCE's procedure were as follows:

- Updated the ET model with 24-hour average daily wind speed instead of daytime average wind speed. This reduced the annual reference ET by approximately 2 inches (about 4 percent). The corresponding reduction to the consumptive irrigation requirement is approximately 1 inch.

- Updated the crop coefficient calculations to account for wet soil evaporation. While having no effect on the reference ET, this increased the consumptive irrigation requirement by approximately 1 inch.

The net result of these modifications is very little change to the final irrigation requirements and therefore NRCE feels that it is not necessary to update the previously reported irrigation requirements to reflect this minor difference. Table 4-2 and Figure 22 (reproduced from NRCE's 2008 report) show the original values compared to the modified values.

Table 4-2: Comparison of the Original and Modified Scenarios (NRCE, 2008)

Value	Zuni	Ojo Caliente	Tekapo	Pescado	Nutria
Original Analysis	24.90	24.90	24.90	22.71	22.79
Modified Analysis	24.86	24.86	24.85	22.51	22.79
Difference	0.18 %	0.18 %	0.20 %	0.86 %	0.00 %

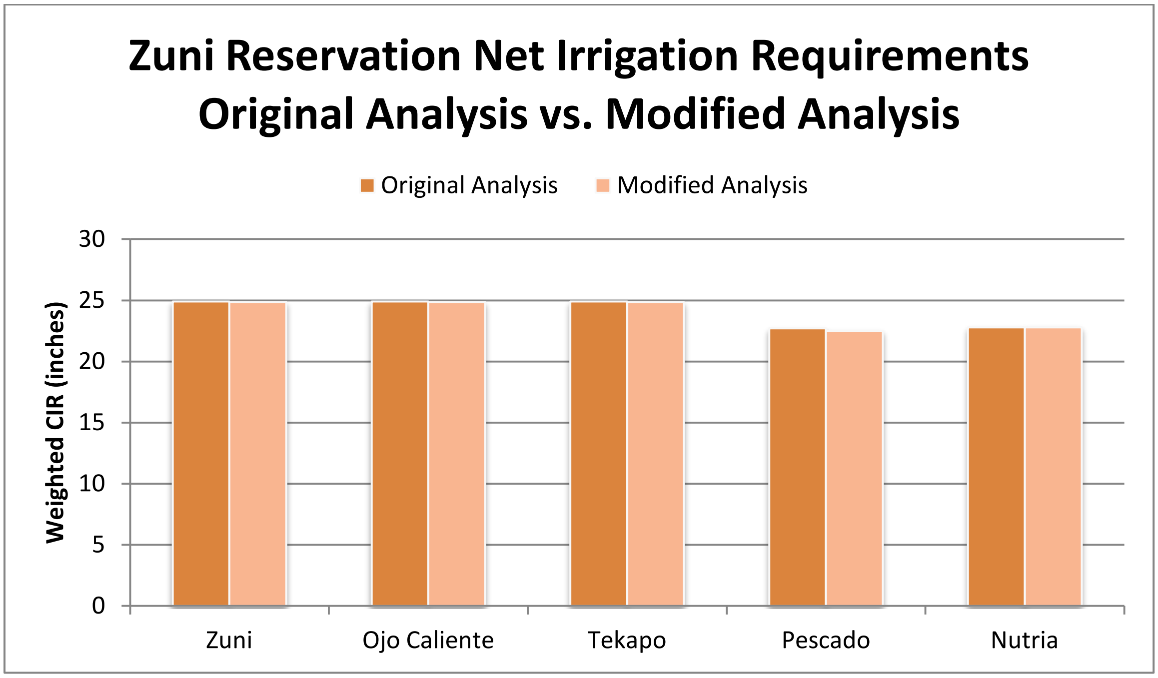

Figure 22 - Original Analysis vs. Modified Analysis (NRCE 2008)

5 GIS MAPPING and HYDROGRAPHIC SURVEY

This section discusses Wear's (2010) geographic information system (GIS) mapping and the survey of hydrologic features and irrigated acreages on the Zuni Reservation conducted by NRCE for the United States.

5.1 Composite of Historically Irrigated Acreage

The historically irrigated acreage developed by NRCE (2008) represents the totality of land irrigated by the Zuni, both historically and presently. The total cumulative acreage (7,018 acres) surveyed for the Zuni does not represent the amount of land that is cultivated or irrigated in any single year. The acreage mapped by NRCE includes all land that NRCE has determined the Zuni irrigated in the past or are presently irrigating.

5.2 Ditches and Points of Diversion

The State's expert agrees with the points of diversion (POD) as identified by NRCE (Wear, 2010). However, the expert questions three of the 293 conveyance structures mapped by NRCE (discussed below). These features were field visited in August of 2010 and NRCE reconsiders the inclusion of some of these features in the survey.

5.2.1 *Pescado Ditch Segments*

There are two ditch segments in the Pescado unit that Wear (2010) has identified as "an intermittent stream channel upstream of the nearest POD." NRCE initially included these segments because they are part of the constructed works that collect runoff from Pescado Draw and convey the water toward the Pescado agricultural unit. This ditch does not have a defined point of diversion nor does it convey water directly to any irrigated acreage. NRCE agrees with these findings and recognizes that the tabulation of irrigation conveyance structures could exclude these ditch segments from the survey of the Pescado agricultural unit.

5.2.2 *Ojo Caliente Ditch Segments*

Wear (2010) identifies a ditch segment in the Ojo Caliente unit as "utilized to supply a stock pond only." There are a couple of ditches appearing to terminate into stock ponds. One of these ponds has only a recorded livestock use (5A-3-SP007) whereas the other pond has recorded irrigation, agriculture, and livestock uses (5A-3-SP001). Neither pond has any historically irrigated acreage in the immediate vicinity, nor do these ditches appear to irrigate any other historic acreage. NRCE agrees with these findings and recognizes that the tabulation of irrigation conveyance structures could exclude these ditch segments from the survey of the Ojo Caliente agricultural unit.

5.3 BIA Irrigation Maps

Wear (2010) questions the source and purpose of the BIA irrigation maps, dated 1956, which NRCE had included in the 2008 report. (NRCE, 2008, Appendix B). The acreages on these maps correspond to a report titled "*Zuni Indian Reservation Engineering Study of Land and Water Resources*" for the Arizona-v-California suit (Exhibit #36). The title blocks of the maps include 606-Z-ARIZvCAL. This BIA report estimates the consumptive use and diversion requirement for the Zuni Pueblo based upon the acreage of 8,570, which is the total of the irrigated and irrigable acreage shown on these BIA maps. Table 5-1 is a summary of the acreage on these maps (as given in the BIA report.) The acres given in this table are similar the acres given in the report by Wear (2010, Table 2), where he determined acreage through analysis of the 1956 BIA maps.

Table 5-1: Zuni Pueblo and Reservation – Irrigated and irrigable lands of various units (reproduced from BIA report, Exhibit #36)

Irrigation Unit	Irrigated (acres)	Irrigation Under constructed Works (acres)	Irrigable, no works (acres)	Total (acres)
Nutria	562	140	0	702
Pescado	827	253	0	1,080
Zuni	3,260	815	818	4,893
Tekapo	275	1	0	276
Ojo Caliente	973	646	0	1,619
Total	*5,897*	*1,855*	*818*	*8,570*

As expected, the irrigated lands surveyed by NRCE do not exactly match these BIA maps. The primary basis for NRCE's mapping is historic aerial photography and digital imagery. The major difference is that NRCE has access to a much longer period of recorded data to consider in the analysis. However, general agreement exists between NRCE's survey and the BIA maps.

The BIA report states, "[t]he irrigated and irrigable lands of the Zuni Pueblo Indians were mapped and classified in 1956." These maps appear to be a composite acreage of all acres that the Zuni have irrigated in the past and up to the time of the survey, similar to the composite acreage developed by NRCE. While the maps distinguish between irrigated land and irrigable land, the crop water requirements in the BIA report are calculated using the total acreage (8,570 acres) shown on these maps.

5.4 Modified Acreage

After completing field visits on October 28th of 2009, July 15-16 of 2010, as well as discussion with the Zuni tribe during these visits and subsequent meetings, NRCE modified the survey of the historically irrigated acreage. During these visits, NRCE reviewed the delineations of fields. These updates to the survey are due to new information about soil conditions, ditch locations, and land topography, and personal accounts provided by Zuni members. Table 5-2 and Figure 23 compare the updated acreage to the acreage presented in NRCE's 2008 report. Maps of these changes are in Appendix A.

Table 5-2: 2008 NRCE Survey Acreage vs. 2011 Modified Acreage

Irrigation Unit	2008 Survey Acreage	2011 Modified Acreage	Percent Change
Nutria	976.6	833.8	-14.6%
Pescado	1,317.9	1,255.4	-4.7%
Zuni	3,629.8	3,606.6	-0.6%
Tekapo	320.6	320.6	0.0%
Ojo Caliente	773.7	876.3	13.3%
Total	***7,018.6***	***6,892.7***	***-1.8%***

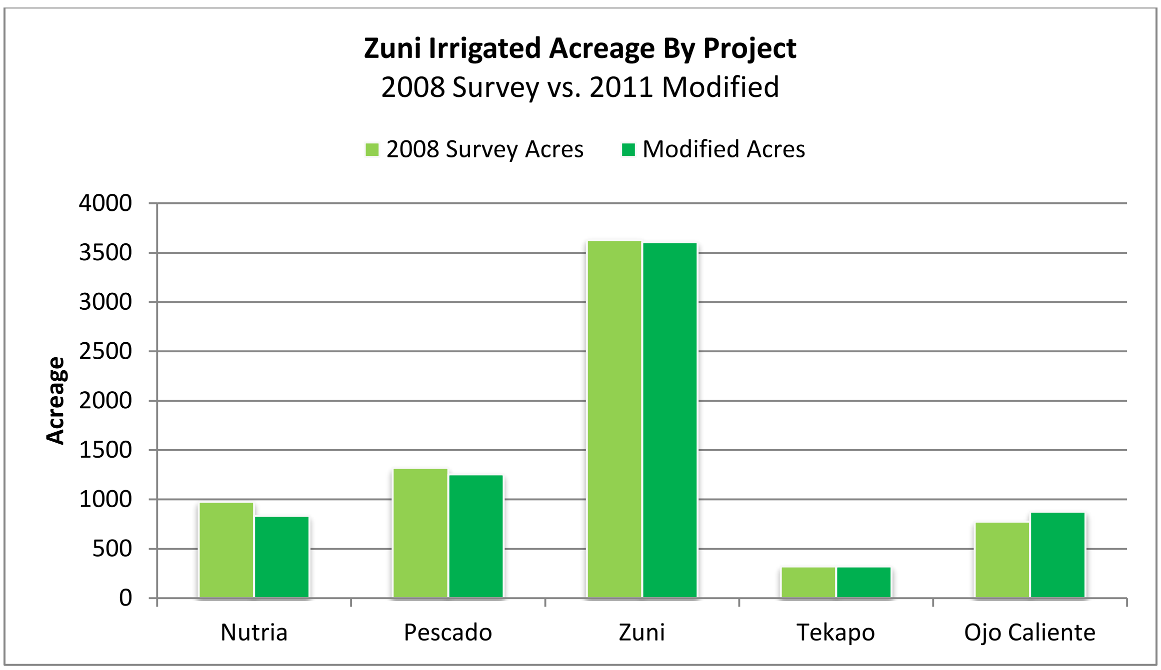

Figure 23 - 2008 NRCE Survey Acreage vs. 2011 Modified Acreage

5.5 Additional Well

During field visits on July 15th of 2010, NRCE located an additional well near the Pescado area near a small house. See Table 5-3 and Figure 24 for location information.

Table 5-3: New Well Surveyed near the Pescado Area

Survey ID	Use	T/R/S	X-Coordinate NAD83 (feet)	Y-Coordinate NAD83 (feet)
2C-5-W009	Domestic / Stock	T10N R16W S07	2,380,194	1,457,939.

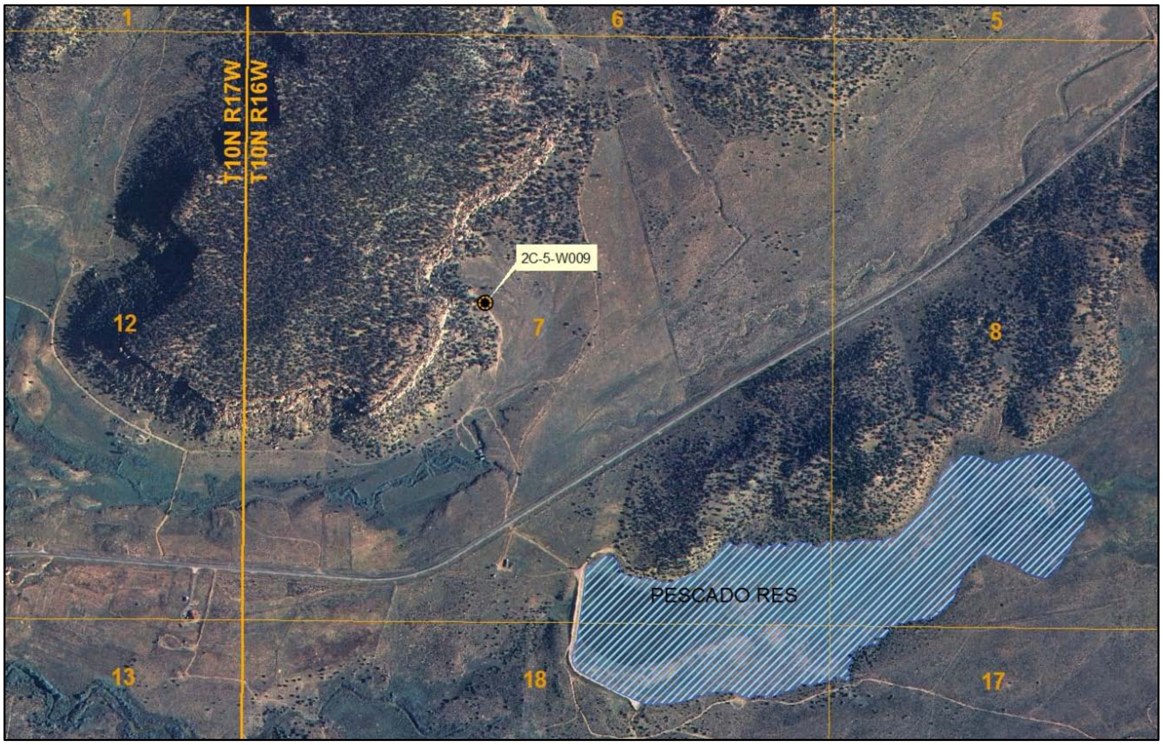

Figure 24 - New Well Surveyed near the Pescado Area (2C-5-W009)

6 WATER SUPPLY

This section concerns the surface water supply analysis of the Zuni Reservation prepared by Laura H. Petronis (2010). NRCE did not attempt a surface water supply analysis of the Zuni River Basin as part of the Past and Present Lands Irrigated by Permanent Works report. Determination of the water supply is not necessary for the calculation of crop irrigation requirements or for the identification of historically irrigated lands.

6.1 Water Supply vs. Water Requirement

NRCE's 2008 analysis is the identification of lands and estimation of crop irrigation requirements for past and present irrigated lands served by permanent irrigation works and did not include a water supply analysis. In previous adjudications by the State of New Mexico (such as Santa Cruz, Rio Chama, Jemez, and Taos), NRCE is unaware of water supply analyses that have been completed in conjunction with the historically irrigated acreage for these hydrographic surveys. Water availability is a management concern (i.e., water users are given priority dates to account for shortages). In New Mexico and other arid states, it is common for the water supply to be less than the adjudicated water rights in most years.

6.2 Data Availability

NRCE agrees with Petronis' assessment that the availability of gage data from the U.S. Geological Survey (USGS) is limited within the Zuni River Basin, with some of the river reaches near agricultural units lacking any sort of data collection. This makes the estimation of current and historical flows, along with diversions and depletions, of the Zuni river system difficult. Particularly, the lack of stream flow data for Pescado and Tekapo make estimates of flows at these areas uncertain (Petronis, 2010).

Gage flow data in the Zuni River Basin is limited. The USGS maintains two active gaging stations in the area, on the Rio Nutria near Ramah (USGS 09386900) and on the Zuni River above Black Rock Reservoir (USGS 09386950). The period of the available daily flow data at these two gages includes water years 1970 through present day. In addition, monthly flow data are available for the Zuni River at Black Rock Reservoir (USGS 09387000) from 1910 through 1930. The combined period of record of the USGS gages 09386950 and 09387000 on the Zuni River above/at Black Rock Reservoir is 49 years (1910-1930 and 1970-Present). The USGS operated a gage on the Zuni River at the New Mexico-Arizona State Line (USGS 09387300) only during water years 1988 through 1989 and 1991 through 1994. The majority of the streams in the Zuni River system, including reaches near some of the agricultural units, have no historical gage data.

The information needed to estimate the historical depletions in the Zuni River Basin is incomplete. There are no records of historical reservoir levels in the basin, which are necessary to estimate the depletions due to changes in storage and net evaporation. NRCE is not aware of records of historical irrigation diversions in the basin. NRCE (2008) estimates the diversion requirements as the product of the irrigated acreage and irrigation water requirements. It is obvious that the average annual surface water supply is insufficient to irrigate all the historical and presently irrigated lands identified by NRCE.

While it may be possible to estimate the historical diversion requirements, without an independent estimate of the available water supply it is not possible to estimate the historical diversions and construct the complete water budget. The water-budget method is not feasible for the Zuni River System for the following reasons:

- Lack of long-term gage flow data on the Zuni River at the New Mexico-Arizona state line.
- Lack of any gage flow data on Rio Pescado and Cebolla Creek.
- Lack of any gage flow data on Plumasano Wash.
- Lack of historical reservoir storage data.
- Lack of historical diversion data.

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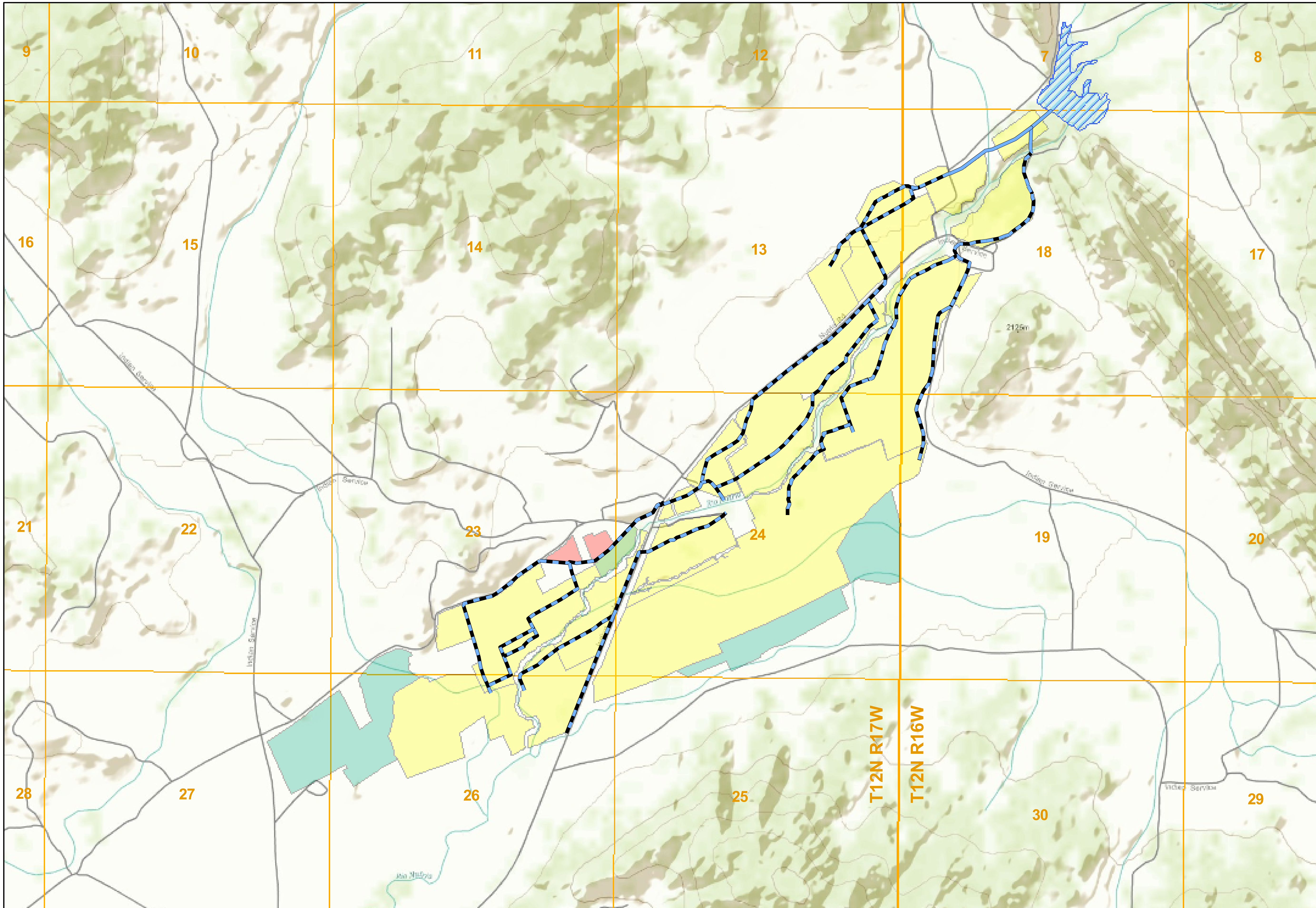
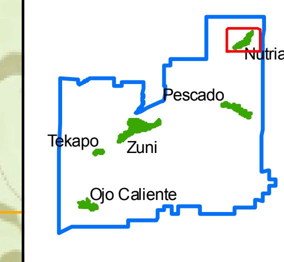
APPENDIX A

Maps of Past and Present Lands Served by Permanent Irrigation Works
2011 Modifications to NRCE 2008 Survey





ZUNI RESERVATION

NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.

September 2011

N

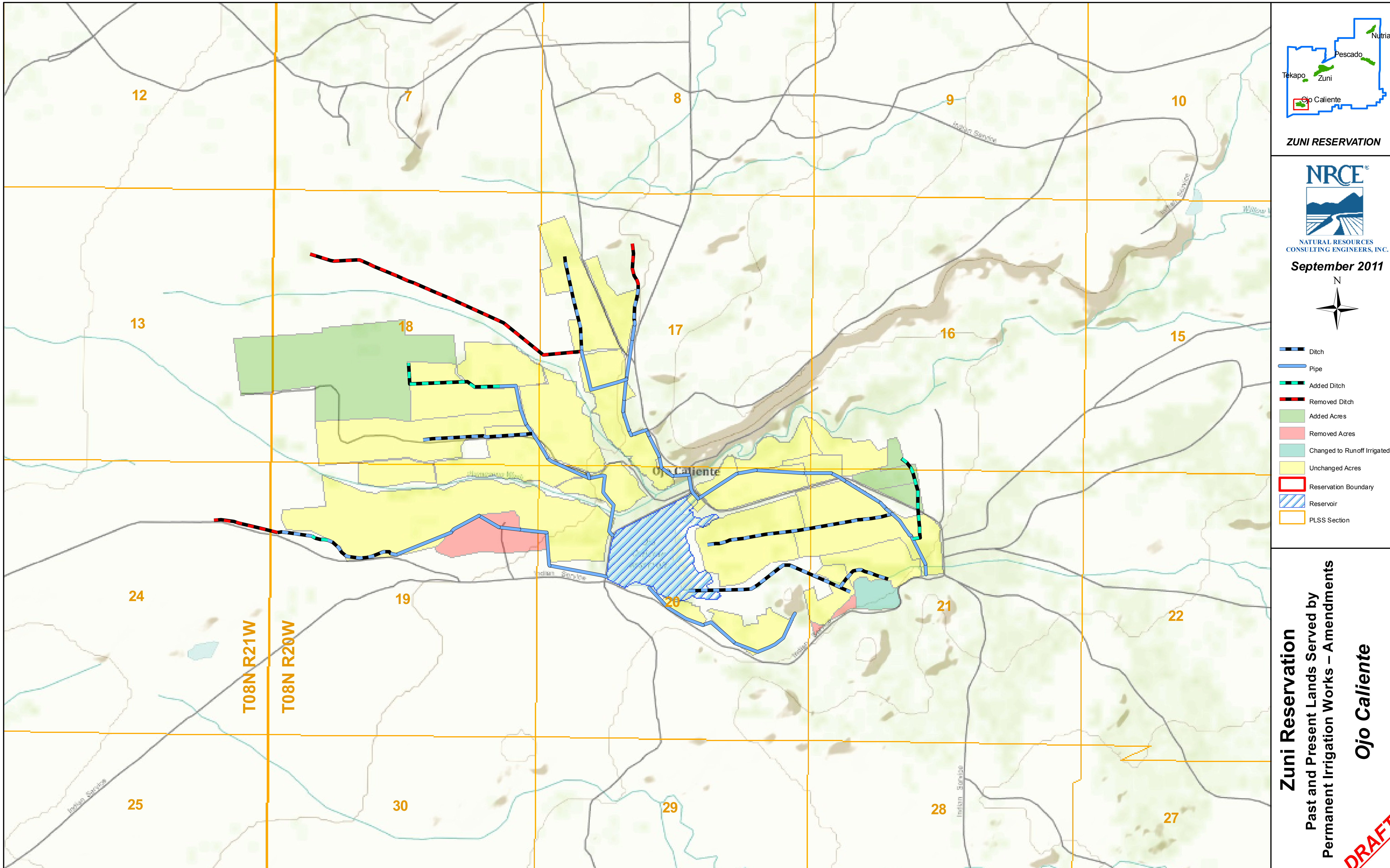
- Ditch
- Pipe
- Added Ditch
- Removed Ditch
- Added Acres
- Removed Acres
- Changed to Runoff Irrigated
- Unchanged Acres
- Reservation Boundary
- Reservoir
- PLSS Section

Zuni Reservation

Past and Present Lands Served by Permanent Irrigation Works – Amendments

Nutria

DRAFT


Zuni Reservation
Past and Present Lands Served by Permanent Irrigation Works – Amendments
Ojo Caliente
DRAFT
ZUNI RESERVATION
Nutria
Pescado
Tekapo
Zuni
Ojo Caliente
NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.
September 2011
N
Ditch
Pipe
Added Ditch
Removed Ditch
Added Acres
Removed Acres
Changed to Runoff Irrigated
Unchanged Acres
Reservation Boundary
Reservoir
PLSS Section
12
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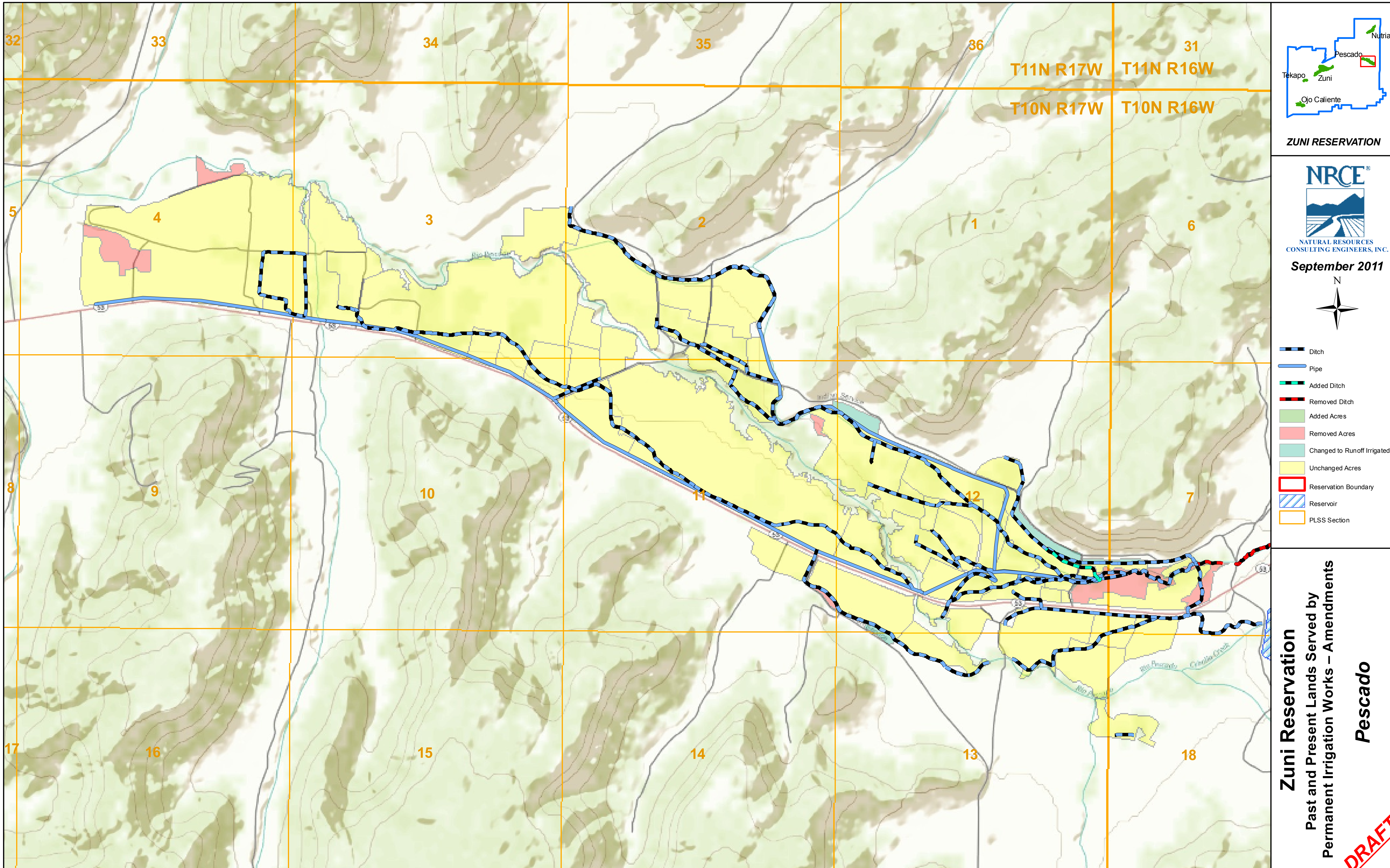
T08N R21W
T08N R20W
Ojo Caliente
Indian Service



T11N R17W
T11N R16W
T10N R17W
T10N R16W
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Rio Pescado
Nutria
Pescado
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Zuni
Ojo Caliente
ZUNI RESERVATION
NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.
September 2011
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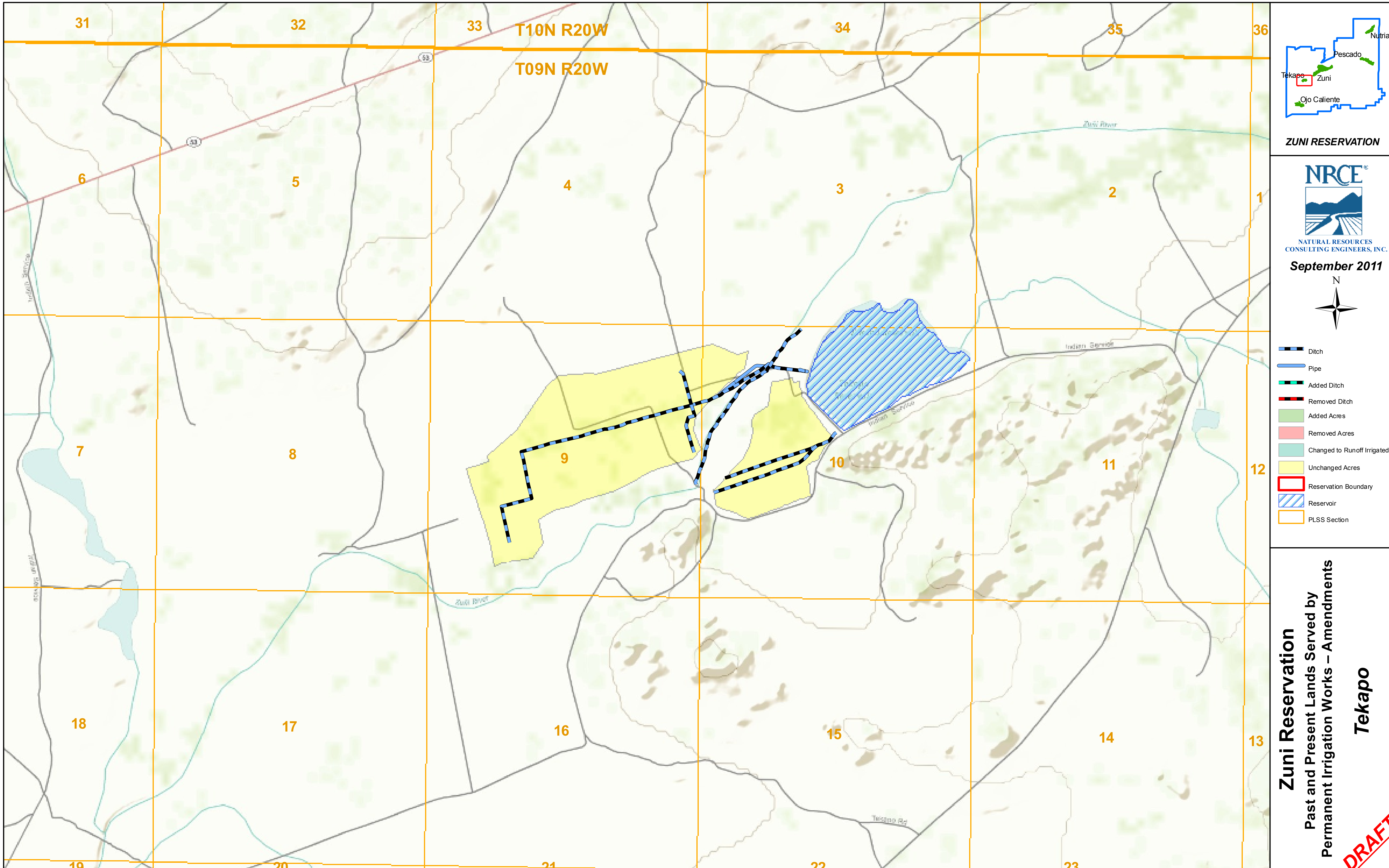
Pipe
Added Ditch
Removed Ditch
Added Acres
Removed Acres
Changed to Runoff Irrigated
Unchanged Acres
Reservation Boundary
Reservoir
PLSS Section
Zuni Reservation
Past and Present Lands Served by
Permanent Irrigation Works – Amendments
Pescado
DRAFT



T10N R20W
T09N R20W
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Zuni River
Indian Service
Tekapo Rd
Nutria
Pescado
Tekapo
Zuni
Ojo Caliente
ZUNI RESERVATION
NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.
September 2011
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Added Ditch
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Reservation Boundary
Reservoir
PLSS Section
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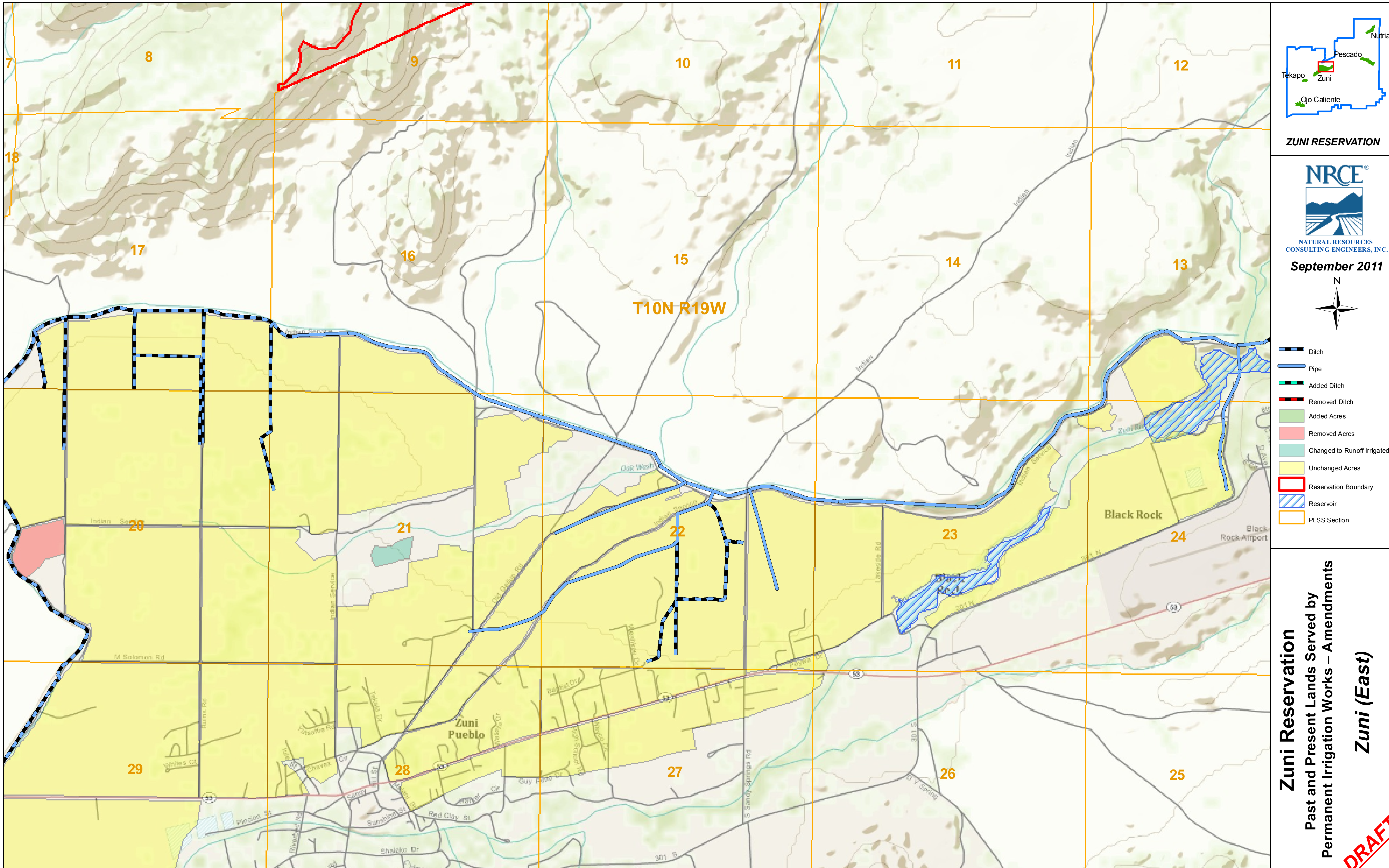
Past and Present Lands Served by Permanent Irrigation Works – Amendments
Tekapo
DRAFT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Pescado
Tekapo
Zuni
Ojo Caliente
NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.
September 2011
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Removed Ditch
Added Acres
Removed Acres
Changed to Runoff Irrigated
Unchanged Acres
Reservation Boundary
Reservoir
PLSS Section
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Black Rock
Zuni Pueblo
Black Rock Airport
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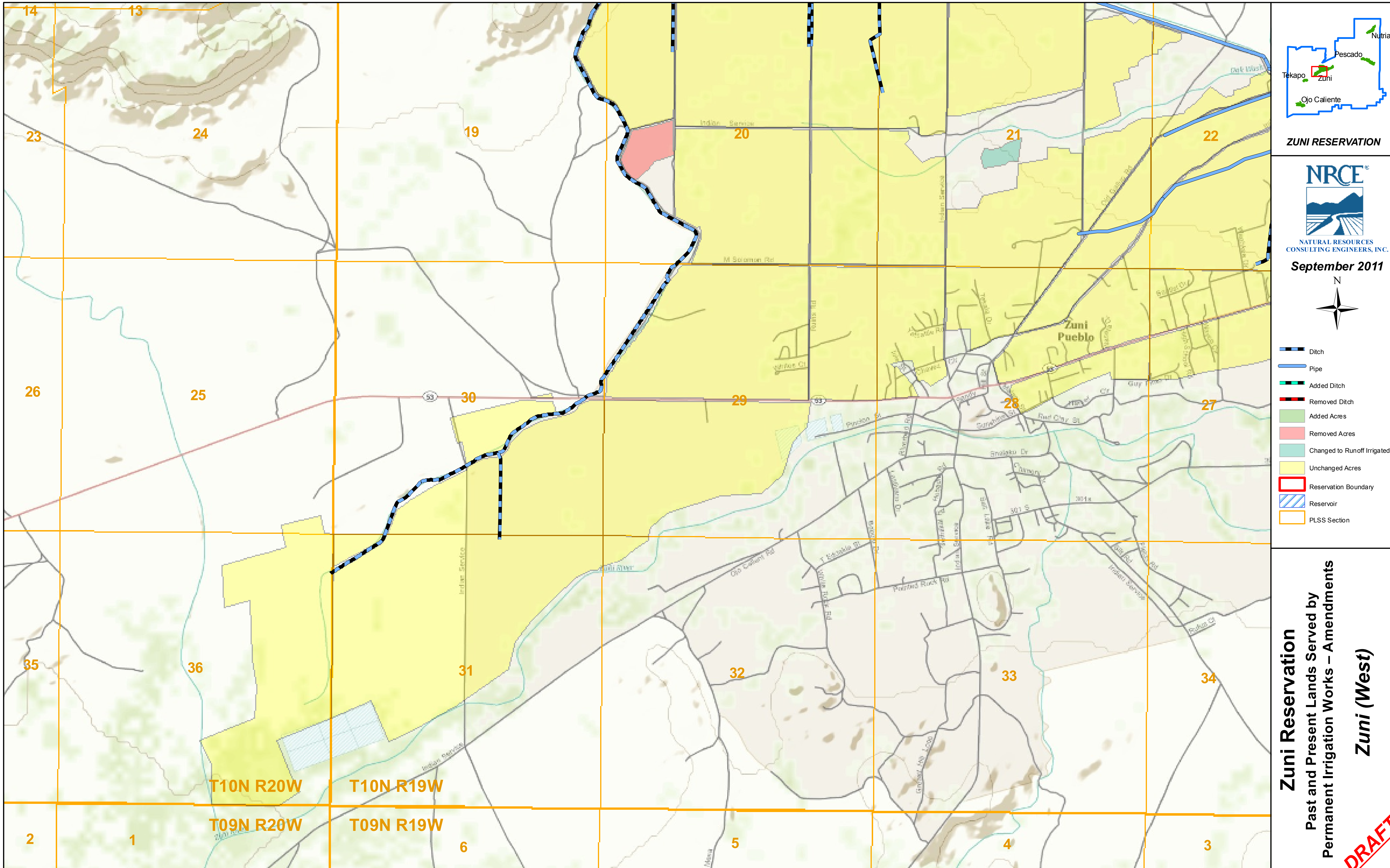
Zuni Reservation
Past and Present Lands Served by Permanent Irrigation Works – Amendments
Zuni (East)
DRAFT


Zuni Reservation
Past and Present Lands Served by
Permanent Irrigation Works – Amendments
Zuni (West)
DRAFT
ZUNI RESERVATION
Nutria
Pescado
Tekapo
Zuni
Ojo Caliente
NRCE
NATURAL RESOURCES CONSULTING ENGINEERS, INC.
September 2011
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Ditch
Pipe
Added Ditch
Removed Ditch
Added Acres
Removed Acres
Changed to Runoff Irrigated
Unchanged Acres
Reservation Boundary
Reservoir
PLSS Section
Zuni Pueblo
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T10N R19W
T09N R20W
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