Analysis and Simulation of the Oakes Aquifer: An Assessment of Groundwater Availability

By
R. L. Cline

Water Resource Investigation No. 50
North Dakota State Water Commission

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Datum and Projections

All map coordinates are UTM zone 14. Horizontal coordinates are referenced to North American Datum of 1983 (NAD 83). Vertical coordinates are referenced to the National Geodetic Vertical Datum of 1929 (NGVD). Elevation, as used in this report, refers to the distance above the vertical datum.

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Introduction

The Oakes aquifer consists of glacio-fluvial, deltaic, and lacustrine sediments deposited in meltwater channels and as a delta extending into Lake Dakota. The aquifer underlies 160 square miles near Oakes, North Dakota. There are presently 13,612 acres permitted for irrigation from the aquifer. The City of Oakes is permitted to use up to 800 acre-feet of water. The aquifer is also impacted by the pumping to irrigate 283 acres permitted from the Middle James aquifer and the 1,165 acres permitted from the Spiritwood aquifer in the area north of Oakes. There are pending water permit applications to irrigate an additional 4,252 acres from the Oakes aquifer with a priority date prior to July 31, 2006. On July 31, 2006 Dickey-Sargent Irrigation District (DSID) filed a water permit application to irrigate 5,000 acres within the Oakes Test Area (OTA) with 5,000 acre-feet of water. Water permit applications junior to the DSID application are not considered in this report.

Between January 1, 1990 and January 1, 1997 permits were granted and subsequently developed to irrigate 3,945 acres from the Oakes aquifer. A pluvial (wet period) began in 1992, as indicated by both water use data and climate data, has continued through 2010. Because of high water table conditions resulting from this pluvial, the number of acres irrigated and the total water use did not increase beyond that of the 1980s. As a result, the impact to the aquifer of this additional allocation is not known.

The OTA was constructed by the U.S. Bureau of Reclamation (USBR) as a field scale research site. The area was tile drained to control the water table height. Title is to be transferred from the USBR to DSID or USBR will decommission the project (Lindvig, 2006). The amount of water available from Jamestown Reservoir is inadequate to reliably irrigate the OTA. There is little additional water available from groundwater within the OTA.

The assessment of the DSID's request for 5,000 acre-feet of water is complicated by the lack of stress imposed on the system by the additional appropriation in the early 1990s and the large amount of water in the pending applications senior to DSID. The only way to evaluate these additional stresses on the aquifer was the development of a groundwater flow model. The U.S. Geological Survey (USGS) groundwater flow model, MODFLOW-2000 was used for this study.

Purpose and Scope

The purpose of this report is to determine how much additional groundwater from the Oakes aquifer is available and from where within the aquifer. This report will provide the hydrologic basis for Dickey-Sargent Irrigation District

(DSID) to determine if the operation of the OTA would be economically viable before accepting transfer of the OTA from the U.S. Bureau of Reclamation (USBR) to them. Specific objectives of the report are to:

1. Evaluate the sustainability of presently approved permits under different climate regimes including the determinations of which senior appropriators will be adversely impacted during drought periods.
2. Evaluate areas of the aquifer that are vulnerable to drought or additional appropriation.
3. Discusses the areas where additional quantities of water can be developed from the aquifer. Discuss distance criteria and locations within the flow systems that would allow additional development. This includes the availability of water within the OTA, areas of greater saturated thickness directly to the east of the OTA, and from the Oakes aquifer deep channel.
4. Discuss issues and limitations of granting additional permits within the bounds of the Appropriation Doctrine as defined in North Dakota Century Code including the problem that there is insufficient water for the pending water permit applications and the DSID permit application.
    - 4.1. Additional appropriation by DSID would adversely impact senior water permits, approved and pending. Discusses strategies where DSID could either supply water to the impacted permits or develop agreements where the impacted pending permit applications would not be developed. Permits that would likely be adversely impacted by the simulated pumping strategies are identified. Strategies not simulated may have different impacts and may require additional analysis.
    - 4.2. There is significant land to the east and south of the OTA where high water tables since the late 1990s have either prevented planting or adversely impacted crop yields. DSID has expressed interest in using the proposed supply wells to also control the water table during pluvial periods. Discusses that wells located for water table control may not be optimal as supply wells. There will be tradeoffs between increased acreage available during pluvials and less water available during droughts due to less water being in storage.
    - 4.3. The DSID, in developing a water supply for the OTA, will need to evaluate the many compromises between costs, reliability of supply, and water table control. This report primarily focuses on whether water is available for the irrigation of 5,000 acres within the OTA. However, the analyses presented in the report does provide a basis for the discussion of these compromises and provides a model that can be revised to analyze other strategies in more detail.

A three-dimensional (3-D) steady-state and transient groundwater flow model was developed to simulate various pumping scenarios and analyze aquifer response. Climate data from nearby weather stations was used to assess local climate variability and to develop scenarios to evaluate the impact of pumping on the aquifer. The model was used to evaluate the impact of pending water permits including the application for 5,000 acre-feet (ac-ft) by DSID to irrigate 5,000 acres within the Oakes Test Area (OTA).

Study-Area Description

The Oakes aquifer underlies 160 square miles (mi^2) in parts of Dickey and Sargent Counties in North Dakota and Brown County in South Dakota (figs. 1 & 2). The Oakes aquifer overlies the Spiritwood, separated by either till or lacustrine aquitards. The area of lacustrine aquitard near Oakes readily transmits water between the two aquifers and this reach of the Spiritwood is included in the aquifer model. The Oakes aquifer is contiguous with the LaMoure aquifer and overlies the Middle James and part of the Spiritwood aquifer (fig. 2).

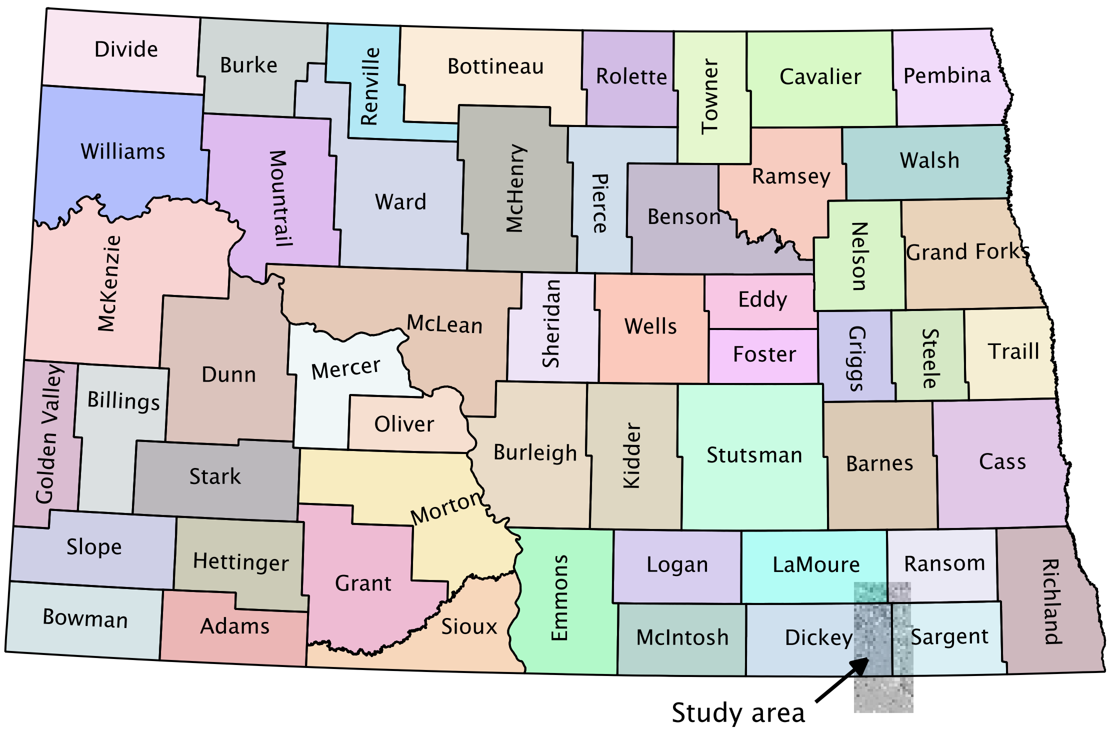


Figure 1. Map of North Dakota showing location of the study area.

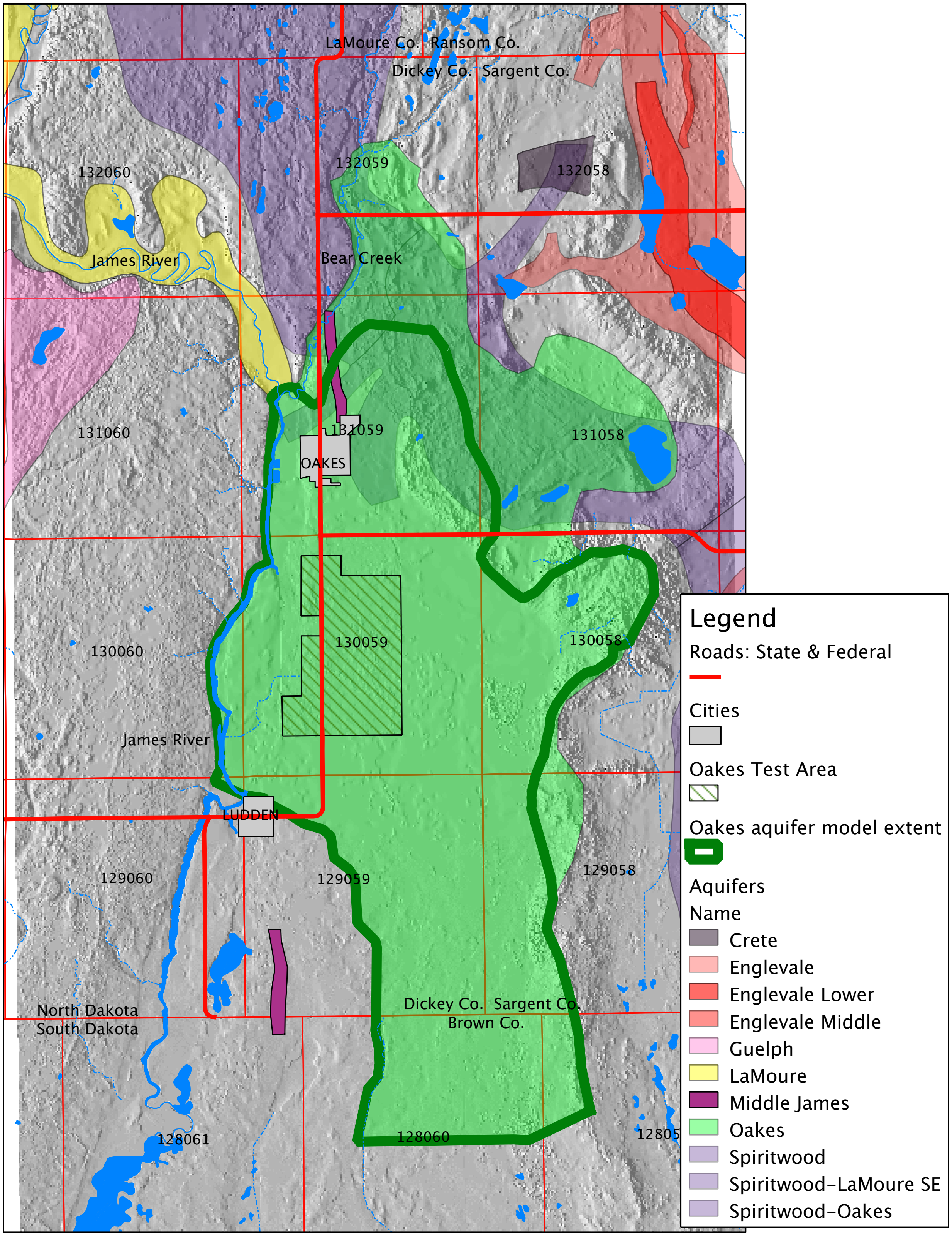


Figure 2. Extent of Oakes aquifer model, location of Oakes aquifer and surrounding aquifers.

Location-Numbering System

The system for denoting the location of test holes or observation wells is based on the federal system of rectangular surveys of public land. The first and second numerals (three digits) indicate Township North and and Range West of the 5th Principal Meridian and the base one (fig. 3). The third numeral (two digits) indicates the section. The letters A, B, C, and D designate respectively the northeast, northwest, southwest, and southeast (160-acre tract), quarter-quarter section (40-acre tract), and quarter-quarter-quarter section (10-acre tract). Therefore a well denoted by 13005904ADD would be located in the SE1⁄4SE1⁄4NE1⁄4 of section 4, Township 130 North, Range 59 West. Consecutive terminal numerals are added if more than one well is located in a 10-acre tract or smallest quarter designation, i.e. 13005904ADD1 and 13005904ADD2.

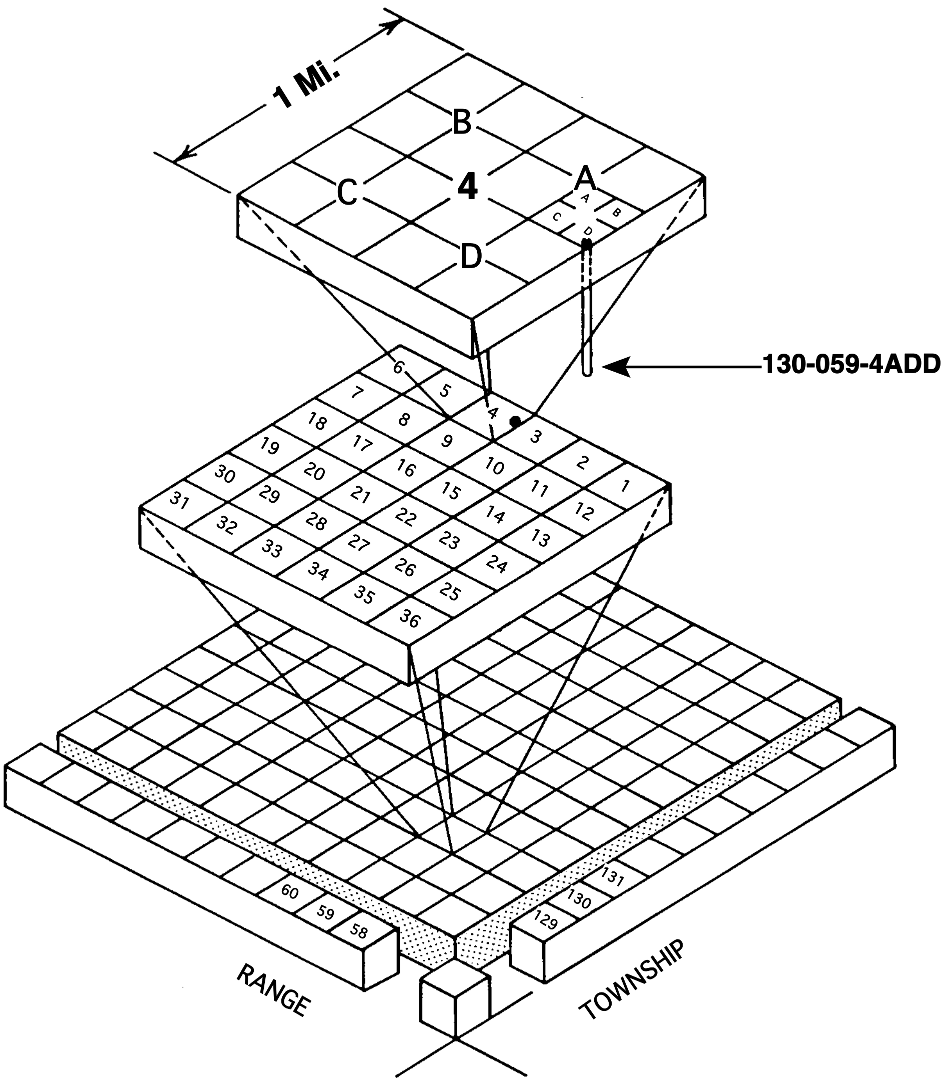


Figure 3. Location-numbering system. As an example, well 130-059-04ADD is located in the SE1⁄4, SE1⁄4, NE1⁄4, section 4, Township 130 North, Range 59 West.

Climate

Introduction

The amount of water that can be sustainably appropriated from an aquifer is determined by the inputs and outputs to an aquifer, the water budget. With a water table aquifer such as the Oakes, the input is recharge from precipitation. The output is evapotranspiration, drains within the OTA, pumping and some discharge to the James River. Irrigation water use is mostly determined by precipitation and the rate of evaporation during the growing season. Prior to irrigation development, over periods of several years, recharge was approximately equal to ET from the water table in areas where the water table was at or close to land surface. For irrigation development to be sustainable, it must, over the long-term, capture as much water from ET as is pumped. Whether an irrigation well can do this is dependent on the saturated thickness, hydraulic properties of the aquifer, and distance to the areas where water is discharged by ET from the aquifer. The assessment of these complex relationships often requires the development of a groundwater flow model as was done for this report. If the amount of recharge and therefore discharge to the aquifer is over/under-estimated, the amount of water available for irrigation will be under/over-estimated. Therefore determining both groundwater recharge, potential evapotranspiration (PET), and irrigation water use are critical to evaluating the amount of water available from an aquifer. To evaluate these factors, an understanding of the local climate must be developed.

Most of the irrigation development overlying the Oakes aquifer occurred from the mid-1970s through the early 1990s. Can the responses to pumping during this period be used to extrapolate impacts of future pumping on water levels? Climate varies both spatially and through time. To gage how representative the climate at Oakes was in the period of 1975 through 2009, comparison is made with both climate prior to 1976 and to climate at nearby observing sites.

Climate data used for these analyses were U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) cooperative observer data obtained from the CD, "CLIMATEDATA: Volume 21.3 NCDC SUMMARY OF THE DAY - WEST 2," which is provided by subscription from Hydrosphere Data Products. Additional NOAA cooperative observer data was obtained from John Enz, former State Climatologist at NDSU. The cooperative observer data consists of daily precipitation and maximum and minimum temperatures. Not all stations collect temperature data. Most of the station data starts in 1948. Additional data covering the summer was obtained from the ND Atmospheric Resource Board (ARB) and the North Dakota Agricultural Weather Network (NDAWN) at NDSU. ARB precipitation data is available for 1977 to the present. Though NDAWN collects climate data throughout the year, precipitation data is generally only available from April through October when temperatures are above freezing. The first NDAWN stations were established in 1990. Stations have been added and dropped since then.

The climate data stations have varying years of data availability. Also, individual stations have varying amounts of missing data running from periods of days to months. To create long-term continuous daily datasets for this study missing precipitation and maximum and minimum temperature data from surrounding stations were used. Table 1 shows the stations used to create the dataset Oakes03. The program used to create the dataset, when missing data is encountered will search down the list until it finds data for that date. Because of this, the climate datasets are not independent of each other and may be identical for certain parts of the record. The available Oakes data starts in 1929. The plots of climate data shown in figures 4 and 5 start in 1905. The data shown in these plots prior to 1929 is from Edgeley, ND and Britton, SD.

Table 1. List of stations used to create the Oakes 03 climate dataset.

Station	Start of record	End of record
Oakes1929 (NDSU)	01/02/1929	12/31/2005
OAKES (NCDC)	09/01/1922	12/31/2009
FULLERTON (NCDC)	07/01/1948	12/31/2009
COLUMBIA 8N, SD (NCDC)	09/01/1949	12/31/2009
VERONA (NCDC)	08/01/1948	12/31/2009
BRITTON, SD (NCDC)	01/01/1913	12/31/2009
ELLENDALE (NCDC)	07/01/1948	12/31/2009
EDGELEY (NCDC)	05/01/1901	12/31/2009

Only the NDAWN monitors the climate factors required to calculate PET. These factors include temperature, net solar radiation, humidity, and wind speed. However, this data is only available since 1990. Because of this, a version of the Penman-Monteith equation that requires only temperature was used (Allen and others, 1998 and Walter and others, 2002). Analysis of the method indicated that the largest source of error was in the estimation of dew point temperature using minimum daily temperature. In the sub-humid climate of North Dakota, during dry weather dew point temperatures can be significantly less than minimum temperatures, resulting in the temperature based method underestimating the amount of PET. Comparison of the PET estimated using Penman-Monteith with available NDAWN data and only temperature shows that they produce similar results, but the variability in the temperature based method is somewhat subdued.

Figure 4 shows the annual water year (Oct 1. to Sept. 30) and winter precipitation. Figure 5 shows annual water year and growing season PET. The 5-year moving averages smooth the data making it easier to observe long term trends. There is considerable variability at the decadal scale in both precipitation and PET.

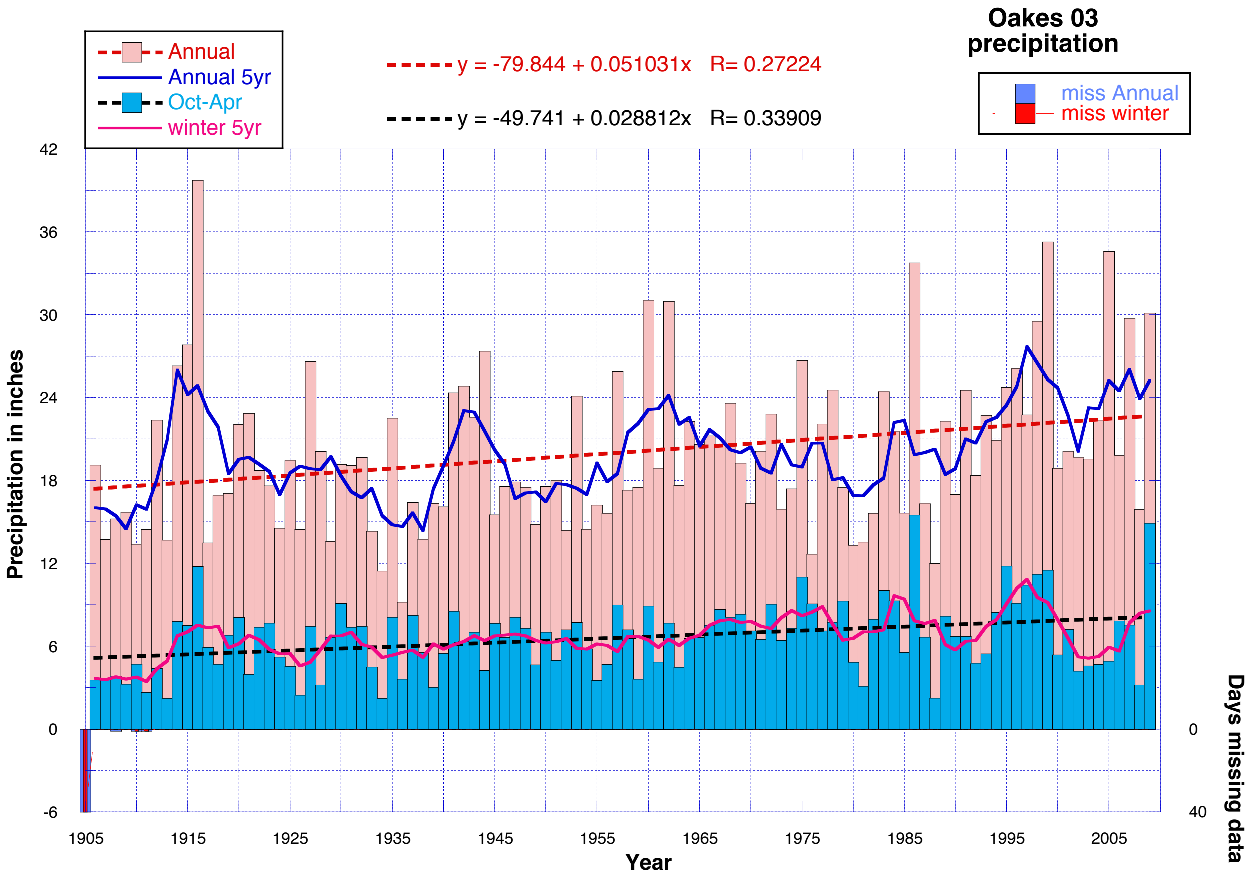


Figure 4. Water year annual and winter precipitation for Oakes, ND (dataset 03).

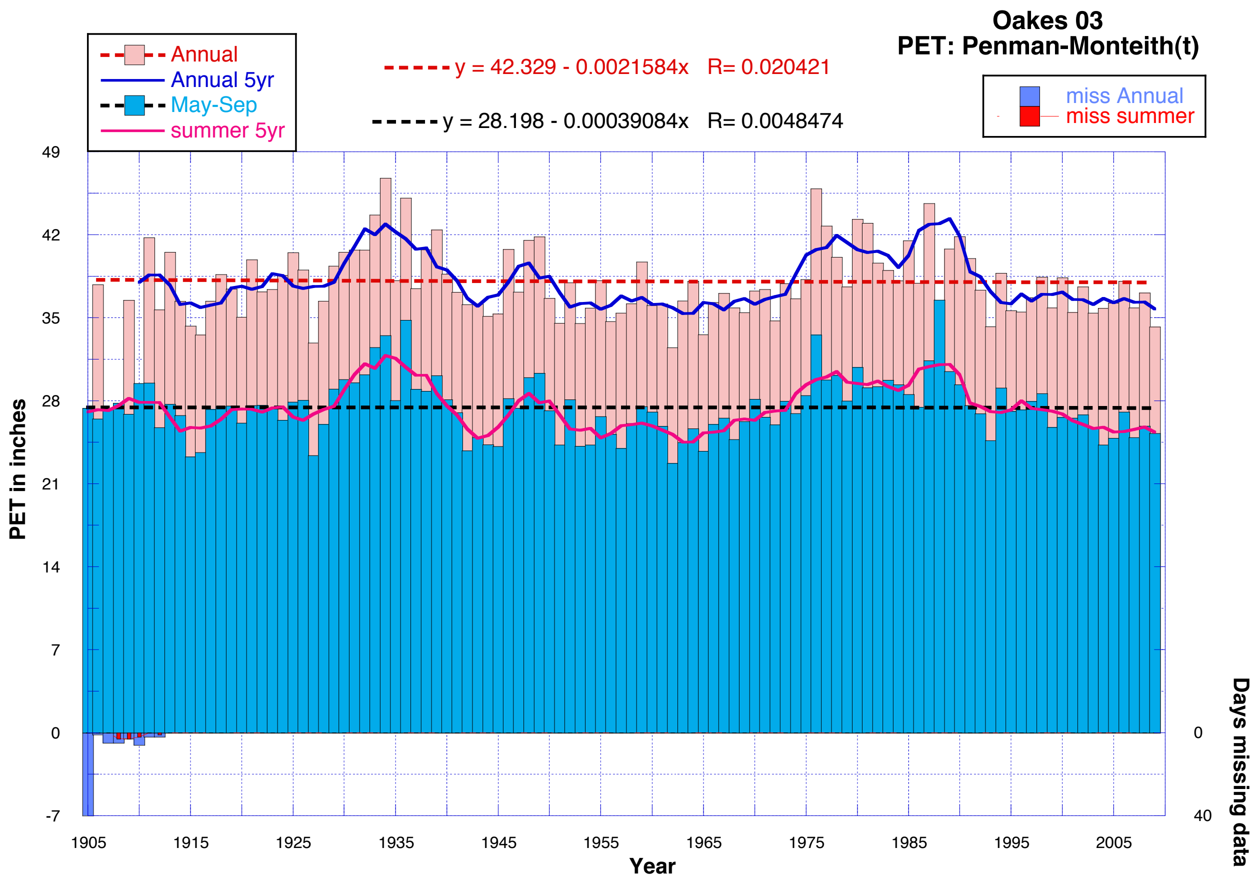


Figure 5. Water year annual and summer potential ET derived from temperature data using the Penman-Monteith equation for Oakes, ND (dataset 03).

Figure 6 compares the the 5-year moving average of the Oakes annual water year precipitation with that of nearby stations at Fullerton, Britton, Forman, and Lisbon. These stations are within a 30 mile radius of Oakes. The plot indicates considerable decadal variation in precipitation. Much of this must be attributed to large random variability in precipitation at the local to regional scale. It is not known as to how fine a scale this amount of variability can be observed, but it is likely that the climate station overlying or nearby an aquifer cannot be considered representative of the amount of precipitation occurring over the entire aquifer. There are definite regional patterns to climate variability observed in the data but the intensity of droughts and pluvials varies significantly.

This large uncertainty in the amount of precipitation occurring over an aquifer leads to large problems in the calibration of a hydrologic model when the inputs are this poorly constrained. It cannot be known whether errors in reproducing water levels in the model are errors defining parameters and boundary conditions within the model or incorrect estimates of recharge and PET.

Additional plots of climate data for stations in the vicinity of Oakes are provided in Appendix A.

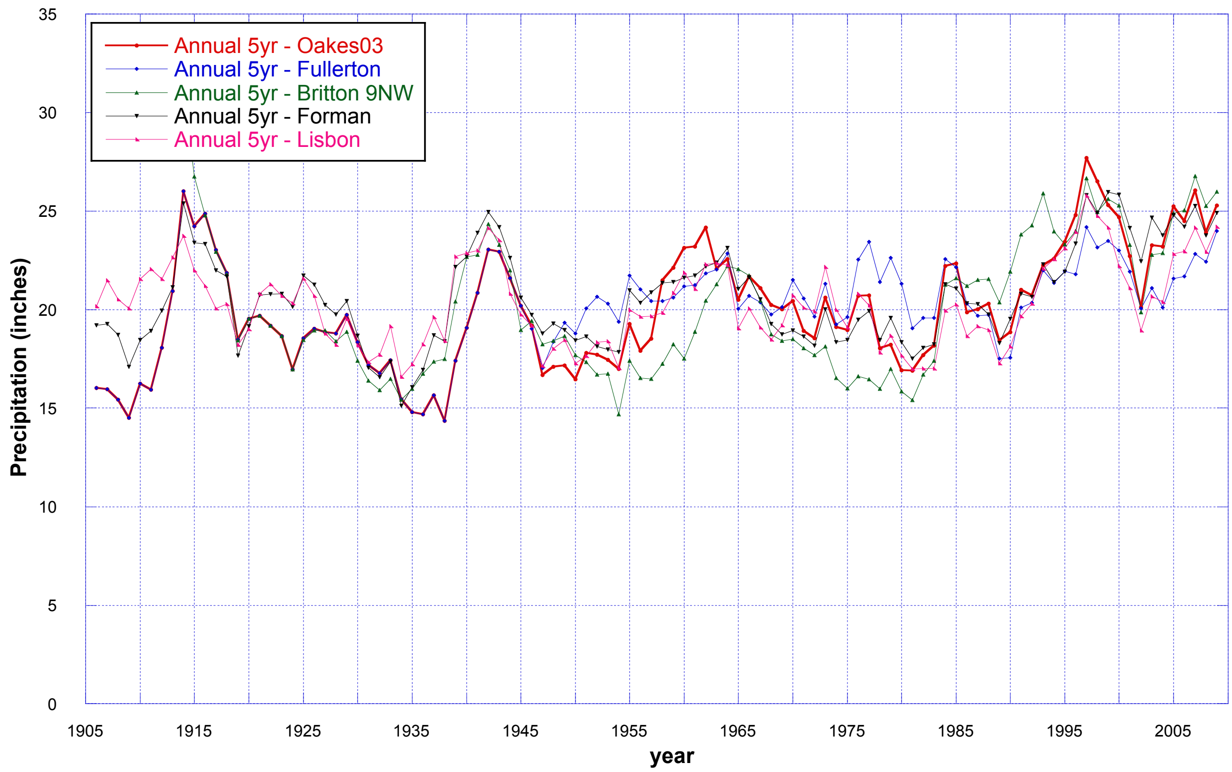


Figure 6. Comparison of 5-year moving average of water year annual for Oakes, ND (dataset 03) and four neighboring stations.

Another perspective on long term regional climate variability is provided by the Palmer Drought Severity Index (PDSI). Figures 7, 8, and 9 show the PDSI for east-central ND, southeast ND, and northeast SD respectively. The plots were obtained from the National Weather Service, Climate Prediction Center website at: http://www.cpc.noaa.gov/products/analysis_monitoring/regional_monitoring/CLIM_DIVS/states_counties_climate-divisions.shtml.

All three plots show the extreme pluvial event occurring from the early 1990s to the present that is observed in the Oakes area climate data. They all show how anomalous the on-going pluvial is. The early 20th century pluvial is evident in the North Dakota divisional data, but not in the South Dakota data.

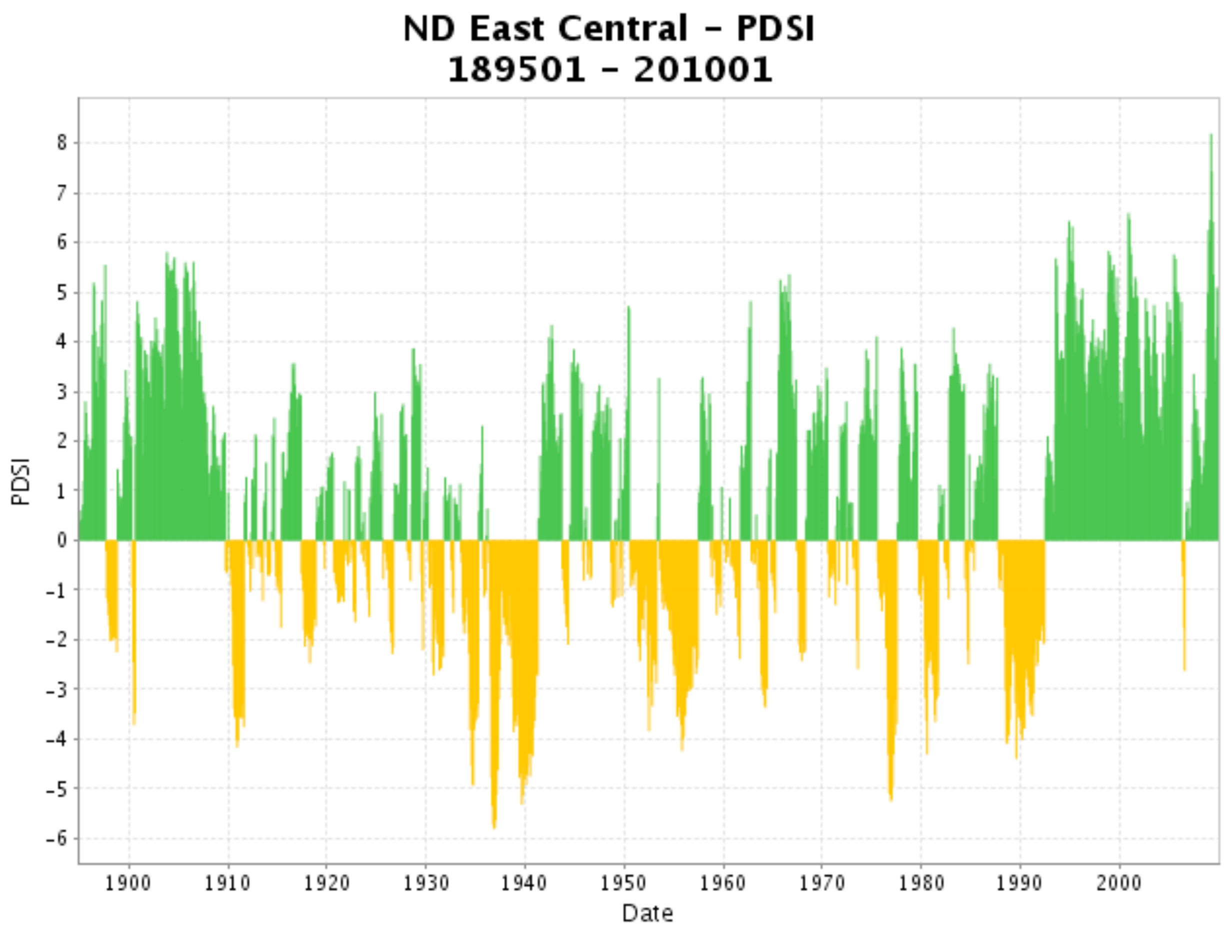


Figure 7. Palmer drought severity index for North Dakota climate division 6 obtained from the National Weather Service, Climate Prediction Center website, http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.

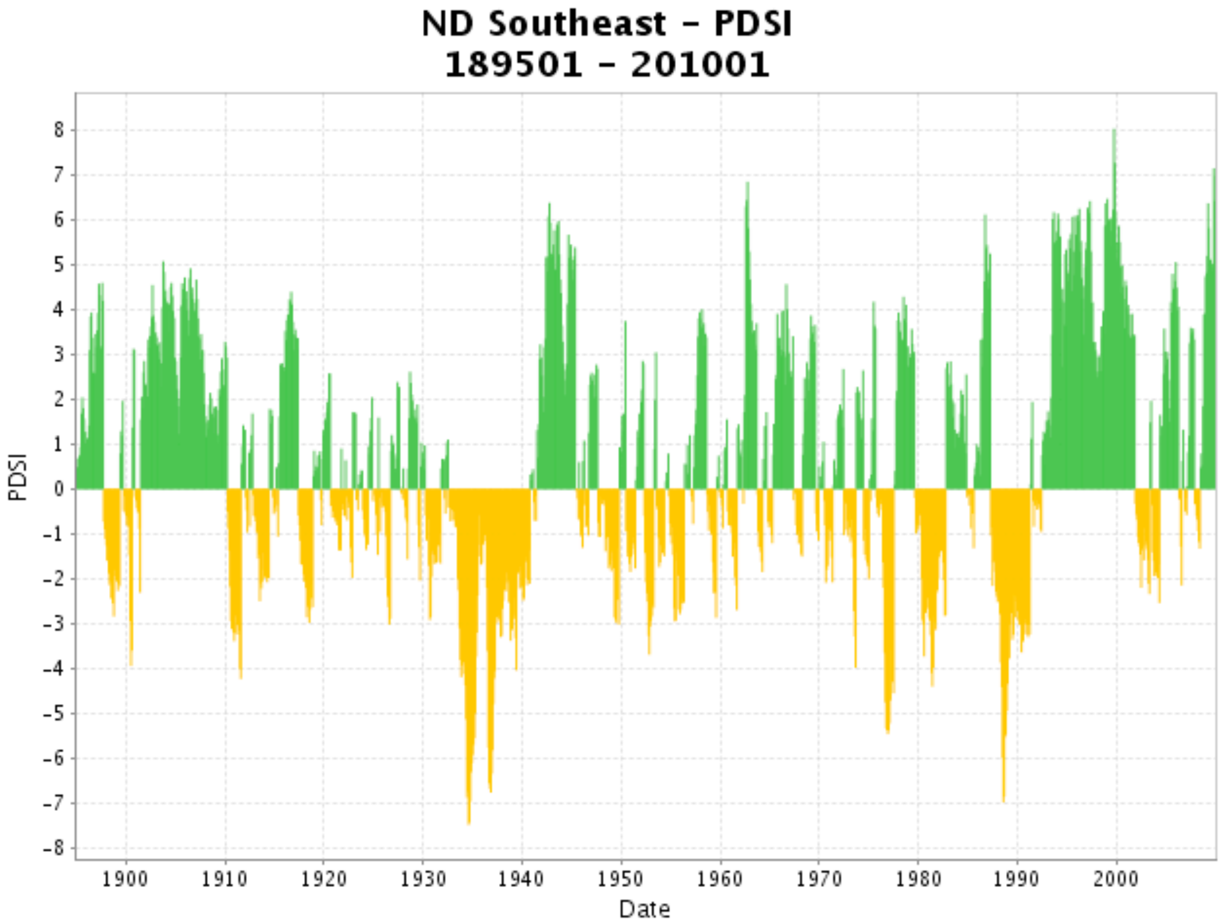


Figure 8. Palmer drought severity index for North Dakota climate division 9 obtained from the National Weather Service, Climate Prediction Center website, http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.

The sustainable management of water resources requires the consideration of both larger patterns of spatial and temporal climate variability, and the large random variability at the local scale. The climate at the nearest weather station must be understood in terms of the variability at nearby stations and the variability at the regional scale. Given the variability between the climate stations near Oakes, 100 years of data is not adequate to capture the scale or random variability in precipitation. In the short run, this local variability can dominate over larger regional patterns.

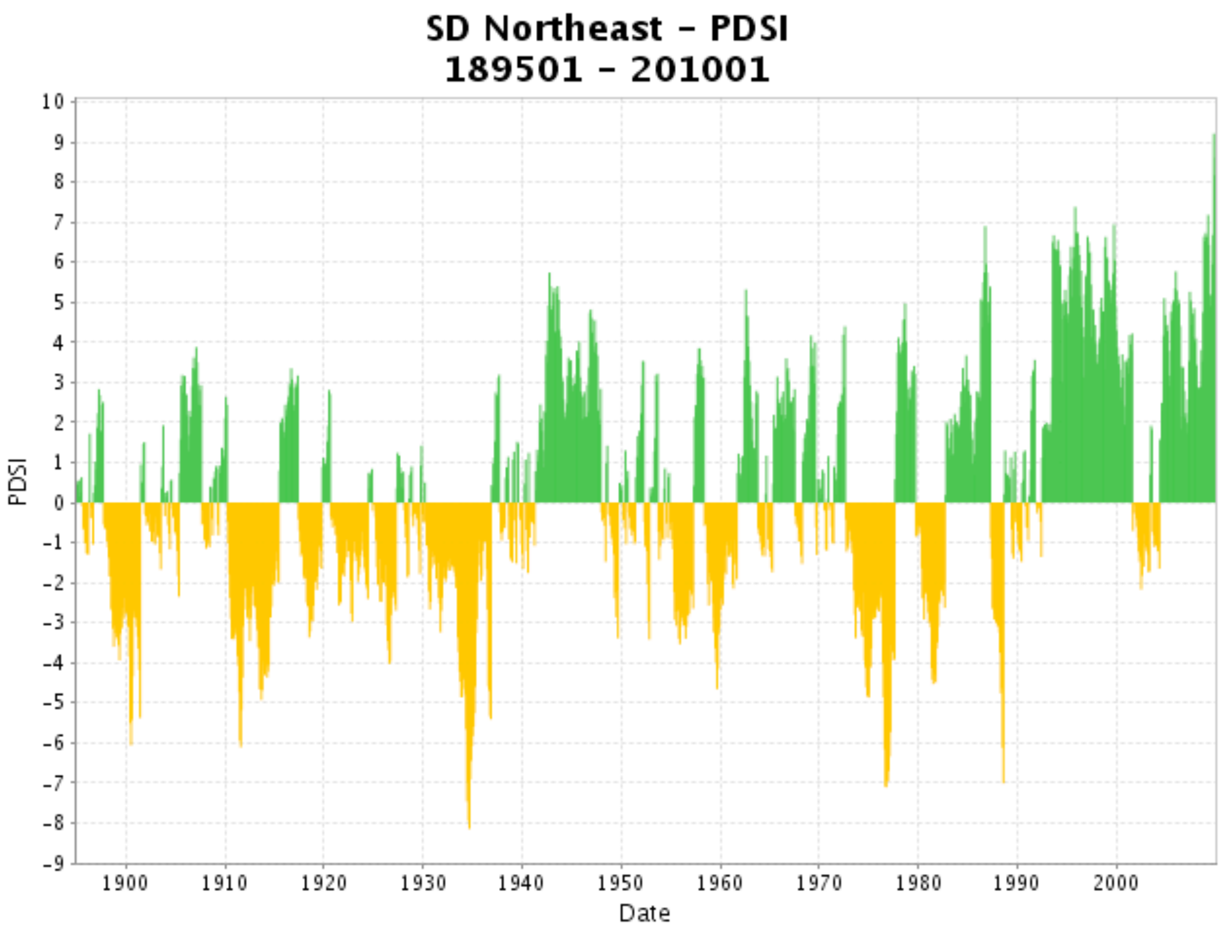


Figure 9. Palmer drought severity index for South Dakota climate division 3 obtained from the National Weather Service, Climate Prediction Center website, http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.

Water Permits

The point of diversion (POD) for an irrigated tract [center pivot(s)] may consist of one or several identified tracts of land and involve more than one water permit. To facilitate the analysis of the water use data and in assigning pumping rates within the model, these tracts were aggregated into a superPOD that irrigates a specified number of acres with one or more irrigation well(s). This also involved the splitting of PODs into more that one superPOD where wells within the POD independently served different pivots. In the maps of PODs only one tract in a superPOD is displayed.

Permit Status

The location of active and cancelled water permits from the Oakes, Middle James, and Spiritwood aquifers are shown in figure 10. Additional irrigation water has been supplied by DSID within the OTA since 1988. The OTA has supplied water to 675 permitted acres that have inadequate water supplies. The source of the OTA water has "been Jamestown Reservoir, artificial recharge water stored in the Oakes aquifer, recapture of drain water discharge to the James River, and James River" (Lindvig, 2006).

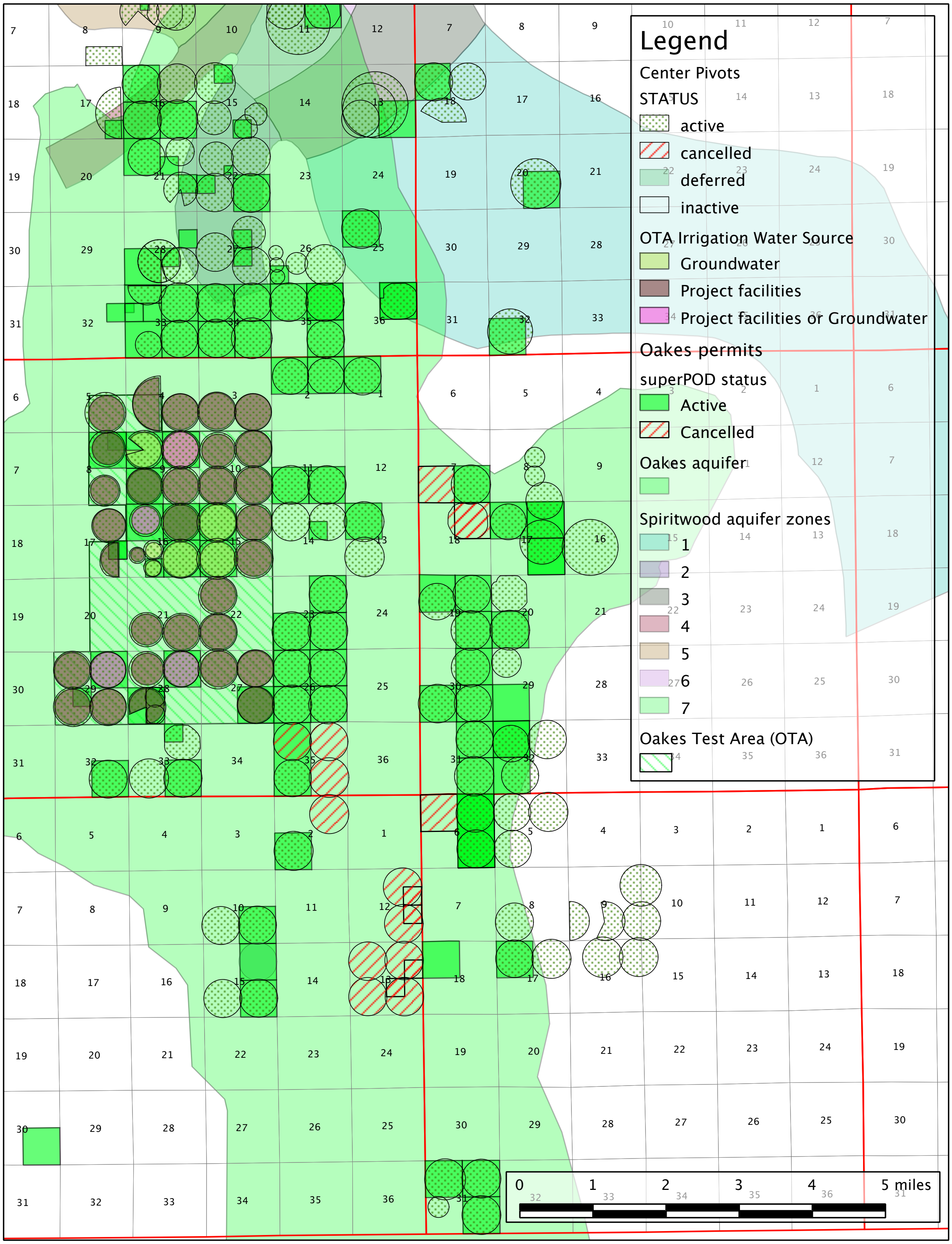


Figure 10. Location of active and cancelled PODs for Oakes and underlying Spiritwood aquifers. Circles show the location of center pivots. Sources of water within the Oakes Test Area are also shown.

There are presently 13,612 acres permitted for irrigation from the Oakes aquifer. Of this amount, 3,945 acres were granted between January 1, 1990 and January 1, 1997. A pluvial (wet period) began in 1992, as indicated by both water use data and climate data, has continued through 2010. Because of high water table conditions resulting from the ongoing pluvial, the number of acres irrigated and the total water use did not increase beyond that of the 1980s. As a result, the impact to the aquifer of this additional allocation is not known.

There are pending water permit applications to irrigate an additional 4,252 acres from the Oakes aquifer with a priority date prior to July 31, 2006. On July 31, 2006 Dickey-Sargent Irrigation District (DSID) filed a water permit application to irrigate 5,000 acres within the Oakes Test Area (OTA) with 5,000 acre-feet of water. The location of the existing and pending water permit applications are shown in figures 11, 12, and 13. Figure 11 shows the acreage pending. Figure 12 shows the acre-feet pending. Figure 13 shows the water permit number for the pending water permit applications. Table 2 lists the pending water permits in order of priority date. Of the total acreage of 4,252 acres, 831 are within the OTA. The pending permits within the OTA are highlighted in yellow in table 2.

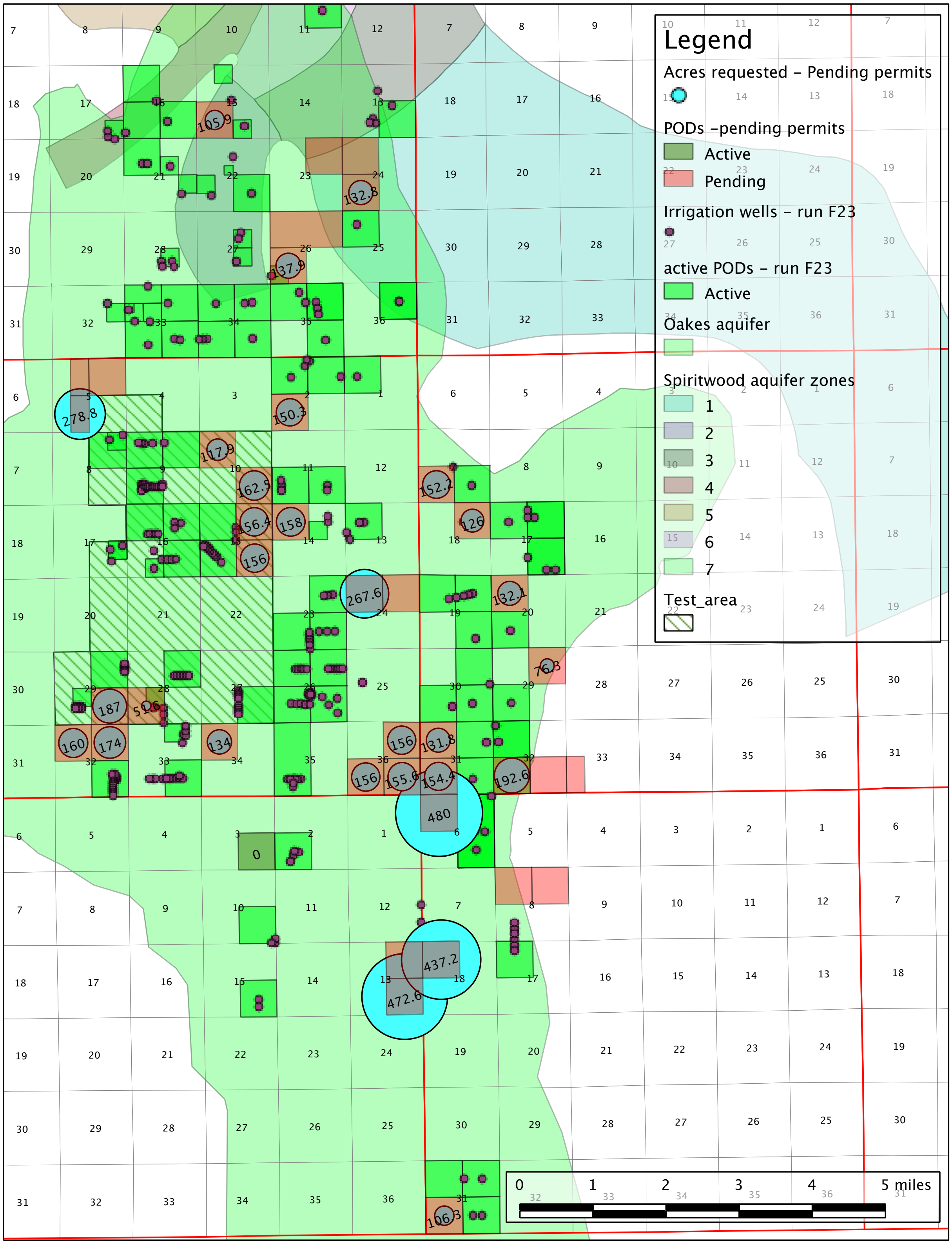


Figure 11. Location of active and pending PODs for Oakes and underlying Spiritwood aquifers. The diameter of the circles show acres requested in pending water permit applications and are labeled with the pending acres. The size of the circle is proportional to the acres requested.

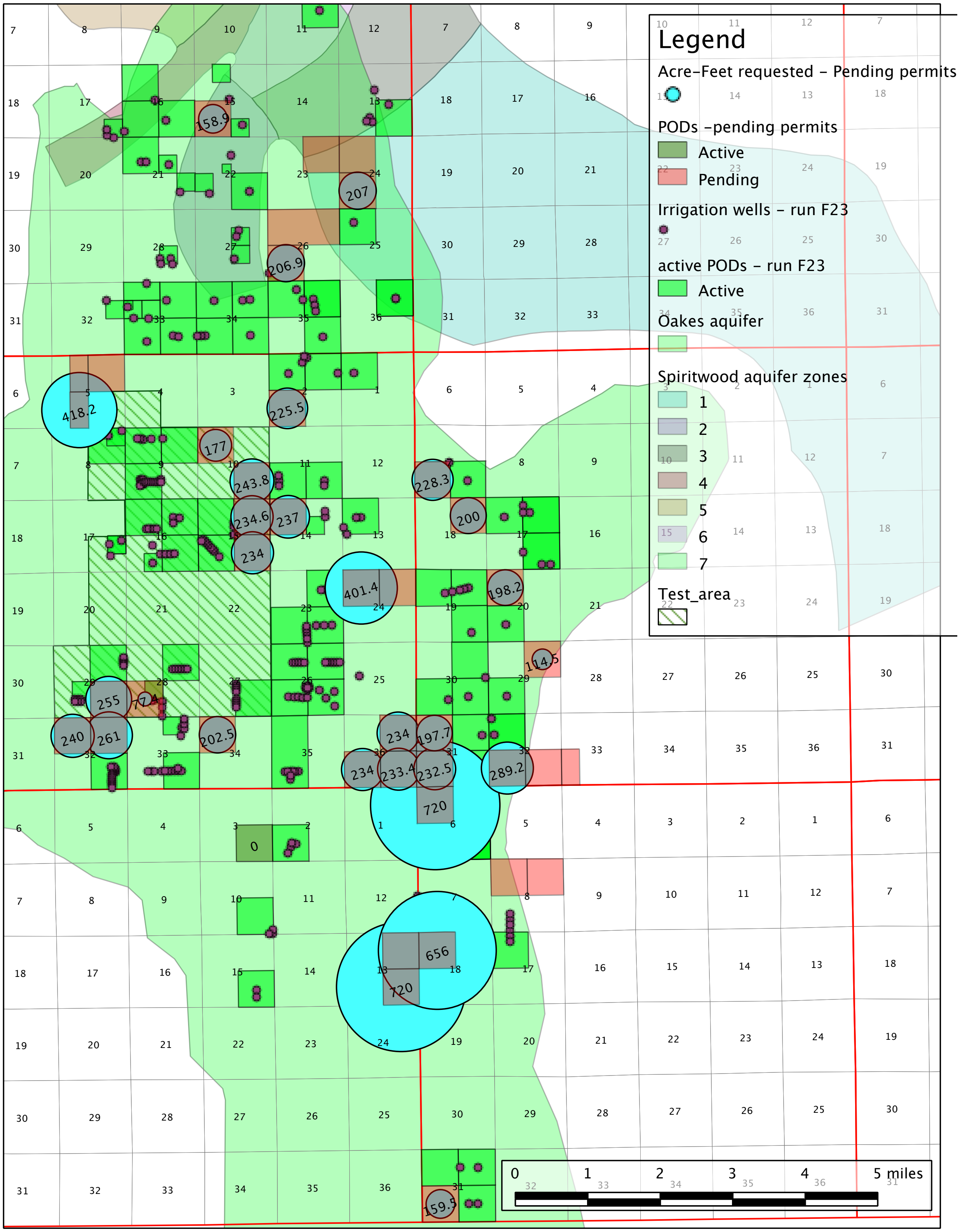


Figure 12. Location of active and pending PODs for Oakes and underlying Spiritwood aquifers. Circles show acre-feet requested in pending water permit applications and are labeled with the pending acre-feet. The size of the circle is proportional to the acre-feet requested.

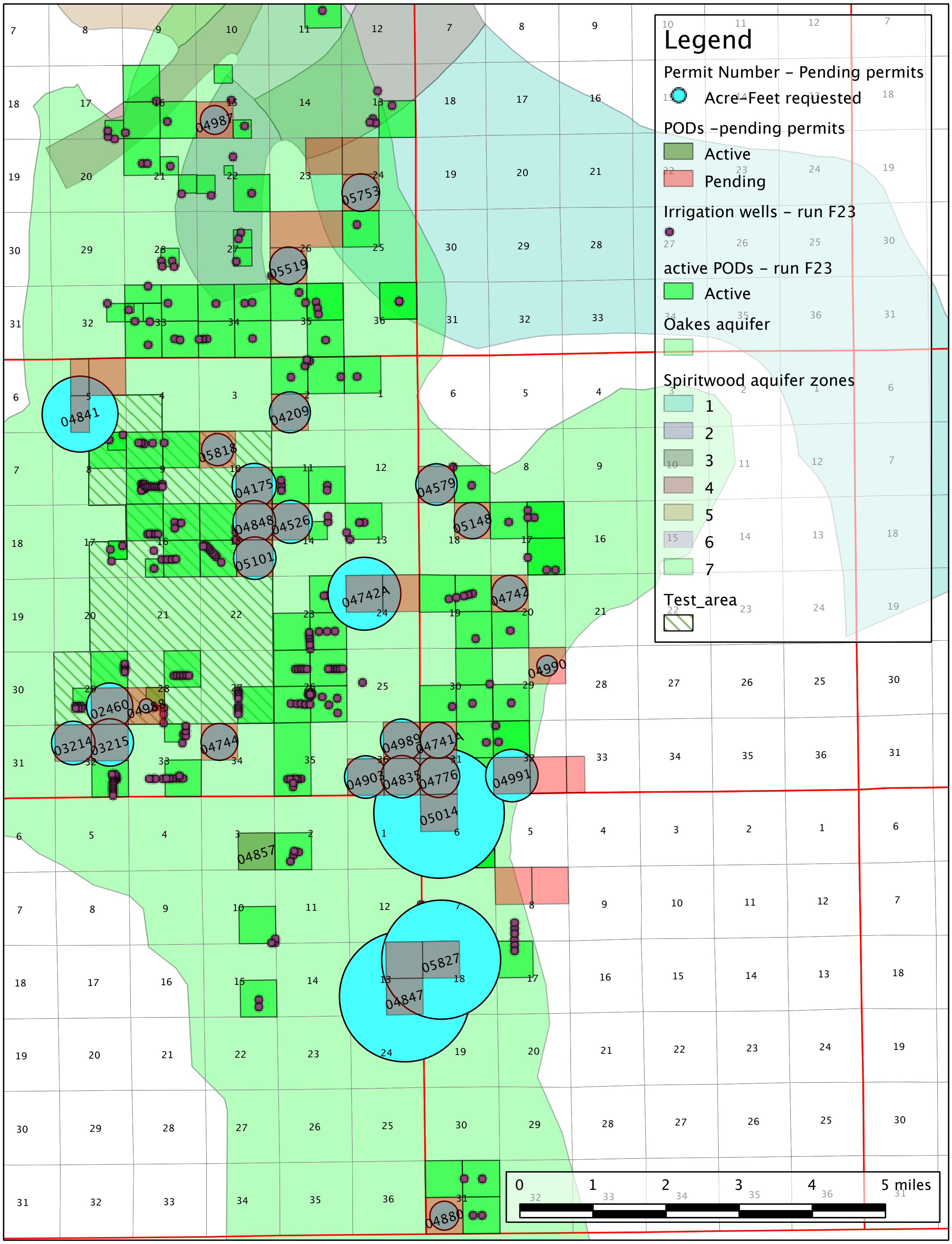


Figure 13. Location of active and pending PODs for Oakes and underlying Spiritwood aquifers. Circles are labeled with the permit number. The size of the circle is proportional to the acre-feet requested.

Table 2. Pending permits in the Oakes aquifer that are senior to Dickey-Sargent Irrigation District water permit application #5842, priority date 7/31/2006. Pending permits within the Oakes Test Area are indicated in yellow. Permit #4835 is approved, but undeveloped. Many of these applications have more than one POD. Only one POD is shown for each permit.

Permit	Owner	POD	Aquifer	Status	Priority Date	Ac-Ft	Acres
2460	VISTO, GARY J.	13005929D	Oakes	Pending	1976-06-01	255.0	187.0
3214	HOKANA, WILLARD R.	13005932B	Oakes	Pending	1980-05-19	240.0	160.0
3215	HOKANA, STANLEY	13005932A	Oakes	Pending	1980-05-19	261.0	174.0
4175	RONEY, DENNIS P.	13005910D	Oakes	Pending	1989-12-21	243.8	162.5
4209	RONEY, LARRY	13005902C	Oakes	Pending	1990-03-14	225.5	150.3
4526	RONEY, DENNIS P.	13005914B	Oakes	Pending	1991-10-17	237.0	158.0
4579	QUANDT, JOHN P.	13005807C	Oakes	Pending	1992-03-27	228.3	152.2
04741A	HANSEN, PHILIP A.	13005831B	Oakes	Pending	1993-12-22	197.7	131.8
4742	KBO FARM PARTNERSHIP	13005820B	Oakes	Pending	1993-12-22	198.2	132.1
04742A	RONEY, DENNIS & RAMONA	13005924B	Oakes	Pending	1993-12-22	401.4	267.6
4744	HVISTENDAHL, DOUGLAS	13005934B	Oakes	Pending	1993-11-09	202.5	134.0
4776	ANDERSON, JOEL	13005831C	Oakes	Pending	1994-04-28	232.5	154.4
4835	SCHMIT, KIM	13005936D	Oakes	Pending	1994-12-22	233.4	155.6
4841	LOCKEN, DAVID	13005905CE	Oakes	Pending	1995-08-11	418.2	278.8
4847	QUANDT BROTHERS	12905913D	NULL	Pending	1994-12-27	720.0	472.6
4848	QUANDT, JAMES	13005915A	Oakes	Pending	1994-12-30	234.6	156.4
4857	LeMIER, GLEN and TWILA	12905903D	Oakes	Active	1995-05-17	177.0	118.0
4880	CLAEYS, GLORIA IRENE	12905831C	Oakes	Pending	1995-02-27	159.5	106.3
4903	HANSEN, PHILIP A.	13005936C	Oakes	Pending	1995-05-08	234.0	156.0
4988	KBO FARM PARTNERSHIP	13005928C	Oakes	Pending	1996-02-16	77.4	51.6
4989	KBO FARM PARTNERSHIP	13005936A	Oakes	Pending	1996-02-16	234.0	156.0
4990	KBO FARM PARTNERSHIP	13005829A	Oakes	Pending	1996-02-16	114.5	76.3
4991	KBO FARM PARTNERSHIP	13005832C	Oakes	Pending	1996-02-16	289.2	192.6
5014	HANSEN, LARRY AND NANCY	12905806B	Oakes	Pending	1996-05-16	720.0	480.0
5101	WHITE, GARY	13005915D	Oakes	Pending	1997-01-29	234.0	156.0
5148	HANSEN, STEVE	13005818A	Oakes	Pending	1998-01-02	200.0	126.0
5818	REHOVSKY, JOSEPH	13005910B	NULL	Pending	2006-03-22	177.0	117.9
5827	QUANDT BROTHERS	12905818B	NULL	Pending	2006-04-07	656.0	437.2

Water Use

Most of the irrigation development from the Oakes aquifer occurred between 1975 and 1982 (fig. 14). Since the early 1980s acres irrigated has ranged between 10,000 and 12,000 acres though there are 13,612 acres permitted. The large drop in acres for 1998 through 2001 is attributed to the high water table and flooding conditions that existed at planting in those years. There are a large number of pivots that have not operated since the mid-1990s due to high water table conditions to the east and south of the OTA which is tile drained.

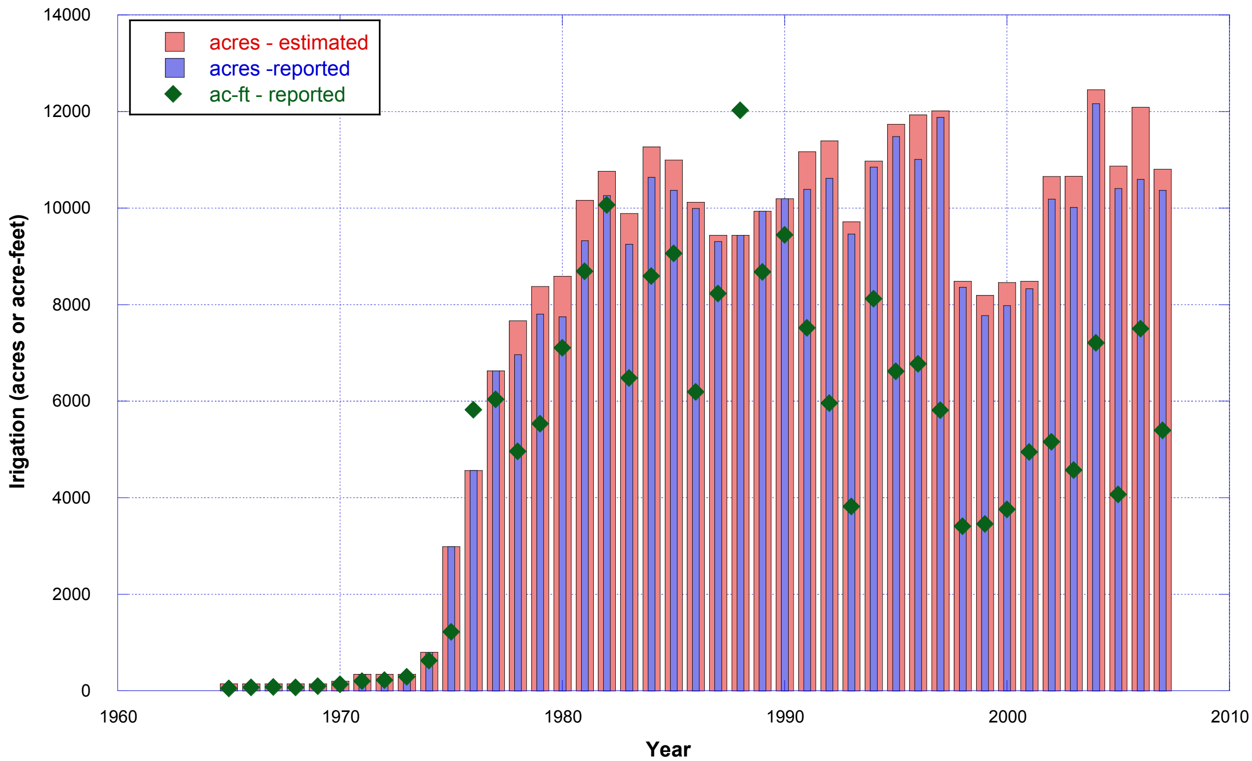


Figure 14. Water use for the Oakes aquifer showing reported acres and acre-feet. Estimated acres were derived from LANDSAT images and aerial photography for years when no water use form was received.

Figure 15 shows the irrigation application rate in inches per acre for both the Oakes and Englevale aquifers. The Englevale aquifer lies to the northeast of the Oakes aquifer in western Ransom and northwestern Sargent Counties (fig.2). The water use is similar between the two aquifers.

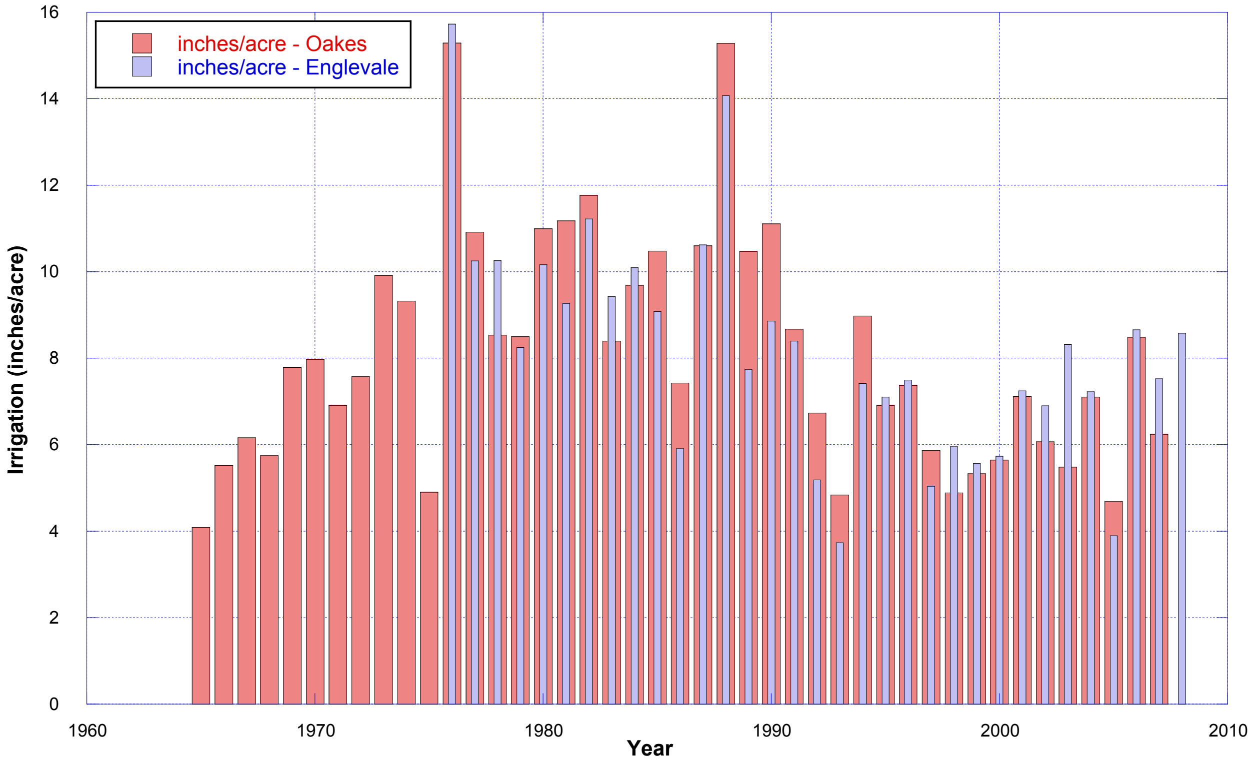


Figure 15. Water use in inches/acre for Oakes and Englevale aquifers.

Figure 16 compares the reported water use and reported water use plus water use for estimated acres with that calculated from climate data using a soil moisture budget. The use of a soil moisture budget model to calculate irrigation water use is discussed later in the section Recharge, ET_{gw}, and Irrigation Water Use of the Model Results. The calculated use tends to run a little higher than the reported use. In figure 17, the reported use is compared to calculated water use from the Oakes, Forman, Fullerton, and Britton climate datasets. The reported use mostly falls within the range of use calculated from the datasets for the nearby climate stations. This would indicate that much of the error in calculated water use from climate data is a result of variations in climate across the aquifer that are not accounted for in the Oakes climate data set and not a result of problems with calculating water use from a soil moisture budget model.

Figure 18 compares the reported water use plus estimated use for non-reporting to that calculated from the Oakes climate dataset. With the exception of 1976 and 1988, the points are well distributed around the one-to-one line indicating the procedure is doing a good job of capturing the variability in water use. Examining both 1976 and 1988 in figure 17 shows Oakes to be the highest value in both years with a particularly anomalous value in 1988. Though figure 18 would indicate that the soil moisture budget model tends to significantly overestimate water use in very dry years, based on the other climate datasets this conclusion does not seem warranted. It is concluded that soil moisture budgeting procedure is an adequate method for estimating irrigation water use from climate data consisting of precipitation, and maximum and minimum temperatures.

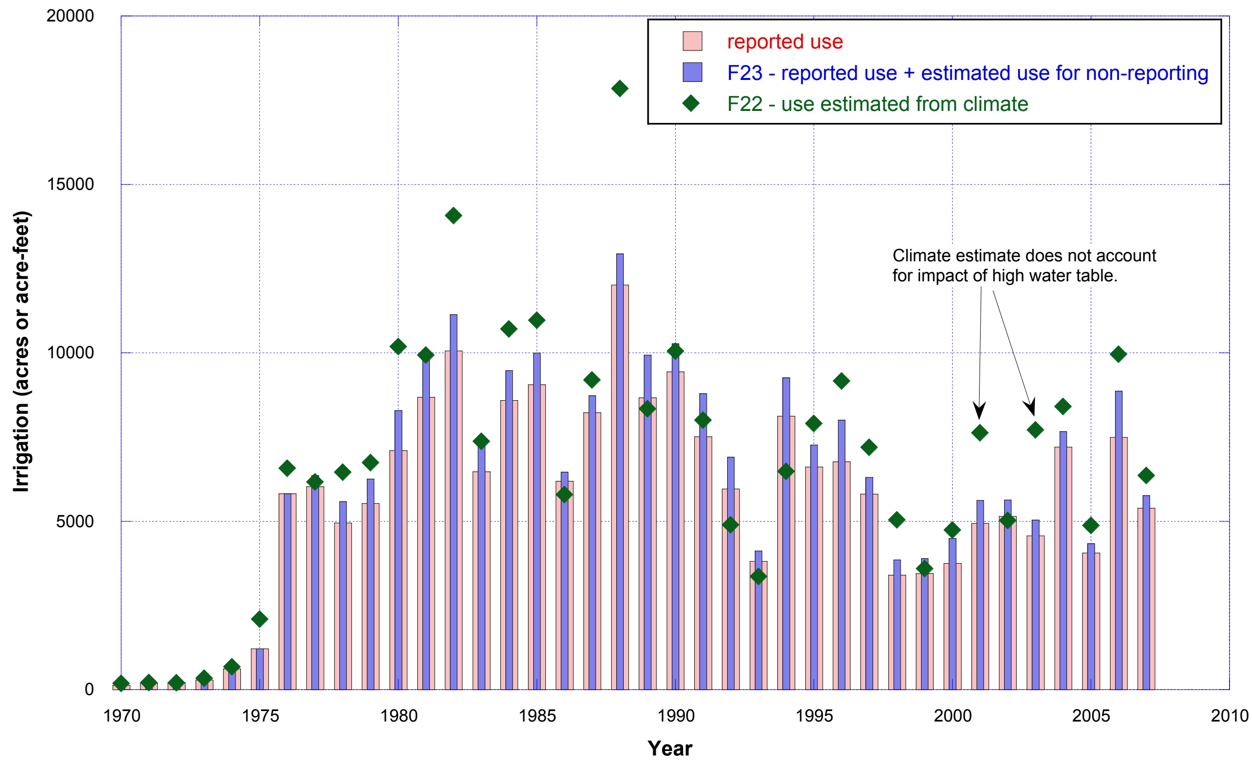


Figure 16. Water use in acre-feet. Graph compares reported use, reported use plus use for estimated acres based on average aquifer use, and water use estimated from Oakes climate data.

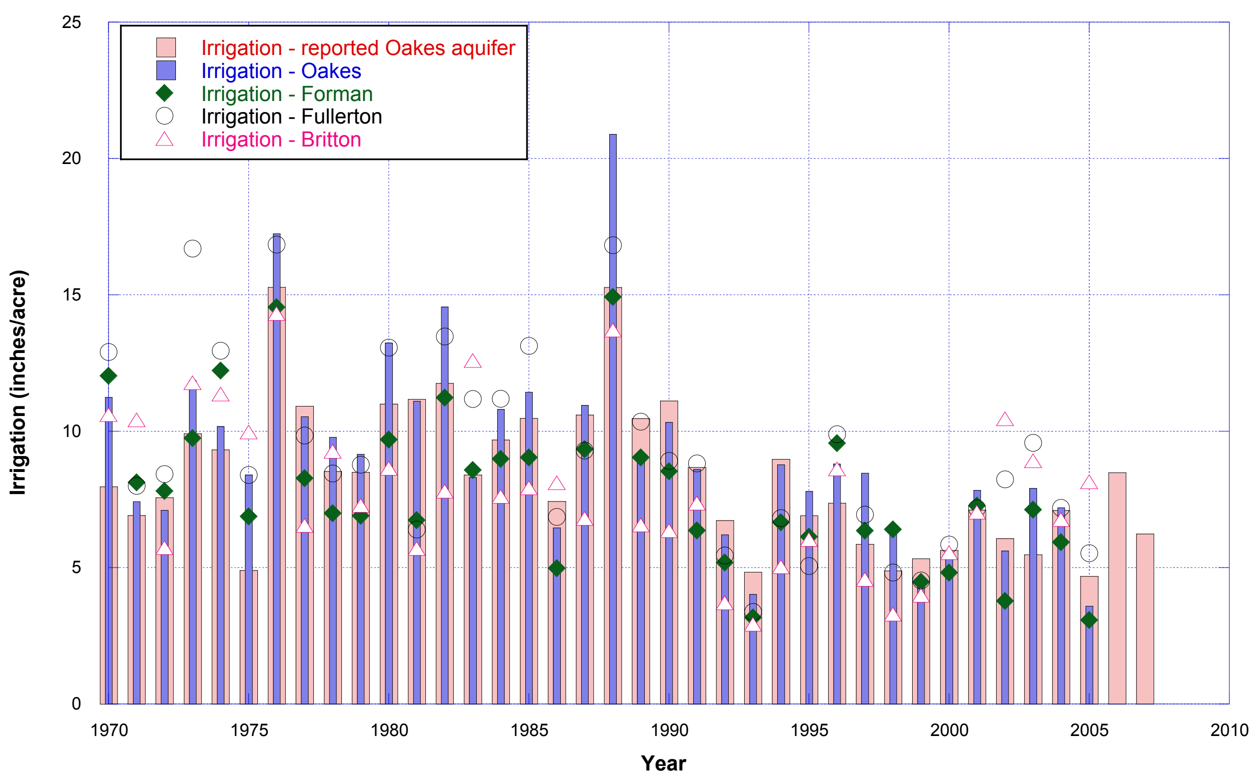


Figure 17. Water use in inches per acre. Graph compares reported use and water use estimated from Oakes, Forman, Fullerton, and Britton climate data.

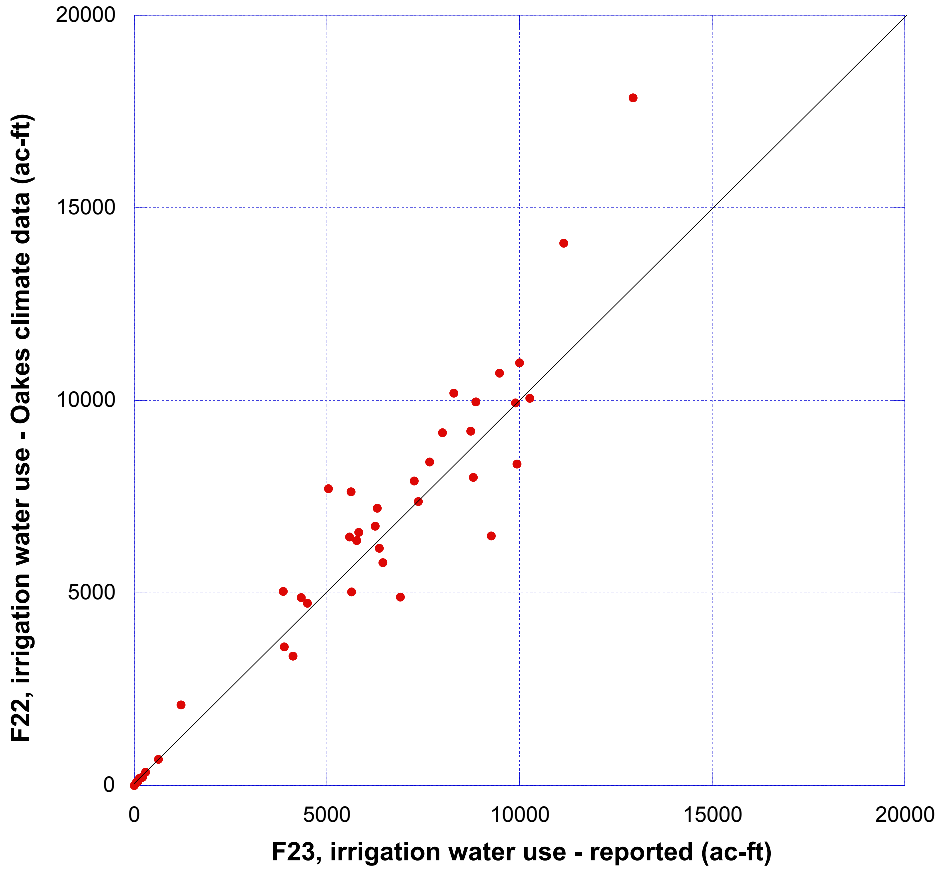


Figure 18. Comparison of irrigation water use reported plus estimated use for non-reporting to irrigation water use estimated from Oakes climate data. Data from model run F22 and F23 datasets.

Oakes Aquifer Water Levels and Drain Flows

Drain Flows

The drains constructed by the USBR are a significant source of discharge from the Oakes aquifer. The pilot drain north of the test area was constructed during 1969, 1970, and 1972. In 1975, 0.5 miles of open drain were converted to pipe drain. The drains within the OTA were constructed during 1983, 1984, and 1985 (Fig 19).

The USGS monitored flows in the pilot drain from 1971 to 1982 (fig. 20). The drop in flows in the early 1970s likely results from the dewatering of the aquifer in the vicinity of the drain. Also, sloughing of the drain sides and subsequent cleaning impacted flows (personal communications, Robert Shaver). The small flows after 1976 are a result of irrigation pumping in the vicinity of the pilot drain lowering water levels (table 3). The highest flows would have been expected during 1969 and 1970 when most of the drain was constructed.

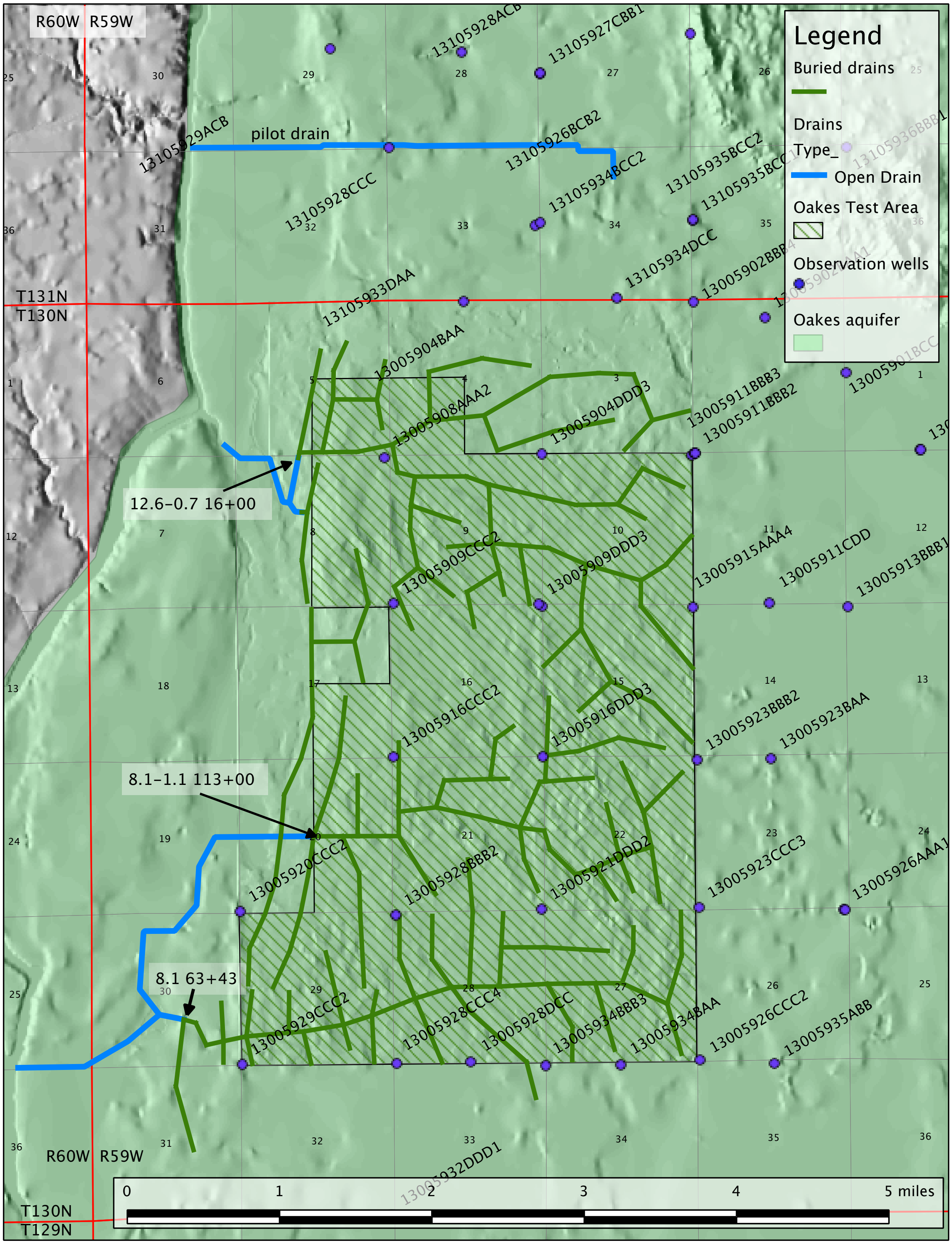


Figure 19 Location of drains within the OTA. Site 8.1 63+43, 8.1-1.1 113+00, and 12.6-0.7 16+00 are places where drain flow is periodically measured by the GDCD.

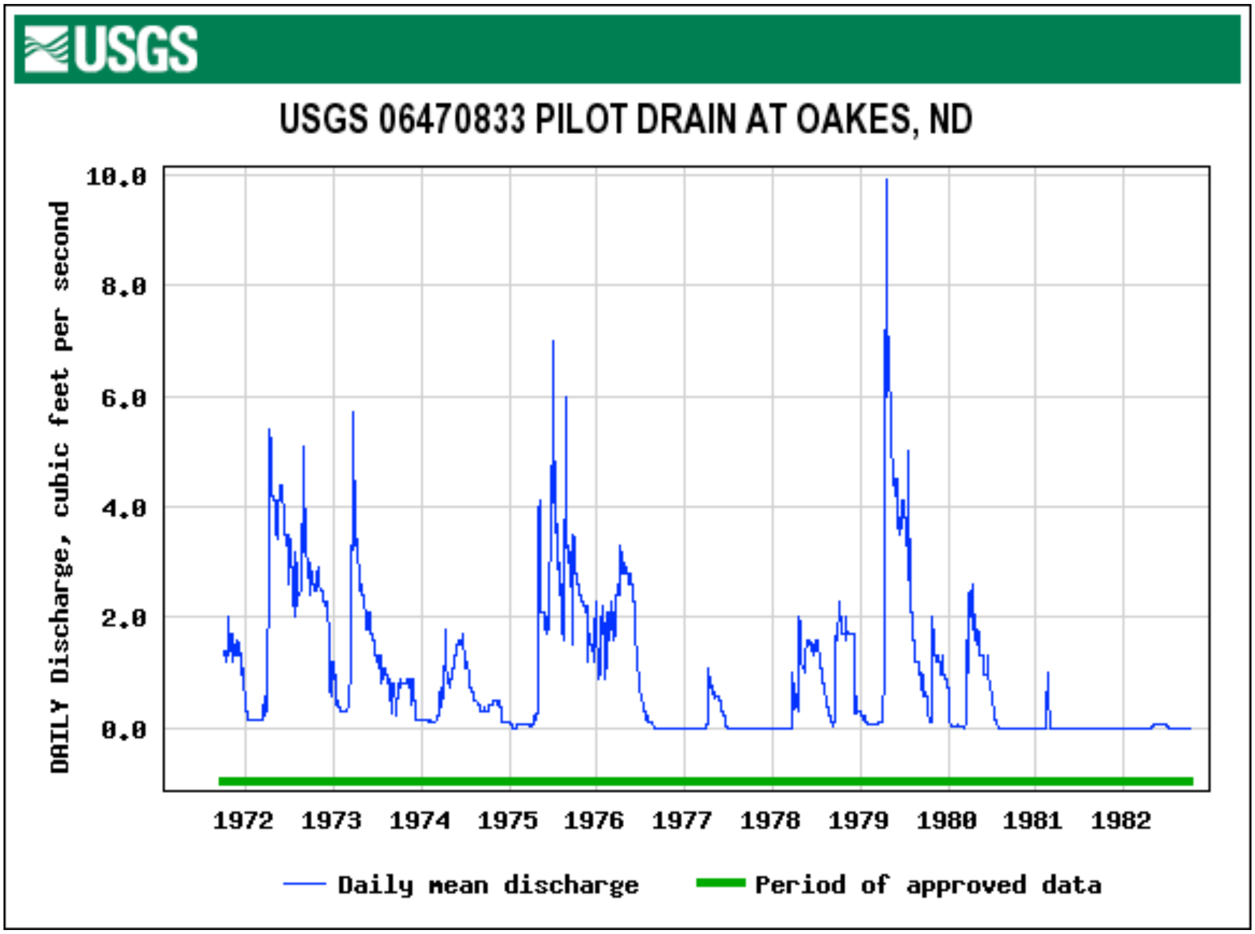


Figure 20. Flow at pilot drain. Graph is from USGS website at http://waterdata.usgs.gov/nd/nwis/dv?cb_00010=on&cb_00060=on&cb_00095=on&format=gif_default&begin_date=1971-01-23&end_date=1982-12-23&site_no=06470833&referred_module=sw. The site was discontinued in 1982.

The total discharge for the drains within the OTA are much larger than those for the pilot drain (fig. 21). Discharge from the OTA drains for the period January 1, 1995 to October 31, 2008 averaged 4,750 ac-ft per year (6.6 cfs). The area affected by the drains is approximately 13.5 mi^2. This is equivalent to a recharge rate of 6.6” per year. This is over twice the average amount of irrigation water applied within the OTA of 3.0” per year (1995 through 2007).

Drain flow from the OTA is monitored at three sites (fig. 19) in addition to the branch drains which are the four later drains downstream from 8.1-1.1. Branch Drains refer to 8.1-1.1-1.9 rt and lt and 8.1-1.1-2.1 rt & lt. The flows for 12.6-0.7, 8.1-1.1, the branch drains, and 8.1 are shown in figures 22 through 25 respectively. The much larger flows at drain outflow 12.6-0.7 are largely a result of it draining approximately twice the area as the other two drain networks.

Table 3. Average annual discharge in cfs for the pilot drain. Data from USGS website at: http://waterdata.usgs.gov/nwis/annual?referred_module=sw&search_site_no=06470833&format=sites_selection_links.

Year	Discharge (cfs)
1972	2.08
1973	1.59
1974	0.663
1975	1.37
1976	1.57
1977	0.106
1978	0.502
1979	1.95
1980	0.691
1981	0.017
1982	0.012

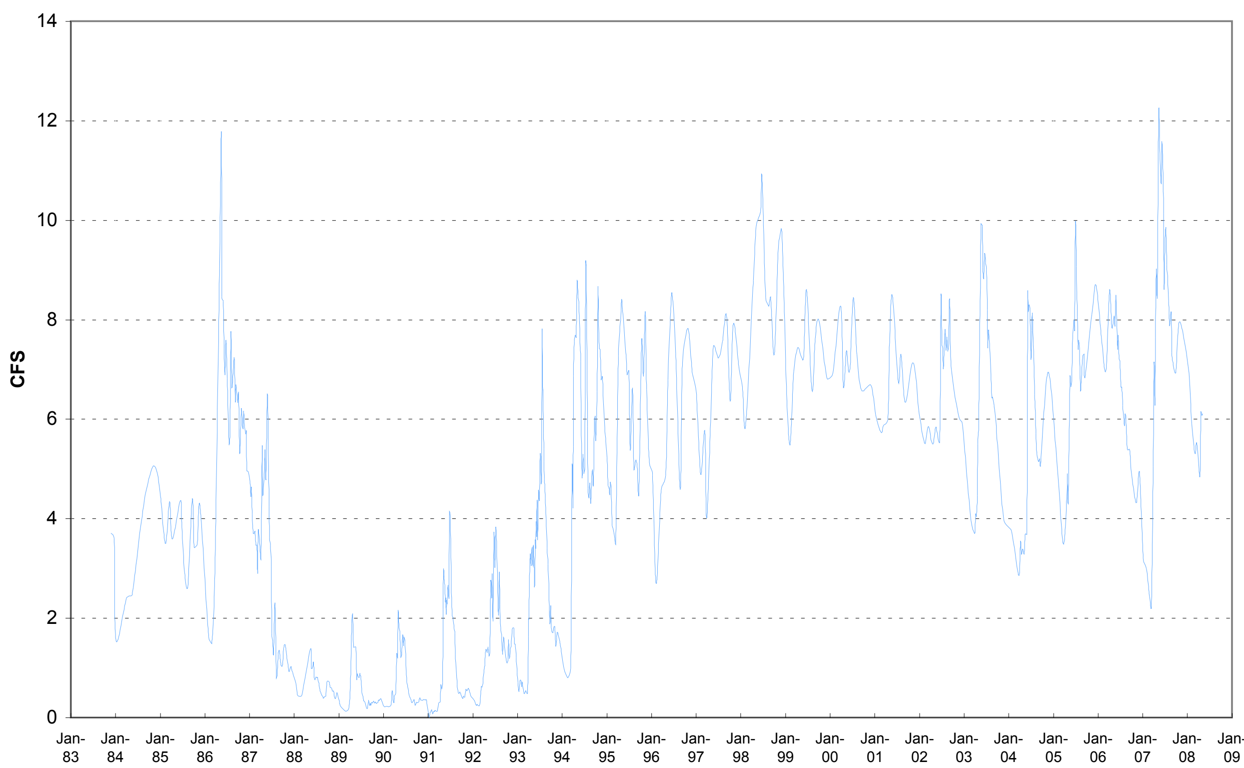


Figure 21. Total OTA flows in cubic feet per second (CFS). Graph provided by Dale Esser, Garrison Diversion Conservancy District.

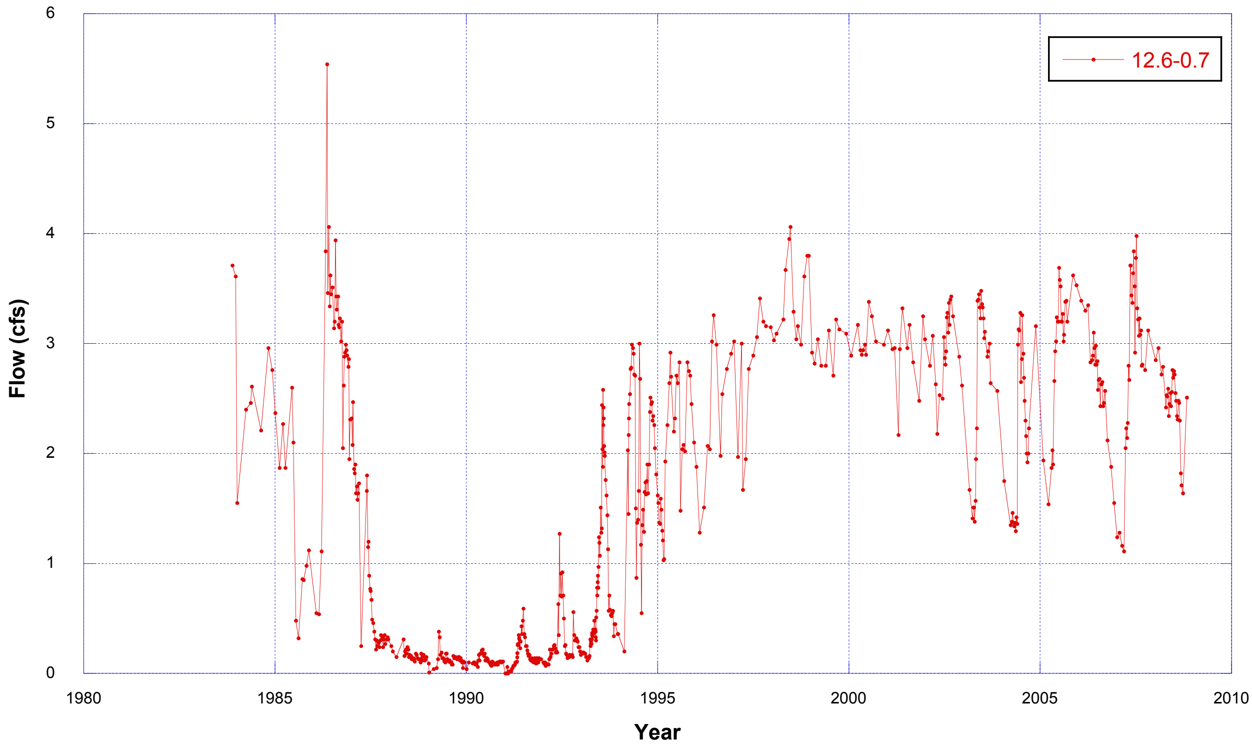


Figure 22. Drain flow at station 12.6-0.7. This drain network drains the northern part of the OTA.

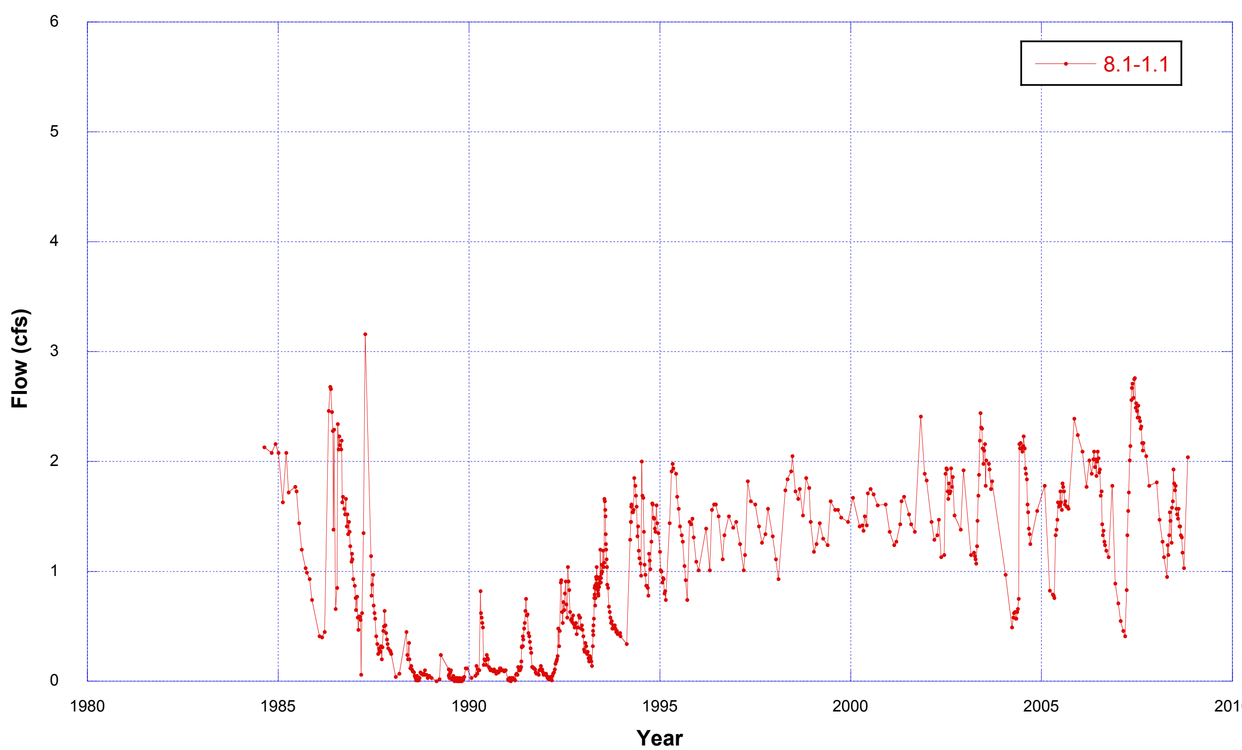


Figure 23. Drain flow at station 8.1-1.1. This drain network drains the central part of the OTA.

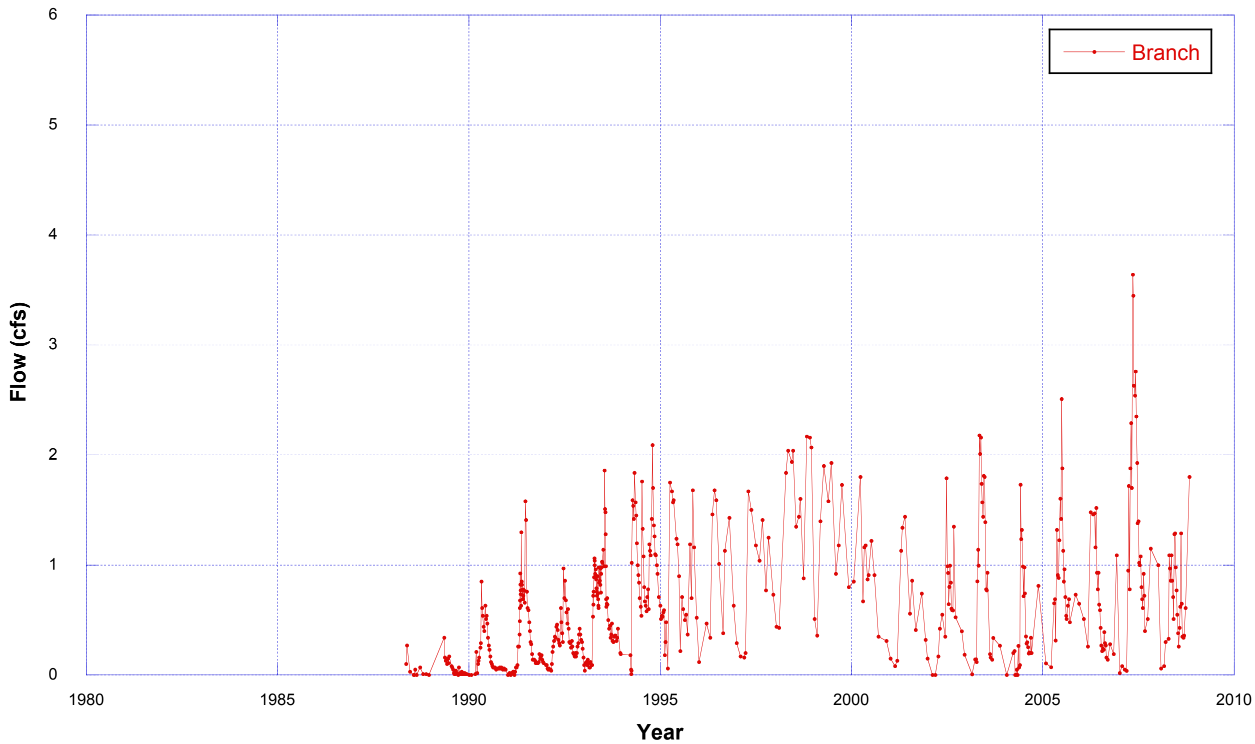


Figure 24. Drain flow at branch drains. The branch drains are the four later drains downstream from 8.1-1.1. Branch Drains refer to 8.1-1.1-1.9 rt and lt and 8.1-1.1-2.1 rt & lt.

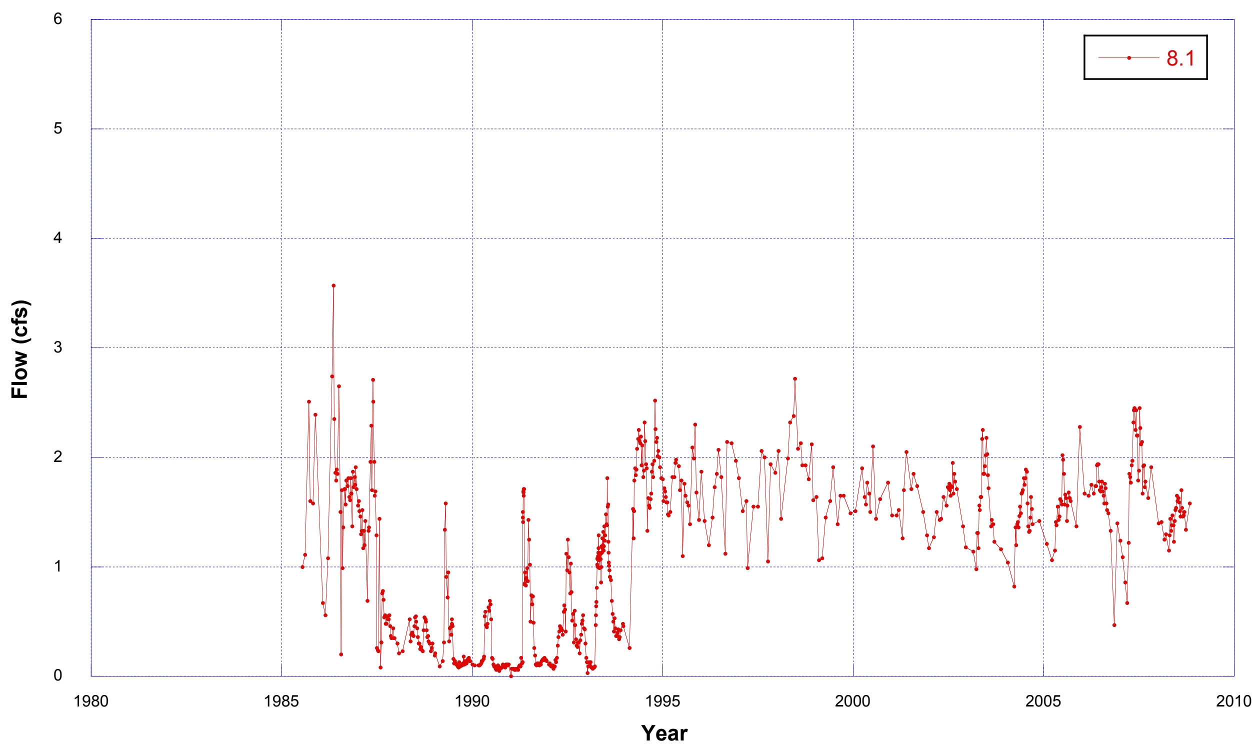


Figure 25. Drain flow at station 8.1. This drain network drains the central part of the OTA.

Water Levels

Water level data indicates the response of the aquifer to both climate and pumping. The USBR began the installation of a large network of observation wells in 1966 across the Oakes Lake Plain extending from just north of Oakes into South Dakota. Additional observation wells were installed in the mid-1970s by the ND State Water Commission (NDSWC) in cooperation with the U.S. Geological Survey for the Dickey-LaMoure and Ransom-Sargent County groundwater studies (Armstrong, 1978, 1979, 1980, and 1982). Additional observation wells were installed by both the USBR and NDSWC from the mid-1970s through the early 1990s. The observation wells currently monitored are shown on the map in figure 26.

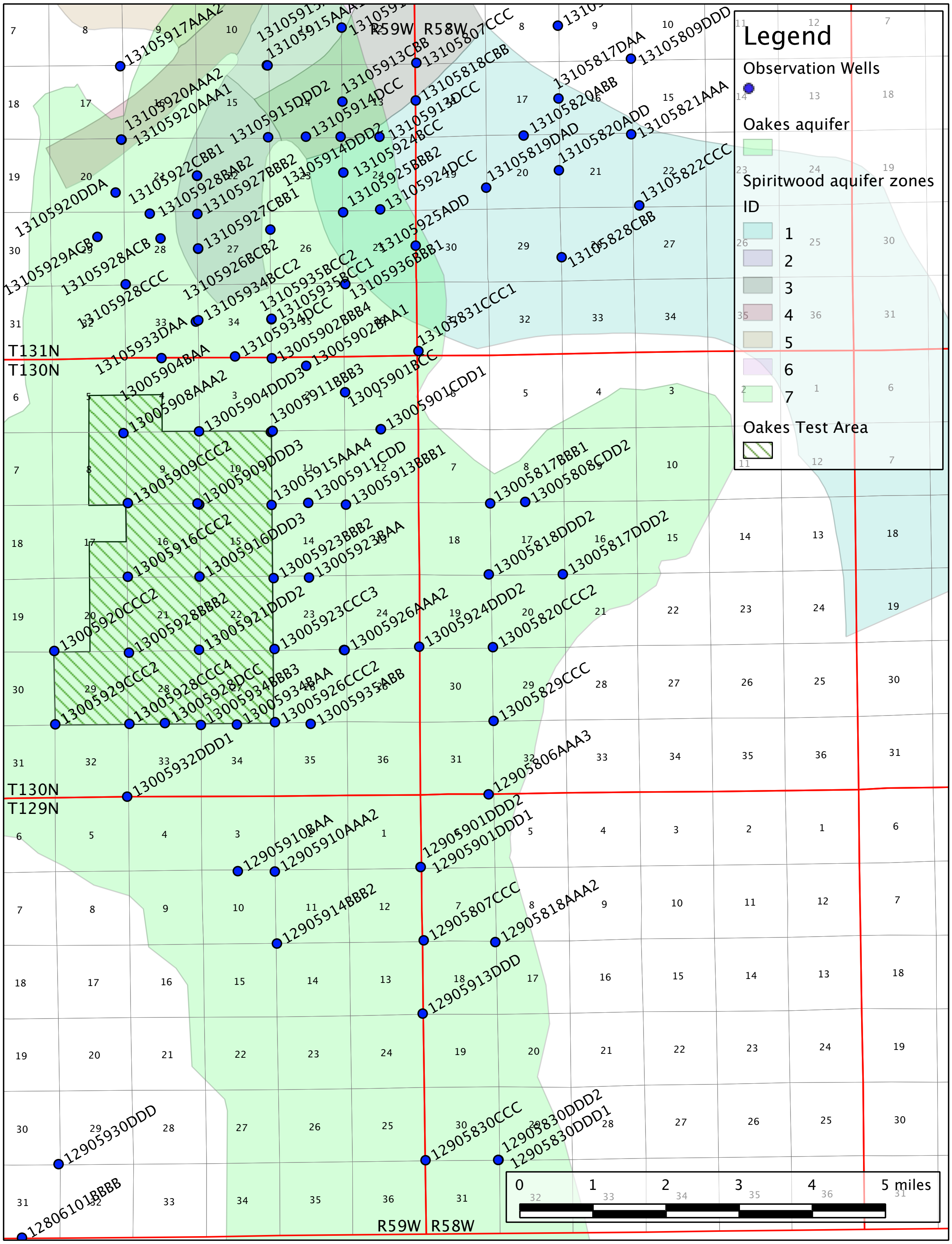


Figure 26. Location of Oakes aquifer observation wells that are currently monitored by the ND State Water Commission and Garrison Diversion Conservancy District.

The only long-term water level record is for observation wells located on the west side of the ball park on the east side of Oakes (fig. 27). Observation well 131-059-28BAB1 was monitored by the USGS from June 21, 1940 to November 30, 1977. The well was destroyed. The NDSWC replaced the well on September 2, 1992 with observation well 131-059-28BAB2. Nearby USBR well 131-059-28ACB is used to extend the record. Water levels are plotted so that 131-059-28BAB2 and 131-059-28ACB match where the period of record overlaps. The highest water levels occur in the mid-1940s during the early 1940s pluvial period (fig. 4). The decline in water level that occurred starting in 1970 is likely due to the installation of the pilot drain (fig. 19) one mile south of the observation well site. The decline from the late 1970s to the early 1990s is a result of the increase in irrigation starting in 1975 (fig 14) and the LTP municipal well that is now abandoned. That the water level has not recovered during the present pluvial to the level in the 1960s is likely the result of the effect of the pilot drain.

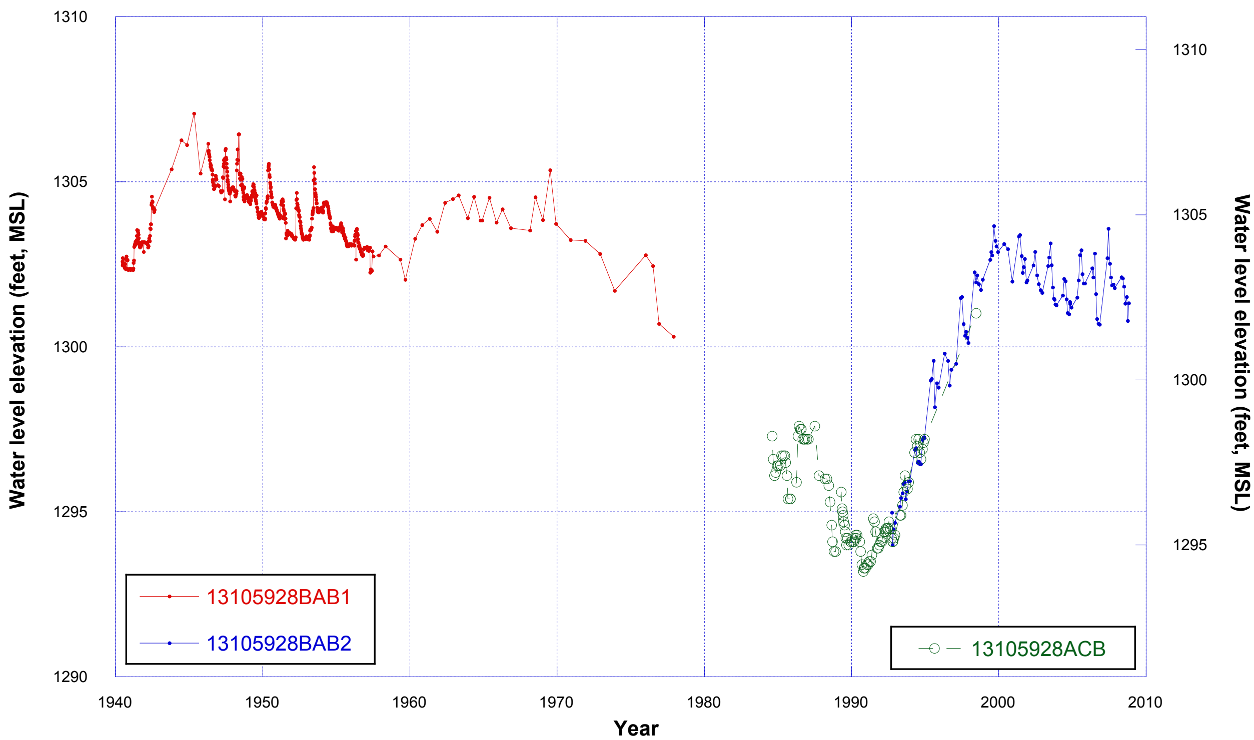


Figure 27. Hydrograph of long-term water level changes at observation wells 131-059-28BAB1 and 131-059-28BAB2 located on the west side of the ball park on the east side of the City of Oakes. Observation well 131-059-28ACB, located to the southeast of this location, is plotted to match the water levels of 131-059-28BAB2 to extend the record.

Figures 28 through 31 show representative hydrographs of observation wells installed in the Oakes aquifer. Additional hydrographs are presented in Appendix B. Water levels at observation well 129-059-01DDD2 (fig. 28) and other wells to the east and south of the OTA are at the same water levels from the mid-1990s to present as they were in the late 1960s. In these periods the water table is controlled by land surface and can rise no higher. Observation wells 130-059-04DDD3 (fig. 31) and 130-059-16CCC2 (fig. 30) are both located near drains within the OTA (fig. 19).

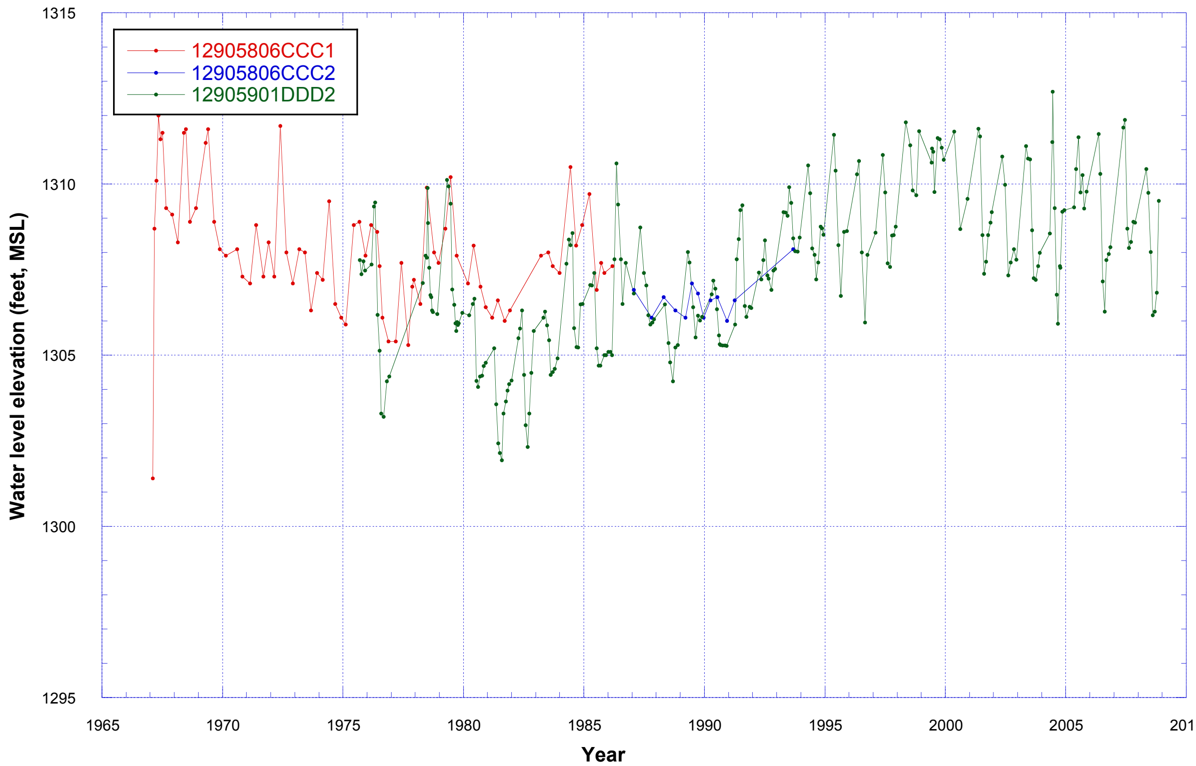


Figure 28. Hydrograph of observation wells 129-058-06CCC1, 129-058-06CCC2, 129-059-01DDD2.

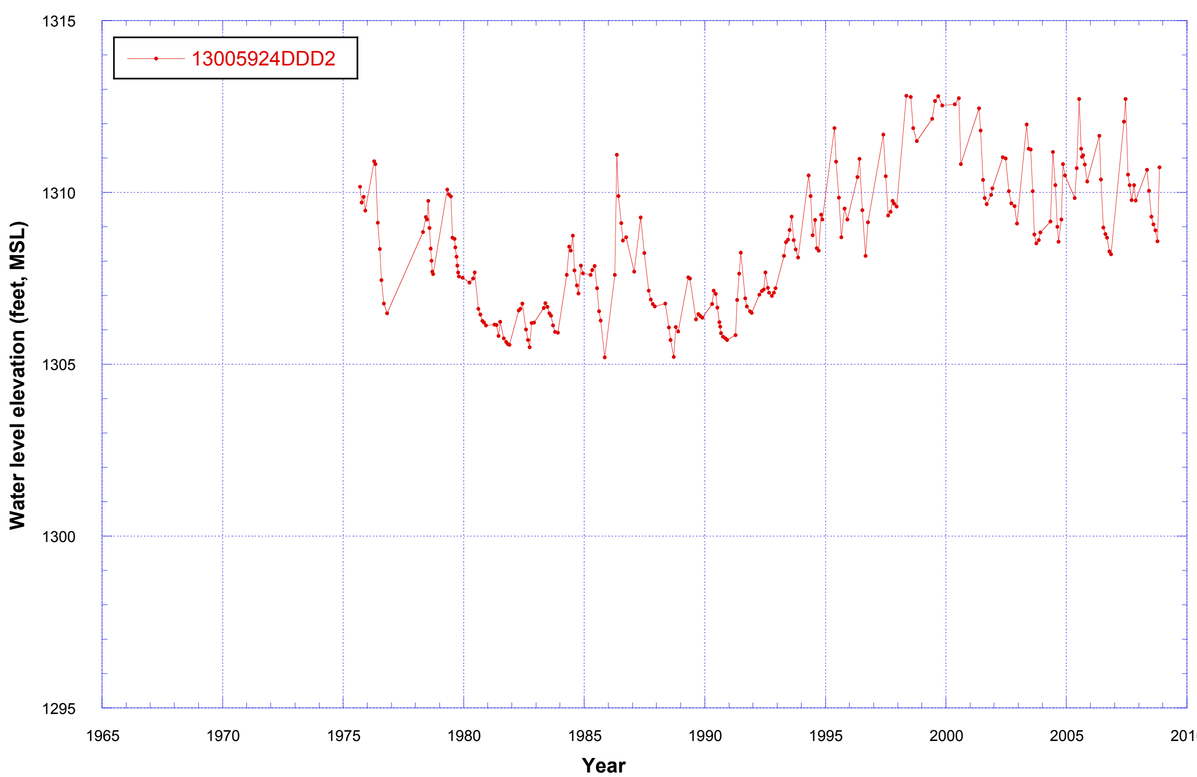


Figure 29. Hydrograph of observation well 130-059-24DDD2.

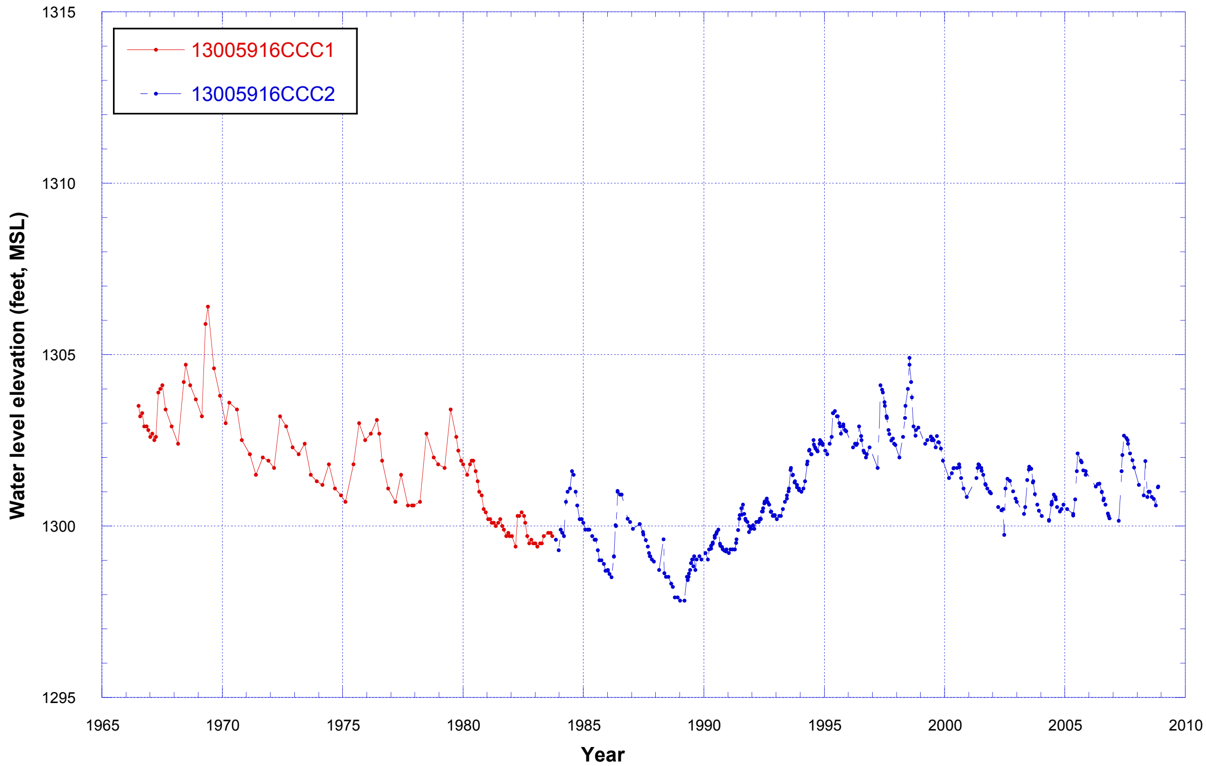


Figure 30. Hydrograph of observation wells 130-059-16CCC1 and 16CCC2 located near west side of OTA.

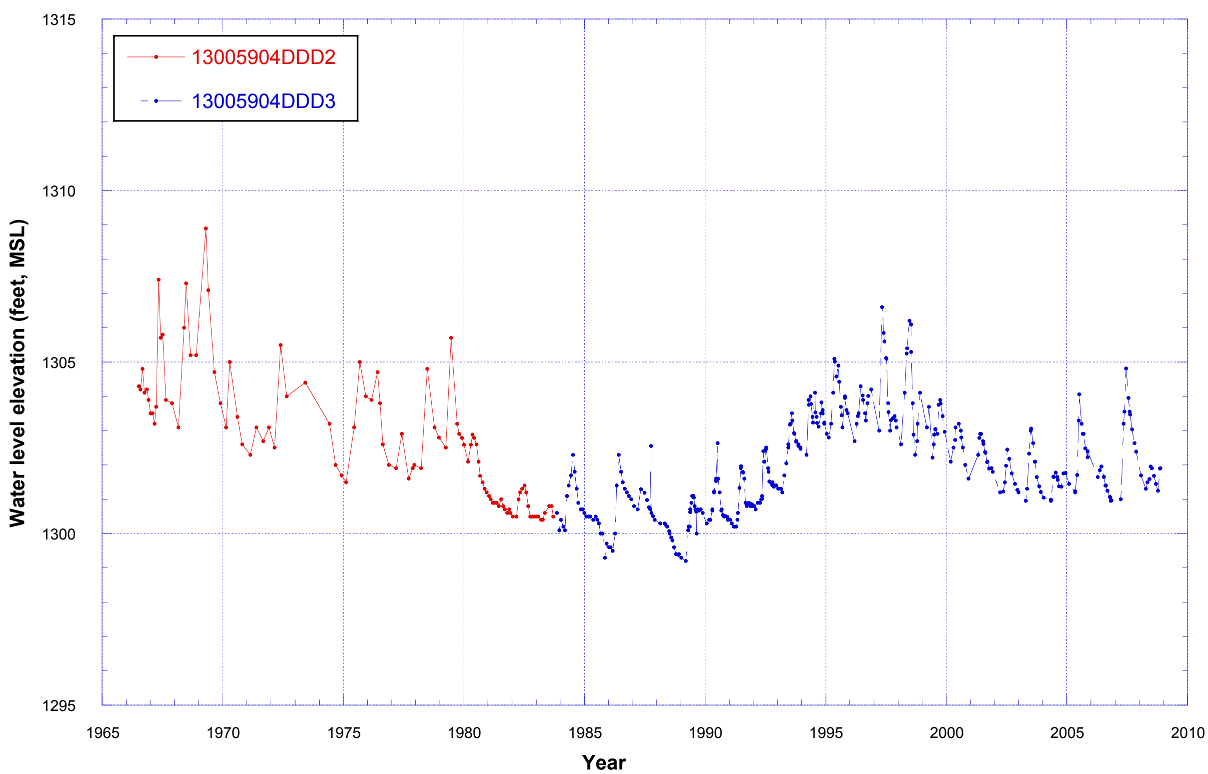


Figure 31. Observation wells 130-059-04DDD2 and 04DDD3 located along the north side of the OTA.

Figures 32 and 33 are contour maps showing water-table elevations based on water levels measured on November 25, 1967 and April 27, 1988 respectively. The direction of groundwater flow is from east to west across the Oakes aquifer. The steep gradient along the west side of the aquifer indicates that flow to the west is greatly restricted. This interpretation is supported by test drilling that indicates the aquifer thins significantly in this area (see Hydrogeology section). Though water level contours shown in figure 32 are prior to irrigation development and figure 33 are after much of the irrigation development, there has been little change in the overall flow system as shown by the similar patterns in the contours. The depth of the water table below land surface on November 25, 1967 is shown in figure 34. Prior to development of irrigation, the low water table occurring in the fall, would be the result of evapotranspiration across the growing season. Water levels across much of the Oakes aquifer are within five feet of land surface. At these shallow depths, plant roots can easily reach the water table to remove water from the aquifer. That the water table largely mirrors land surface at these shallow depths indicates that ET is the primary control on the shape of the water table. The flow system is largely up-down, that is water enters the aquifer as recharge largely in the spring and is discharged locally by ET. Though the gradient is to the west, only a small amount of the water recharging the system actually flows to the west with most of it being removed locally by ET.

The banding observed in figure 34 is an artifact of the USGS 10 meter digital elevation model (DEM) (land surface elevation data) that was used to generate the depth to water map. This banding is not observed within the OTA. The DEM data for the OTA was obtained from Dale Esser, GDCD. This DEM was generated from 1 foot contour elevation maps created by the USBR as part of their Garrison Diversion design work. The USGS DEM data was generated from the 7.5” topographic maps with 5 or 10 foot contour intervals. In the flat hummocky terrain overlying the aquifer, the DEMs tend to stair step in 5 foot intervals.

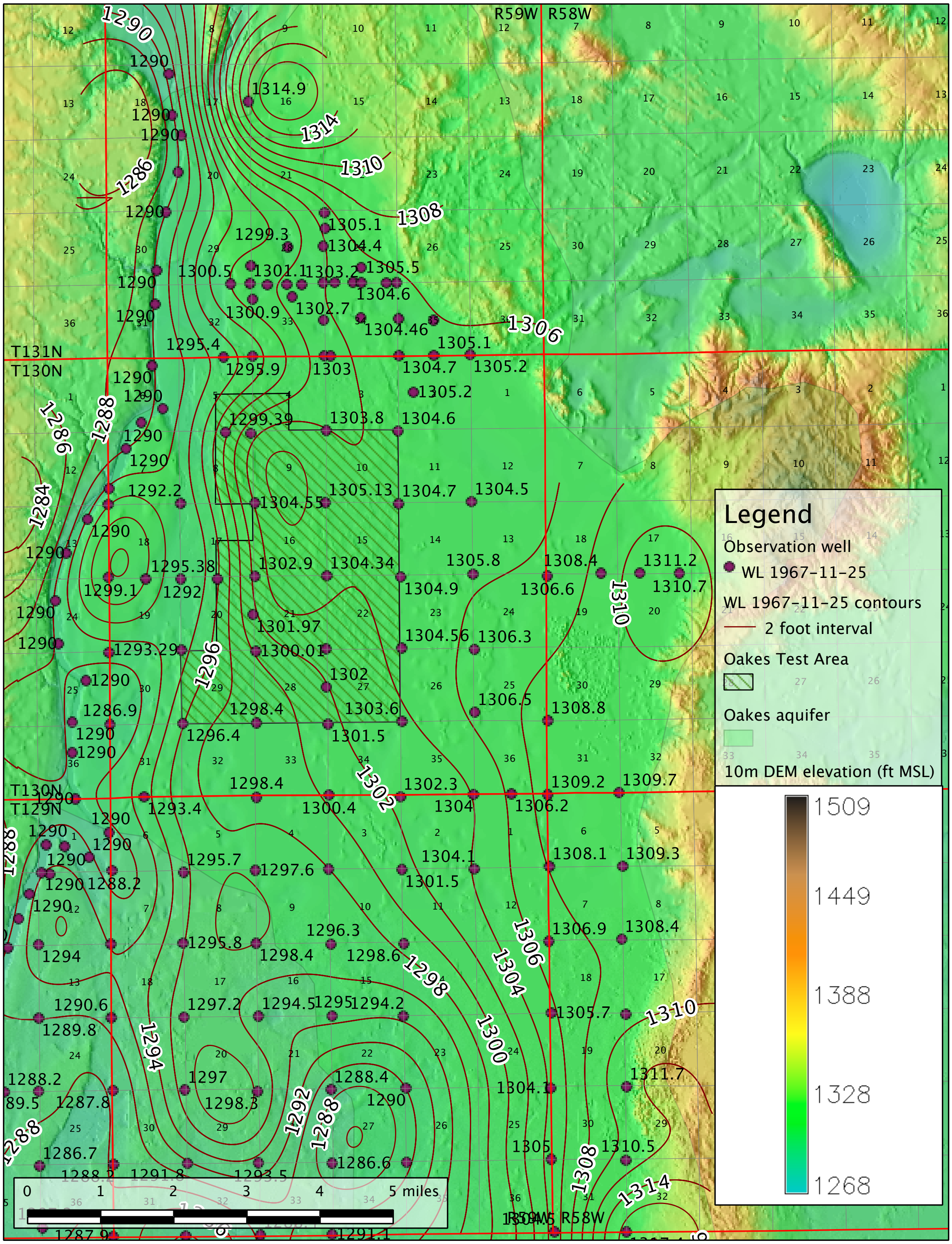


Figure 32. Water table map for the Oakes aquifer, November 25, 1967.

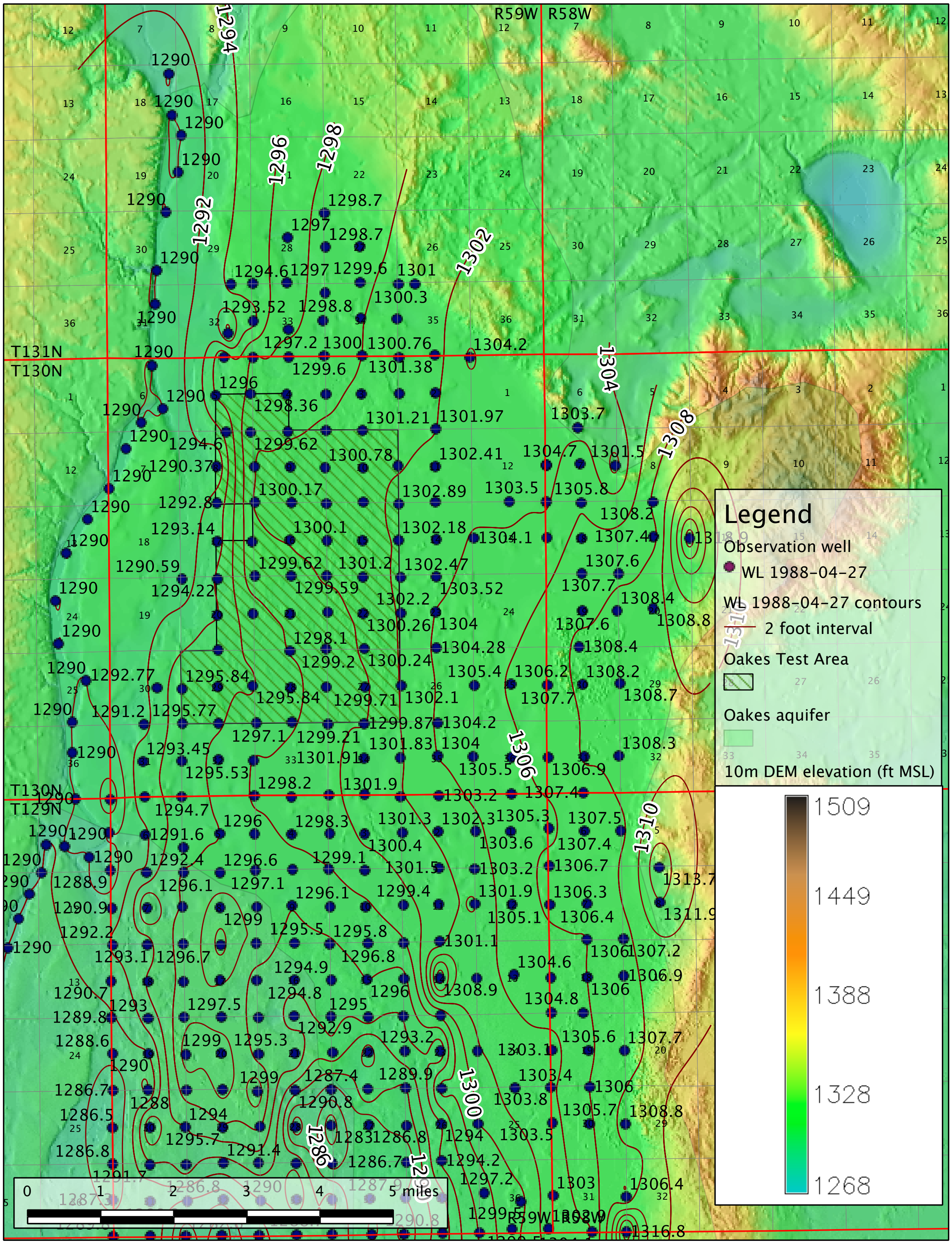


Figure 33. Water table map for the Oakes aquifer, April 27,1988.

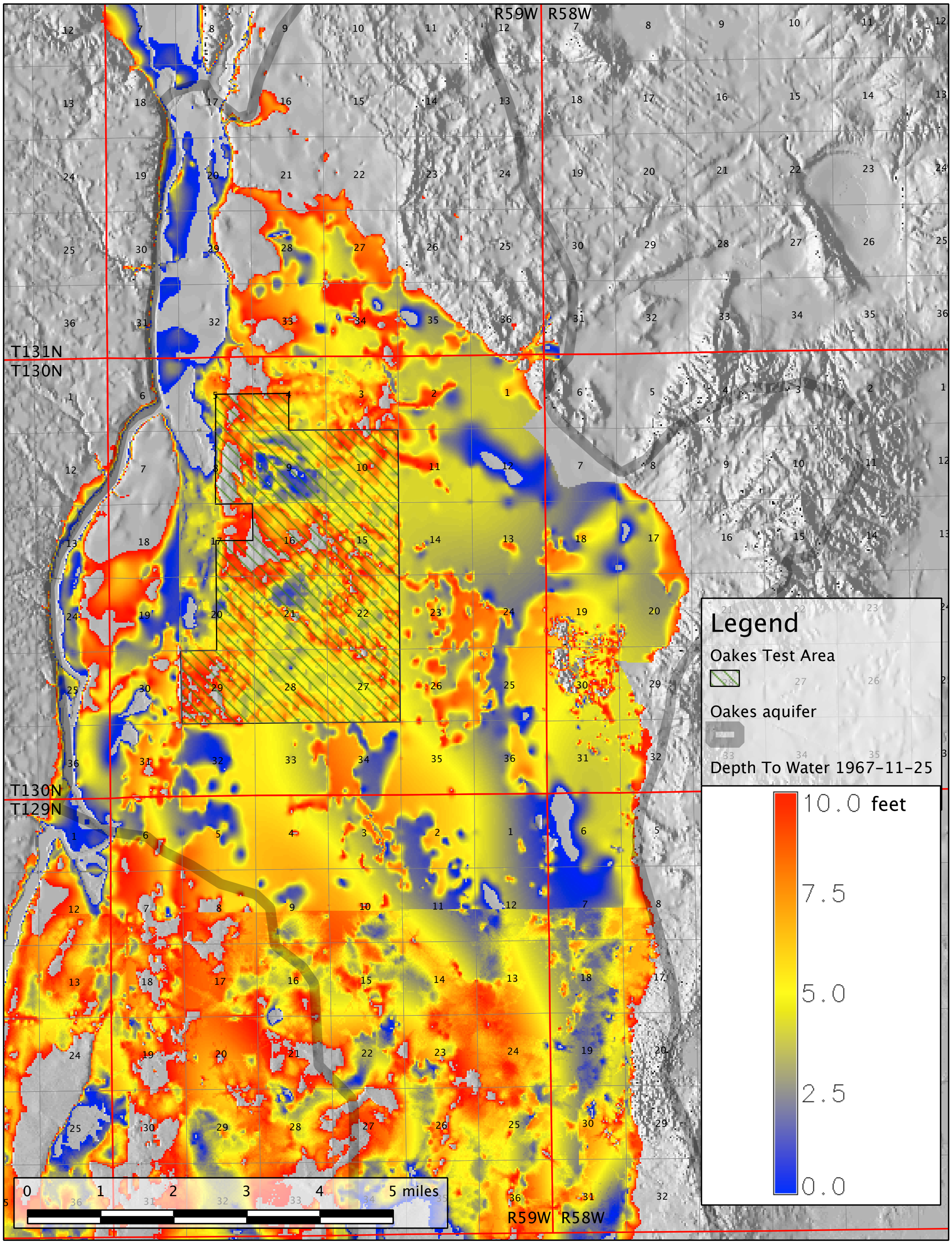


Figure 34. Areas where water levels are less than 10 feet below land surface on November 25, 1967.

LANDSAT Images

LANDSAT imagery and color infrared photography (CIR) are used to assess areas of open water and shallow water tables as indicated by vegetation health. Figures 35 through 38 are LANDSAT images of the Oakes aquifer showing the transition from the dry conditions of the 1980s to the present wet conditions. Additional LANDSAT images are shown in Appendix C.

In figures 35 and 36, May 19, 1985 and August 10, 1992 respectively, only small areas of open water (black) are visible. Many fields that are being irrigated with center pivot systems can be seen to the east and south of the OTA. By May 1, 1996 (fig. 37) significantly more ponding is observed than in the previous images. The water table is higher at this time than at the time of the other two images (figs. 27 to 31). By April 29, 2001 (fig, 38), the area to the east and south of the test area is dominated by open water as a result of the high water table conditions. This has continued through the fall of 2010. Note the areas of irrigation to the east of the test area in figure 36 that are now inundated.

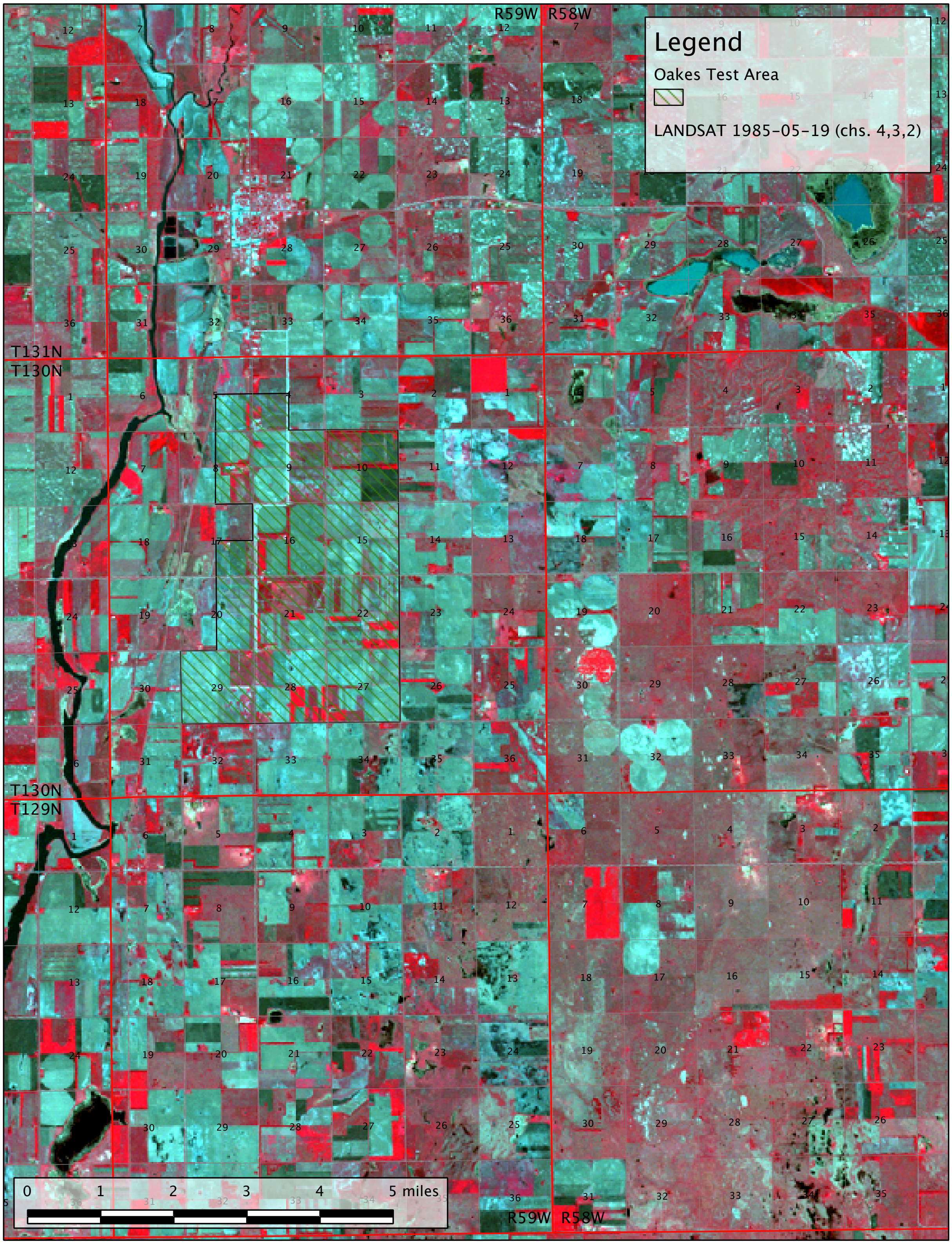


Figure 35. LANDSAT image for May 19, 1985 bands 4,3,2. This is equivalent to CIR photography.

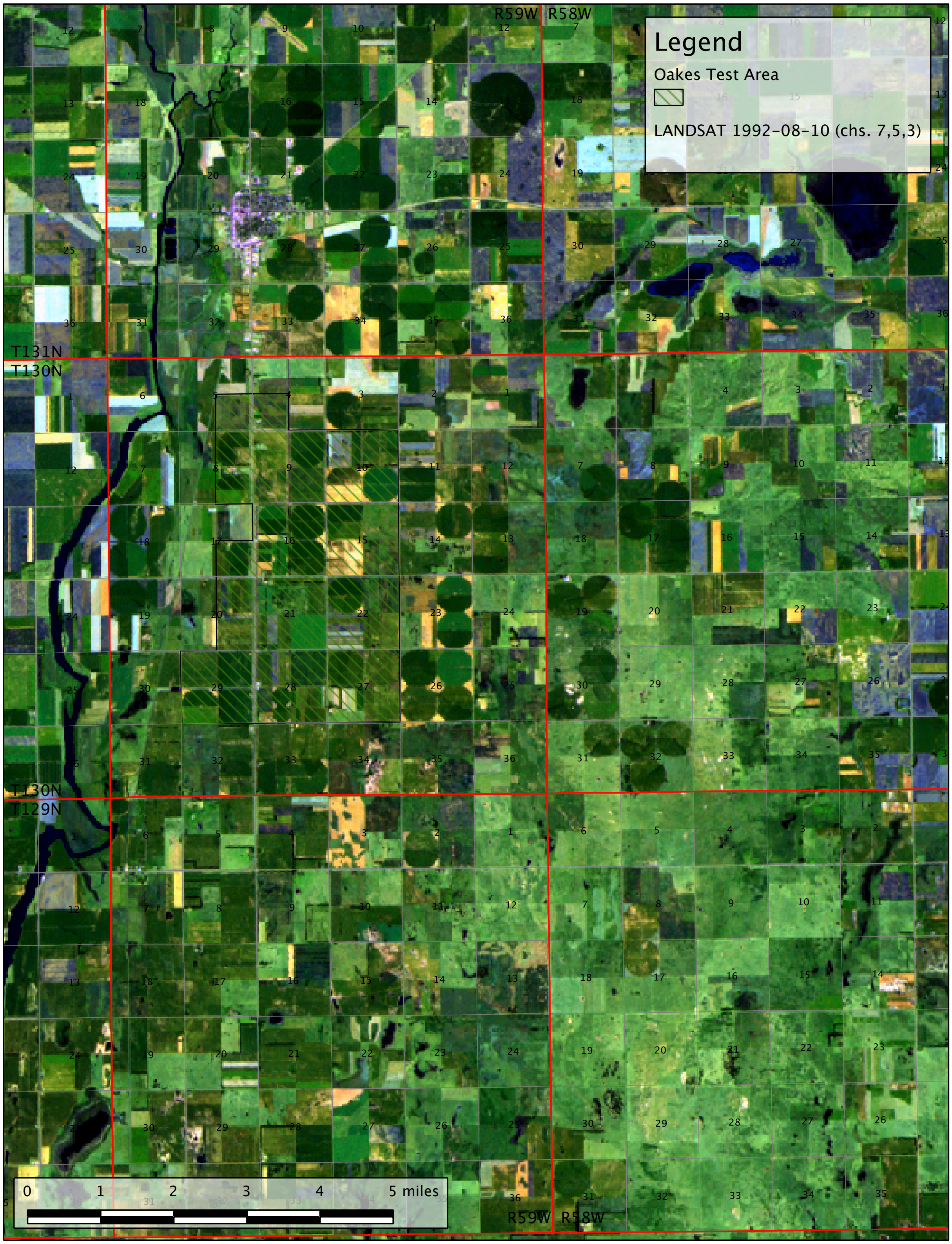


Figure 36. LANDSAT image for August 10, 1992 bands 7,5,3.

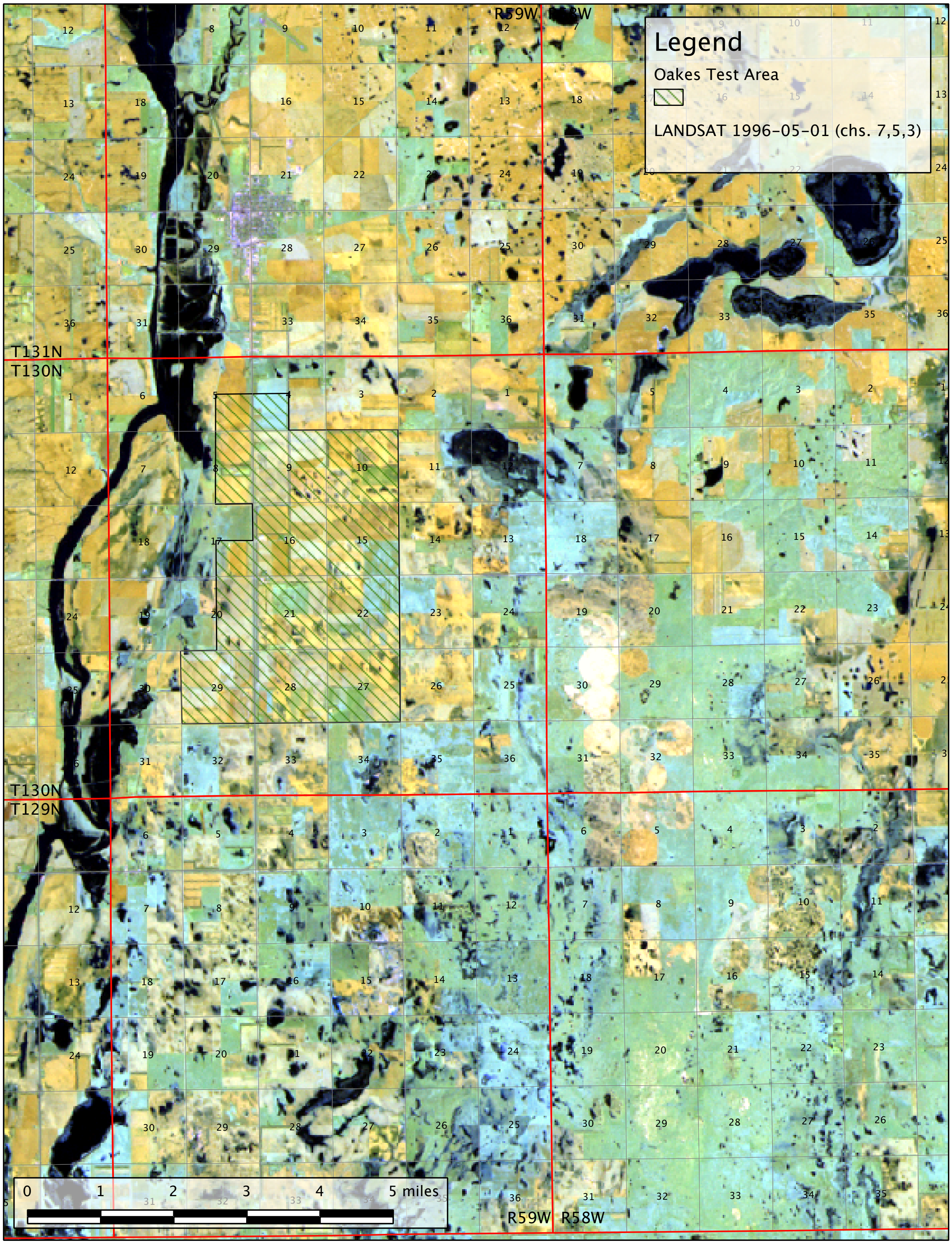


Figure 37. LANDSAT image for May 1, 1996 bands 7,5,3.

Figure 38. LANDSAT image for April 29, 2001 bands 7,5,3.

Hydrogeology of the Oakes aquifer

The Oakes aquifer consists of valley fill deposits prior to the formation of Lake Dakota (Armstrong, 1980). When the valley became blocked in South Dakota, Lake Dakota formed, extending from South Dakota to north of Oakes near the present junction of the James River and Bear Creek. A delta formed at this time at the north end of the lake depositing sand and gravel in the area near Oakes. The deltaic sediments consist mostly of fine to medium sands and silts away from the developing delta front. The lake sediments consist primarily of silts and clays. The northern end of the aquifer overlies the buried valley Spiritwood aquifer (fig. 2). The confining units separating the aquifers are generally glacial till. However, in the two units of the Spiritwood projecting towards Oakes, the confining units are primarily silt allowing significant leakage between the two aquifers. Pumping of irrigation water in these units of the Spiritwood derives water from the Oakes aquifer and therefore must be considered as part of the Oakes aquifer water budget. A more detailed discussion of the hydrogeology of the Oakes aquifer will be provided in the second part of this report, "Analysis and Simulation of the Oakes Aquifer: Model Development and Documentation."

The Oakes aquifer is bounded on the west by the James River in the area near Oakes and areas of mostly lacustrine sediments to the south of Oakes. On the east, the aquifer is bounded by the Lake Oakes Hills which is an overridden feature (Bluemle, 1979b). Bluemle, 1979b, states that "*When the glacier overrode the area, repeated ice thrusting also occurred. It is probable that the glacier overrode the materials deposited during an earlier stage of Lake Dakota, which flooded a several-township portion of western Sargent County. Elevations on the flatter areas of the till-mantled lake plain in western Sargent County are nearly identical to elevations on parts of the lake plain further to the west in Dickey County, which were not overridden. The early western Sargent County glacial Lake Dakota, prior to the time it was overridden by the glacier, consisted of complex topography that included offshore lake silt beds; shore features, perhaps including beaches; and broad areas of wind blown sand dunes*." Test drilling to the east of Oakes in Township 159 North indicates glacial till, with a contact elevation of approximately 1,280 feet mean sea level (MSL), underlying lacustrine and fluvial sediments extending to either bedrock shales or underlying Spiritwood aquifer. In Townships 129 and 130 North there is little test drilling along the Lake Oakes Hills. In general, test drilling shows the Lake Oakes Hills are underlain by lacustrine sediments with a thin mantle of glacial till. The Oakes aquifer in these two townships is largely bounded on the east and west by lacustrine sediments. The aquifer extends into South Dakota along the Dickey-Sargent County line. The limited test drilling in South Dakota makes it difficult to evaluate the hydrogeology of the aquifer as it extends south.

The location of bores with lithologic logs and the location of the cross-sections described in this report are shown in figure 39. The size of the blue circle is proportional to the depth of the well. The small dots are generally the USBR borings that are less than 30 feet deep. The bores were mostly NDSWC and USBR drilling. Only a few private contractors logs for test holes and irrigation wells were used. These are primarily in areas where NDSWC drilling was inadequate to define features such as the deep channel.

The cross-sections are shown in figures 40 through 45, extending from north to south. The legend for the cross-sections is in figure 46. The yellows and reds are sands and gravels, the blues are lacustrine and fluvial clays, the tans are silts, and the green is glacial till.

Sand and gravel above 1,260 feet MSL is considered to be the Oakes aquifer. Sand and gravel below this depth is considered to be the deep channel of the Oakes aquifer hereafter referred to as the deep channel. The cross-sections indicate the delta built from near the present day junction of the James River and Bear Creek to the south east with the deeper part of the channel from the cross-section D-D' to the south along the eastern edge of the aquifer.

Sections D-D' and E-E' show the limited saturation thickness of the aquifer under the test area. The area where the aquifer pinches out corresponds to the area of steep water table gradient seen in figure 32.

The deep channel runs along the eastern side of the aquifer as seen in cross-sections E-E' through A-A' and extends southward into South Dakota. The widest part of the deep channel is in the vicinity of cross-section B-B'. Within Township 130 North the deep channel is less than 0.5 miles wide and possibly less than 0.25 miles wide at the north end. To the north of B-B' the deeper part of the channel is incised into glacial till. As seen in the cross-sections the till surface deepens to the south. The stream that occupied this narrow meltwater channel discharged into a lower stage of Lake Dakota.

The broad accumulation of sediments that occurred (figs. 44 and 45) in this reach of the deep channel are the remains of a large delta that formed where the stream discharged into a lower stage of Lake Dakota. Most of this delta occupies an interval between 1,200 and 1,260 feet in elevation. It is this large delta that presents the potential for obtaining significant additional water for irrigation or other uses. The narrow meltwater channel that fed this delta from the north would not provide much additional water over what the wider overlying Oakes aquifer would yield.

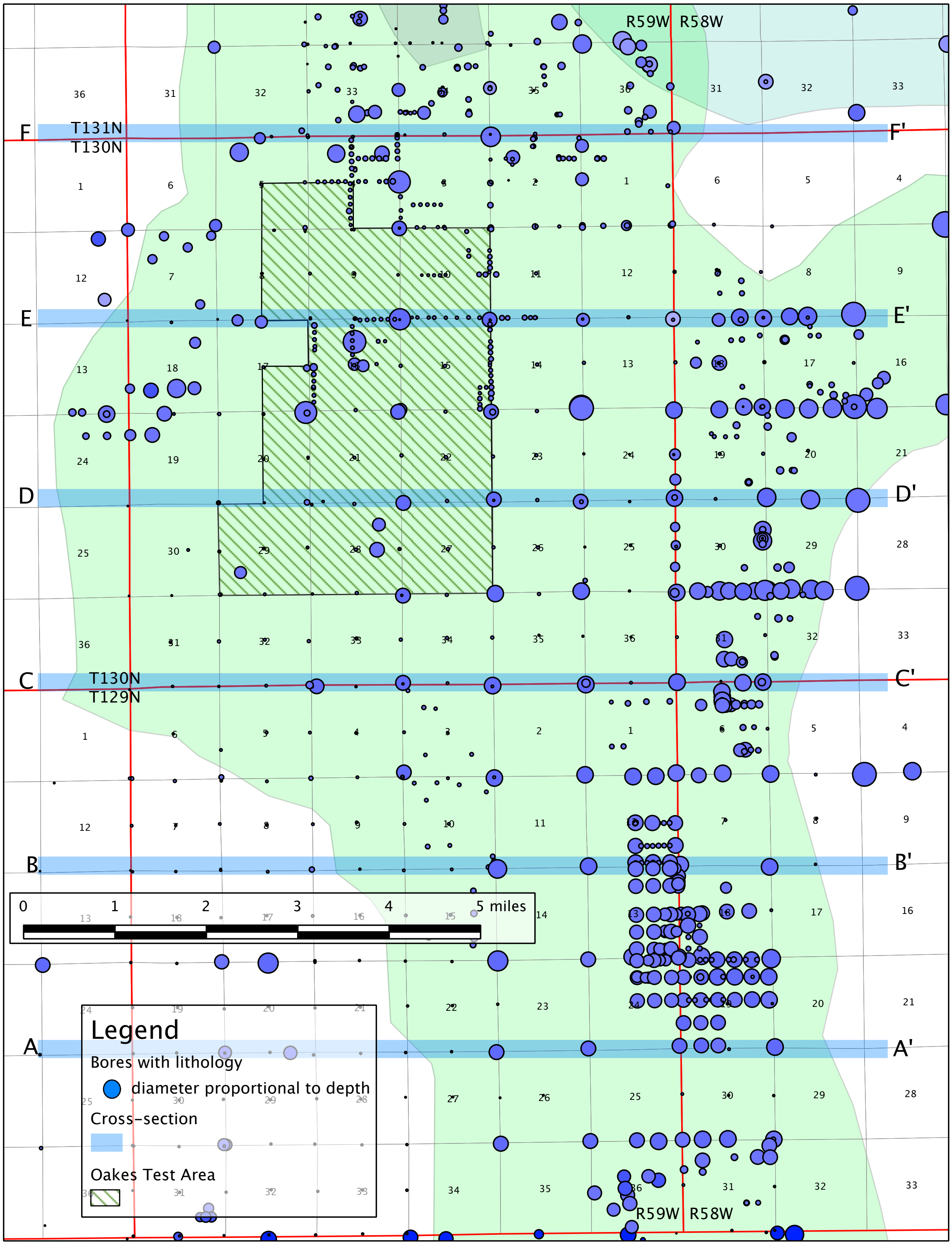


Figure 39. Locations of cross-sections A-A' through F-F'. Circles show location and depth of bores used in the analysis of the Oakes aquifer.

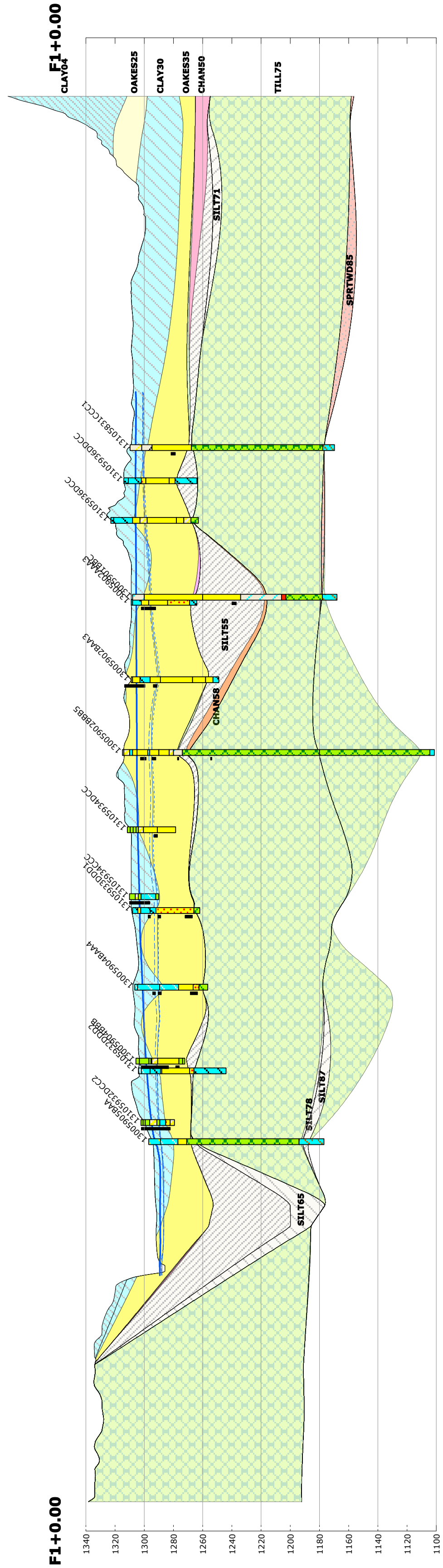


Figure 40. Cross-section F-F'

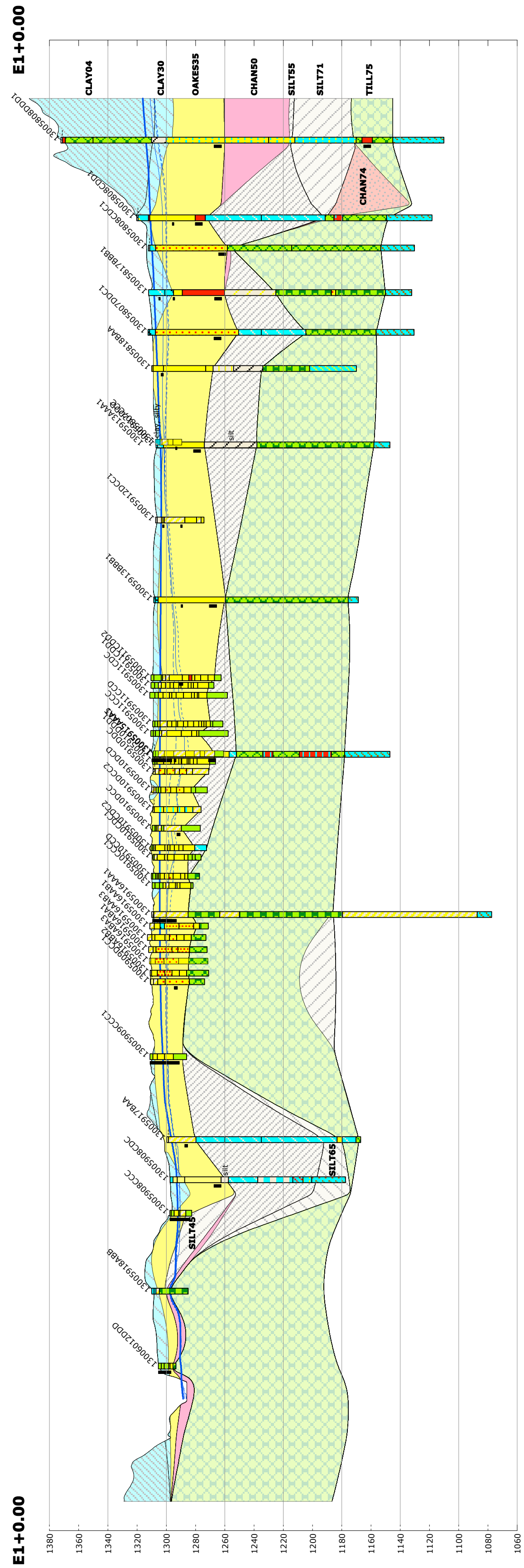


Figure 41. Cross-section E-E'

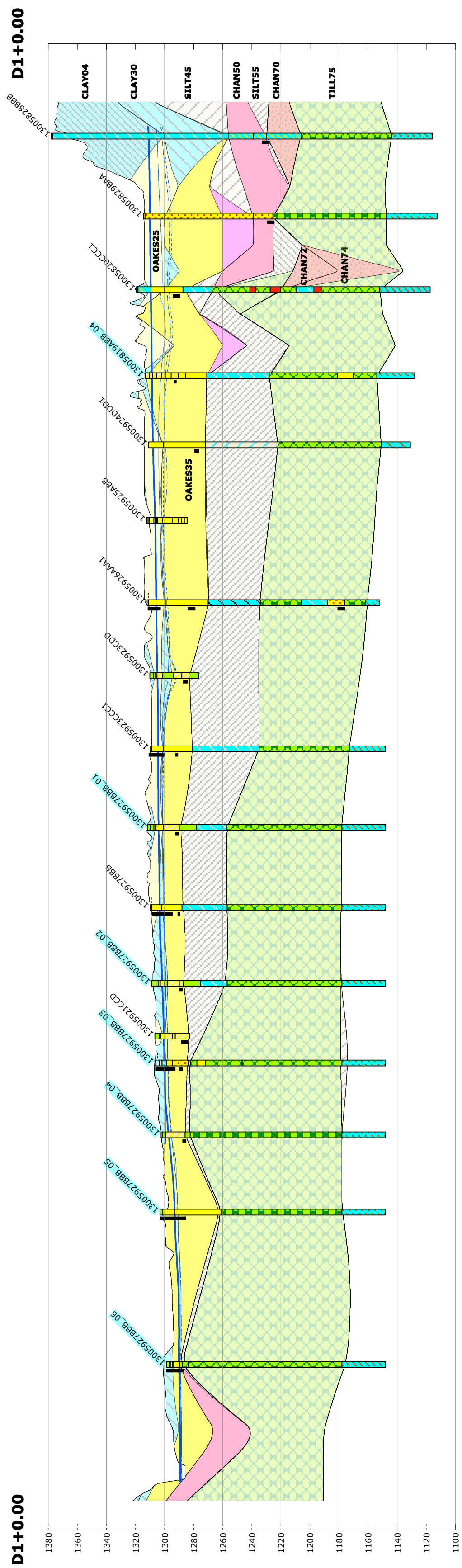


Figure 42. Cross-section D-D

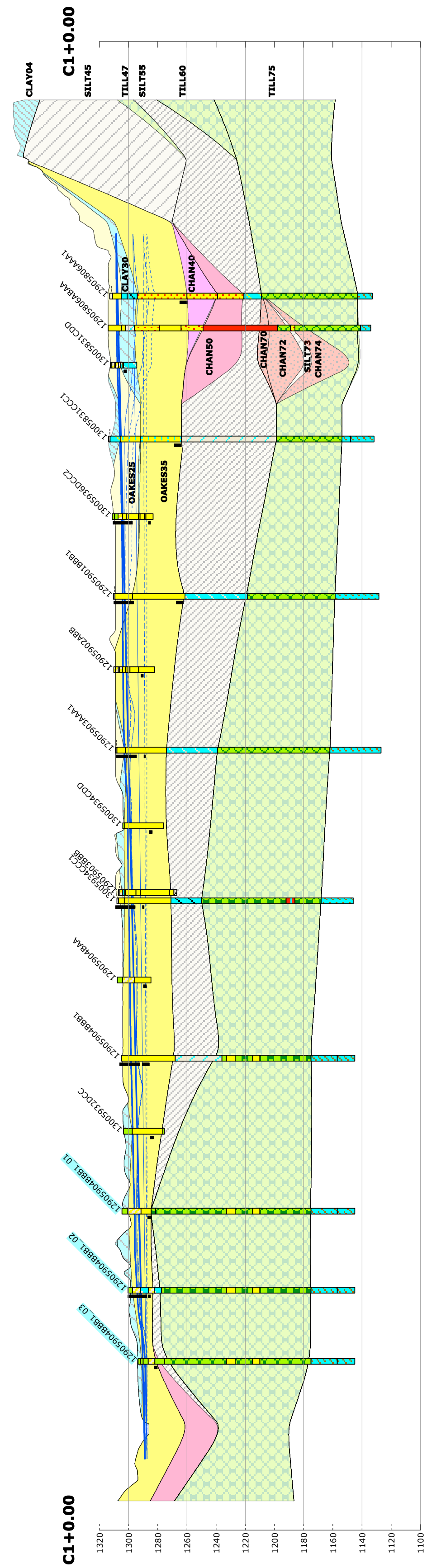


Figure 43. Cross-section C-C'

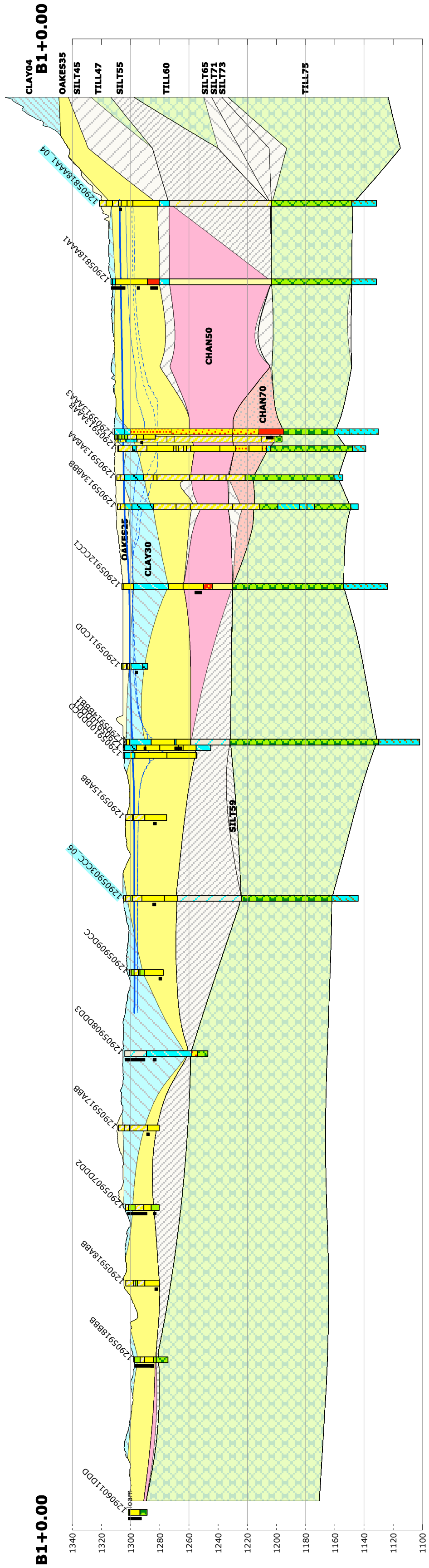


Figure 44. Cross-section B-B’

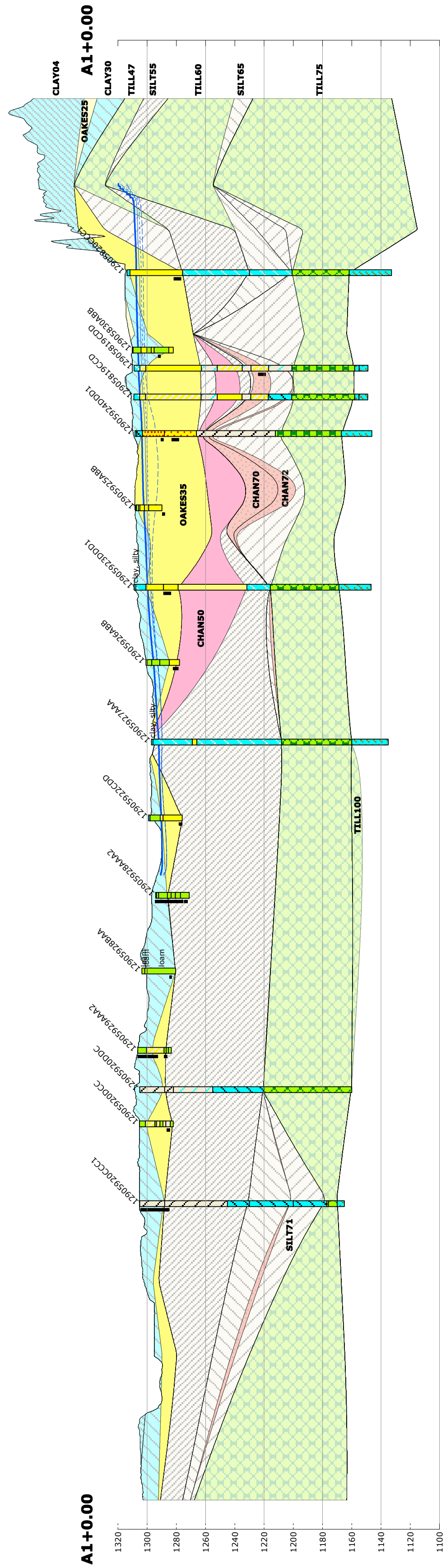


Figure 45. Cross-section A-A’

Figure 46. Legend for cross-sections.

Hydraulic Properties

The Oakes aquifer area was divided into 28 hydrostratigraphic units based on texture and likely facies. The fill patterns connecting the logs in figures 40 through 45 are the hydrostratigraphic units. As can be seen in the cross-sections, each hydrostratigraphic unit at each bore can be composed of several textures. At each bore, the average hydraulic properties were calculated for each hydrostratigraphic unit. The hydraulic properties assigned to each texture-facies class are given in tables 4 and 5.

For computer interpolation routines (gridding) to accurately represent a feature, a narrow channel, the spacing of bores across the feature needs to be approximately one-third the size of the feature. Where the deep channel is less than 0.5 miles wide, a grid of bores less than 900 feet apart is needed. If bores forming a cross-section of the channel are far apart, the interpolation routine will represent the channel as a chain of unconnected holes. As can be seen in figure 39, this criteria is not met. An accepted procedure to deal with this problem is to create synthetic bores to force the creation of reasonable looking geology. The synthetic bores are created by copying existing bores to new locations. Tops and bottoms of lithologic units are adjusted as needed to interpolate between bores. Textures may also be changed. As part of this procedure, NDSWC bores were often used to extend the depth of shallow USBR bores. The supplemental bores (red) and extended bores (green) are shown in figure 47. The lines show the parent bore from which the synthetic bore was derived.

Table 4. Default hydraulic properties assigned to textures. If the hydrostratigraphic unit was TILL03, TILL47, TILL60, or TILL75, then the properties were set to that of loam, gravelly so that sand and gravel lenses in the till did not dominate properties of till zones.

Texture	Facies	Hyd. Cond. (f/d)	K_z/K_x	Specific Yield	Specific Storage (1/f)
clay	Default	2.00E-03	1.00	0.03	1.00E-04
clay, silty	Default	2.00E-03	1.00	0.03	1.00E-04
clay, sandy	Default	2.00E-03	1.00	0.03	1.00E-04
silt	Default	3.00E+00	1.00	0.07	1.00E-05
silt, clayey	Default	1.00E+00	1.00	0.07	1.00E-05
silt, sandy	Default	1.10E+01	1.00	0.07	1.00E-05
sand	deltaic(sand)	4.00E+01	1.00	0.22	5.00E-06
sand	eolian	6.00E+01	1.00	0.22	5.00E-06
sand	Fluvial(silt, clay)	1.20E+01	1.00	0.22	5.00E-06
sand	Default	1.70E+02	1.00	0.22	5.00E-06
sand, clayey	Default	1.00E+00	1.00	0.1	1.00E-05
sand, silty	Default	3.00E+01	1.00	0.15	1.00E-05
sand, gravelly	Default	3.00E+02	1.00	0.22	5.00E-06
gravel	Default	8.00E+02	1.00	0.2	5.00E-06
gravel	Lacustrine	1.00E+00	1.00	0.07	1.00E-05
gravel, clayey	Default	1.00E+00	1.00	0.1	1.00E-05
gravel, silty	Default	2.00E+02	1.00	0.15	1.00E-05
gravel, sandy	Default	4.00E+02	1.00	0.22	5.00E-06
cobbles+	Default	9.00E+02	1.00	0.17	5.00E-06
loam	Default	5.00E+00	1.00	0.06	1.00E-05
loam, gravelly	Default	4.00E-04	1.00	0.03	1.00E-05
clay-silt interbedded	Default	2.00E+00	0.10	0.05	1.00E-05
clay/interbedded sand	Default	2.00E+01	0.10	0.02	1.00E-05
silt/interbedded sand	Default	3.00E+01	0.10	0.05	1.00E-05
sand/interbedded silt/clay	Default	4.00E+01	0.20	0.1	1.00E-05
claystone	Default		1.00		
siltstone	Default		1.00		
mudstone	Default		1.00		
sandstone	Default		1.00		
gravel/interbedded silt/clay	Default	1.00E+02	0.10	0.15	1.00E-05
sand, sl. gravelly	Default	2.00E+02	1.00	0.22	5.00E-06
clay/interbedded gravel	Default	1.00E+01	0.10	0.08	1.00E-05
silt/interbedded gravel	Default	2.00E+01	0.10	0.07	1.00E-05
silt, gravelly	Default	1.00E+01	1.00	0.07	1.00E-05
clay, gravelly	Default	2.00E-01	1.00	0.01	1.00E-05

Texture	Facies	Hyd. Cond. (f/d)	K_z/K_x	Specific Yield	Specific Storage (1/f)
sand, very fine	Default	2.60E+01	1.00	0.22	5.00E-06
sand, fine	Default	5.40E+01	1.00	0.22	5.00E-06
sand, medium	Default	1.34E+02	1.00	0.22	5.00E-06
sand, coarse	Default	1.60E+02	1.00	0.22	5.00E-06
sand, very coarse	Default	2.14E+02	1.00	0.22	5.00E-06
gravel, very fine	Default	3.00E+02	1.00	0.2	5.00E-06
gravel, fine	Default	4.00E+02	1.00	0.2	5.00E-06
gravel, medium	Default	6.00E+02	1.00	0.2	5.00E-06
gravel, coarse	Default	8.00E+02	1.00	0.2	5.00E-06
gravel, very coarse	Default	1.20E+03	1.00	0.2	5.00E-06
topsoil	Default	0.5	1	0.04	1.00E-04

Table 5. Properties assigned to USBR test hole lithologies. If the hydrostratigraphic unit was TILL03, TILL47, TILL60, or TILL75, then the properties were set to that of loam, gravelly so that sand and gravel lenses in the till did not dominate properties of till zones.

Texture	Facies	Hyd. Cond. (f/d)	K_z/K_x	Specific Yield	Specific Storage (1/f)
clay	Default	2.00E-03	1.00	0.03	1.00E-04
clay, silty	Default	2.00E-03	1.00	0.03	1.00E-04
clay, sandy	Default	2.00E-03	1.00	0.03	1.00E-04
silt	Default	3.00E+00	1.00	0.07	1.00E-05
silt, clayey	Default	1.00E+00	1.00	0.07	1.00E-05
silt, sandy	Default	1.10E+01	1.00	0.07	1.00E-05
sand	deltaic(sand)	4.00E+01	1.00	0.22	5.00E-06
sand	eolian	6.00E+01	1.00	0.22	5.00E-06
sand	Fluvial(silt, clay)	1.20E+01	1.00	0.22	5.00E-06
sand	Default	2.50E+02	1.00	0.22	5.00E-06
sand, clayey	Default	1.00E+00	1.00	0.1	1.00E-05
sand, silty	Default	1.00E+02	1.00	0.15	1.00E-05
sand, gravelly	Default	4.00E+02	1.00	0.22	5.00E-06
gravel	Default	8.00E+02	1.00	0.2	5.00E-06
gravel, clayey	Default	1.00E+00	1.00	0.1	1.00E-05
gravel, silty	Default	2.00E+02	1.00	0.15	1.00E-05
gravel, sandy	Default	4.00E+02	1.00	0.22	5.00E-06
cobbles+	Default	9.00E+02	1.00	0.17	5.00E-06
loam	Default	5.00E+00	1.00	0.06	1.00E-05
loam, gravelly	Default	4.00E-04	1.00	0.03	1.00E-05
clay-silt interbedded	Default	2.00E+00	0.10	0.05	1.00E-05
clay/interbedded sand	Default	2.00E+01	0.10	0.02	1.00E-05
silt/interbedded sand	Default	3.00E+01	0.10	0.05	1.00E-05
sand/interbedded silt/clay	Default	4.00E+01	0.20	0.1	1.00E-05
claystone	Default		1.00		
siltstone	Default		1.00		
mudstone	Default		1.00		
sandstone	Default		1.00		
gravel/interbedded silt/clay	Default	1.00E+02	0.10	0.15	1.00E-05
sand, sl. gravelly	Default	2.00E+02	1.00	0.22	5.00E-06
clay/interbedded gravel	Default	1.00E+01	0.10	0.08	1.00E-05
silt/interbedded gravel	Default	2.00E+01	0.10	0.07	1.00E-05
silt, gravelly	Default	1.00E+01	1.00	0.07	1.00E-05
clay, gravelly	Default	2.00E-01	1.00	0.01	1.00E-05
sand, very fine	Default	2.60E+01	1.00	0.22	5.00E-06

Texture	Facies	Hyd. Cond. (f/d)	K_z/K_x	Specific Yield	Specific Storage (1/f)
sand, fine	Default	9.40E+01	1.00	0.22	5.00E-06
sand, medium	Default	2.54E+02	1.00	0.22	5.00E-06
sand, coarse	Default	3.50E+02	1.00	0.22	5.00E-06
sand, very coarse	Default	5.00E+02	1.00	0.22	5.00E-06
gravel, very fine	Default	5.00E+02	1.00	0.2	5.00E-06
gravel, fine	Default	6.00E+02	1.00	0.2	5.00E-06
gravel, medium	Default	7.00E+02	1.00	0.2	5.00E-06
gravel, coarse	Default	8.00E+02	1.00	0.2	5.00E-06
gravel, very coarse	Default	1.20E+03	1.00	0.2	5.00E-06
topsoil	Default	0.5	1	0.04	1.00E-04

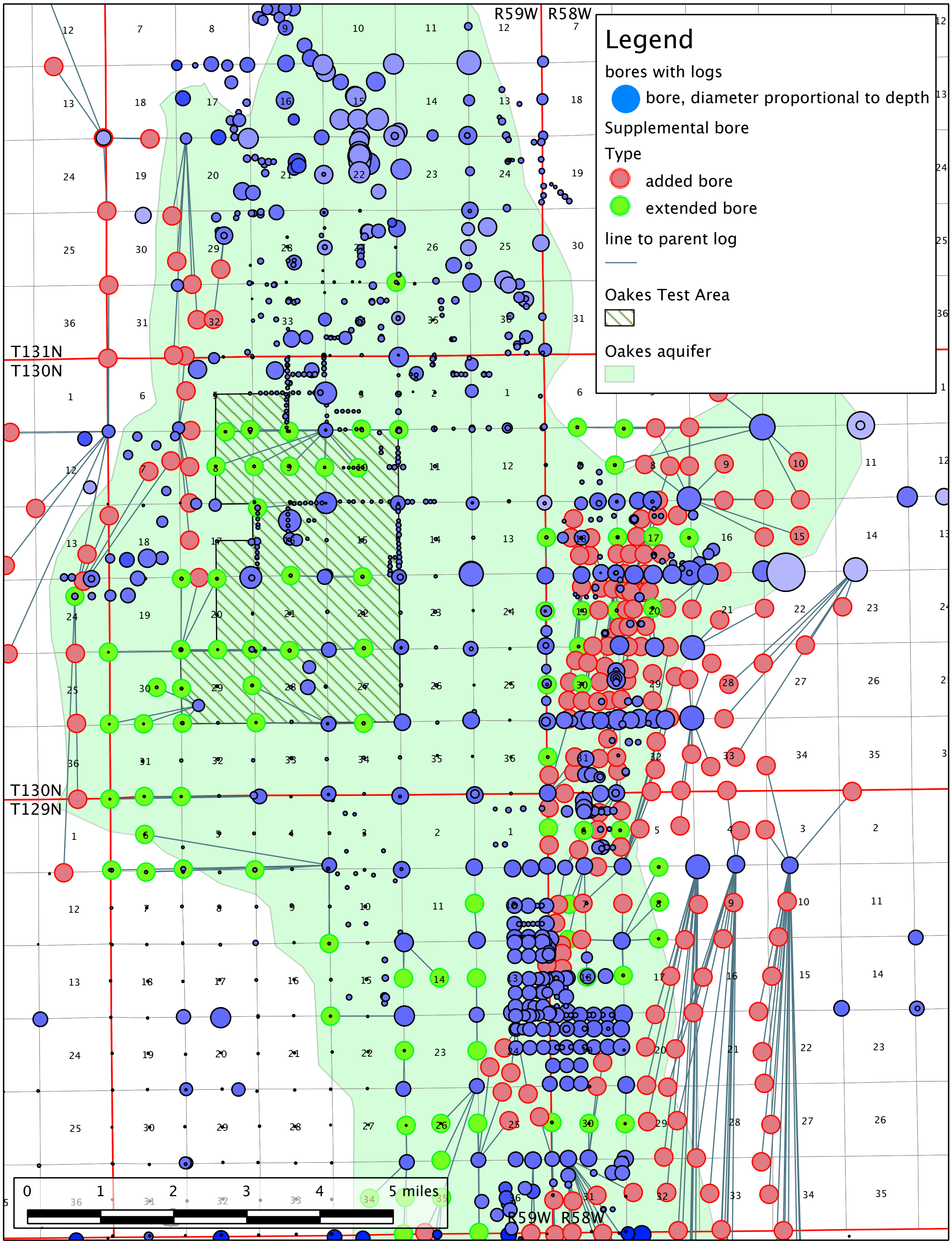


Figure 47. Map showing location of synthetic logs that were created and the location of the parent log to force the gridding of bottom of hydrostratigraphic units to give reasonable geologic representations.

The aquifer was divided into seven layers for the groundwater flow model. The transmissivities for the sum of all layers is given in figure 48. The transmissivity of the aquifer or layer is the average hydraulic conductivity multiplied by the aquifer or layer thickness. The larger the value, the greater the ability to transmit water. Figure 48 includes both the Oakes aquifer and the underlying Spiritwood aquifer. Figure 49 shows the transmissivity for the interval above 1,260 feet in elevation (layers 1 and 2). The Oakes aquifer occurs within this interval. The existence of a high transmissivity zone is observed extending from near the confluence of the James River and Bear Creek to the north end of the deep channel and then south. With the exception of the northeast corner of the OTA, the transmissivities within the test area are low.

The deep channel occurs primarily within the interval 1,200 to 1,260 feet in elevation (layers 3 and 4, fig. 50). The deep channel is observed extending from the west central area of T. 130 N., R. 58 W. to the south where it widens into a broad delta in the middle of T. 129 N. This broad delta presents the potential for the additional appropriation of water.

The transmissivity for the interval from 1,140 feet to 1,200 feet (layers 5 and 6) is shown in figure 51. The Spiritwood aquifer to the north of Oakes and a narrow channel forming the base of the northern part of the deep channel are the only aquifers occurring in this interval. This channel appears to terminate where the delta seen in figure 50 begins. This may indicate that, at least in the early stages, this deeper channel was a tunnel valley flowing under the ice with the delta forming where the stream discharged from under the ice. Given the amount of drilling by the USBR and the NDSWC (fig. 39) south of the apparent termination of this channel, it is unlikely that the channel continues to the south.

Below 1,140 feet in elevation (fig. 52) both the Spiritwood north of Oakes and the deep channel are observed.

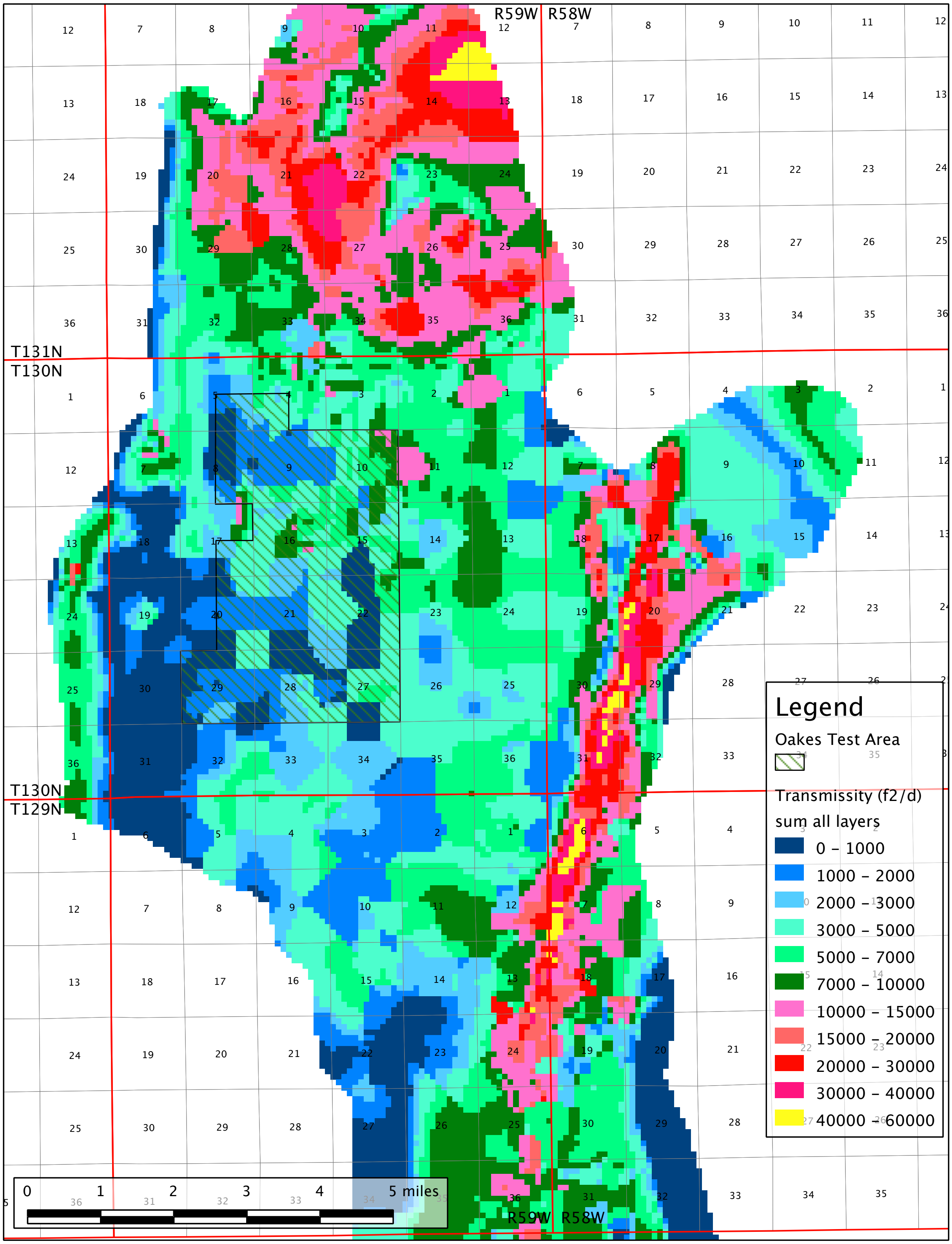


Figure 48. Transmissivity for the Oakes aquifer model summed for all layers.

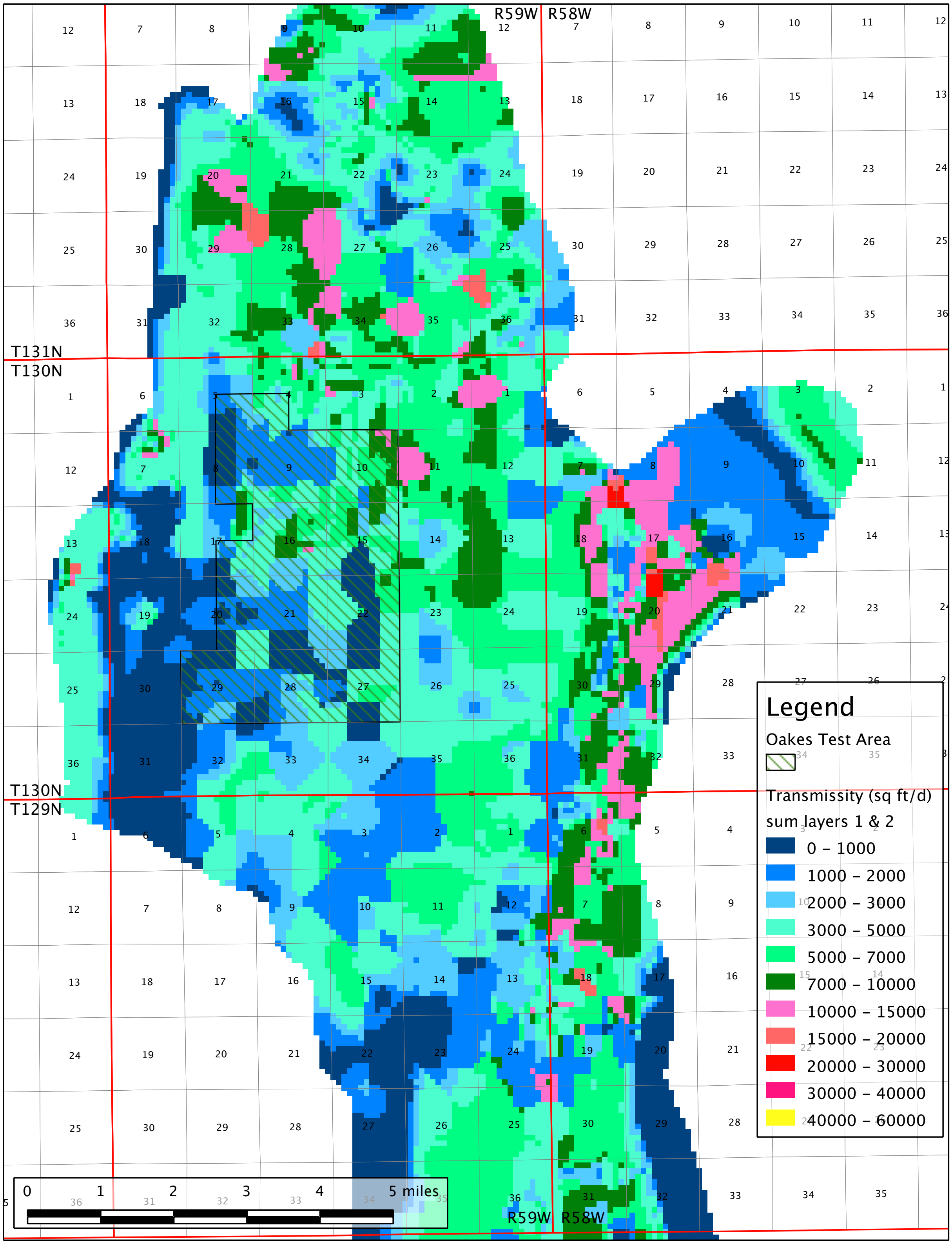


Figure 49. Transmissivity of layers 1 and 2. This is the transmissivity for sediments in the interval above 1,260 ft. in elevation. This interval represents the depth range in which the Oakes aquifer occurs.

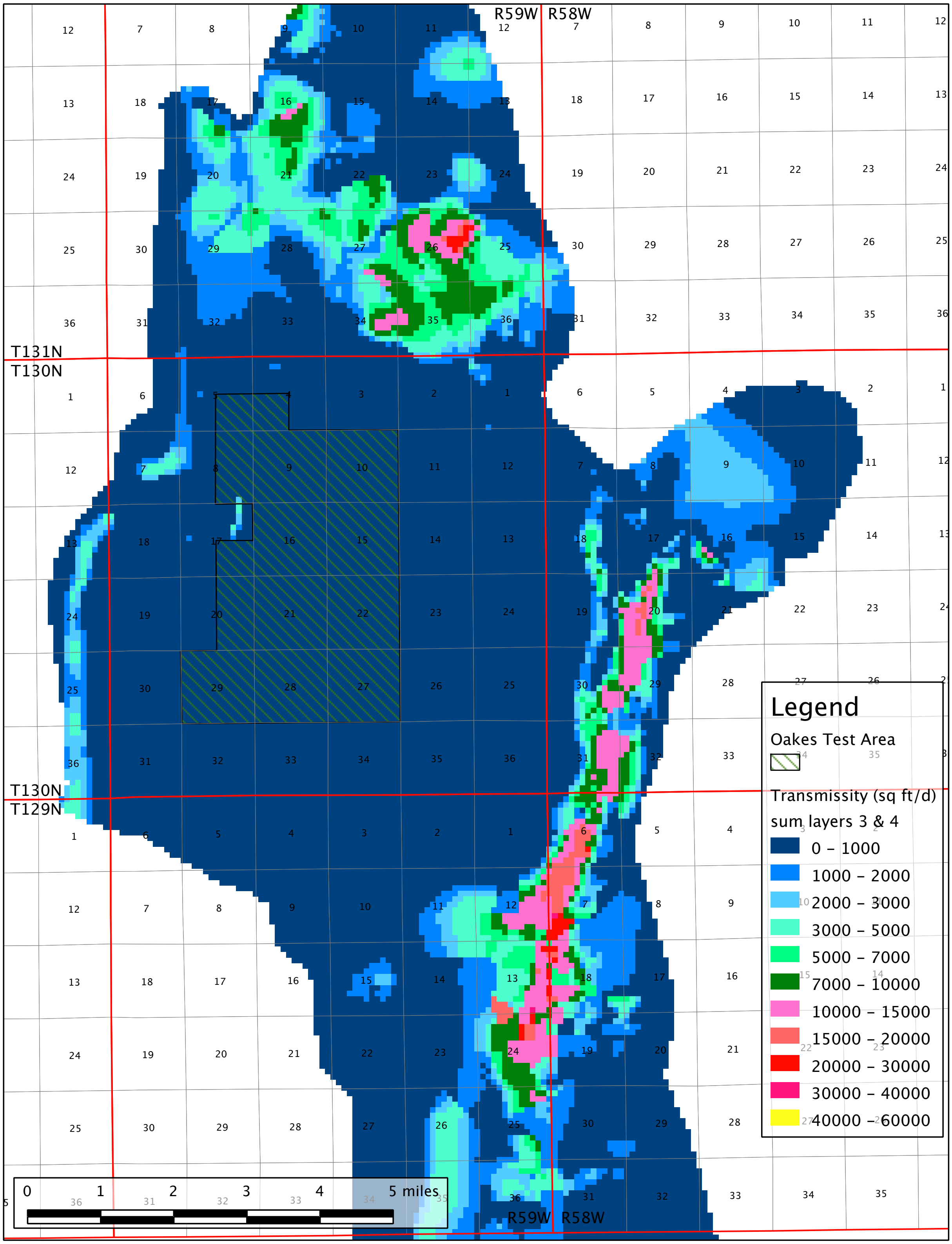


Figure 50. Transmissivity of layers 3 and 4. This is the transmissivity for sediments in the interval between 1,200 and 1,260 ft. in elevation. The deep channel and the large delta it built are seen along the eastern margin of the Oakes aquifer.

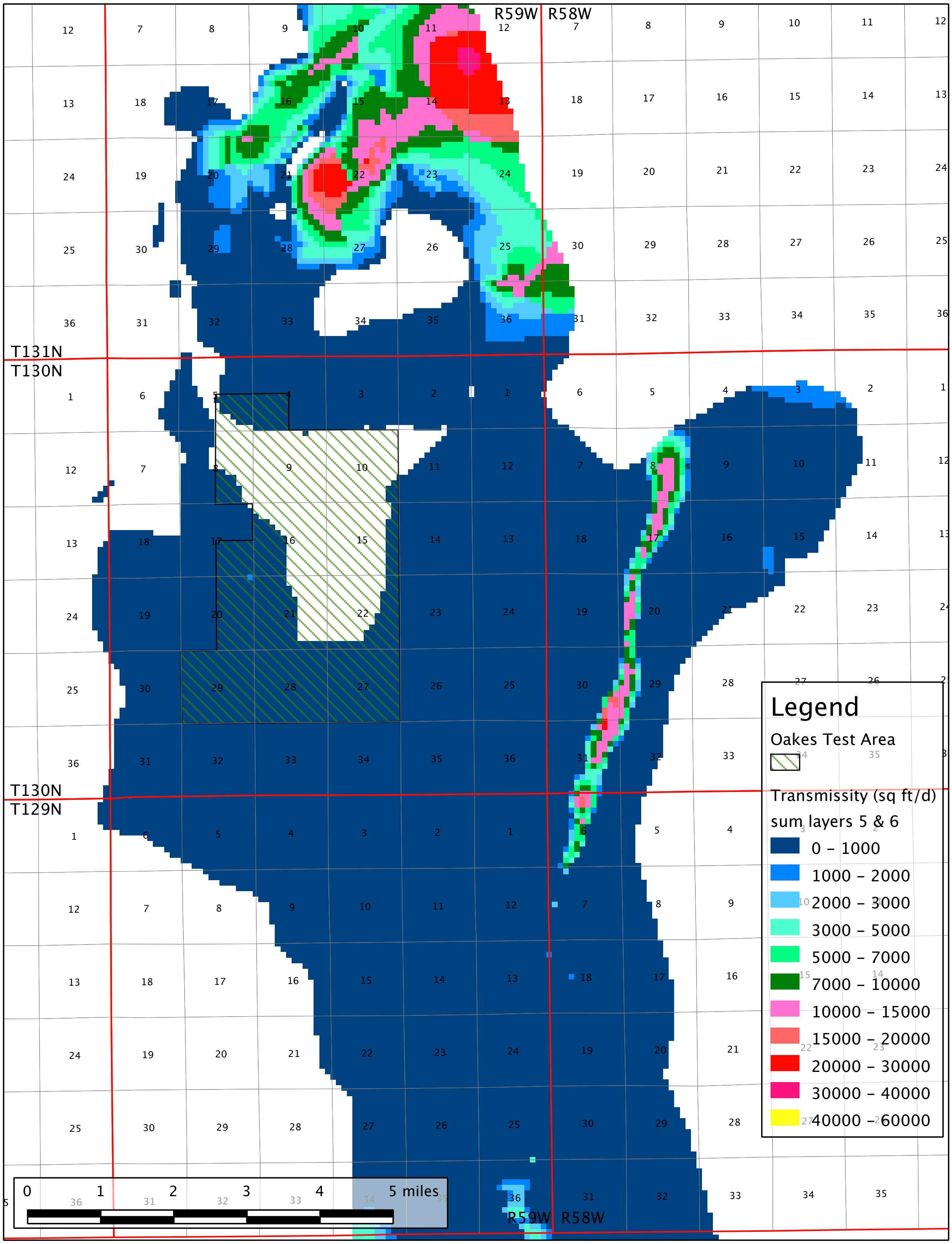


Figure 51. Transmissivity of layers 5 and 6. This is the transmissivity for sediments in the interval between 1,140 and 1,200 ft. in elevation. The deep channel is seen along the eastern margin of the Oakes aquifer. The high transmissivities of the Spiritwood aquifer are seen in the area north of Oakes where it underlies the Oakes aquifer.

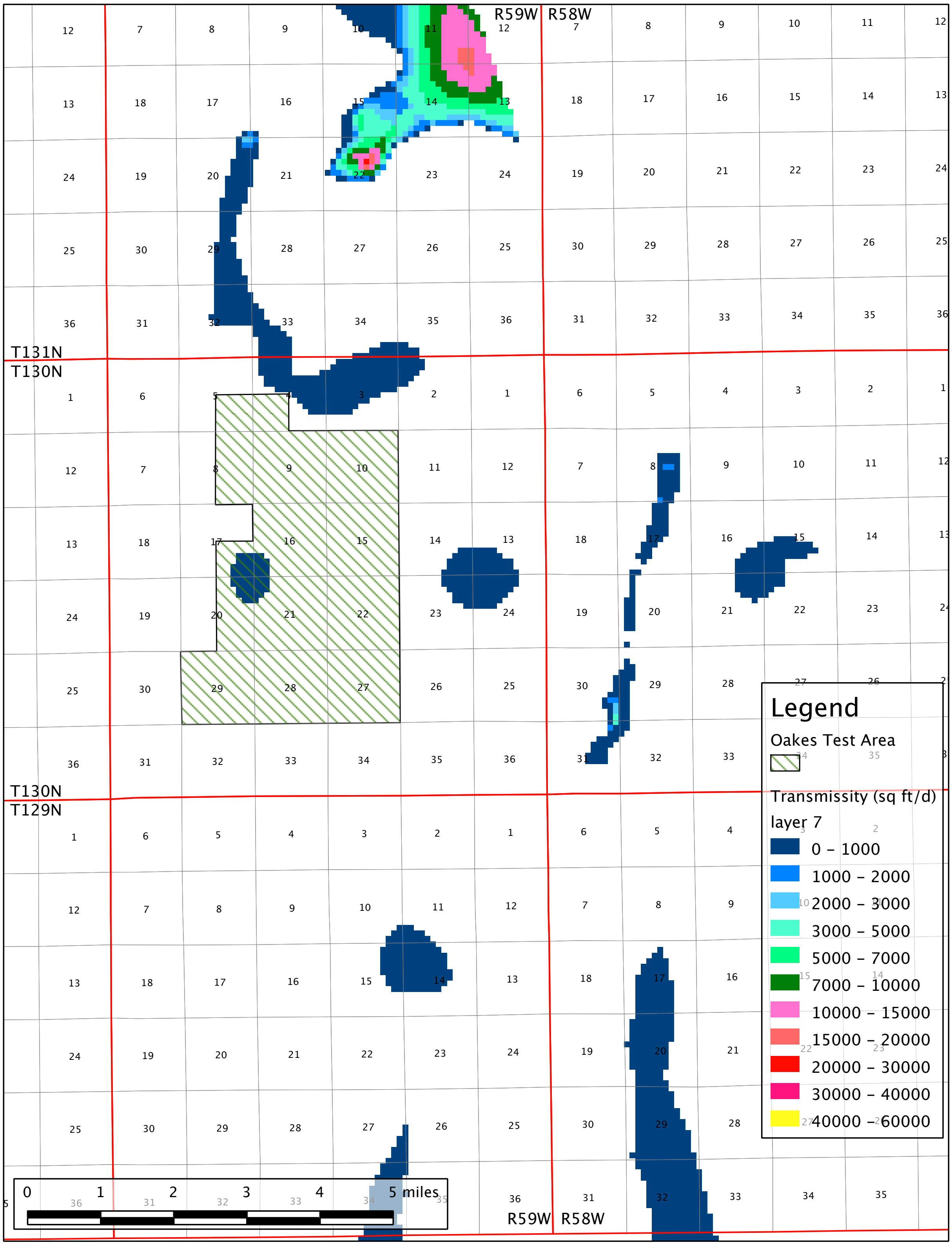


Figure 52. Transmissivity of layer 7. This is the transmissivity for sediments in the interval below 1,400 ft. in elevation. The high transmissivities of the Spiritwood aquifer are seen in the area north of Oakes where it underlies the Oakes aquifer.

Water Quality

Water quality from the Oakes aquifer is generally very good. However, a band of poor quality water extends from a mile north of the OTA to the east into sections 1 and 12, T. 130 N., R. 59 W. (fig. 53). Total dissolved solids in this area can exceed 12,000 mg/l (Williams, 1984). This zone of poor water quality underlies a shallow depression of approximately 6 square miles (Williams, 1984). The water in this zone is predominately a sodium-sulfate type (Williams, 1984). This depression can be observed in the LANDSAT image in figure 37 where a large wetland exists in sec. 12, T. 130 N., R. 59 W. There is a very low groundwater divide that separates this area from the OTA to the west. This divide, creating a closed flow system, has allowed ET to concentrate salts within this shallow depression. Significant groundwater pumping to the west has the potential to break down this groundwater divide allowing the accumulated salt to migrate to the irrigation wells to the west. This has the potential to result in a large and unacceptable decline in water quality within the OTA's interim well field and other neighboring irrigation wells.

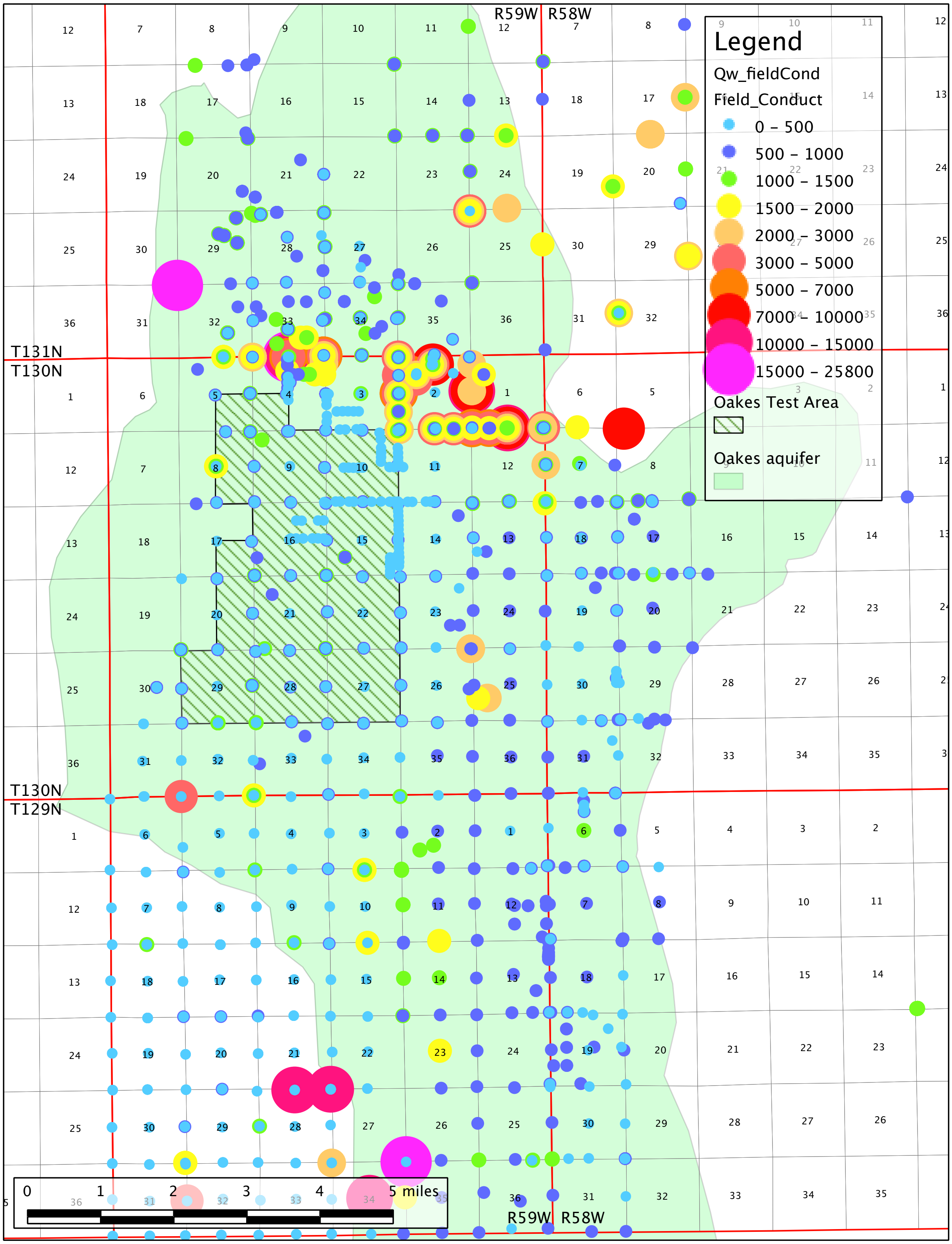


Figure 53. Map of field conductivities of water from the Oakes and Spiritwood aquifers.

Model Development

Introduction

To assess the appropriation of additional water from the Oakes aquifer, it was determined that a groundwater flow model would need to be developed. The USGS finite-difference model, MODFLOW-2000 (Harbaugh and others, 2000), was selected for the analysis of the Oakes aquifer. This is a widely used model for flow and contaminate transport studies within the United States and Internationally.

The steady-state model was developed using the Hydrogeologic Unit Flow package (HUF) (Anderman and Hill, 2000; Anderman and others, 2002; and Anderman and Hill, 2003) because of HUFs ability to simulate complex hydrostratigraphy. Unfortunately, it could not be used for the transient calibration and projections of pumping impacts because of excessive run times. For the transient simulations, the model was converted to Block-Center Flow package (BCF) using HUFPRINT (Banta and Provost, 2008).

Being able to estimate the flow from the pilot drain and the drains within the OTA is important (fig. 19). The Stream Flow Routing package (SFR1) (Prudic and others, 2004) was used to simulate drain flow. It was created to simulate ephemeral streams in the western U.S. It works well for simulating drains because inflow and outflow can occur along the length of the drain network. It also allows the specification of gages along the drain network to monitor flow. Gages were specified in the model at the sites monitored by the GDCD so that simulated flows could be compared with measured flows.

The Multi-Node well package (MNW1) (Halford and Hansen, 2002) was used to simulate the irrigation and municipal wells in the project area. MNW1 calculates well drawdowns, not just drawdown for the node in which the well is located. It also will reduce pumping rate and cease pumping if water levels fall below a specified level and then return to the specified rate when water levels recover. This eliminates the problem of having well nodes go dry and remaining off for the remainder of the simulation.

In conjunction with the MODFLOW model, a soil moisture budget model was developed to estimate aquifer recharge, ET from groundwater, and irrigation water use. The Versatile Soil Moisture Budget Model (VB2000) was used (Baier and others, 2000; and Dyer and Mack, 1984). The model was developed in the late 1970s for use on the Canadian prairies to estimate available water within the root zone and has seen several enhancements since its original release.

A more detailed discussion of the model development will be provided in the second part of this report, “Analysis and Simulation of the Oakes Aquifer: Model Development and Documentation.”

Model Grid

In a finite difference model, the aquifer is divided into rectangular blocks. The center of a block is referred to as a node. The Oakes model uses blocks 400 feet on each side. The model consists of 250 rows, 147 columns, and 7 layers. The active nodes are shown in figure 54. The model simulates all of the sediments between land surface and the underlying bedrock shale. Because of serious limitations in the tools that the NDSWC has available to create hydrostratigraphy, the aquifer was divided into seven layers independent of hydrostratigraphy. The bottom elevations for layers one through seven are respectively 1,280, 1,260, 1,240, 1,200, 1,140, and 1,100. Nodes are set to inactive if the node in that layer is completely shale. A disadvantage of not having layers align with hydrostratigraphy is that wells often cross layer boundaries requiring the well to be specified in more than one layer. Maximum drawdown for wells is set to the bottom of the deepest layer the well intersects, not the base of the aquifer within that layer. This can result in MNW1 overestimating well yields.

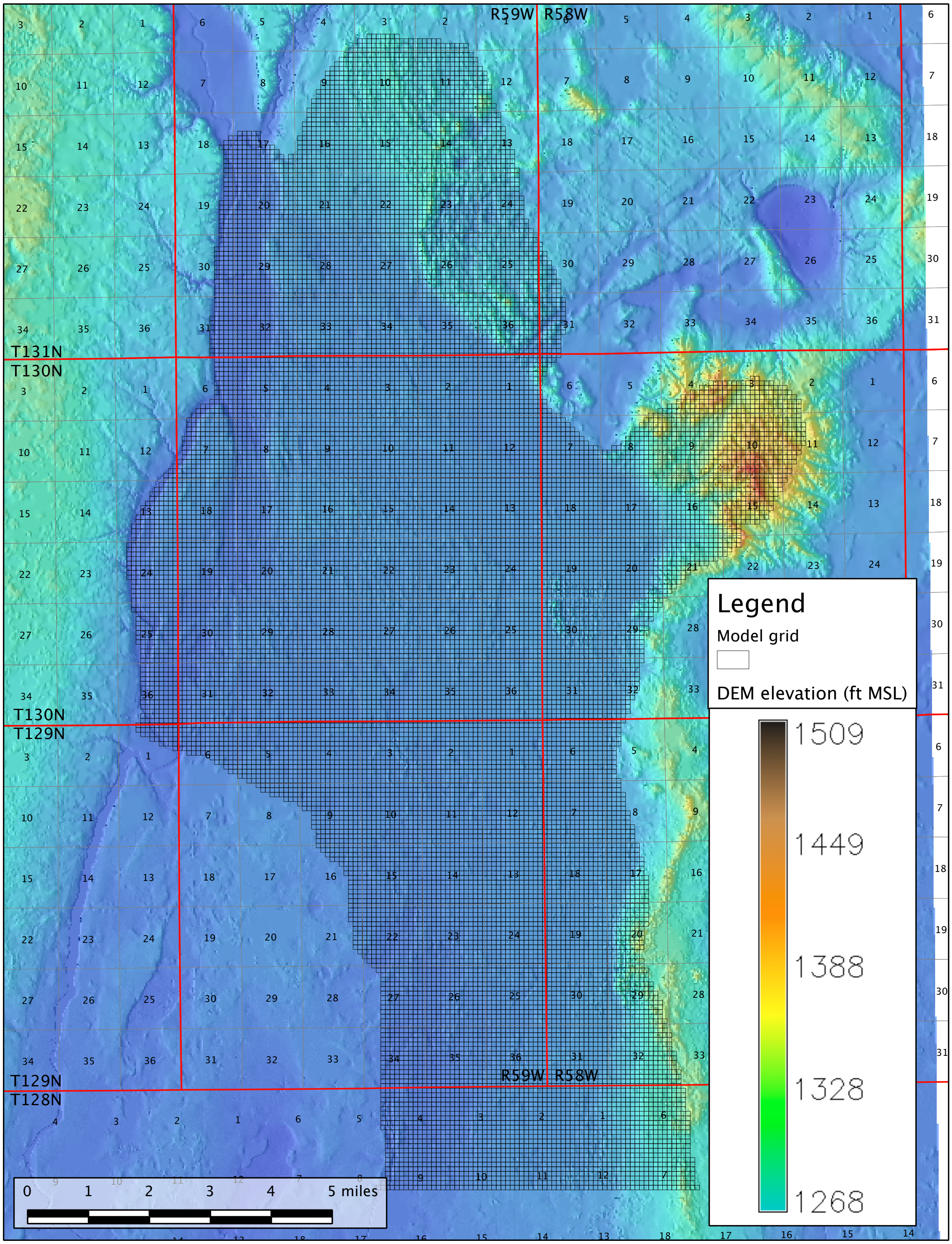


Figure 54. Location of active grid in the Oakes aquifer groundwater flow model.

Model Calibration

The first stage in developing a groundwater model is the development of the steady-state model. Output from the steady-state model provides the initial heads for subsequent transient simulations. The steady-state model gives an approximation of what the water table and flow system would be with average rates of recharge, ET, stream stages, pumping rates, etc. For the Oakes model, as with most modeling studies, the objective of the steady-state model is to reproduce average predevelopment water levels. The target for the Oakes steady-state model was to reproduce the November 25, 1967 water levels (fig. 32). The steady-state model, run F12 (fig. 55), reproduces the November 25, 1967 water levels reasonably well (fig. 56). The overall flow pattern is similar between simulated and observed. Water level differences are generally within a couple of feet. This is well within the error in the land surface from the 10 meter USGS DEMs. The model also reproduces the steep gradient in the southern part of the model near the South Dakota border. This has been a problem in previous steady-state models (Shaver, 1990).

Figure 57 shows ET occurring across the Oakes Lake plain indicating that the water table elevation is largely controlled by ET. Some banding occurs in the ET rates. This is an artifact of the USGS DEMs. In flat hummocky topography the DEMs tend to stair step instead of producing the likely uniform gradient. At the base of these steps ET is overestimated and is underestimated at the top of the step. The closed flow system with large ET is reproduced in sec. 12, T. 130 N., R. 59 W. where the poor water quality area occurs.

Because of the flat water table gradients with most of the recharge lost locally to ET, the steady-state model provides little constraint on aquifer hydraulic properties.

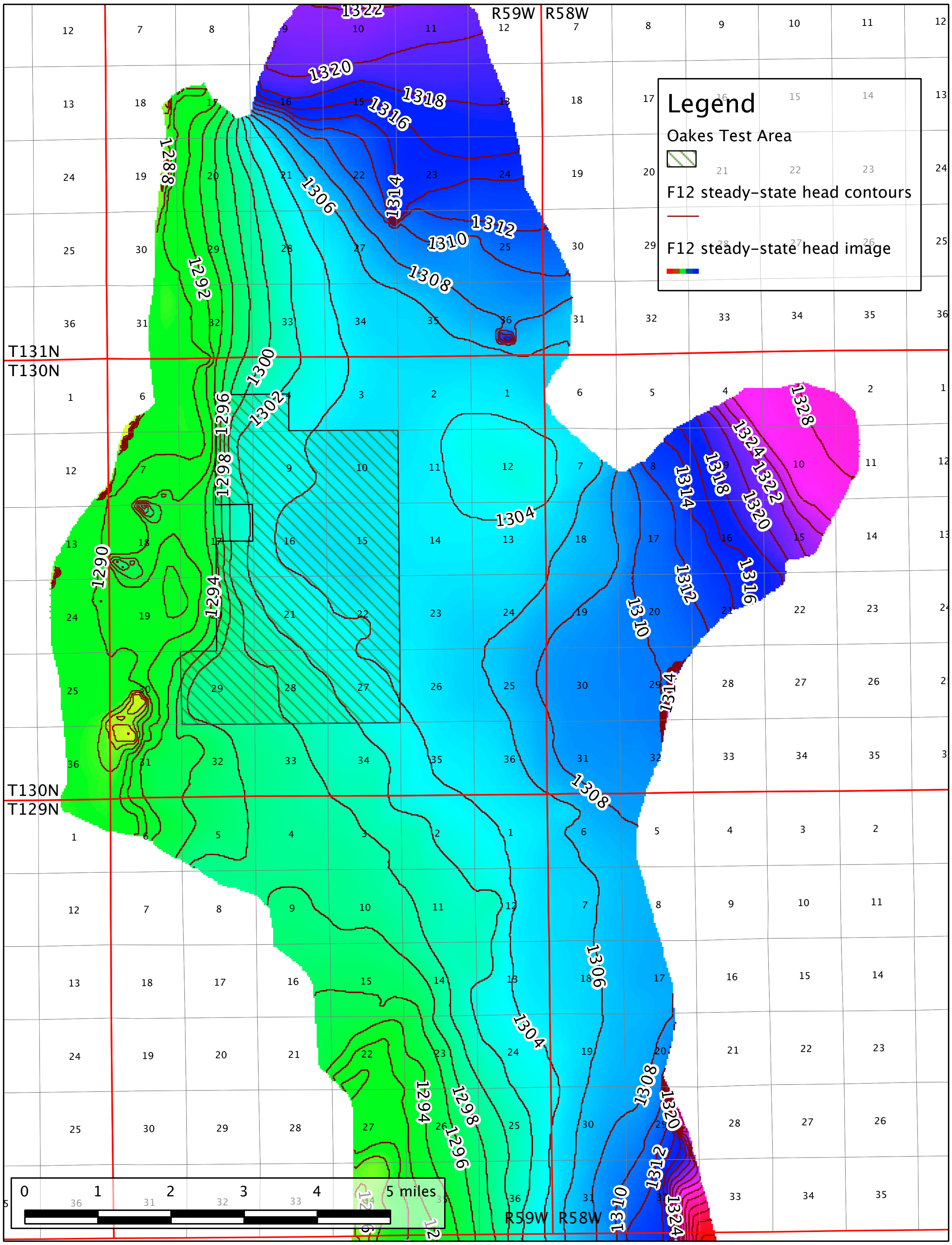


Figure 55. Water level elevations for layer 1 in steady-state model run F12.

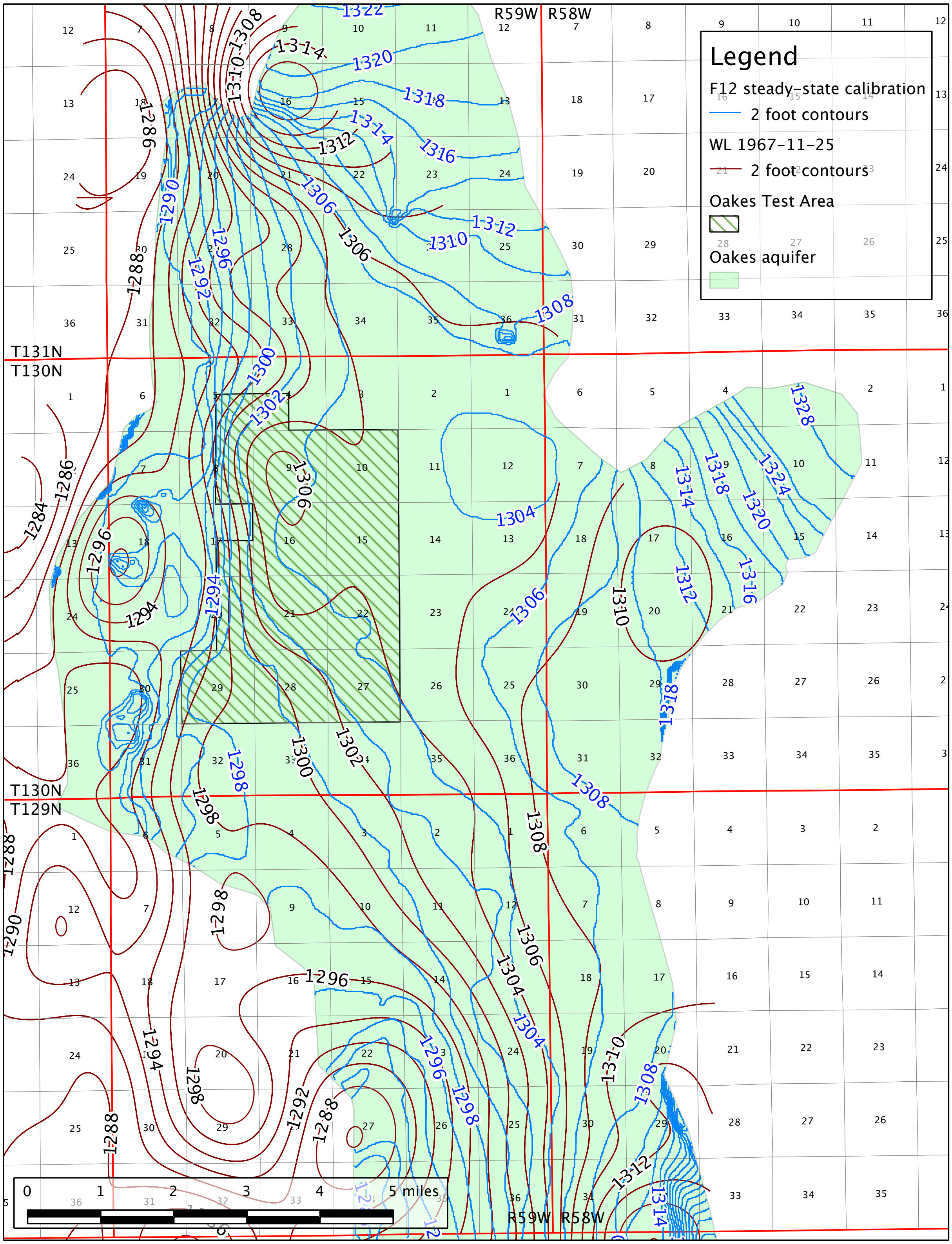


Figure 56. Comparison of water level elevations for steady-state calibration (run F12) with November 25, 1967 water levels.

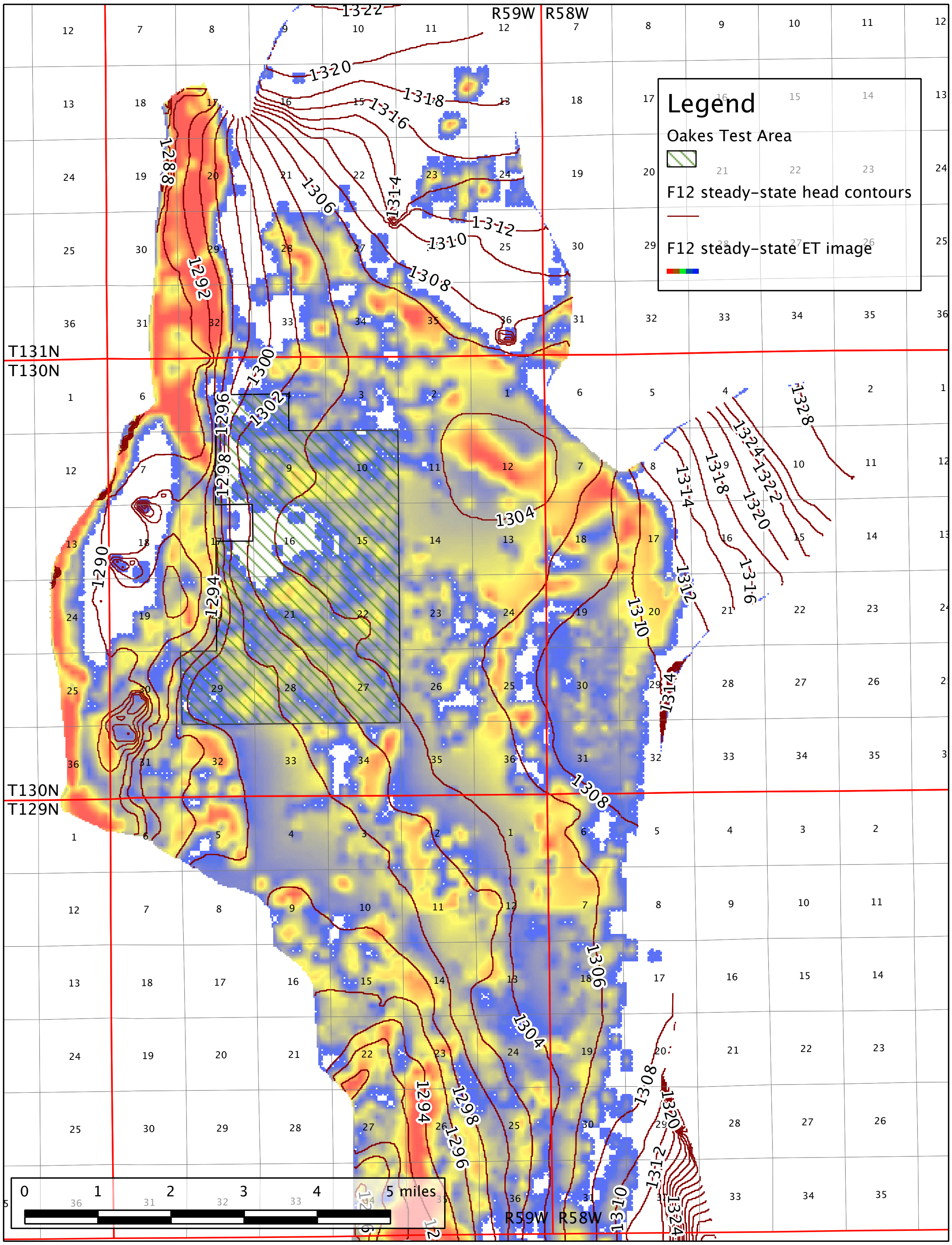


Figure 57. Areas of ET occurring in steady-state simulation run F12. Blue is area of low ET and red is area of high ET. White areas have no ET occurring.

The transient calibration used the Oakes climate data set to calculate recharge and ET from groundwater. Reported water use including adjustments made based on power consumption for use prior to 1995 were used to calibrate the model. The results of the transient calibration are shown in figures 58 through 60, comparing observed with simulated water levels at observation wells 129-058-06AAA3, 130-059-13BBB1, and130-059-04DDD3 respectively. Additional hydrographs are presented in Appendix D. The model is very good at reproducing water levels through 1990. The pattern of water level change is reproduced well after the mid-1990s, but generally significantly underestimates water level elevations. The problem largely appears to occur in the early 1990s when observed water levels are increasing while simulated water levels are either flat or still declining. This is likely a result of the Oakes climate dataset not being representative of the Oakes aquifer during this time period.

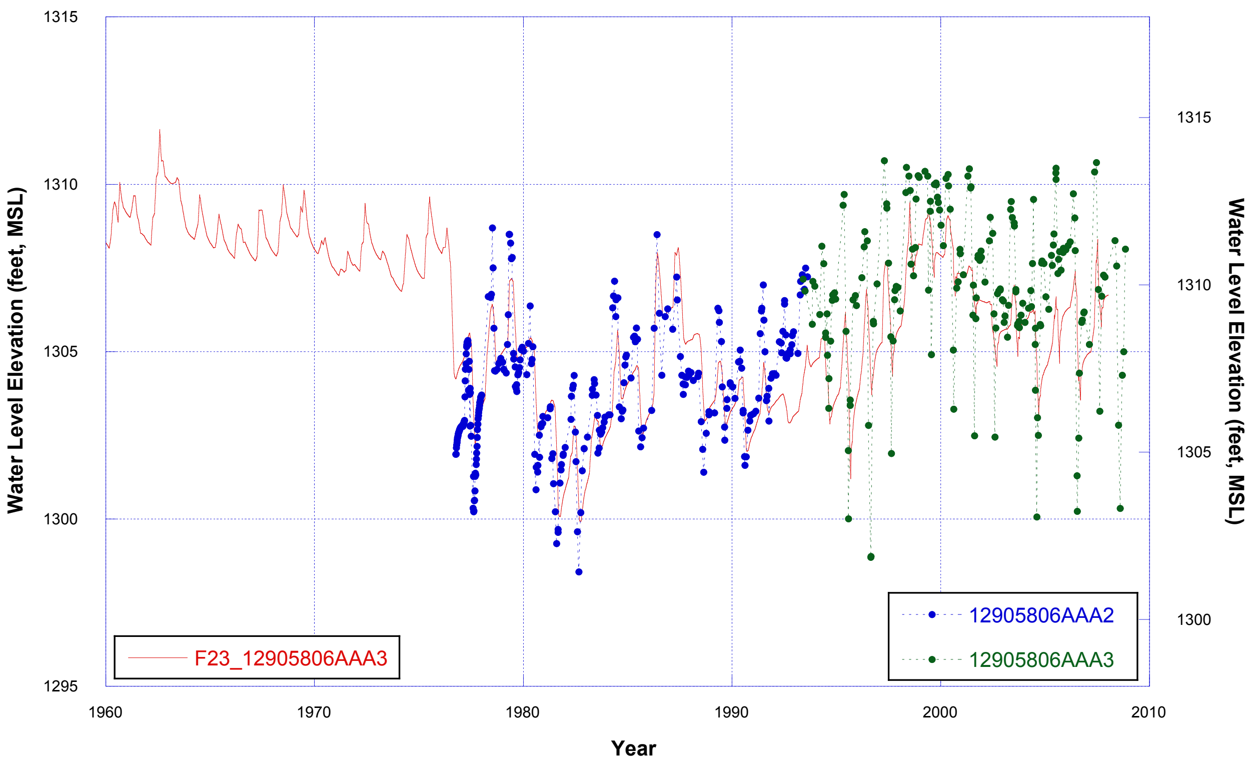


Figure 58. Comparison of transient calibration water levels, run F23, to observed water levels at observation well 129-058-06AAA3. Land surface elevation is 1,315.9 feet MSL.

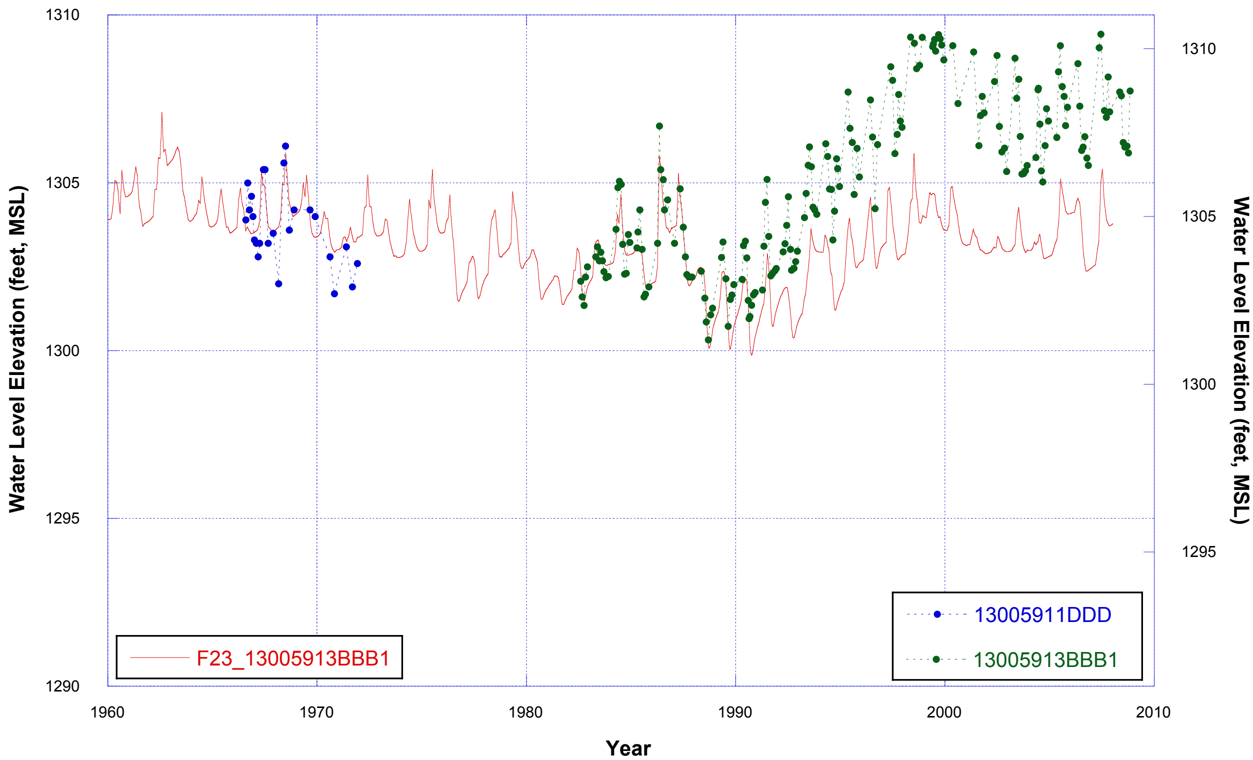


Figure 59. Comparison of transient calibration water levels, run F23, to observed water levels at observation well130-059-13BBB1. Land surface elevation is 1,308.42 feet MSL.

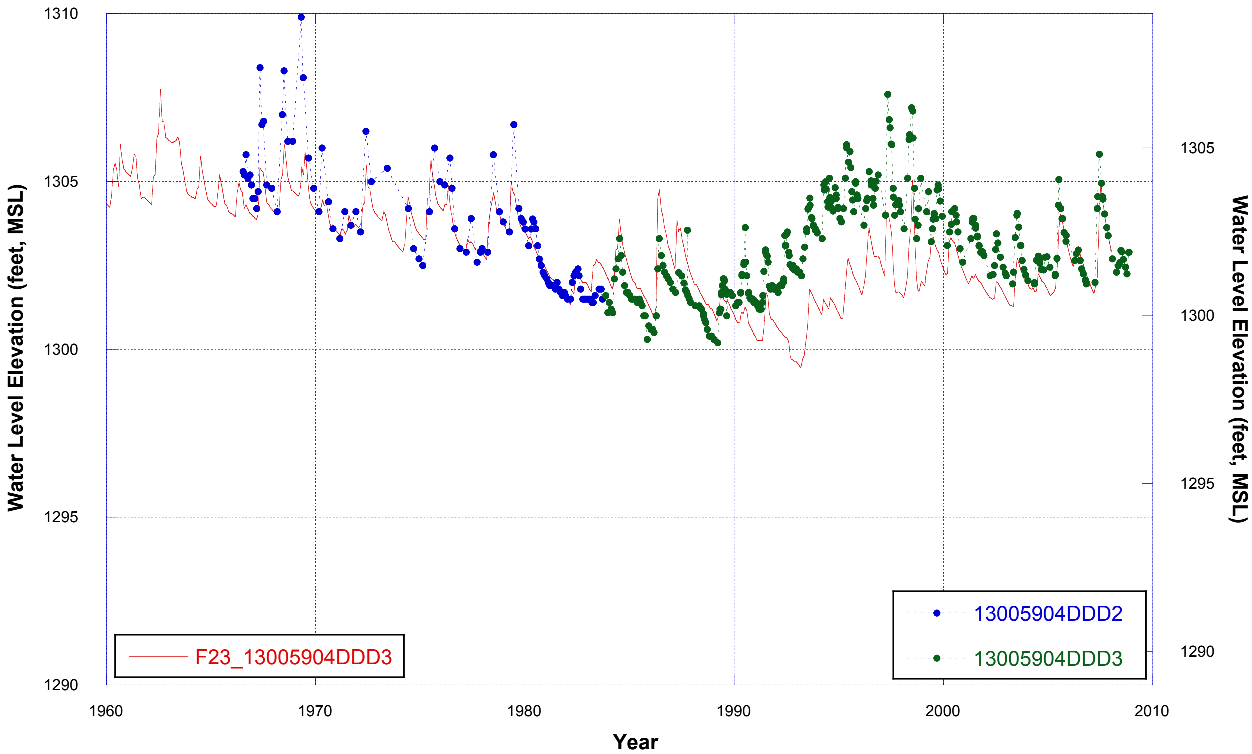


Figure 60. Comparison of transient calibration water levels, run F23, to observed water levels at observation well 130-059-04DDD3. Land surface elevation is 1,311.40 feet MSL.

The simulated discharge for the drains at the gaging sites is shown in figures 61 through 64. The drain outflow appears to be about half that of the measured flow. The average drain outflow for 1995 (stress period 420) through 2007 (stress period 576) was 3.1 cfs. The area influenced by the drains is assumed to be 13.5 square miles. This is equivalent to a drainage rate of 3.15” per year. The measured flow rate was 6.6 cfs. During 1995 through 2007, the average recharge within the OTA was 6.56” per year (Table 6) which is the same as the measured drain flow rate of 6.6” per year. This would indicate that the model is significantly underestimating recharge in the test area.

Table 6. Recharge for steady-state and transient calibrations.

Run	Period	Years	Recharge: Average (inches/year)	Recharge: sands (inches/year)
F12: steady-state	---	1	4.66	5.50
F23: transient	1960 - 2007	48	4.82	5.69
F23: transient	1960 - 1979	20	5.31	6.27
F23: transient	1980 - 1992	13	3.41	4.03
F23: transient	1995 - 2007	13	5.56	6.56

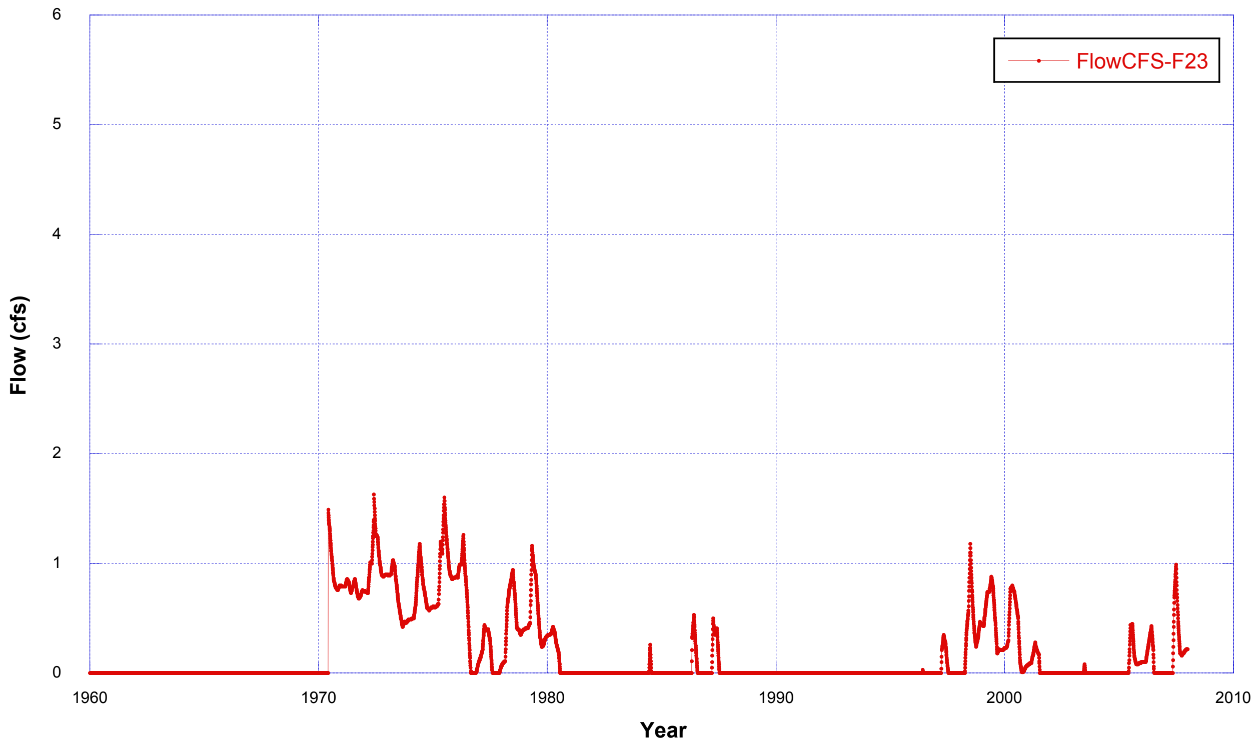


Figure 61. Simulated drain flow at station 14.0, pilot drain.

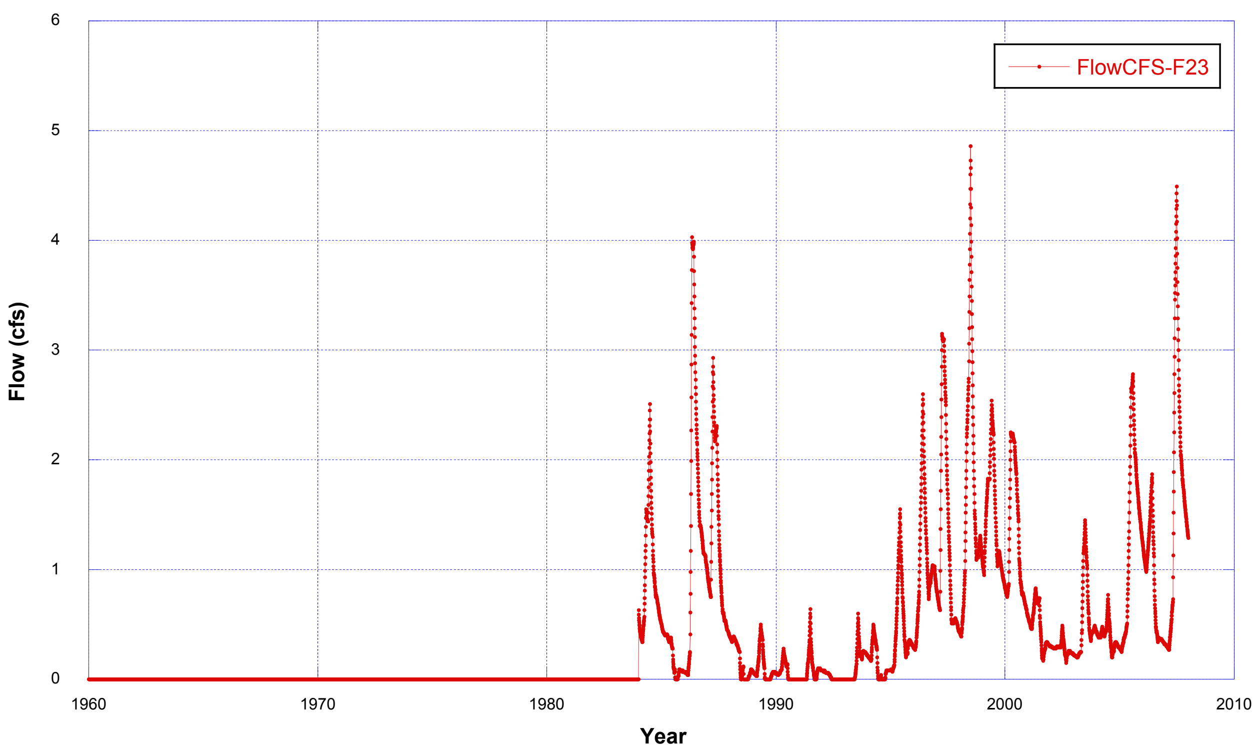


Figure 62. Simulated drain flow at station 12.6-0.7. This network drains northern part of OTA.

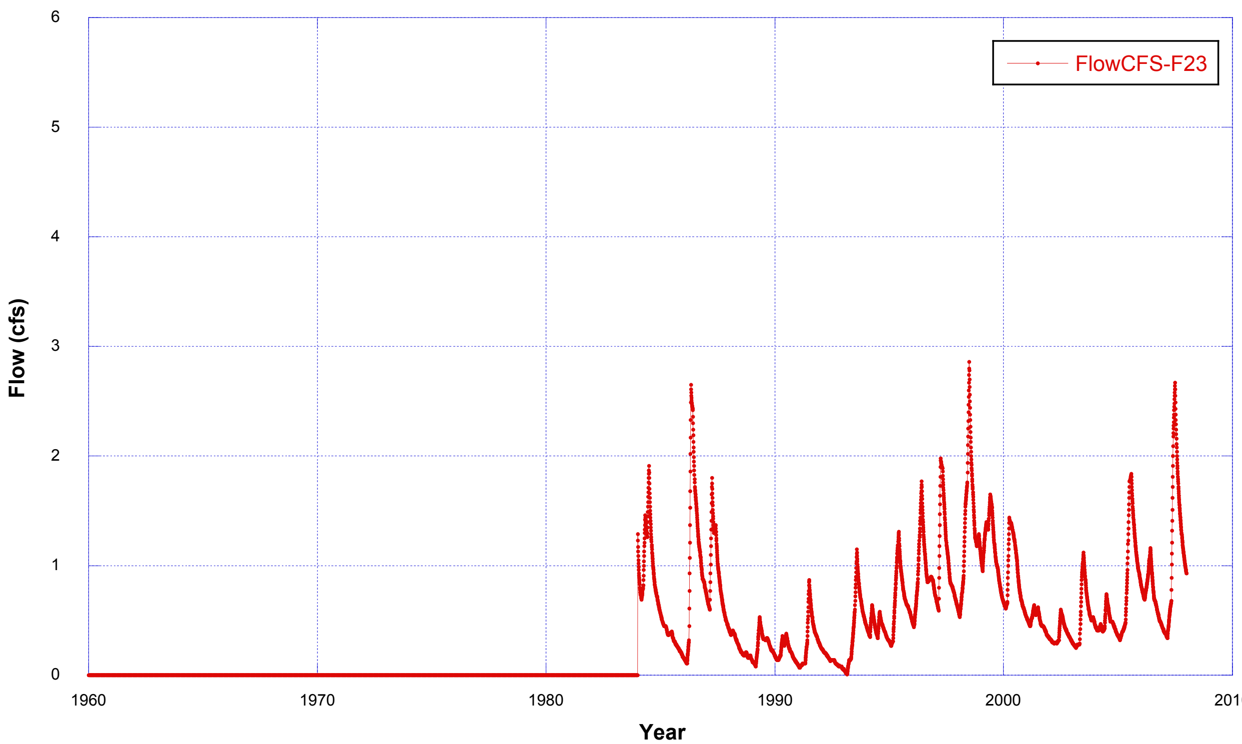


Figure 63. Simulated drain flow at station 8.1-1.1. This network drains central part of OTA.

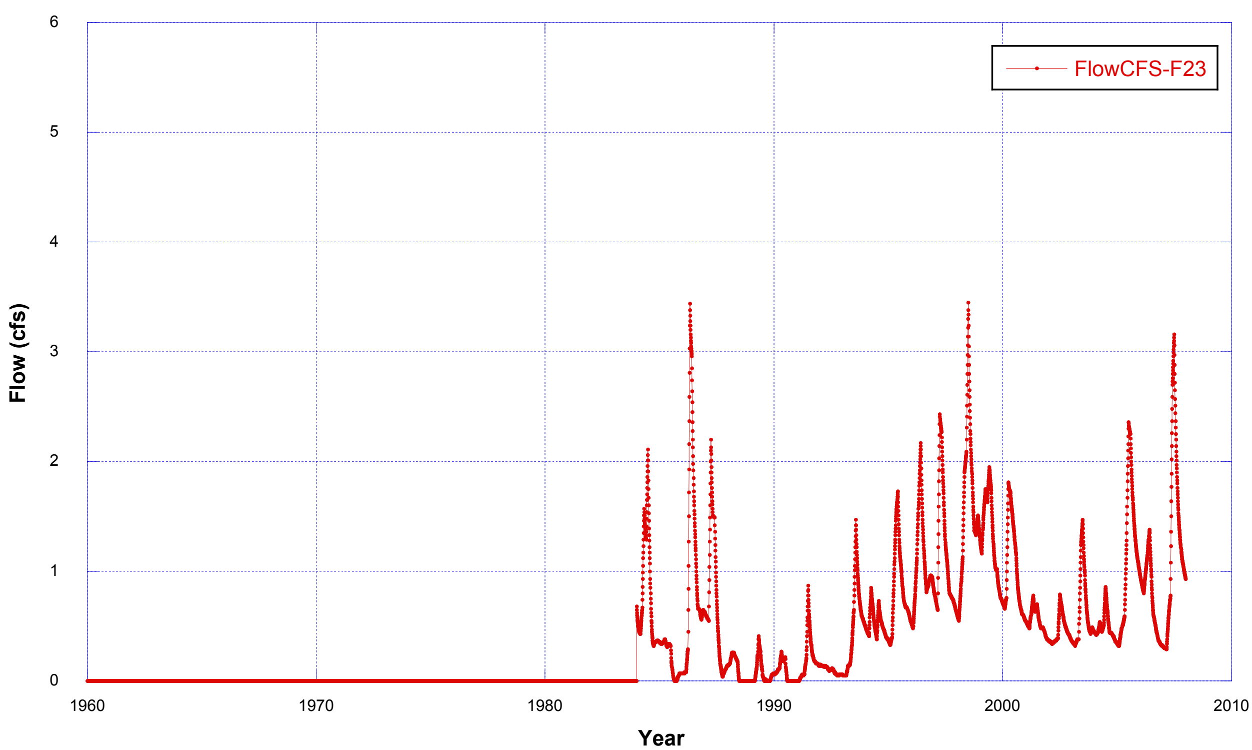


Figure 64. Simulated drain flow at station 8.1. This network drains southern part of OTA.

Recharge for the model is calculated using VB2000 soil moisture budget model. The model is run separately from MODFLOW. This procedure assumes that the elevation of the water table has no significant impact on the water table. To simplify the analysis, it is also assumed that recharge to the aquifer can be represented by one soil. For the Oakes model, the Hecla soil series was used. Because the modeled area also includes soils with till and lacustrine silts and clays as parent material, it was necessary to use a multiplier to reduce recharge in these areas (fig. 65). The blue area, which includes the OTA, is an area with sandy soils. The multiplier is set to 1.0 for this area. The northern part of the aquifer is covered with a thin till sheet. This is the light green area in figure 65. For this area, VB2000 was run using a Barnes-Seva soil series to develop a relationship for the multiplier. The multipliers were adjusted during calibration. Assuming that recharge can be approximated with a single soil dampens the variation in recharge with variation in climate. Even though the results of this procedure reasonably estimate recharge under average conditions, the procedure underestimates recharge during wet periods and overestimates recharge during dry periods. A significant error in recharge estimation likely results from not distinguishing between irrigated and non-irrigated soils. Ideally recharge should be calculated for each soil and crop or native vegetation type including whether it is irrigated or not. This would have added considerable overhead in data processing to prepare the necessary datasets and a huge increase in computational requirements.

The calibration of the steady-state model resulted in a recharge rate of 5.5” per year for the sands and an overall recharge rate of 4.66” per year (table 6). Prior efforts to model the Oakes aquifer used a recharge rate of 4” per year (Shaver, 1994). Because of differences in the extent of this model to prior efforts, the 4” per year from prior models should be compared to the 5.5” per year recharge on sandy soils. This model is significantly wetter than prior models, but is it wet enough? The recharge in the steady-state model compares well with the results from various periods in the transient model. The small difference in recharge between the period 1995 through 2007 and the slightly drier period 1960 through 1979 was not expected given the extensive flooding due to the high water table that has occurred during 1995 to 2010 and not in the previous period.

Some of the high drain flows within the OTA can be explained by the importation of water for irrigation into the OTA (fig. 66). To account for the impact of irrigation on recharge, the application of irrigation water would need to be added to the precipitation data. VB2000 uses a daily time step. Any budget model adding irrigation to the estimation of groundwater recharge would need to do its own irrigation scheduling.

Ideally, the soil moisture budget model should accurately estimate recharge and ET from groundwater during both wet and dry periods. However, the modeling procedure probably significantly underestimates the variability in these inputs to the groundwater model by not accounting for soil and land use variations, particularly irrigation, and estimates of PET from temperature data. From a groundwater management perspective, it is better to make good estimates of recharge and ET from groundwater during dry periods than wet periods. With the tools available when this project started, calibrating the model to reproduce the drain flows from the OTA would have resulted in a model that was excessively wet during dry conditions.

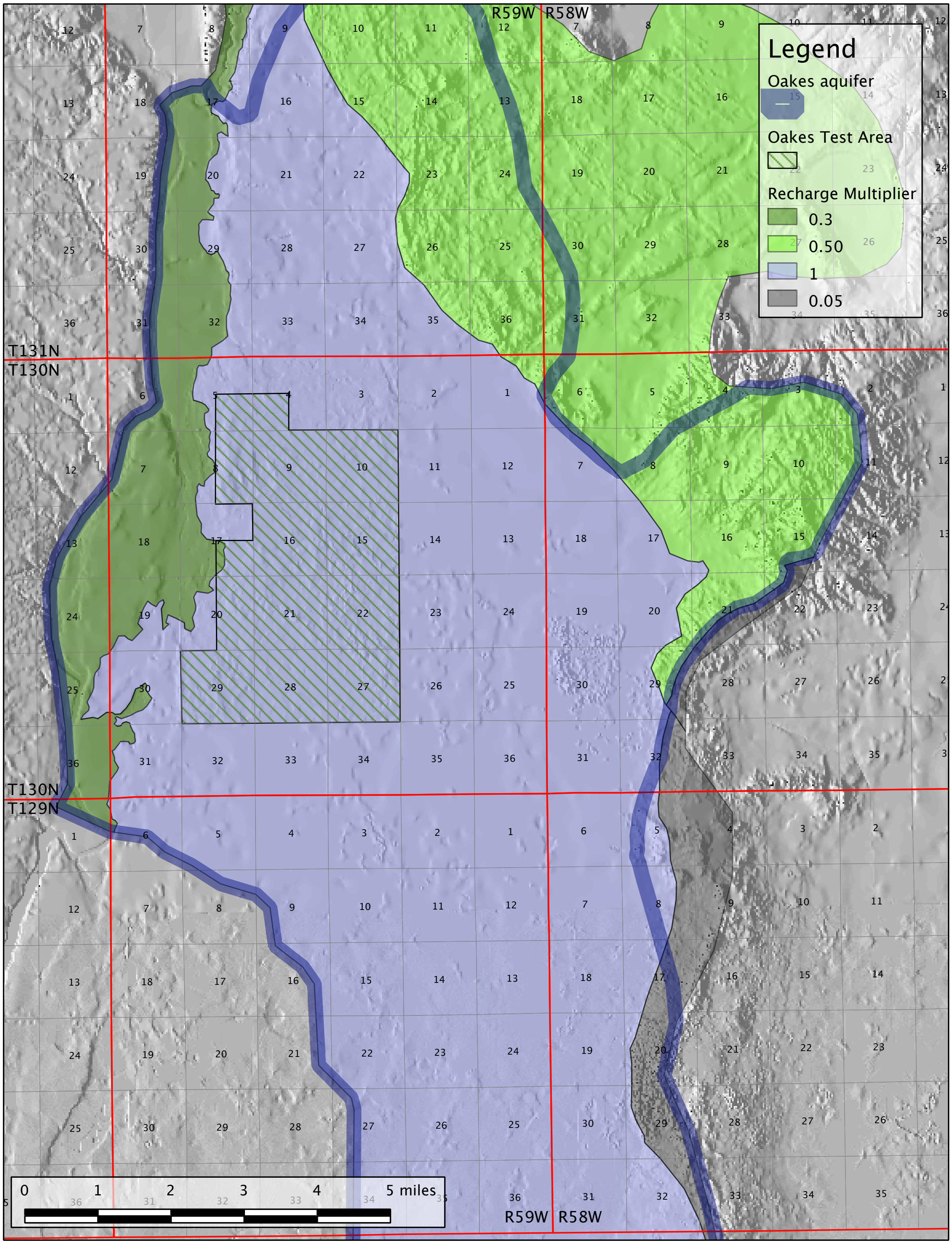


Figure 65. Location of recharge zones in the Oakes aquifer model. Each is a scaling factor applied to the model recharge rate. The zones are based on parent soil material type. Low values are areas of silts, clays, and glacial till.

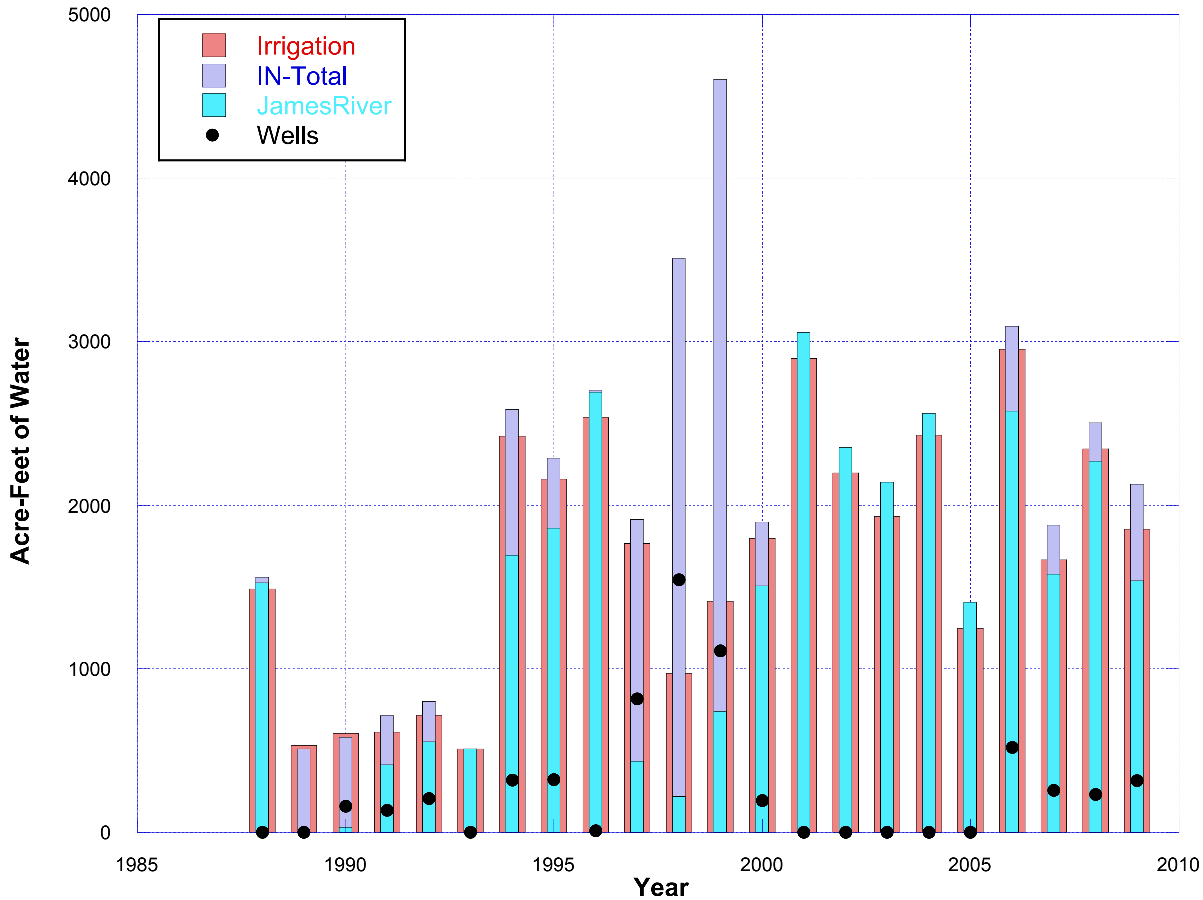


Figure 66. Water use and sources of water for the OTA for years 1988 through 2009. The IN-Total is sum of water from the James River, pumped from drains, and wells. IN-Total in excess of irrigation flowed into the James River. Data provided by Dale Esser, GDCD.

The location of PODs with reported water use and their associated irrigation wells and the USBR interim well field that were used for the transient calibration of the model are shown in figure 67. Not all of the irrigation wells were able to yield their reported use in the simulation (figure 68). The wells located in section 15, T. 131 N., R. 59 W. to the northeast of Oakes were never capable of reproducing reported use of the calibration simulations or estimated use in the later impact scenarios. This is a result of the well field being located on a groundwater divide that was used as the boundary of the model in this area. This has no impact upon the area of interest to the south in this report. The other wells that have problems yielding water are primarily within the OTA.

The hydrostratigraphy was developed primarily from NDSWC and USBR bore lithologic data. Often, the irrigation wells did not have logs and when logs were available there is uncertainty as to actual textures of sediments and bore locations. The NDSWC and USBR data was considered adequate for developing the regional hydrostratigraphy of the aquifer. The wells within and near the OTA are multi-well fields that were located after extensive test drilling to locate sites of larger saturated thickness and/or coarser textures, and are generally not representative of the area in the vicinity of the well.

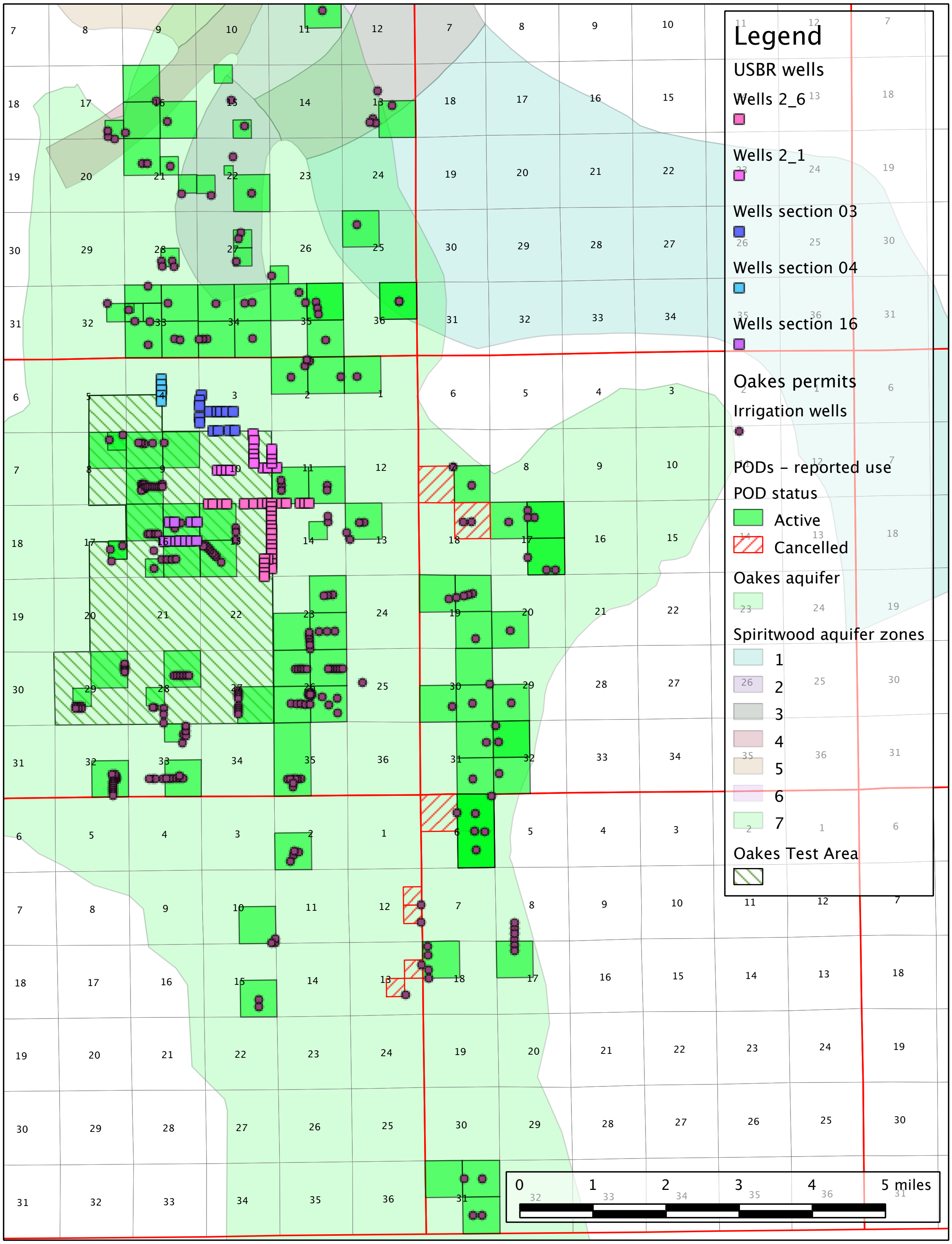


Figure 67. Location of irrigation wells and USBR interim well field used in development of transient calibration run F23.

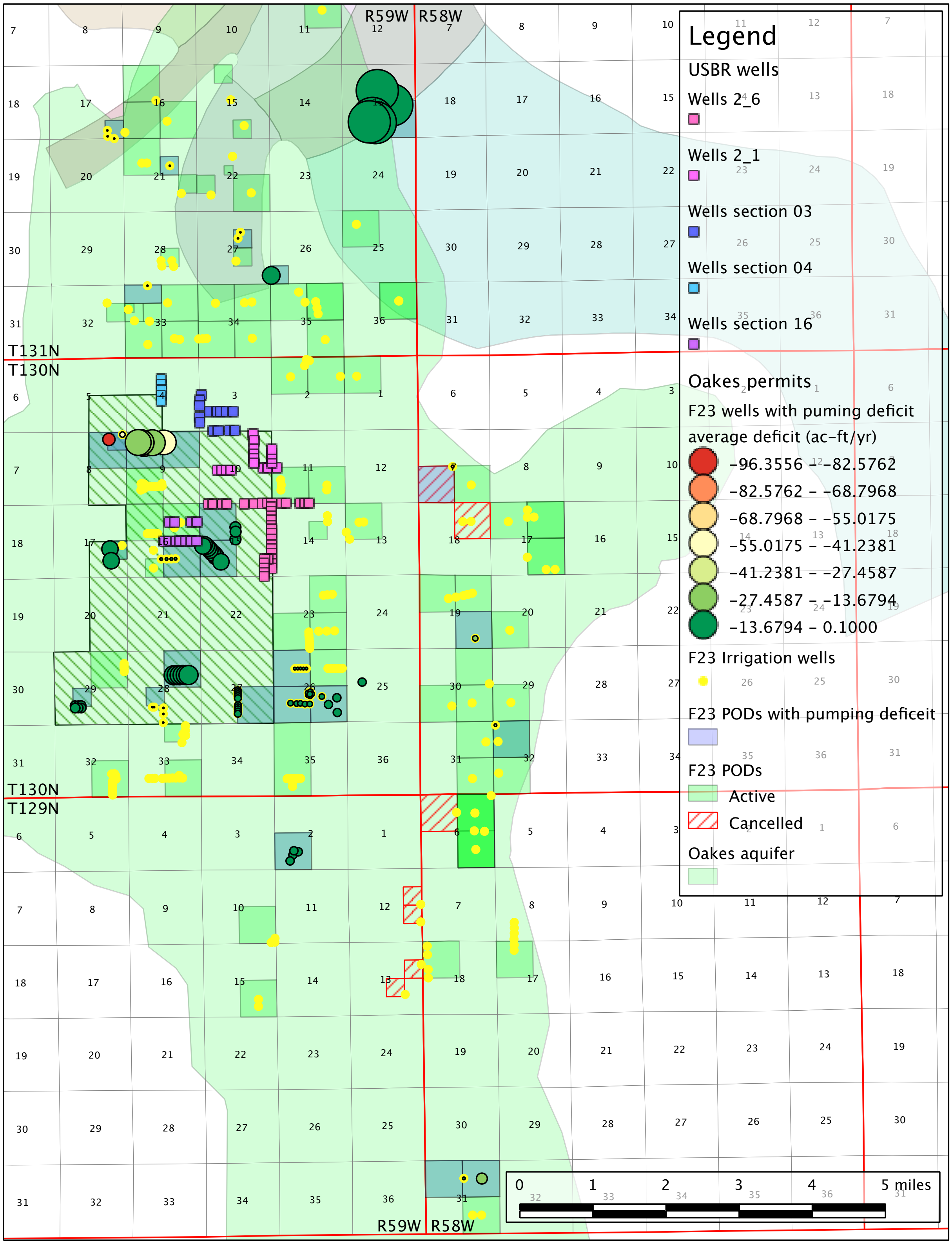


Figure 68. Location of irrigation wells with pumping deficits, that is where the simulated wells did not yield reported water and/or estimated water use. The size of the circle indicates the number of years a pumping deficit occurred. Run F23.

Any attempt to reproduce finer scale variability in the hydrostratigraphy would require the creation of a large number of synthetic logs without much basis as to the location or lithology. If this type of detailed hydrostratigraphy is needed then geostatistical methods would be required. Otherwise there is no method to assess whether the additions are making the model better or worse as a predictive tool.

The volume of water that the simulation under-predicts irrigation water use is shown in figure 69. This is not a large percentage of the total use, particularly when wells outside the area of interest that are north of Oakes are considered. The underestimation of well yield results from the simulated well not being able to produce the quantity of water the actual well produces. This is probably a result of the aquifer in the vicinity of the well being coarser and/or thicker than is simulated in the model. If drawdown in the well is too large to sustain the pumping rate, the well yield is reduced in the model. The underestimation of water use results in the impact on the surrounding area being underestimated and in an overestimation of drawdown. Both the interim wells and the Oakes municipal wells were able to produce the reported use (figs. 70 and 71).

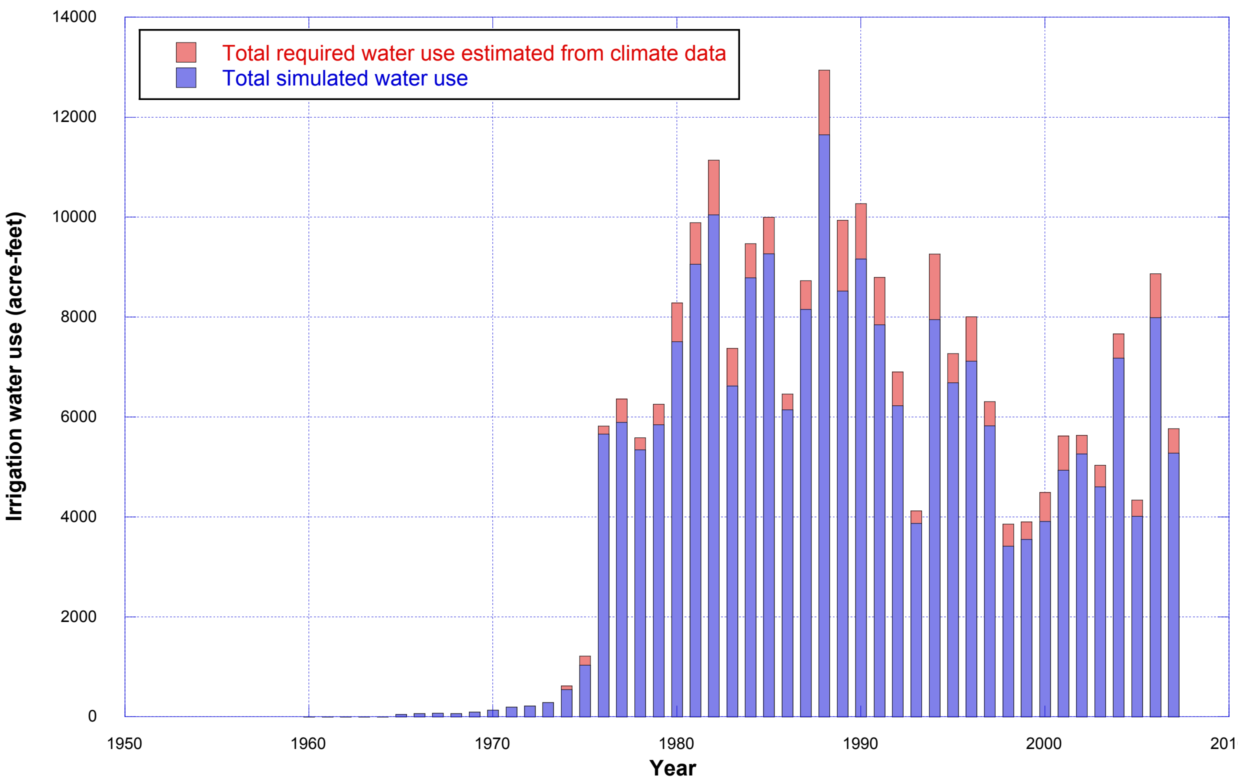


Figure 69. Irrigation well water use for transient calibration run F23 using reported and estimated water use (red bar) and the total simulated use (blue bar). The difference results from wells that are not able to produce the reported amount. Simulation period is from 1960 through 2007.

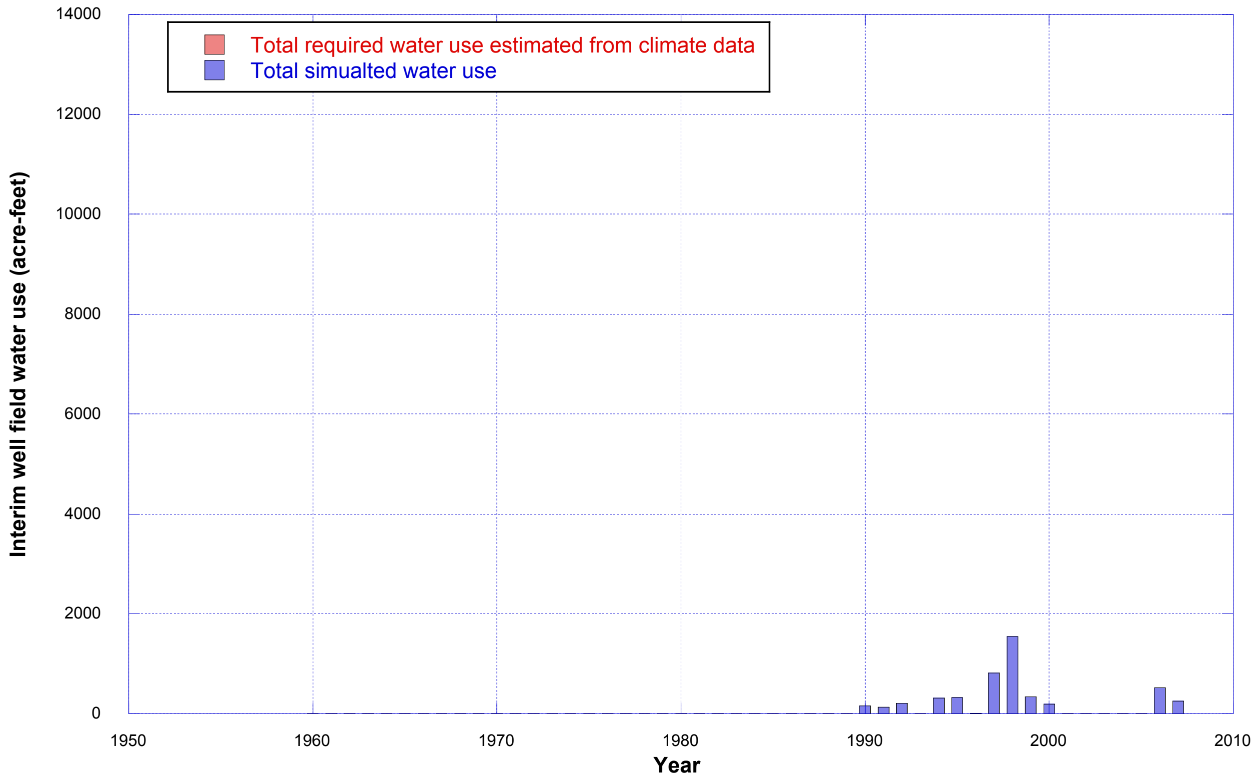


Figure 70. USBR interim well field water use for transient calibration run F23 using reported use (red bar) and the total simulated use (blue bar). All wells produce the reported amount. Simulation period is from 1960 through 2007.

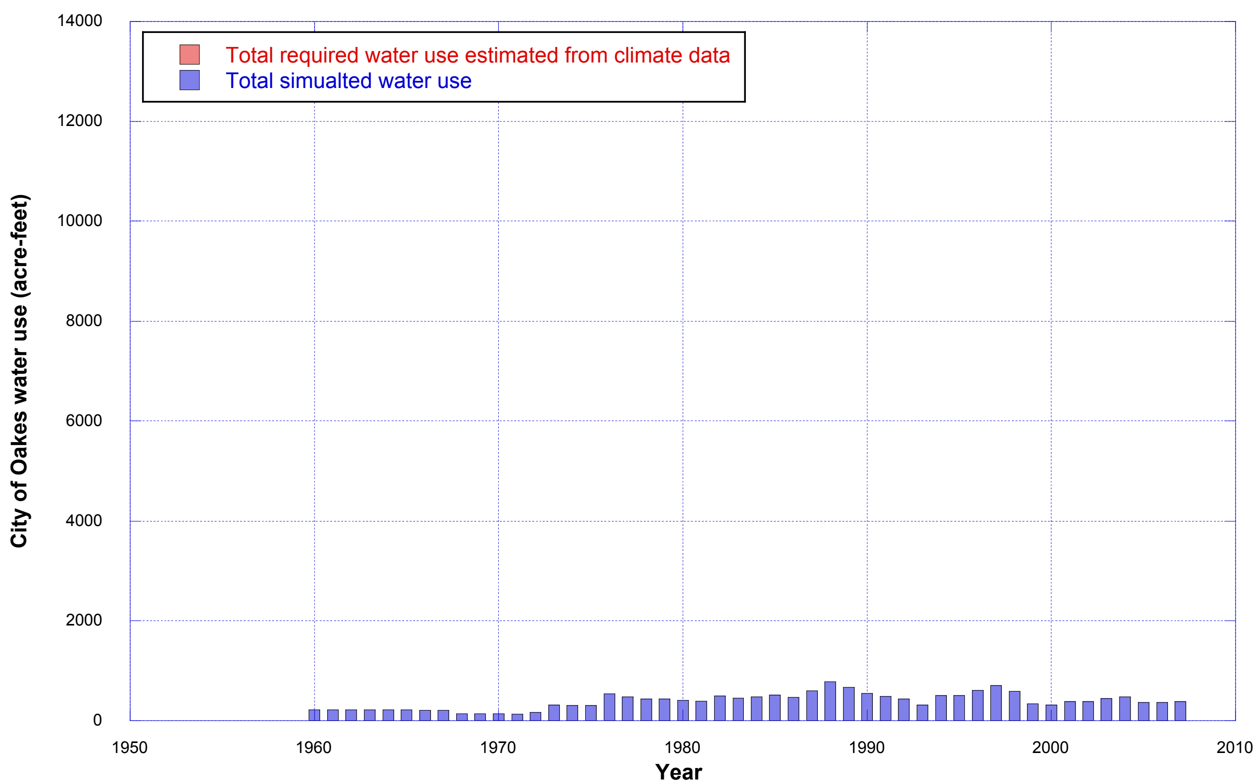


Figure 71. City of Oakes water use for transient calibration run F23 using reported use (red bar) and the total use simulated use (blue bar). All wells produce the reported amount. Simulation period is from 1960 through 2007.

Model Results

Introduction

As discussed previously, there were 3,945 acres approved and developed for irrigation after 1990. Little is known about the impact the irrigation of these acres would have on the Oakes aquifer due to the fact that much land has not been irrigable as a result of the high water table conditions and small demand for water since the mid-1990s due to the present pluvial. There has not been a significant change in water use or acres irrigated since the early 1980s (fig. 14). Water permit applications with a priority date before July 31, 2006 request to irrigate an additional 4,252 acres. In the following discussion, this set of permits is referred to as pending irrigation. On July 31, 2006 DSID applied to irrigate 5,000 acres with 5,000 acre-feet of water. There is also the question of the how typical the climate has been for the Oakes aquifer area during the period of irrigation development from the mid-1970s to present, both spatially and temporally.

To evaluate climate and use scenarios, climate datasets for 1905 through 2005 were developed for Oakes, Britton, Forman, Fullerton, and Lisbon. The following section discusses the results of scenarios comparing water levels assuming: no irrigation, permitted irrigation, permitted plus pending irrigation, and permitted plus some pending plus DSID.

Recharge, ET_{gw}, and Irrigation Water Use

The use of the soil moisture budget model VB2000 to calculate recharge and evapotranspiration from groundwater (ET_{gw}) is described in greater detail in the second part of this report, “Analysis and Simulation of the Oakes Aquifer: Model Development and Documentation.” The VB2000 model is run separately from the MODFLOW model. Output from the VB2000 model is used to generate input for the MODFLOW model. Input to VB2000 is daily climate data consisting of precipitation, maximum and minimum temperatures, and soil hydraulic properties data. Hecla soil was considered representative of the area overlying the Oakes aquifer. The soil was divided into six layers with unique hydraulic properties assigned to each layer. The year was divided into seven periods to approximate seasonal root growth, water uptake of the crop, and distribution of ET in the layers. The crop type was assumed to be corn. Some adjustments were made to soil water holding capacity to obtain a better match to water levels during the calibration process. The climate data presented in this section may not match the updated data in the previous climate stations as different stations and/or ordering may have been used to infill missing data. The following discusses the Oakes dataset. The other climate datasets showing estimated recharge, ET_{gw}, and irrigation water use are presented in Appendix E.

The available climate data for Oakes begins in 1929. Data prior to this date is largely from Fullerton. With the VB2000 model, PET can either be calculated using the Baier-Robertson method or PET can be used as an input. For all of the simulations, PET is input to the VB2000 model and is calculated using the Penman-Monteith method from maximum and minimum daily temperatures as discussed previously. The precipitation and PET data used as input to the VB2000 model for the Oakes climate data set are shown in figures 72 and 73 respectively. Actual evapotranspiration (AET) is calculated by the VB2000 model (fig. 74). Comparing PET (fig. 73) with AET (fig. 74) shows an inverse relationship. This results because when PET is high (low), the soil moisture water content is low (high) so there is less (more) available water to evaporate. In a very humid climate, PET will equal AET, as available energy is the limiting factor in evaporation and not available water.

PET from groundwater (ET_{gw}) (fig. 75) is not determined by the VB2000 model. It is calculated by the following relationship: ET_{gw} = PET - precipitation + recharge. The precipitation that does not run off or is groundwater recharge must be subtracted from the PET as this water is evaporated from the unsaturated zone and not from the water table. When the water table is at land surface, ET_{gw} = PET - precipitation, therefore the recharge added to the groundwater must be added to ET_{gw} for the water budget to balance. Recharge is the water that flows through the bottom of the soil zone in the VB2000 model (fig. 76). Irrigation water use (fig. 77) is calculated from VB2000 output data using PET, AET, and soil water content.

Though the VB2000 uses a daily time step, the recharge, PET_{gw}, and irrigation water use are summed to provide monthly totals. The Oakes model uses 12 monthly stress periods per year of simulation.

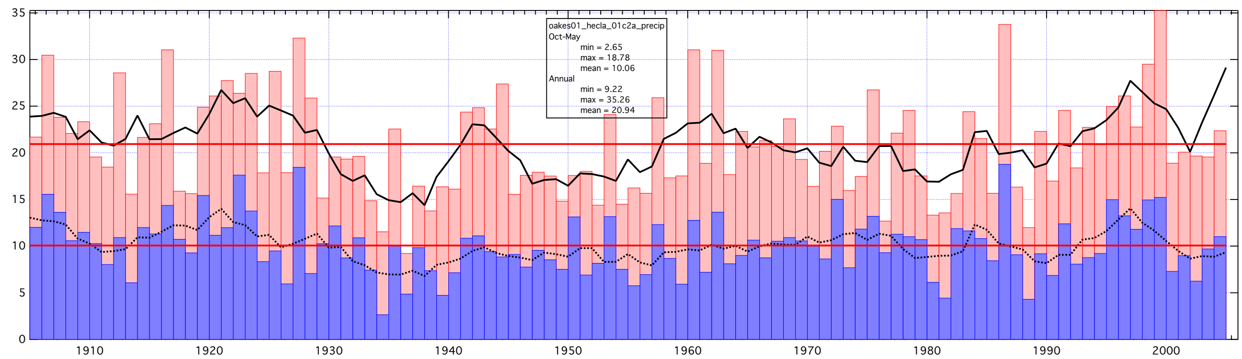


Figure 72. Annual water year and winter precipitation (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. The solid and dashed lines show the five year moving average respectively.

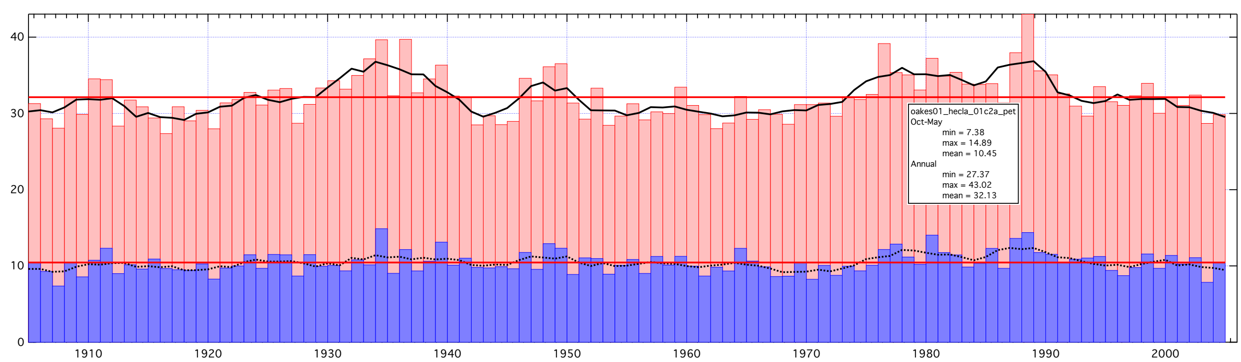


Figure 73. Annual water year and winter PET (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. The solid and dashed lines show the five year moving average respectively.

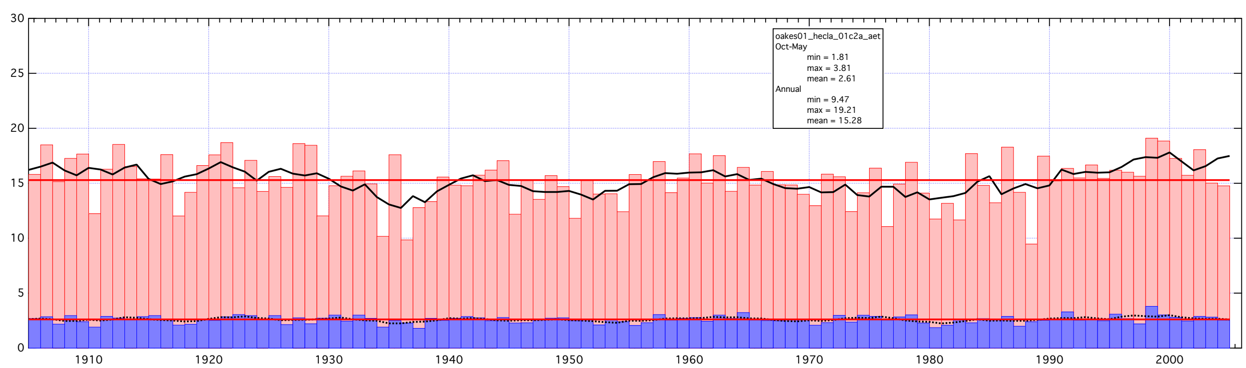


Figure 74. Annual water year and winter actual evapotranspiration (AET) (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. The solid and dashed lines show the five year moving average respectively.

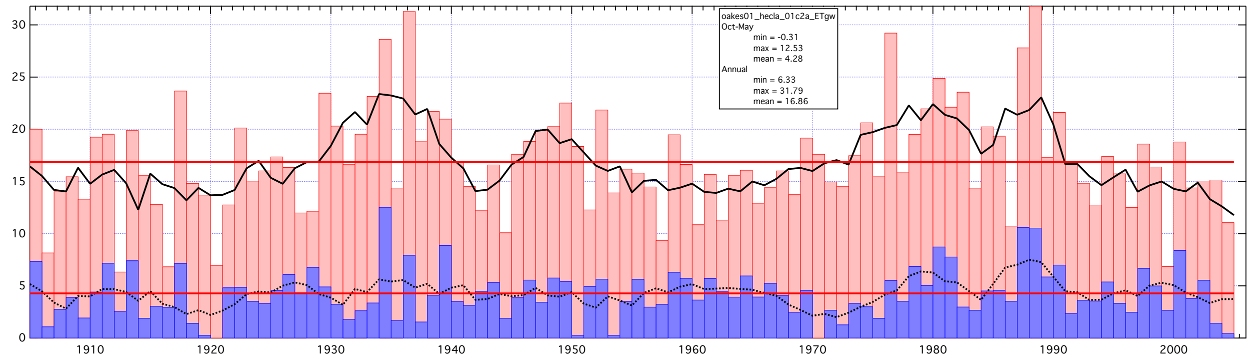


Figure 75. Annual water year and winter ET from groundwater (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. This is PET - precipitation + recharge. The solid and dashed lines show the five year moving average respectively.

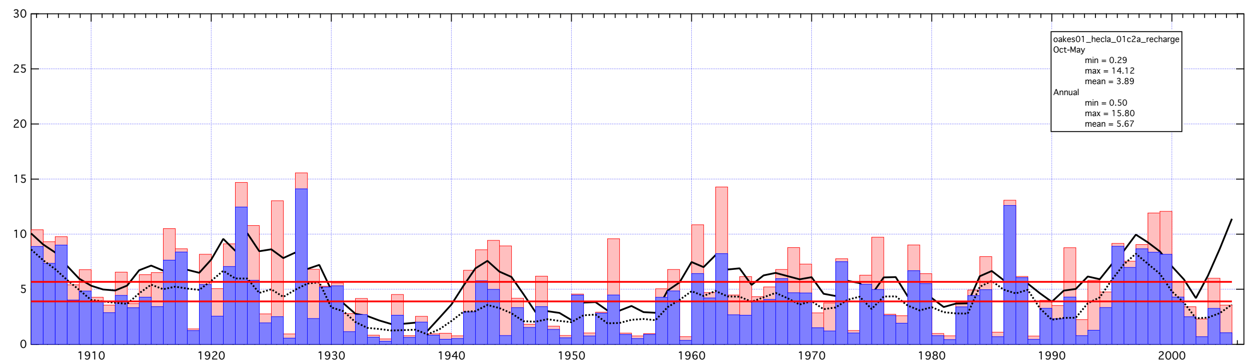


Figure 76. Annual water year and winter Recharge (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. The solid and dashed lines show the five year moving average respectively.

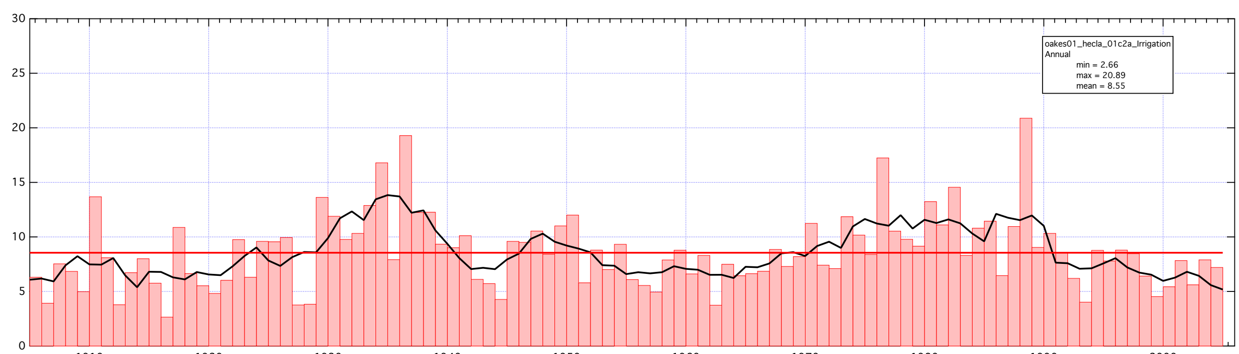


Figure 77. Annual irrigation (inches) 1905 through 2004 from VB2000 dataset oakes01_hecla_01c2a. The solid line shows the five year moving average.

Simulations

To evaluate the sustainability of the existing permitted irrigation and permitted plus pending irrigation, simulations of OTA drains, no wells; permitted irrigation; and permitted plus pending irrigation were run using the 1905 through 2005 climate datasets for Oakes, Britton, Forman, Fullerton, and Lisbon. Only the Oakes case is discussed here. A more detailed discussion including all five datasets is included in Appendix F. The model runs used in the development of this report are listed in table 7.

Table 7. Listing of model runs used in this report.

RUN	Years	Simulation	Acres (Interim Wellfield)	Acres (DSID)	WETDRY	Climate Set	Well pkg.	Total Acres	RUNS Directory	Drain pkg.
F10-SS	STEADY-STATE	initial STEADY_STATE using grid_tran04			HUF2	rech = 5.5"/yr, et rate = 20"/yr	-			-
F10-SS2	STEADY-STATE	F10-ss with top layer set confined			HUF2	rech = 5.5"/yr, et rate = 20"/yr	-			-
F11	STEADY-STATE	uses STRT001_tran04_F10-SS.mf			HUF2	rech = 5.5"/yr, et rate = 20"/yr	-			-
F12	STEADY-STATE	uses STRT001_tran04_F10-SS.mf			HUF2	rech = 5.5"/yr, et rate = 20"/yr	-			-
F13	1951-2007	tmstp=4			F	oakes01_hecla_01c2-50-07.monthly	-			drainsRev2GRD400-0200setInstallDates51-07.sfr
F13b	1951-2007	tmpstp=30			F	oakes01_hecla_01c2-50-07.monthly	-			drainsRev2GRD400-0200setInstallDates51-07.sfr
		lay 1: confined/unconfined								
F15	1951-2007	tmstp=4, lay 1 set to LAYCON=3 instead of 1, spikes if WL > TOP			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted2.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F15a	1951-2007	test diff permitted2.mnw & permitted.mnw			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F15b	1951-2007	tmstp=30			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted2.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F15c	1951-2007	tmstp=15			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted2_c.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F15d	1951-2007	segmentation fault			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted2_d.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
							2.MNW, 2_c.MNW & 2_d.MNW are the same, ed.MNW is bad format			
	TEST TSTP and PCGN									
F17	1951-2007	15stp			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted+sprt2.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F17b	1951-2007	30stp			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted+sprt2b.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F17c	1951-2007	15stp, run failed?			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted+sprt2c.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
F17d	1951-2007	15stp			F	oakes01_hecla_01c2-50-07.monthly	WELL001_tran03_oakes01c2permitted+sprt2d.MNW			drainsRev2GRD400-0200setInstallDates51-07.sfr
						ranges from 01/01/1951 - 12/01/2007	well pkgs. are identical			
F20	1960-2007	drains, no wells			F	oakes01_hecla_01c2.monthly	-			drainsRev2GRD400-0200setInstallDates60-07.sfr
F20b	1960-2007	no drains, no wells			F	oakes01_hecla_01c2.monthly	-			-
F20d	1960-2007	changed PCGN, same as F20b			F	oakes01_hecla_01c2.monthly	-			-
F21	1960-2007	wrong drain pkg.			F		WELL001_tran03_tst02.MNW			tran03_F21.sfr
F21x	1960-2007	using corrected drain pkg.			F	oakes01_hecla_01c2.monthly	WELL001_tran03_tst02.MNW			drainsRev2GRD400-0200setInstallDates60-07.sfr
F22	1960-2007				F	oakes01_hecla_01c2.monthly	WELL001_tran03_oakes04climate.MNW			drainsRev2GRD400-0200setInstallDates60-07.sfr
F23	1960-2007	same as F21x			F	oakes01_hecla_01c2.monthly	WELL001_tran03_oakes04.MNW (reported use)			tran03_F23.sfr (same as above)
F24	1960-2007	Haak-Locken r=21'			F	oakes01_hecla_01c2.monthly	WELL001_tran03_oakes04grpAdj.MNW			drainsRev2GRD400-0200setInstallDates60-07.sfr
F25	1960-2007				F	oakes01_hecla_01c2.monthly	WELL001_tran03_60-07reportedNoSpWd.MNW			drainsRev2GRD400-0200setInstallDates60-07.sfr
F30	1905-2005	no drains, no wells			F	Oakes1905COMP_03.daily.vb2k			GRID122L07tranb03	
F31	1905-2005	drains, no wells			F	Oakes1905COMP_03.daily.vb2k			GRID122L07tranb03	
F32	1905-2005	drains, wells (permitted)	1668		F	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005approved.MNW		GRID122L07tranb03	
F33	1905-2005	drains, all pending prior to DSID	1668		F	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005allPending.MNW		GRID122L07tranb03	
F35	1905-2005	drains, approved, no Spiritwood	1668		F	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005approvedNoSpWd.MNW		GRID122L07tranb03	
F36	1905-2005	drains, all pending, no Spiritwood	1668		F	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005allPendingNoSpWd.MNW		GRID122L07tranb03	
F38	1905-2005	drains, all pending prior to DSID	1668		T, 1.0 m.	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005allPending.MNW		GRID122L07tranb03	
F38b	1905-2005	drains, all pending prior to DSID	1668		T, 0.5 m.	Oakes1905COMP_03.daily.vb2k	WELL001_tran03_oakes04-1905-2005allPending.MNW		modflowFORMAN	
F50	1905-2005	no drains, no wells			F	forman01_hecla_01c2a-0505.monthly			modflowFORMAN	
F51	1905-2005	drains, no wells			F	forman01_hecla_01c2a-0505.monthly			modflowFORMAN	
F52	1905-2005	drains, wells (permitted)	1668		F	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2permitted.MNW		modflowFORMAN	
F53	1905-2005	drains, all pending prior to DSID	1668		F	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2pending.MNW		modflowFORMAN	
F53B	1905-2005				T, 0.5 m.	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2pending.MNW		modflowFORMAN	
F61	1905-2005	drains, no wells			T, 0.5 m.	britton_hecla_01c2a.monthly			modflowFORMAN	
F62	1905-2005	drains, wells (permitted)	1668		T, 0.5 m.	britton_hecla_01c2a.monthly	WELL001_tran03_brittion01c2permitted.MNW		modflowFORMAN	
F63	1905-2005	drains, all pending prior to DSID	1668		T, 0.5 m.	britton_hecla_01c2a.monthly	WELL001_tran03_brittion01c2pending.MNW		modflowFORMAN	
F71	1905-2005	drains, no wells			T, 0.5 m.	lisbon01_hecla_01c2a.monthly			modflowFORMAN	
F72	1905-2005	drains, wells (permitted)	1668		T, 0.5 m.	lisbon01_hecla_01c2a.monthly	WELL001_tran03_lisbon01c2permitted.MNW		modflowFORMAN	
F73	1905-2005	drains, all pending prior to DSID	1668		T, 0.5 m.	lisbon01_hecla_01c2a.monthly	WELL001_tran03_lisbon01c2pending.MNW		GRID122L07tranb03	
F81	1905-2005	drains, no wells			T, 0.5 m.	fullerton01_hecla_01c2a.monthly			modflowFORMAN	
F82	1905-2005	drains, wells (permitted)	1668		T, 0.5 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fuller01c2permitted.MNW		modflowFORMAN	
F83	1905-2005	drains, all pending prior to DSID	1668		T, 0.5 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fuller01c2pending.MNW		modflowFORMAN	
G30	1905-2005	drains, wells (superPOD4)	1200	0	T, 1.0 m.	oakes01_hecla_01c2a-0505.monthly	WELL001_tran03_oakes01c2DS_noAgree.MNW		GRID122L07tranb03_b	
G31	1905-2005	drains, wells (superPOD6)	1200	3050	T, 1.0 m.	oakes01_hecla_01c2a-0505.monthly	WELL001_tran03_oakes01c2DS_3050ac.MNW		GRID122L07tranb03_b	
G32	1905-2005	drains, wells (superPOD5)	1200	3800	T, 1.0 m.	oakes01_hecla_01c2a-0505.monthly	WELL001_tran03_oakes01c2DS_3800ac.MNW		GRID122L07tranb03_b	
G33	1905-2005	drains, wells (superPOD7)	1200	2300	T, 1.0 m.	oakes01_hecla_01c2a-0505.monthly	WELL001_tran03_oakes01c2DS_2300ac.MNW		GRID122L07tranb03_b	
G50	1905-2005	drains, wells (superPOD4)	1200	0	T, 1.0 m.	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2DS_noAgree.MNW		GRID122L07tranb03_b	
G51	1905-2005	drains, wells (superPOD6)	1200	3050	T, 1.0 m.	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2DS_3050ac.MNW		GRID122L07tranb03_b	
G52	1905-2005	drains, wells (superPOD5)	1200	3800	T, 1.0 m.	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2DS_3800ac.MNW		GRID122L07tranb03_b	
G53	1905-2005	not run	1200	2300	T, 1.0 m.	forman01_hecla_01c2a-0505.monthly				

RUN	Years	Simulation	Acres (Interim Wellfield)	Acres (DSID)	WETDRY	Climate Set	Well pkg.	Total Acres	RUNS Directory	Drain pkg.
G80	1905-2005	drains, wells (superPOD4)	1200	0	T, 1.0 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fullerton01c2DS_noAgree.MNW		GRID122L07tranb03_b	
G81	1905-2005	drains, wells (superPOD6)	1200	3050	T, 1.0 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fullerton01c2DS_3050ac.MNW		GRID122L07tranb03_b	
G82	1905-2005	drains, wells (superPOD5)	1200	3800	T, 1.0 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fullerton01c2DS_3800ac.MNW		GRID122L07tranb03_b	
G83	1905-2005	not run								
H31	1905-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	T, 1.0 m.	oakes01_hecla_01c2a-0505.monthly	WELL001_tran03_oakes01c2DS_esser01.MNW		GRID122L07tranb03	
H51	1905-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	T, 1.0 m.	forman01_hecla_01c2a-0505.monthly	WELL001_tran03_forman01c2DS_esser01.MNW		GRID122L07tranb03	
H81	1905-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	T, 1.0 m.	fullerton01_hecla_01c2a.monthly	WELL001_tran03_fulerton01c2DS_esser01.MNW	15853.76	GRID122L07tranb03	
J31	1945-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	F	oakes01_hecla_01c2a-4505.monthly	WELL001_tran03_oakes01c2DS_esser01-4505.MNW	15853.76	GRID122L07tranb03	
J51	1945-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	F	forman01_hecla_01c2a-4505.monthly	WELL001_tran03_forman01c2DS_esser01-4505.MNW	15853.76	GRID122L07tranb03	
J81	1945-2005	drains, wells (superPOD6)	-0.25 * ESSER	ESSER	F	fullerton01_hecla_01c2a-4505.monthly	WELL001_tran03_fullerton01c2DS_esser01-4505.MNW	15853.76	GRID122L07tranb03	

Though the transient calibration simulations of the drains within the OTA significantly underestimated drain discharge, the drains do have a large impact on water levels and ET within and near the OTA. Simulations were made for the period 1905 through 2005 using the Oakes climate dataset without drains (run F30) and with the pilot and OTA drains (run F31). Neither simulation included any irrigation. Comparisons of water levels and areas of ET for May 31, 1978, August 31, 1978, August 31, 1988, and August 31, 2000 are shown in figures 78, 79, 80, and 81 respectively. At all of the times shown, the drains reduce the amount of ET occurring within and near the OTA and reduce the water levels. On May 31, 1978 (fig. 78), water levels are reduced between 1 and 3 feet by the OTA drains.

In all of these figures, the poor water quality area located in sections 1 and 12, T. 130 N., R. 59 W. (fig. 53) is a distinct closed basin. However, in the cases where the drains are present, the groundwater divide that maintains the closed basin is shifted to the east very close to the poor water quality area. With the flow barrier weakened by the OTA drains, little additional stress, such as irrigation pumping to the west of the groundwater divide, would cause its disappearance resulting in the migration of the poor quality water to the west.

Though water flows from east to west across the Oakes aquifer, most of the water that reaches the water table as groundwater recharge is discharged as ET within a few thousand feet of where it entered the aquifer. The water table gradient is very flat, less than 2 feet per mile, across most of the Oakes aquifer. With a recharge rate of 5.5 inches per year, recharge occurring in one section will total 293 ac-ft per year of water. If the gradient out of this section is 1 foot per mile, then only 50 acre-feet per year of water flows out of this section. The remainder is discharged as ET. With ET determining the depth of the water table below land surface, the water table gradient is largely controlled by the slope of the land surface. In the set of simulations with no irrigation, ET is occurring across most of the Oakes aquifer even in late summer as seen in figures 78 through 81. Irrigation development is capturing water that was naturally lost to evapotranspiration by lowering the water table so that ET is reduced by the amount pumped. Once most of this natural discharge by ET is captured, additional pumping will result in long term water level decline.

b)

a)

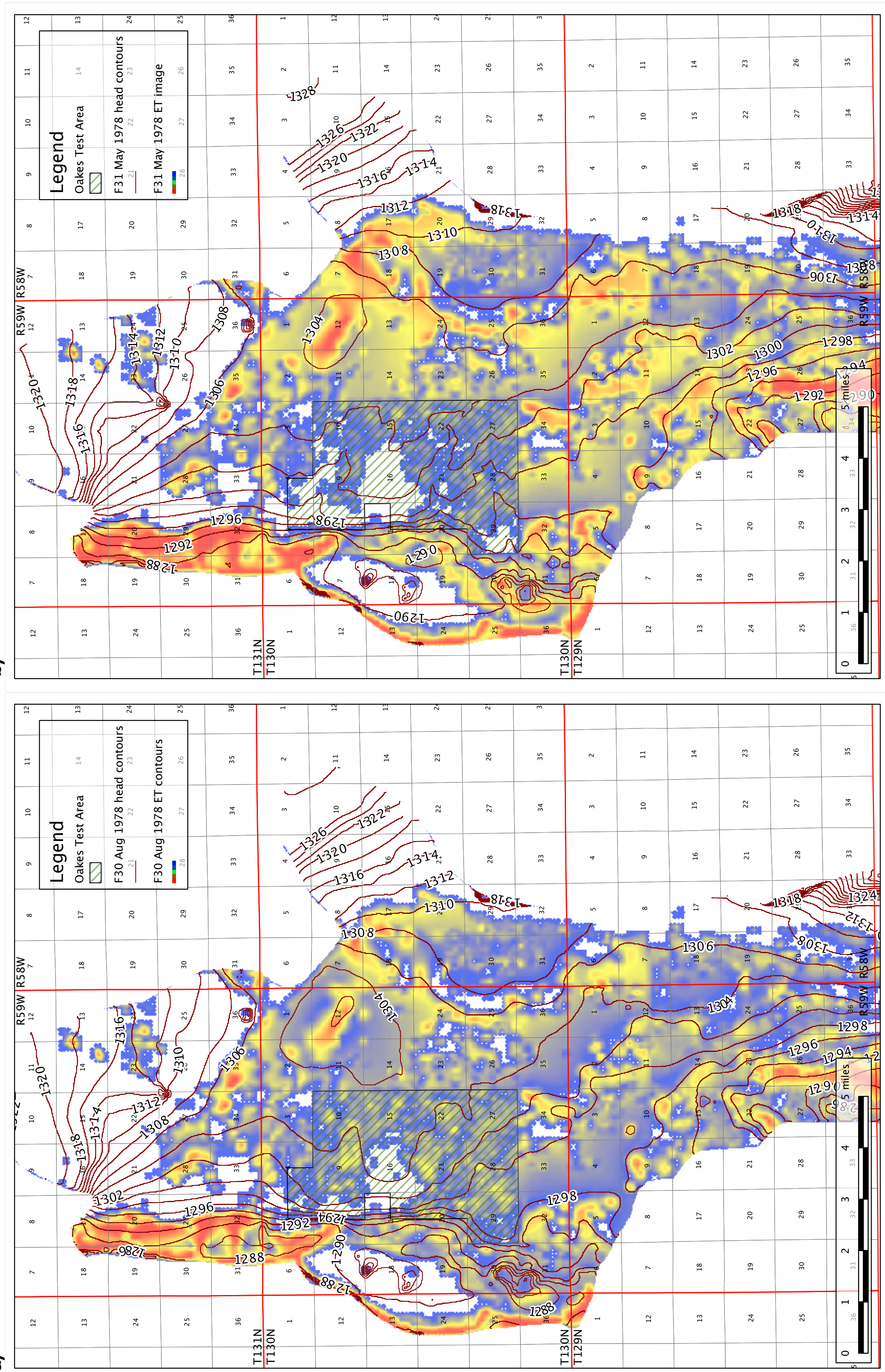


Figure 78. Impact of drains on water levels. Comparison of water levels and areas of ET between a) no irrigation and no drains and b) drains and no irrigation for **May 31, 1978** of 1905 to 2005 simulation.

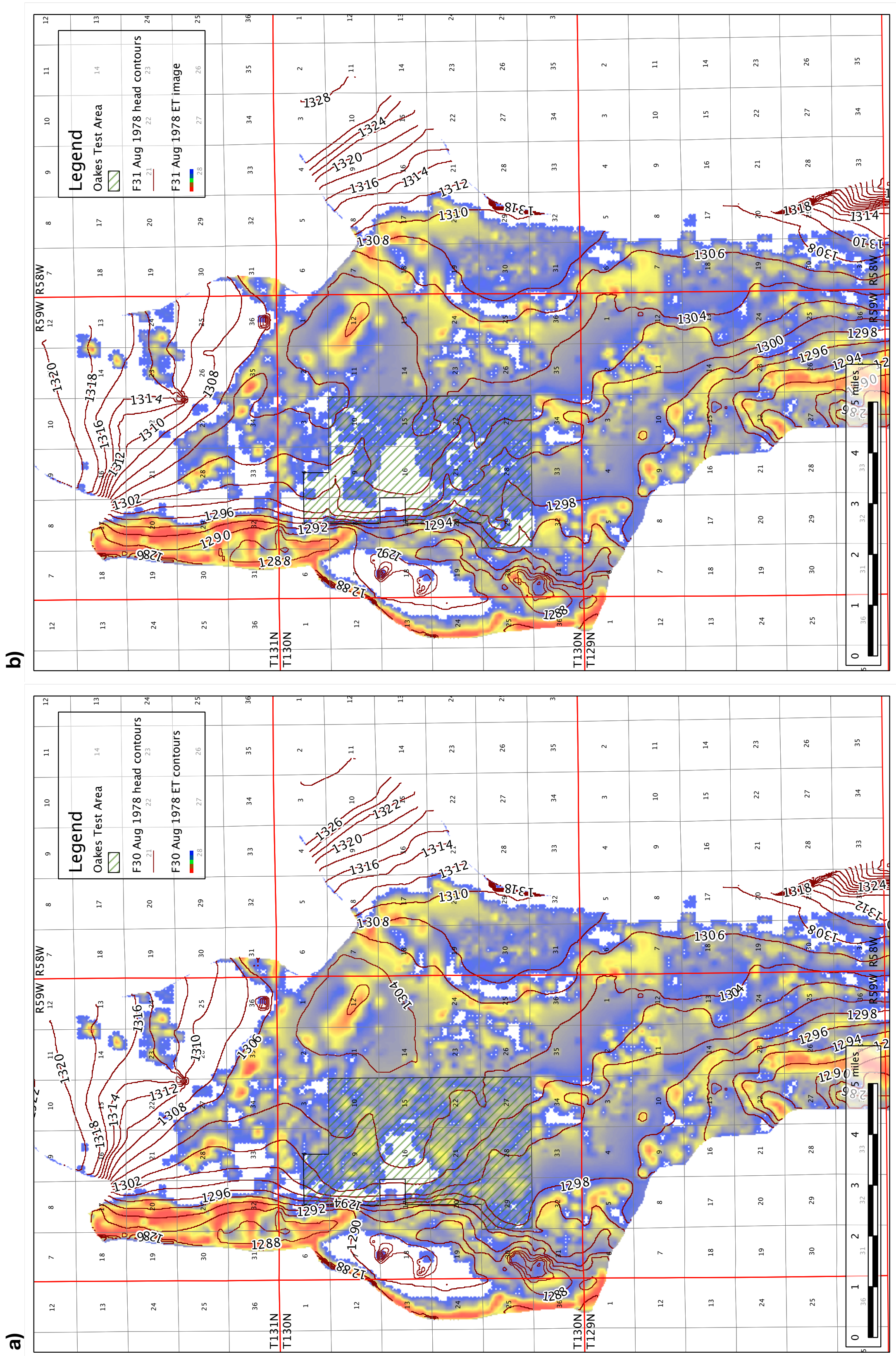


Figure 79. Impact of drains on water levels. Comparison of water levels and areas of ET between a) no irrigation and no drains and b) drains and no irrigation for **Aug. 31, 1978** of 1905 to 2005 simulation.

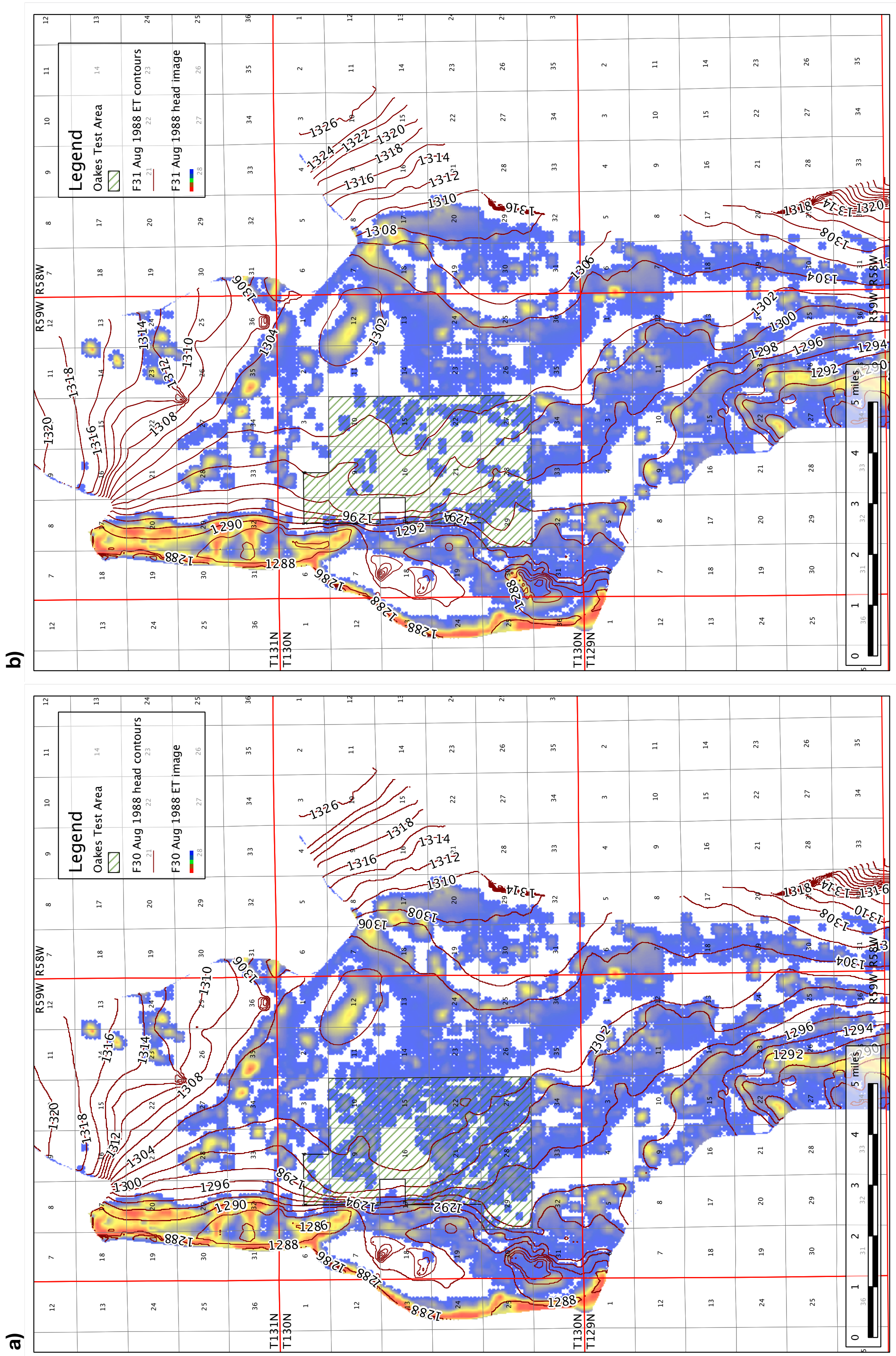


Figure 80. Impact of drains on water levels. Comparison of water levels and areas of ET between a) no irrigation and no drains and b) drains and no irrigation for **Aug. 31, 1988** of 1905 to 2005 simulation.

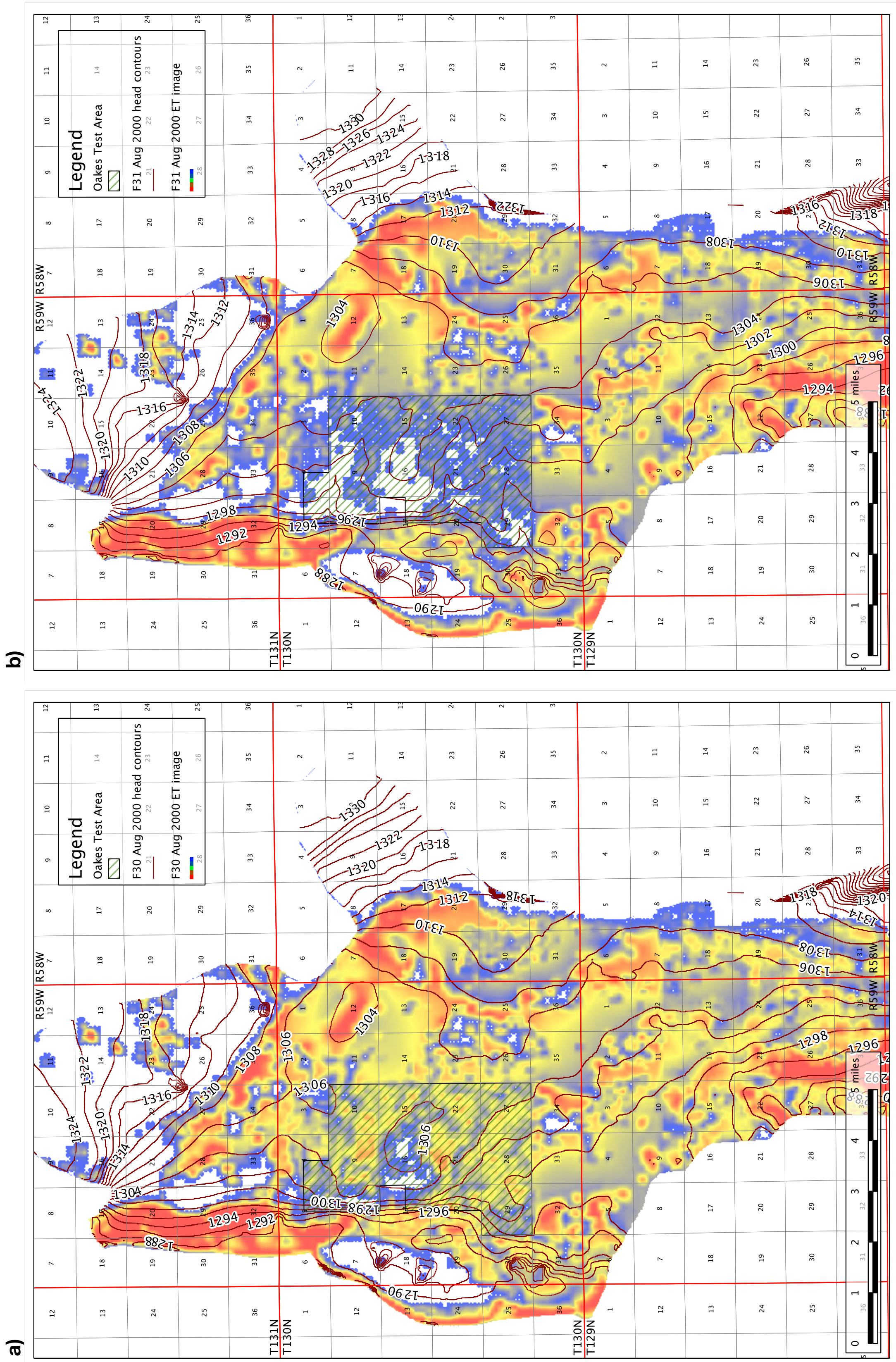


Figure 81. Impact of drains on water levels. Comparison of water levels and areas of ET between a) no irrigation and no drains and b) drains and no irrigation for **Aug. 31, 2000** of 1905 to 2005 simulation.

For simulations of permitted and permitted plus pending irrigation, it is assumed that 1,669 acres of permitted irrigation within the OTA are supplied with water from USBR interim well field (table 8). The permits in this table are from Lindvig (2006) and permits that have generally been supplied by DSID. Permits labeled OTA in table 8, which total 675.8 acres, have inadequate water supplies and have been supplied by DSID. These are in an area of very thin saturated thickness along the west side of the OTA. Those labeled OTAx total 326 acres and have also been supplied by DSID and are considered to have inadequate water supplies. Lindvig (2006) recommended that an additional 667.0 acres of land (OTArpl in table 8) be served by DSID. The OTArpl permits have largely been served by groundwater. However, these permits are in areas of thin saturated thickness and are likely to experience significant declines in yields during periods of drought.

The interim well field in the simulations was able to produce the requested quantity of water in all cases. Many of the well fields for the 1,669 acres of permitted irrigation were not able to produce the required quantity of water in the simulations. Therefore, it was the simplest procedure to include the acres in the area supplied by the interim well field. Based on the NDSWC and USBR drilling, it was considered unlikely that the low yields of these wells were a result of underestimating the areal hydraulic properties within the OTA. Therefore, the higher yields are a result of locally higher hydraulic conductivity or saturated thickness. This type of variability is observed in the test holes drilled to locate the interim well field and in the large range of pumping rates of the interim wells. In reality, even without DSID operation of the interim well field, many of these permits would have problems obtaining adequate water.

Table 8. OTA and OTAx are water permits within the OTA that are presently supplied by the DSID. OTArpl are permits that are presently served by groundwater that Lindvig (2006) recommended that DSID supply. Permits shown in yellow were recommended in Lindvig (2006), to be served by DSID. All simulations supply these permits from the interim well field.

	Permit	Owner	POD	Status	Priority Date	Ac-Ft	Acres
OTA	2010	HAAK, NORMAN D. AND AR-LENE	13005908AA	Active	1973-12-04	168.0	112.0
OTA	1929	TITUS, ROBERT	13005917DA	Active	1974-01-17	107.7	71.8
OTA	2233	HOKANA, STANLEY	13005929CA	Active	1975-03-17	189.0	125.5
OTA	2272	VISTO, GARY J.	13005909C	Active	1975-05-30	180.0	128.0
OTA	2356	FENNO, KATHY	13005916A	Active	1975-12-31	196.0	130.5
OTArpl	2356	FENNO, KATHY	13005916B	Active	1975-12-31	127.5	85.0
OTArpl	2356	FENNO, KATHY	13005916CD	Active	1975-12-31	99.0	66.0
OTArpl	2356	FENNO, KATHY	13005916D	Active	1975-12-31	196.0	130.6
OTAx	02460A	KBO FARM PARTNERSHIP	13005928CA	Active	1976-06-01	99.0	66.0
OTArpl	2460	VISTO, GARY J.	13005929A	Active	1976-06-01	225.0	150.0
OTAx	2859	HANSON, ROBERT	13005927D	Active	1977-05-11	195.0	130.0
OTAx	2939A	HANSON, LOVILA	13005927D	Active	1977-06-02	195.0	130.0
OTArpl	3013	LOCKEN, DAVID	13005909A	Active	1977-12-19	196.5	131.0
OTArpl	3013	LOCKEN, DAVID	13005909B	Active	1977-12-19	192.5	128.0
OTA	3160	HAAK, NORMAN D. AND AR-LENE	13005908A	Active	1979-02-16	162.5	108.0

Figures 82 through 89 compare water level elevations and areas of ET from groundwater for the case of no drains and no irrigation (run F30), drains and permitted irrigation (run F32) and drains and permitted plus pending irrigation (run F38b) for May 31, 1940; August 31, 1940; May 31, 1978; August 31 1978; August 31 1988; May 31, 1989; May 31, 2000; and August 31, 2000 respectively. During periods of drought (fig 81, 82, and 83), both the permitted and permitted plus pending cases eliminate almost all ET from the aquifer. In the other cases, the permitted irrigation has greatly reduced but not eliminated the amount of ET occurring from the aquifer. The permitted plus pending case leaves little ET occurring from the aquifer, except during the recent wet period. In both the permitted and permitted plus pending simulations, in all but the recent pluvial, the groundwater divide between the poor quality water area and the irrigation to the west is eliminated and the poor quality water moves to the west.

Figures 90 through 97 compare drawdown for drains and permitted irrigation (run F32) and drains and permitted plus pending irrigation (run F38b) for May 31, 1940; August 31, 1940; May 31, 1978; August 31 1978; August 31 1988; May 31, 1989; May 31, 2000; and August 31, 2000 respectively. During drought years 1940 and 1988 there are large drawdowns occurring in the area north of Oakes extending south into the northwest corner of the OTA near the interim well field. The other areas with large drawdowns are along the deep channel.

The area north of Oakes includes pumping from the Spiritwood aquifer where it is hydraulically connected to the overlying Oakes aquifer. This overestimates drawdown in the area, while removing the Spiritwood aquifer wells underestimates drawdown. This may be a result of either underestimating surficial recharge to the Oakes aquifer or not accounting for flow into this reach of the Spiritwood aquifer from adjoining reaches of the Spiritwood aquifer that lie to the north. The large drawdowns observed in the simulations for the large block of irrigation to the west of Oakes where Oakes and Spiritwood aquifers are coupled in T. 131 N., R. 59 W. are of concern. Though the Oakes aquifer extends to the north and east of this irrigation, it is higher in elevation, thinner, and overlain with glacial till (North Oakes aquifer) indicating it is a poor source of water to support this irrigation. The potential for large drawdowns in this area does impact water levels in the northern part of the OTA and therefore reduces the potential for the appropriation of additional water from within the northern part of the OTA. Additional test drilling is needed in the North Oakes aquifer and the underlying Spiritwood aquifer to understand how it impacts this concentration of irrigation.

Though parts of the deep channel have in excess of 100 feet of saturation, there are many irrigation wells in T. 130 N., R. 58 W. and section 6, T. 129 N., R. 58 W. adjoining the channel that have less than 60 feet of saturation. Large drawdowns in this area would significantly impact the yields of these wells. The amount of drawdown simulated in the deep channel should not adversely impact the ability to obtain water by the permitted case, though in some cases additional wells may need to be added. The case of permitted plus pending results in significant additional drawdown in both the deep channel and areas between the deep channel and the OTA.

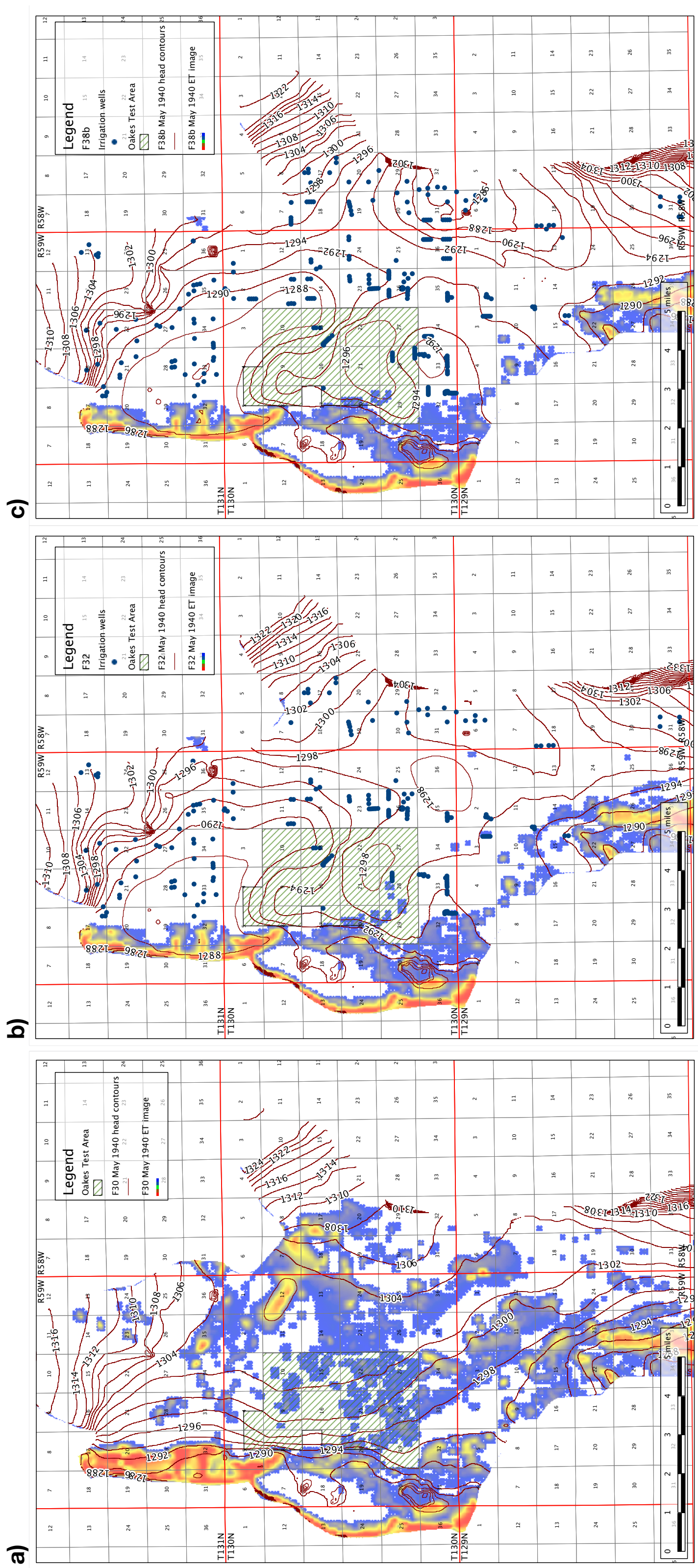


Figure 82. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **May 31, 1940** of 1905 to 2005 simulation.

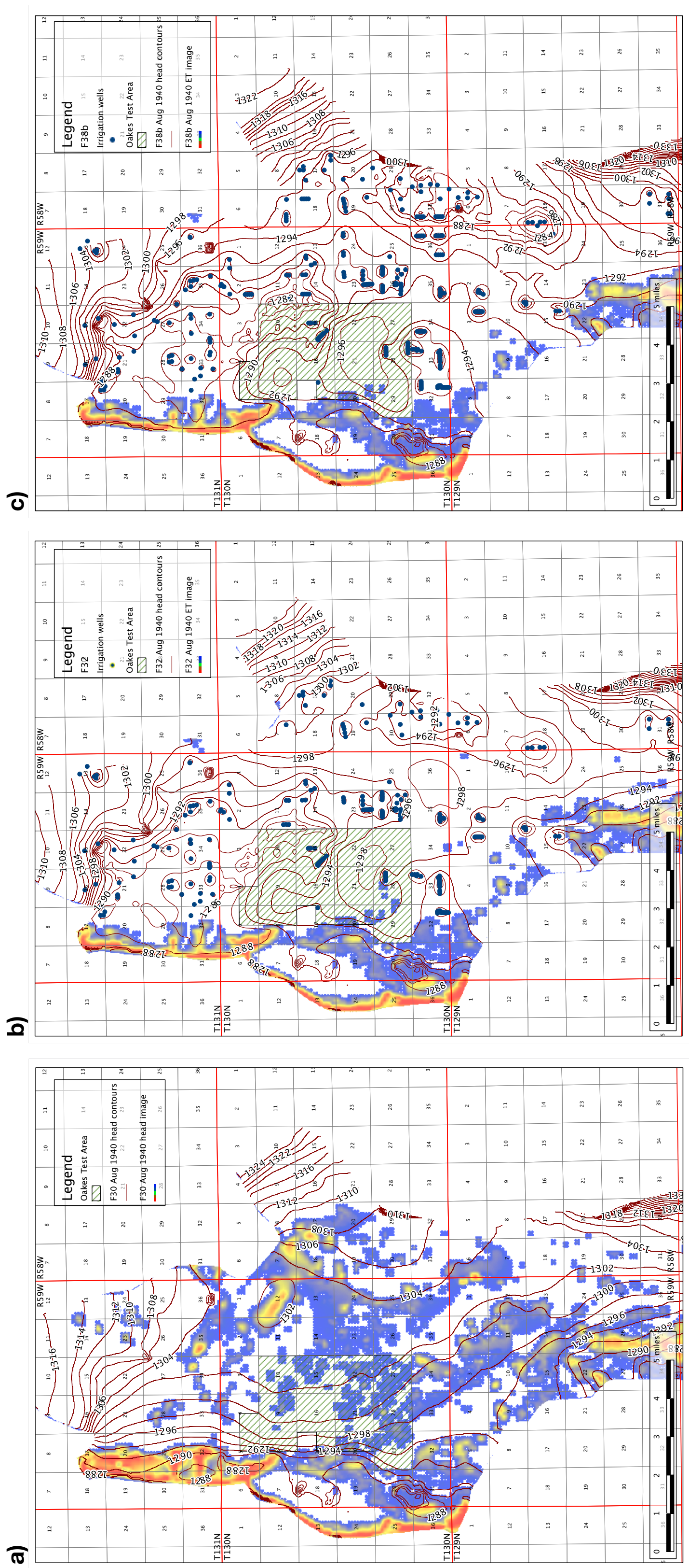


Figure 83. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **August 31, 1940** of 1905 to 2005 simulation.

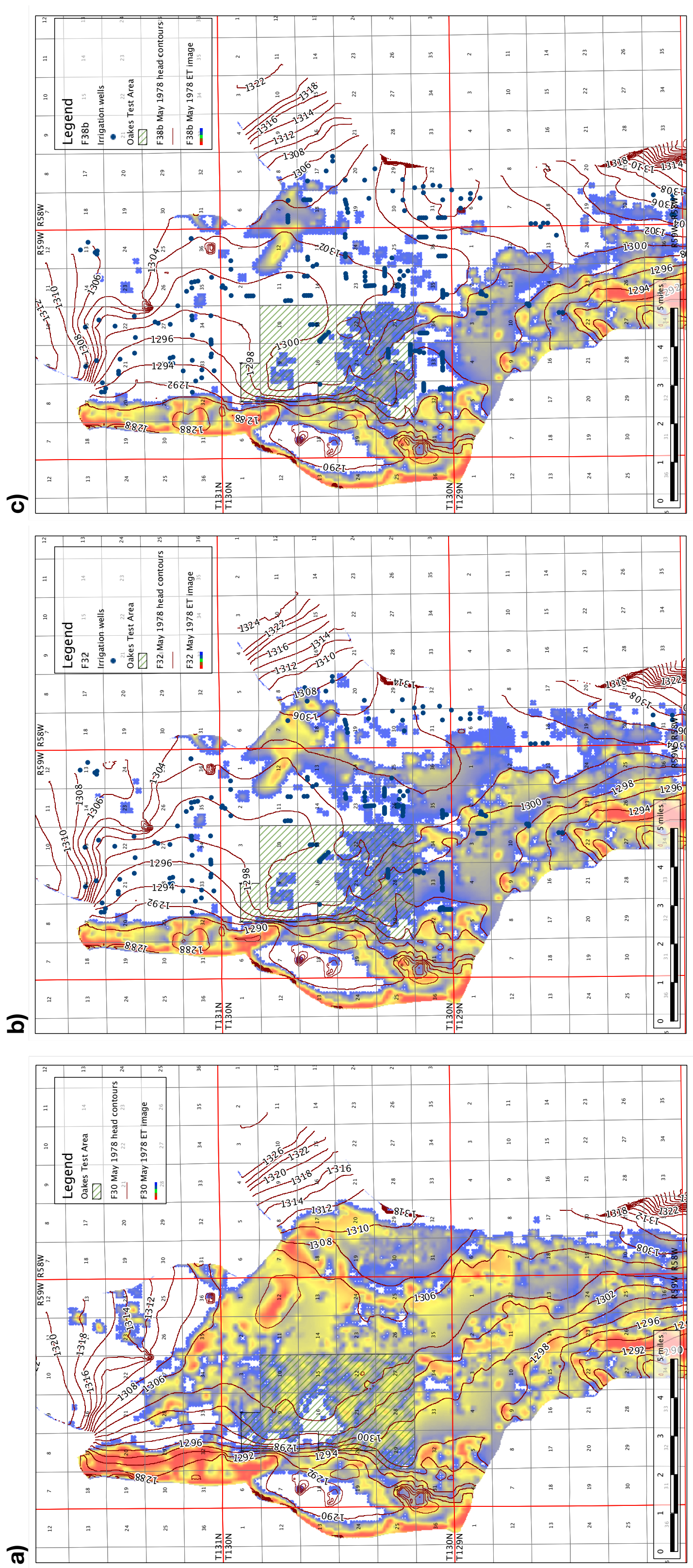


Figure 84. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **May 31, 1978** of 1905 to 2005 simulation.

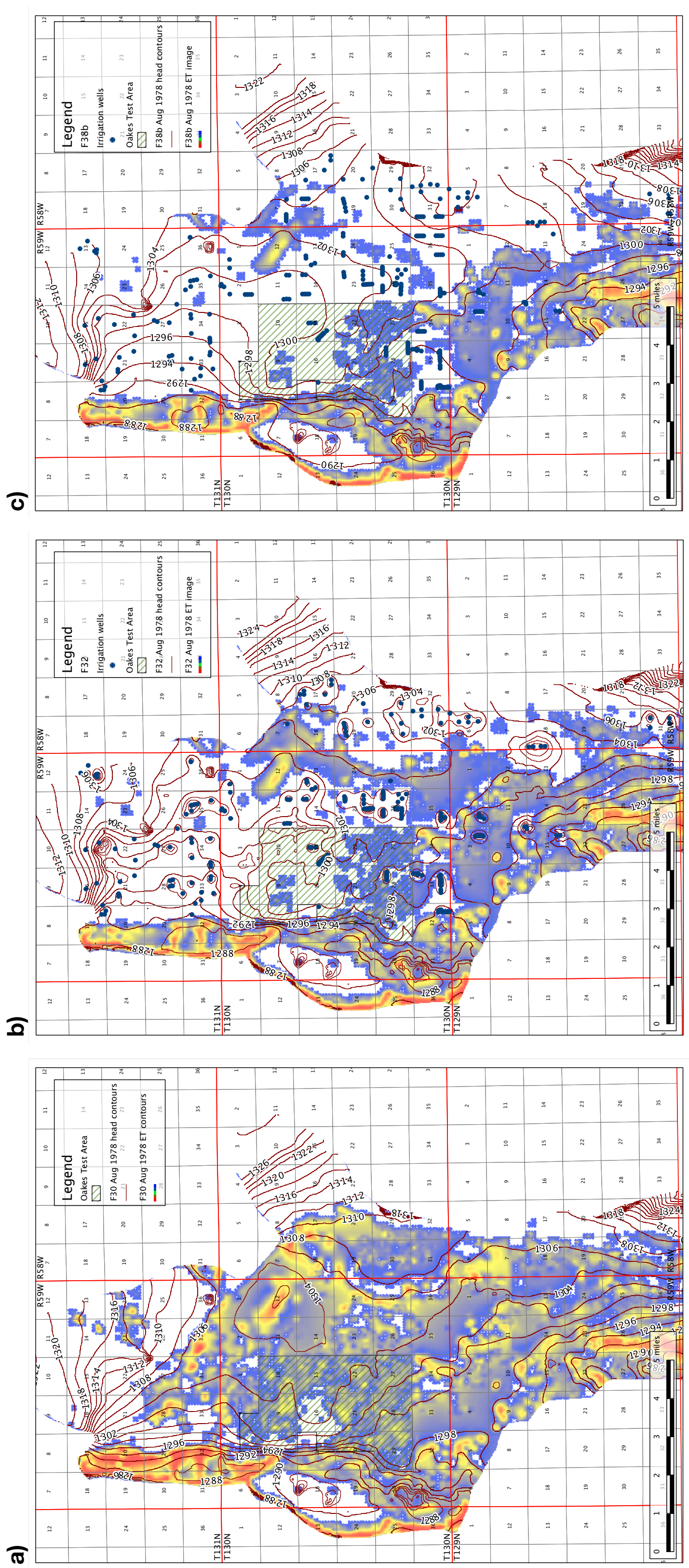


Figure 85. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **August 31, 1978** of 1905 to 2005 simulation.

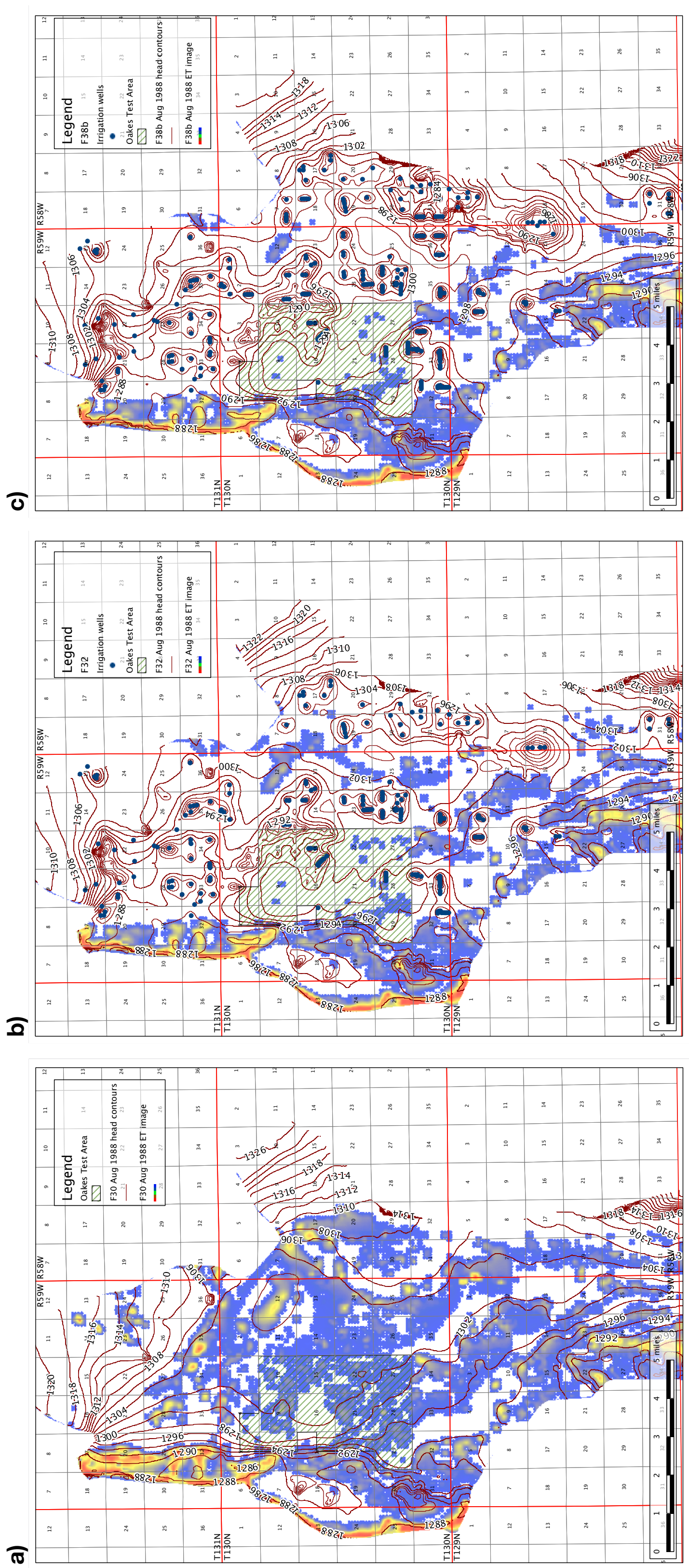


Figure 86. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **August 31, 1988** of 1905 to 2005 simulation.

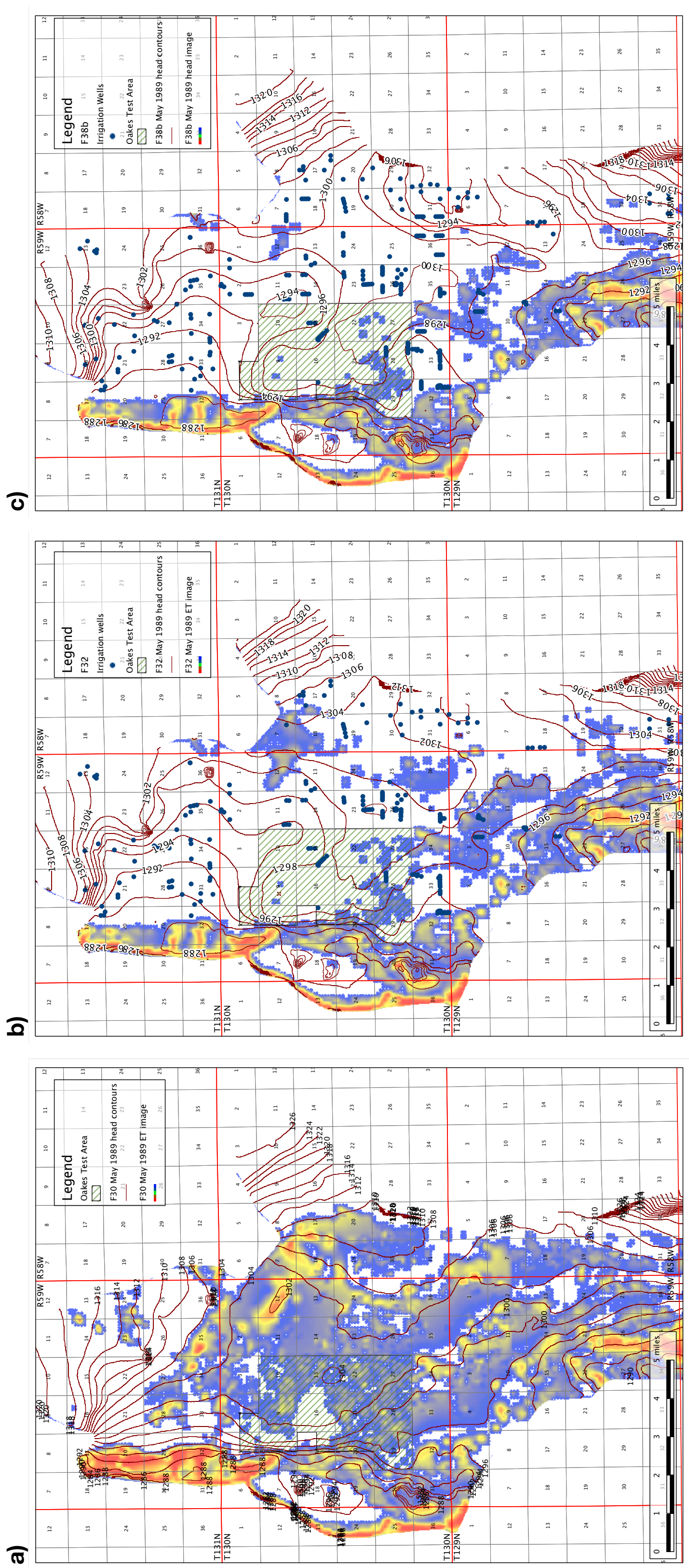


Figure 87. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **May 31, 1989** of 1905 to 2005 simulation.

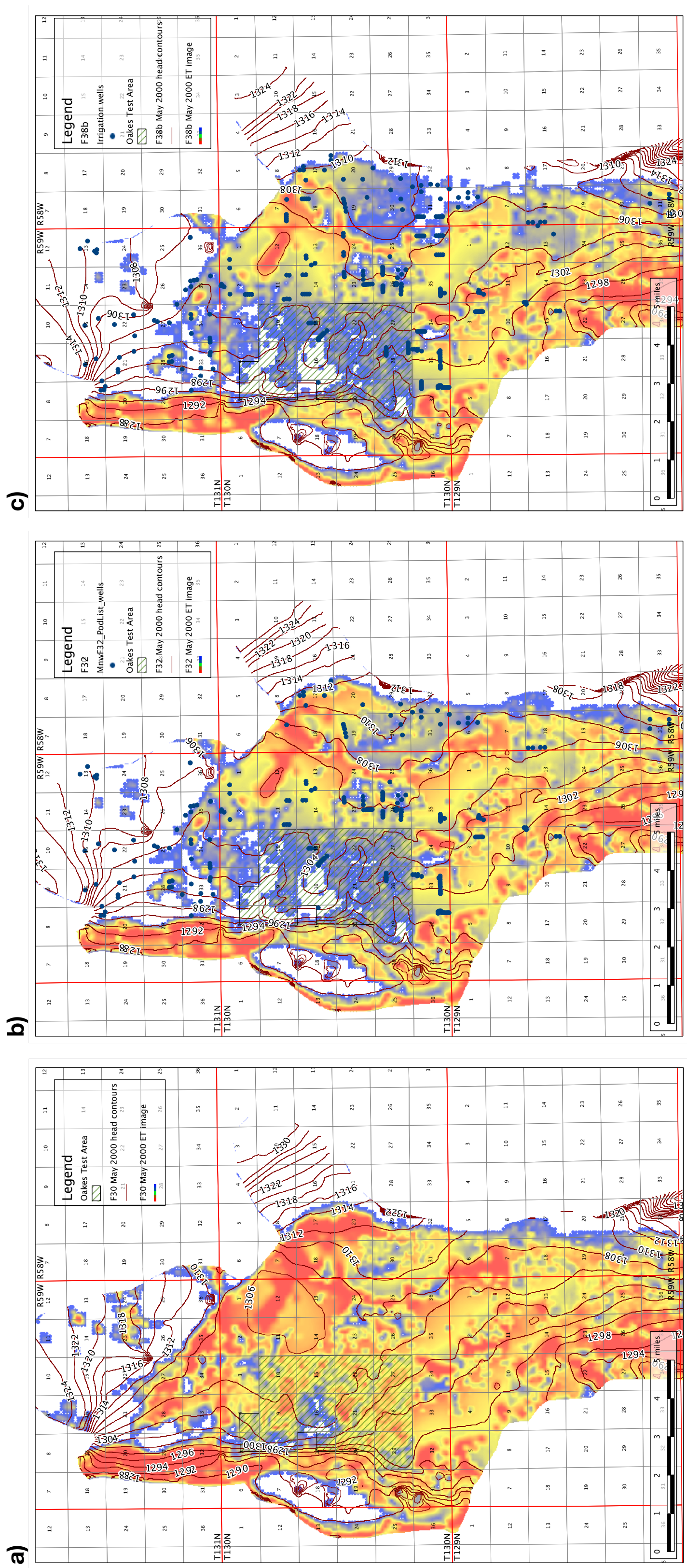


Figure 88. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **May 31, 2000** of 1905 to 2005 simulation.

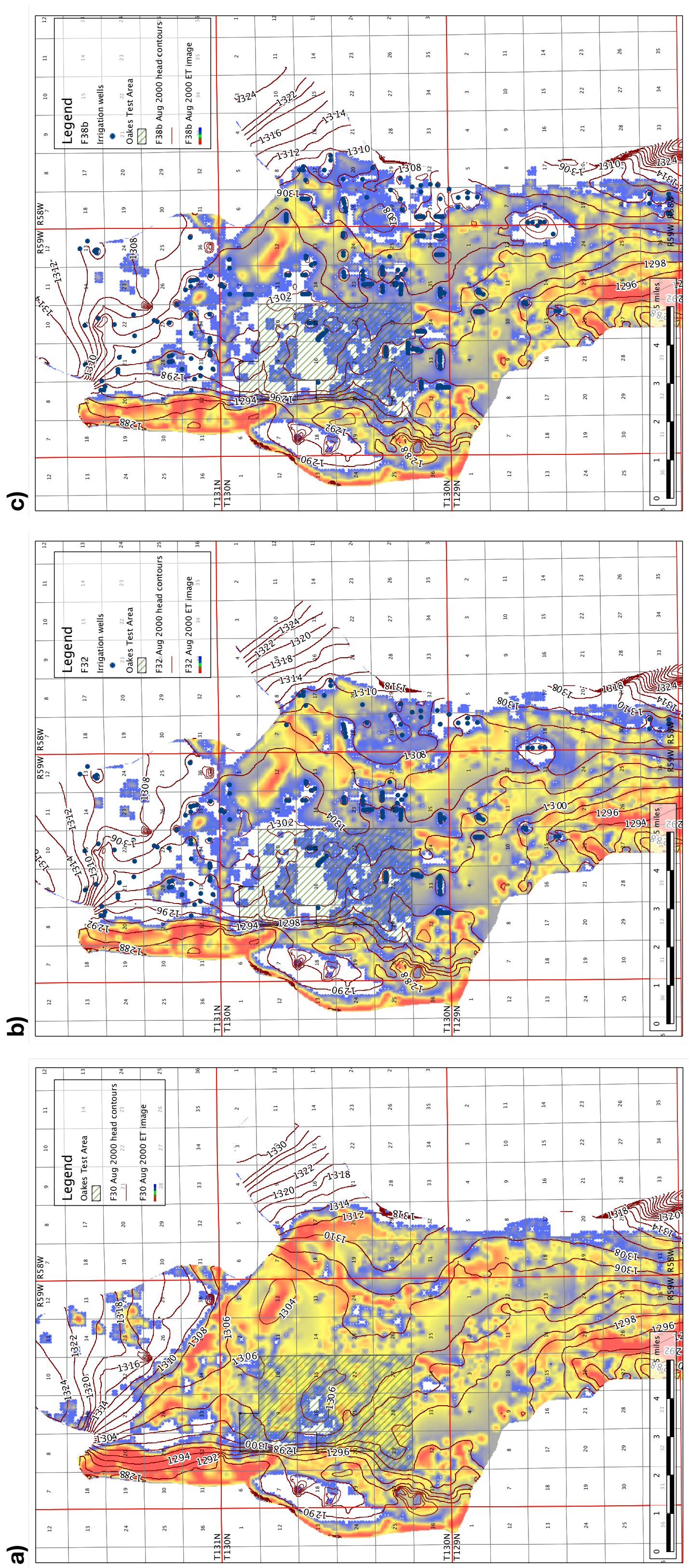


Figure 89. Comparison of water levels and areas of ET between a) no irrigation and no drains, b) drains and permitted irrigation and c) drains and permitted + pending irrigation for **August 31, 2000** of 1905 to 2005 simulation.

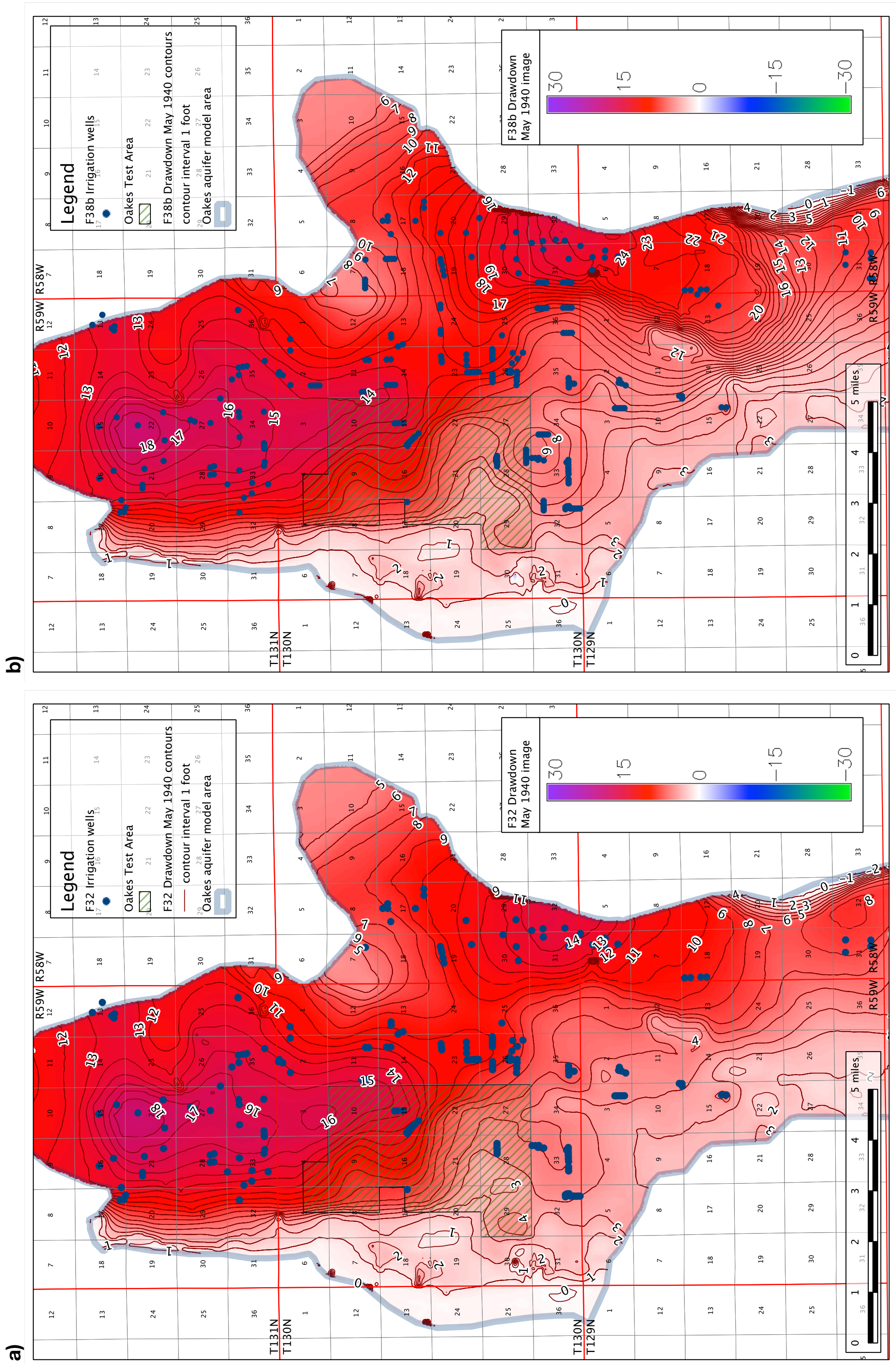


Figure 90. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **May 31, 1940** of 1905 to 2005 simulation.

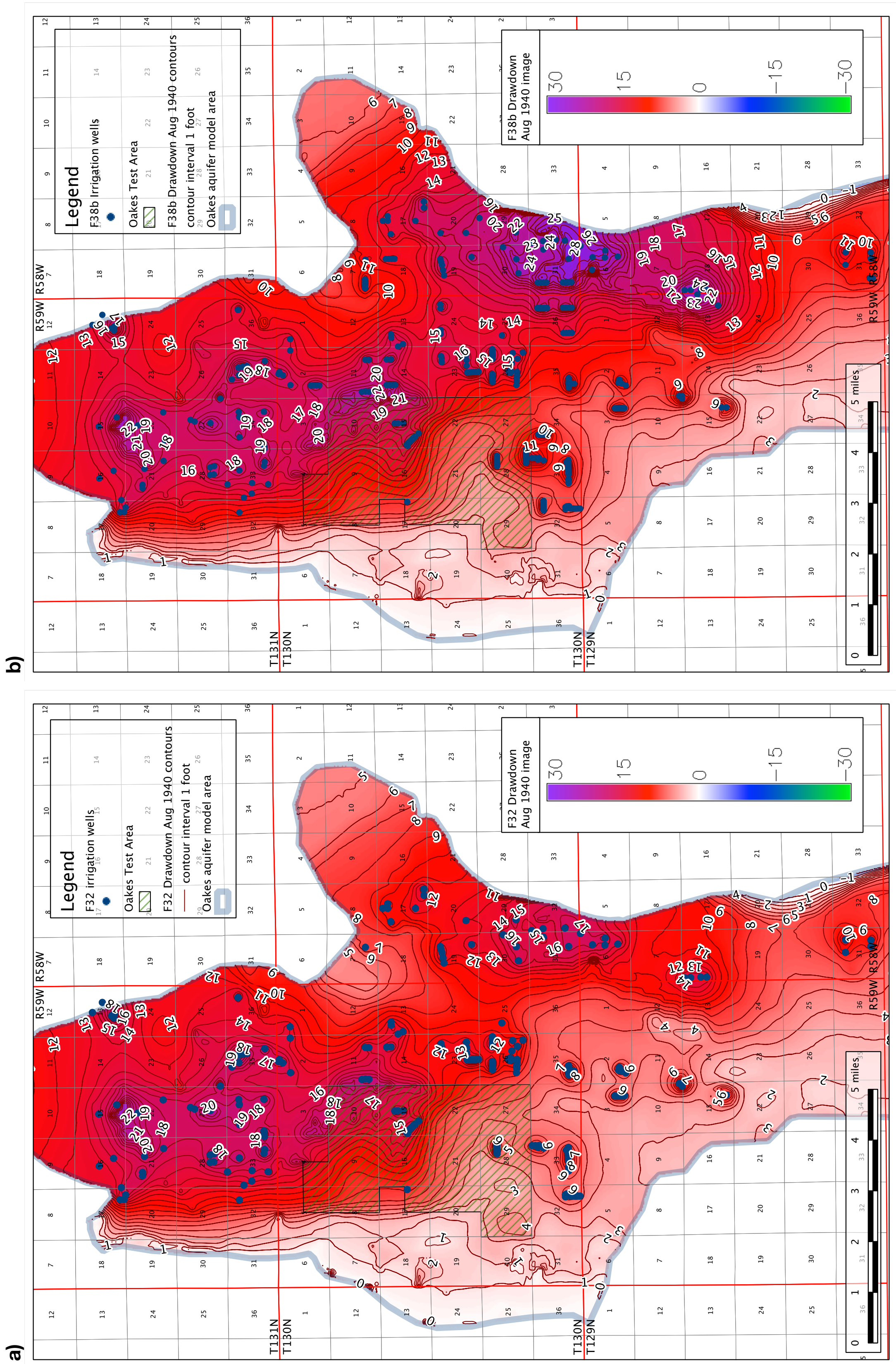


Figure 91. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **August 31, 1940** of 1905 to 2005 simulation.

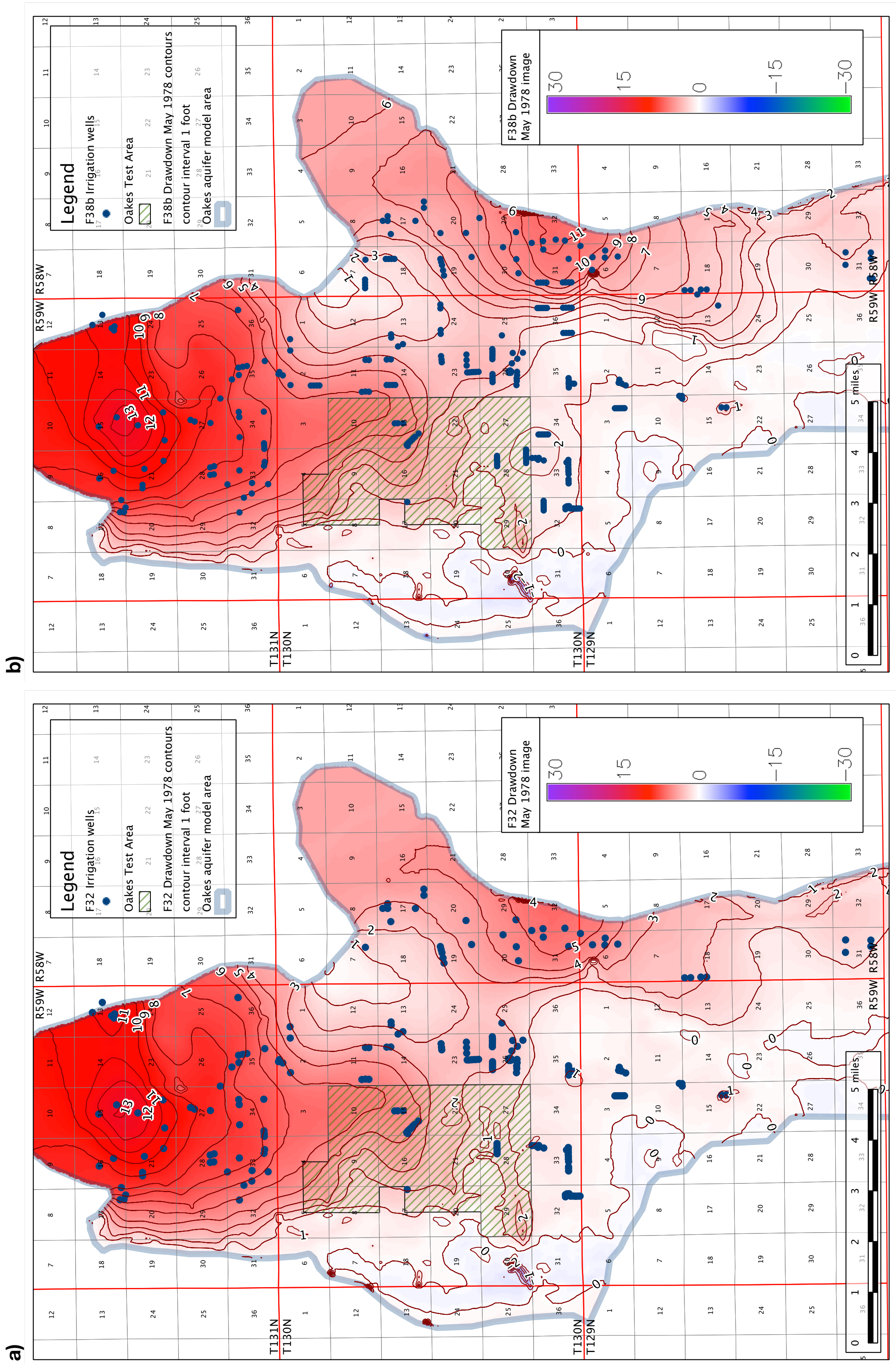


Figure 92. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **May 31, 1978** of 1905 to 2005 simulation.

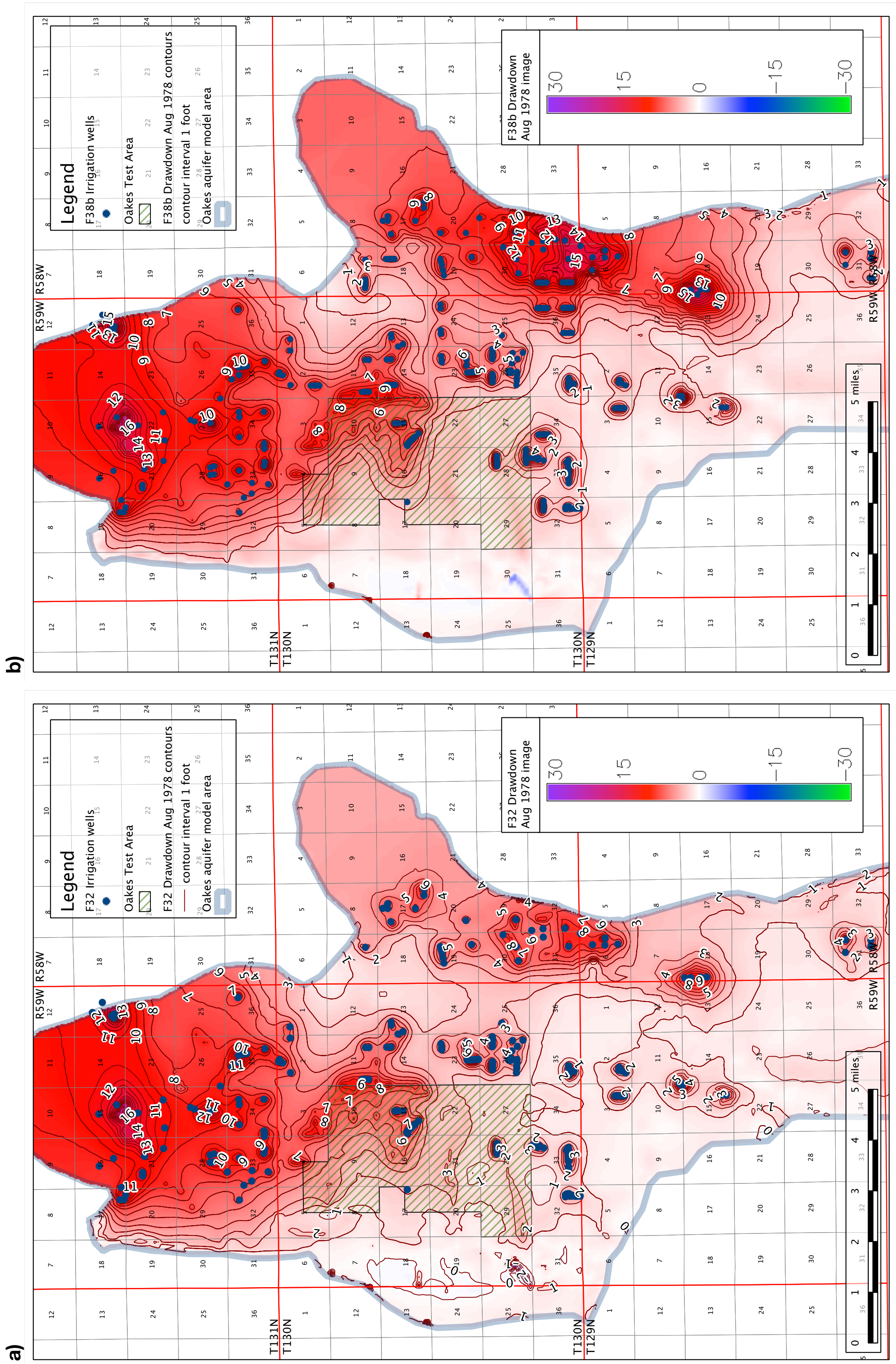


Figure 93. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **August 31, 1978** of 1905 to 2005 simulation.

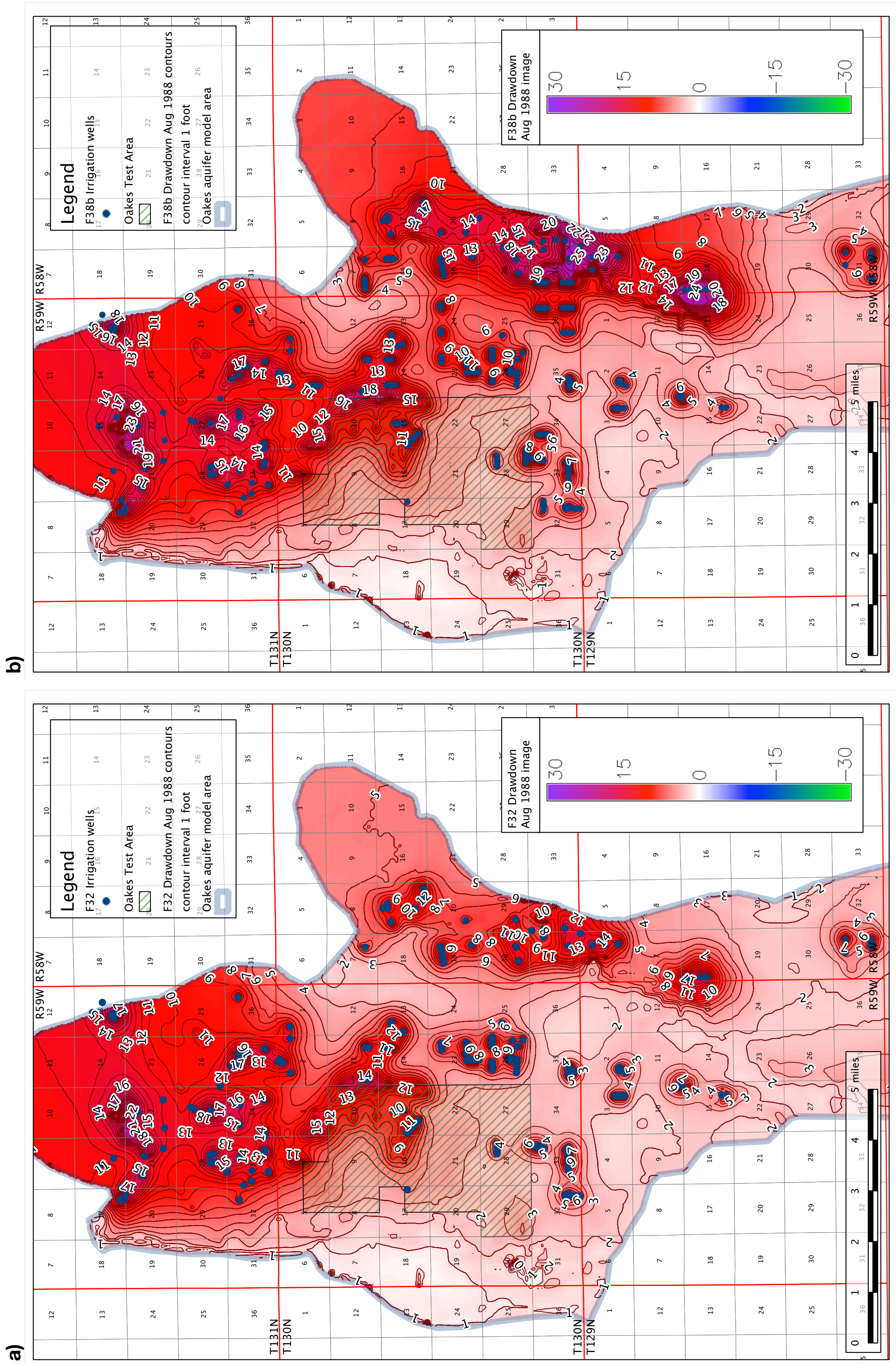


Figure 94. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **August 31, 1988** of 1905 to 2005 simulation.

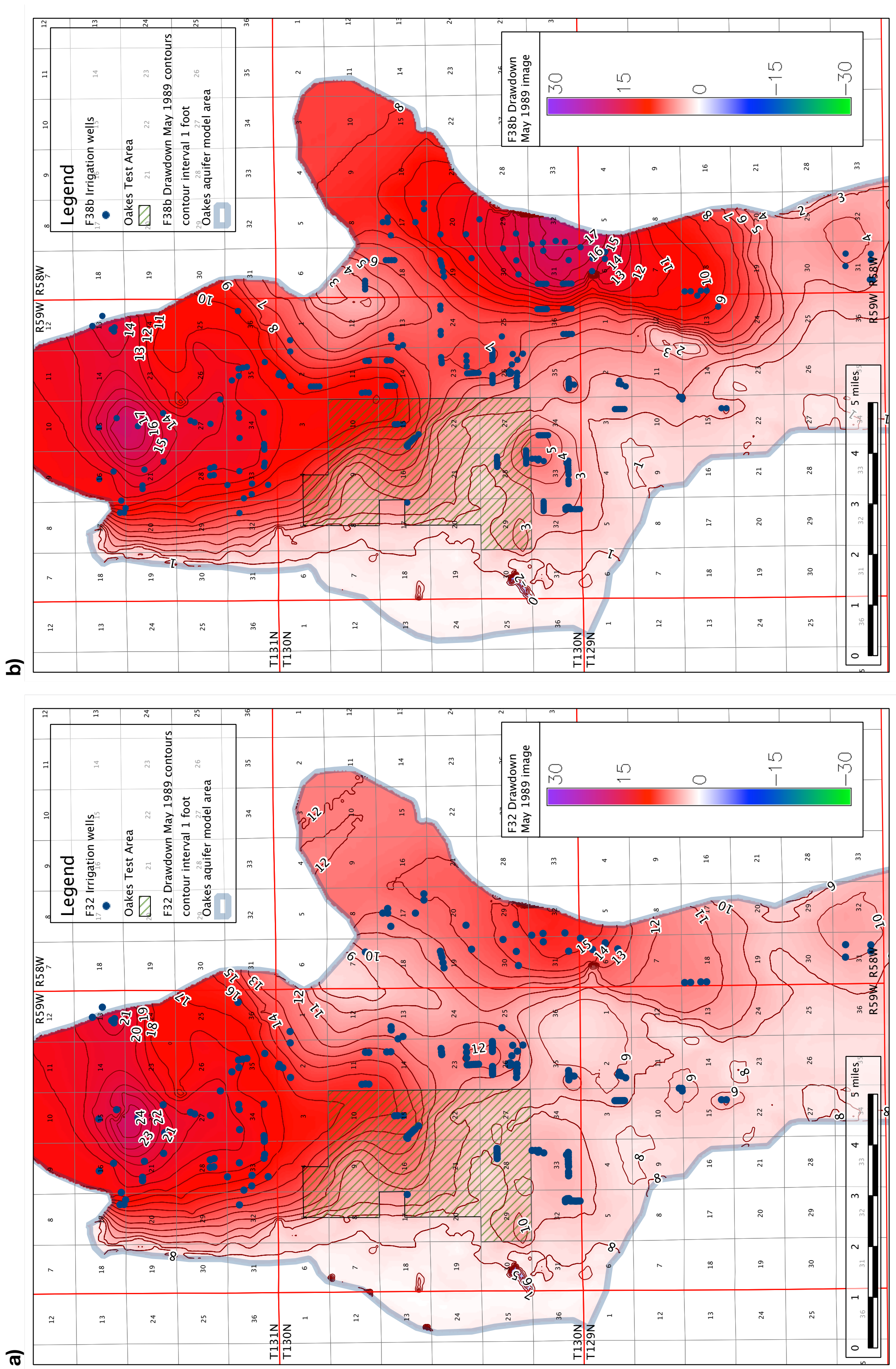


Figure 95. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **May 31, 1989** of 1905 to 2005 simulation.

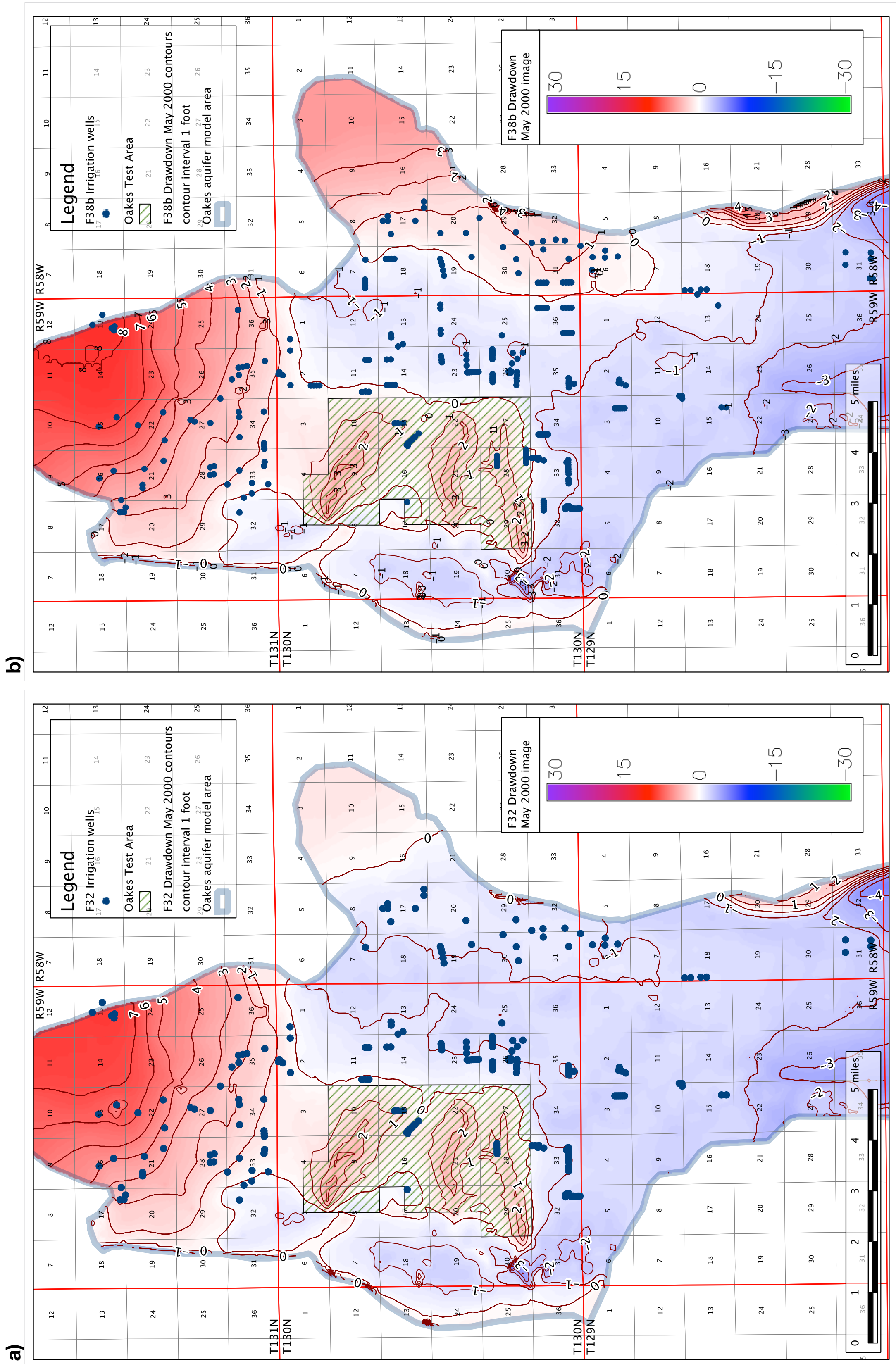


Figure 96. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **May 31, 2000** of 1905 to 2005 simulation.

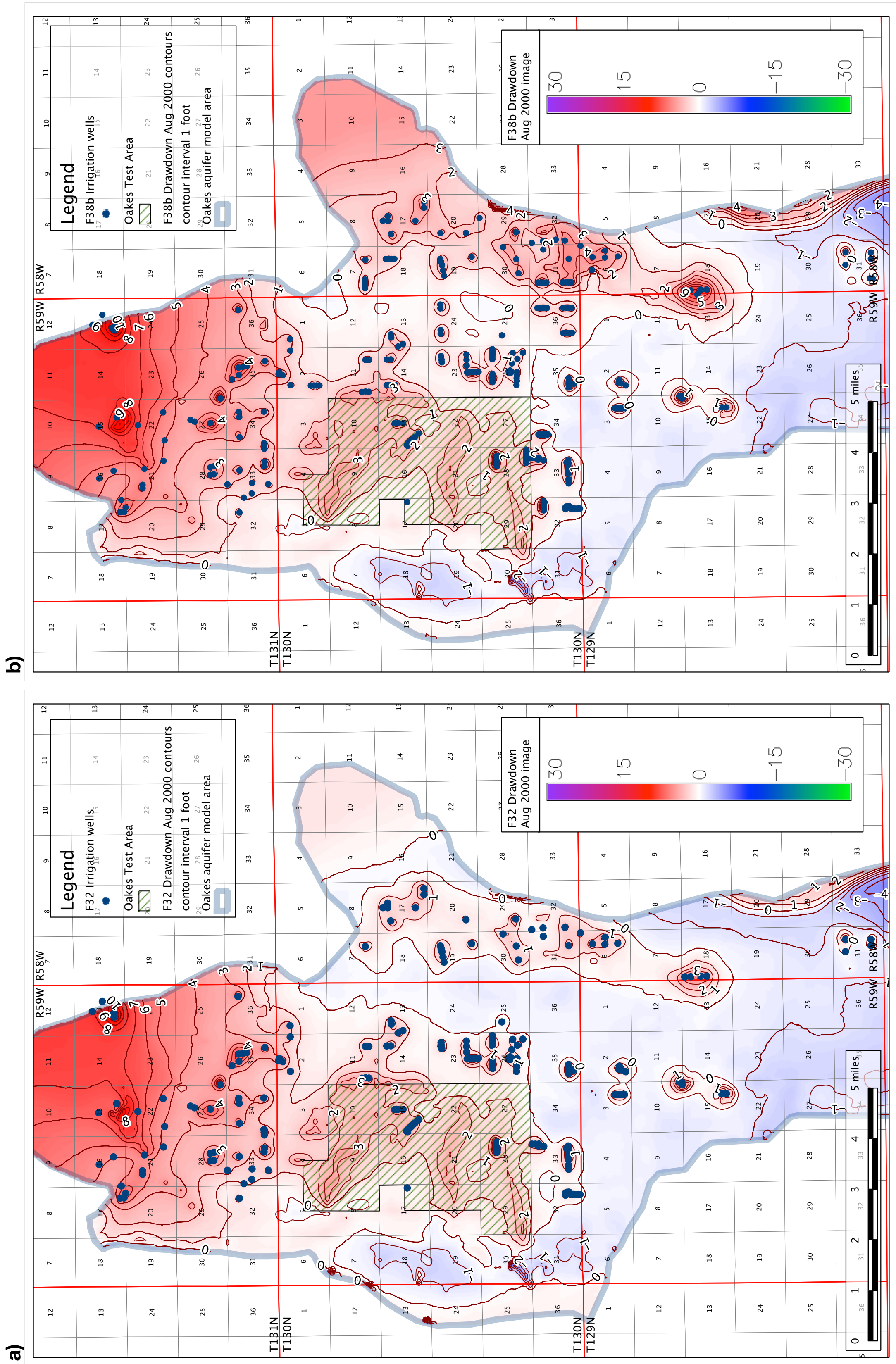


Figure 97. Comparison of drawdown between a) drains and permitted irrigation and b) drains and permitted + pending irrigation for **August 31, 2000** of 1905 to 2005 simulation.

The monthly amount of irrigation water required in inches is determined by using the soil moisture budget model using daily climate data for a specified climate dataset. The pumping rate per well is the monthly water use times the number of acres that the well irrigates. This is the pumping rate that is specified in the model for that well. Where multiple wells serve a center pivot, it was assumed that the pumping rate for each well was the same.

The Oakes aquifer model uses the USGS Multi-Node Well package (MNW) (Halford and Hanson, 2002) to simulate production wells. MNW is capable of estimating the drawdown at the well. The drawdown for the well node, particularly in a thin water table aquifer such as Oakes, does not give a good perspective that the well yield may be sensitive to additional drawdown. For an aquifer with limited available drawdown, such as the Oakes aquifer, it also has the capability of reducing pumping rate for the well and shutting the well down when pumping rates become too low. In these simulations, if a well's pumping rate dropped to 40 percent of the specified rate, the well would cease pumping. The well would start pumping again when the well could pump 60 percent of the specified rate.

The locations of wells that the simulation calculated less water pumped than requested for the permitted case with the Oakes climate dataset are shown in figure 98. The total annual water required for irrigation and the annual amount pumped in the model are shown in figure 99. The differences occur largely in the dry years with high water use. Because the limit on drawdown was set to the bottom elevation of the lowest layer with a well and not the bottom of the aquifer, the simulations will underestimate the decline in well yields that would occur. To some extent this is offset by the aquifer being coarser or thicker at the well than it is in the model with its regional properties.

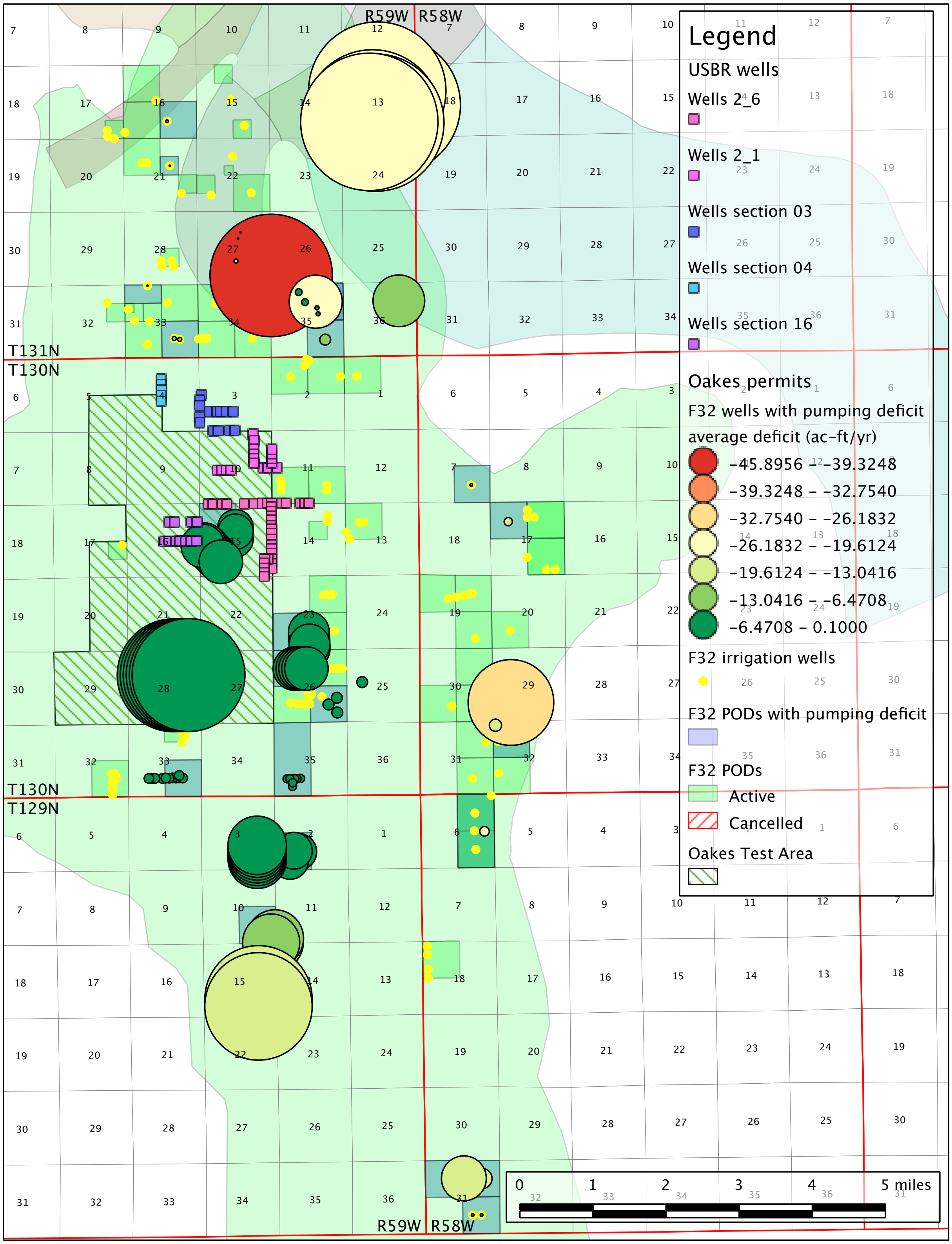


Figure 98. Simulation of permitted irrigation using Oakes climate dataset (run F32). Map showing location of irrigation wells where simulated pumping is less than water requirements.

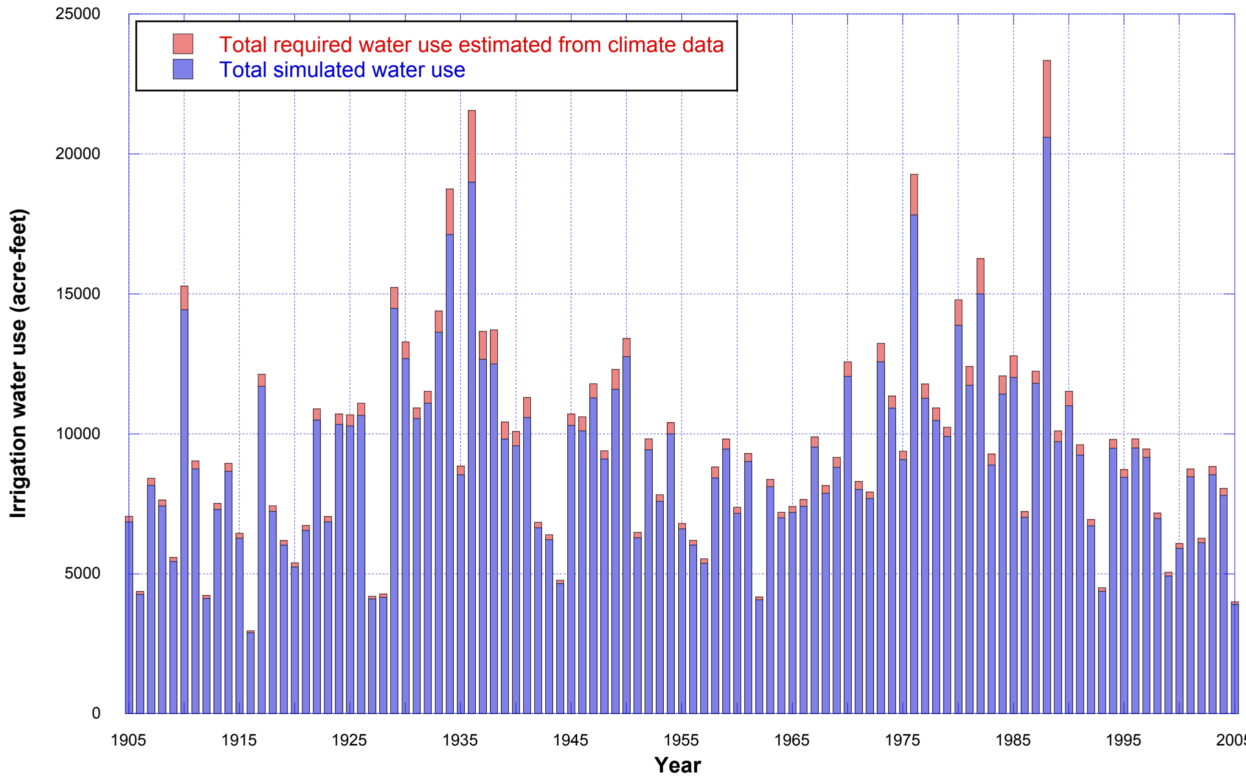


Figure 99. Simulation of permitted irrigation using Oakes climate dataset (run F32). Histogram of Oakes aquifer water requirements and simulated water use for irrigation.

Locations of wells, that the simulation calculated less water pumped than requested for the permitted plus pending case with the Oakes climate dataset, are shown in figure 100. The total annual water required for irrigation and the annual amount pumped in the model are shown in figure 101. The pending plus permitted case results in greater impacts upon well yields. This is largely due to the increased drawdown in the deep channel impacting adjacent areas to the west. The permitted plus pending pumping scenarios does not include the four pending permits within the northern part of the OTA.

The analysis of the water levels from the simulations indicate that 1978 is a representative year for average pumping impacts. In August, 1978 (fig. 93), the three areas of significant drawdown are the area north and west of Oakes, near the northeast area of the OTA, and the deep channel. Based on the model results, no additional water is available in the area north of Oakes. No ET remains in the area to be captured. The development in this area largely derives its water from reduced discharge to the James River. The model appears to underestimate recharge in this area, but until the source of this recharge is determined, no additional permits should be granted in this area.

The large drawdown along the northeast side of the OTA results from assuming that the interim well field is used to irrigate 1,669 acres that are permitted within the OTA. Though the interim wells did not lose capacity in the simulation, the yield capacity of these wells is likely overestimated as the maximum drawdown of a well is set to the bottom elevation of the deepest node containing the well and not the bottom of the aquifer elevation. Even if the wells in the OTArpl permits (table 8), which have mostly used groundwater, were used instead of the interim wells to supply this irrigation, the impact would be similar. The cross-section A1-A1' in figure 102 is through the northern part of the OTA along the path of cross-section E-E' (fig. 39). It extends from the west side of the OTA to 0.5 miles east of the OTA. The aquifer is very thin, less than 20 feet of saturation, except along the east side of the OTA. A few deeper channels or coarse zones may be present in this thin area, but in general well yields are going to be small. Wells developed in this area cannot tolerate any additional well interference. Within the interim well field along the east side of cross-section A1-A1', drawdowns in 1988 resulted in a large loss of saturated thickness in this area. It is concluded that there is no additional water available for irrigation within the OTA.

The other area of large drawdown is the deep channel area. Drawdowns in the August 1978 simulations for the permitted case exceeded 16 feet (fig. 93) and in the August 1988 permitted plus pending case exceeded 26 feet (fig. 94). Considering that many irrigation wells located in or near the deep channel are less than 60 feet deep, this amount of drawdown would likely result in a large drop in well yield. Though saturated thickness in the deep channel exceeds 100 feet, drawdown must be limited to protect water rights with generally less than 60 feet of saturated thickness adjacent to the deep channel. Drawdown in the area of the deep channel extending north from section 6, T. 129 N., R. 58 W. should not exceed 20 feet, except during extreme drought. It is expected that within this area some irrigation wells will either need to be deepened or additional wells added to obtain a reliable water supply.

Cross-section B1-B1' (fig. 103) extends from the southeast corner of the OTA to a point 3 miles east in the center of the deep channel. The development of the pending permits has little impact on water levels within 1 mile of the OTA. However, large changes in saturated thickness occur in the vicinity of the deep channel. The development of the permits in the W1/2 sec. 31 T. 130 N., R. 58W. and sec. 36, T. 130 N., R. 59 W. would likely have water supply issues during periods of drought and would therefore restrict any additional development from the deep channel to the south.

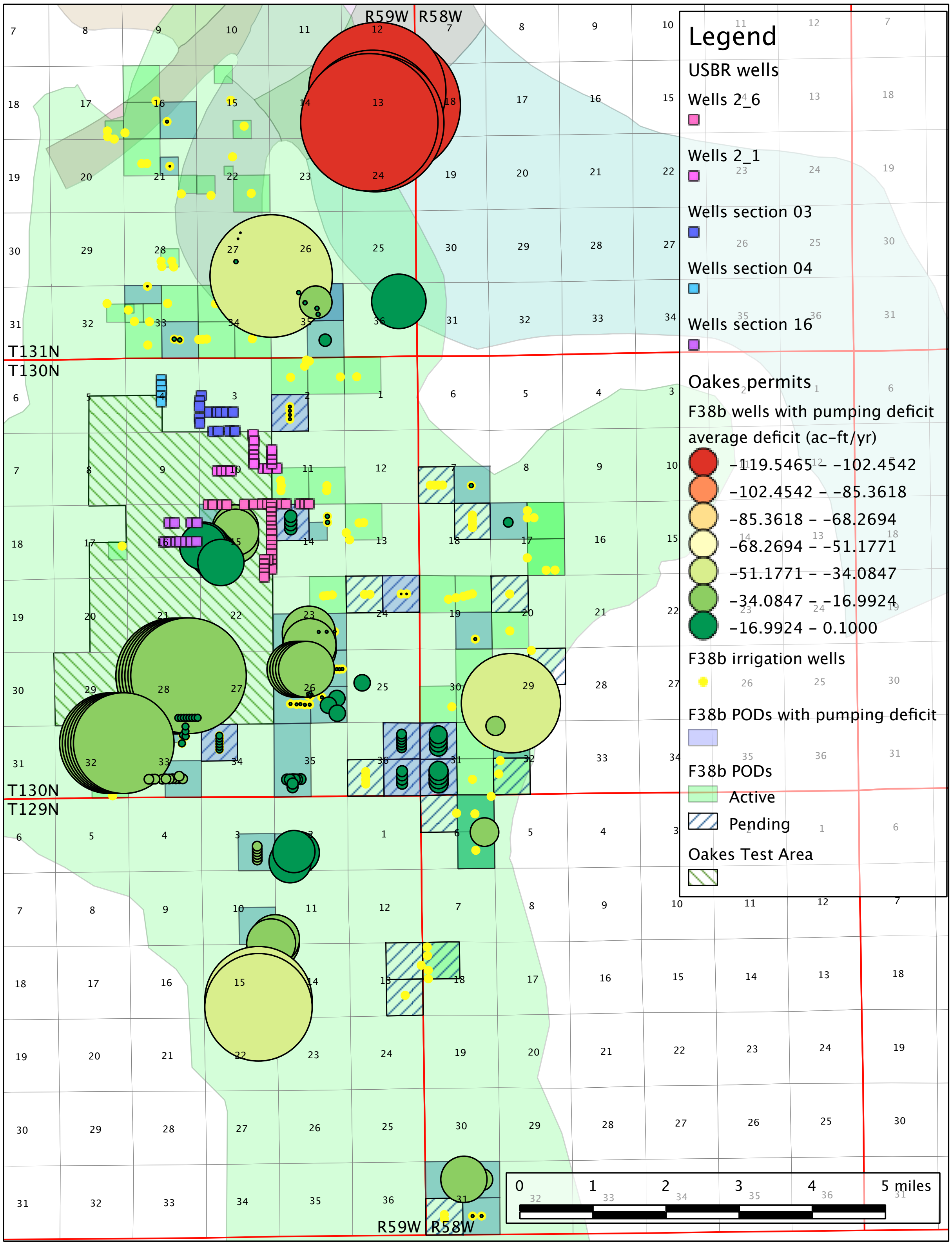


Figure 100. Simulation of permitted plus pending irrigation using Oakes climate dataset (run F38b). Map showing location of irrigation wells where simulated pumping is less than water requirements.

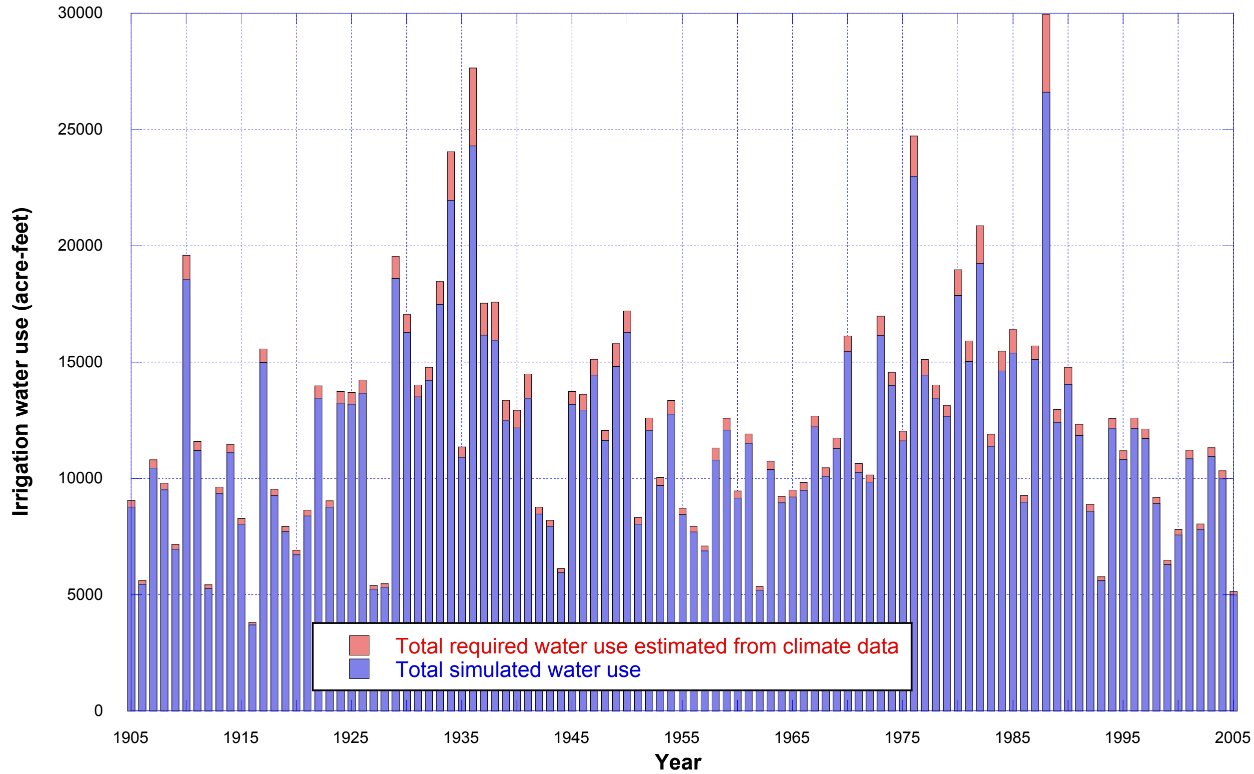


Figure 101. Simulation of permitted irrigation plus pending using Oakes climate dataset (run F38b). Histogram of Oakes aquifer water requirements and simulated water use for irrigation.

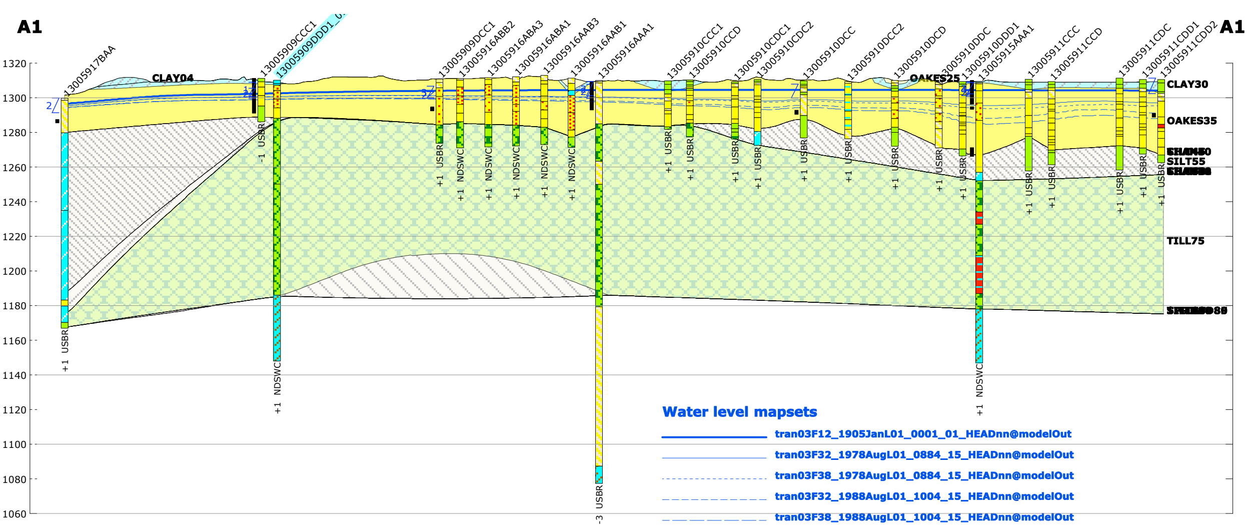


Figure 102. Cross-section through OTA and interim well field extending from west side of OTA to 0.5 mile east of OTA.

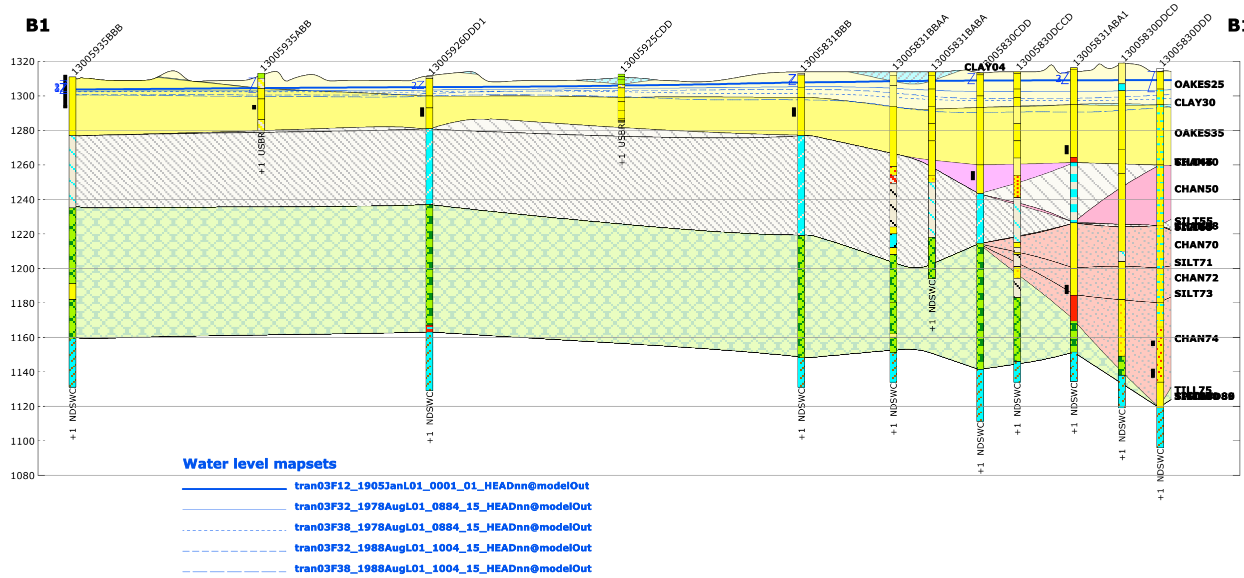


Figure 103. Cross-section from southeast corner of OTA extending 3 miles east to center of deep channel.

DSID Irrigation

The analysis has indicated that no water is available from the Oakes aquifer beyond that requested in the pending permits. It was assumed DSID could reach agreements with the holders of these pending permits so that DSID could proceed with development to irrigate 5,000 acres within the OTA. Analysis indicated that DSID could not obtain sufficient quantities of groundwater to make the operation of the OTA economically viable. This analysis is discussed at the end of this section. Therefore, it was assumed that groundwater would be used to supplement surface water from the James River. The OTA is presently supplied with water available from Jamestown Reservoir conservation pool, surplus James River flows, and drain return flows. Dale Esser, GDCD, undertook the analysis of the availability of water from these sources to determine how much groundwater would be needed to supplement the surface water supplies. The estimated annual irrigation water use in inches per acre for the period 1905 to 2005 for the Oakes, Forman, and Fullerton climate datasets was supplied to Dale Esser, GDCD. Using stream gage data at Jamestown, LaMoure, and State Line (Ludden Dam) estimates were made of how much of the annual irrigation requirement could be met from Jamestown Reservoir conservation pool and surplus James River flows. Mr. Esser assumed that 500 ac-ft, which he considered conservative, would be supplied each year by drain return flows. The data provided start in 1929, as no stream flow data for the James River is available before this date. For the groundwater model, a linear regression of inches per acre estimated use versus groundwater need was used to estimate groundwater needed for the period 1905 to 1928. The assumptions and procedures Mr. Esser used in the analysis are discussed in more detail in Appendix G. The total irrigation demand to irrigate 5,000 acres and the amount needed from groundwater using Oakes, Forman, and Fullerton climate are shown in figures 104, 105, and 106 respectively. The results are summarized in table 9. Though peak groundwater needed was 8,704 acre-feet in a year, median use ranged from 1,229 to 1,646 ac-ft. Groundwater is needed to supply 42 to 45 percent of the irrigation water required to irrigate 5,000 acres within the test area.

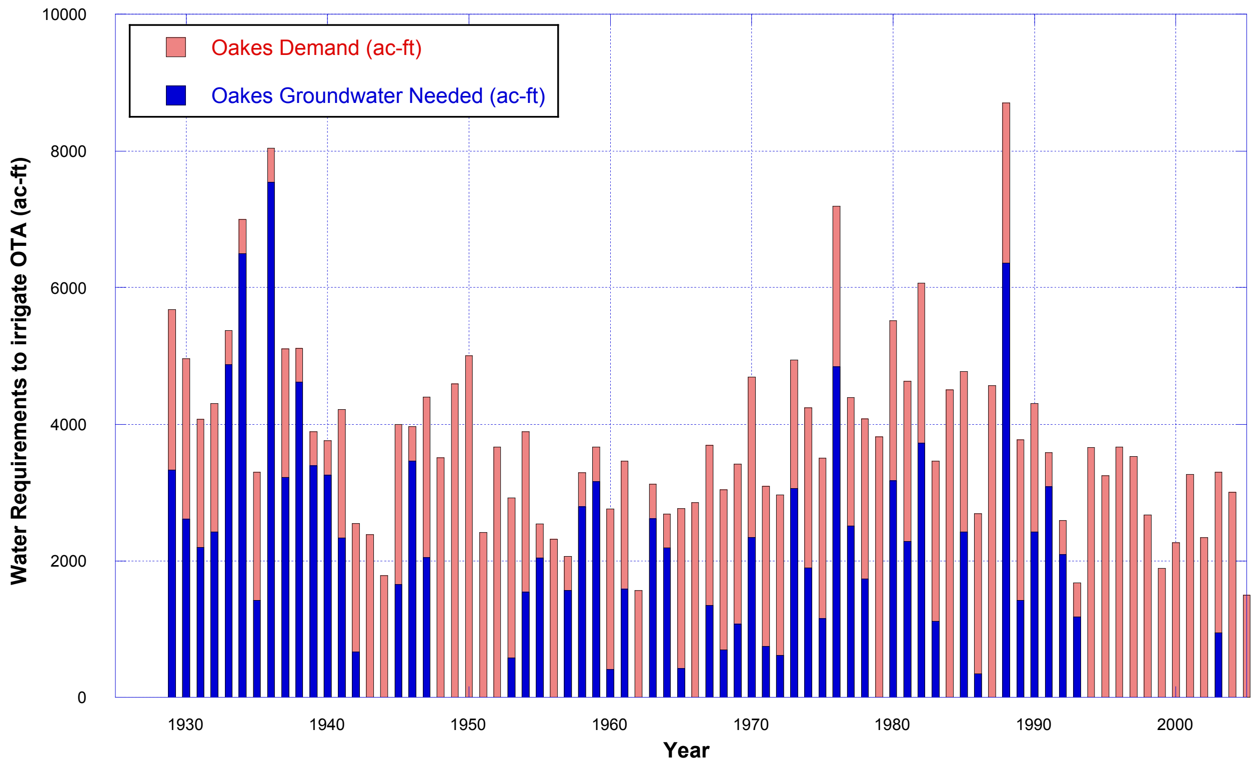


Figure 104. Using the Oakes climate dataset, estimated total annual demand and amount of groundwater required to irrigate 5,000 acres in the OTA. Data provided by Dale Esser, GDCD.

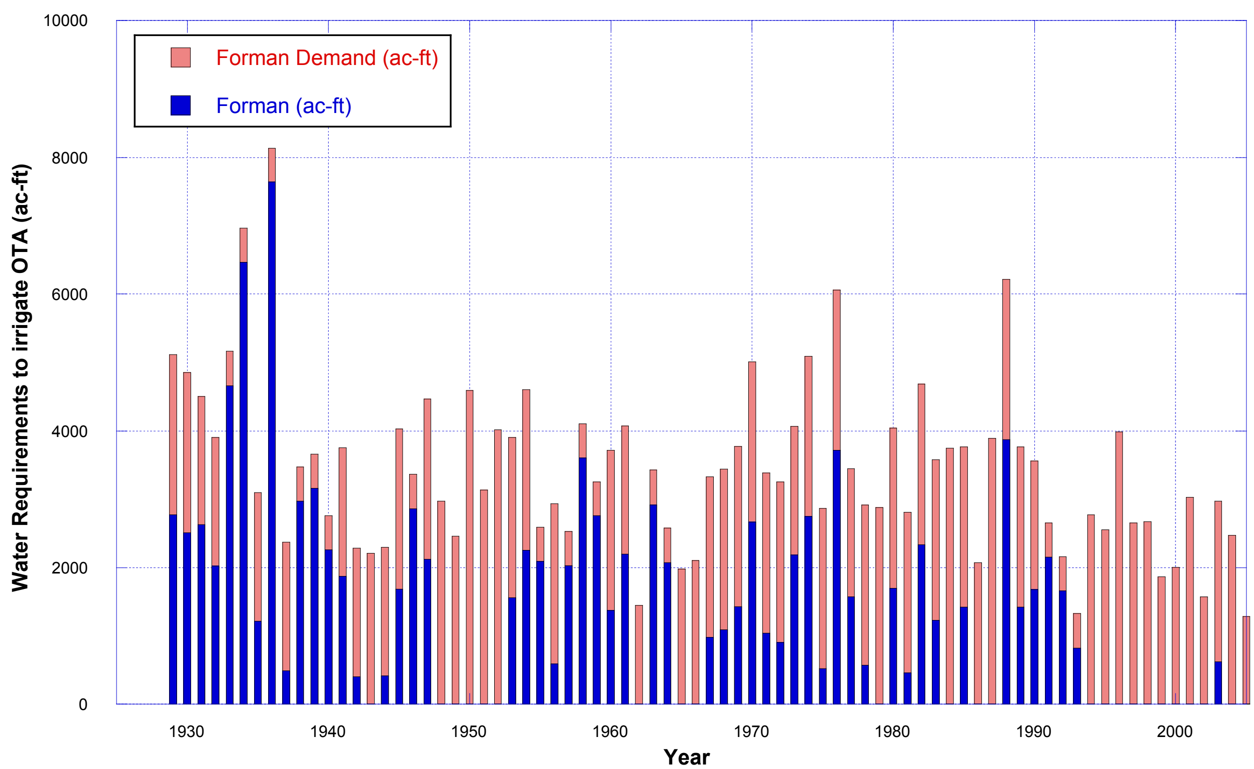


Figure 105. Using the Forman climate dataset, estimated total annual demand and amount of groundwater required to irrigate 5,000 acres in the OTA. Data provided by Dale Esser, GDCD.

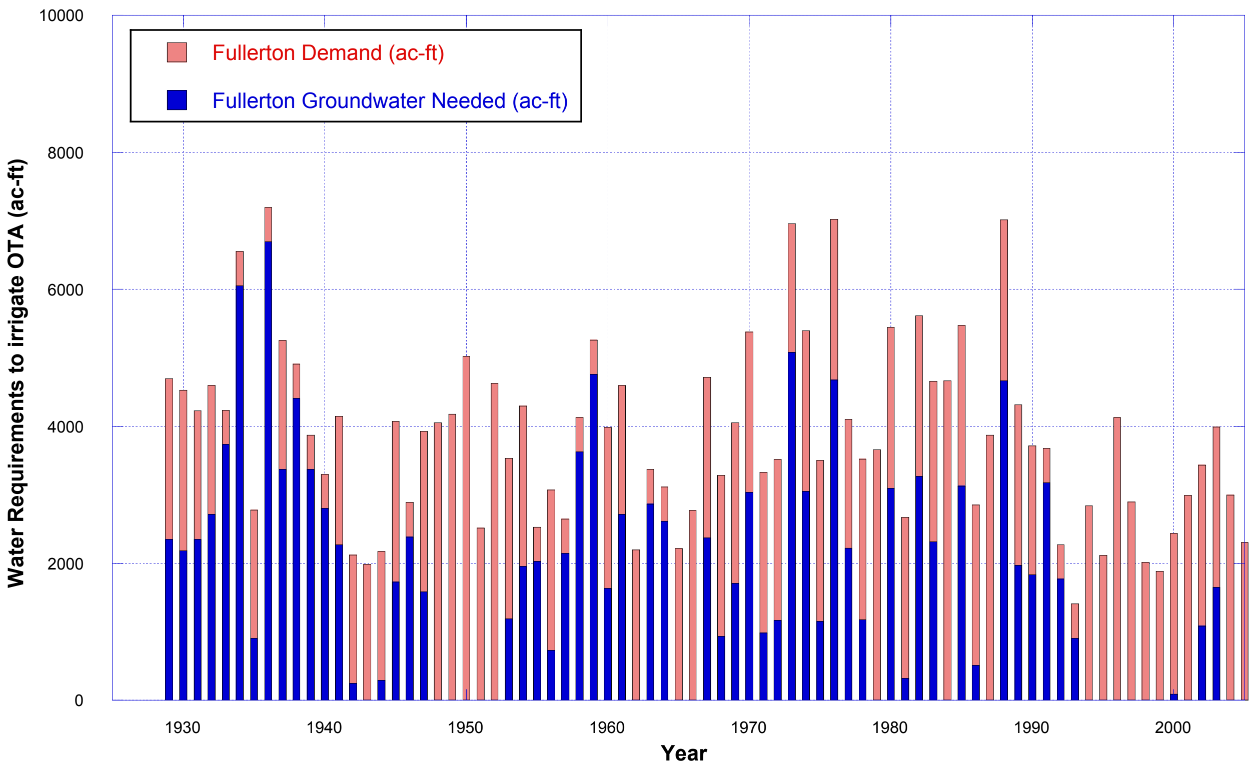


Figure 106. Using the Fullerton climate dataset, estimated total annual demand and amount of groundwater required to irrigate 5,000 acres in the OTA. Data provided by Dale Esser, GDCD.

Table 9. Summary of groundwater requirements and total water demand to irrigate the OTA when used as a supplement to James River water. Statistics are for the analysis using the annual water use determined for Oakes, Fullerton, and Forman climate datasets.

	Oakes Groundwater (ac-ft)	Fullerton Groundwater (ac-ft)	Forman Groundwater (ac-ft)	Oakes Total Demand (ac-ft)	Fullerton Total Demand (ac-ft)	Forman Total Demand (ac-ft)
Minimum	0	0	0	1496	1408	1283
Maximum	7542	6696	7638	8704	7196	8138
Mean	1650	1728	1434	3782	3841	3434
Median	1420	1646	1229	3658	3875	3363

It is assumed that all pending permits within the OTA will be supplied by DSID and are not considered in this simulation. Table 10 lists the pending permits that were eliminated from this set of simulations. With the exception of permit #4742, if approved these permits would have limited available drawdown and would restrict further development of the deep channel. The simulations based on the groundwater requirements determined by Dale Esser, GDCD, with permitted irrigation and pending permits, excluding those within the test area and those listed in table 10, shall be referred to as DSID-Esser.

Table 10. List of pending permits outside of OTA that were not included in DSID-Esser simulations.

Permit	POD	Owner	Acres Irrigated
5014	12905806B	HANSEN, LARRY AND NANCY	405
4741A	13005831B	HANSEN, PHILIP A.	131.8
4776	13005831C	ANDERSON, JOEL	135
4742	13005924A	KBO FARM PARTNERSHIP	133.8
4742	13005924B	KBO FARM PARTNERSHIP	133.8
4989	13005936A	KBO FARM PARTNERSHIP	135
4903	13005936C	HANSEN, PHILIP A.	135
4835	13005936D	SCHMIT, KIM	135

It was assumed that DSID would obtain water from the interim well field and new well fields located in E1/2 sec. 24, E1/2 sec. 25, T. 130 N., R. 59 W.; SW1/4 sec. 7, T. 129 N., R. 58 W.; and E1/2 sec. 24, T.129 N., R. 59 W. The water use was proportioned among the wells as 25, 10, 6, 29.5 and 29.5 percent respectively (fig. 107).

For the DSID-Esser simulations, comparisons of water levels and areas of ET for May 31, 1940; August 31, 1940; May 31, 1978; August 31, 1978; August 31, 1988; May 31, 1989; May 31, 2000; and August 31, 2000 are shown respectively in figures 108, 109, 110, 111, 112, 113, 114, and 115. In these figures, map a) is the Oakes climate dataset, map b) is the Forman climate dataset, and map c) is the Fullerton climate dataset. Comparing map a), DSID-Esser irrigation from Oakes climate dataset (figures 108 through 115) with map b), permitted irrigation, and map c), permitted plus pending irrigation, both using Oakes climate data set shown in figures 82 through 89, it is apparent that the impact of the permitted plus some pending plus DSID is less than the impact of permitted plus pending. The difference in impacts, with the Oakes climate dataset, are further illustrated in figures 116 through 123 where the difference in water levels between the DSID-Esser case and permitted irrigation and DSID-Esser case and permitted plus pending irrigation are compared for the same set of dates as above. The blue areas in figures 116 through 123 are areas where the DSID-Esser pumping scenario results in less drawdown and the red areas are areas of increased drawdown compared to either the permitted or permitted plus pending cases.

With the DSID-Esser scenario, the amount of water pumped from near the northern end of the OTA is reduced from either the permitted or permitted plus pending case, resulting in less drawdown in the area around the northern end of the OTA. This is an advantage because it reduces the movement of the poor quality water in sections 1 and 12 toward irrigation wells located in the area of reduced drawdown. In the years 1978 (figs. 110 and 111) and 2000 (figs. 114 and 115) there is no gradient to drive water from the poor quality water area to the irrigation to the west. The interim well field would be a source of water for DSID during wetter periods, but they would need to restrict or eliminate pumping during dry periods to preserve water quality. The pumping impacts are shifted to the southern part of deep channel where available drawdown is greater over a larger area.

Comparisons of water levels at selected observation wells (fig. 124) for the cases of drains, no wells; permitted irrigation; permitted plus pending irrigation; DSID-Esser; and DSID-Esser 1945-2005 are shown in figures 125 through 132. Each figure compares a) Oakes climate dataset; b) Forman climate dataset; and c) Fullerton climate dataset. For the case of Oakes climate dataset, the reported use simulation is displayed. In all pumping cases for the Oakes climate dataset, the drawdown is significantly larger than that in the reported use case, indicating that the full impacts of the permitted development are not observed in the observation well data. The DSID-Esser scenario results in drawdowns that are very similar to the permitted plus pending simulation. The DSID-Esser scenarios were run for the periods 1905 to 2005 and 1945 to 2005. In the 1905 to 2005 scenario, there was a prolonged residual drawdown from the 1930s' drought. The 1945 tp 2005 simulations converges with the 1905 to 2005 simulation in the mid-1960s indicating that the impact of the 1930s' drought has finally dissipated using the Oakes climate data set. However, the Fullerton data set shows little residual from the 1930s' drought.

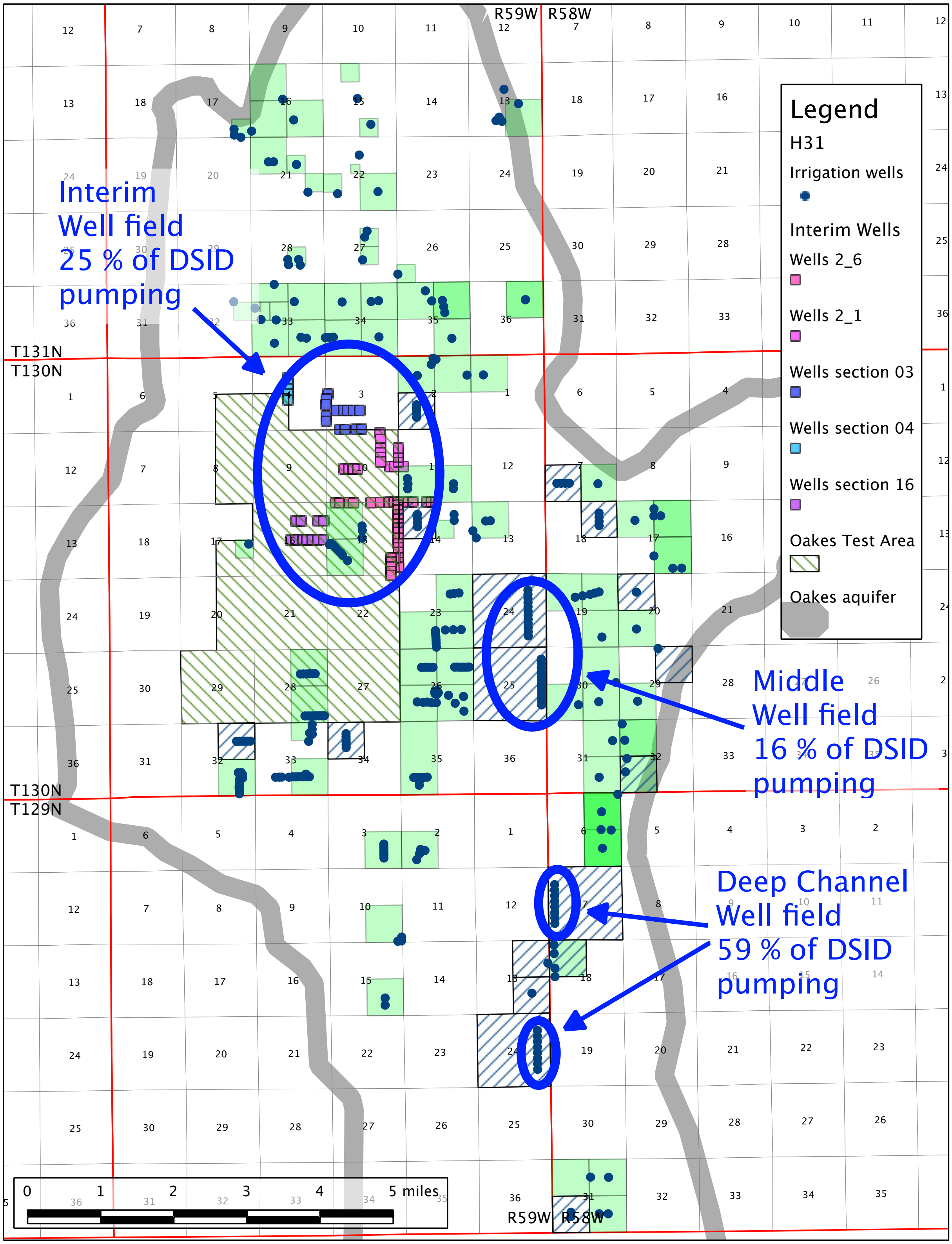


Figure 107. Location of DSID-Esser well fields used in simulations.

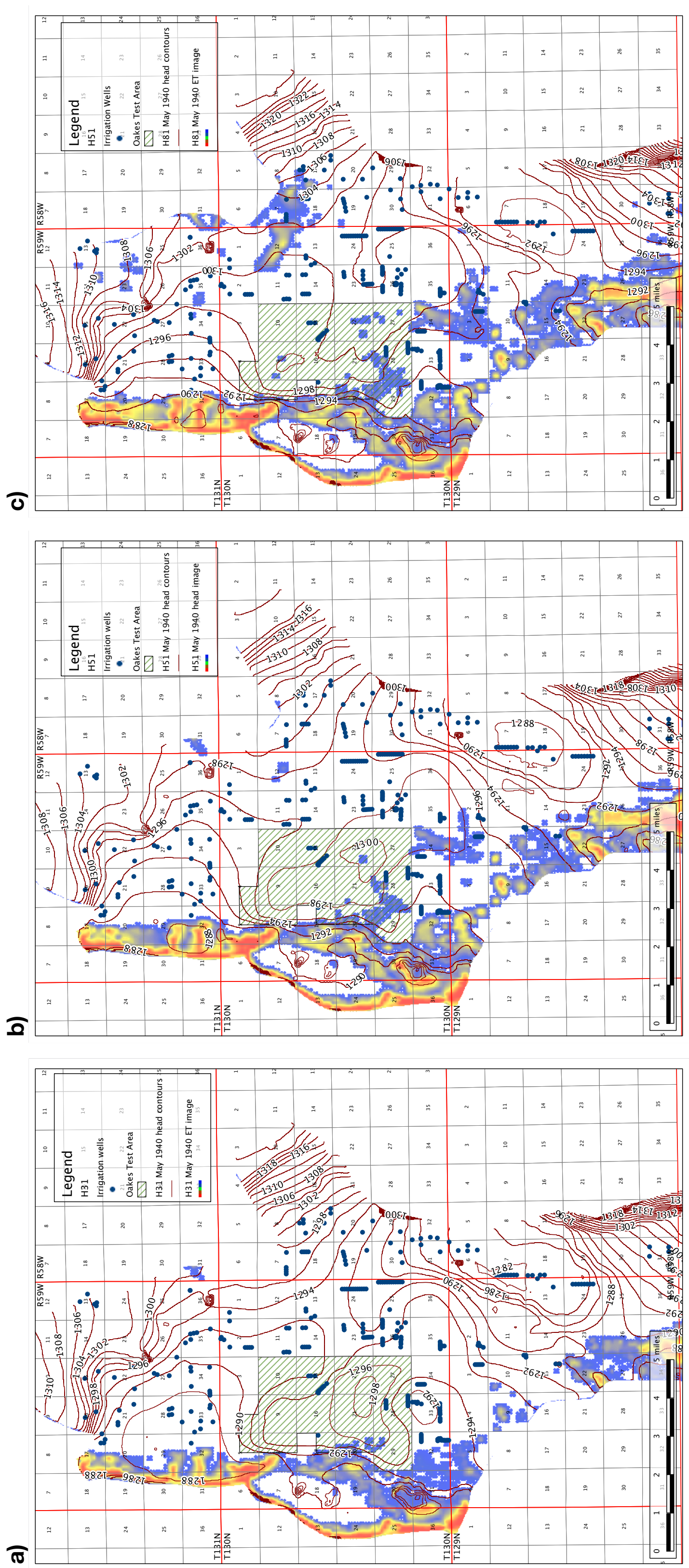


Figure 108. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **May 31, 1940** of 1905 to 2005 simulation.

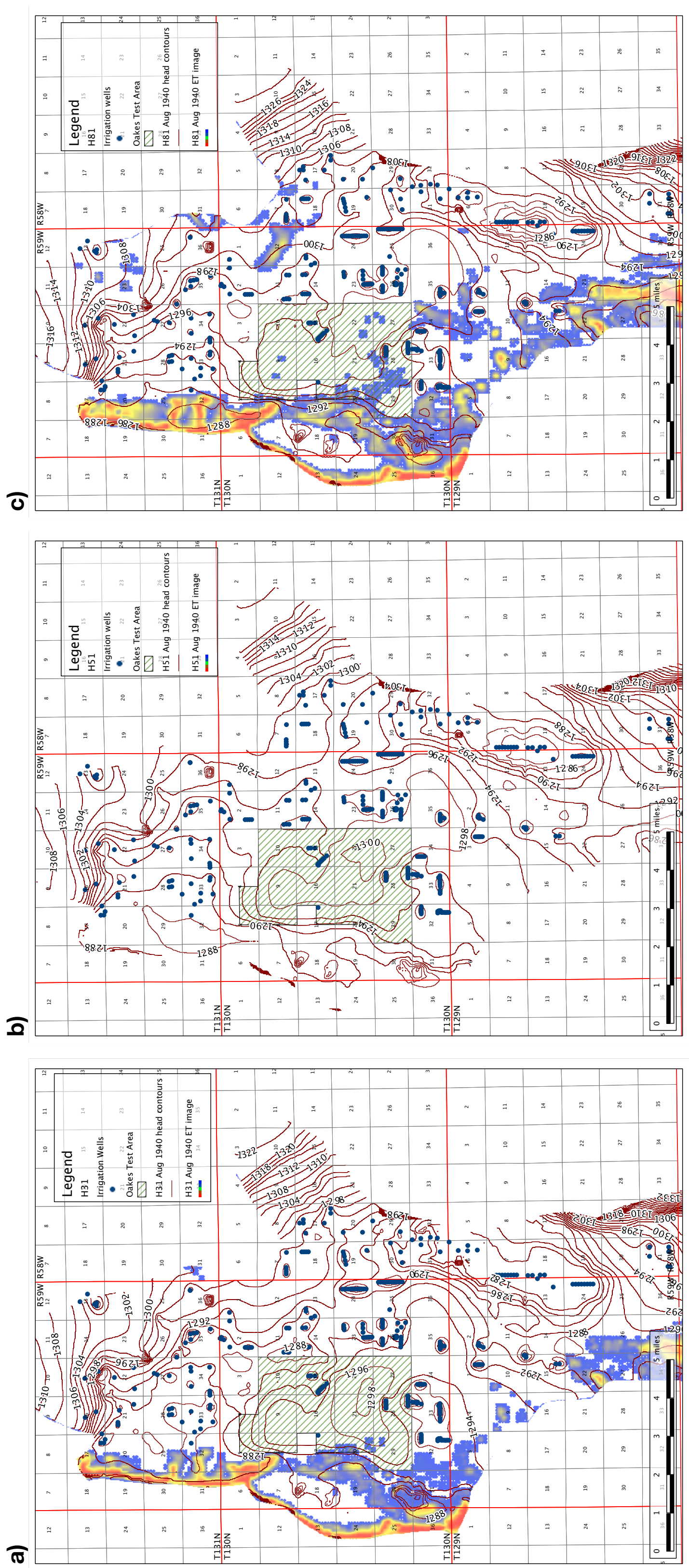


Figure 109. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **August 31, 1940** of 1905 to 2005 simulation. No ET_{gw} occurred in August 1940 Forman climate dataset as precipitation exceeded PET.

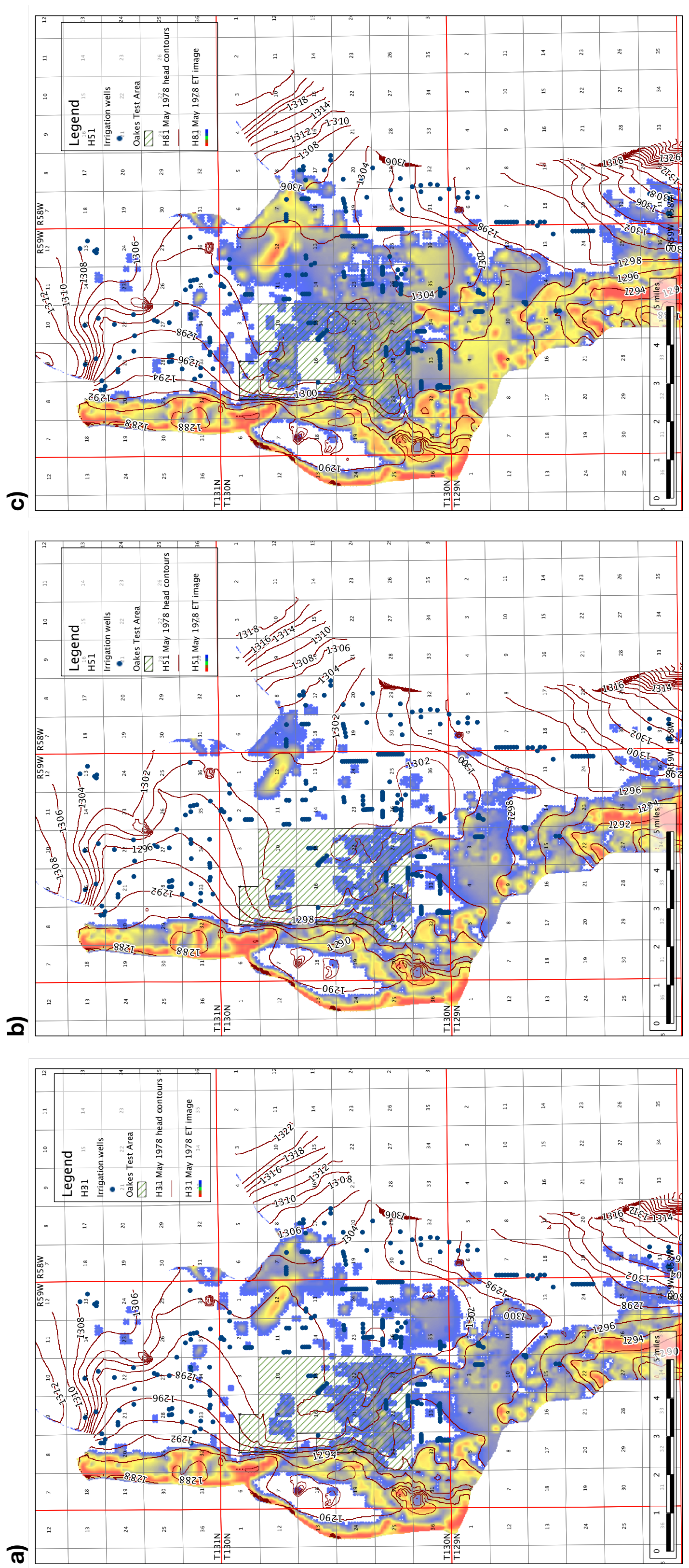


Figure 110. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **May 31, 1978** of 1905 to 2005 simulation.

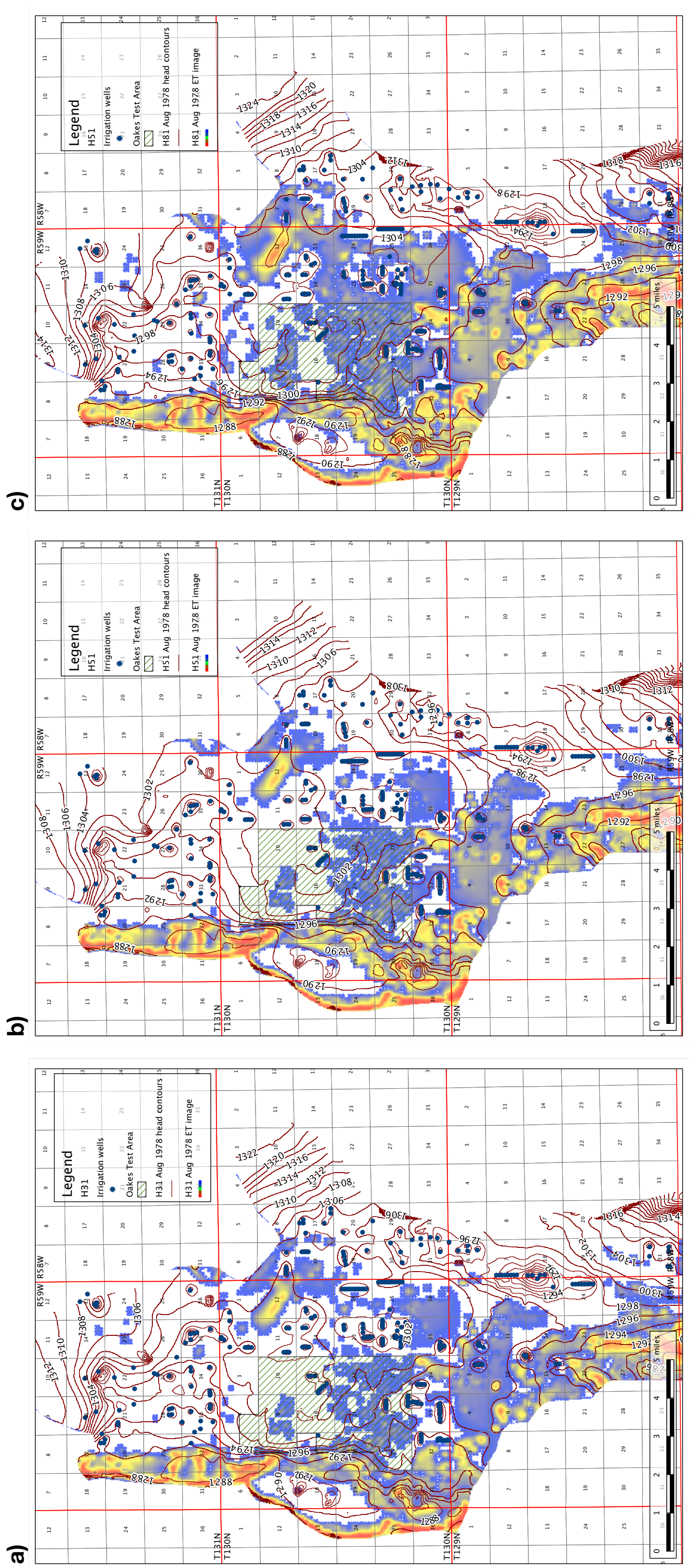


Figure 111. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **August 31, 1978** of 1905 to 2005 simulation.

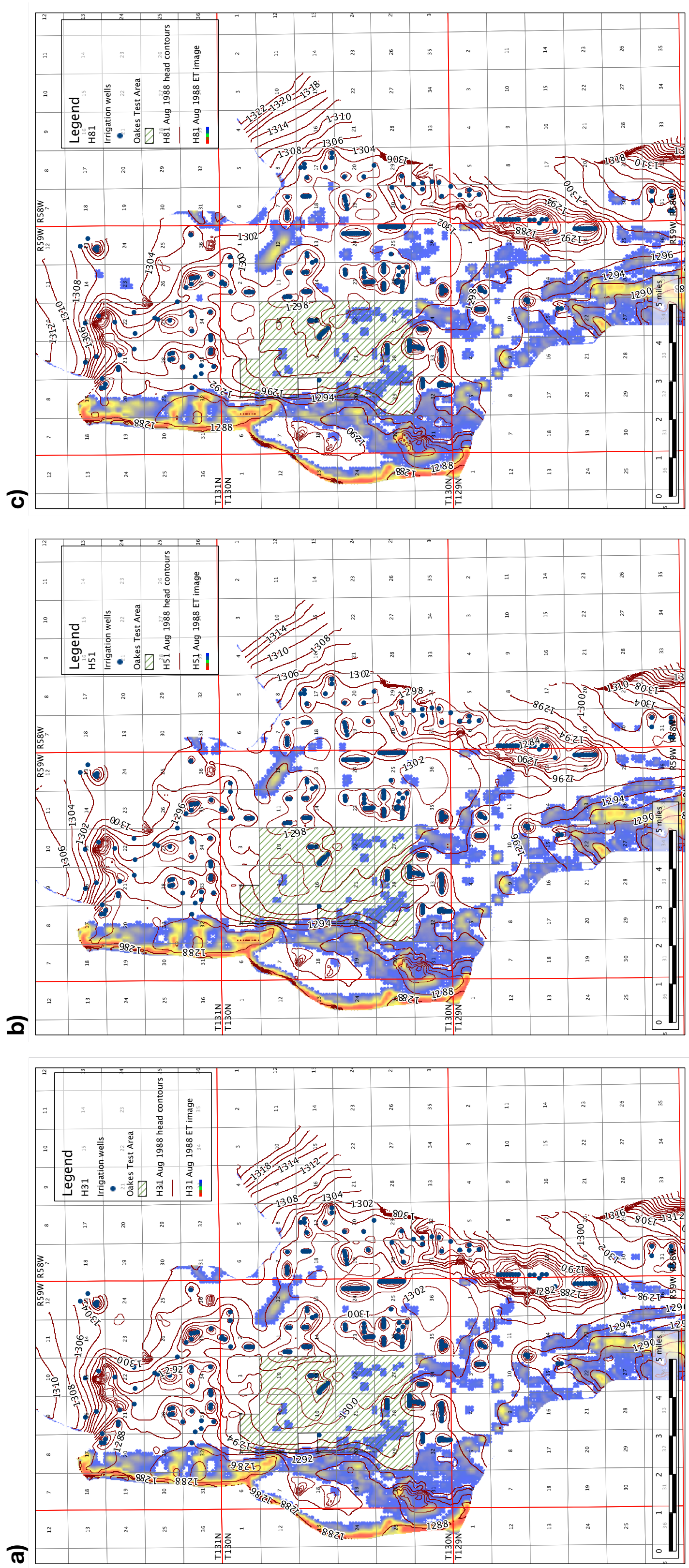


Figure 112. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **August 31, 1988** of 1905 to 2005 simulation.

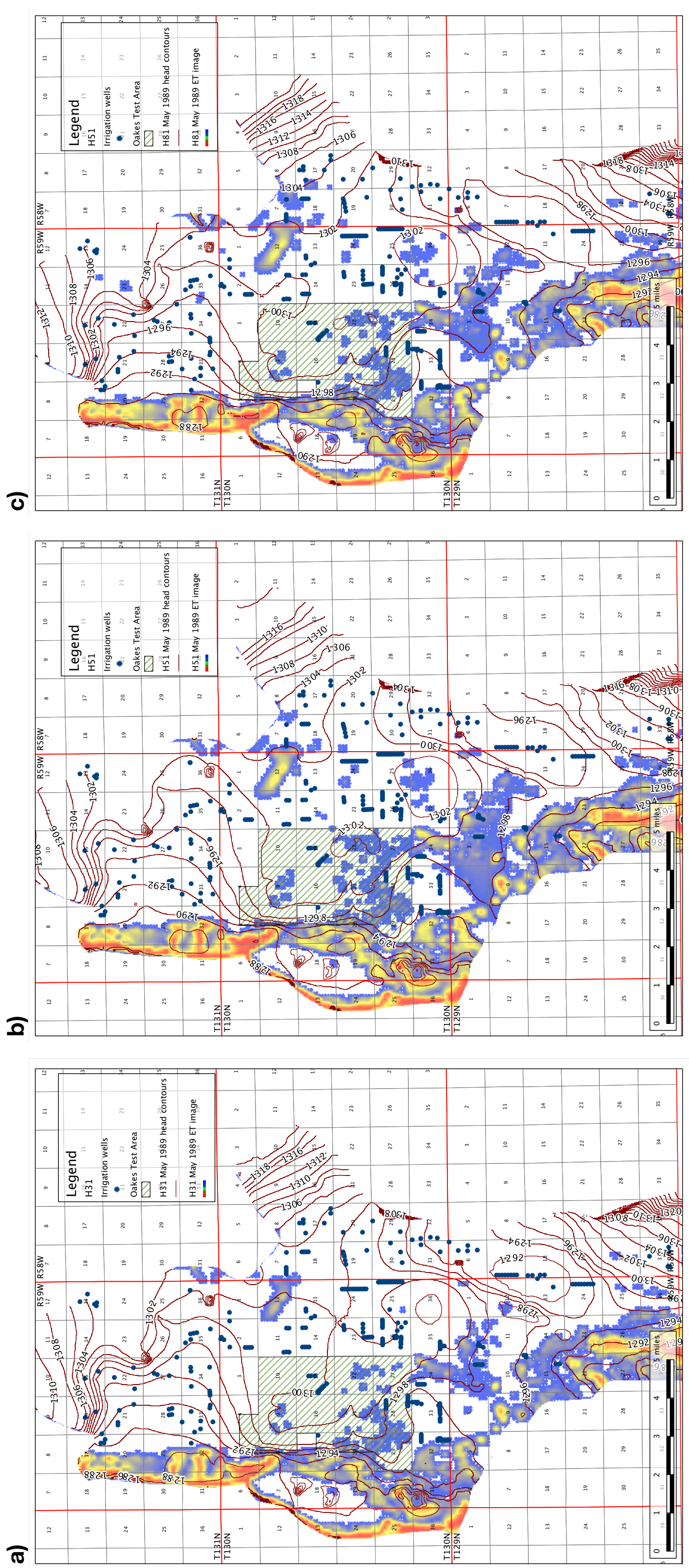


Figure 113. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **May 31, 1989** of 1905 to 2005 simulation.

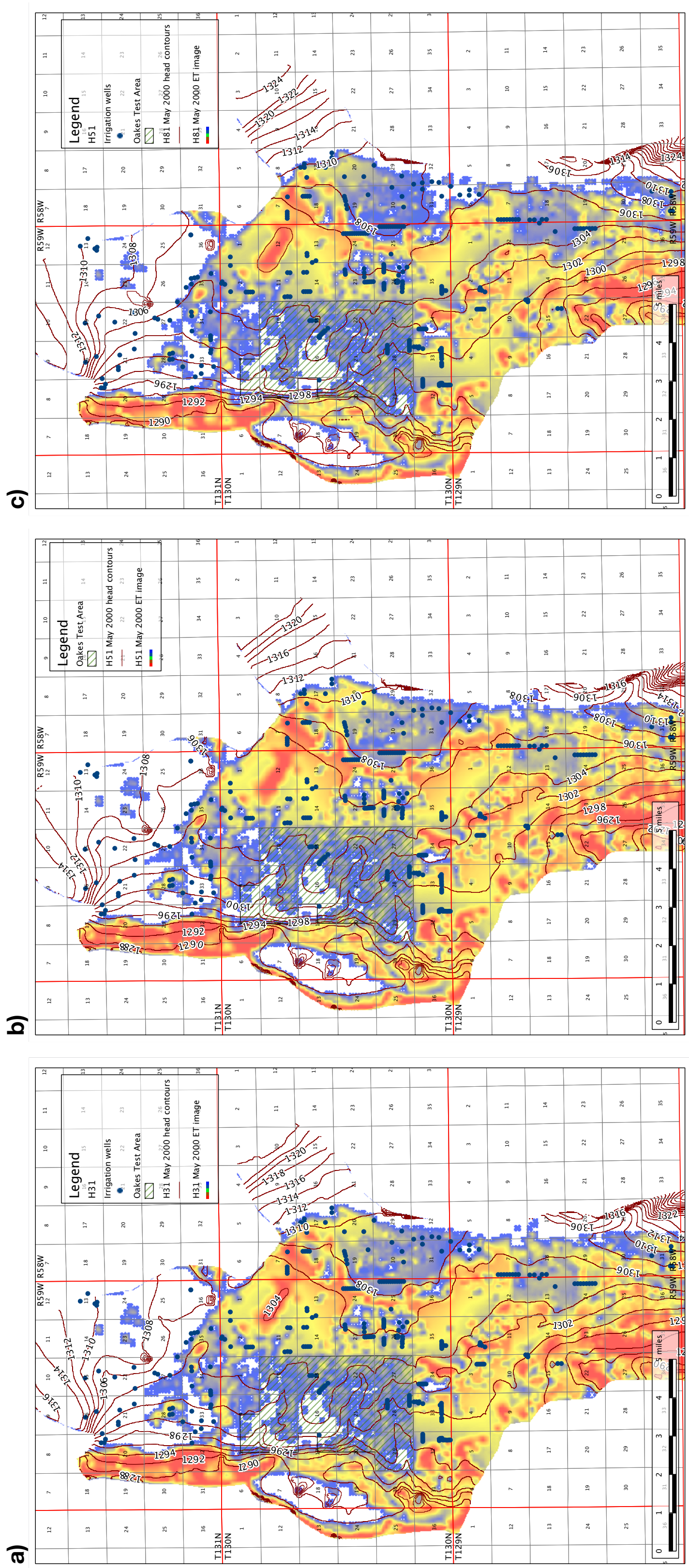


Figure 114. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **May 31, 2000** of 1905 to 2005 simulation.

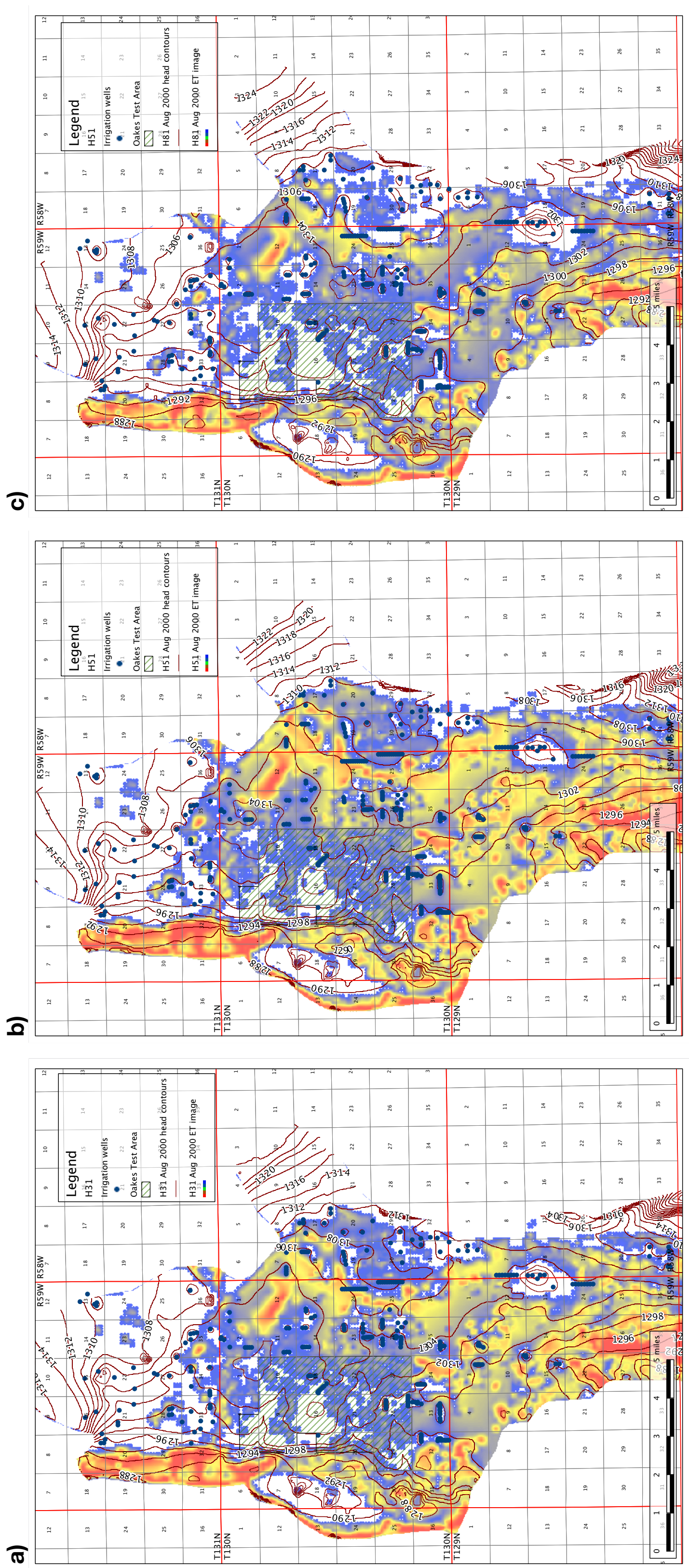


Figure 115. Comparison of water levels and areas of ET between a) Oakes climate, b) Forman climate and c) Fullerton climate for permitted + selected pending + DSID irrigation for **August 31, 2000** of 1905 to 2005 simulation.

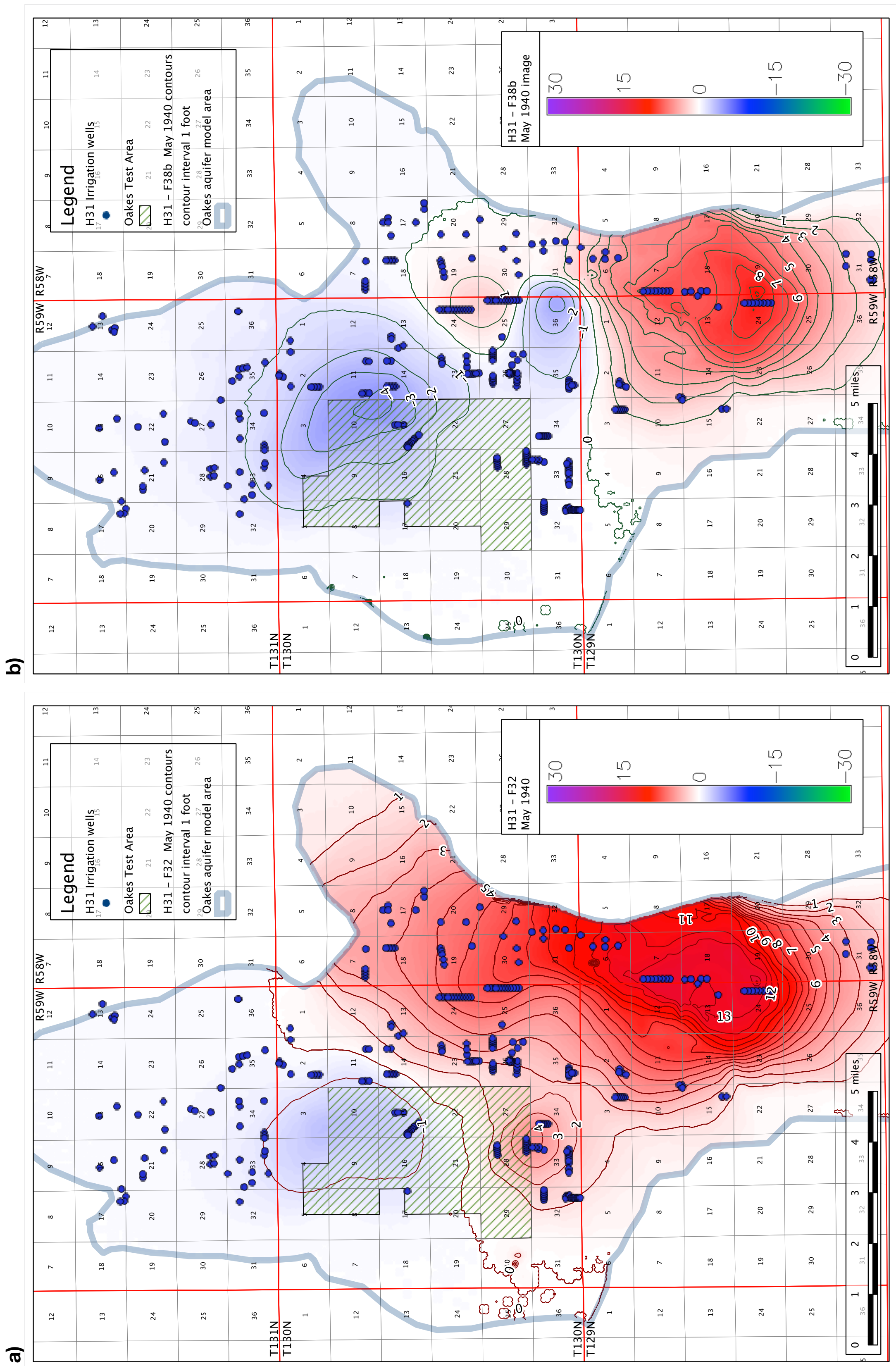


Figure 116. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **May 31, 1940** of 1905 to 2005 simulation.

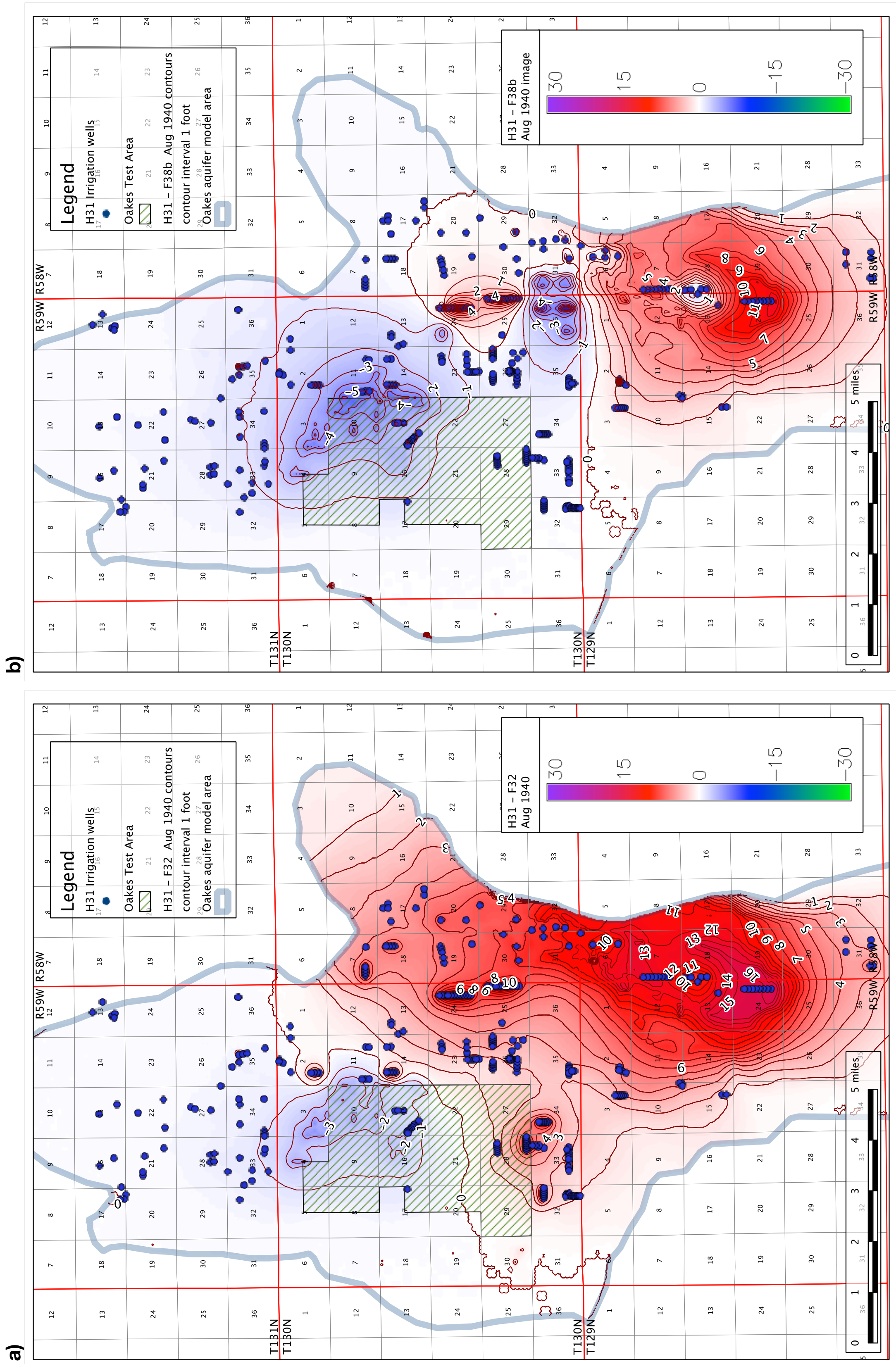


Figure 117. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **August 31, 1940** of 1905 to 2005 simulation.

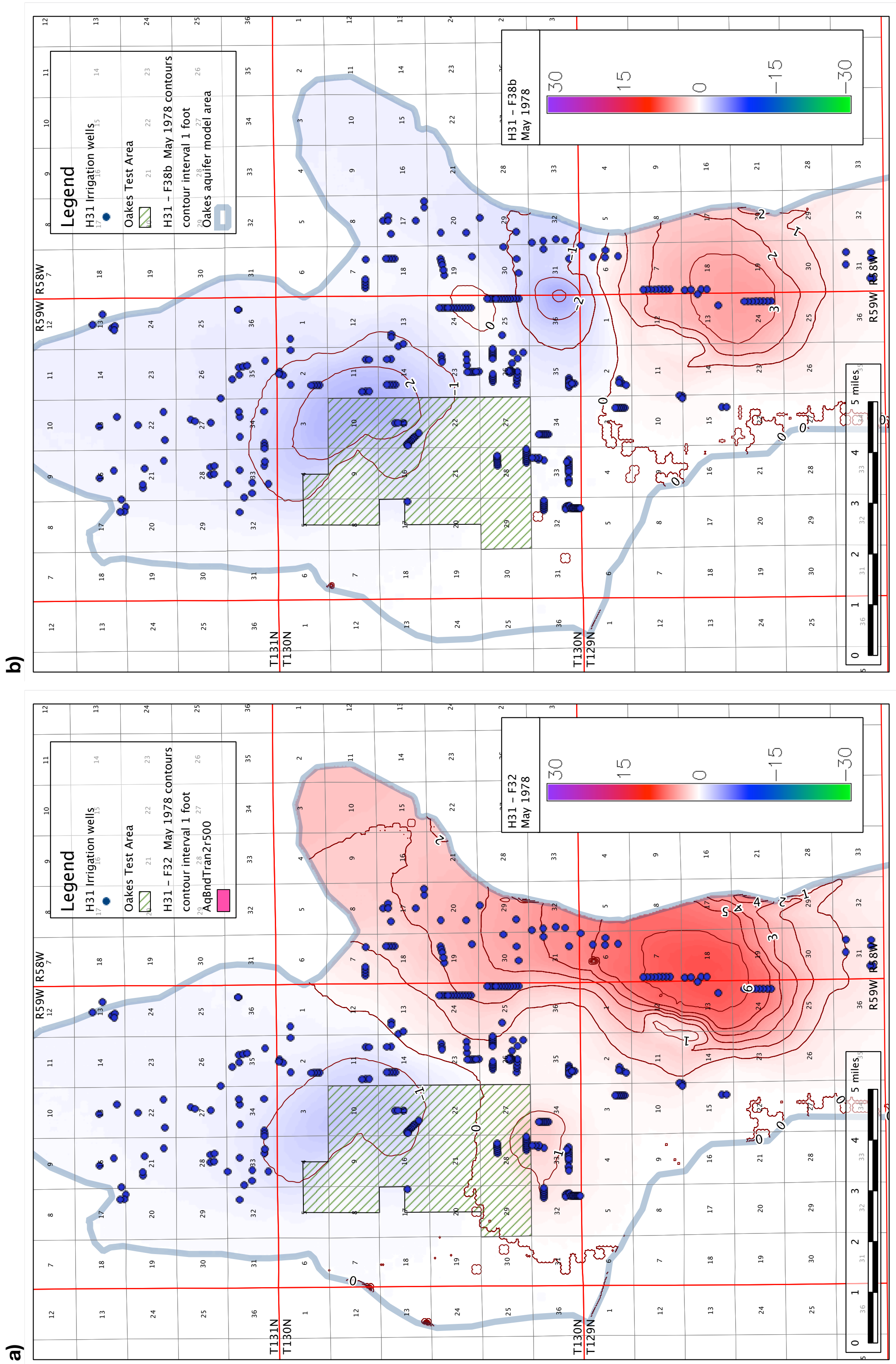


Figure 118. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **May 31, 1978** of 1905 to 2005 simulation.

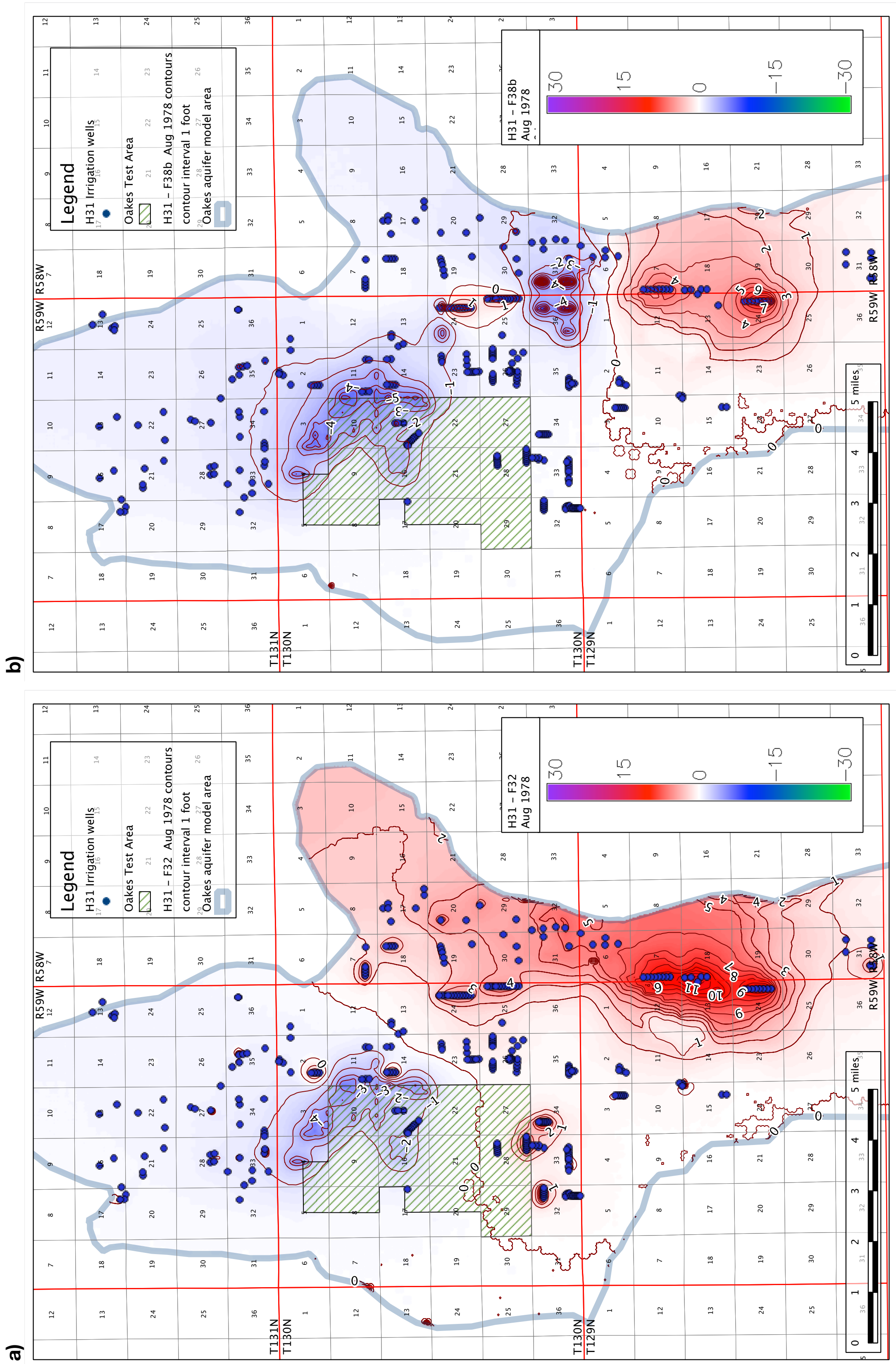


Figure 119. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **August 31, 1978** of 1905 to 2005 simulation.

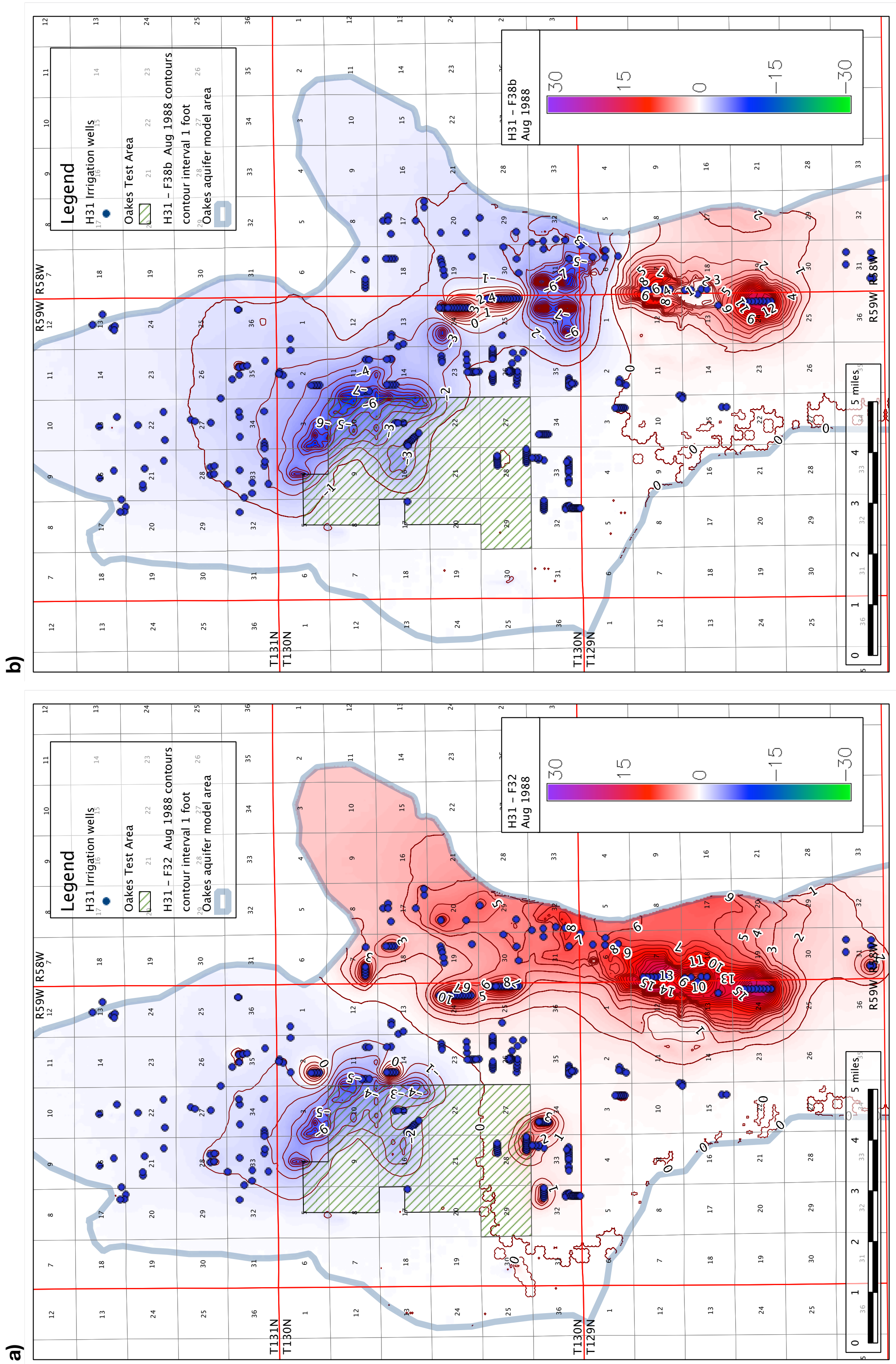


Figure 120. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **August 31, 1988** of 1905 to 2005 simulation.

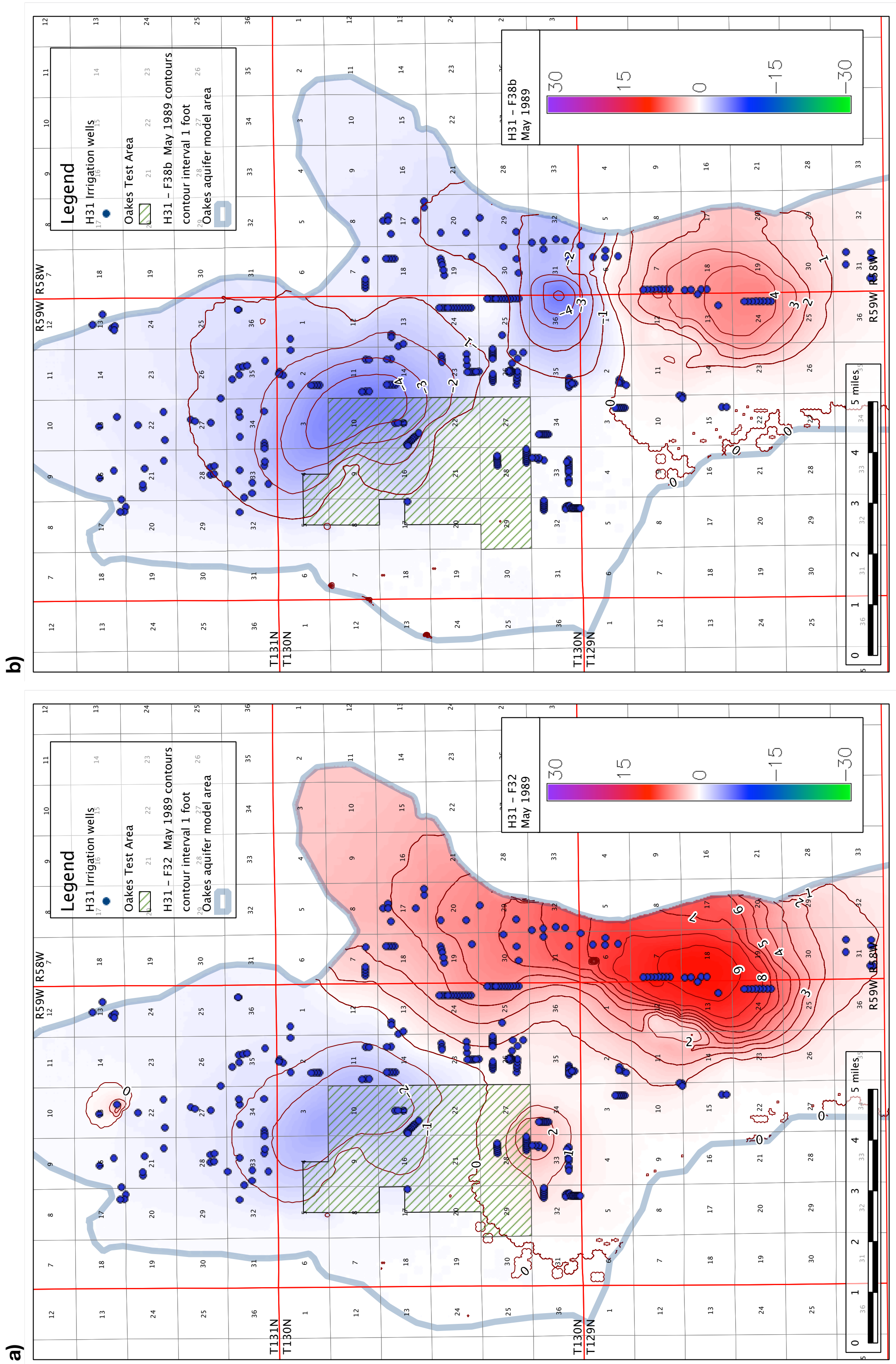


Figure 121. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **May 31, 1989** of 1905 to 2005 simulation.

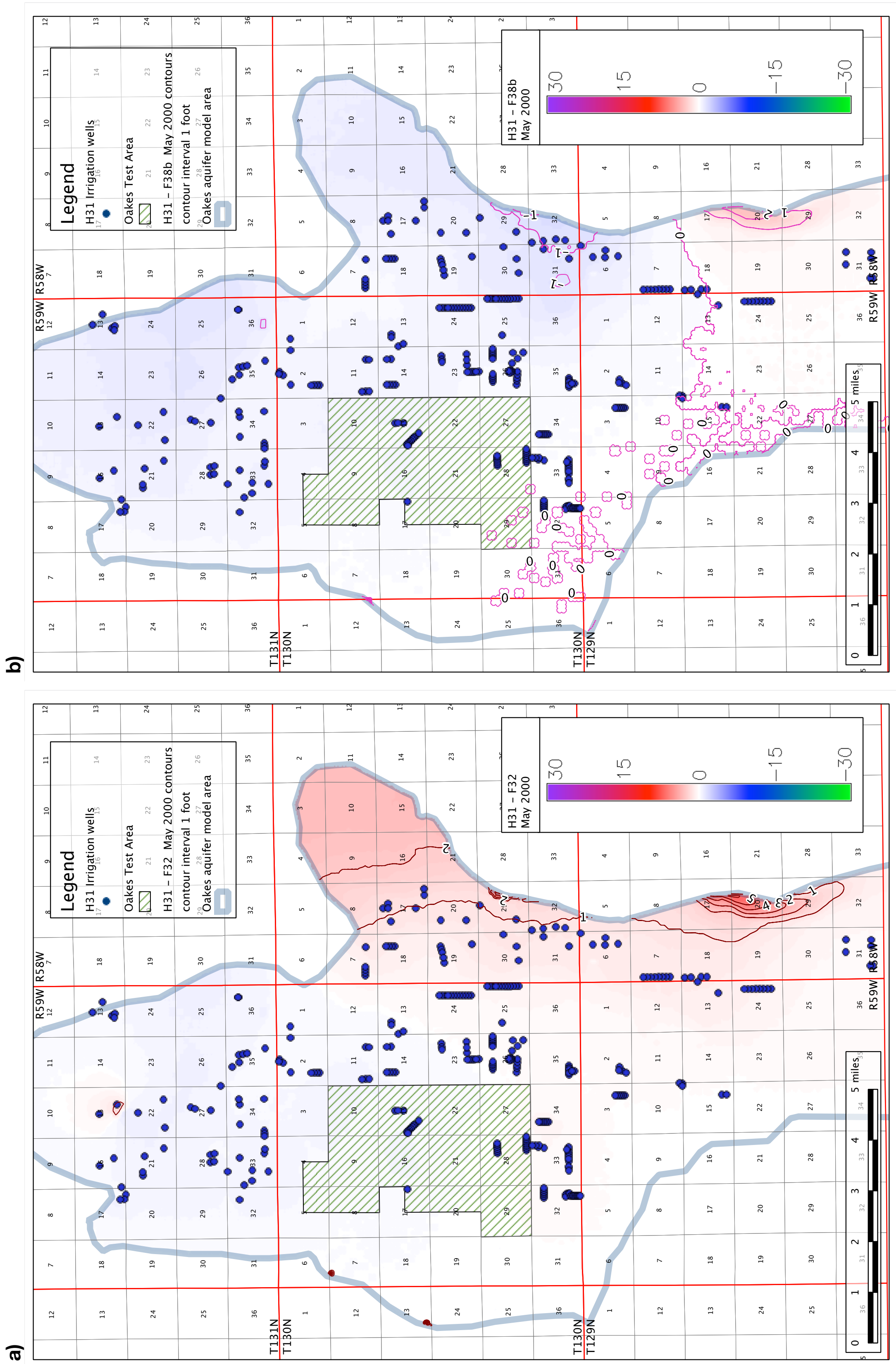


Figure 122. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **May 31, 2000** of 1905 to 2005 simulation.

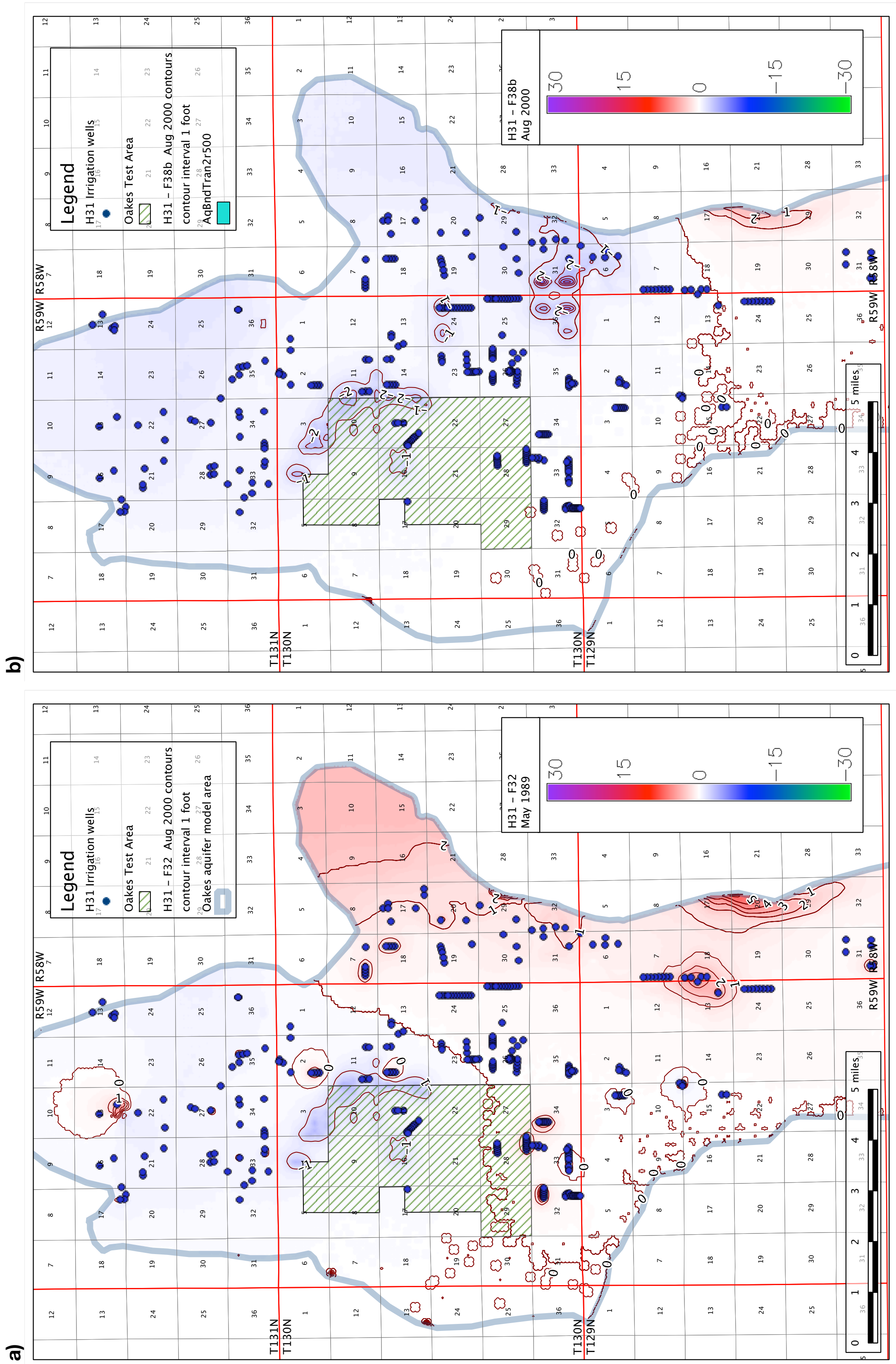


Figure 123. Difference in water levels between DSID-Esser and a) permitted and b) permitted + pending for **August 31, 2000** of 1905 to 2005 simulation.

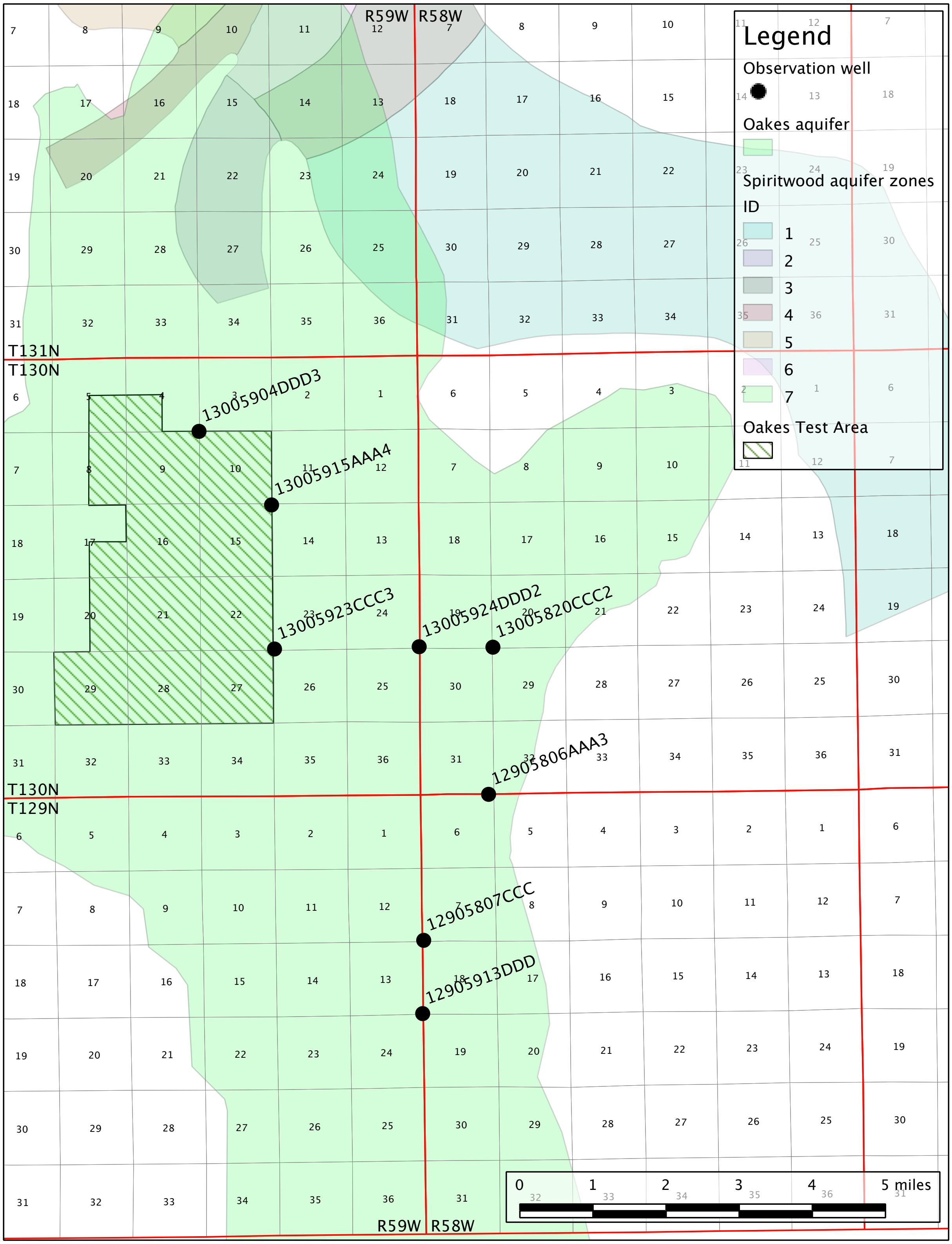
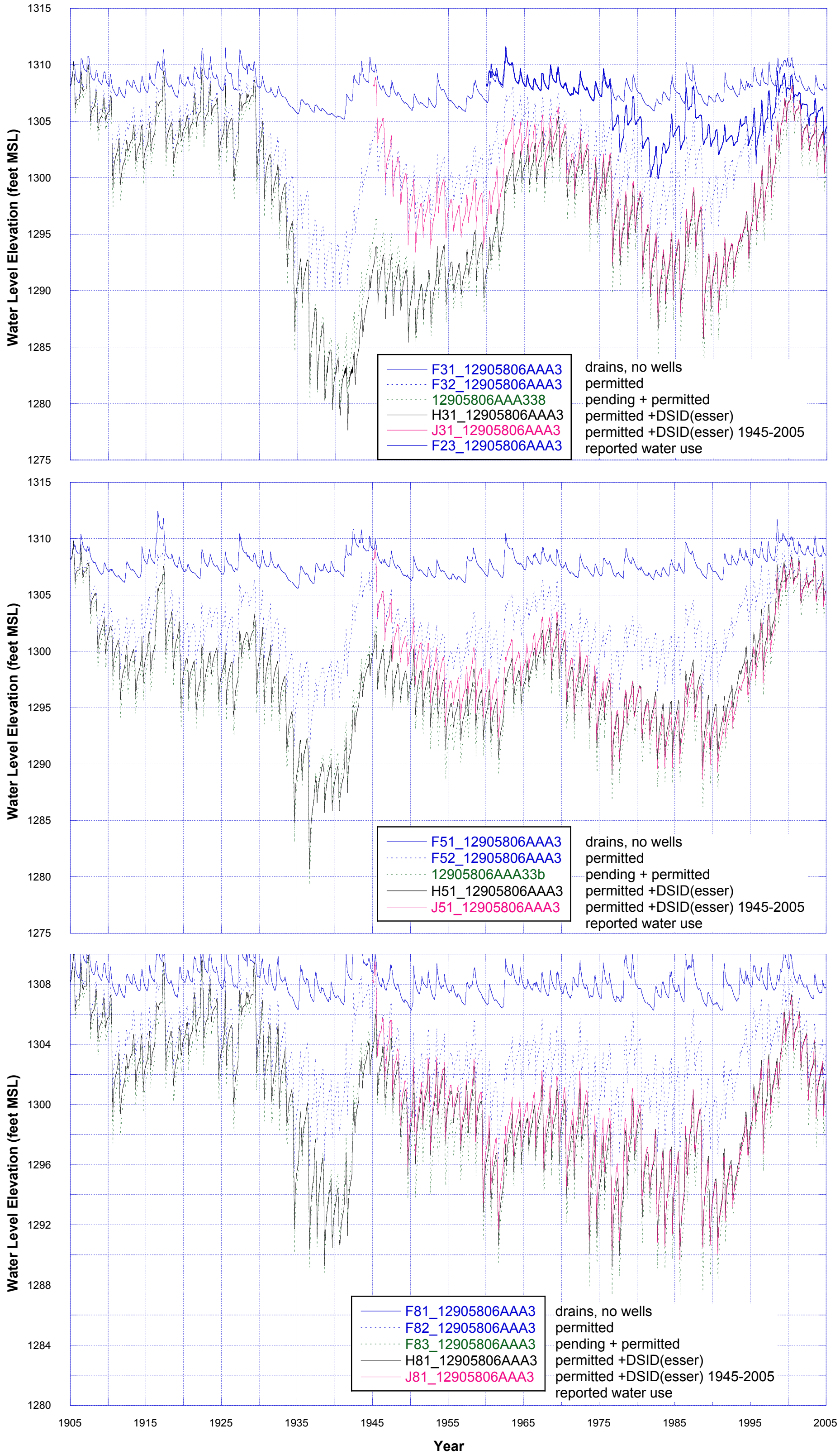


Figure 124. Location of observation wells for which hydrographs of simulated water levels are shown in figures 125 to 135.



a)

b)

c)

Figure 125. Comparisons of drawdowns at observation well **129-058-06AAA3** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

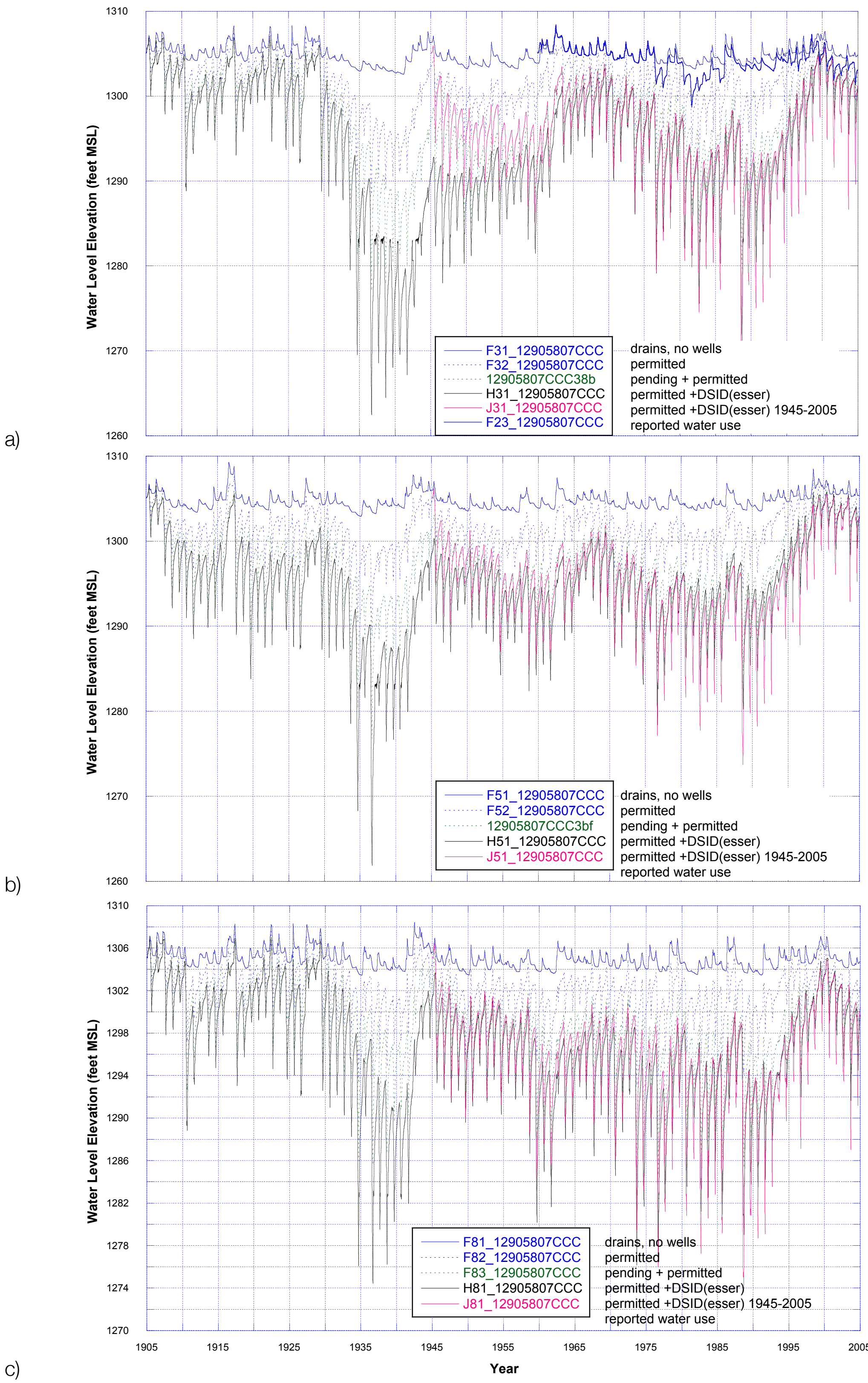


Figure 126. Comparisons of drawdowns at observation well **129-058-07CCC** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

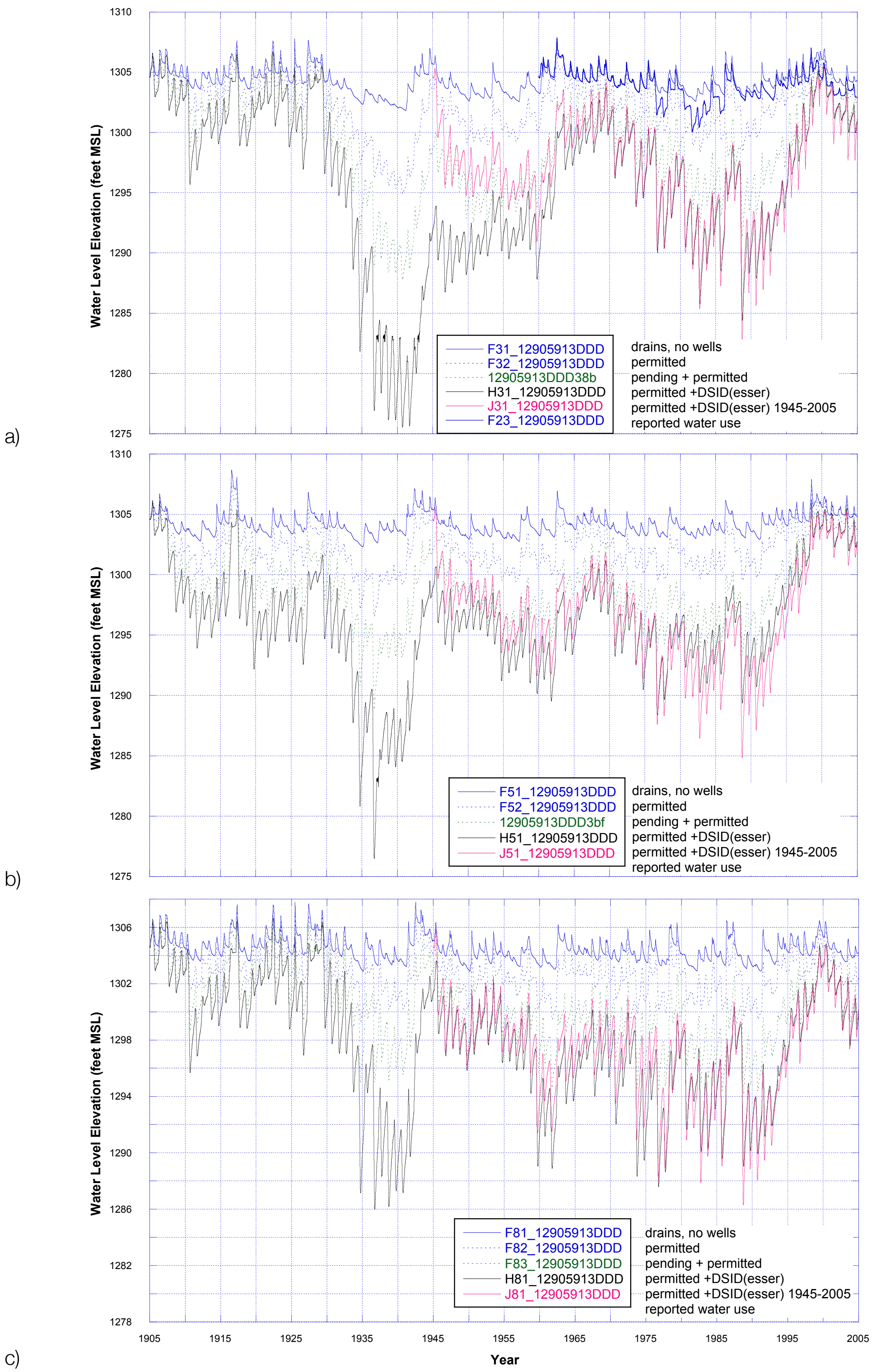
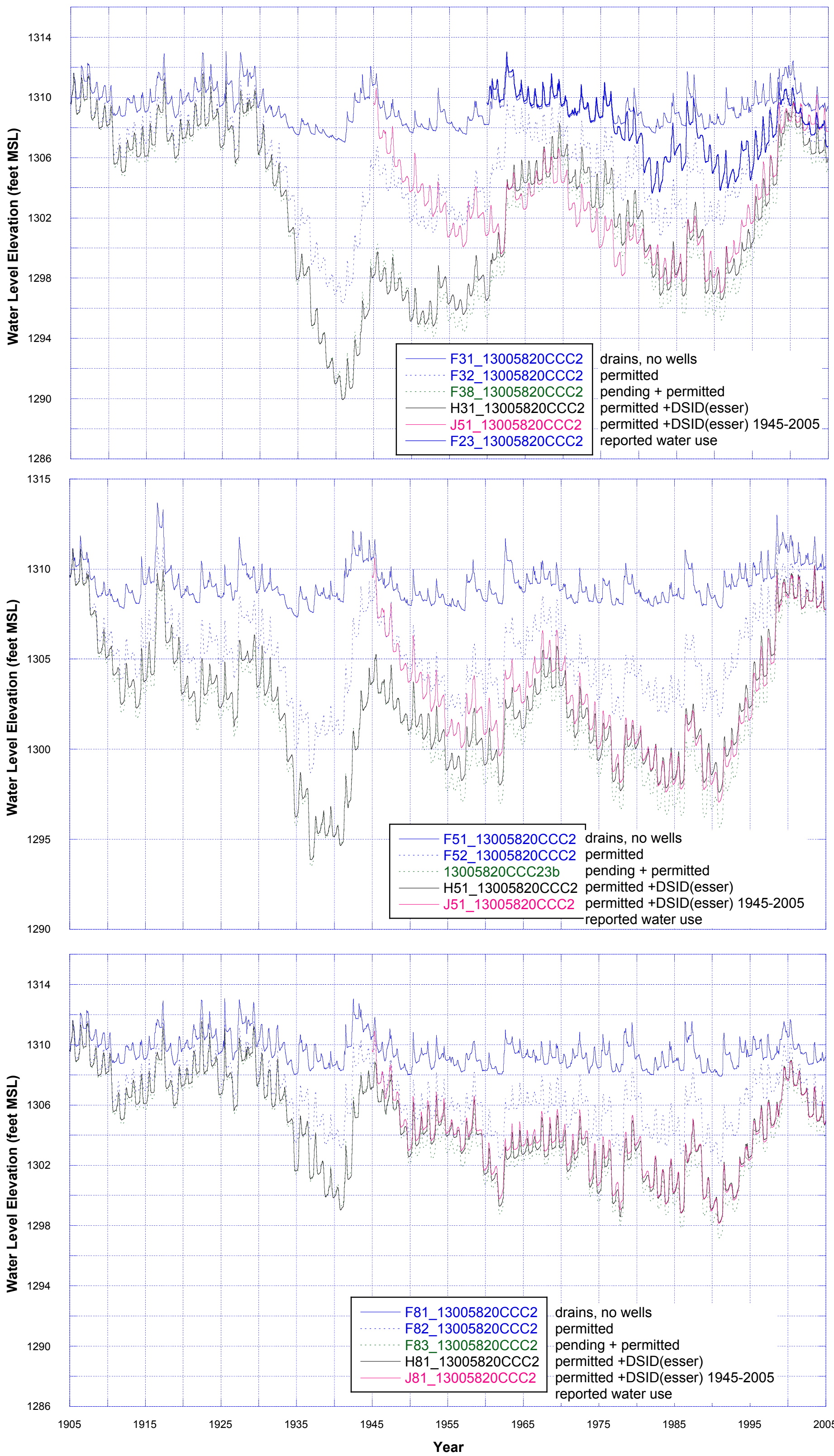


Figure 127. Comparisons of drawdowns at observation well **129-059-13DDD** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.



a)
b)
c)

Figure 128. Comparisons of drawdowns at observation well **130-058-20CCC2** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

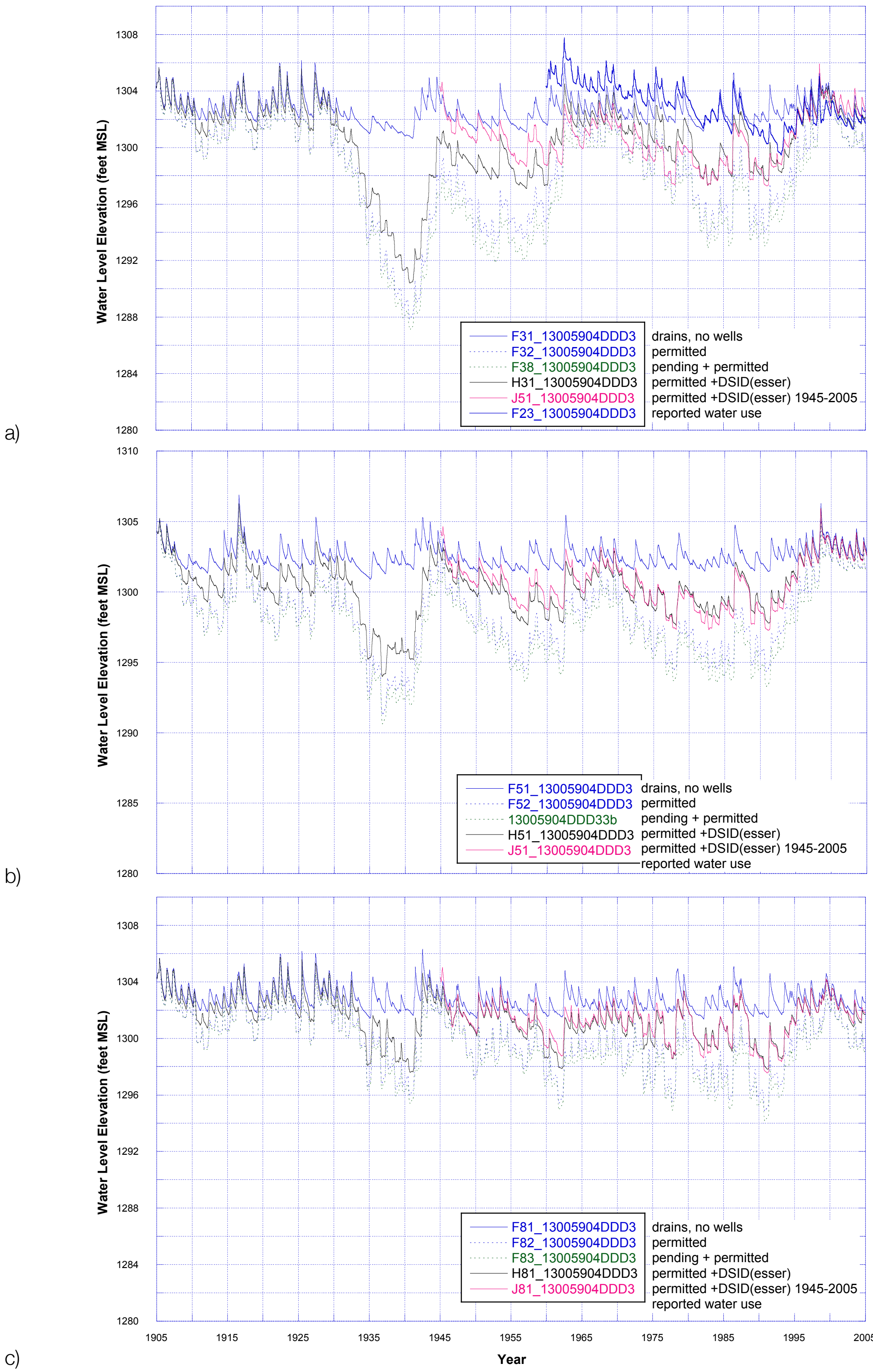
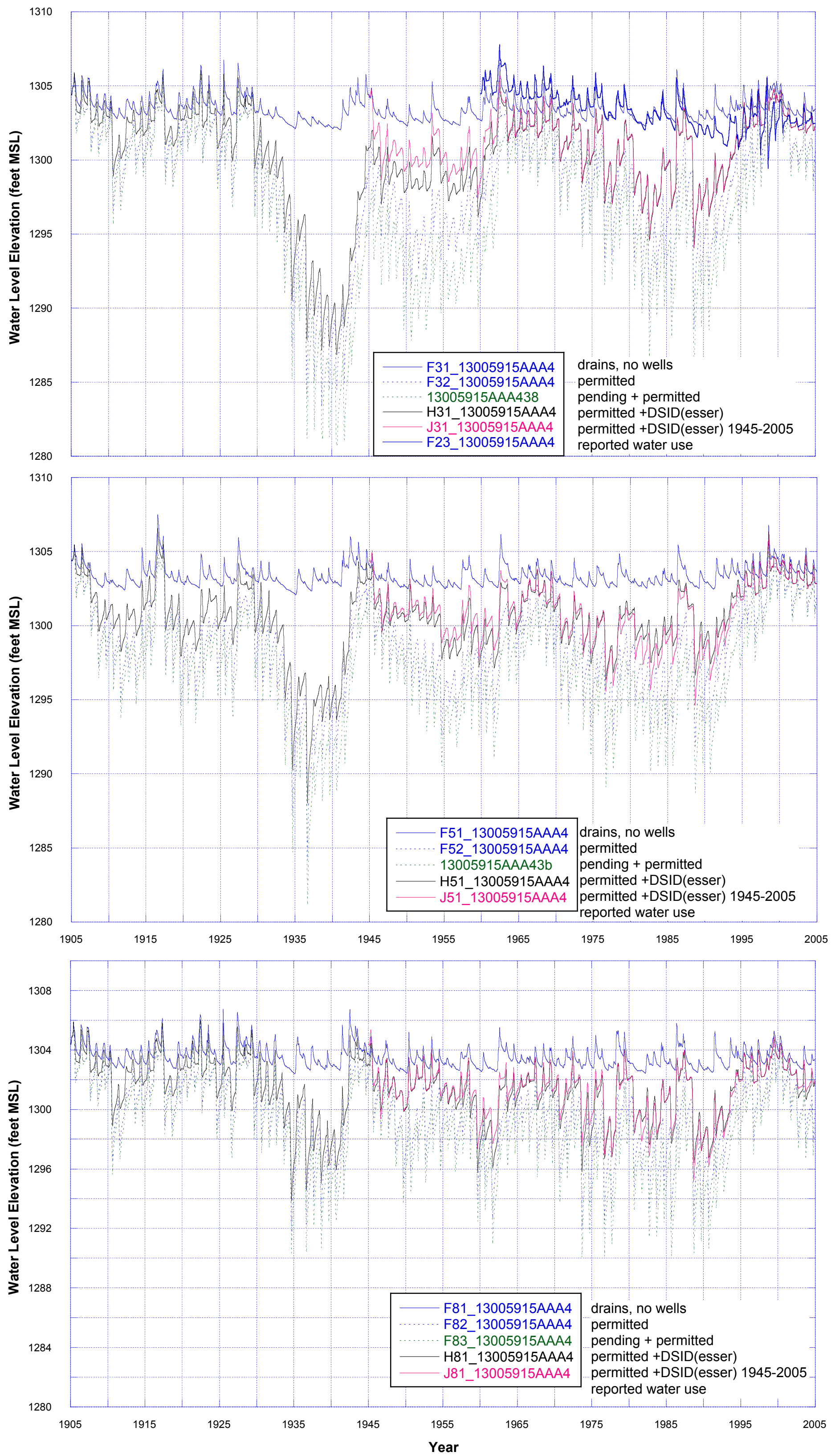


Figure 129. Comparisons of drawdowns at observation well **130-059-04DDD3** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.



a) b) c)

Figure 130. Comparisons of drawdowns at observation well **130-059-15AAA4** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

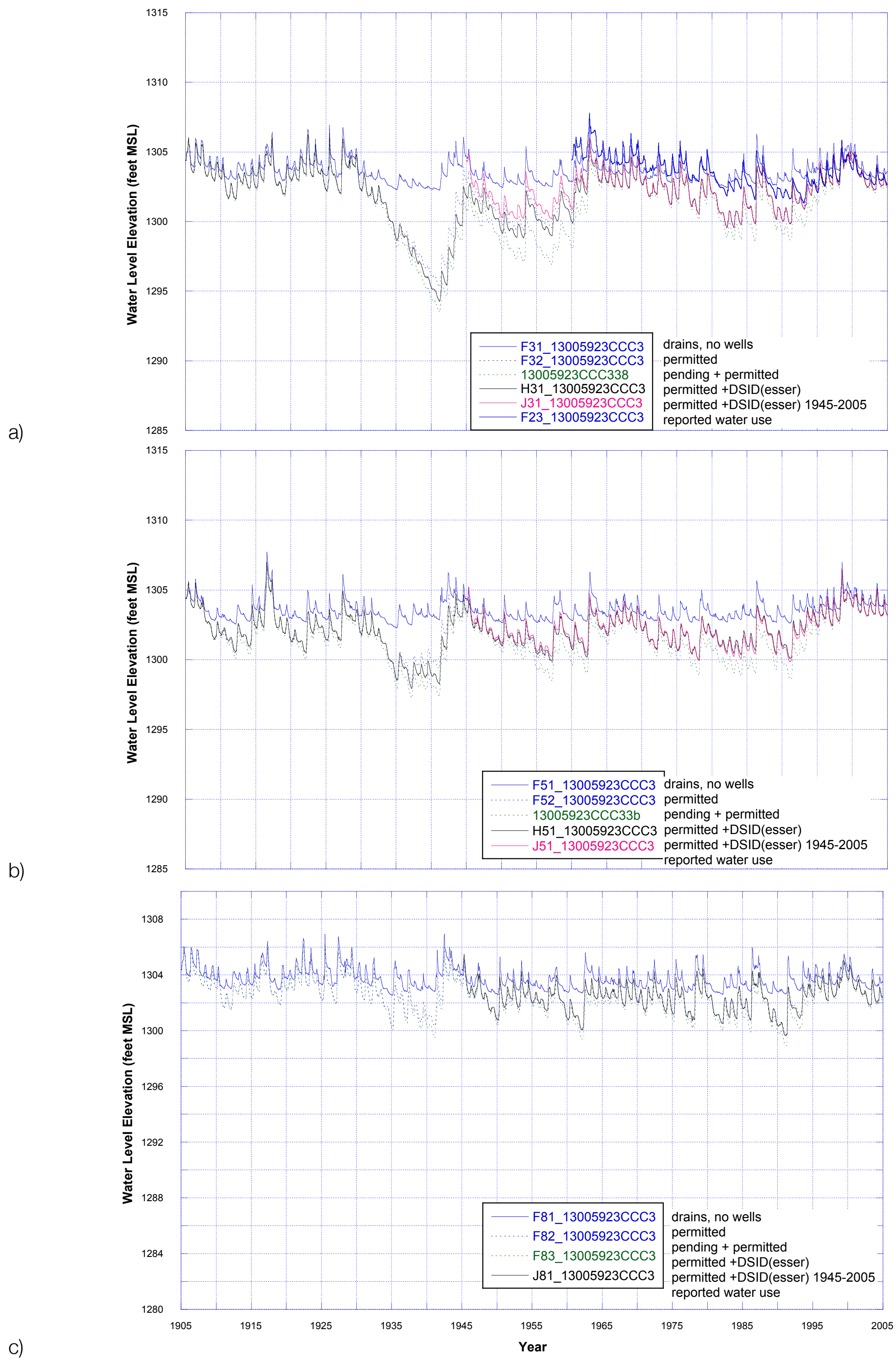


Figure 131. Comparisons of drawdowns at observation well **130-059-23CCC3** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

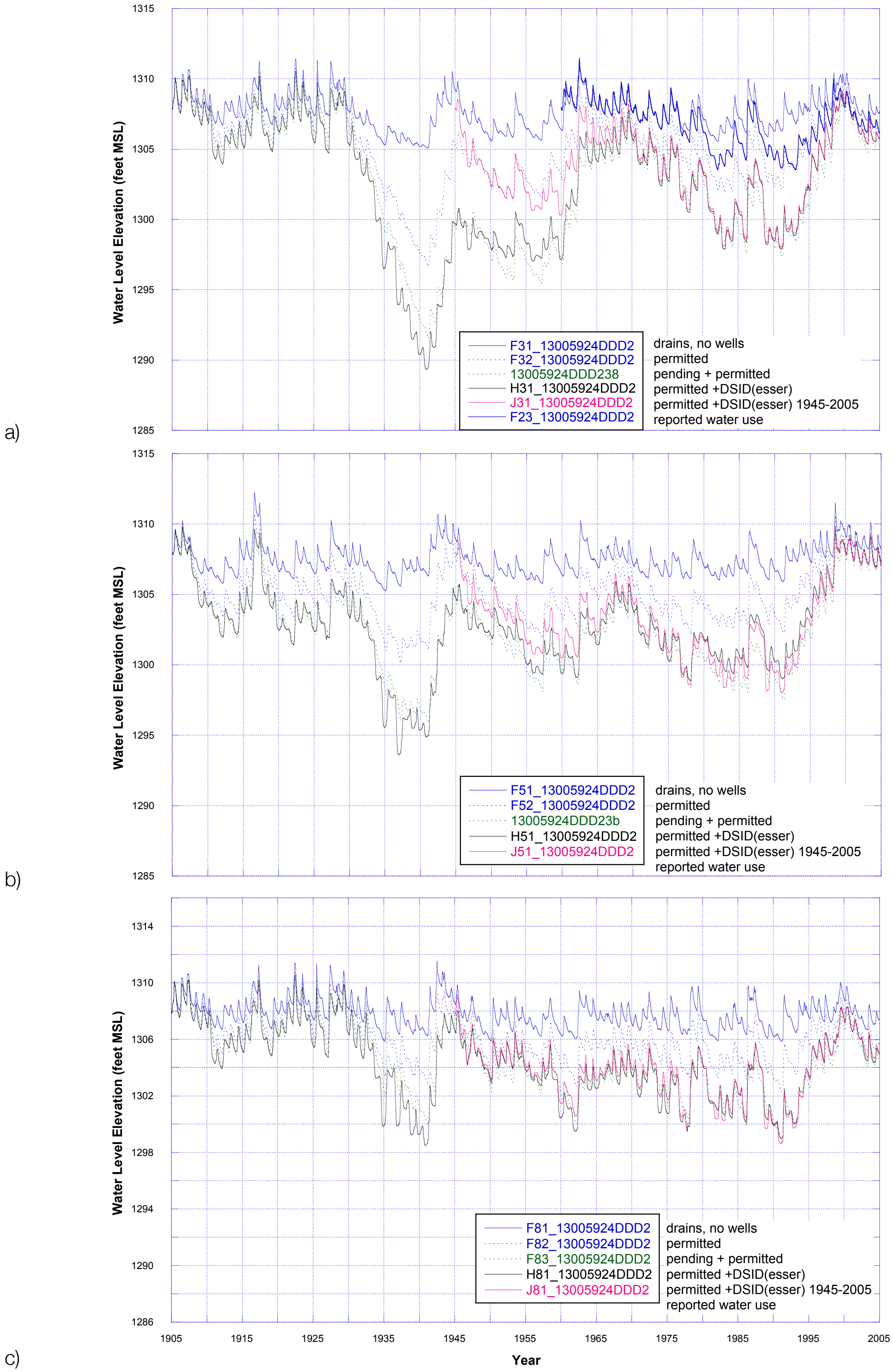


Figure 132. Comparisons of drawdowns at observation well **130-059-24DDD2** for a) Oakes climate, b) Forman climate, and c) Fullerton climate.

DSID - Groundwater Only

Prior to considering the DSID-Esser case, the feasibility of supplying water to the OTA using only groundwater was examined. It was assumed that 1,200 acres were irrigated from the interim well field. Wells located in E1⁄2 sec. 24 and E1/2 sec. 25, T. 130 N., R. 59 W. and deep channel wells located in sec. 7, T. 129 N., R. 58 W. and SW1/4 sec. 13 and E1/2 sec. 24, T. 129 N., R. 59 W. were considered in these scenarios. Besides the 1,200 ac-ft from the interim well field, case of 0, 3,050, 3,800, and 2,300 ac-ft were considered from the proposed well fields. Pending permits within the OTA and those listed in table 10 were excluded from the simulations. The simulated impacts of these scenarios in comparison to DSID-Esser at three observation wells in the deep channel are shown in figures 133, 134, and 135. Even the 2,300 ac-ft case results in drawdown exceeding that of the DSID-Esser case. All three cases result in prolonged residuals following the 1930s' drought with large drawdown. These drawdowns would likely adversely impact senior appropriators in and near the deep channel. Given present estimates of groundwater recharge, it appears unlikely that the water to irrigate over 2,000 acres can be obtained from the Oakes aquifer. To irrigate 5,000 acres in the OTA requires a mix of surface water and groundwater as presented in the DSID-Esser case.

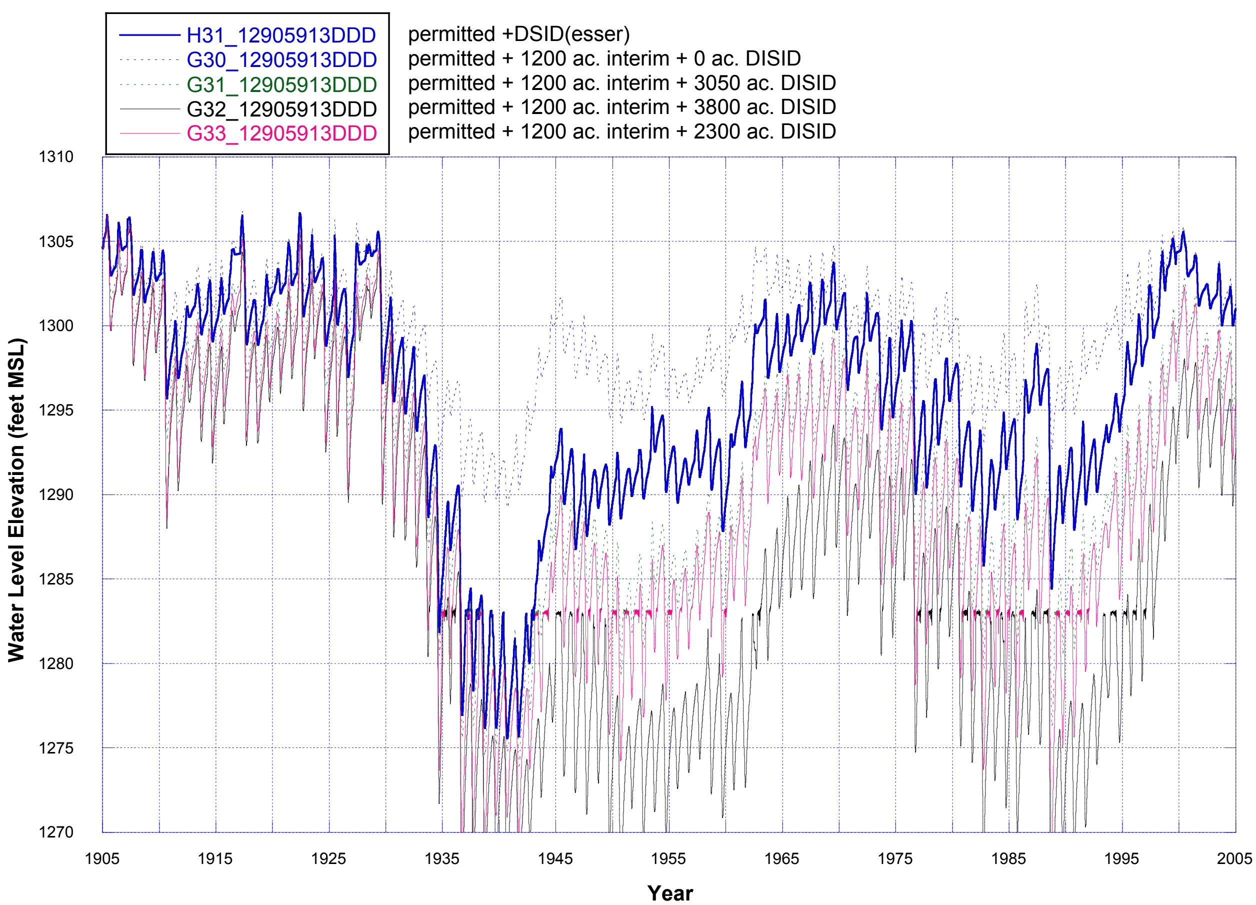


Figure 133. Comparisons of drawdowns at observation well **129-059-13DDD** for irrigation of 1,200 acres from interim well field and 0, 3,050, 3,800, and 2,300 from the deep channel. Includes permitted plus some pending water permits.

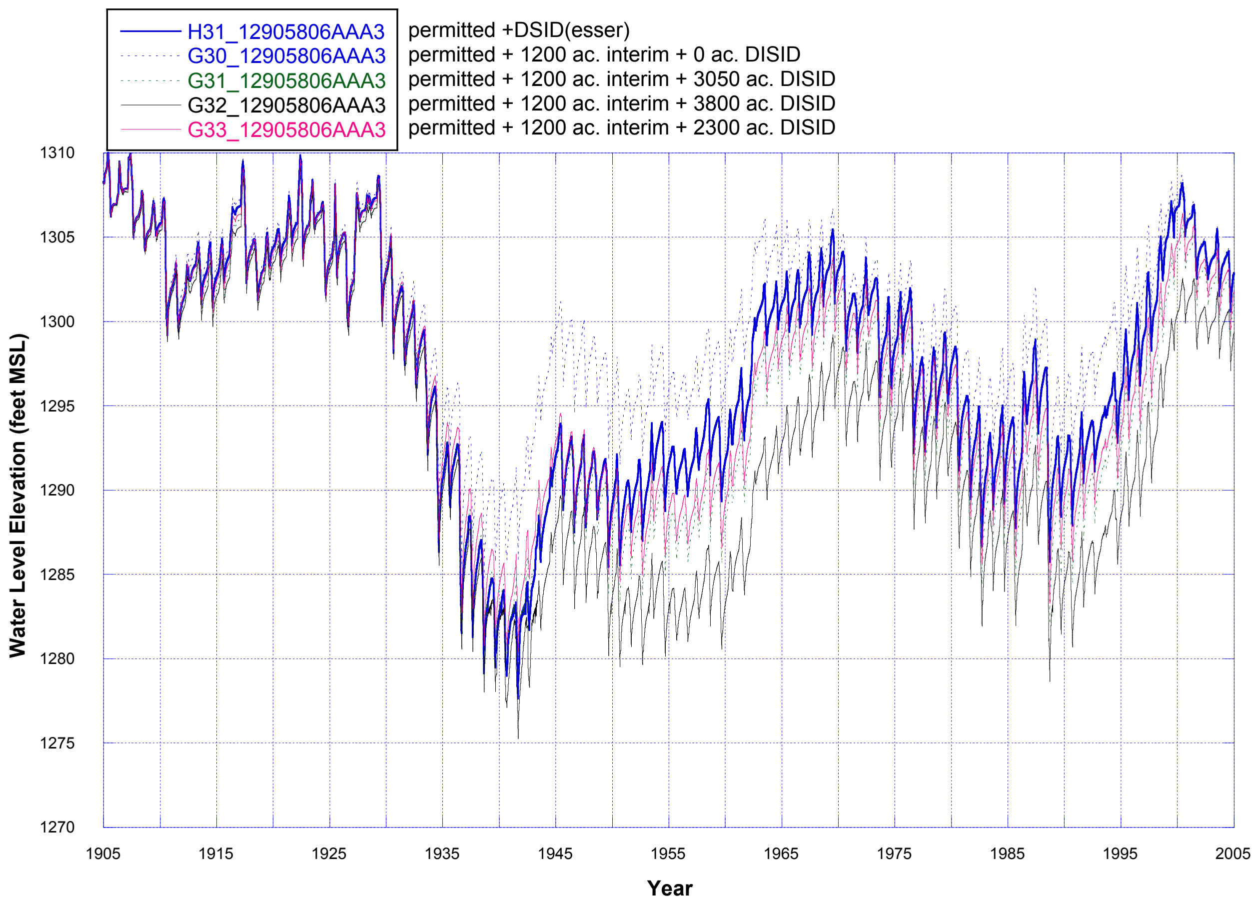


Figure 134. Comparisons of drawdowns at observation well **129-058-06AAA3** for irrigation of 1,200 acres from interim well field and 0, 3,050, 3,800, and 2,300 from the deep channel. Includes permitted plus some pending water permits.

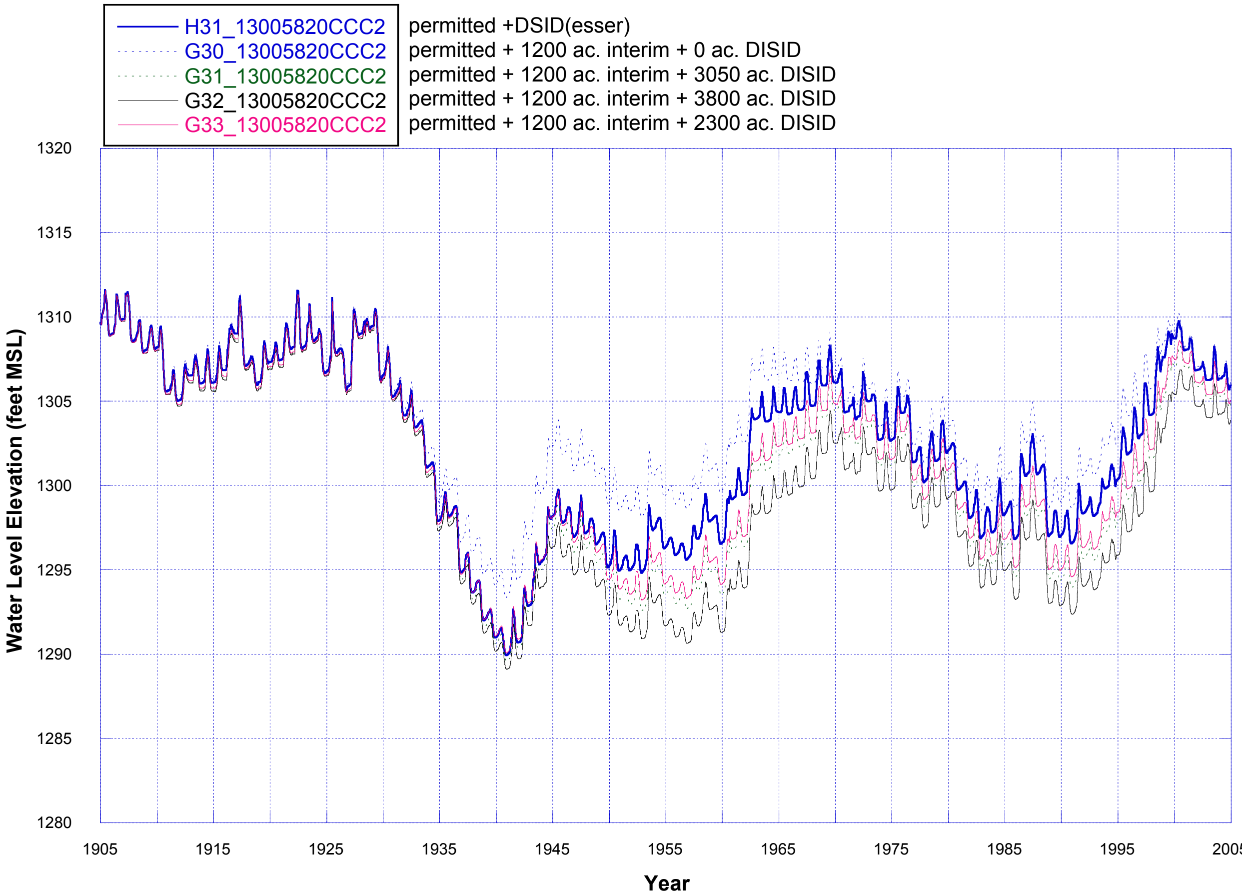


Figure 135. Comparisons of drawdowns at observation well **130-058-20CCC2** for irrigation of 1,200 acres from interim well field and 0, 3050, 3800, and 2300 from the deep channel. Includes permitted plus some pending water permits.

Summary and Conclusions

The permitted irrigation from the Oakes aquifer is 13,612 acres. In addition, the area north of Oakes is permitted for 1,165 acres of irrigation from the Spiritwood aquifer and 283 acres of irrigation from the Middle James aquifer which underlie and are hydraulically connected to the Oakes aquifer. The total acres irrigated from the Oakes aquifer and hydraulically connected units is 15,060 acres. Between January 1, 1991 and January 1, 1997 permits were granted to irrigate an additional 3,945 acres from the Oakes aquifer. Of this total, 2,182 acres were from the deep channel and 921 acres were from an area 1 to 2 miles to the west of the deep channel. This was a 35 percent increase in acres irrigated. However, because of the wet period that began in 1993 and the resulting high water table conditions, this resulted in no increase in actual acres irrigated and a decline in total water use. There are pending permits from the Oakes aquifer, with a priority date prior to July 31, 2006, to irrigate 4,252 acres. On July 31, 2006 DSID applied for 5,000 acre-feet of water to irrigate 5,000 acres. The granting of any additional water has significant uncertainties because little is known about the impact of the 3,945 acres granted in the 1990s.

There is considerable decadal variability of precipitation as seen in the comparison of Oakes, Forman, Fullerton, Lisbon, and Britton. By examining the response of the Oakes aquifer using these various climate datasets, a greater understanding of the reliability of the aquifer with a given amount of irrigation can be developed.

Calibration of the model indicates an average recharge rate of 5.5 inches per year. Estimation of PET from only maximum and minimum temperatures will underestimate the variability in PET between wet and dry periods. In a sub-humid climate such as the Oakes area, minimum temperature is not a good approximation of dew point temperature used in the calculation of PET. Also, using only a single soil to estimate groundwater recharge, ET_{gw}, and irrigation water use will not reproduce the variability of recharge due to climate that accounting for all of the variability in soils and land use across the aquifer would. Though the transient calibration reproduces 1967 to 1990 water levels, it underestimates water levels from 1991 through 2007. Part of this is due to the Oakes climate dataset underestimating precipitation over the aquifer in the early 1990s. The model significantly underestimates drain flows from the OTA during the wet period from the mid-1990s to present, which indicates that the model is significantly underestimating recharge during this period. Modeling of the Englevale and Trappers Coulee aquifers has had a similar problem of reproducing the rise in water levels in the 1990s. Because of the underestimation of recharge in wet periods, the model is too dry on average, but how much is not known. Until issues with the the soil moisture budget model underestimating the variability in recharge between wet and dry periods is resolved, trying to history match wet periods during calibration of the model likely would result in significantly underestimating water level declines in dry periods which could result in overallocation of water.

With the flat water table gradient across the Oakes aquifer, irrigation wells derive most of their water by lowering the water table sufficiently in the vicinity of the well to capture the amount of water that would be lost from ET. The present permitted irrigation eliminates much of the ET from the aquifer. The permitted plus pending simulations indicate that almost all of the ET is being captured indicating that no water is available beyond the pending permits (priority date prior to July 31, 2006). This leaves no water available for DSID if most of the pending irrigation is developed.

The analysis indicates that the only way that DSID can proceed with development of a groundwater supply for the OTA is to obtain agreements with the holders of pending permits that would allow the granting of the DSID permit ahead of these pending permits with the higher priority date. In this analysis, three sources of water are considered to supply the OTA. These are the existing interim well field, middle well field consisting of wells in E1/2 section 24 and E1/2 section 25, T. 130 N., R. 59 W., and the deep channel well field consisting of wells located in the SW1/4 sec. 7, T. 129 N., R. 58 W., SE1/4 sec. 13, and E1/2 sec. 24, T. 129 N., R. 59 W. In the DSID-Esser simulations, the middle well field only supplied 16 percent of the water which could be obtained from the deep channel well field. The interim well field supplied 25 percent and the deep channel well field supplied 59 percent of the total groundwater required by DSID-Esser.

In the simulations, the interim well field was used to supply water to existing water permits within the OTA that do not have adequate water supplies (table 8). The permits in this table are from Lindvig (2006) and permits that have generally been supplied by DSID. Permits labeled OTA in table 8 have inadequate water supplies and have been supplied by DSID. These are in an area of very thin saturated thickness along the west side to the OTA. Without an alternate supply of water, any additional development within and adjacent to the OTA would adversely impact these senior appropriators and therefore would not be granted. A possible source of water for some of these permits could be the channel in the W1/2 sections 8 and 17, T. 130 N., R. 59 W. At NDSWC observation well 13005908CDC, over 30 feet of a very fine to medium sand is saturated. Further test drilling in this channel is needed to assess its yield capability.

The pending permits near the interim well field are listed in table 11. The simulations assumed that permits #4209 and #4526 were developed, but those permits within the OTA would not be developed. The model indicates that permits #2095 and #3252 may be adversely impacted by pumping of the interim well field during droughts (table 12). The DSID may need to supply these two permits with water during periods of drought. The model also indicates that additional development near the northern part of the OTA has the potential to pull very poor quality water from the east in sections 1 and 12 into this area. No simulations were made as to how much, if any, additional water could be granted if DSID was not supplying water to permits with inadequate water supplies. However, it is unlikely that any of these permits would be granted, particularly those within the OTA, as previously discussed.

In the operation of the interim well field, DSID will need to restrict usage during dry periods to avoid pulling in poor quality water from the west. If DSID proceeds with development or pending permits are approved, then additional observation wells need to be installed to ensure that the poor quality water is not being pulled to the west.

Table 11. Pending permits near the interim well field. Pending permits within the OTA are indicated in yellow. Pending permits 4209 and 4526 were included in the simulations.

Permit	Owner	POD	Aquifer	Status	Priority Date	Ac-Ft	Acres
4175	RONEY, DENNIS P.	13005910D	Oakes	Pending	1989-12-21	243.8	162.5
4209	RONEY, LARRY	13005902C	Oakes	Pending	1990-03-14	225.5	150.3
4526	RONEY, DENNIS P.	13005914B	Oakes	Pending	1991-10-17	237.0	158.0
4848	QUANDT, JAMES	13005915A	Oakes	Pending	1994-12-30	234.6	156.4
5101	WHITE, GARY	13005915D	Oakes	Pending	1997-01-29	234.0	156.0
5818	REHOVSKY, JOSEPH	13005910B	NULL	Pending	2006-03-22	177.0	117.9

Table 12. Permits near interim well field within the OTA that may be adversely impacted by additional development within their vicinity. Neither of these permits have been served by the OTA.

Permit	Owner	POD	Aquifer	Status	Priority Date	Ac-Ft	Acres
2095	DANIELS, THOMAS N.	13005915B	Oakes	Pending	1974-05-03	232.5	155.0
3252	KBO FARM PARTNERSHIP	13005915C	Oakes	Pending	1980-04-17	200.7	133.8

The simulations included the middle well field which is capable of supplying a limited amount of water to the OTA. If development of this well field were pursued, then DSID would need to reach an agreement with the owner of the permit listed in table 13 not to develop.

Table 13. Pending permits east of OTA at site of proposed DSID well field in the E1/2 section 24 and E1/2 section 25, T. 130 N., R. 59 W.

Permit	Owner	POD	Aquifer	Status	Priority Date	Ac-Ft	Acres
04742A	RONEY, DENNIS & RAMONA	13005924B	Oakes	Pending	1993-12-22	401.4	267.6

The primary source of groundwater available to DSID is the southern part of the deep channel. The deep channel in T. 130 N., R. 58 W. is less than 0.5 miles wide. This part of the channel will not yield significantly more water than is presently permitted from this area. The model indicates that there is little additional ET available in this area to salvage. In T. 129. the fluvial sand and gravels of the channel broaden significantly in the interval between 1,200 and 1,260 feet in elevation indicating what is likely a delta formed at an earlier stage of Lake Dakota. It is within this delta and the underlying meltwater channel that DSID has the opportunity to develop a supplemental water supply for the OTA. However, there are pending permits along the margins and in the deep channel listed in table 14 that if granted would preclude additional development within the deep channel. The disposition of pending permits further to the north in or near the deep channel, though there would be some impact from a DSID deep channel well field, will mostly be determined by neighboring permits.

To determine, which of the permits listed in table 14 would potentially be granted will require additional analysis with the Oakes model. This will require running the model with various combinations of these pending permits.

Table 14. Pending permits in or near the deep channel that would be impacted by DSID pumping from the southern deep channel to supply the OTA. Permit 4991 was included in simulations, but has been sold. It now may not have a POD with a viable water supply.

Permit	Owner	POD	Aquifer	Status	Priority Date	Ac-Ft	Acres
04741A	HANSEN, PHILIP A.	13005831B	Oakes	Pending	1993-12-22	197.7	131.8
4776	ANDERSON, JOEL	13005831C	Oakes	Pending	1994-04-28	232.5	154.4
4835	SCHMIT, KIM	13005936D	Oakes	Pending	1994-12-22	233.4	155.6
4903	HANSEN, PHILIP A.	13005936C	Oakes	Pending	1995-05-08	234.0	156.0
4989	KBO FARM PARTNERSHIP	13005936A	Oakes	Pending	1996-02-16	234.0	156.0
4991	KBO FARM PARTNERSHIP	13005832C	Oakes	Pending	1996-02-16	289.2	192.6
5014	HANSEN, LARRY AND NANCY	12905806B	Oakes	Pending	1996-05-16	720.0	480.0

The study has shown that it is unlikely that there is sufficient water for DSID to irrigate 5,000 acres within the OTA, including existing permits from groundwater, even if the pending permits are not developed. However, using the estimates of available surface water to irrigate the OTA provided by Dale Esser, there is sufficient groundwater available to irrigate 5,000 acres in the OTA. Groundwater would supply on average 40 percent of the water to irrigate the test area. Most of this water would need to come from the southern part of deep channel. The existing development in the Oakes aquifer is capturing most of the ET within its vicinity precluding any significant additional development except from the southern part of the deep channel.

Because the model underestimates recharge in the wetter periods, it is considered conservative in its estimation of available water. Further refinement of the model may indicate that additional water is available. A return to a drier climate with increased stress that included the full impact of the present permitted irrigation would allow a re-calibration of the model. Improved methods of estimating groundwater recharge and ET_{gw} would also allow the model to be re-calibrated.

The Oakes aquifer model described in this report can now be used to explore various pumping scenarios for the evaluation of the pending permits individually. The model will provide the basis for the management of the Oakes aquifer for many years to come. A model is not a static entity, but evolves through time as additional data and modeling techniques become available.

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