Hydrogeology and Modeling of the Trappers Coulee Aquifer

By

R. L. Cline

Water Resource Investigation No. 41

North Dakota State Water Commission

2007, editorial revisions in 2017

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Datum and Projections

All vertical elevations in this study are referenced to the National Geodetic Vertical Datum of 1929. Horizontal coordinates are referenced to the North American Datum of 1927. All map coordinates are in UTM zone 14.

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Abstract

The Trappers Coulee aquifer is composed of a meltwater channel and outwash plain that developed where a tunnel valley discharged along the Martin End Moraine that has been significantly eroded since the down cutting of the Sheyenne River meltwater trench to the south of the project area.

The modeling of the Trappers Coulee aquifer has raised a set of issues that are not unique to this aquifer, but dominate this modeling exercise, where in more extensive aquifers they play a lesser role and are often offset by compensating errors within other parts of the model. Only one-third of the inflow to the aquifer is received from direct recharge with the remainder occurring from either an adjoining outwash, inflow from the Fox Hills Formation, or infiltration of runoff from adjacent areas. The modeling indicates that a likely significant source of recharge to the aquifer is from surface water runoff from adjoining areas. This process has not been accounted for in the model. Given the important role that it plays, its incorporation into the model will be required to use the model to make management decisions.

The following factors are significant to many aquifer areas; 1) areas of surficial outwash that have saturated thicknesses of less than ten and often less than five feet. These areas can be very difficult to simulate because of nodes going dry and general instability and convergence problems in the model. Because of the difficulty in modeling, these areas are often ignored. 2) Surface-water runoff either as sheetflow from surrounding hillsides or small streams adding additional recharge to the aquifer. This process likely amplifies the variability in recharge due to climatic fluctuations. 3) Inflow into the aquifer from surrounding low permeability sediments. 4) A less common problem is the cross-sectional area of the aquifer changes significantly with changes in water table elevation, resulting in the choice between a significant conceptualization error or severe model instability issues with nodes with thin saturated thickness converting between wet and dry compounded by the simulation of the small permeability sediments into which the channel is incised.

The model indicates that the present level of development from the Trappers Coulee aquifer is sustainable under the range of climatic variability that was observed in north-central North Dakota during the 20th century. The appropriation of water to irrigate an additional 270 acres is sustainable under average climatic conditions, however drought conditions have occurred in the region in the 20th century that would result in well yields being adversely affected.

Introduction

To date, the State Engineer has granted 1171 acre-feet of water to irrigate 840.5 acres from the Trappers Coulee aquifer. The location and status of water permits is shown in figure 1. Priority dates of water permits and applications are shown in figure 2. The first two quarters of irrigation development occurred in 1978 under water permit #2534 supplied by an irrigation well located in the center of the NW1/4 Section 29, Township 153 North, Range 71 West. No additional irrigation development took place until the fall of 1997 when two irrigation wells were drilled to supply water to permits #2589 and #3029. The new irrigation development was for the production of seed potatoes. During the fall of 1997 and spring of 1998, water permit applications #5173, #5187 (to increase the appropriation under #2534 to 18 inches per acre), 5196, and 5224 were received.

Because of the concern about the ability of the aquifer to sustain significant development (permit #3029), the last 202.5 acre-feet granted was conditioned as follows:

The permit to appropriate 202.5 acre feet of water to irrigate the S½NW½ and N½SW½ Section 28, Township 153 North, Range 71 West will expire December 31, 2008. Prior to the expiration date of December 31, 2008, the appropriation will be re-evaluated and will be re-instated if it is found that the source (Trappers Coulee aquifer) can sustain the appropriation for a longer period of time. The permit holder shall be notified of the results of the evaluation by the expiration date of December 31, 2008. The State Engineer may re-evaluate the permit at any time before the December 31, 2008 expiration date and remove the expiration date if it is determined that the source will support the appropriation.

There are three pending permit applications for new irrigation for a total of 1140 acre-feet to irrigate 758 acres from the Trappers Coulee aquifer. At an expected annual water use of 10 inches per year, the average appropriation would increase 632 acre-feet per year. There are presently 1261 acre-feet of water appropriated from the Trappers Coulee aquifer to irrigate 840.5 acres of land. Again, assuming annual water use of 10 inches per year, the present appropriation uses an average of 700 acre-feet per year. Assuming an annual recharge rate of 3.5 inches per year for the 3-mile reach of the aquifer, total recharge is 260 acre-feet per year indicating that most of the water must come from the adjacent outwash, the Fox Hills aquifer, or surface runoff infiltrating into the aquifer. The only way to develop an understanding of these components of the aquifer's water budget was to develop a ground-water model of the aquifer.

The U.S. Geological Survey's ground-water flow model, MODFLOW, was used to develop the model. All hydrogeologic data used in this study, including water-level data, bore hole lithologies, and water-quality data are available from the NDSWC website at URL http://www.swc.nd.gov/info_edu/map_data_resources/ either through the "Map Services" or "Ground - Surface Water" and "Private Contractor Logs" web pages.

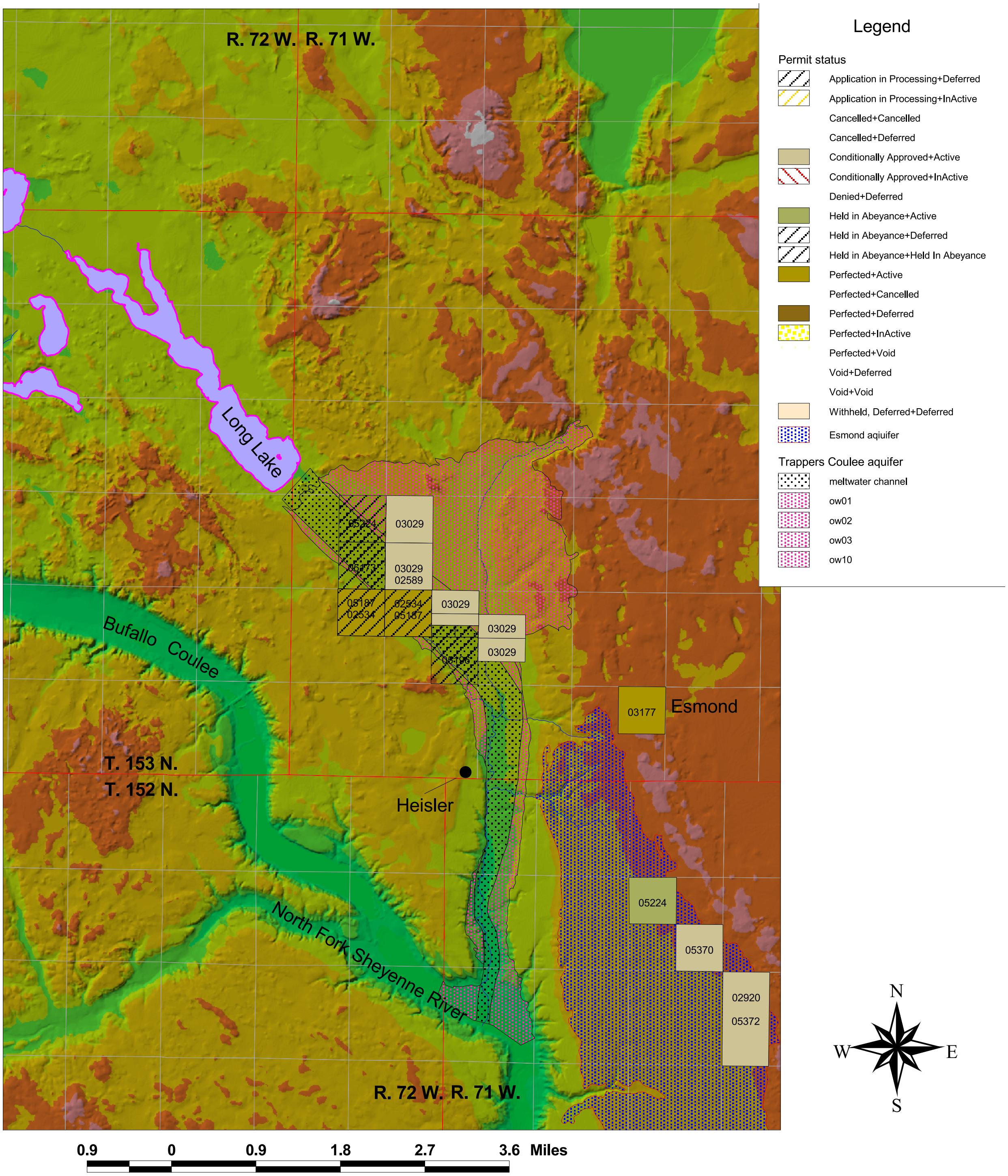


Figure 1. Location and status of water permits in the Trappers Coulee and Esmond aquifers.

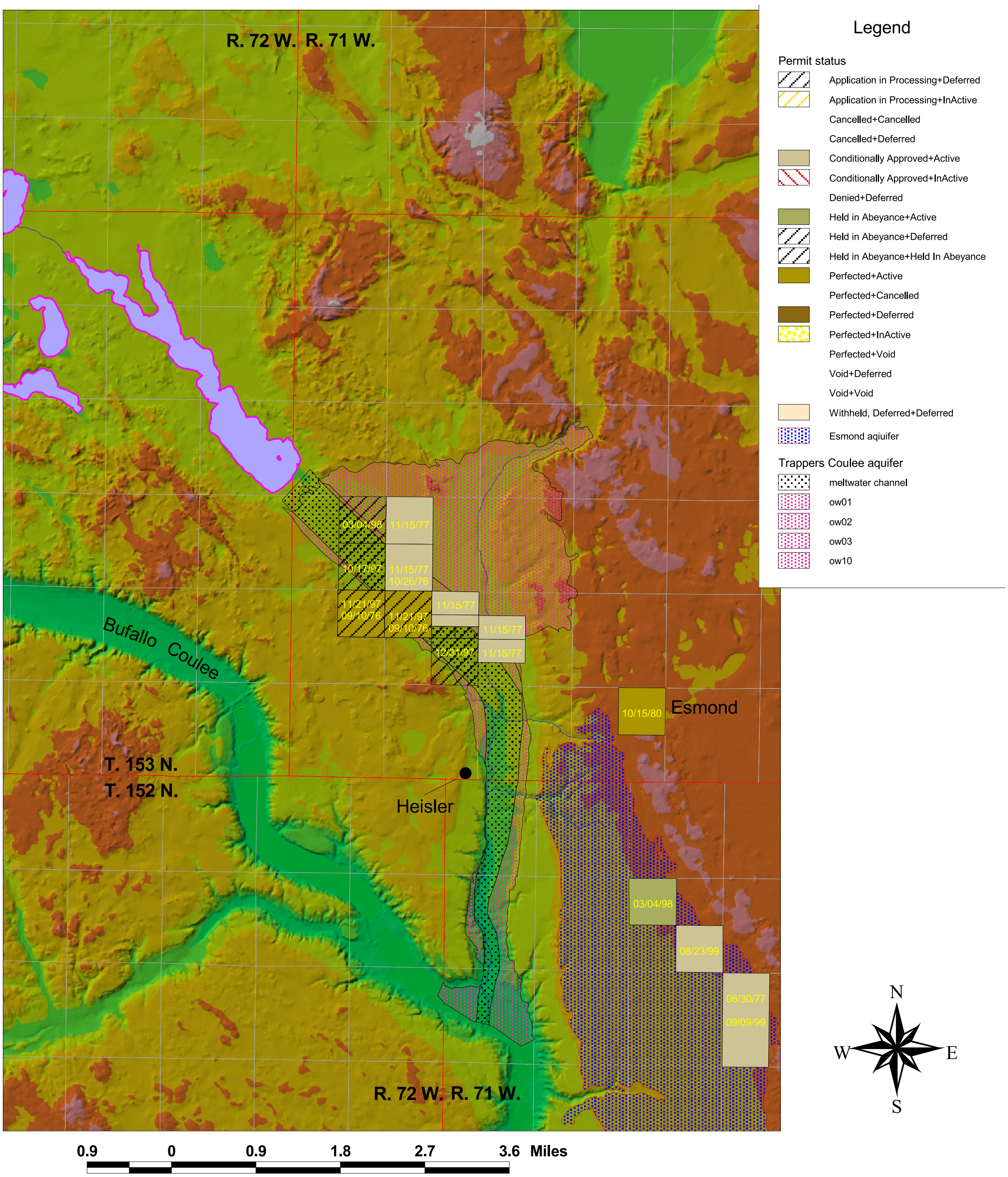


Figure 2. Priority date and status of water permits in the Trappers Coulee and Esmond aquifers.

Purpose and Scope

The purpose of this study was to develop a ground-water flow model to provide a basis for assessment of the pending water permit applications that took into account the interaction of the Trappers Coulee aquifer with the Fox Hills aquifer into which it is incised and its interaction with the thin outwash adjacent to the aquifer.

The joint-calibration of a soil moisture budget model to calculate recharge, evapotranspiration from groundwater, and estimation of irrigation water use with a ground-water flow model had proved promising in the past for the evaluation of water availability from water table aquifers. This small aquifer with significant discharge to stream flow was an ideal candidate to test and refine procedures for joint-calibration of a soil moisture and ground-water flow model. The refinement of these techniques was a major focus of this study.

Description of Study Area

The study area is located along the Benson-Pierce County line in north-central North Dakota (fig. 3). This area is located in the Drift Prairie section of the Central Lowland physiographic province (Randich, 1977). The Trappers Coulee aquifer extends from near the southeast end of Long Lake to the North Fork of the Sheyenne River (fig. 1). The aquifer is composed of Pleistocene glacio-fluvial sediments that were discharged by a subglacial stream exiting from under the ice at the Martin End Moraine, initially cutting a narrow meltwater channel that was subsequently filled with sand and gravel that spread out into a broader outwash plain when the channel filled. This area was subsequently dissected by erosion when the meltwater channels that are now occupied by Buffalo Coulee and the North Fork of the Sheyenne River formed. The Trappers Coulee aquifer is narrow, less than 0.5 miles wide, and 6.5 miles long. The area of development and proposed development is less than 3 miles long. It is incised into the Fox Hills Formation. The outwash to the north of the aquifer is either very thin or is largely unsaturated.

The headwaters of Trappers Coulee, elevation 1585 feet, are in the NW1/4 Section 15, T153N, R71W and it flows south to where it joins the North Fork of the Sheyenne River at an elevation between 1475 and 1480 feet (fig. 1). Where Trappers Coulee flow first intersects the meltwater channel, the elevation is 1550 feet. In the steep reach of Trappers Coulee between the point of intersection and the Sheyenne River, the stream gains significant ground-water flow, which comprises a large part of the aquifer discharge. Maximum elevation in the study area is approximately 1650 feet. Broad flat areas between 1570 and 1600 feet in elevation generally are part of or are remnants of the outwash plain associated with the meltwater channel. Drainage is well developed in the area as small streams such as Trappers Coulee cut headward from the deeply incised meltwater channels now occupied by Buffalo Coulee, North Fork of the Sheyenne River, and the Sheyenne River. Land surface elevations in the area of development overlying the aquifer are between 1560 and 1570 feet in elevation. Land surface rises to over 1600 feet within 0.5 miles south of the aquifer where a hummocky landscape lies between 1580 and 1600 feet until it sharply drops off into the Buffalo Coulee channel at an elevation of less than 1480 feet.

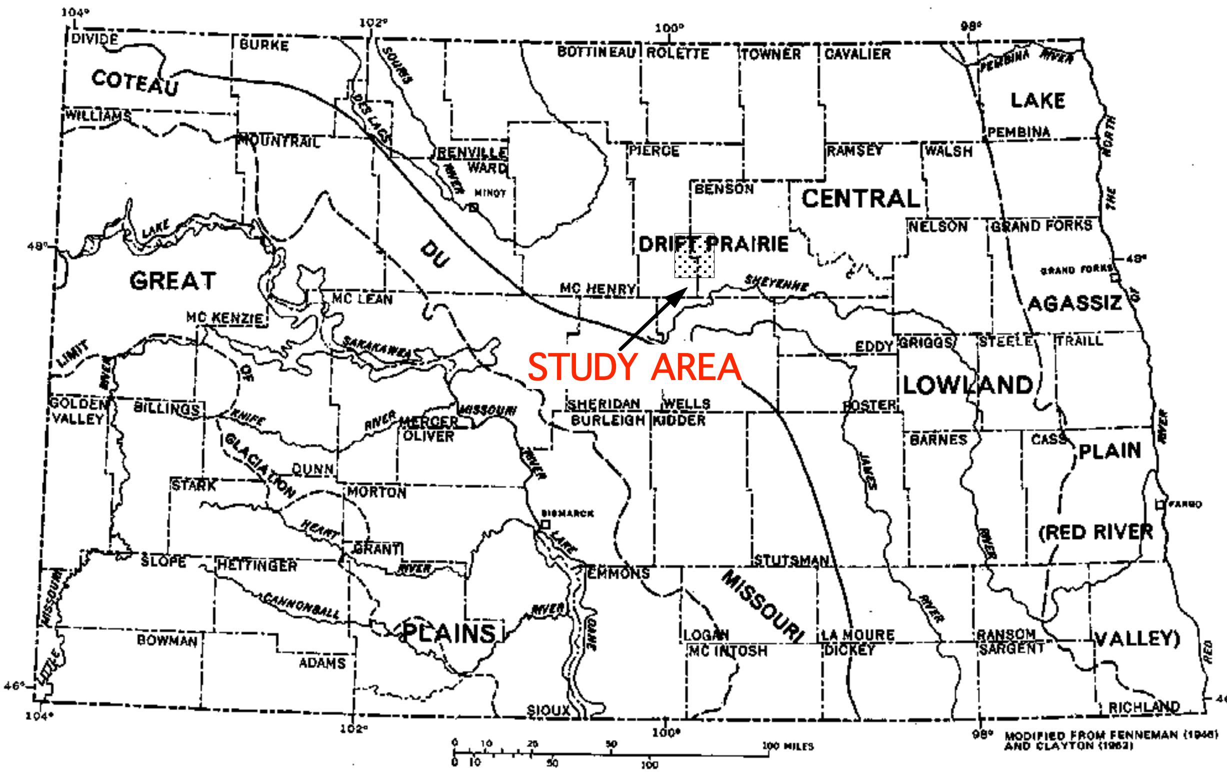


Figure 3. Location of study area and physiographic divisions in North Dakota.

Acknowledgments

Thanks are extended to Robert Shaver for technical review of this report and to Jennifer Weier for a final editorial review and corrections.

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 (3 digits) indicate Township North and Range West of the 5th Principal Meridian and the base line (fig. 4). The third numeral (2 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 153-071-29DDAA would be located in the NE1⁄4, NE1⁄4, SE1⁄4, SE1⁄4 of Section 29, Township 153 North, Range 71 West. Consecutive terminal numerals are added if more than one well is located in a 10-acre tract or smallest quarter designation, i.e. 153-071-29DDAA1 and 153-071-29DDAA2.

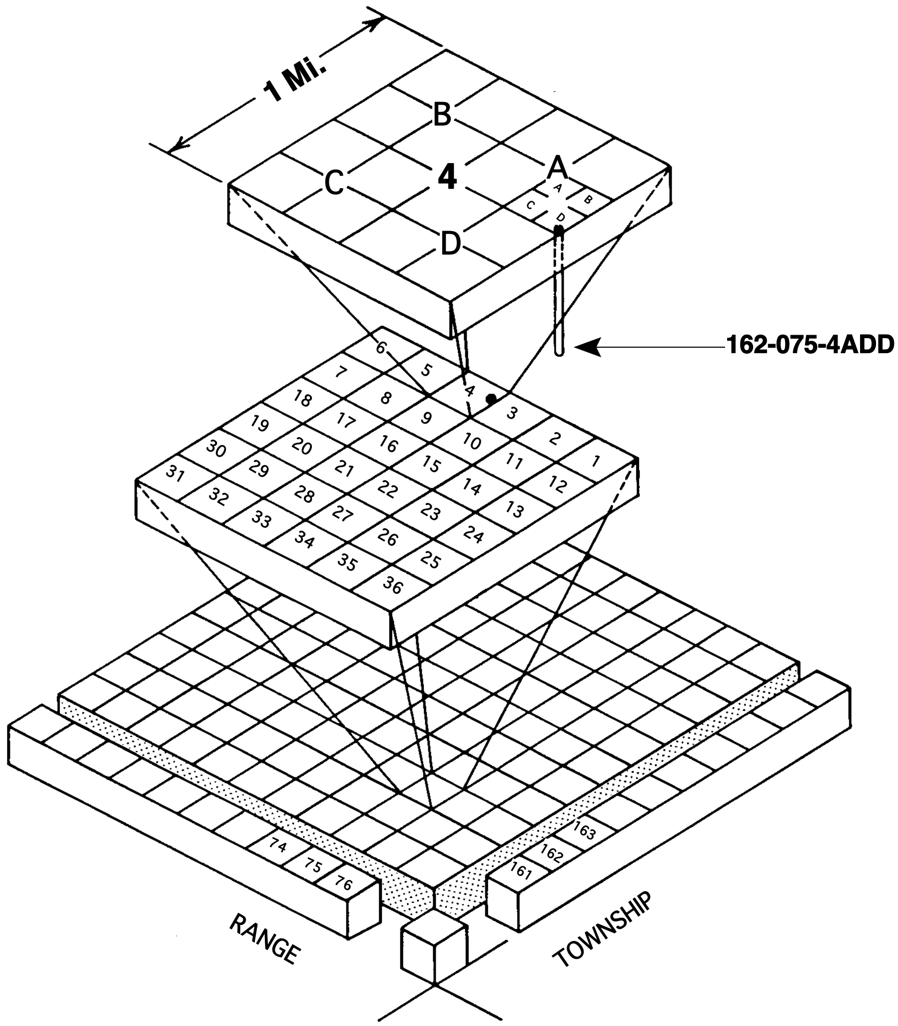


Figure 4. Location-numbering system. As an example, well 162-075-04ADD is located in the SE1/4, SE1/4, NE1/4, Section 4, Township 162 North, Range 75 West.

Previous Work

The geology of the study area is described in Carlson and Freers (1975). The hydrogeology is discussed by Randich (1977). Randich (1977) identified the Esmond aquifer to be a broad and extensive aquifer.

Hydrogeology

The study area was originally mapped by Randich (1977) as one aquifer known as the Esmond aquifer. Based on new test drilling, soils maps, and re-interpretation of old test drilling, the aquifer is now split into the Esmond and Trappers Coulee aquifers, which have a limited hydraulic connection (figs. 1 and 7). Both the Esmond and Trappers Coulee aquifers are composed of glacio-fluvial deposits. These aquifers either directly overlie the Fox Hills Formation or a thin intervening glacial till. The Fox Hills Formation is a significant source of water for domestic and stock wells and the City of Esmond.

Geologic setting

The glacial sediments in the study area are deposited upon the Cretaceous age Fox Hills Formation. Carlson and Freers (1975) describe the Fox Hills Formation as "consisting of thinly bedded shale and sand probably deposited near shorelines during the regressive phase of the Cretaceous seas."

The Trappers Coulee-Esmond aquifer developed between the Martin End Moraine (Cblmc) and the Heimdal End Moraine (CblH) (figure 5a). The glacial advances that formed both moraines are considered contemporaneous, with the ice that formed the Martin End Moraine flowing from the northwest and the ice that formed the Heimdal End Moraine flowing from the northeast. The Martin End Moraine is mislabeled on the Benson-Pierce County geologic map as Cblmc. It should be labeled Cb1m.

The meltwater channel that contains the Trappers Coulee aquifer appears to be a northerly extension of the channel containing the Heimdal aquifer in Wells County (Bluemle, et.al., 1967). This meltwater channel formed as an ice marginal stream to the Heimdal End Moraine. The part of the meltwater channel the Trappers Coulee aquifer occupies extends northward from the Sheyenne River to the southwestern part of Section 28, Township 153 North, Range 71 West and then trends to the northwest to near the east end of Long Lake. The meltwater channel is incised into the Fox Hills Formation. It would appear that the meltwater channel should continue to the northwest underlying Long Lake and the other three lakes stretching almost to Balta. There is no indication of this channel by drilling in the Balta vicinity.

Long Lake and the adjoining lakes to the northwest lie within a small area of outwash that bisects the Martin End Moraine. This may represent a collapse feature overlying a tunnel valley that drained the ice sheet to west of the moraine. The meltwater channel extending to the east of the Martin End Moraine may be a tunnel valley that was exposed as the ice sheet retreated to the position of the Martin and Heimdal End Moraines or formed as an ice marginal stream. It is likely that the sediments composing the Trappers Coulee and Esmond aquifers are a large sand and gravel fan that developed where the tunnel channel emerged from under the ice discharging its sediment load. Benn and Evans (1998) state that there "is the tendency for tunnel valleys to terminate abruptly at major moraines, where they may grade into large subaerial ice–contact fans. The surface of these fans may lie up to 100 meters (328 feet) above the tunnel valley bottom, reflecting deposition from pressurized meltwater emerging from beneath the ice." The base of the Trappers Coulee aquifer is 1477 feet at observation well 153-071-18CCC3 and 1448 feet at observation well 153-071-30AAAA1. The fan that developed from the sediments discharged by the tunnel valley aggraded to an elevation of 1600 feet, filling the meltwater channel and then forming a broad outwash plain 3 miles wide extending over 9 miles to the south from the Martin End Moraine (sand parent material soils in figure 6). Subsequently, the present Sheyenne River valley was incised into this outwash plain to an elevation of 1475 feet. This resulted in considerable erosion of the outwash plain, splitting it into the hydrologically separate ground-water units.

This can be seen in figure 6 where the areas of soils with sandy parent material (white area) indicate this outwash plain. The principle areas of outwash correspond to the Trappers Coulee and Esmond aquifers in figure 7. There is a thin area of outwash mantling the hill between Trappers Coulee and Buffalo Coulee to the south corresponding in elevation to the Esmond aquifer.

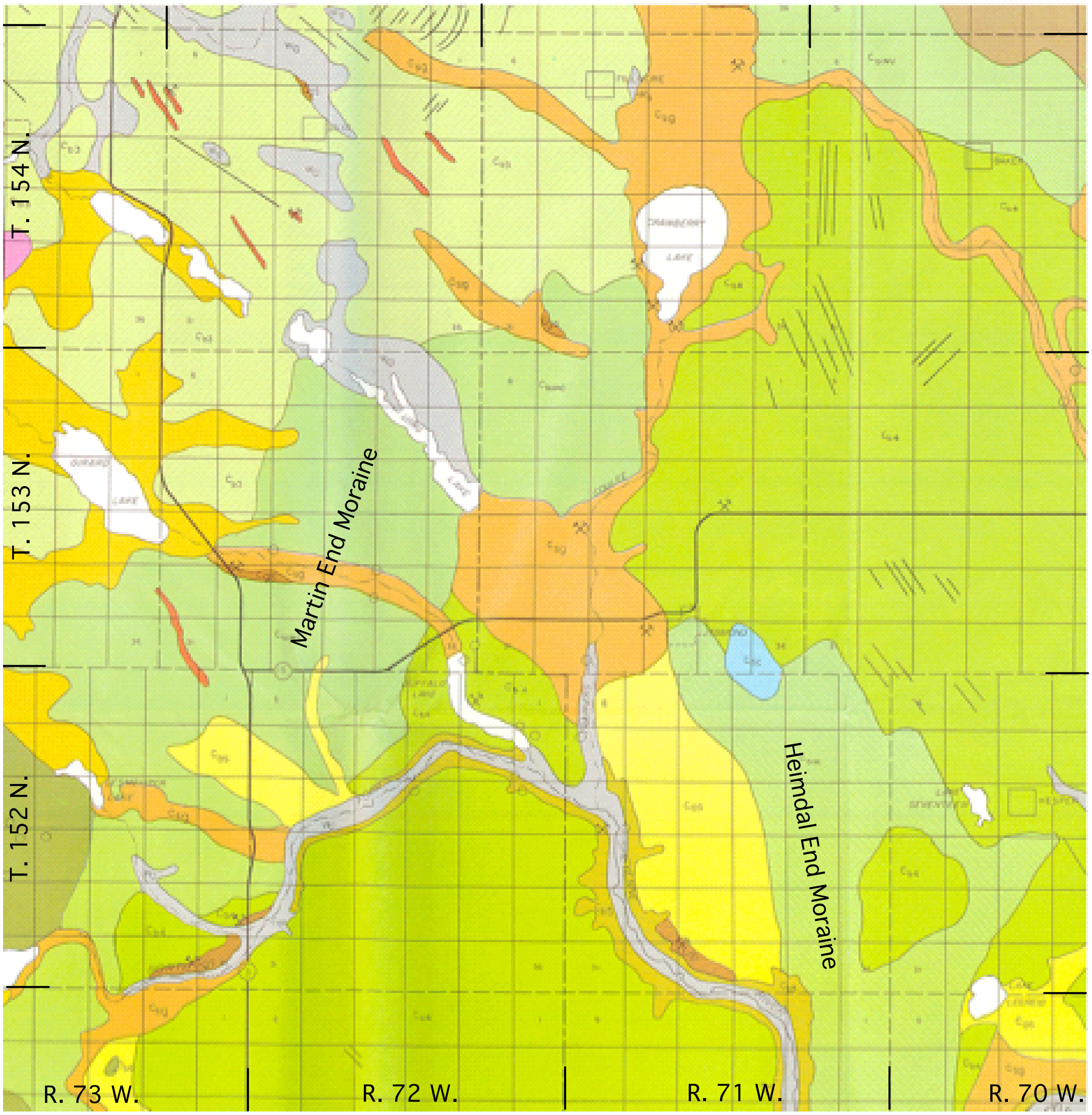


Figure 5a. Geology of study area. Legend shown in Figure 5b. Adapted from Carlson and Freers (1975).

EXPLANATION				
LITHOLOGY			MAP SYMBOL	LANDFORM; CHARACTERISTICS
WALSH FORMATION	SILT AND CLAY FACIES	Medium gray to dark gray silt, silty clay and clayey silt.	Ws	Sloughs or undrained depressions.
WALSH FORMATION	SAND FACIES	Yellowish brown to medium brown, fine to very fine grained sand.	Wsd	Low dunes.
WALSH FORMATION	MIXED SAND–SILT–CLAY FACIES	Grayish brown to medium and dark gray silty, clayey sand, clayey silt, and silty clay.	Wc	Stream floodplains; valley floor deposits.
COLEHARBOR FORMATION	BOULDER CLAY FACIES	The boulder clay facies typically consists of a nonsorted, nonstratified mixture of boulders, cobbles, pebbles, and sand grains in a matrix of silt and clay. Usually yellowish brown to olive gray in the near surface oxidized zone.		Cb1 Subunits.
			Cb1NV	Cb1NV - North Viking End Moraine(?). Ice marginal and/or low to high relief stagnation deposits. Circular disintegration ridges common.
			Cb1M	Cb1M - Martin End Moraine(?).
			Cb1H	Cb1H - Heimdal End Moraine(?).
			Cb1MC	Cb1MC - McHenry End Moraine(?).
			Cb2	Cb2 - Low relief stagnation deposits; washboard moraines are common in parts of area; ice-contact deposits also common, circular disintegration ridges present in some areas.
			Cb3	Cb3 - Low relief stagnation deposits; caps over-ridden hills in some areas; washboard moraines and circular disintegration ridges present in some areas; generally absent in siltier, sandier areas.
			Cb4	Cb4 - Low relief stagnation deposits; circular disintegration ridges and washboard moraines generally faint, poorly developed, or absent.
			Cb5	Cb5 - Eroded slope deposits—veneer of drift on pre-existing nonglacial topography.
			Cb6	Cb6 - Drift covered ice-shove features—till surface with a core of disturbed bedrock or glacial drift.
COLEHARBOR FORMATION	SAND AND GRAVEL FACIES	Gravel, gravelly sand and sand.	Cgs	Cgs - Gravel and gravelly sand; occurs as kame deposits along present drainages; as ice-marginal deposits adjacent to areas of Cb1.
			Csg	Csg - Gravel, gravelly sand and sandy gravel. Occurs as channel deposits or outwash aprons in areas between present drainages and areas mapped as Cb1.
			Ccgs	Ccgs - Gravel, gravelly sand and sandy gravel. Occurs in areas near areas mapped as Cb1; characterized by medium to high relief; probably deposited on stagnant ice.
			Cos	Cos - Sand and gravelly sand. Areas of low relief near areas of Cb1.
			Cls	Cls - Sand and silty sand. Low relief, well sorted, thin bedded, lacustrine deposits.
COLEHARBOR FORMATION	SILT AND CLAY FACIES	Silt, clayey silt, silty clay and clay.	Csc	Csc - Silt, clayey silt and silty clay. Low relief, thin laminated lacustrine deposits.
COLEHARBOR FORMATION	MIXED FACIES	Variable lithology. In some areas mostly sand and gravel; some unsorted drift; some silt and clay.		Cic - Kames, eskers.
HELL CREEK FORMATION		Sandstone, very light gray and light brownish gray, very fine grained, silty; silty clays, carbonaceous lenses.	△	Exposed in ice-shove hills.
FOX HILLS FORMATION		Sandstone, yellowish brown, fine to very fine grained; silt and shale, generally thin bedded.	○	Exposed along valley walls and ice-shove hills.
PIERRE FORMATION		Gray to black shale; a few bentonitic layers.	×	Exposed along valley walls.
			////	**Washboard moraines, low linear ridges, prominent on aerial photos.**
			⚒	**Gravel pit.**

Fig 5b. Legend to geology of study area.

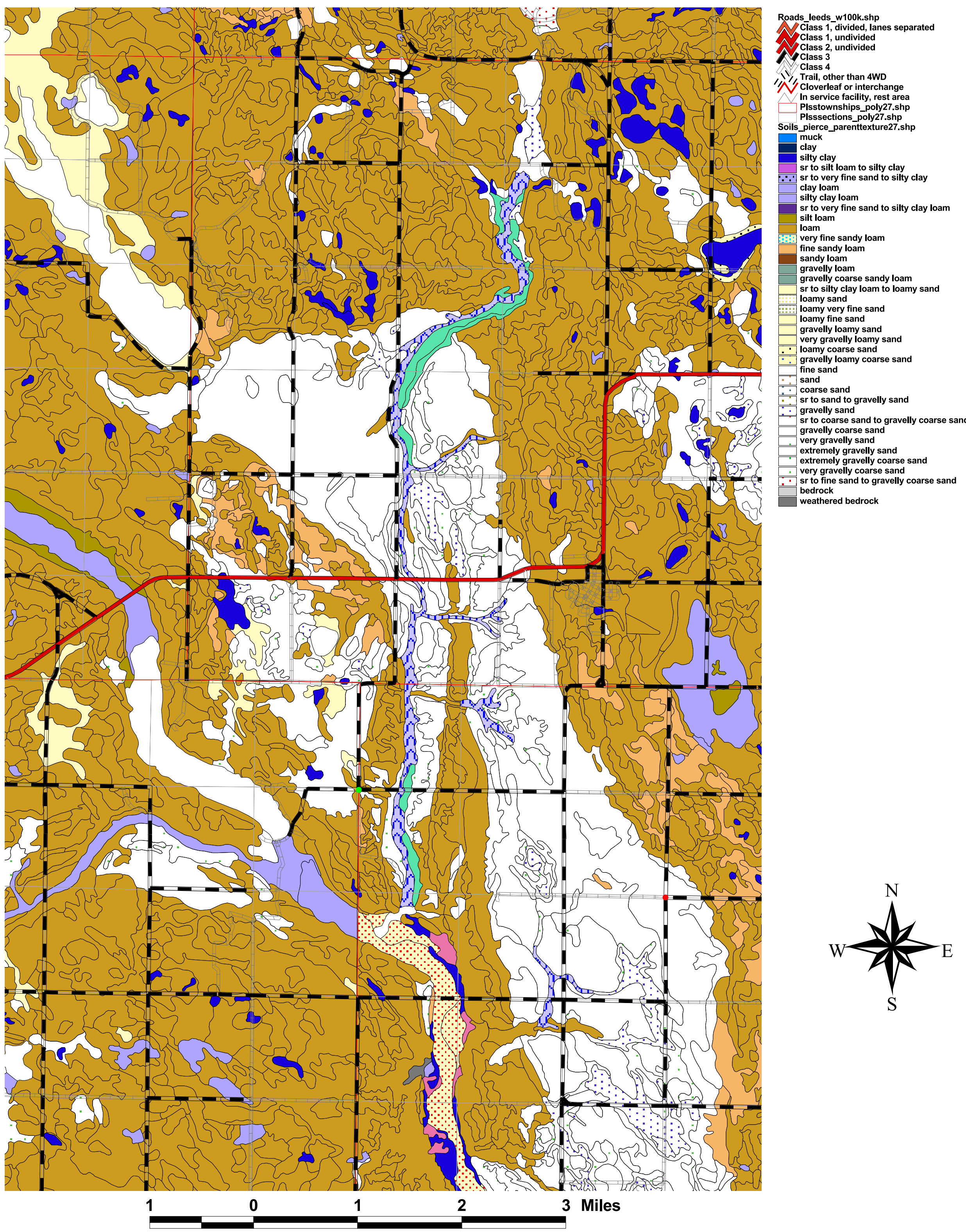


Figure 6. Parent material of dominant soil within mapping unit of soils in study area. Derived from NRCS SSURGO Benson and Pierce County datasets (USDA NRCS 2006a and 2006b).

No test drilling has been done along the chain of lakes extending northwest of Long Lake because of the inaccessibility of the area due to the lakes and wetlands. However, drilling in the vicinity of Balta gives no indication of any aquifer underlying this chain of lakes. It is likely that this depression formed as a collapse feature overlying the course of the tunnel valley and is largely filled with till and lacustrine sediments. If the Trappers Coulee aquifer is an alluvial fan formed at the ice margin by the discharge of a tunnel valley underlying the present location of Long Lake, then the 74 feet of saturated aquifer at 153-071-18CCC would be considerably larger than the amount of glacio-fluvial aquifer that would underlie Long Lake and extend to the northwest. It is very possible that there is little or no aquifer underlying the lakes and the primary source of water to the lakes is from the Fox Hills Formation discharging to the outwash surrounding the lakes and from surficial runoff into the lakes.

Trappers Coulee aquifer

The depression occupied by Long Lake and the chain of lakes trending northwest toward Balta is the same width as the Trappers Coulee aquifer (figs. 5a and 7) and therefore indicates that the aquifer could underlie this chain of lakes. Water level data and modeling results do not support this view. Water level elevations decline in elevation from 1542 feet at Long Lake to 1530 feet at the northwestern-most lake of the four (elevations from USGS 7.5″ maps). The reservoir at Balta has a water level elevation of 1512 feet. These lake level elevations indicate that flow in any aquifer underlying the chain of lakes must be to the northwest. Flow in the Trappers Coulee aquifer to the southeast of Long Lake is to the southeast, which indicates that Long Lake would sit on a ground-water flow divide. Long Lake flows into the adjoining lake to the northwest, which drains to the southwest. The outflow elevation for Long Lake is ≈ 1543 feet. These lakes receive sufficient runoff and ground-water flow to maintain lake levels except during severe drought. Aerial photography from 8/13/90 indicates Long Lake was close to being dry. Long Lake has a surface area of 680 acres. NRCS estimates lake evaporation in this area to be 31.5 inches per year (USDA SCS, 1979) and average precipitation is 17 inches per year. Therefore, over 820 acre-feet per year of water are required to maintain the level of Long Lake. Given the small drainage area of Long Lake, it would appear that much of this must be supplied by groundwater. NDSWC observation wells 153-071-18CCC1,2, &3 located 700 feet from the edge of the Long Lake have water levels 8 feet higher than the level of the lake indicating a poor hydraulic connection between the Trappers Coulee aquifer and the lake. For this large lake to exist on a ground-water divide in the Trappers Coulee aquifer, large flows would need to enter the aquifer laterally from the Fox Hills Formation supplying sufficient water to to maintain the lake level and maintain aquifer flow to both the southeast and northwest. The ability of ground-water to sustain this chain of lakes is explored further in the discussion of the ground-water flow model.

For this discussion, the Trappers Coulee aquifer will be divided into the Upper and Lower Trappers Coulee aquifer (UTC and LTC respectively). The upper part extends from Long Lake to NDSWC observation well 135-071-29DDAA (figs. 7 and 8) and includes the outwash plain on the north side of this reach of the meltwater channel. It is in the upper reach that the existing and proposed appropriations are located. The lower aquifer extends from NDSWC observation well 135-071-29DDAA to the North Fork of the Sheyenne River. In this reach, Trappers Coulee descends from an elevation of 1550 to 1478 feet and is a gaining stream. The longitudinal profile of the aquifer is shown in cross-section A-A′ (fig. 8). The transverse cross-sections of the UTC aquifer (B-B′) and the LTC aquifer (C-C′) are shown in figures 9 and 10. The outwash on the north side of the channel in cross-section B-B′ and of the Esmond aquifer in cross-section C-C′ are of equivalent elevation and were deposited by the same fluvial event. The effect of subsequent erosion where much of the outwash in the LTC has been removed can be seen in both cross-sections A-A′ and C-C′. In the LTC area, the Esmond aquifer outcrops in the valley wall above the Trappers Coulee aquifer where it discharges by springs and seeps. This is seen as an area of poorly drained soils in the valley wall in figure 11 and as an area of large ET in the CIR photography shown in figure 12.

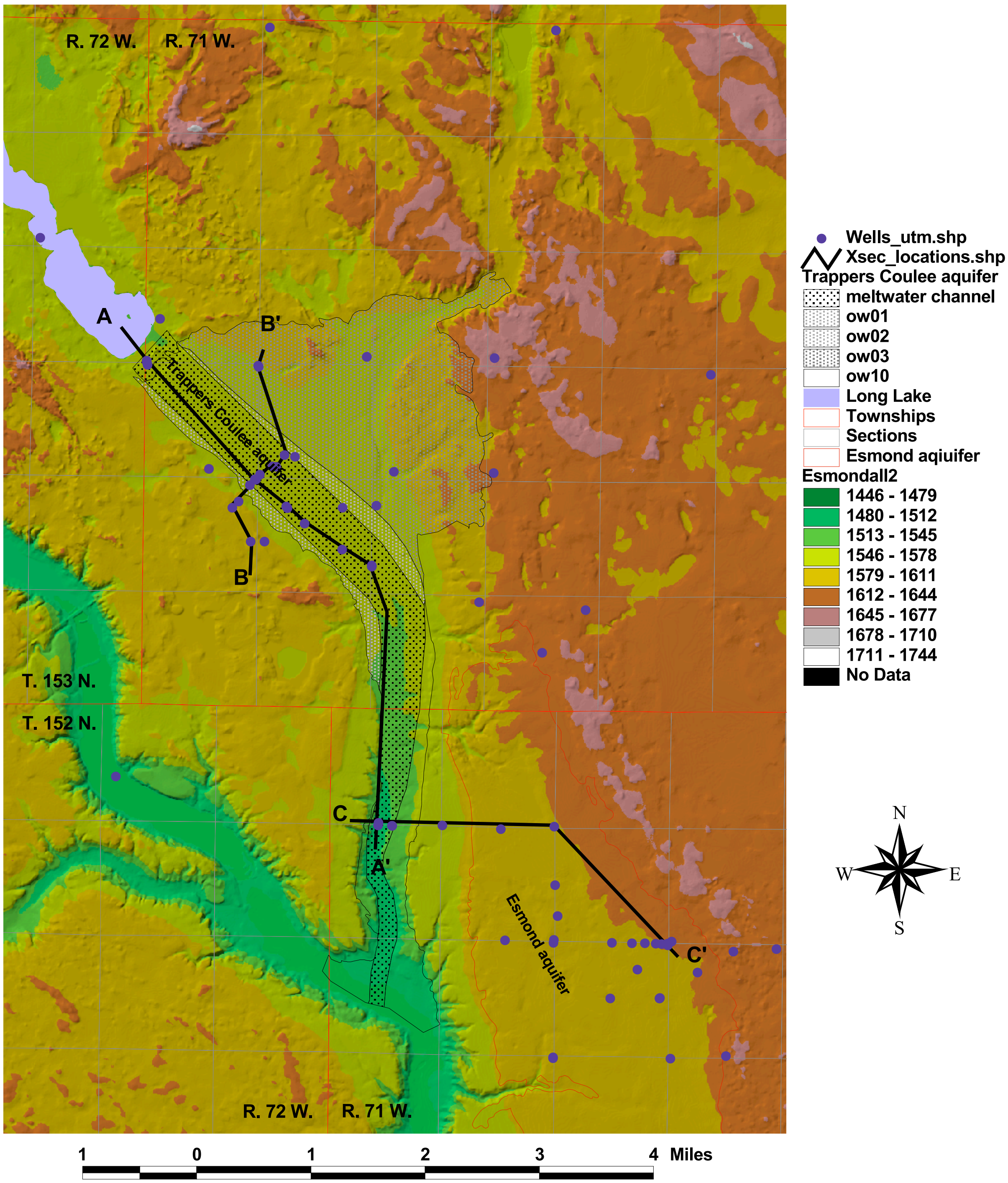


Figure 7. Location of Trappers Coulee and Esmond aquifers and geologic cross-sections A-A' to C-C'.

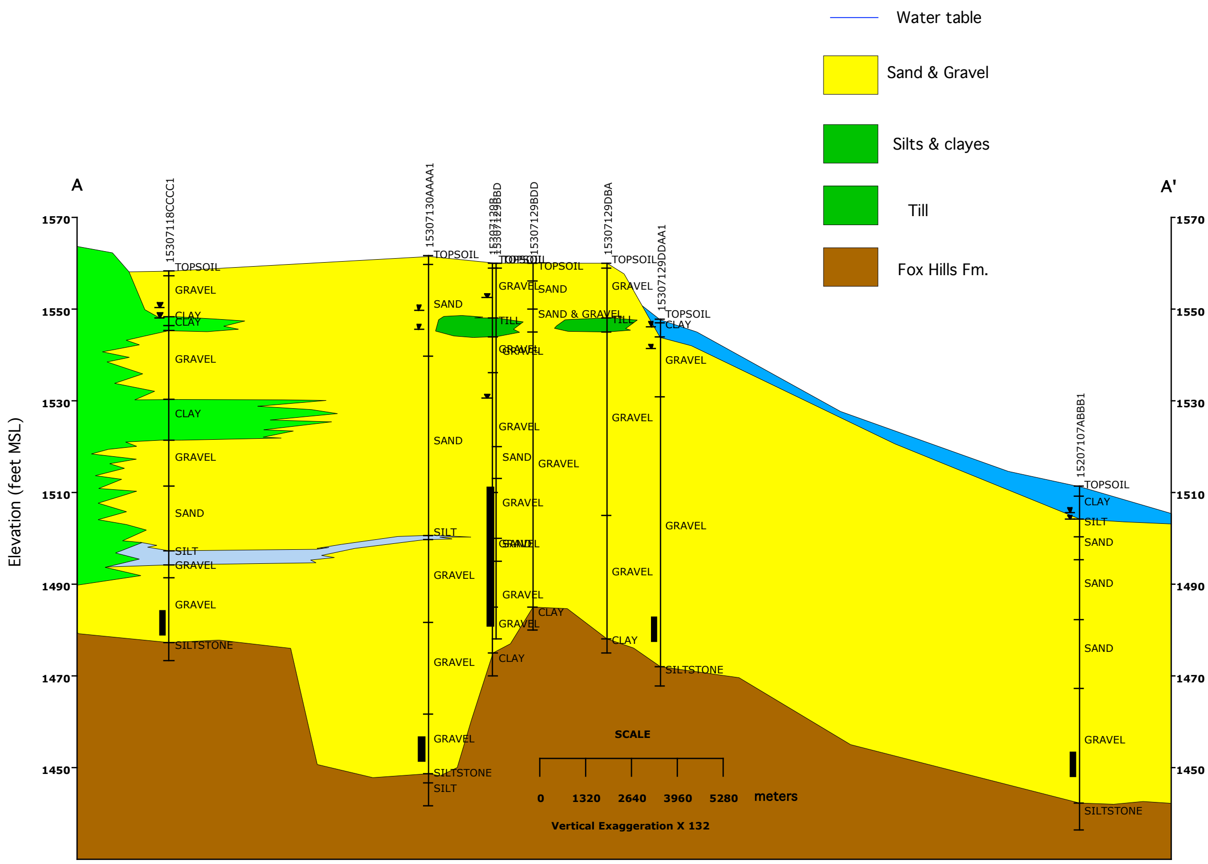


Figure 8. Longitudinal cross-section A-A' of the Trappers Coulee aquifer from Long Lake to near the Sheyenne River.

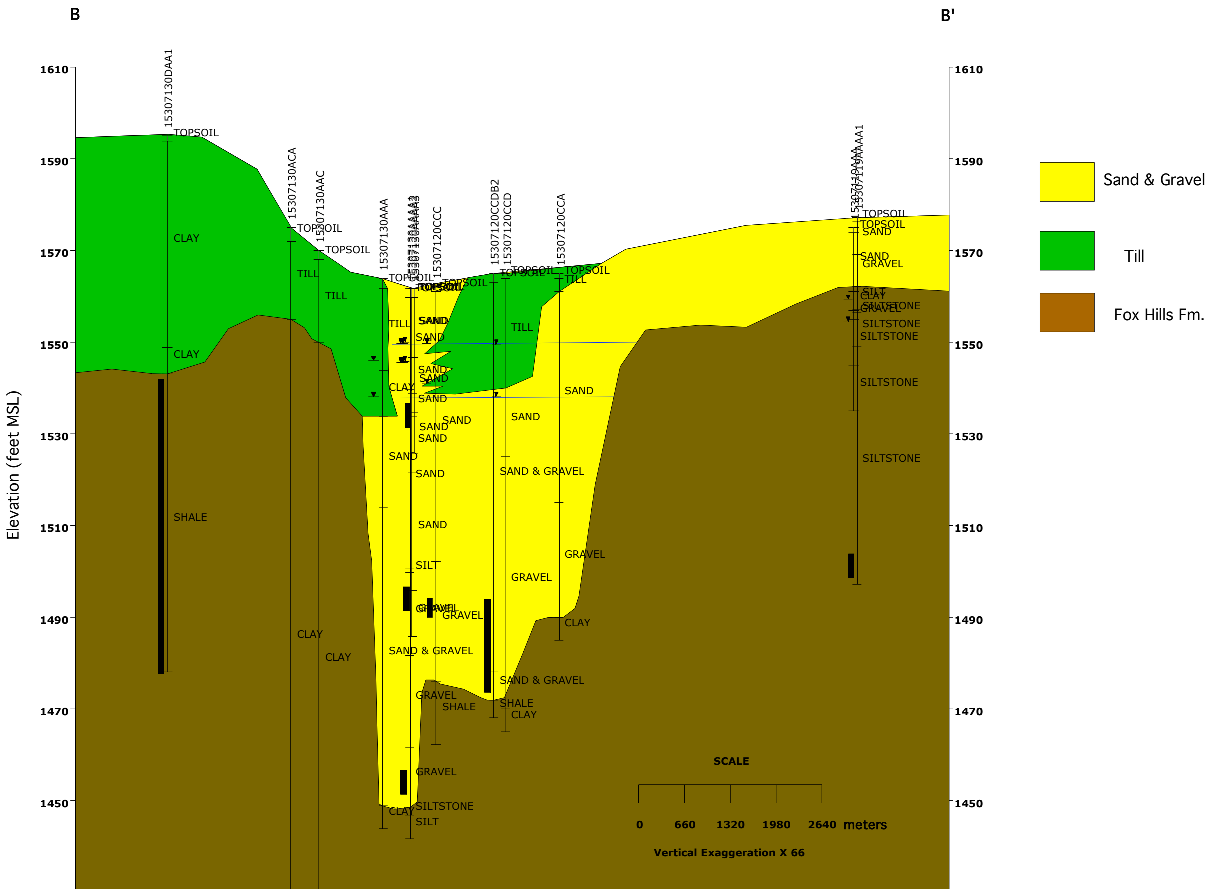


Figure 9. Cross-section B-B' of Trappers Coulee aquifer.

Esmond aquifer

The base of the Esmond aquifer is above an elevation of 1560 feet. This is above the land surface elevation of much of the Trappers Coulee aquifer. From Section 33, Township 153 North, Range 71 West to the south, the Esmond aquifer crops out in the east valley wall of Trappers Coulee. The outcrop of the Esmond aquifer is very apparent in CIR photography taken on August 20, 1998 with lush vegetation occurring along the outcrop as this is an area of ground-water discharge from the aquifer (fig. 12). Till and/or the Fox Hills Formation is exposed in the valley wall below the outcrop of the Esmond aquifer as indicated by the presence of boulders on the surface and occurrence of soils with till parent materials. The Esmond aquifer discharges by springs and seeps along the contact between the aquifer and the underlying low permeability Fox Hills Formation. This seep area is indicated by the poorly drained soils in the valley wall seen in figure 11. The city of Esmond lies to the east and north of the Esmond aquifer and sits on glacial till overlying the Fox Hills Formation. Most of the wells in Esmond are completed in Fox Hills siltstone with a few in the overlying Fox Hills sandstone.

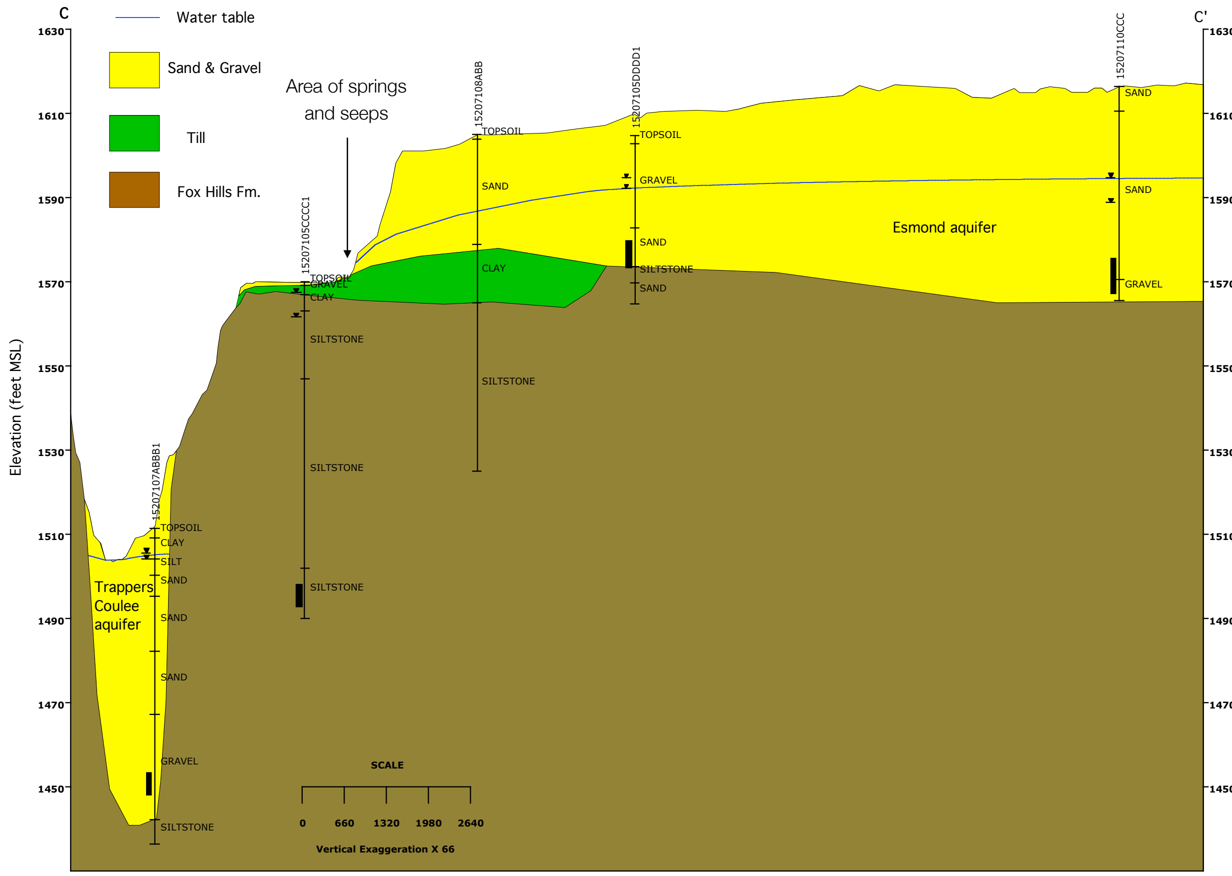


Figure 10. Cross-section C-C' of Trappers Coulee and Esmond aquifers.

To the northwest of Esmond, the broad flat area on the north side of the Trappers Coulee aquifer probably represents a remnant of the Esmond aquifer where much of the aquifer has been removed by subsequent erosion. This area has a thin mantle of sand and gravel (fig. 6). The bottom of this aquifer lies above the water level elevation in the Trappers Coulee aquifer (fig. 9). Water likely drains to the south through this thin aquifer on the north side of Trappers Coulee aquifer, but would not be affected by head changes in the Trappers Coulee aquifer except by changes in leakage through the underlying Fox Hills aquifer. The bottom of the aquifer at NDSWC test holes 153-071-17DDD1&2 is at 1532 feet. This is probably a small channel that follows Trappers Coulee to the north.

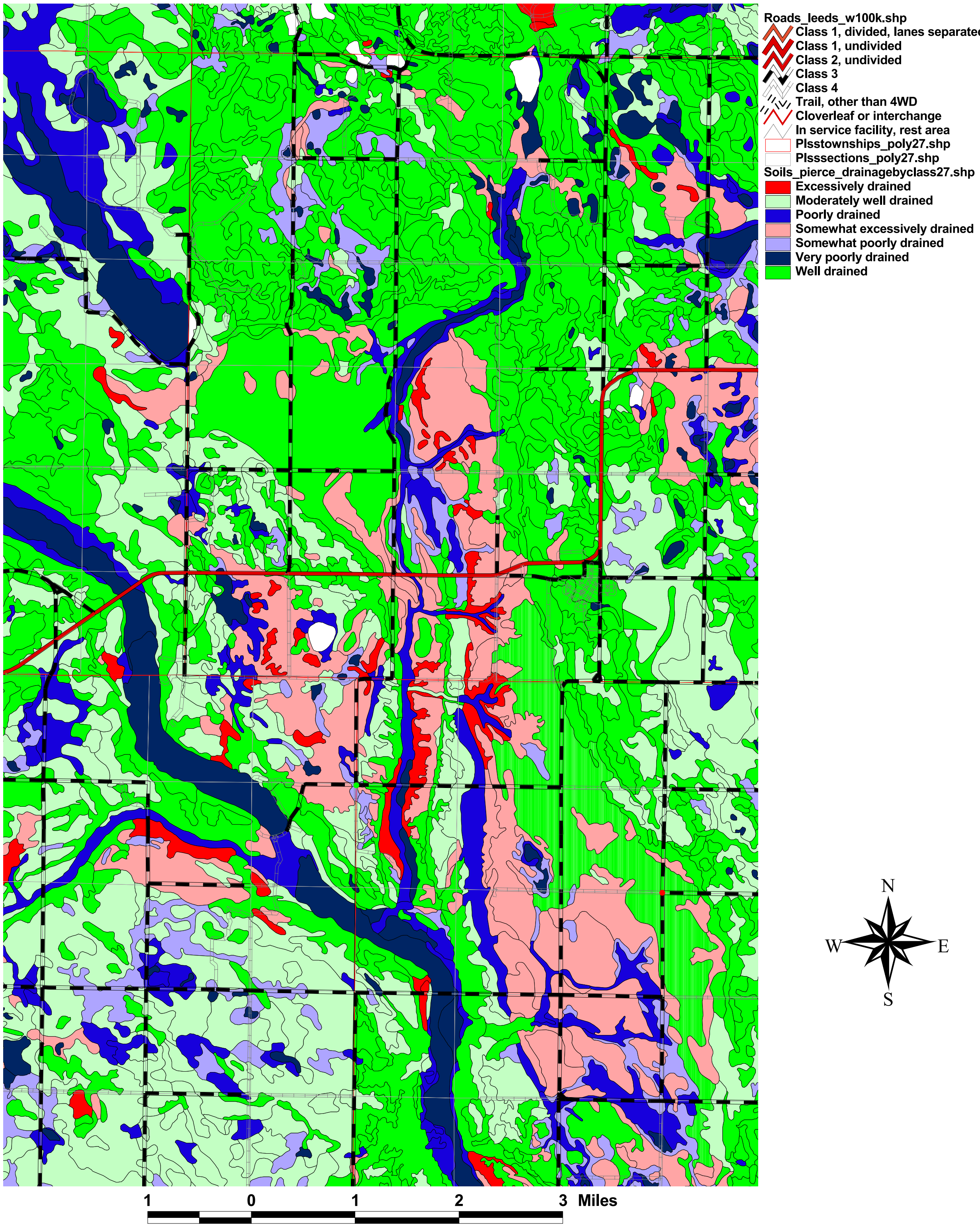


Figure 11. Dominant drainage class of soil mapping in study area. Derived from NRCS SSURGO Benson and Pierce County datasets (USDA NRCS, 2006a and 2006b).

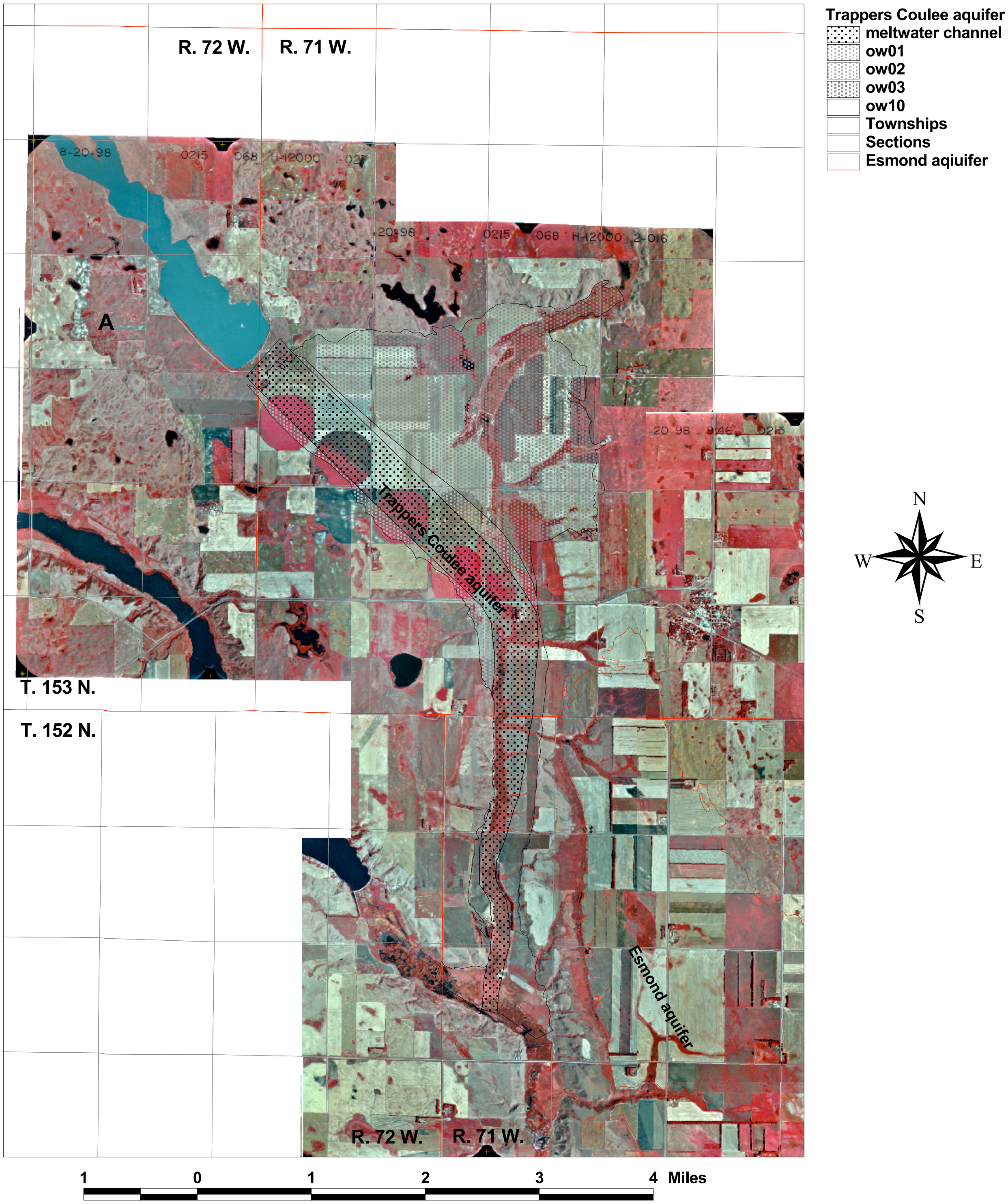


Figure 12. Color Infrared Image of Trappers Coulee aquifer area from August 20, 1998.

Fox Hills aquifer

Randich (1977) describes the Fox Hills aquifer in Benson and Pierce Counties as follows "The Fox Hills aquifer consists of semiconsolidated sandstone in the upper part of the Fox Hills Formation. The lower part of the formation is mostly siltstone interbedded with shale and claystone, which are too fine grained to be of importance as an aquifer. … Laboratory analyses of drill cuttings from the aquifer indicate porosities of 43 to 45 percent and hydraulic conductivities of 7 to 16 ft/d (2 to 5 m/d). Based on these and field data, wells developed in the aquifer should yield 4 to 100 gal/min (0.3 to 6 l/s), with the larger yields occurring in areas of greatest hydraulic conductivity and sandstone thickness."

The domestic wells within the city of Esmond and most of the domestic and stock wells within the vicinity of the Trappers Coulee aquifer are completed within the the Fox Hills Formation. However, unlike reported by Randich, the wells are completed in what the water well drillers refer to as "shale." NDSWC test drilling in the area indicates that this is a fractured siltstone.

The United States Bureau of Reclamation (Schock, 1985 and USBR, 1976) in their investigation of the Lonetree Dam site conducted a pumping test from a well completed in a fractured siltstone of the Fox Hills Formation. The well was pumped at 442 gpm for 23 hours. Reported transmissivity (T) and storativity (S) for four observation wells are as follows:

Transmissivity(feet squared per day)	Storativity
17,143	4X10-4
12,091	1X10-2
14,107	2X10-4

Distance drawdown transmissivities of 34,648 and 36,644 feet squared per day were calculated for 10 and 15 hours, respectively. Given the approximate doubling of T and the high S values for the time drawdown determination, it is likely that a boundary was encountered early in the test. The USBR results indicate that, at least locally, the fractured siltstones and claystones of the Fox Hills can have hydraulic conductivities comparable to sands and gravels.

Hydraulic conductivity was estimated from specific capacities determined from private drillers logs in the vicinity of the aquifer (fig. 13). The aquifer thickness was assumed to be the screened interval. This is only valid if Kz/Kr is small, that is, there is little vertical flow during the time of the test. Therefore the calculated hydraulic conductivities represent a maximum value. Most of the wells are open hole completions with the remainder being slotted casing. The hydraulic conductivity for the two sand wells are low at 3 and 5 feet per day compared to the range reported by Randich (1977). The fractured claystones and siltstones of the Fox Hills have significantly larger hydraulic conductivities than the sands.

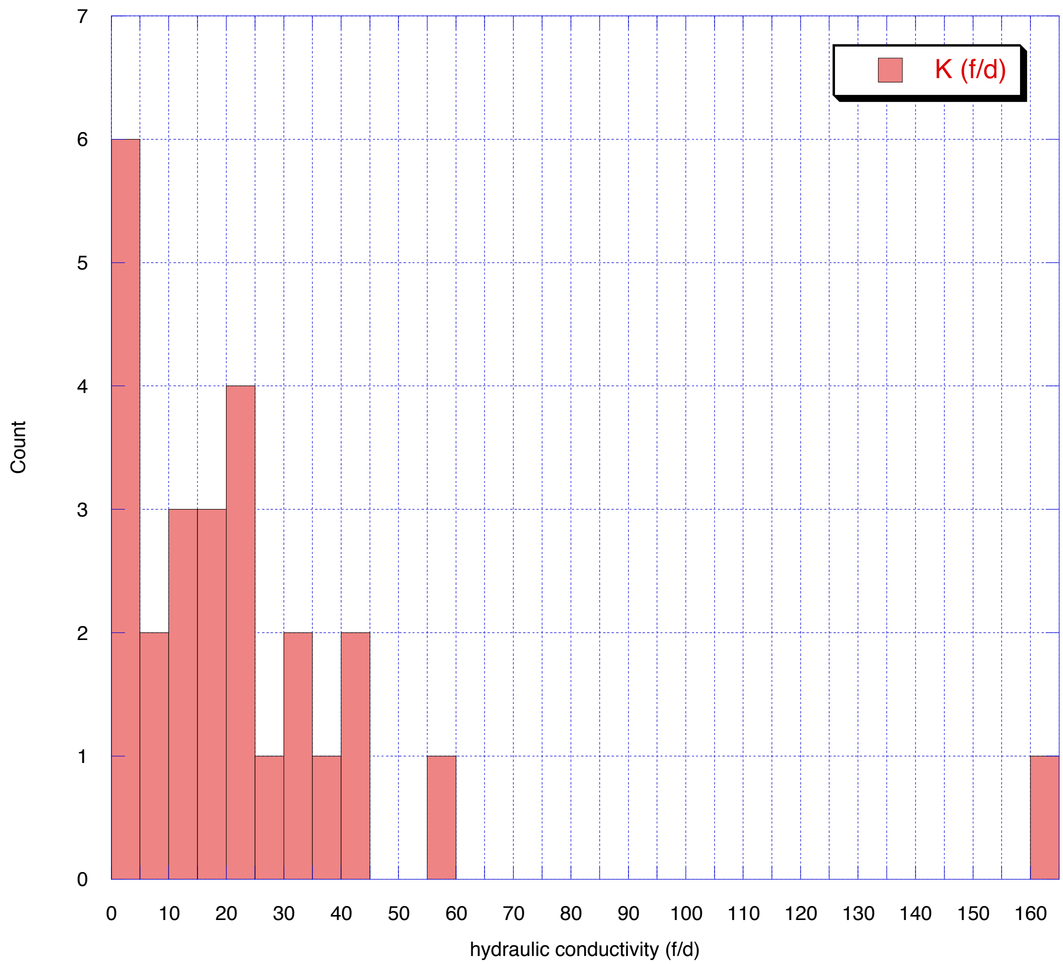


Figure 13. Hydraulic conductivity of Fox Hills wells completed in siltstone facies. Values are estimated from specific capacity data obtained from Well Drillers' Reports. Units are in feet/day.

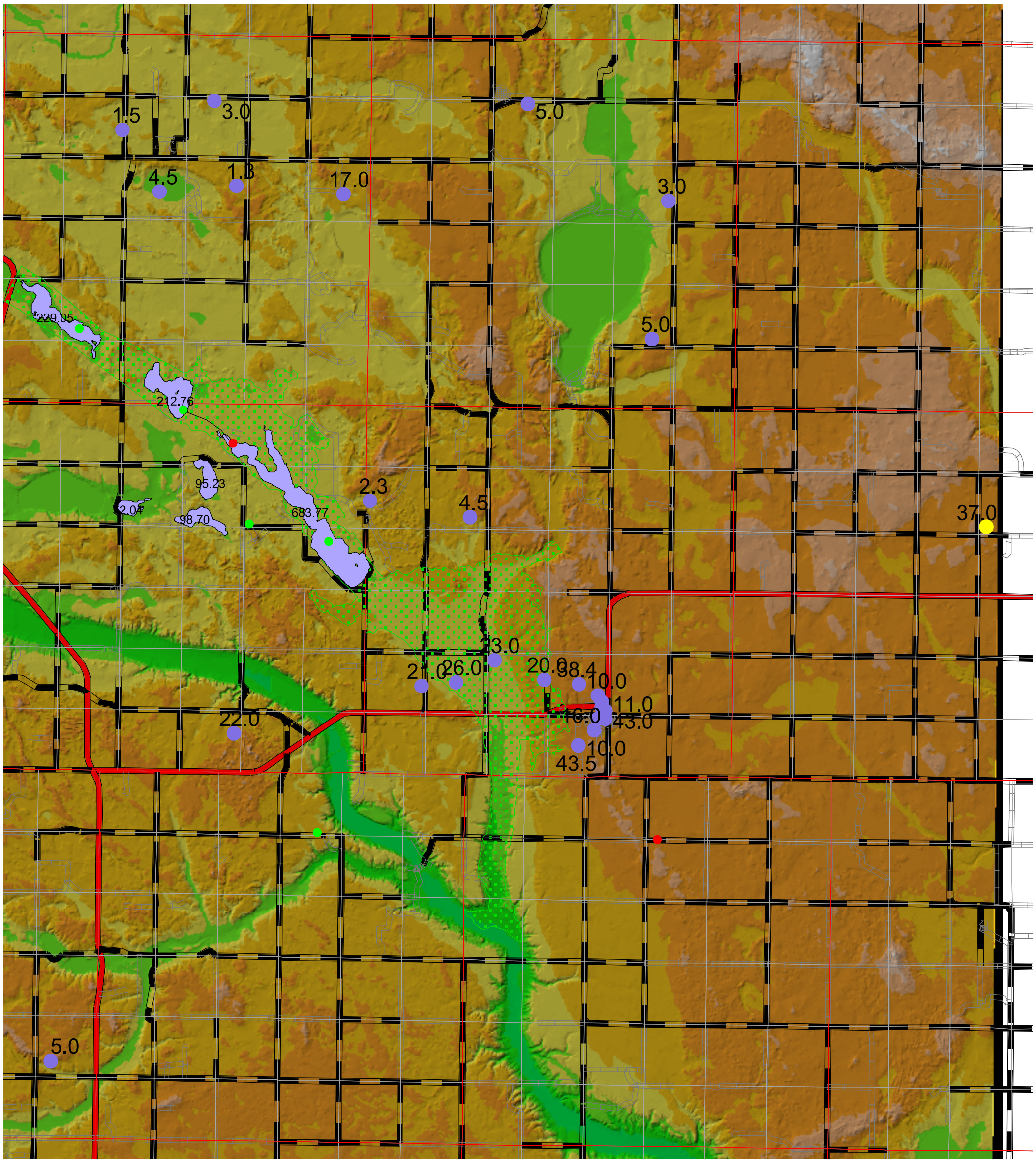


Figure 14. Map showing hydraulic conductivity of Fox Hills wells completed in shale facies. Values are estimated from specific capacity data obtained from Well Drillers' Reports.

The map in figure 14 indicates that the hydraulic conductivity of the Fox Hills aquifer north of the Trappers Coulee aquifer is generally 5 feet per day or less. Near Esmond, the hydraulic conductivity ranges for 20 to 40 feet per day.

The estimated hydraulic conductivity at domestic well 153-071-30DAA is 21 feet per day. The reported water level elevation at this well is approximately 1580 feet. This is 30 feet higher than the 1550-foot water level elevation in the Trappers Coulee aquifer less than 1500 feet to the northeast. In Buffalo Coulee, 8500 feet to the southwest, land surface elevation is 1480 feet. It would require a very high recharge rate to maintain the indicated groundwater mound in this area between the Trappers Coulee aquifer and Buffalo Coulee. It would appear that if hydraulic conductivities were this large, the aquifer would drain to Buffalo Coulee. A similar issue exists with the Esmond aquifer to the south of Esmond where the elevation of the base of the aquifer is approximately 1570 feet and Trappers Coulee to the west of the aquifer ranges from an elevation of 1470 to 1520 feet. Part of this difference in elevation might be explained by a small Kz/Kh restricting vertical leakage through the bottom of the Esmond aquifer into the Fox Hills aquifer.

The base of the Fox Hills Formation is approximately 1300 feet in the vicinity of the Trappers Coulee aquifer. NDSWC test hole 152-072-22BBB indicates the contact between the Fox Hills and the Pierre at 1290 feet. Based on a total Fox Hills thickness of 250 feet, the Trappers Coulee aquifer is incised through 40 percent of the formation. This is consistent with the elevation of the base of the Fox Hills in McHenry County to the west (fig. 15).

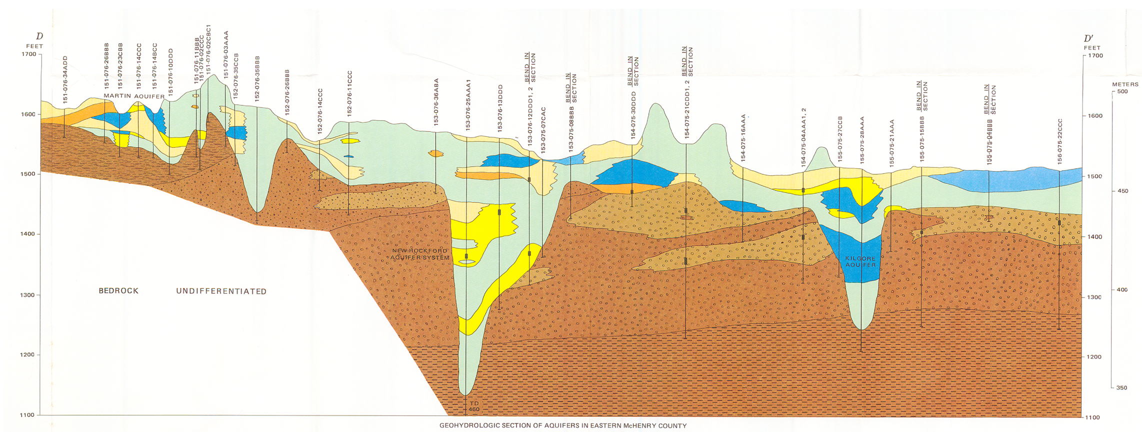


Figure 15. South to north geologic cross section of eastern McHenry County (from Randich,1981, plate 2).

The USBR investigation of the Lonetree Dam site, located 30 miles southwest of the Trappers Coulee aquifer, provides data on the hydraulic properties of the Fox Hills Formation. In construction of the dam, dewatering wells were installed in the Fox Hills aquifer. Schock (1985) states "the majority of flows came from isolated zones of intensely fractured rock within the siltstone/sandstone, with flows increasing very little below the fractured zones." Shock (1985) further states that in the installation of observation wells near the relief wells "It was also apparent from careful logging of the holes that 80 to 90% of the flow from those small wells was from the isolated fractured bedrock zone." The fracture zone was identified at 15 to 35 feet below the top of the bedrock. The fracture zone is approximately 40 feet below the base of the Hell Creek Formation. Shock (1985) states "The average pumped discharge from the original six (relief) wells was about 550 gpm each. The additional four wells in the upstream and downstream rows averaged about 320 gpm each, while the three wells in the middle row, where 60 feet of surface casing cut off most of the fractured zone, produced only 65 to 70 gpm each."

Wanek (1988) reviewed the response to dewatering at the Lonetree Dam site with pumping averaging 4,200 gpm between March 10 and September 17. Wells located in the Hell Creek Formation to the west of the dam did not respond to the dewatering. Water levels in the Hell Creek Formation south of the dam declined 0 to 11 feet during the dewatering with a well OW #32 located 2 miles from the dam site declining 11 feet and well OW #38 located over 4 miles from the dam site declining 3.5 feet. There is considerable spatial variation in drawdown indicating preferred flow paths within the fractured siltstone and/or significant variations in vertical leakage. Observation wells completed in the fractured siltstone 1.5 miles north of the dam site declined 10 and 21 feet respectively. At larger distances, domestic wells are the only wells completed in the fractured siltstone. Domestic wells 1.75 miles south and 1.75 miles northwest recovered 8 and 10 feet respectively when pumping ceased. A domestic well 4 miles west of the dam site declined at least 7 feet. The results indicate that the fractured siltstone has some areal extent, but vertical leakance into the siltstone aquifer is low.

Equation 1 can be used to calculate the distance to a groundwater divide between two streams of different elevation. Here it is used to evaluate the location of the groundwater divide between the Trappers Coulee aquifer and Buffalo Coulee to the southwest.

From Bear(1979) p. 181:

$$x\Big|_{h=h_{\max}} = \frac{L}{2} - \frac{K}{2NL}\left(h_0^2 - h_l^2\right) \qquad \text{eq. 1}$$

where:

L = distance between the two streams
K = hydraulic conductivity
N = recharge rate
h_0 = head above base of aquifer at x=0
h_l = head above base of aquifer at x=L

After the position of the ground-water divide is determined by equation 1, the height of the divide can be determined using equation 2, which is used to estimate the water level elevation between two streams where h_0 is equal to h_l. Since the gradient is zero at the groundwater divide, the equation can be used to derive the head for any position x between the x=0 and x=L :

From McWhorter(1977), p. 149:

$$h^2 = h_0{}^2 - \frac{W}{K}\left\{x^2 - \left(L/2\right)^2\right\} \qquad \text{eq. 2}$$

where:

L/2 = distance from the stream to the divide (x or L-x)
K = hydraulic conductivity
W = recharge rate
h_0 = elevation of stream at x=0 if L/2 = x or
elevation of stream at x=L if L/2 = (L-x)
h = head above base of aquifer at x or L-x

By applying these two equations to the area between the Trappers Coulee aquifer, water level elevation 1450 feet, and Buffalo Coulee to the south, water level elevation 1478 feet, an estimate can be made of the hydraulic conductivity of the intervening Fox Hills Formation. At domestic well 153-071-30DAA1, 1⁄4 mile south of the Trappers Coulee aquifer, the water level elevation was approximately 1600 feet in 1994. To create the observed groundwater mound between Trappers Coulee and Buffalo Coulee requires that hydraulic conductivity is below 1 foot per day with a recharge rate of 4 inches per year. Recharge for the till-derived soils overlying the Fox Hills is not known, but is likely in the range of 0.25 to 2 inches. Therefore, hydraulic conductivity likely ranges from 0.05 to 0.5 feet per day. This indicates a very large discrepancy between the hydraulic conductivity determined from domestic wells and regional hydraulic conductivity of the Fox Hills Formation. Since most of the permeability results from fractured siltstones, it indicates that though local fracturing is significant, on a larger scale the fractures are poorly connected. Part of the difference may also reflect very large anisotropy with the conductivity along one fracture axis being much larger than along the other axis.

Ground-Water Flow

Ground-water flows from the beginning of the melt-water channel near the southeast end of Long Lake to the southeast to where the aquifer intersects Trappers Coulee (UTC) and then to the south where Trappers Coulee flows into the North Fork of the Sheyenne River (LTC). In the LTC, flow in Trappers Coulee increases due to discharge from the aquifer. Flow in the Esmond aquifer is mostly to the west from the Heimdal End Moraine to Trappers Coulee and the North Fork of the Sheyenne where they have incised through the aquifer. The Esmond aquifer discharges by springs and seeps where it out crops in the valley wall (figs. 11 and 12).

Water Levels

The locations of observation wells and stream flow measuring sites are shown in figure 16. Hydrographs for the Trappers Coulee aquifer are shown in figures 17 through 21. The wells descend along a flow path from where the meltwater channel begins near Long Lake (fig. 16) to a point 1.5 miles north of the North Fork of the Sheyenne River. Along this flow path, water level elevations decline from 1551 feet to 1506 feet. Esmond aquifer hydrographs are shown in figures 22 and 23. Fox Hills aquifer hydrographs are shown in figures 24 though 26. Only the Trappers Coulee aquifer at NDSWC observation well 153-071-20CCC (fig. 18) shows a large response to the 1988 to 1992 drought with 4 feet of water level decline. The Esmond aquifer declined about 1.5 feet at 152-071-10CCC (fig. 23) and the Fox Hills south of Long Lake declined 2 feet at 153-072-03DDD (fig. 24). Water level responses in a small channel that is probably a tributary to the meltwater channel are shown in figures 27 and 28.

Water levels in the Esmond aquifer at 152-071-05DDDD1 are 1595 feet compared to the water level elevation in the Trappers Coulee at 152-071-07ABBB of 1506 feet. The Fox Hills aquifer at 152-071-05CCCC1, between these two wells, has a water level of 1567 feet. The locations of these observation wells and screened intervals are shown in figure 10. The large difference in water levels between the Trappers Coulee and Esmond aquifers is a good indication of the small regional hydraulic conductivity of the Fox Hills aquifer in this area; otherwise, the Esmond aquifer would be unsaturated.

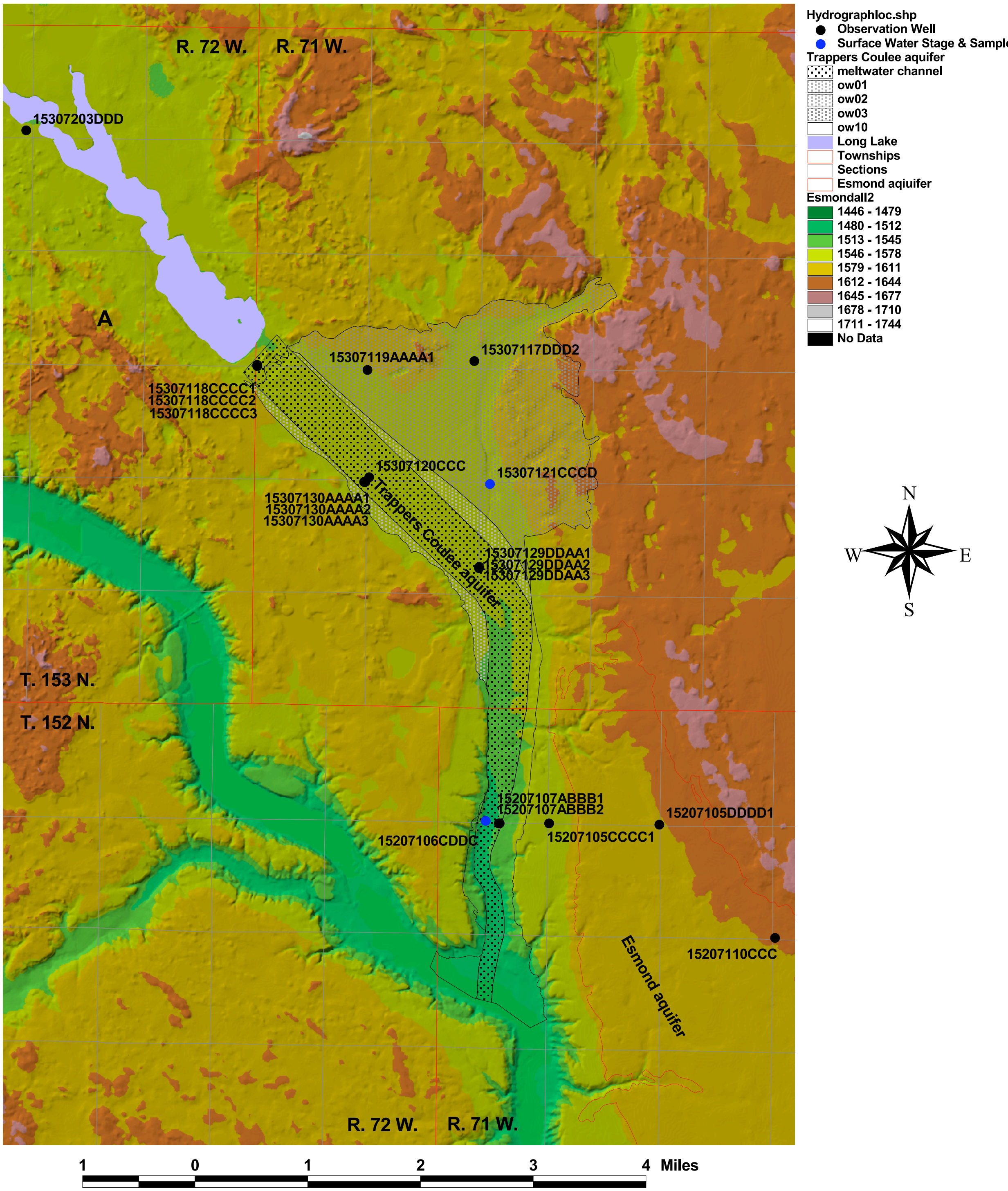


Figure 16. Locations of observation well hydrographs and stream flow measurements.

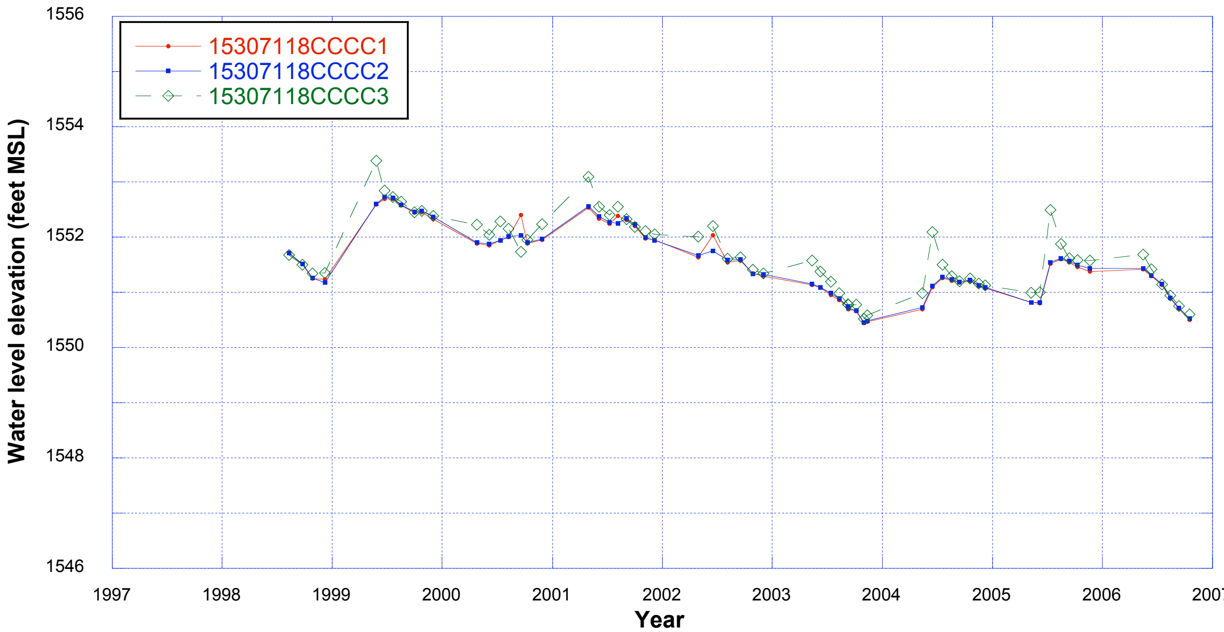


Figure 17. Hydrographs of NDSWC observation wells 153-071-18CCCC1, 2 & 3 screened in Trappers Coulee aquifer.

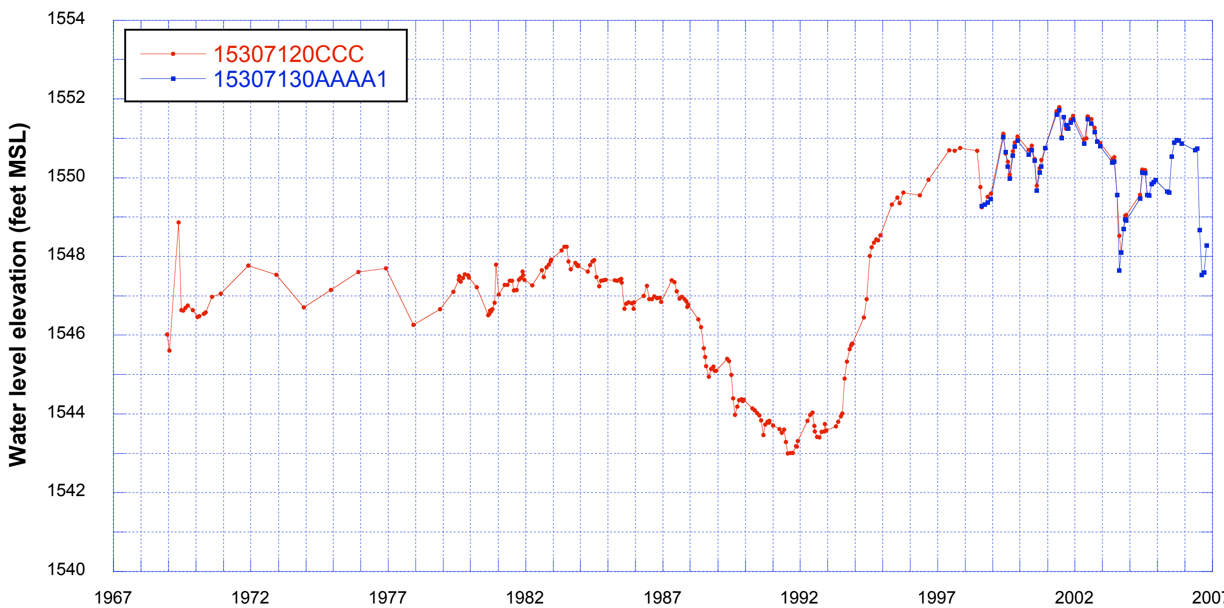


Figure 18. Hydrographs of NDSWC observation wells 153-071-20CCC and 153-071-30AAAA1 screened in Trappers Coulee aquifer.

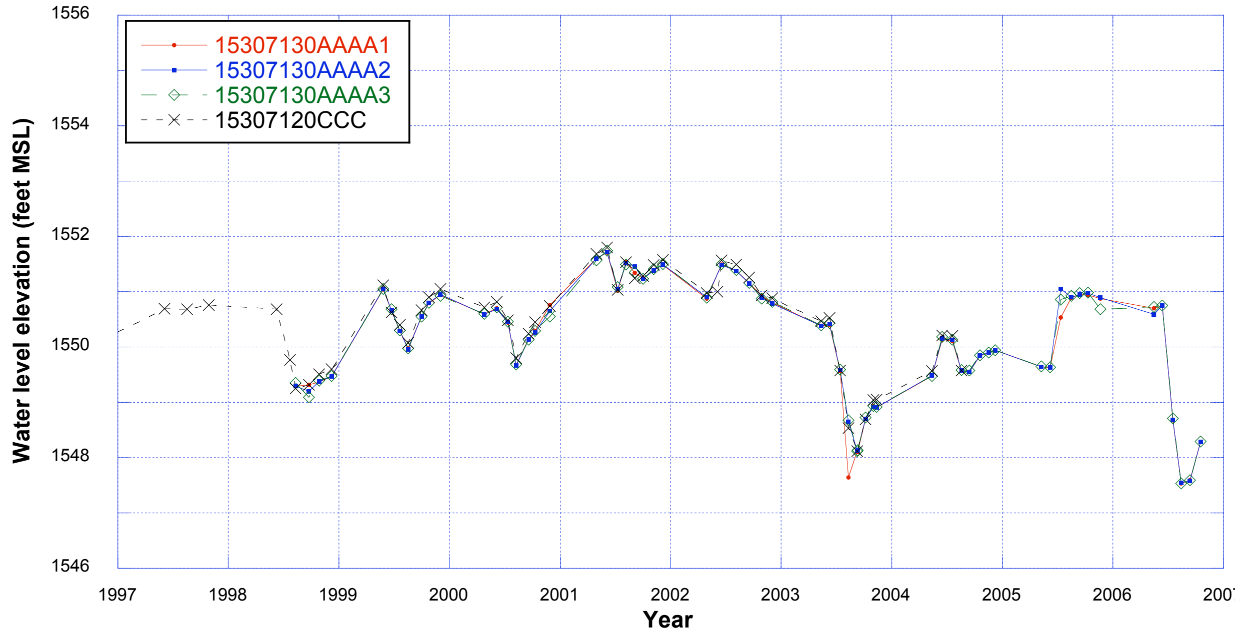


Figure 19. Hydrographs of NDSWC observation wells 153-071-20CCC and 153-071-30AAAA1, 2, & 3 screened in Trappers Coulee aquifer.

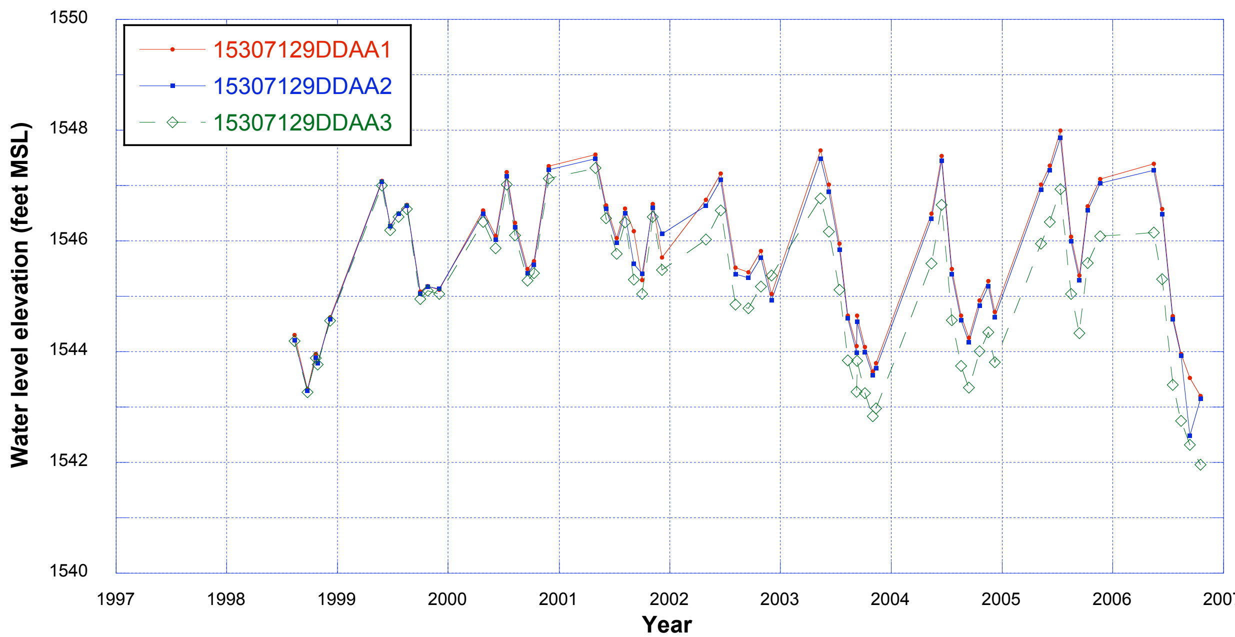


Figure 20. Hydrographs of NDSWC observation wells 153-071-29DDAA1, 2, & 3 screened in Trappers Coulee aquifer. The apparent decline in water levels in observation well 153-071-29DDAA3 relative to the other two wells is a result of a frost heave slowly jacking the shallow well out of the ground.

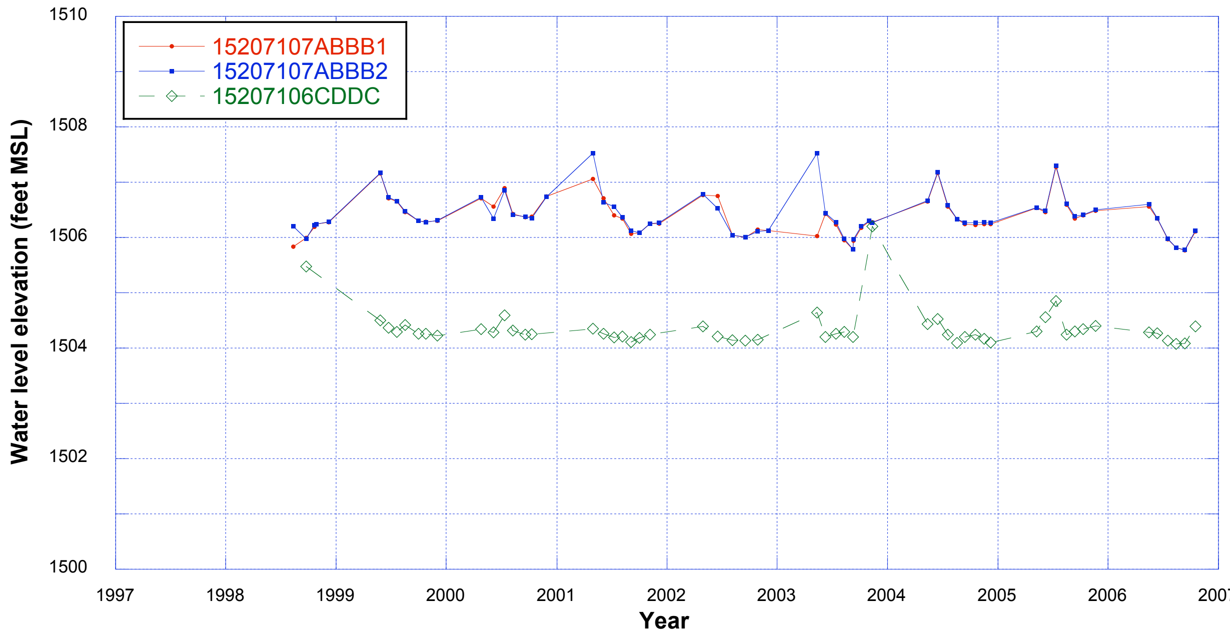


Figure 21. Hydrographs of NDSWC observation wells 152-071-07ABB1, & 2 screened in Trappers Coulee aquifer and stream stage in Trappers Coulee at 152-071-06CDDC.

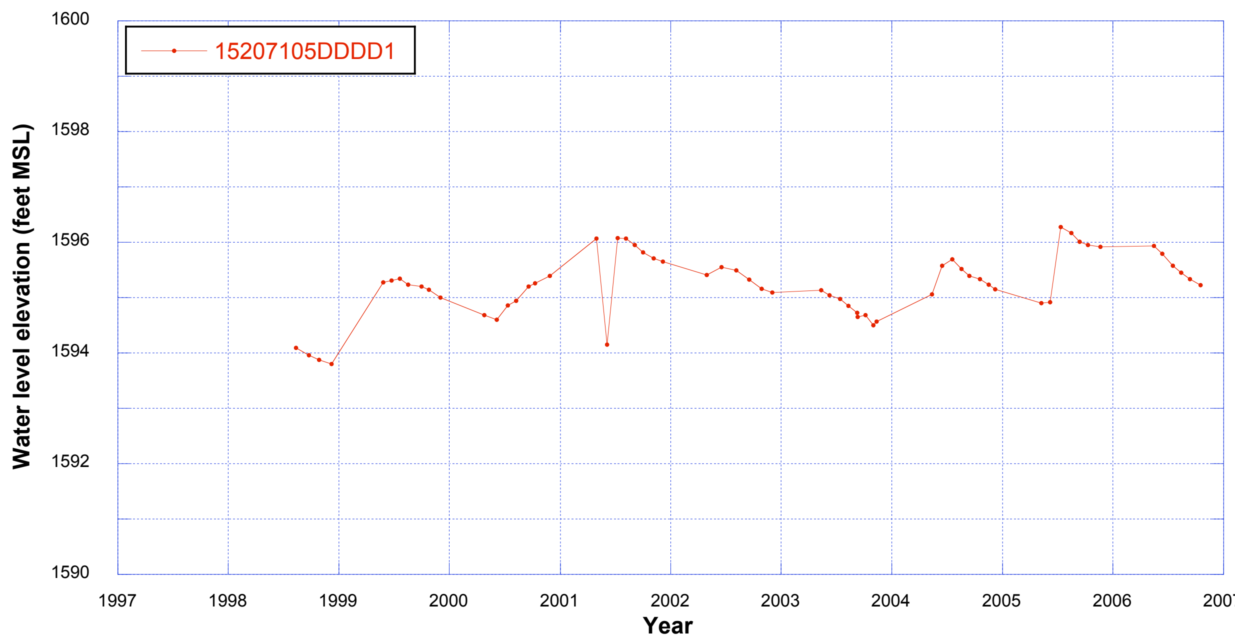


Figure 22. Hydrograph of NDSWC observation well 152-071-05DDDD1 screened in Esmond aquifer.

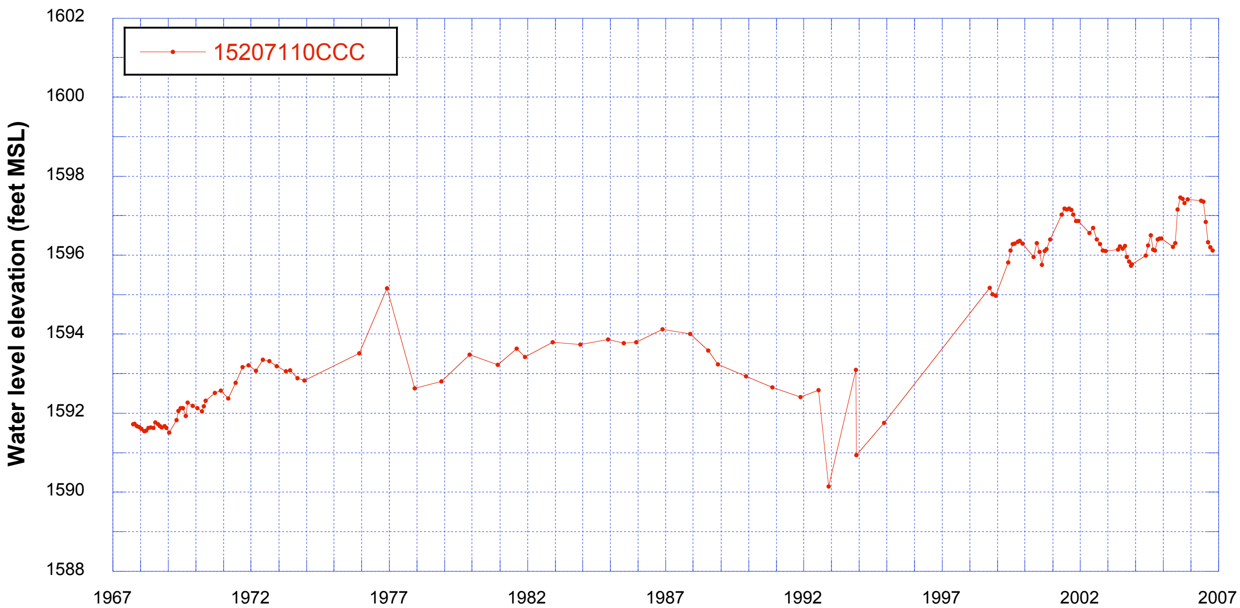


Figure 23. Hydrograph of NDSWC observation well 152-071-10CCC screened in Esmond aquifer.

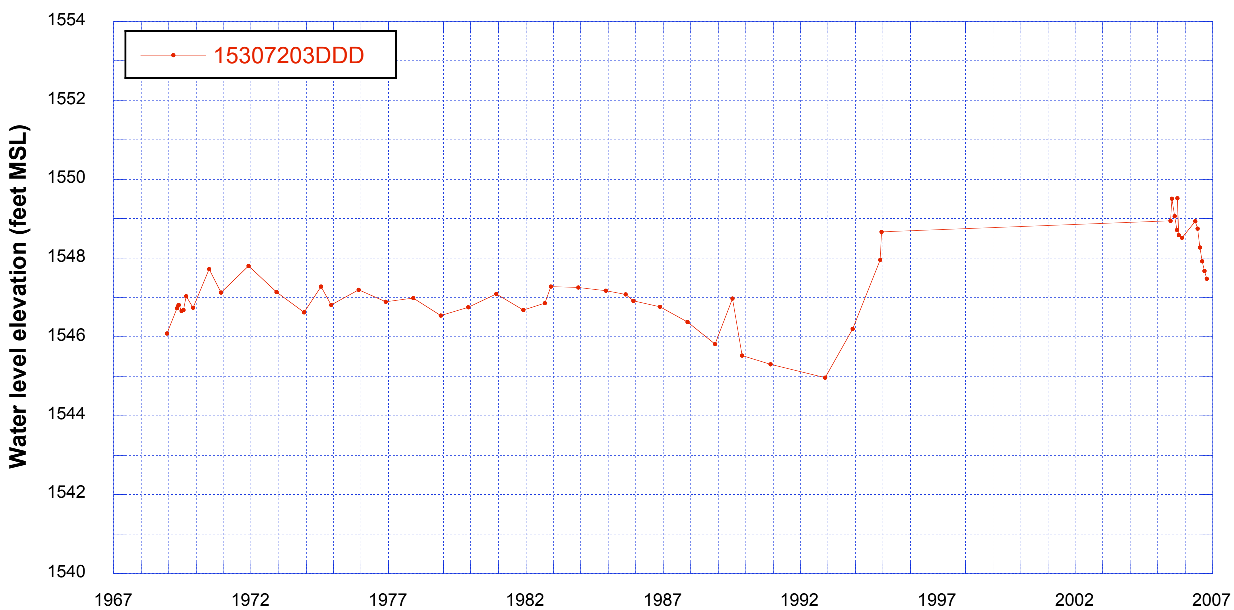


Figure 24. Hydrograph of NDSWC observation well 153-072-03DDD screened in Fox Hills aquifer.

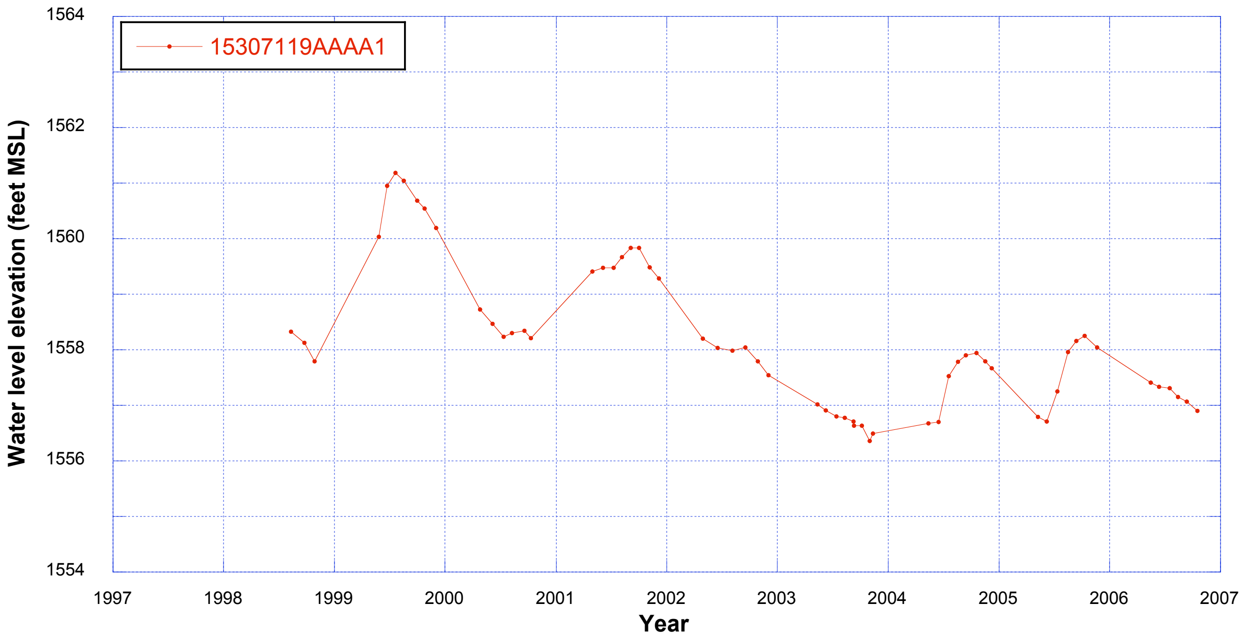


Figure 25. Hydrograph of NDSWC observation well 153-071-19AAAA1 screened in Fox Hills aquifer.

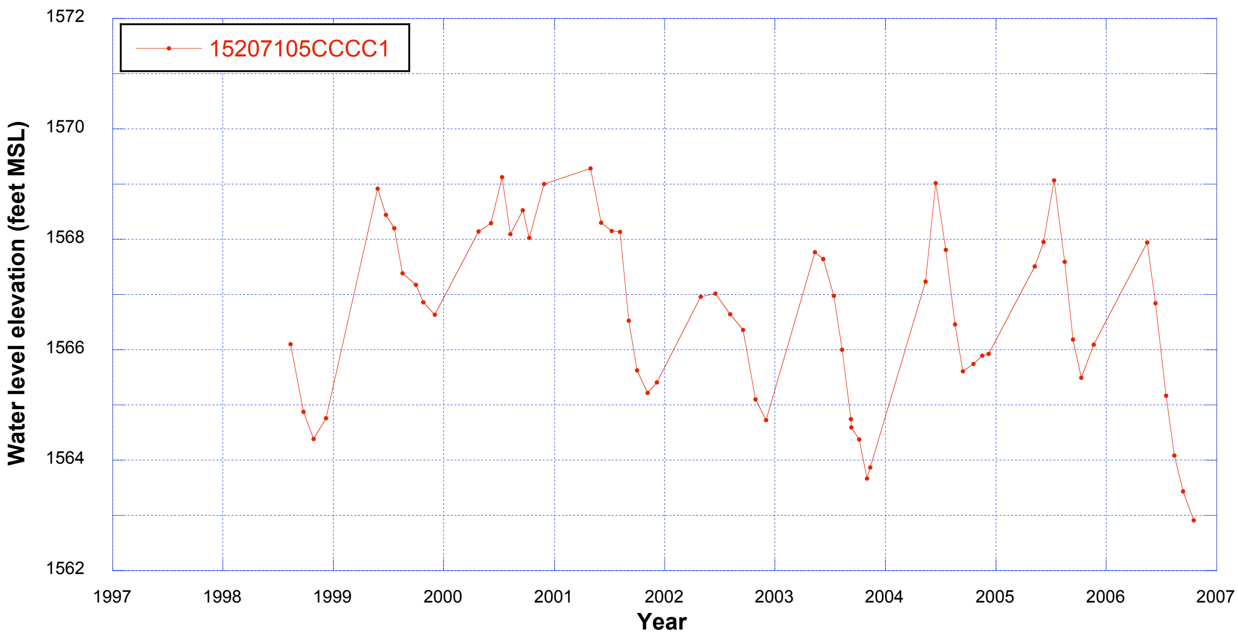


Figure 26. Hydrograph of NDSWC observation well 152-071-05CCCC1 screened in Fox Hills aquifer.

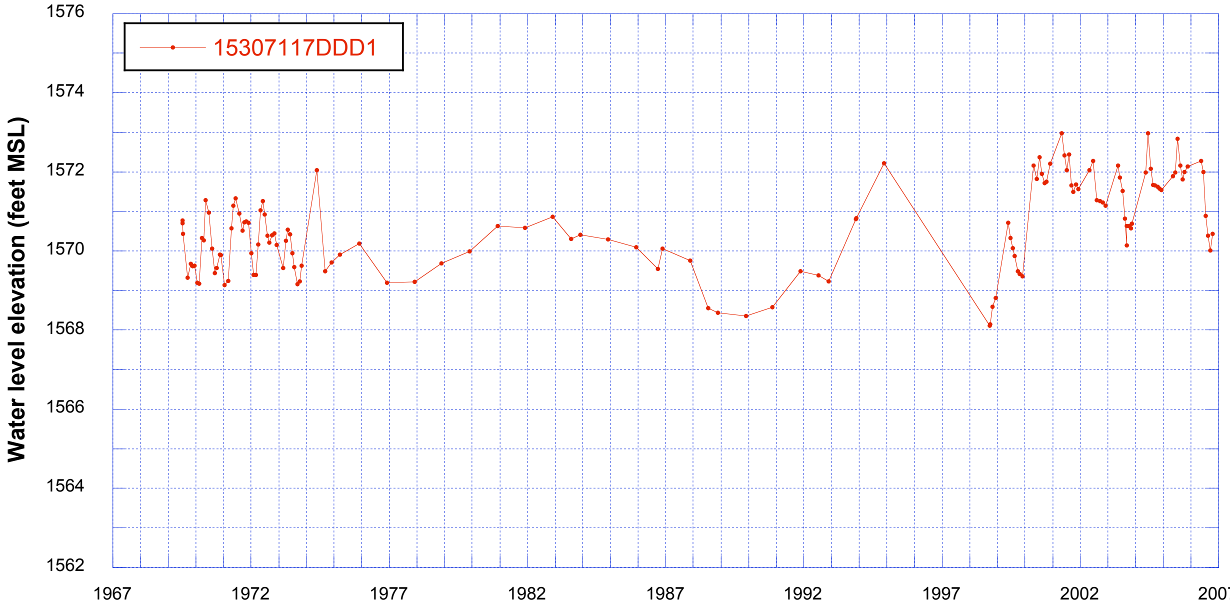


Figure 27. Hydrograph of NDSWC observation well 153-071-17DDD1 screened in tributary to Trappers Coulee meltwater channel, 1969 through 2006.

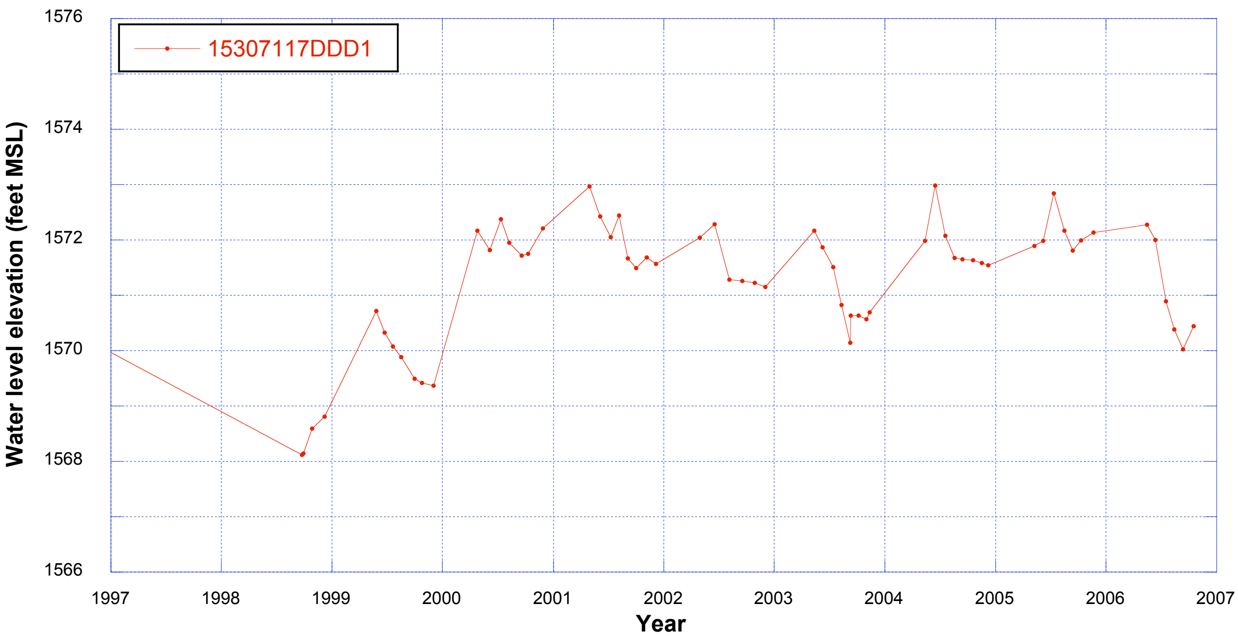


Figure 28. Hydrograph of NDSWC observation well 153-071-17DDD1 screened in tributary to Trappers Coulee meltwater channel, 1997 through 2006.

Ground-Water Discharge

Prior to irrigation development, discharge from the Trappers Coulee aquifer occurred by evapotranspiration (ET) and discharge to Trappers Coulee where it overlies the LTC aquifer. Unlike most water table aquifers in eastern North Dakota, stream discharge is a significant part of the aquifer water budget. The appropriation of water for irrigation has become a significant part of the aquifer water budget. It is the ability to capture water that was previously discharged either by evapotranspiration or flow into Trappers Coulee that determines the amount of irrigation the aquifer can sustain.

Evapotranspiration

Discharge by ET from the Trappers Coulee aquifer occurs in areas where the water table is within a few feet of land surface. These areas will be characterized by poorly drained soils. Those areas of poorly drained soils (fig. 11) that overlie the Trappers Coulee aquifer (fig. 7) are significant discharge areas from the Trappers Coulee aquifer. These discharge areas occur only along Trappers Coulee. These discharge areas can also be seen in the August 20, 1998 CIR photography shown in figures 12 and 29. The discharge area on the east side of Trappers Coulee in the Section 28, Township 153 North, Range 71 West running from the center of the south side of the section to the center of the northwest quarter is more pronounced in the CIR than in the drainage classification map. This is an area of thin sand and gravels overlying the Fox Hills Formation that receives both runoff and discharge from the Esmond aquifer to the east. Increased ET is likely a result of the very wet conditions that existed from 1993 to 1998 when the photography was shot.

Neither the UTC or the outwash area on the north side of the UTC loses significant water to evapotranspiration as indicated by well drained soils overlying this area and lack of indication of evapotranspiration in the CIR photography at a time of high water levels (fig. 18). This suggests that any recharge occurring in the outwash area either discharges to Trappers Coulee or the meltwater channel.

Stream Flow

A major part of the discharge from the Trappers Coulee aquifer is the gain in stream flow in Trappers Coulee as it flows across the aquifer. Discharge at stream gaging site 152-072-06CDDC (fig. 16) in August 1998 was 485 acre-feet per year. Additional flow measurements at 153-071-21CCCD above where Trappers Coulee intersects the aquifer and at 152-072-06CDDC are shown in figure 30. The year 2005 was a wet year with significant runoff as seen by the large flows at 153-071-21CCDC. Figure 30 shows the difference in flows at the two gaging stations and therefore should represent the discharge to the stream from the aquifer above the gaging site. An unknown part of this flow is discharge from the Esmond aquifer that flows down into Trappers Coulee through the channels seen in figure 12 leading from the Esmond aquifer outcrop in the valley wall to Trappers Coulee. Through the summer of 2006 flow was approximately 600 acre-feet per year. Flow increased to 1400 acre-feet per year in October, similar to the flow in October 2005, and then declined to 710 acre-feet per year in November. The October increase likely represents the cessation of ET. If October is representative of base flow, then freezing conditions have a very large impact on flows in the late fall. This large decline seems unrealistic and needs further monitoring.

Runoff into Trappers Coulee above where it flows onto the aquifer and sheet runoff onto the aquifer could be a significant source of recharge to the aquifer. To evaluate this, annual water year stream flow data for the USGS gage on the Sheyenne River near Warwick was examined. The data were converted to inches of runoff per year based on the reported contributing area. The results for the total contributing area and the contributing area between the Warwick and Harvey gages are presented in figure 32. Very little difference was observed. To extend the record to before 1950, data was used from the discontinued gage near Sheyenne (contributing area 660 mi^2) that was upstream of the Warwick gage (contributing area 760 mi^2). Runoff (inches per year) from water year 1940 to 2005 is presented in figure 33. Runoff ranges from 0.1 inches per year to 4 inches per year. Prior to 1993, runoff averaged about 1 inch per year. Runoff since 1993 has more than doubled. This is another indicator of the very unique nature of the climate of the last decade.

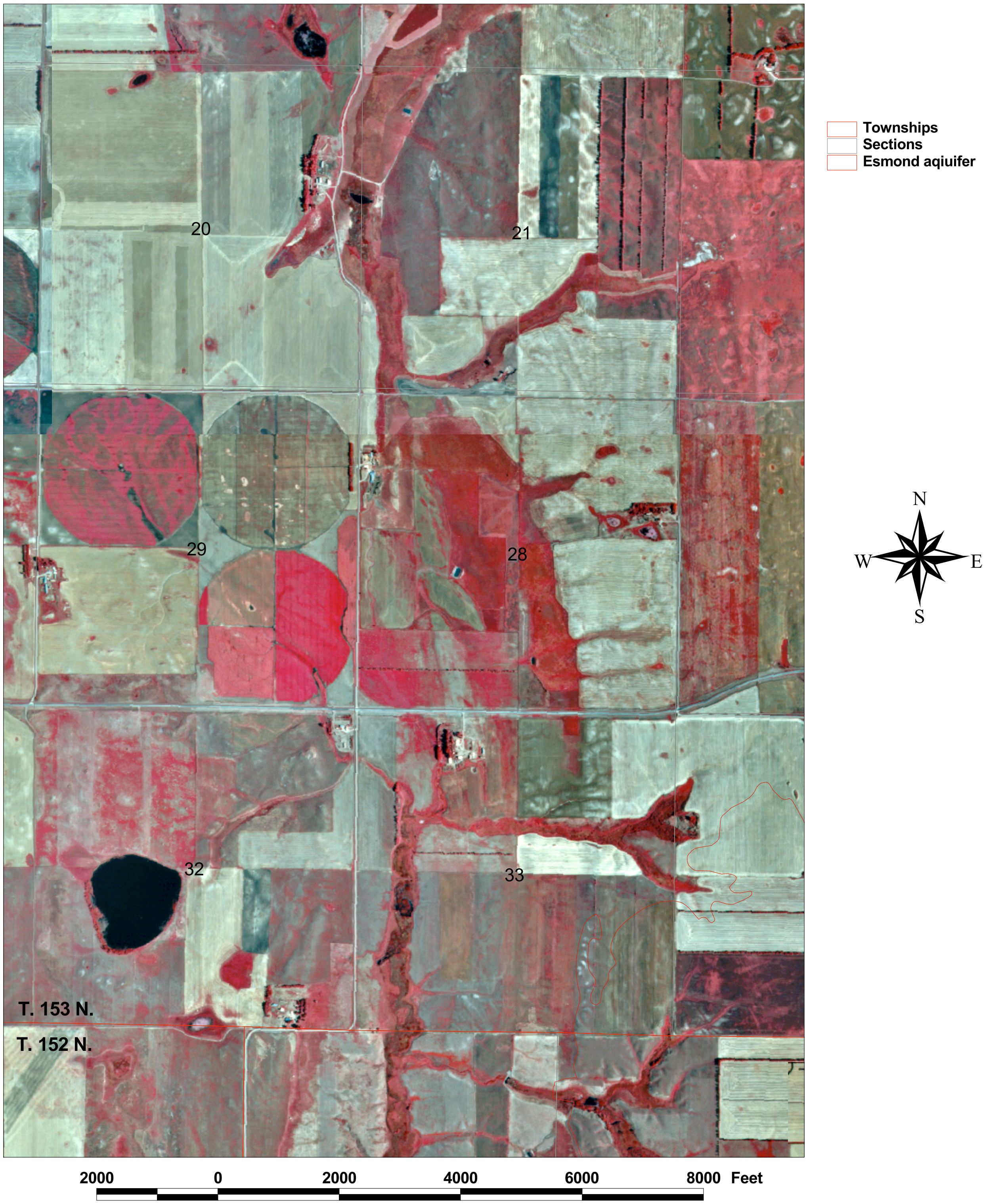


Figure 29. Color Infrared Image from August 20,1998 of the area where Trappers Coulee flows onto the meltwater channel.

Stream Flows

Figure 30. Comparison of flows in Trappers Coulee at 153-071-21CCCD and 152-071-06CDDC.

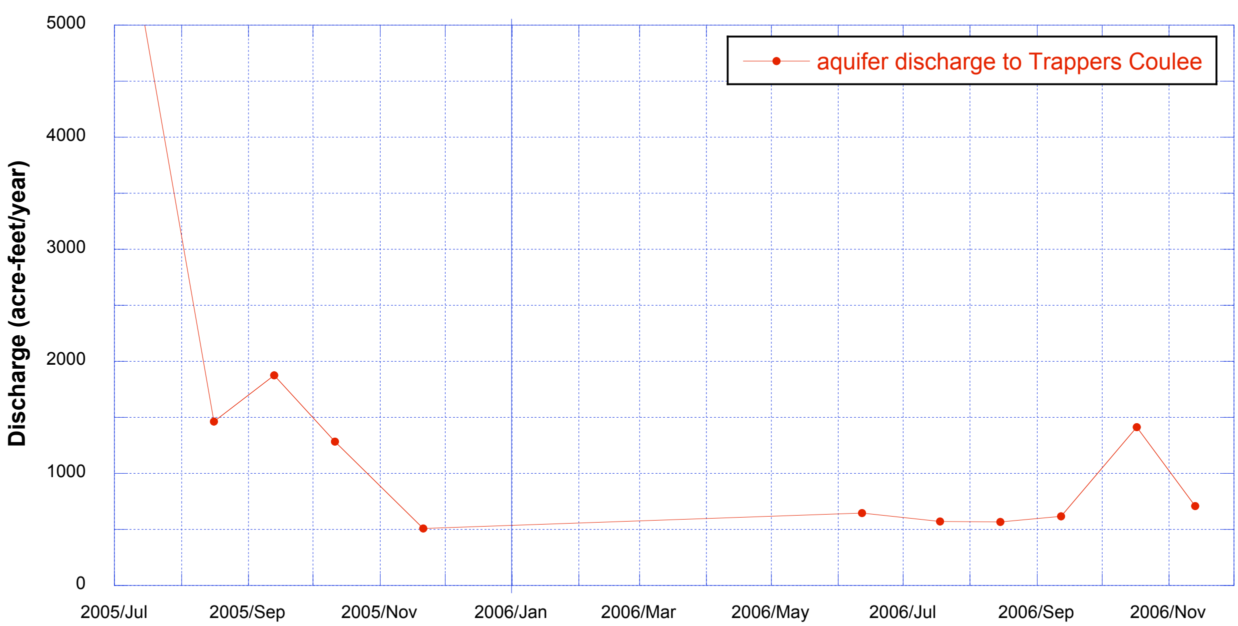


Figure 31. Gain in stream flow in Trappers Coulee between gaging sites 153-071-21CCCD and 152-071-06CDDC.

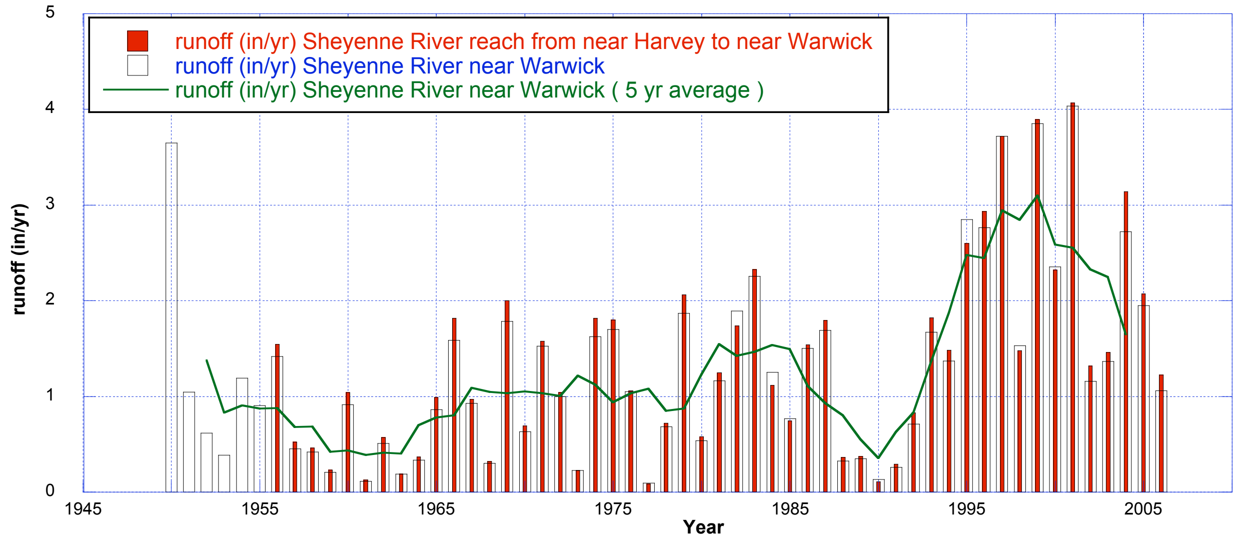


Figure 32. Annual runoff (inches) at USGS gage Sheyenne River near Warwick, ND, contributing area 760 mi^2 and for reach of Sheyenne River between USGS gages near Harvey, ND and Warwick, ND, contributing area 606 mi^2.

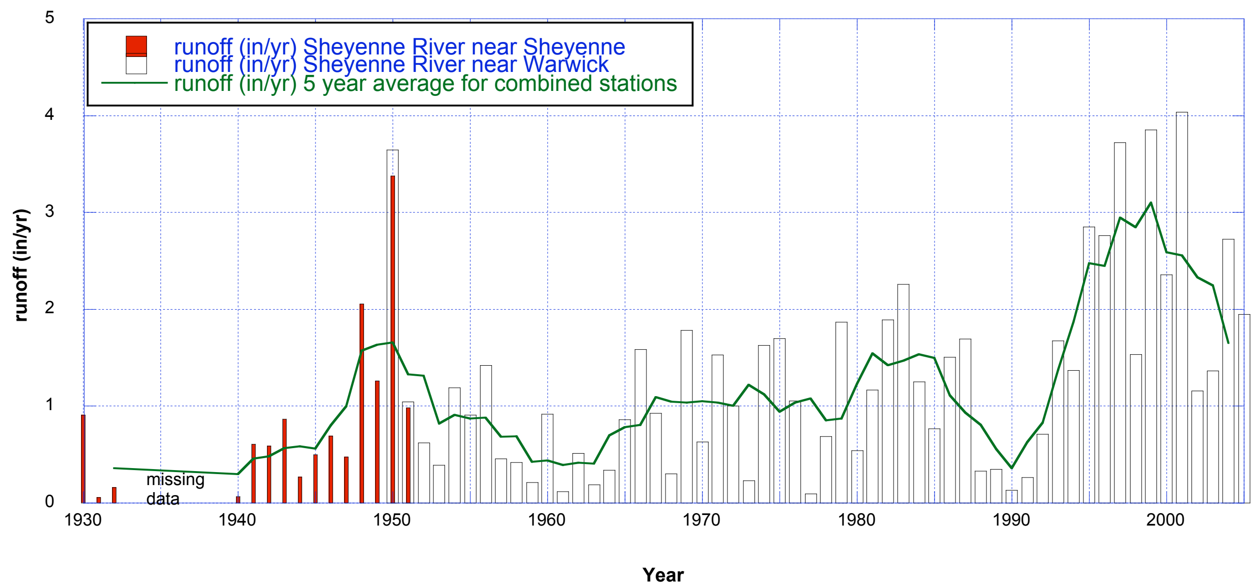


Figure 33. Annual runoff (inches) at USGS gage Sheyenne River near Sheyenne, ND, contributing area 660 mi^2 and for reach of Sheyenne River near Warwick, ND, contributing area 760 mi^2.

Water Use

The city of Esmond uses only a very small quantity of water (fig. 34) from the Fox Hills aquifer, and the use is ignored in this study. Irrigation has become a significant source of discharge from the aquifer. There are three irrigation permits that appropriate water from the Trappers Coulee aquifer, each with one irrigation well. Water use data for these three permits is presented in figures 35 to 37. Total water use is presented in figure 38. The number of acres irrigated and the amount of water used per acre increased in 1998 when seed potato production started in the area. Prior to that, the amount of water used by water permit #2534 was small as the operator grew primarily small grains and sunflowers under irrigation.

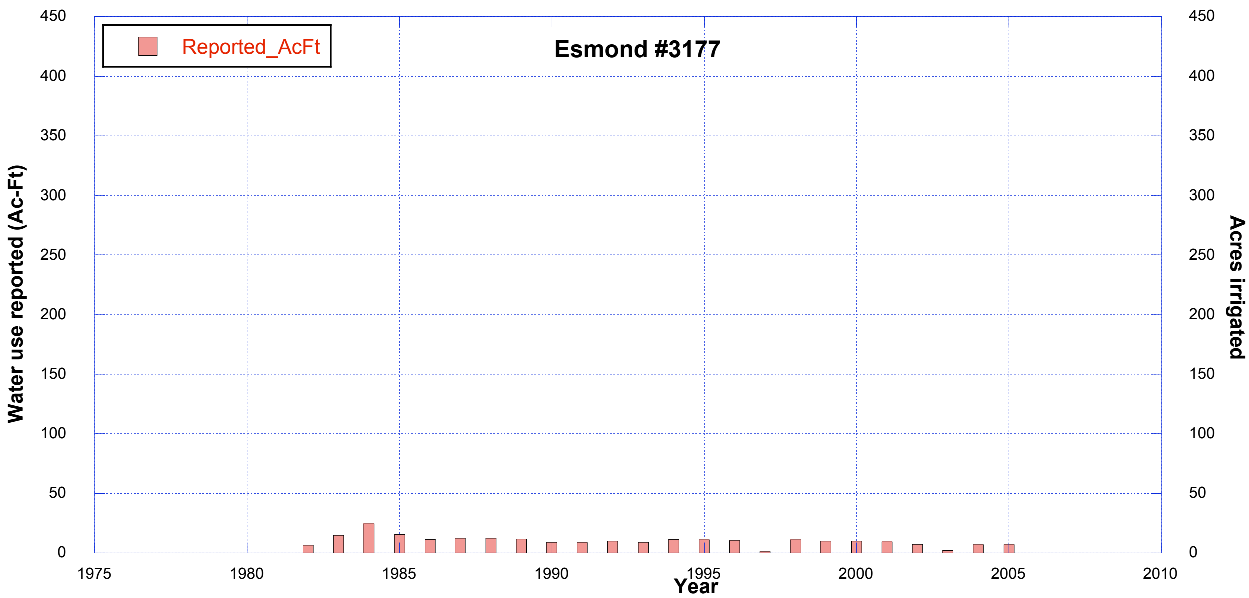


Figure 34. Water use from Fox Hills aquifer by City of Esmond from point of diversion at 153-071-34B.

The amount of water used per acre from the Trappers Coulee aquifer is presented in figure 39a. Because of the crops grown under irrigation prior to 1998, water use per acre for this period was not typical and cannot be compared to estimated water use from soil moisture budget models. The Karlsruhe aquifer is located 40 miles to the west of the Trappers Coulee aquifer. Alan Wanek, through personal communications, supplied water use data for the Karlsruhe aquifer (fig. 39b). Water use is similar for 1998 through 2004 and therefore, Karlsruhe water use is considered a good proxy for irrigation water use from the Trappers Coulee aquifer. Karlsruhe water use is a good approximation for what normal, not supplemental, irrigation water use would be between 1975 and 1997.

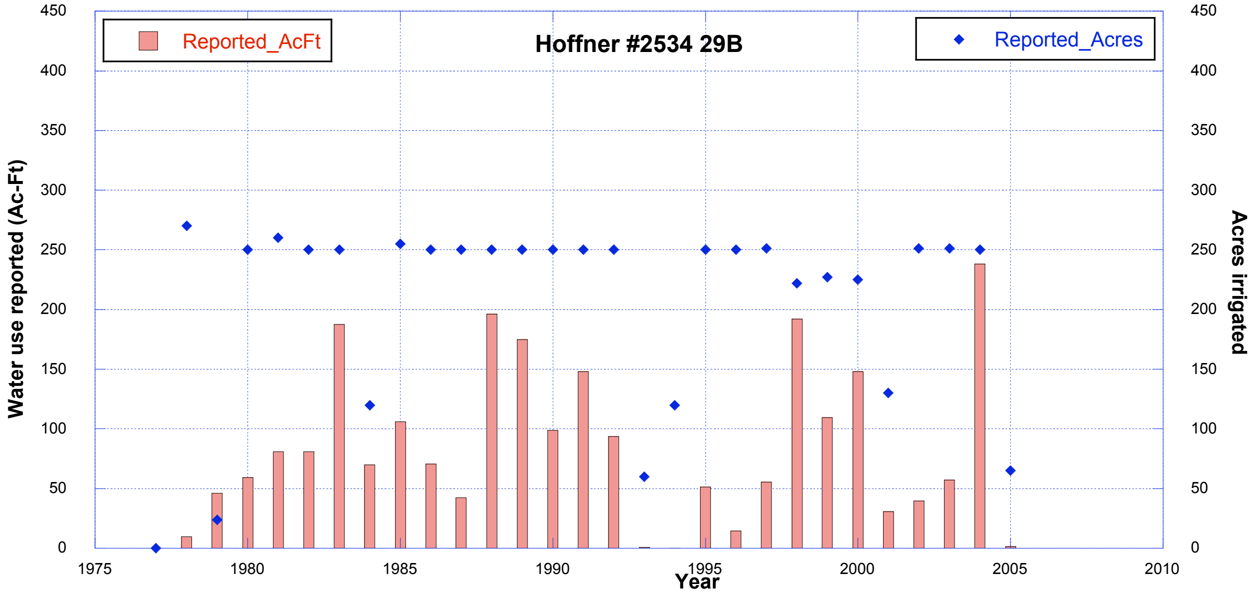


Figure 35. Water use from Trappers Coulee from irrigation well at 153-071-29BBD, water permit #2534.

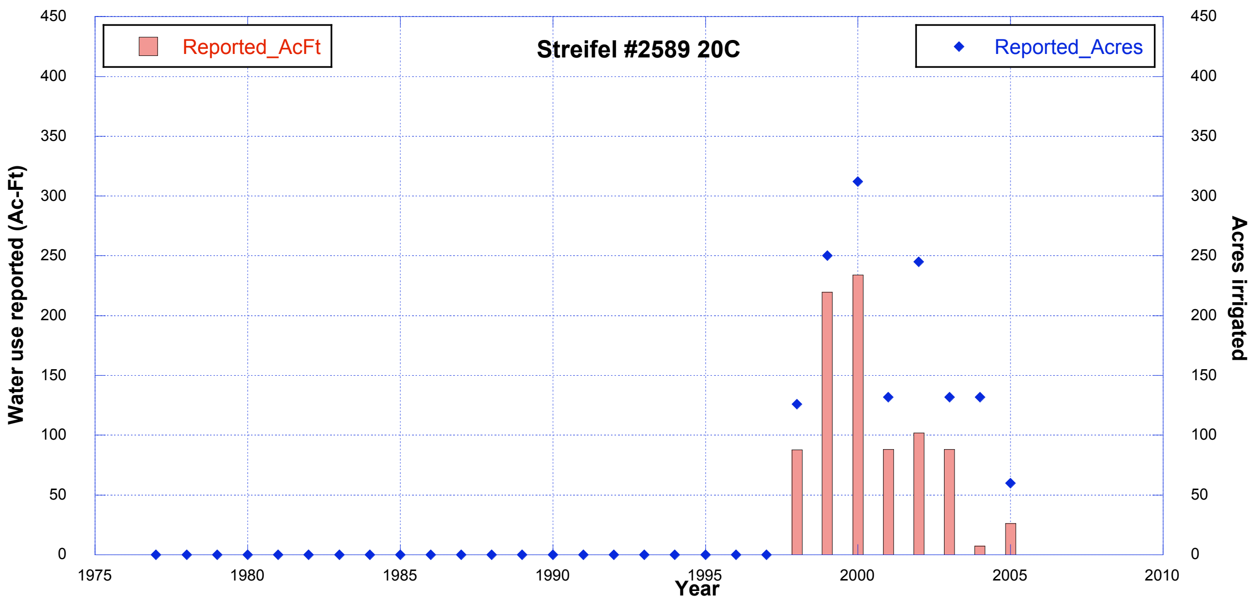


Figure 36. Water use from Trappers Coulee from irrigation well at 153-071-20CCDB2, water permit #2589.

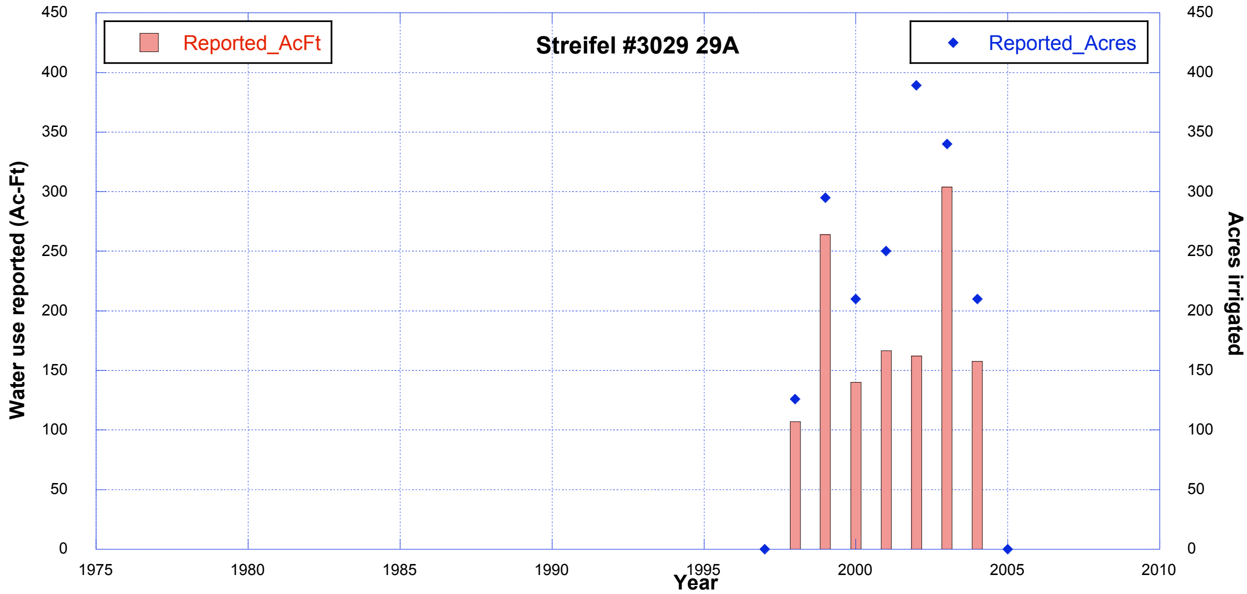


Figure 37. Water use from Trappers Coulee from irrigation well at 153-071-29ACAA2, water permit #3029.

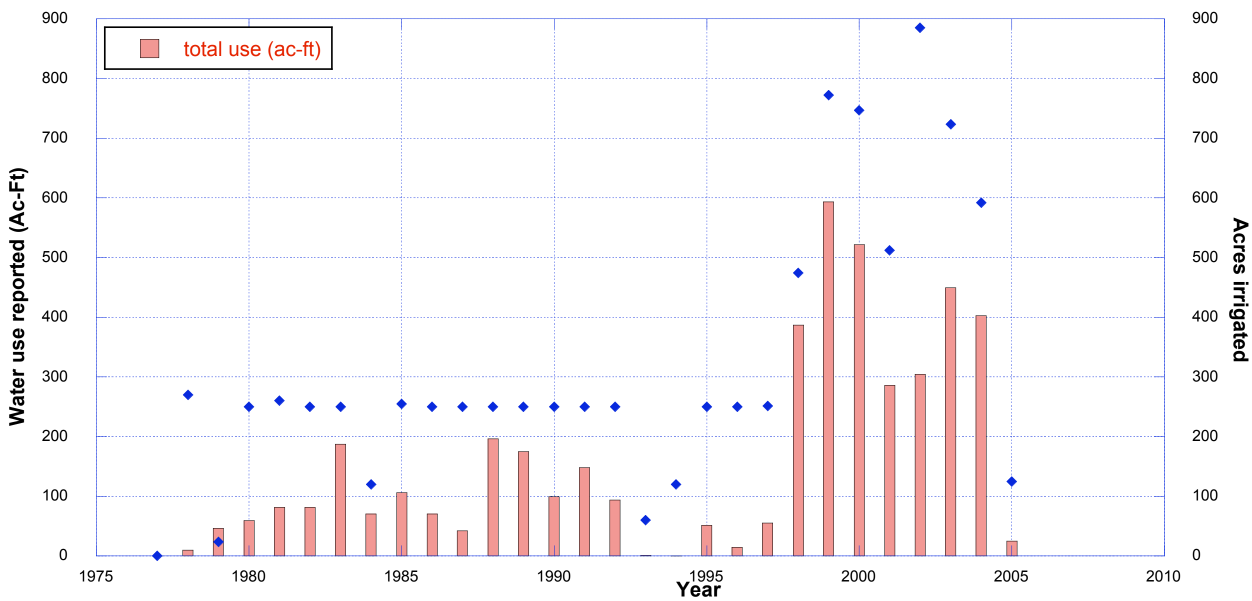
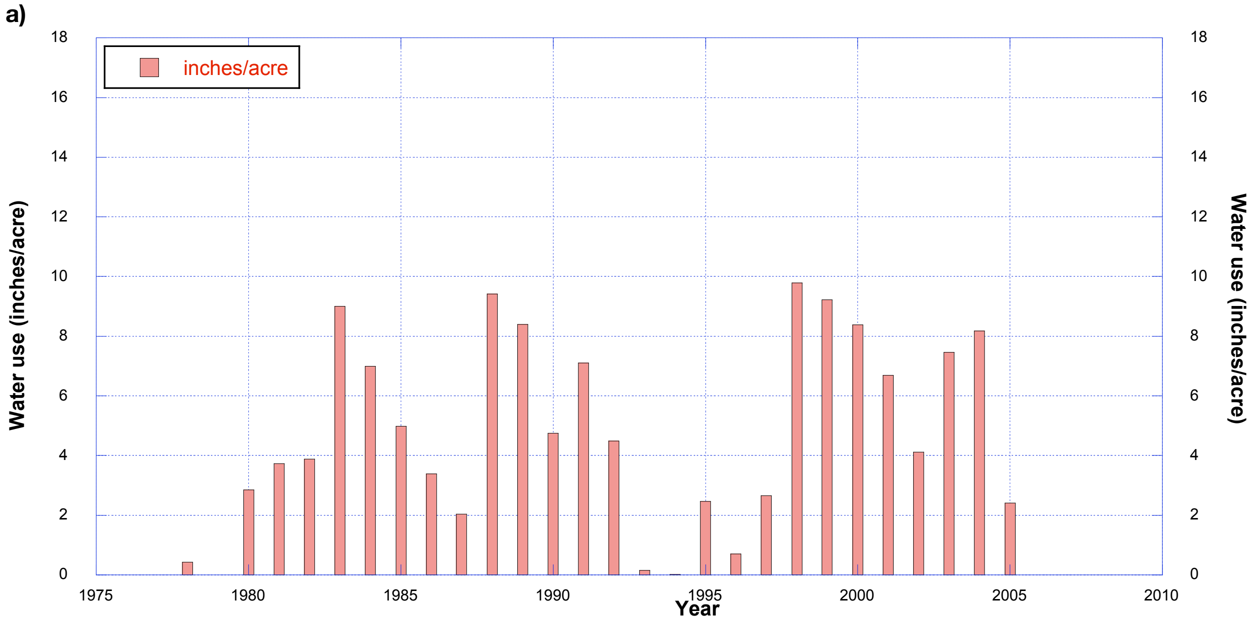


Figure 38. Total water use from the Trappers Coulee aquifer.

a)



b)

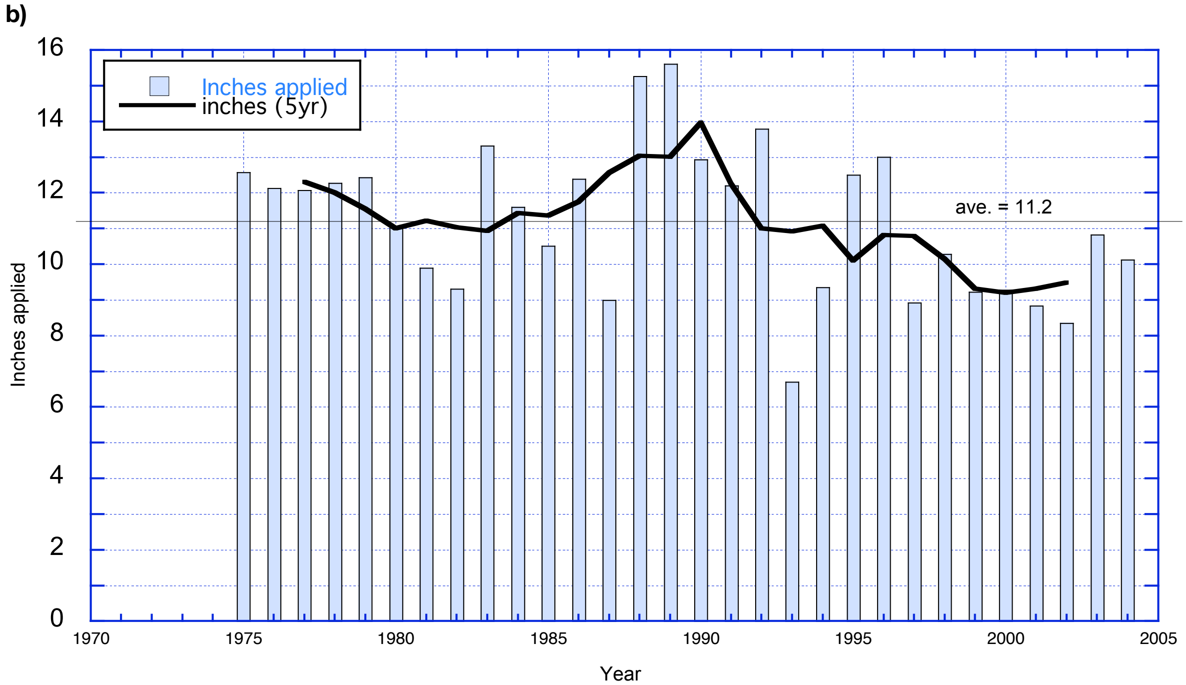


Figure 39. Average irrigation water use in inches per year. **a)** Trappers Coulee aquifer. **b)** Karlsruhe aquifer (Wanek, personal communications).

Water Quality

The water near the bottom of the Trappers Coulee aquifer and the Fox Hills Formation on the north side of the aquifer is a sodium-bicarbonate type. Water near the top of the Trappers Coulee aquifer and the Fox Hills Formation on the south side of the aquifer is a calcium-magnesium-bicarbonate type (figs. 40 and 41)(Tables 1 and 2). Total dissolved solids (TDS) in the water pumped from the three irrigation wells ranges from 511 to 559 milligrams per liter (mg/l). However, the sodium adsorption ratio (SAR) ranges from 3.9 to 7.4, and the residual sodium carbonate (RSC) ranges from 3 to 6. This water represents a potential sodium hazard to the soils it is used to irrigate. However, the soils being irrigated are primarily Fordville loams with little clay content, and with proper management the water quality may not present a problem.

The water quality in the Trappers Coulee aquifer is stratified with the lower part of the aquifer being primarily sodium-bicarbonate water, indicating water enters the aquifer from the surrounding Fox Hills Formation, and the upper part being a calcium-magnesium-bicarbonate water, which originates as local ground-water recharge (figs. 42a, 42b, and 42c). The assumption, based on water level data, that the aquifer begins near NDSWC observation wells at 153-071-18CCC is supported by the water quality data for the site. Water at this site is of poorer quality (higher sodium) throughout the aquifer interval than at 153-071-30AAAA. This indicates a stronger bedrock influence on the water quality at 153-071-30AAAA. If this were the beginning of the aquifer, then it would be an area of relatively stagnant flow with a smaller fraction of the water in the aquifer coming from direct recharge. At 153-071-30AAAA only the deep well has large sodium concentrations with small TDS concentration calcium-magnesium-bicarbonate water occurring in the middle and upper well (figure 42b). At 153-071-29DDAA the sodium concentration is greatest near the bottom of the aquifer, though less than that observed at either 153-071-30AAAA or 153-071-18CCCC. The upper and middle wells also have higher sodium than that observed at 153-071-30AAAA (figures 42a, 42b, and 42c). The wells at 153-071-29DDAA are adjacent to a ground-water discharge area that lies to the east. This results in upward flow in the vicinity of the wells at 153-071-29DDAA resulting in a mixing of the sodium-bicarbonate water near the base of the aquifer with the calcium-magnesium-bicarbonate water that occurs up gradient to the northwest.

Water quality in the irrigation wells should improve, at least over the short run of the next decade, as calcium-magnesium-bicarbonate water from the shallower part of the aquifer is pulled down to the screened interval and enters the well. Changes in water quality in the long run will depend on the quality and quantity of induced recharge entering the aquifer from the Fox Hills Formation. The Fox Hills water on the north side of the aquifer is a sodium-carbonate type while that on the south side is a calcium-magnesium-bicarbonate type (fig. 41). The difference results from the fact that water entering the Trappers Coulee aquifer from the north is from a regional flow system, and therefore, the water is typical of the Fox Hills Formation. To the southwest of the Trappers Coulee aquifer, a ground water divide must exist between the aquifer and Buffalo Coulee 1.5 miles to the southwest. As Buffalo Coulee is 100 feet lower in elevation than the land overlying the aquifer, the divide would likely be much closer to the Trappers Coulee aquifer than to Buffalo Coulee. Water recharging the Fox Hills aquifer on the north side of the divide would flow to the Trappers Coulee aquifer. As this would be a relative short flow path, the area has been flushed of the sodium-bicarbonate type water by low TDS calcium-magnesium-bicarbonate water typical of recharge waters that have a short flow path. Long-term changes in water quality in the Trappers Coulee aquifer will depend on how much recharge is induced from the Fox Hills on the north side versus how much is induced on the south side. Given the very good quality of the water in the Fox Hills on the south side of the aquifer, it would seem unlikely that a significant degradation of water quality would occur though some individual wells could be more susceptible than others depending on their proximity to the northern aquifer boundary.

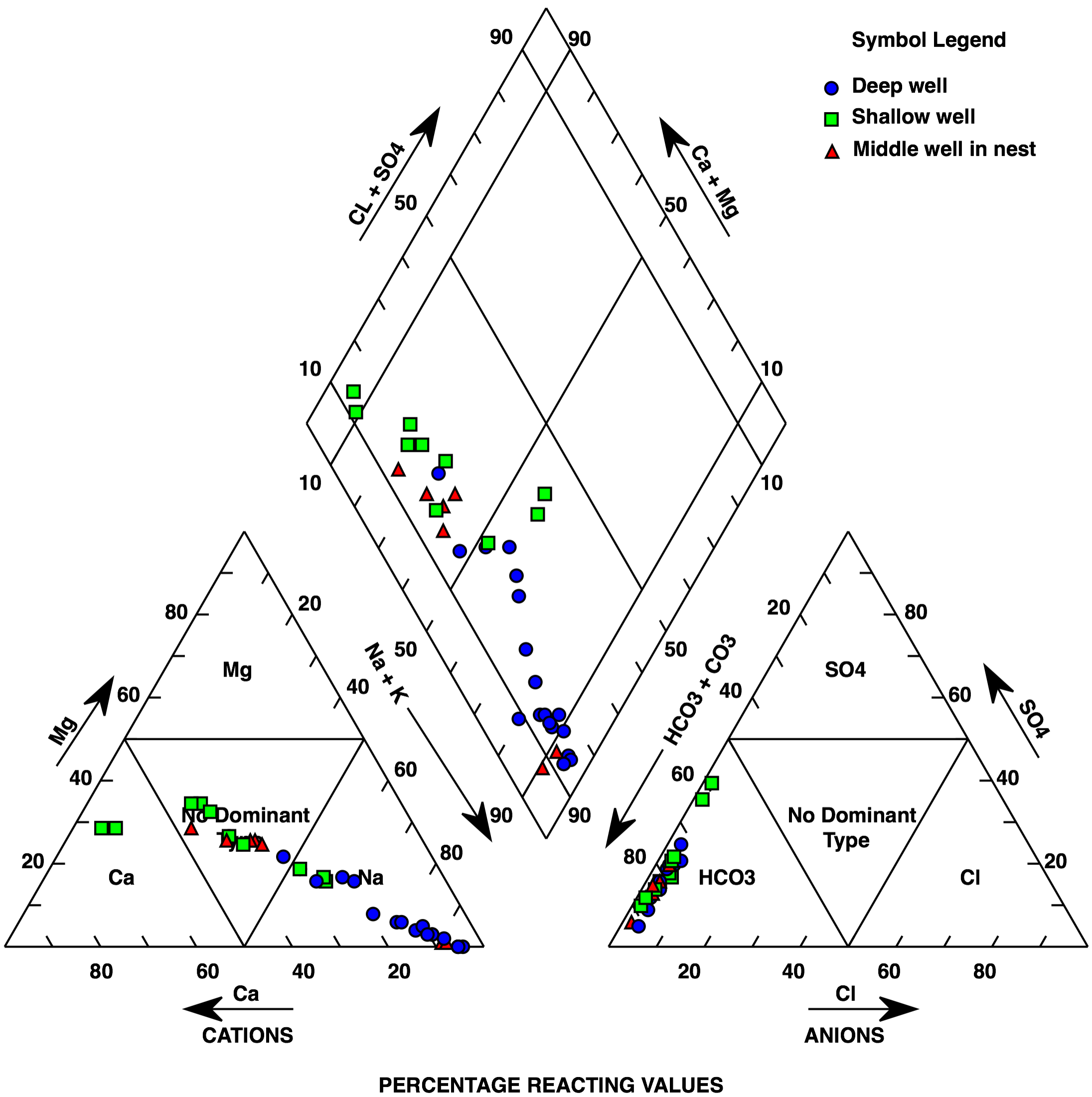


Figure 40. Piper diagram showing relative distribution of major ions in ground water from the Trappers Coulee aquifer.

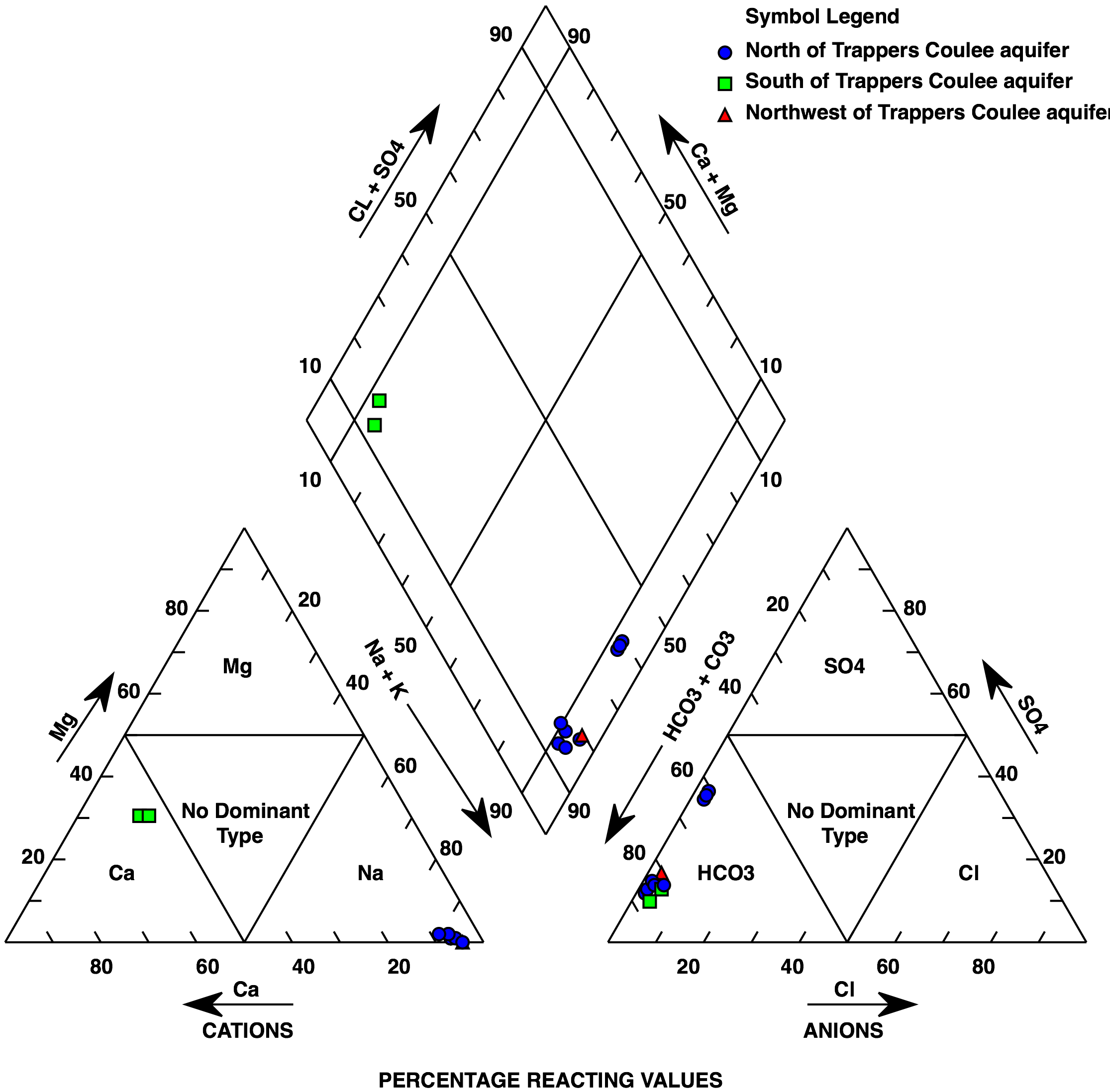


Figure 41. Piper diagram showing relative distribution of major ions in ground water from the Fox Hills aquifer.

Location	Aquifer	Date Sampled	Field Cond.	Lab Cond.	TDS Det.	TDS Calc.	SAR	RSC	Percent Na
15207105CCCC1	Fox Hills	08/13/98	1,991.0	2,050.0	1,350.0	1,350.0	27.0	14.0	94.0
15207105CCCC1	Fox Hills	09/11/03	1,810.0	2,100.0		1,390.0	31.5	13.0	94.8
15307119AAAA1	Fox Hills	08/12/98	596.0	640.0	443.0	386.0	13.0	6.0	92.0
15307119AAAA1	Fox Hills	09/11/03	539.0	632.0		388.0	17.0	6.0	94.1
15307119DCC2	Fox Hills	10/21/98	527.0	619.0	391.0	360.0	0.5	0.0	11.0
15307128BBC1	Fox Hills	10/21/98	1,023.0	1,130.0	719.0	729.0	35.0	11.0	97.0
15307130DAA1	Fox Hills	10/21/98	650.0	747.0	469.0	437.0	0.6	0.0	13.0
15307203DDD	Fox Hills	05/15/69		1,110.0	717.0	747.0	40.0		98.0

Table 1. Water quality of ground water in Fox Hills wells in vicinity of Trappers Coulee aquifer. Cond. = Conductance, Det. = Determined, Calc. = Calculated.

Location	Aquifer	Sample Date	Field Cond.	Lab Cond.	TDS Det.	TDS Calc.	SAR	RSC	Percent Na
15207106CDDC	SW	08/12/98	987.0	988.0	658.0	616.0	3.9	5.0	54.0
15207106CDDC	SW	09/22/05	830.0	875.0		521.0	3.0	3.0	48.0
15207107ABBB1	TC	08/12/98	865.0	897.0	566.0	552.0	5.0	4.0	65.0
15207107ABBB1	TC	09/11/03	770.0	813.0		504.0	4.6	4.0	62.8
15207107ABBB2	TC	08/12/98	631.0	670.0	412.0	398.0	1.0	0.0	23.0
15207107ABBB2	TC	10/21/98	577.0	692.0	429.0	431.0	1.0	0.0	22.0
15207107ABBB2	TC	09/11/03	670.0	710.0		433.0	1.3	0.0	26.4
15307118CCCC1	TC	08/12/98	935.0	971.0	650.0	593.0	29.0	9.0	97.0
15307118CCCC1	TC	09/11/03	904.0	928.0		578.0	32.3	9.0	97.3
15307118CCCC2	TC	08/11/98	741.0	803.0	532.0	467.0	15.0	7.0	92.0
15307118CCCC2	TC	09/11/03	797.0	803.0		495.0	16.6	7.0	92.6
15307118CCCC3	TC	08/11/98	1,141.0	1,200.0	830.0	771.0	4.9	3.0	60.0
15307118CCCC3	TC	09/11/03	994.0	1,210.0		805.0	4.9	2.0	58.2
15307120CCC	TC	05/15/69		790.0	562.0	524.0	10.0		85.0
15307120CCC	TC	07/30/81	810.0	819.0	524.0	561.0	10.0	7.0	85.0
15307120CCC	TC	07/07/95	658.0	669.0	449.0	441.0	11.0	6.0	89.0
15307120CCC	TC	08/12/98	679.0	735.0	497.0	450.0	11.0	6.0	89.0
15307120CCC	TC	06/04/02	744.0	771.0	472.0	454.0	11.0	6.0	88.0
15307120CCD	TC	08/12/98	973.0	1,040.0	694.0	636.0	15.0	9.0	91.0
15307120CCDB2	TC	08/11/98	762.0	771.0	520.0	458.0	7.4	6.0	80.0
15307129ACAA2	TC	08/01/98	781.0	841.0	559.0	526.0	3.9	3.0	58.0
15307129BBD	TC	08/12/98	741.0	770.0	511.0	476.0	6.1	5.0	73.0
15307129DDAA1	TC	08/12/98	812.0	905.0	553.0	553.0	1.9	2.0	34.0
15307129DDAA1	TC	10/21/98	1,020.0	1,170.0	741.0	748.0	4.0	5.0	52.0
15307129DDAA1	TC	09/11/03	967.0	1,010.0		634.0	3.3	4.0	47.8
15307129DDAA2	TC	08/12/98	969.0	1,050.0	665.0	654.0	2.5	2.0	39.0
15307129DDAA2	TC	10/21/98	919.0	1,050.0	675.0	652.0	2.5	3.0	39.0
15307129DDAA2	TC	09/11/03	890.0	972.0		603.0	2.7	3.0	41.3
15307129DDAA3	TC	08/12/98	1,086.0	1,160.0	776.0	733.0	4.0	4.0	53.0
15307129DDAA3	TC	10/21/98	860.0	979.0	611.0	629.0	2.0	1.0	34.0

Table 2. Water quality of ground water in Trappers Coulee aquifer wells and in surface water samples. SW = Surface Water, TC = Trappers Coulee, Cond. = Conductance, Det. = Determined, Calc. = Calculated.

Location	Aquifer	Sample Date	Field Cond.	Lab Cond.	TDS Det.	TDS Calc.	SAR	RSC	Percent Na
15307129DDAA3	TC	09/11/03	720.0	838.0		516.0	2.2	2.0	37.3
15307130AAA	TC	08/12/98	634.0	674.0	429.0	408.0	7.5	6.0	81.0
15307130AAAA1	TC	08/11/98	811.0	875.0	584.0	542.0	23.0	8.0	96.0
15307130AAAA1	TC	09/11/03	792.0	795.0		492.0	26.0	8.0	96.6
15307130AAAA2	TC	08/11/98	448.0	487.0	311.0	281.0	0.9	1.0	25.0
15307130AAAA2	TC	09/11/03	483.0	501.0		296.0	1.4	1.0	32.9
15307130AAAA3	TC	08/11/98	410.0	417.0	252.0	237.0	0.3	0.0	9.0
15307130AAAA3	TC	09/11/03	364.0	362.0		204.0	0.2	0.0	5.4

Table 2 continued. Water quality of ground water in Trappers Coulee aquifer wells and in surface water samples. SW = Surface Water, TC = Trappers Coulee, Cond. = Conductance, Det. = Determined, Calc. = Calculated.

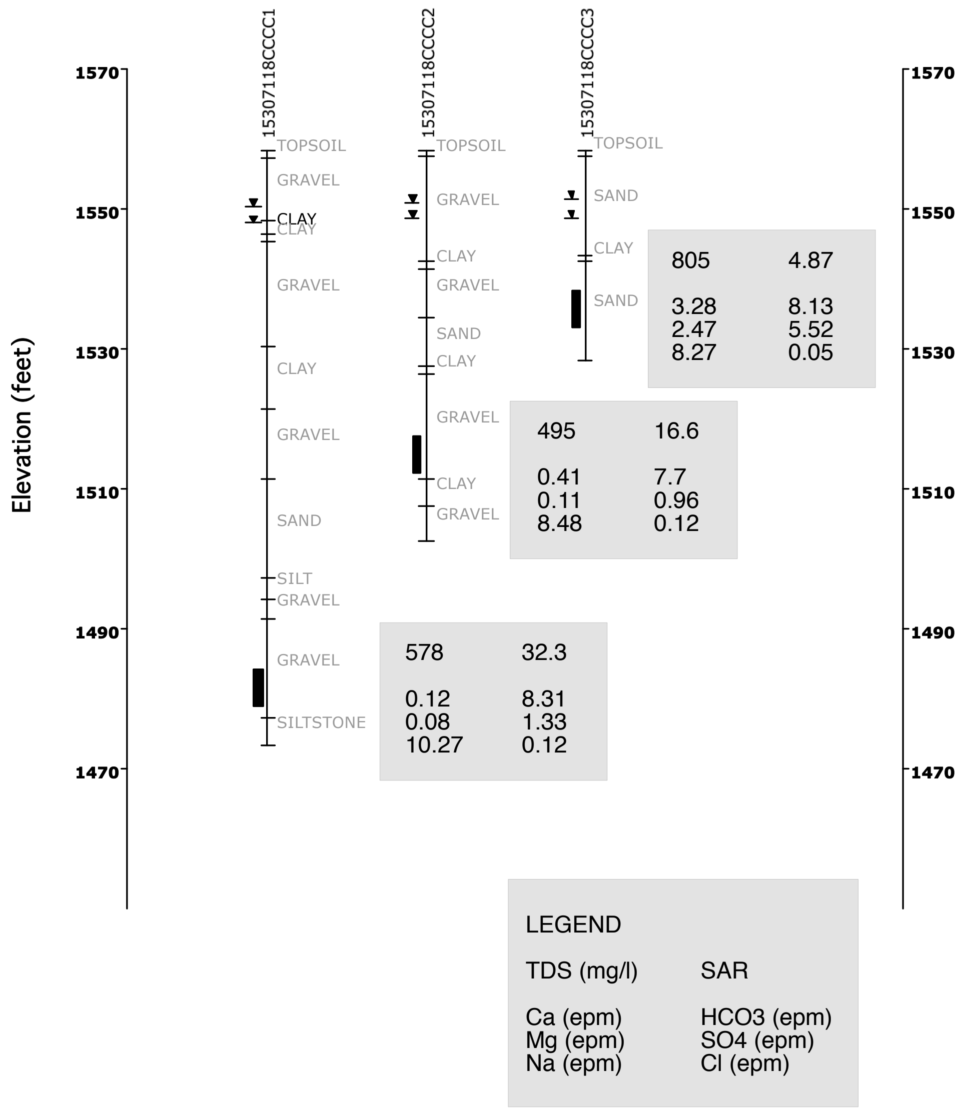


Figure 42a. Water quality at NDSWC observation well nest 153-071-18CCCC.

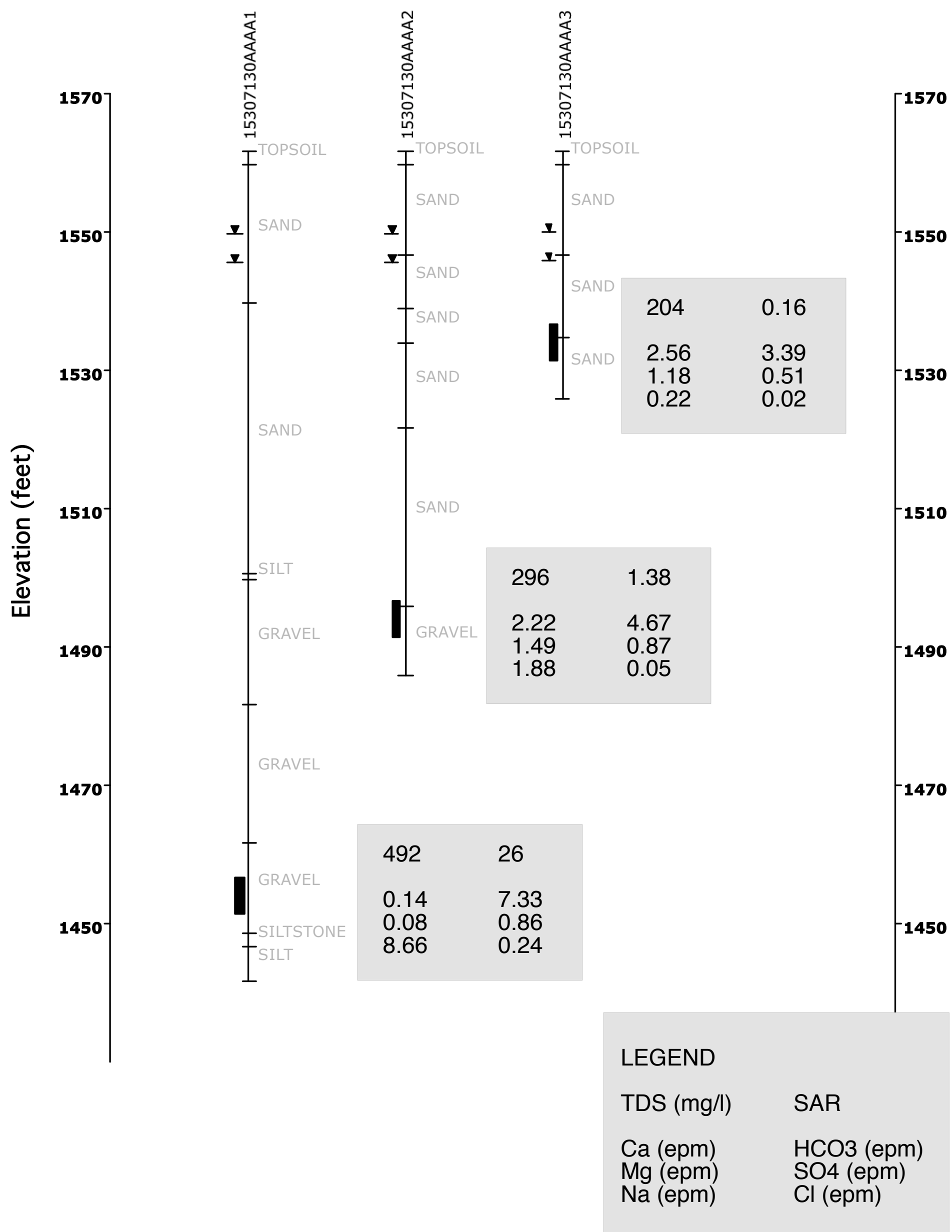


Figure 42b. Water quality at NDSWC observation well nest 153-071-30AAAA.

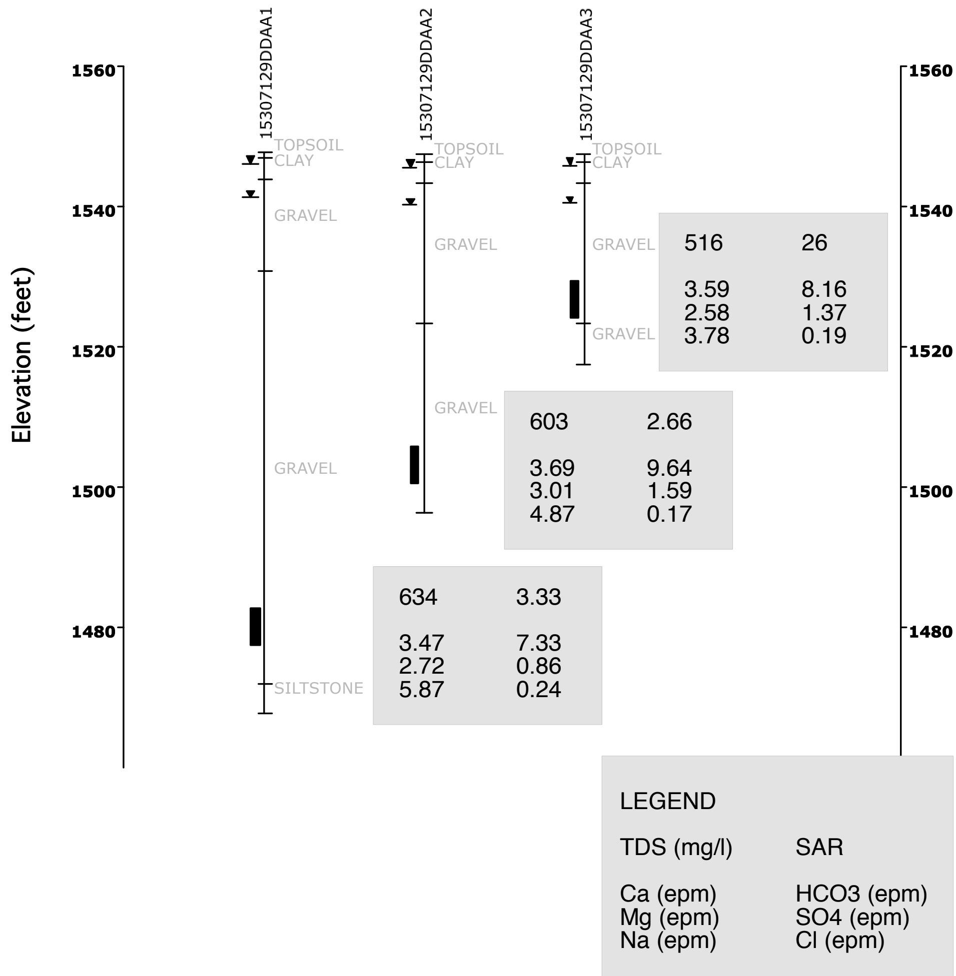
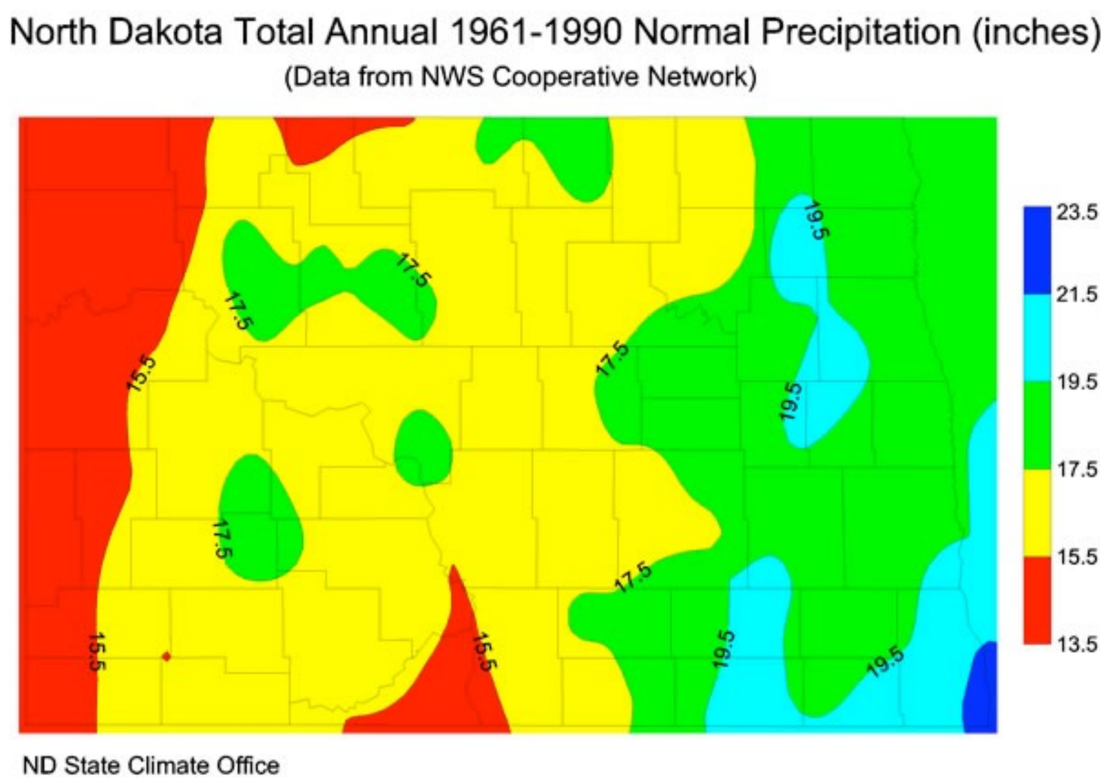


Figure 42c. Water quality at NDSWC observation well nest 153-071-29DDAA.

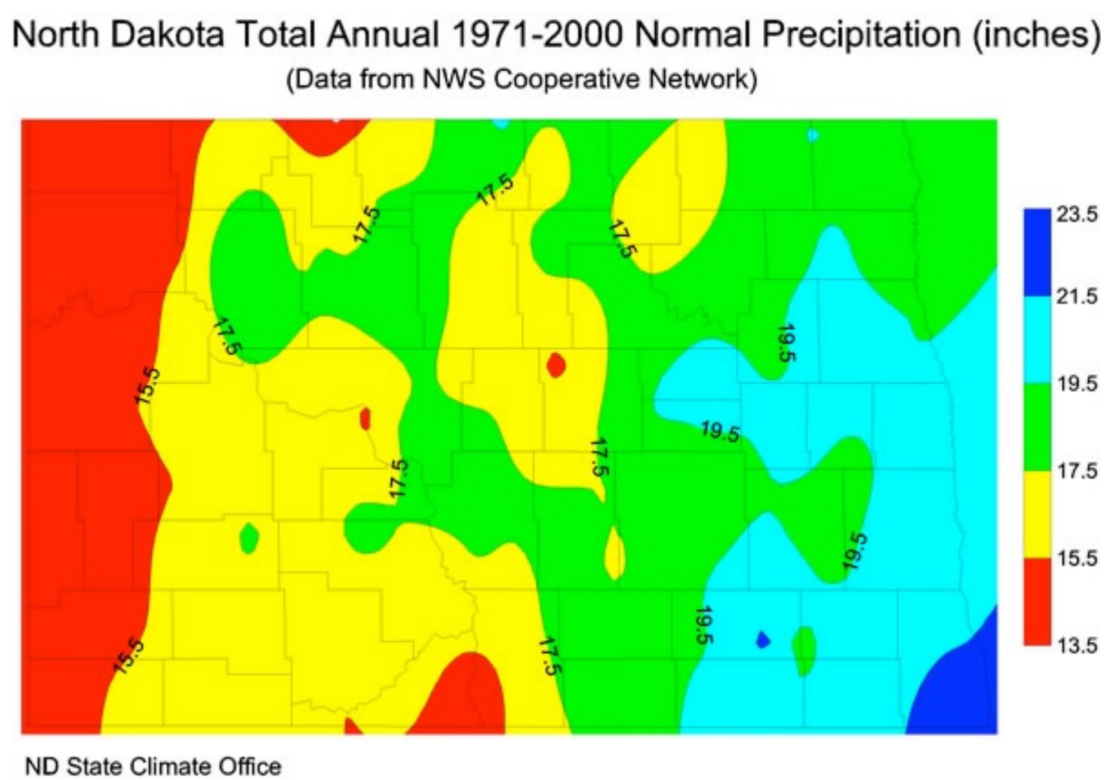
Climate

Regional Climate

The project area has an annual total precipitation of approximately 17 inches. As can be seen in figure 43, there is little trend in precipitation across the study area. Though the 1971-2000 normals are a little wetter than for 1961-1990 there is significant variability across the area. This indicates the region around the project area has a similar mean precipitation and the differences represent random variability. The annual precipitation from the North Dakota Hydrology Manual (USDA SCS, 1979) (fig. 44) shows a drier climate, but the same broad region of similar total precipitation near the project area. Figure 45 shows annual lake evaporation for North Dakota (USDA SCS, 1979) with 32 inches per year occurring at the study area. However, there is a significant increase in lake evaporation moving west-southwest across the study area. Table 3 provides the percentage of annual lake evaporation that occurs by month.



a)



b)

Figure 43. Annual North Dakota precipitation: a) 1961-1990 normal, b) 1971-2000 normal. From Office of the North Dakota State Climatologist website at URL http://www.soilsci.ndsu.nodak.edu/ndawn/StateSummaries/Normals/normalmaps/index.htm.

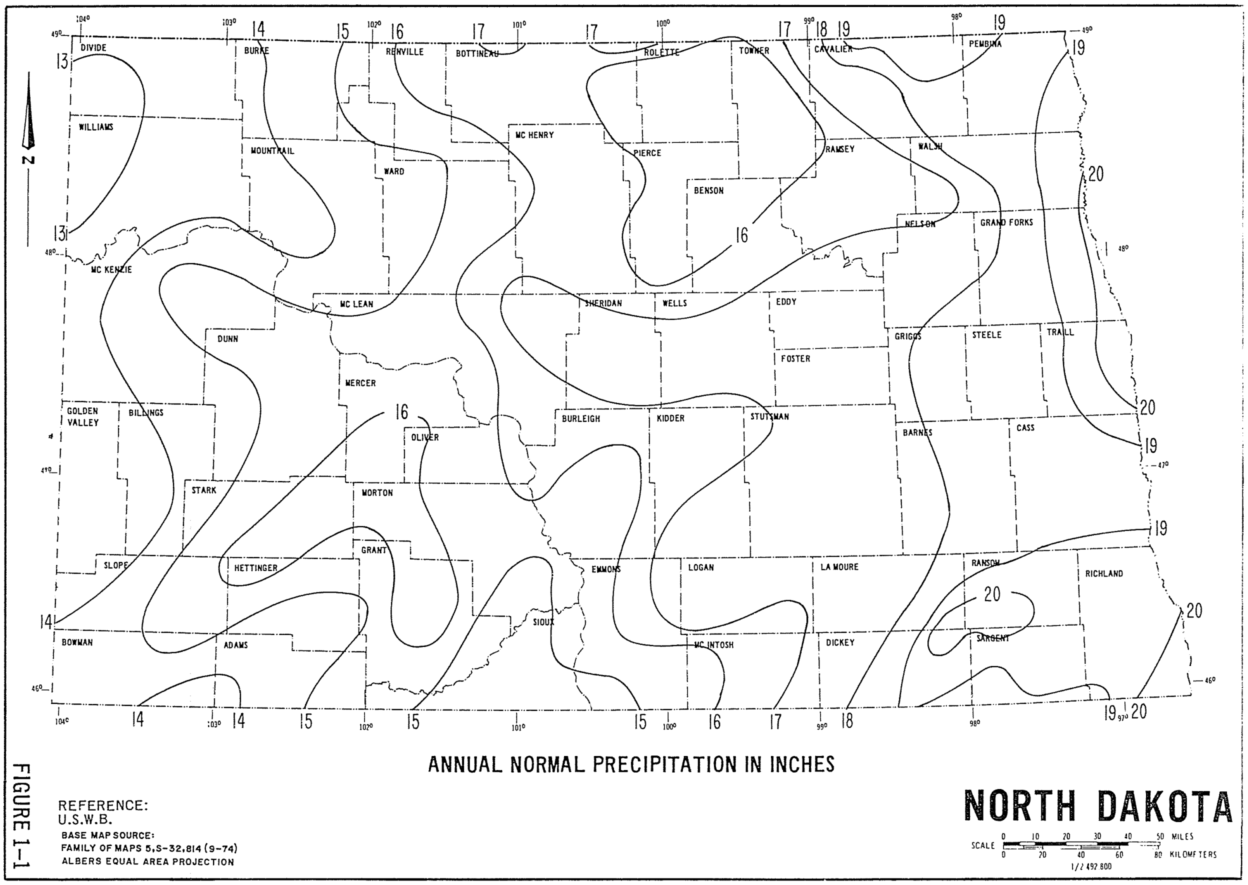


Figure 44. Annual North Dakota precipitation (from USDA SCS, 1979).

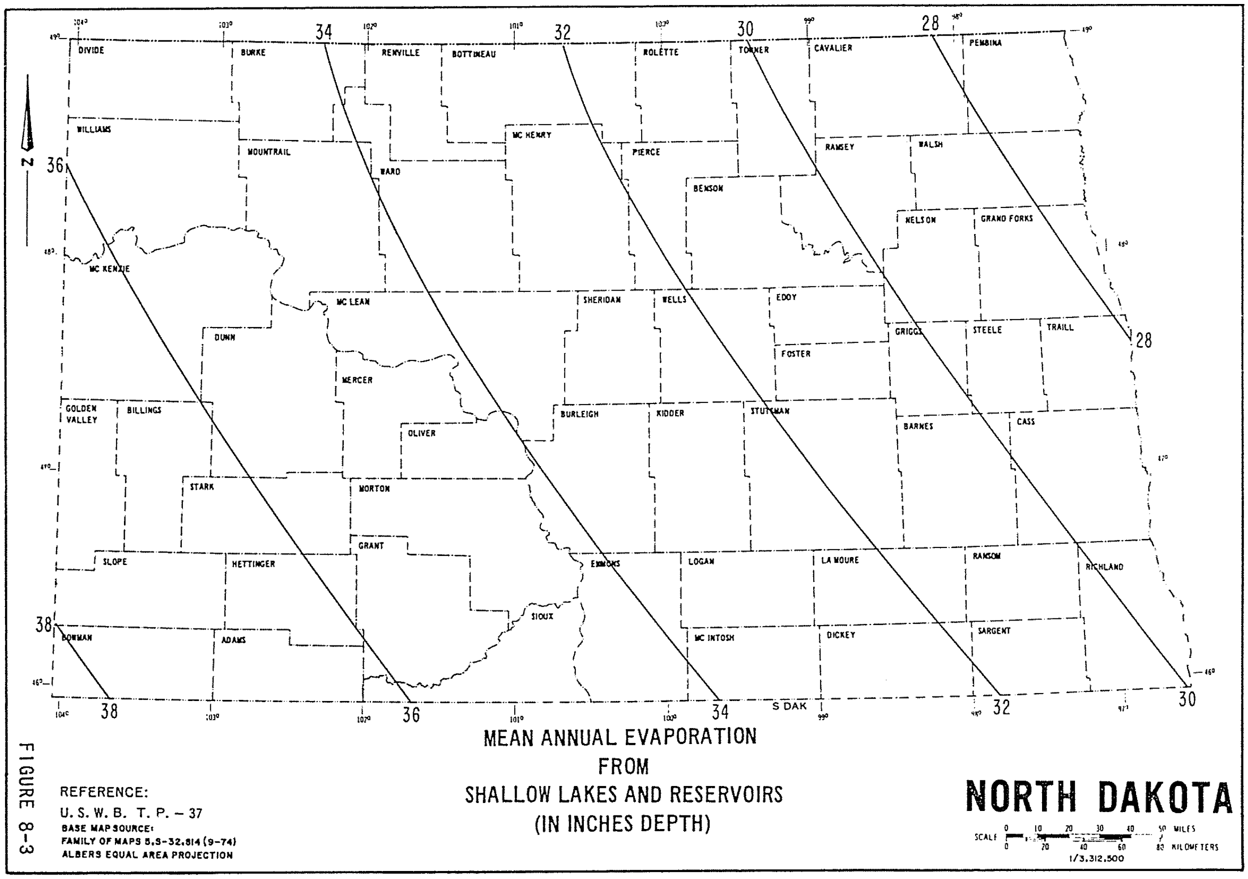


Figure 45. Annual lake evaporation (from USDA SCS, 1979).

Month	Monthly Evaporation Rate (% of mean annual)
January	0.75
February	0.95
March	2.3
April	5.85
May	10.33
June	13.57
July	18.59
August	20.16
September	14.95
October	8.53
November	3
December	1.02

Table 3. Percentage of annual lake evaporation by month (from USDA SCS, 1979).

Climate Datasets

For purposes of modeling groundwater recharge using a soil moisture budget model and analyzing climate statistics, complete data sets of daily precipitation and maximum and minimum temperatures are required. All National Climate Data Center (NCDC) observer data has some missing measurements. Often the period of record for individual data sets is inadequate. To solve this problem, a program called hydrosphereNCDC was written. The program reads NCDC cooperative observer files, North Dakota Agricultural Network (NDAWN) files and North Dakota Atmospheric Resource Board (ARB) files. Daily data for a set of stations in an area are selected and read into the program. The stations are then ordered in preference of data selection. The start and end date for the dataset to be generated are entered. The program reads the data for the first station in the ordered list, and if the data exists, it is written to the dataset file. If the data is missing, the program will search down through the list of stations in the list until it finds valid data for that day and writes that value to the dataset. In this way a complete dataset is built with no missing data by compositing daily data from several climate stations.

To analyze the climate around the project area, datasets were developed for the Granville (fig. 46), Maddock (fig. 50), Rugby (fig. 53), and Towner (fig. 57) areas. Each of the four datasets consists of a unique set of stations. Within each of these station sets, three climate datasets where generated by varying the order of the stations, with the exception of Maddock where only two sets were generated.

For each climate dataset a figure is presented showing a) potential evapotranspiration (PET) calculated using Penman-Monteith from maximum and minimum temperature (Allen, 1998 and Walter, 2002), b) annual water year precipitation and October to April precipitation, and c) stations used to fill missing data. In the missing data station plot, if a bar is plotted for a positive value of maximum temperature (mx tmp), minimum temperature (mn tmp), precipitation (precip), or evaporation (evap) then no data was found for that day and the dataset contains missing data. If a bar is plotted for a negative value of mx tmp, mn tmp, precip, or evap then the date was filled. The bars are offset upward 0.5*(1-n) where n is the index of the station in the list. The plots for the Granville set are shown in figures 47 to 49, Maddock set are shown in figures 51 to 52, Rugby set are shown in figures 54 to 56, and Towner set are shown in figures 58 to 60.

Data for most of the NCDC stations starts in 1948. Climate datasets were also developed for stations with long periods of record (data may start in 1905). These datasets are the Minot (fig. 61), Hansboro (fig. 64), and Fessenden (fig. 66) datasets. Climate datasets developed from these are shown in figures 62 and 63 (Minot), figure 65 (Hansboro), and figure 67 (Fessenden), and the datasets are discussed with the soil moisture budget model.

Calibration curves for windspeed and dewpoint temperatures to calculate PET from temperature using Penman-Monteith were developed for several NDAWN stations (fig. 68) across the state. The Harvey 2SW calibration curves were used in all PET calculations in this report. The required data for the Penman-Monteith equation are available from NDAWN. The earliest stations were established in 1990 and more have been added since then. Generally at least 10 years of record can be found within an area. For most aquifers this is less than a third of the calibration period. The other issue is that the data is largely for a wetter than normal climate.

PET, using the Penman-Monteith method, can be be calculated from maximum and minimum temperature by estimating solar radiation, wind speed, and dewpoint temperature. Daily average wind speed is estimated using a ninth order polynomial fit of wind speed at selected NDAWN stations. Solar radiation is estimated from temperature data using standard procedures (Allen, 1998). Allen (1998) is often referred to as FAO-56 and the terminology is used in this report. The dewpoint is set to minimum daily temperature, however this is not particularly accurate in areas of advection (Allen, 1998). A daily dewpoint correction was derived by fitting a ninth order polynomial to the difference between the dewpoint temperature and minimum daily temperature. In comparing temperature-based estimates of PET with those using all the data, the means are similar, however the variability is greatly reduced. Estimation of solar radiation has no significant impact on estimates of monthly PET. Errors in estimating dewpoints from minimum temperature are the source of much of the error. During wet periods, minimum temperature often underestimates the dewpoint and therefore overestimates PET. Under these conditions there is significant variation in the dewpoint temperature during the day with the highest values occurring in mid-afternoon when PET is at its peak and lowest after dawn. Noctilucent thunderstorms account for much of summer precipitation on the Great Plains indicating the night time instability of the boundary layer resulting in mixing that reduces the surface dewpoint. During drier days, the dewpoint is over-estimated by the minimum temperature, as the air never cools down to the dewpoint. On July 12, 2006, the NWS at Bismarck Airport reported a minimum temperature of 69°F with a dewpoint of 53°F.

There are no NCDC observer stations close to the Trappers Coulee aquifer. ARB maintains a set of observers that measure daily precipitation from April through September of the year. This is the time of year dominated by convective storms and therefore has the greatest spatial variability in precipitation. Since accurate local (on aquifer) precipitation is needed to estimate recharge for model calibration where observed water levels are fit, this dataset appeared to give the best local coverage. The location and date of operation of each ARB observer in the vicinity of the Trappers Coulee aquifer is shown in figure 69. Four groups of observers were created and shown in figure 69 as the central, west, northeast, and south groups. Again multiple station orderings within the group were sometimes used. The growing season precipitation (May-September) for these datasets are shown in figures 70 to 78.

Granville NCDC dataset

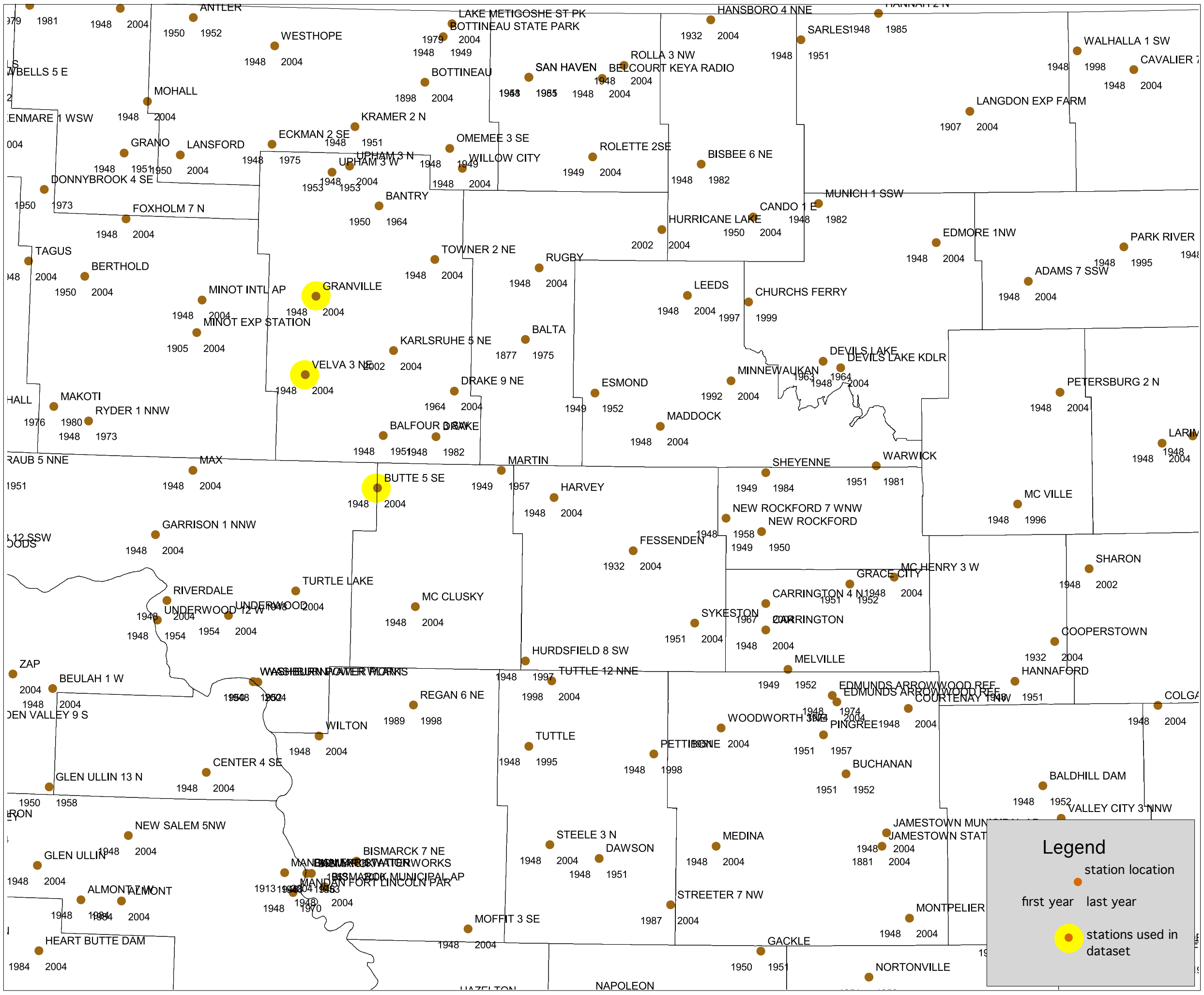


Figure 46. Location of stations used in Granville composite climate dataset.

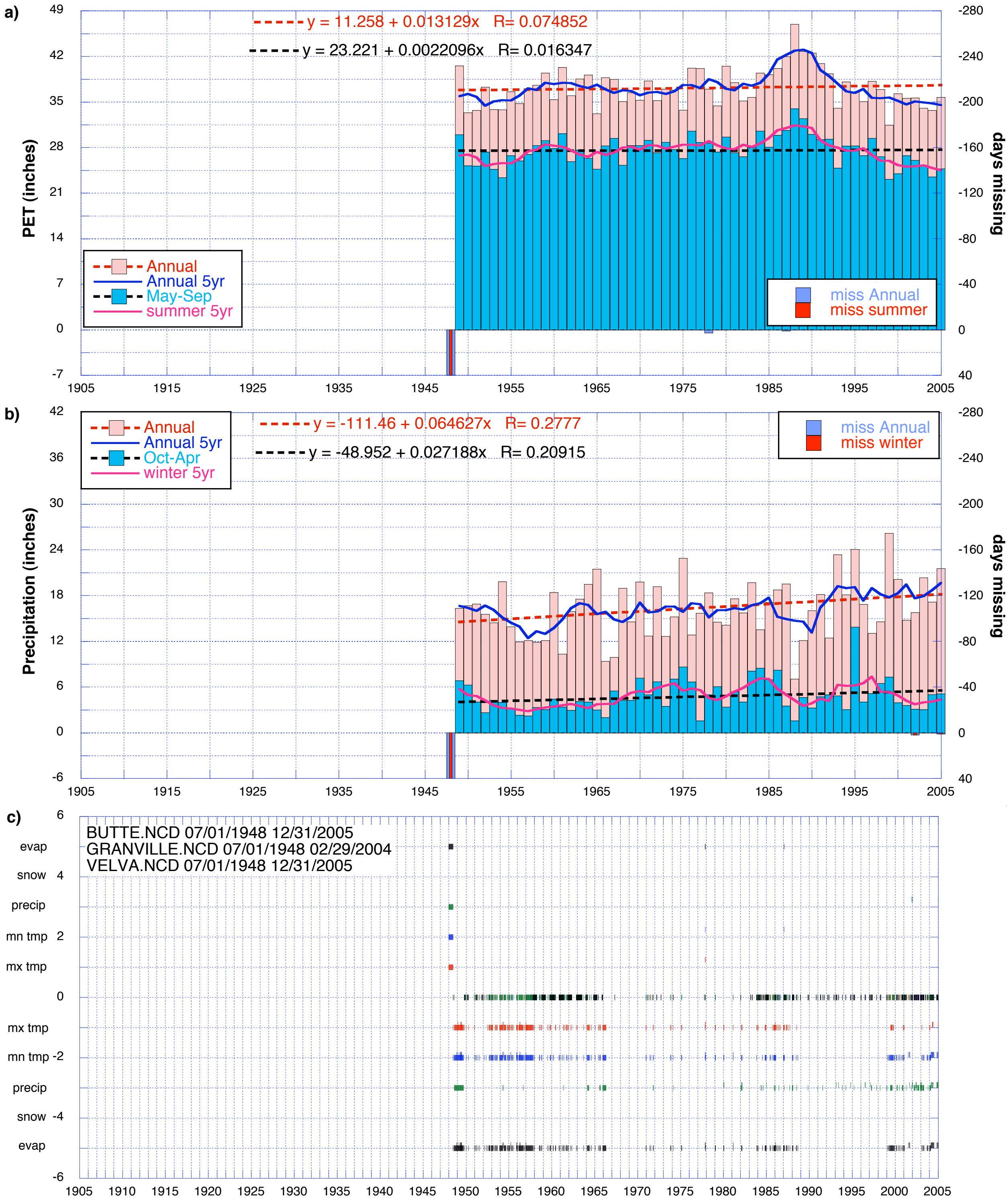


Figure 47. Butte from Granville composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

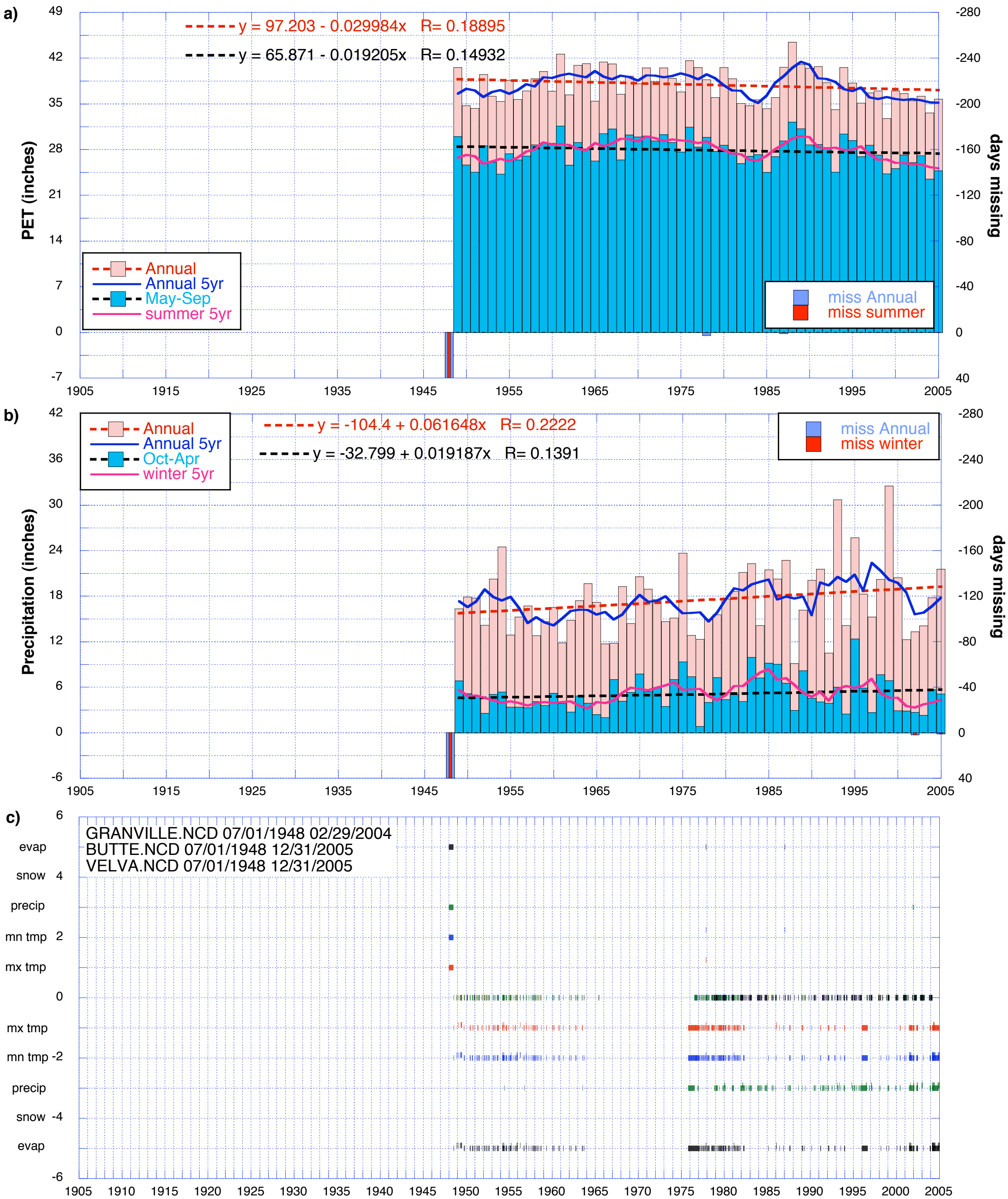


Figure 48. Granville from Granville composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

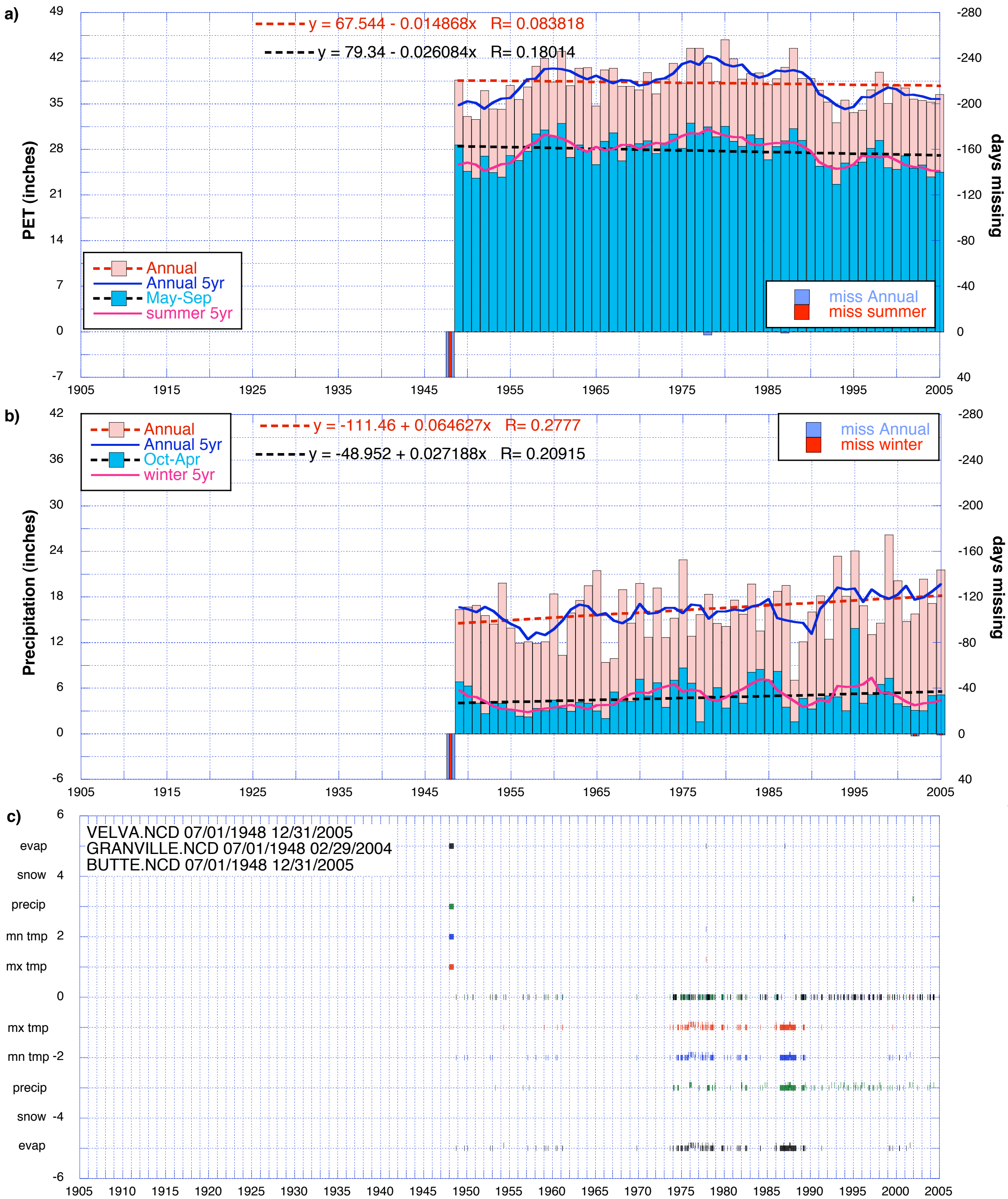


Figure 49. Velva from Granville composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Maddock NCDC dataset

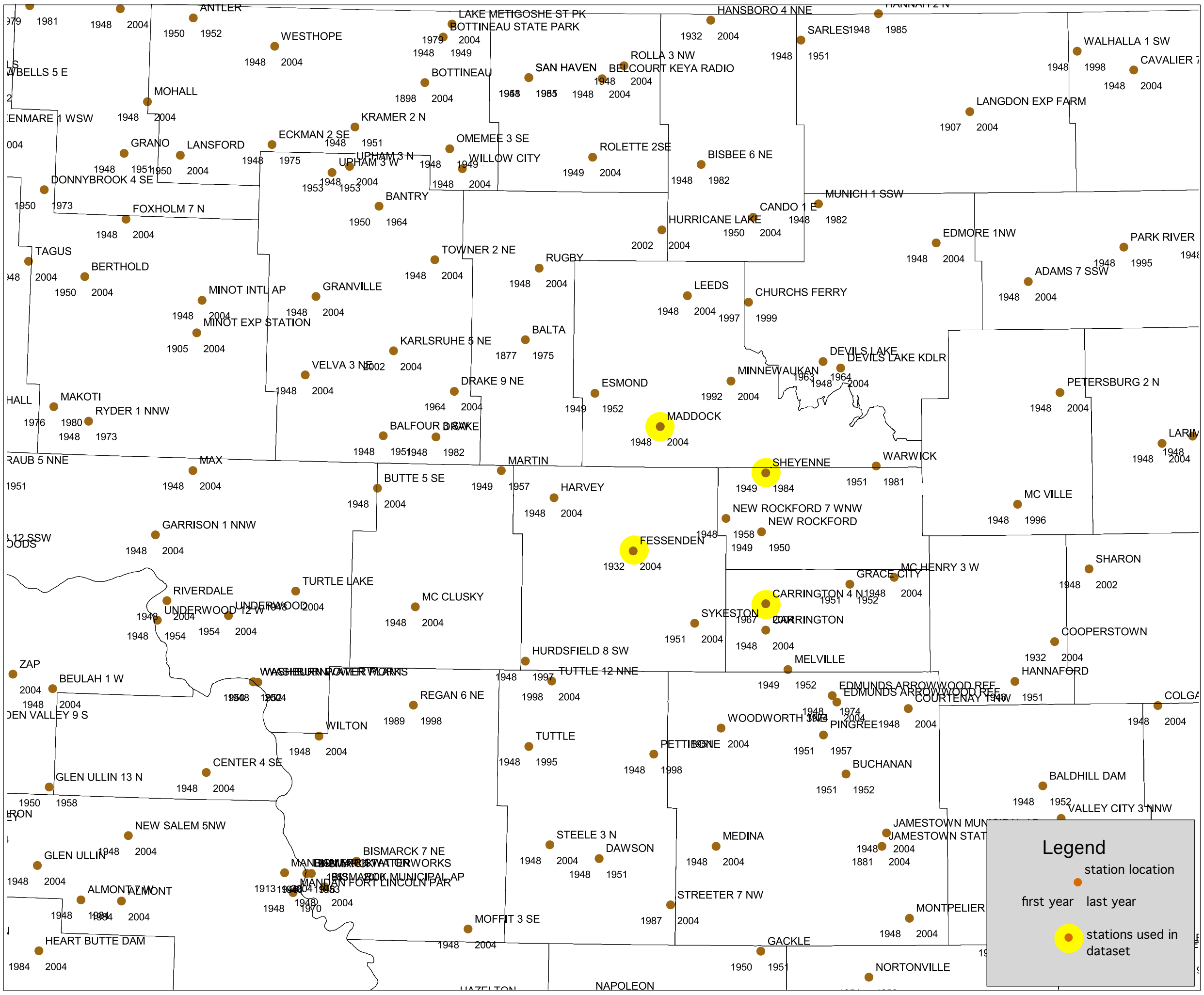


Figure 50. Location of stations used in Maddock composite climate dataset.

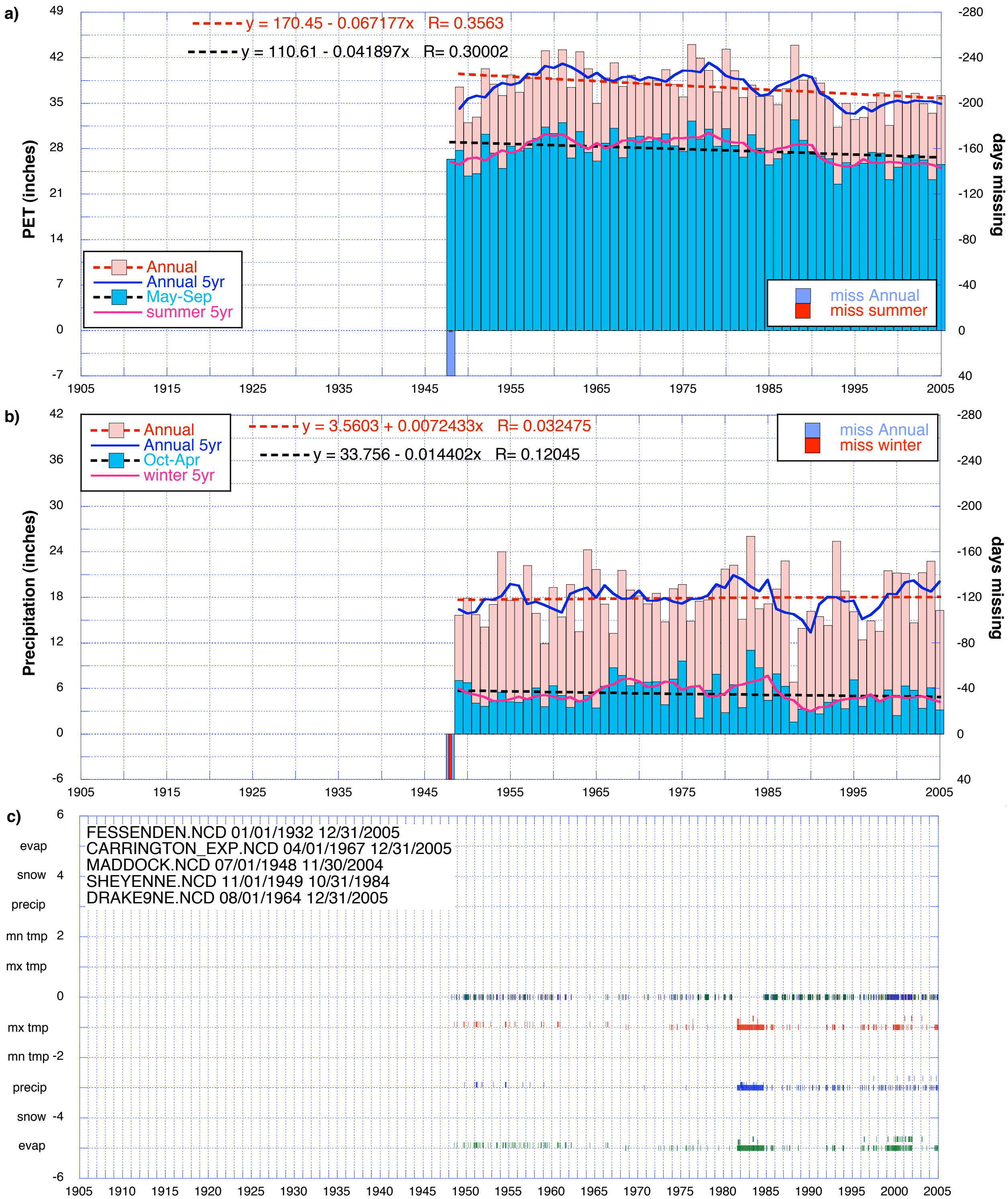


Figure 51. Fessenden from Maddock composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

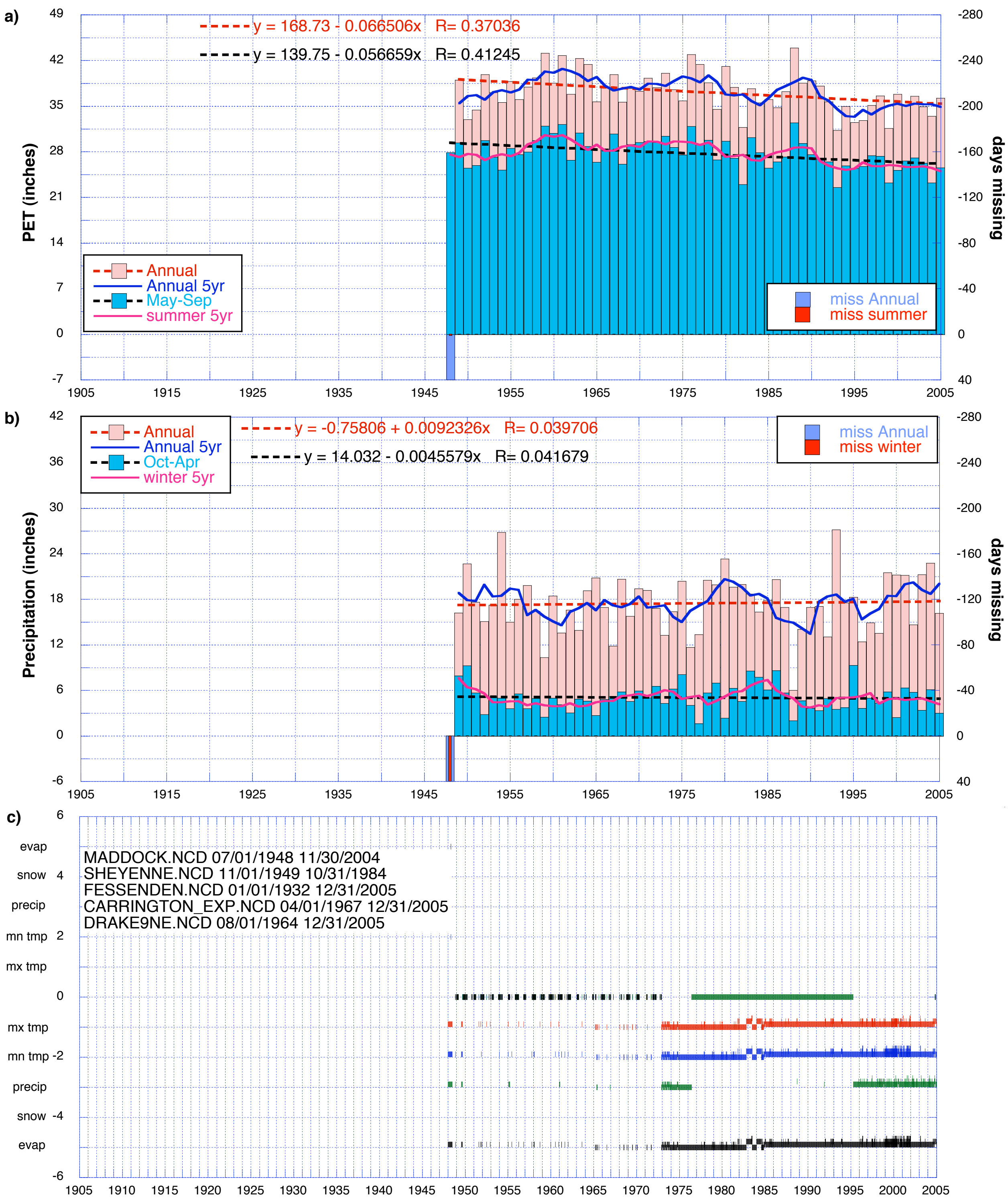


Figure 52. Maddock from Maddock composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Rugby NCDC dataset

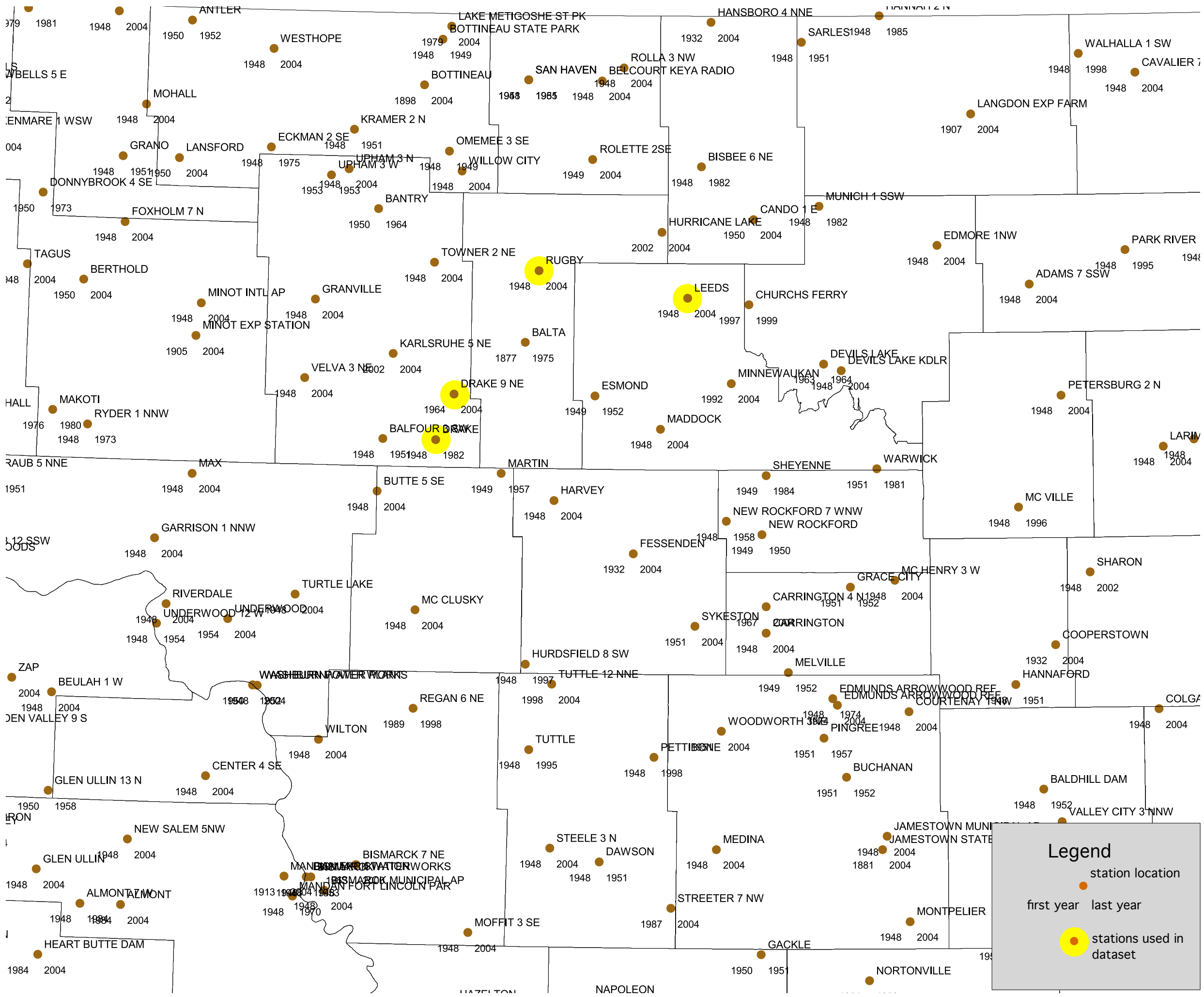


Figure 53. Location of stations used in Rugby composite climate dataset.

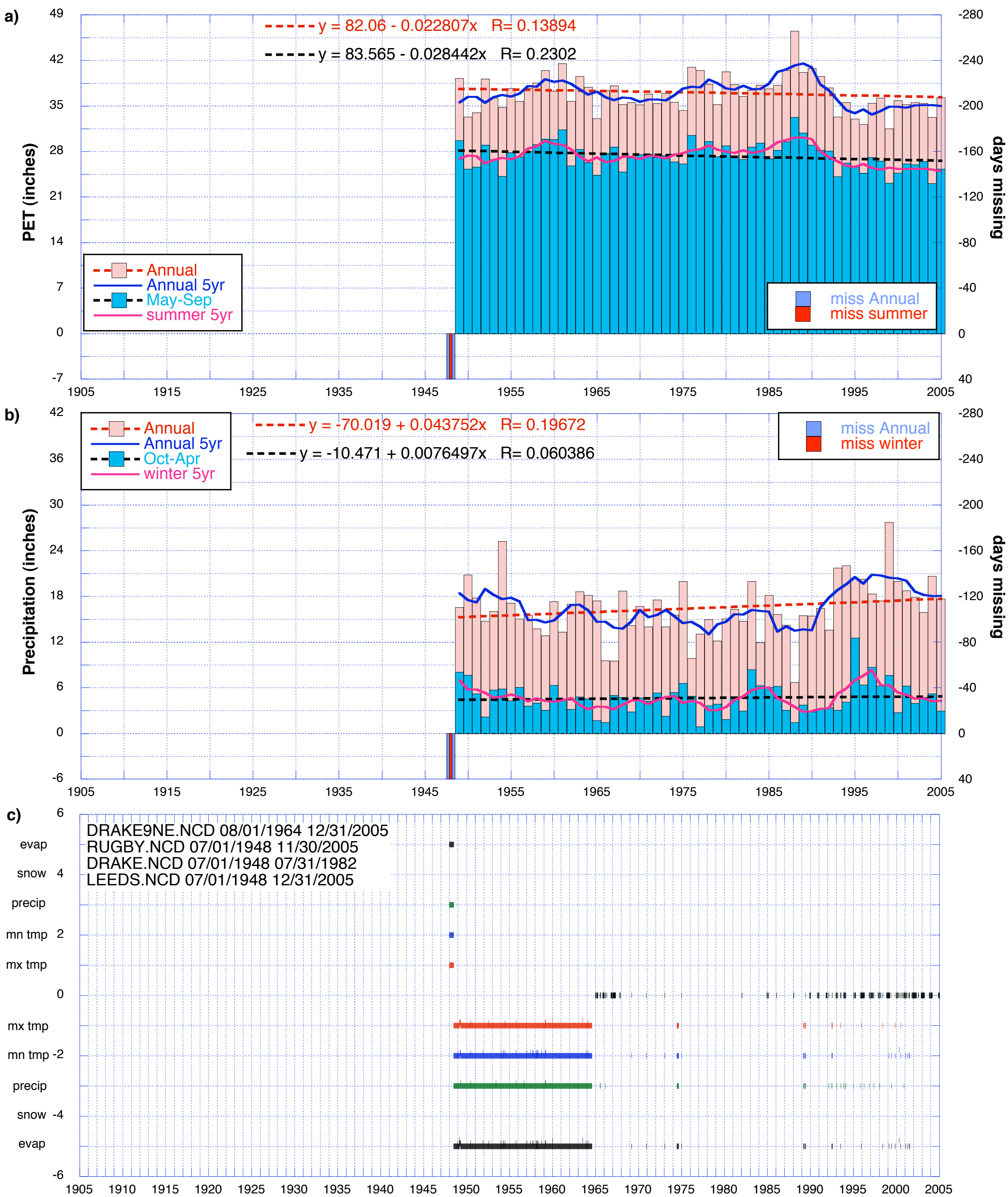


Figure 54. Drake 9NE from Rugby composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

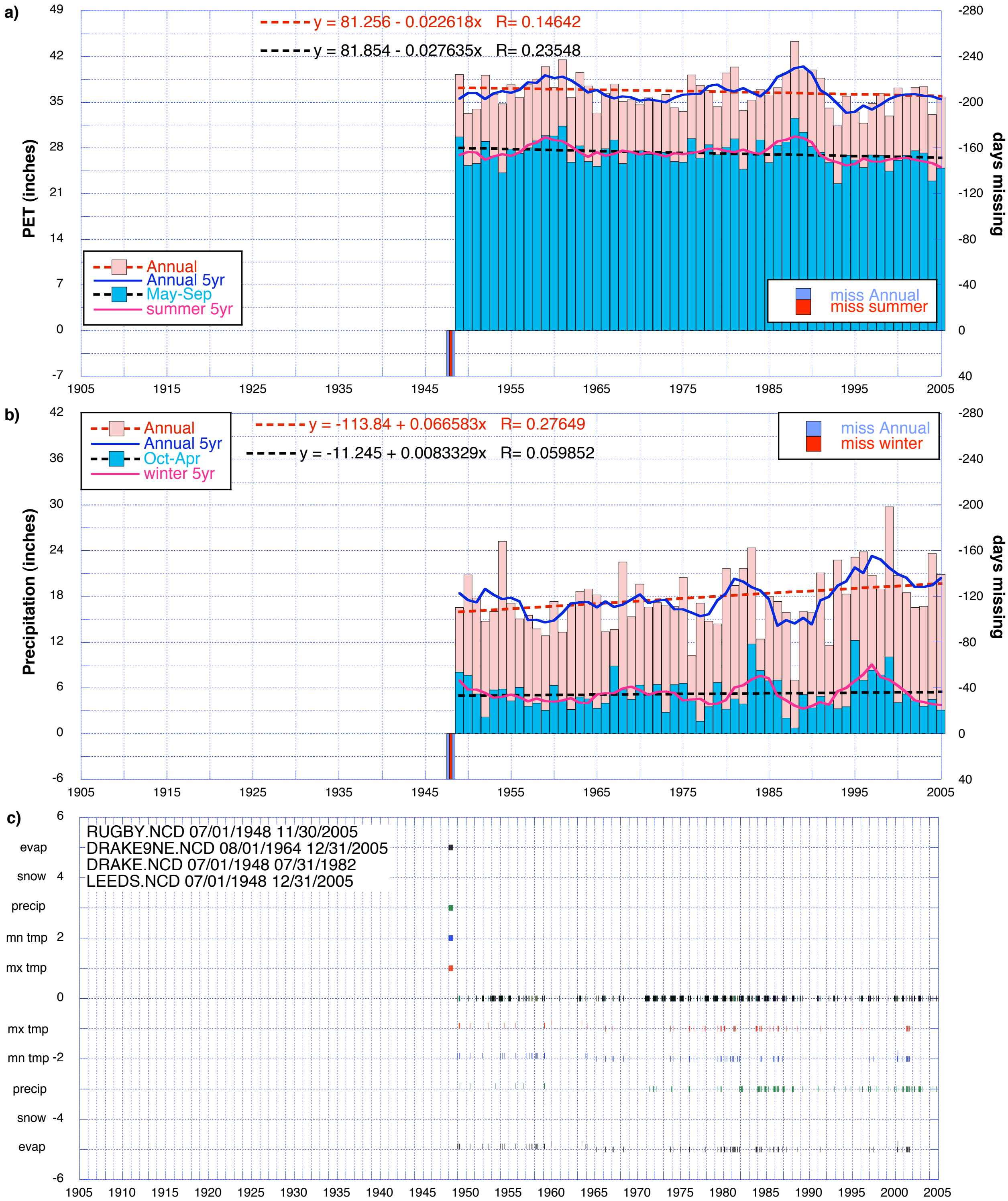


Figure 55. Rugby from Rugby composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith(FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

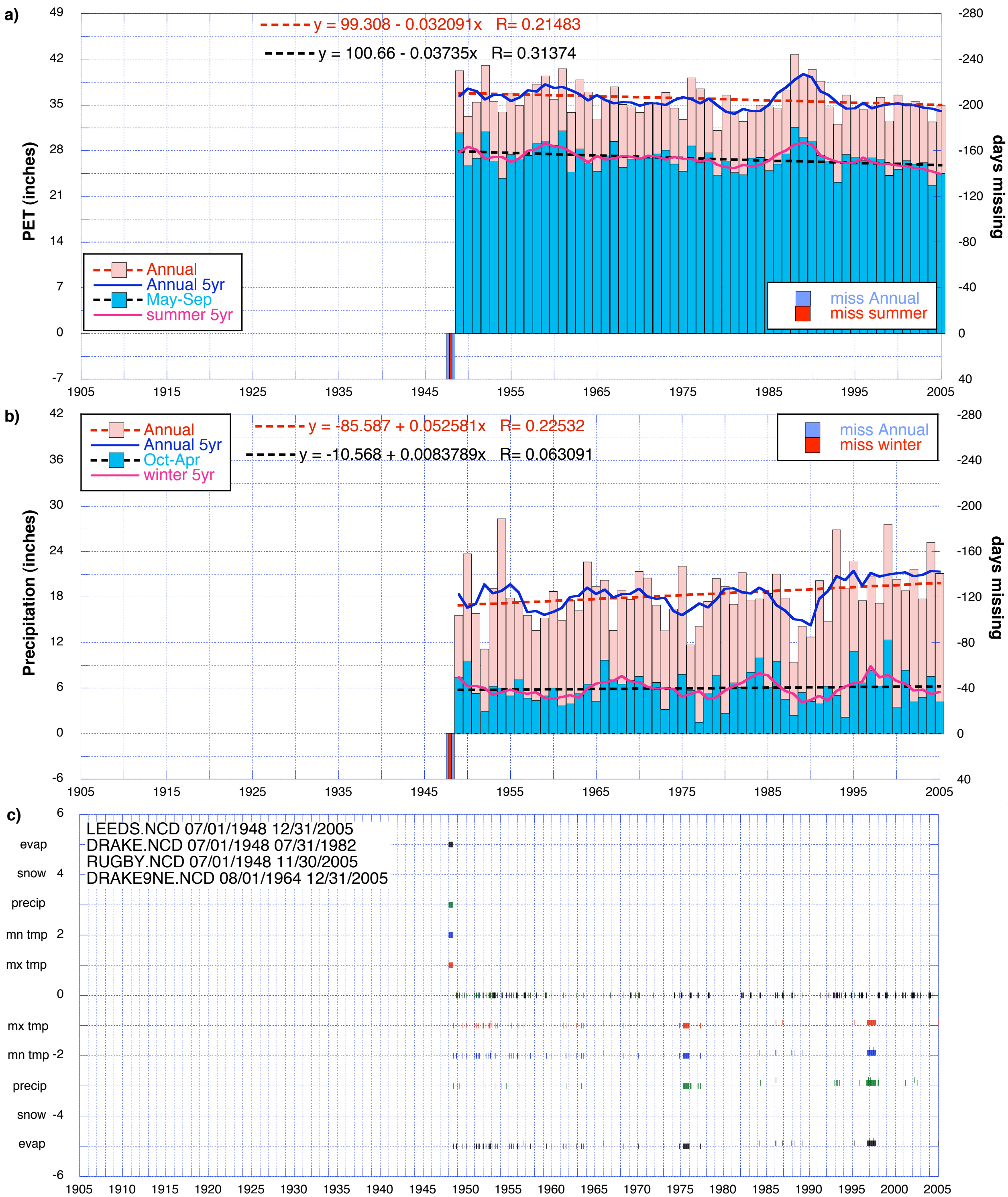


Figure 56. Leeds from Rugby composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Towner NCDC dataset

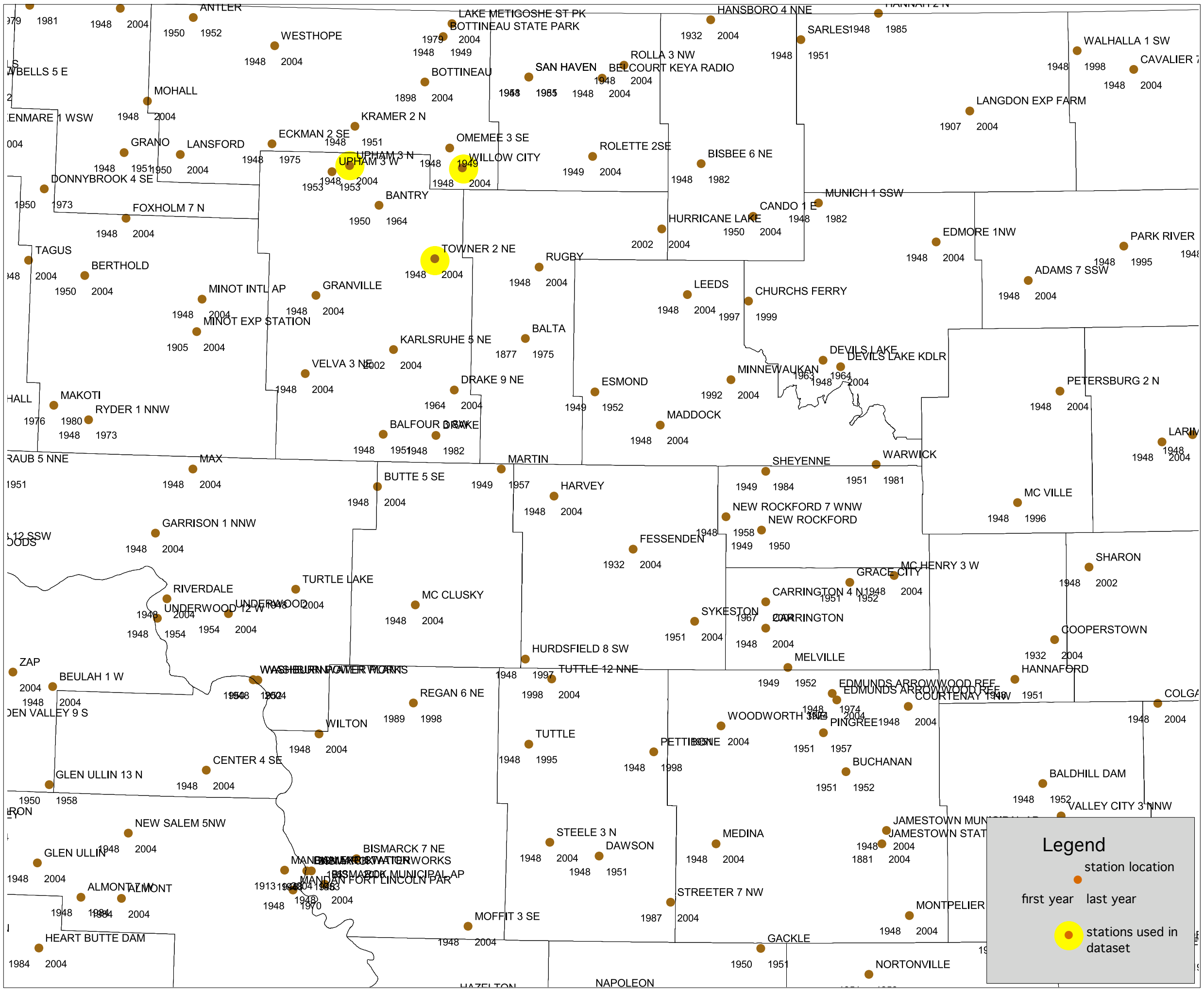


Figure 57. Location of stations used in Towner composite climate dataset.

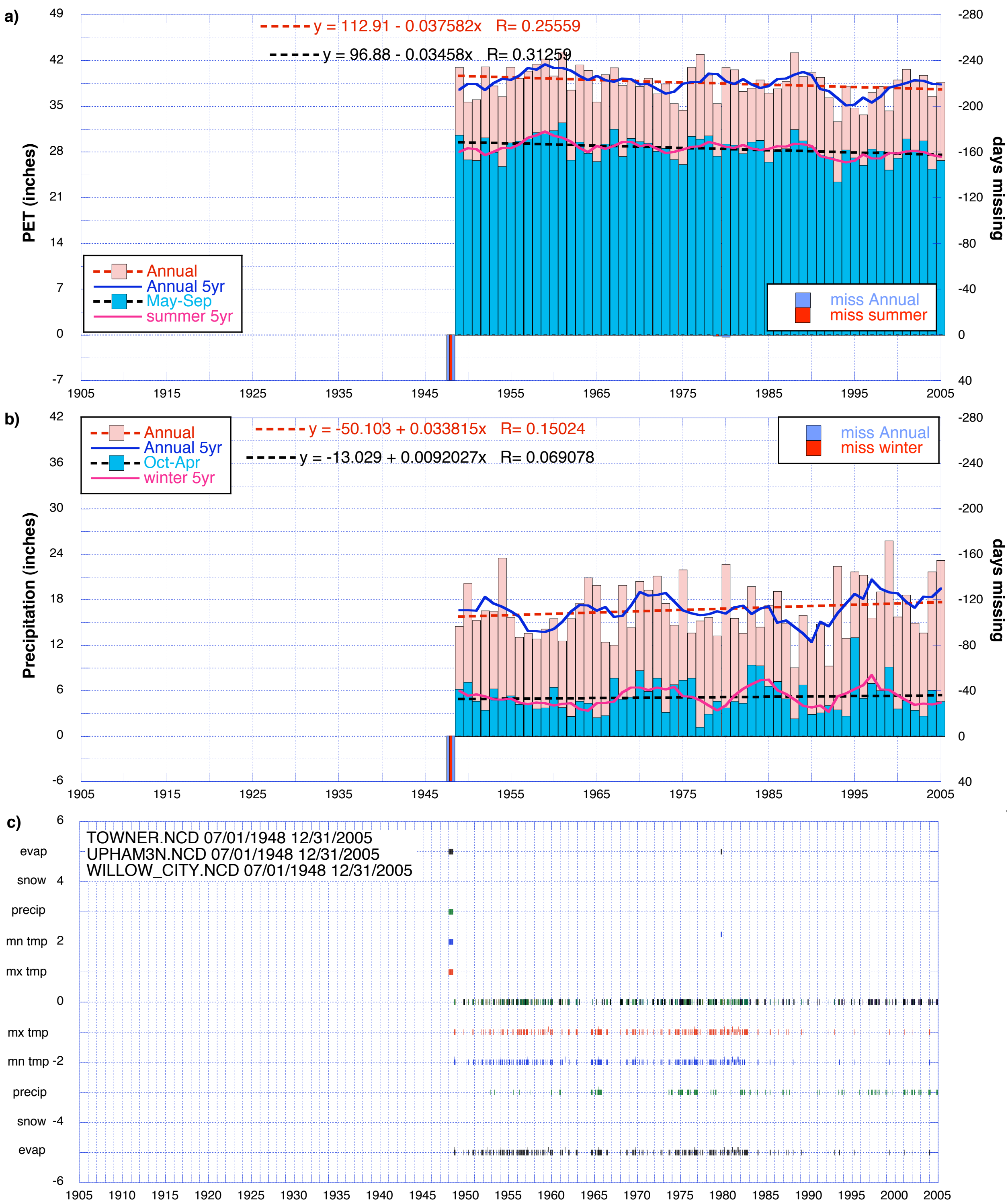


Figure 58. Towner from Towner composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

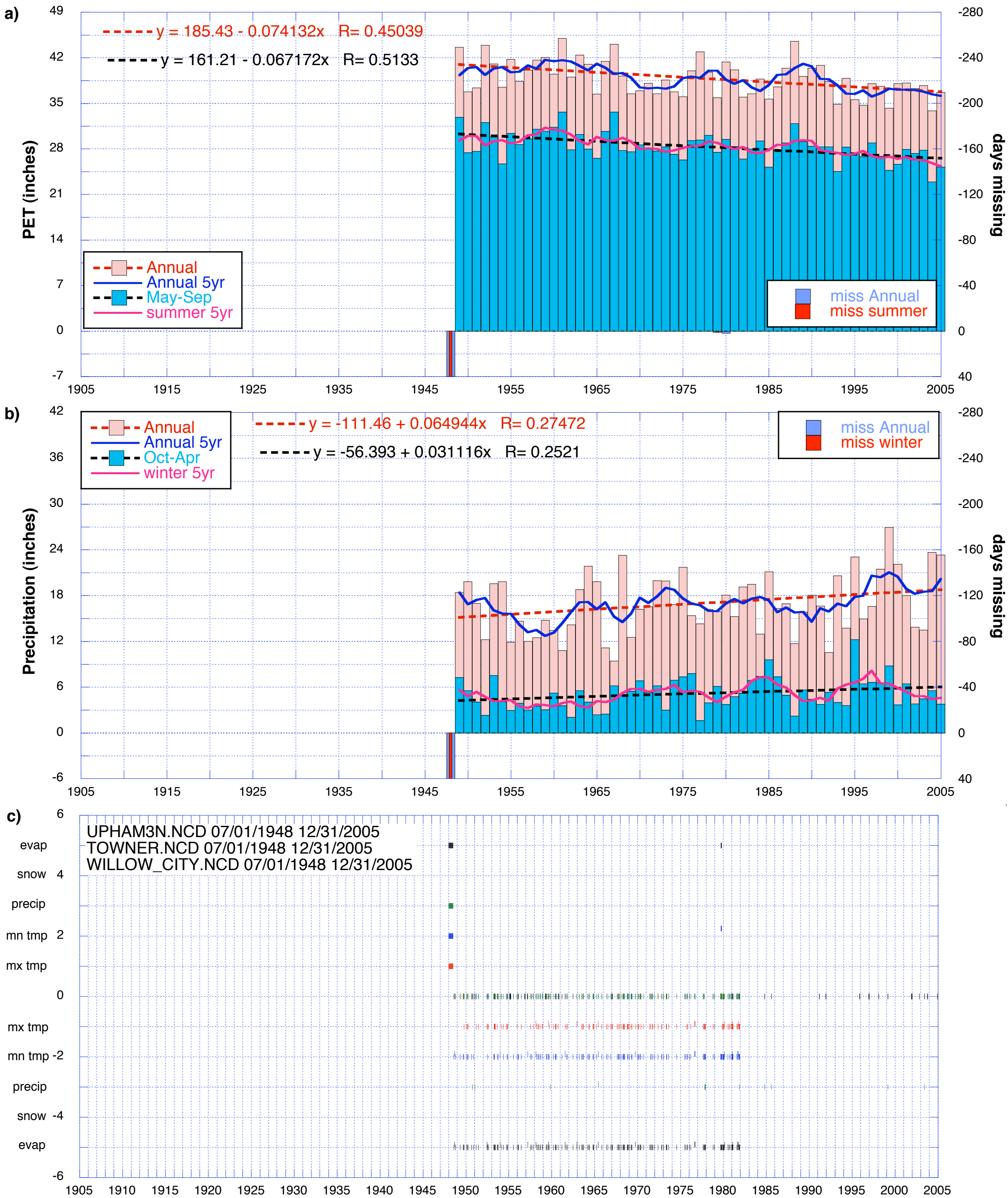


Figure 59. Upham 3N from Towner composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

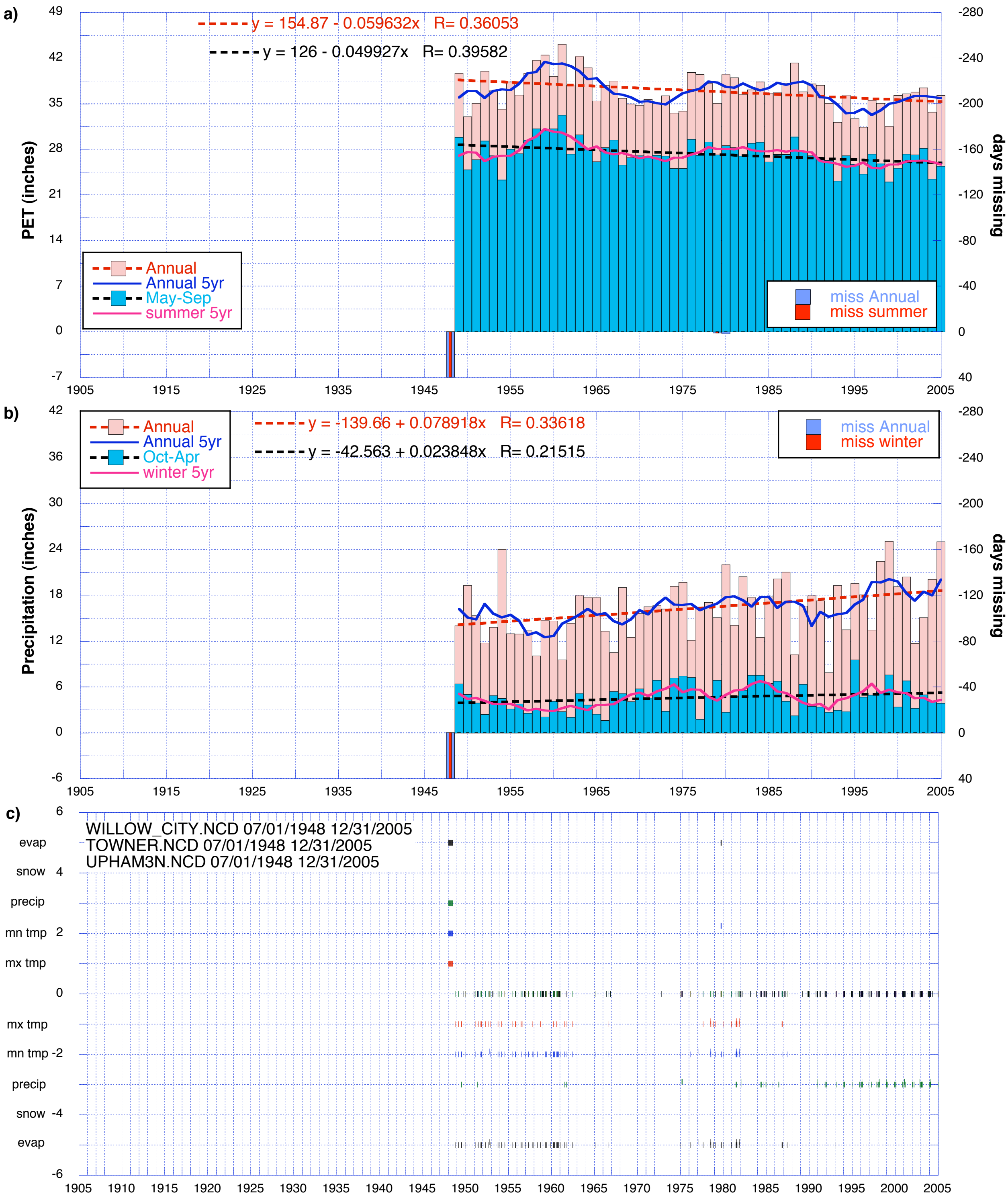


Figure 60. Willow City from Towner composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Minot NCDC dataset

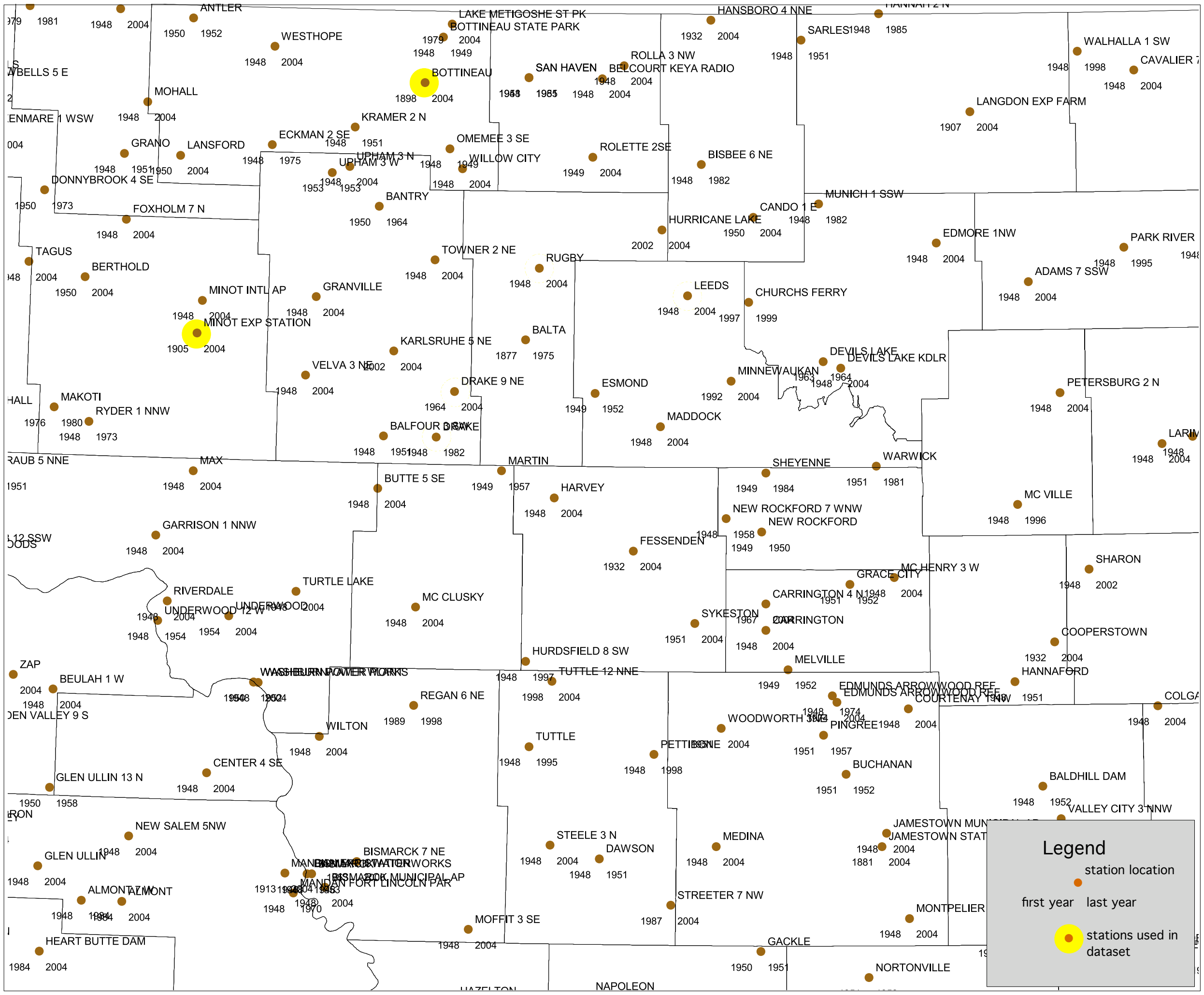


Figure 61. Location of stations used in Minot composite climate dataset.

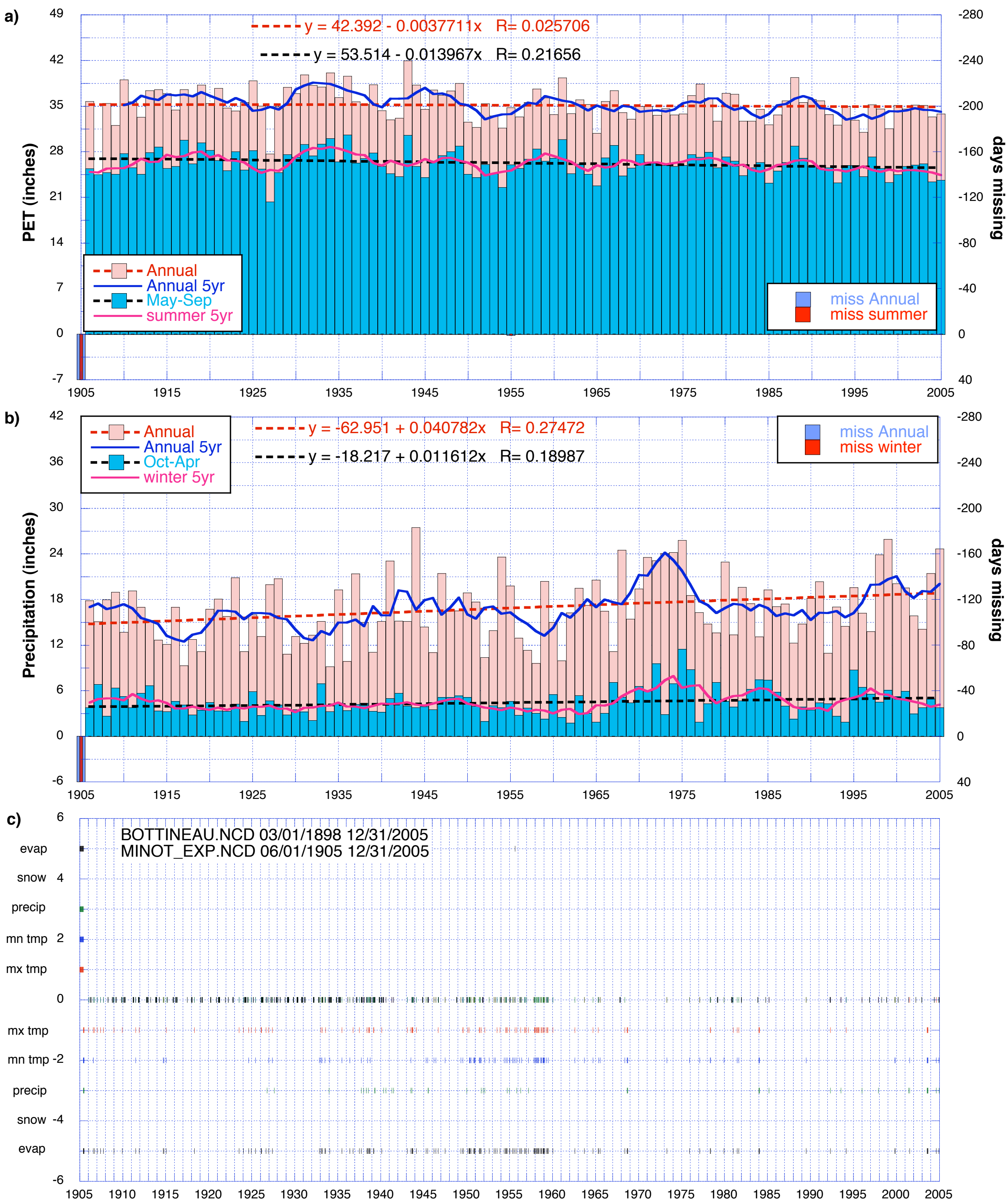


Figure 62. Bottineau from Minot composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

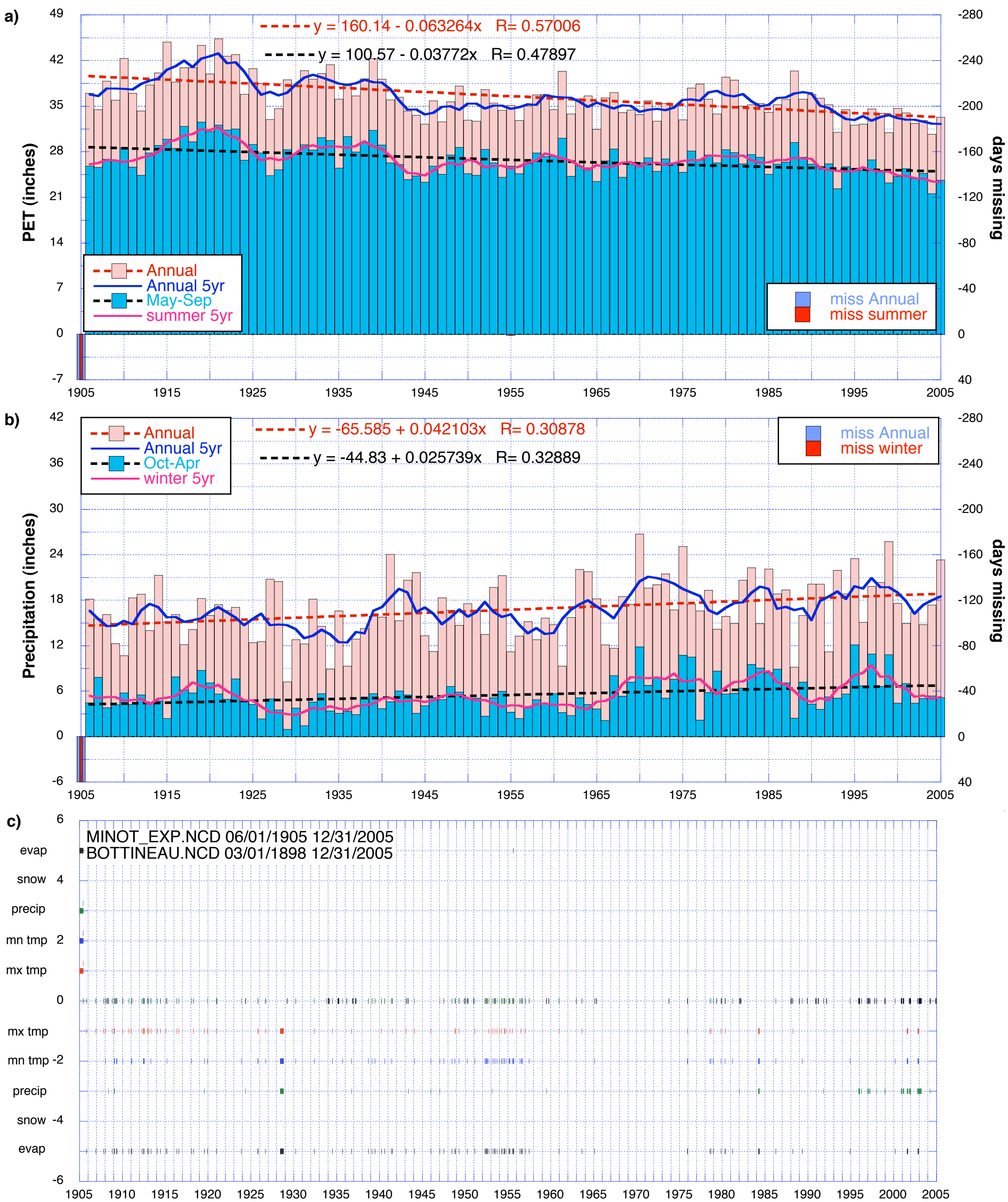


Figure 63. Minot from Minot composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Hansboro NCDC dataset

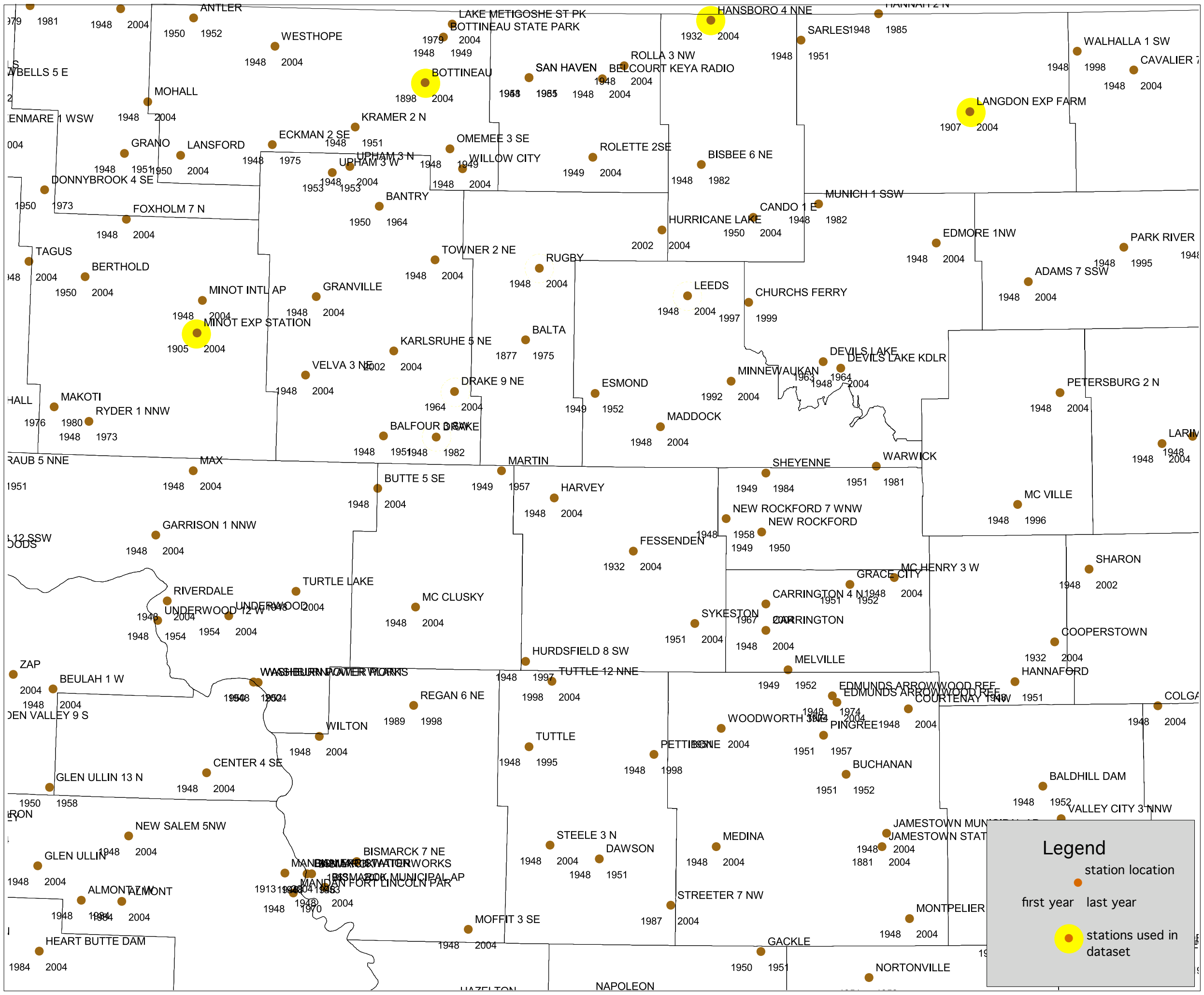


Figure 64. Location of stations used in Hansboro composite climate dataset.

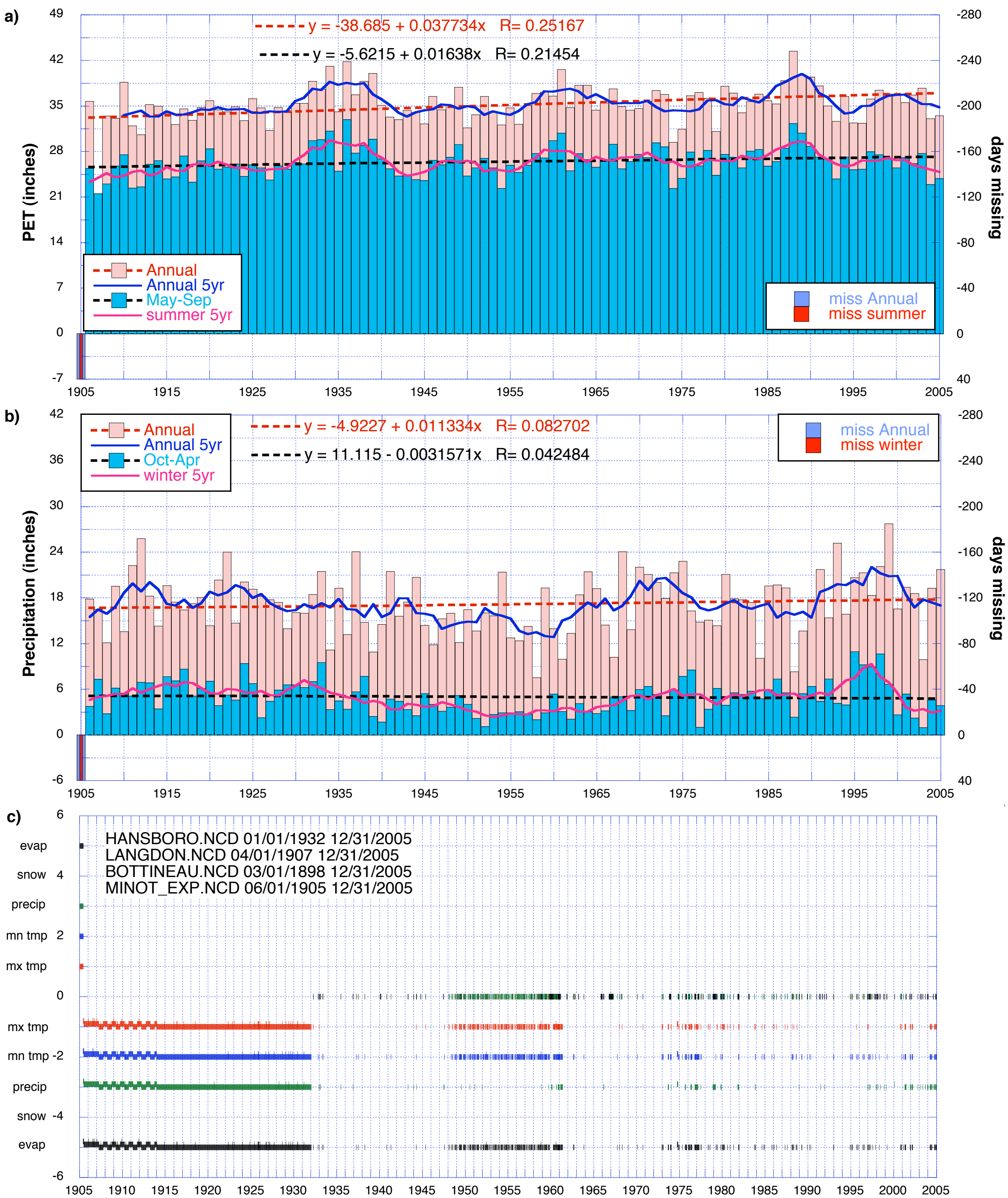


Figure 65. Hansboro from Hansboro composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

Fessenden NCDC dataset

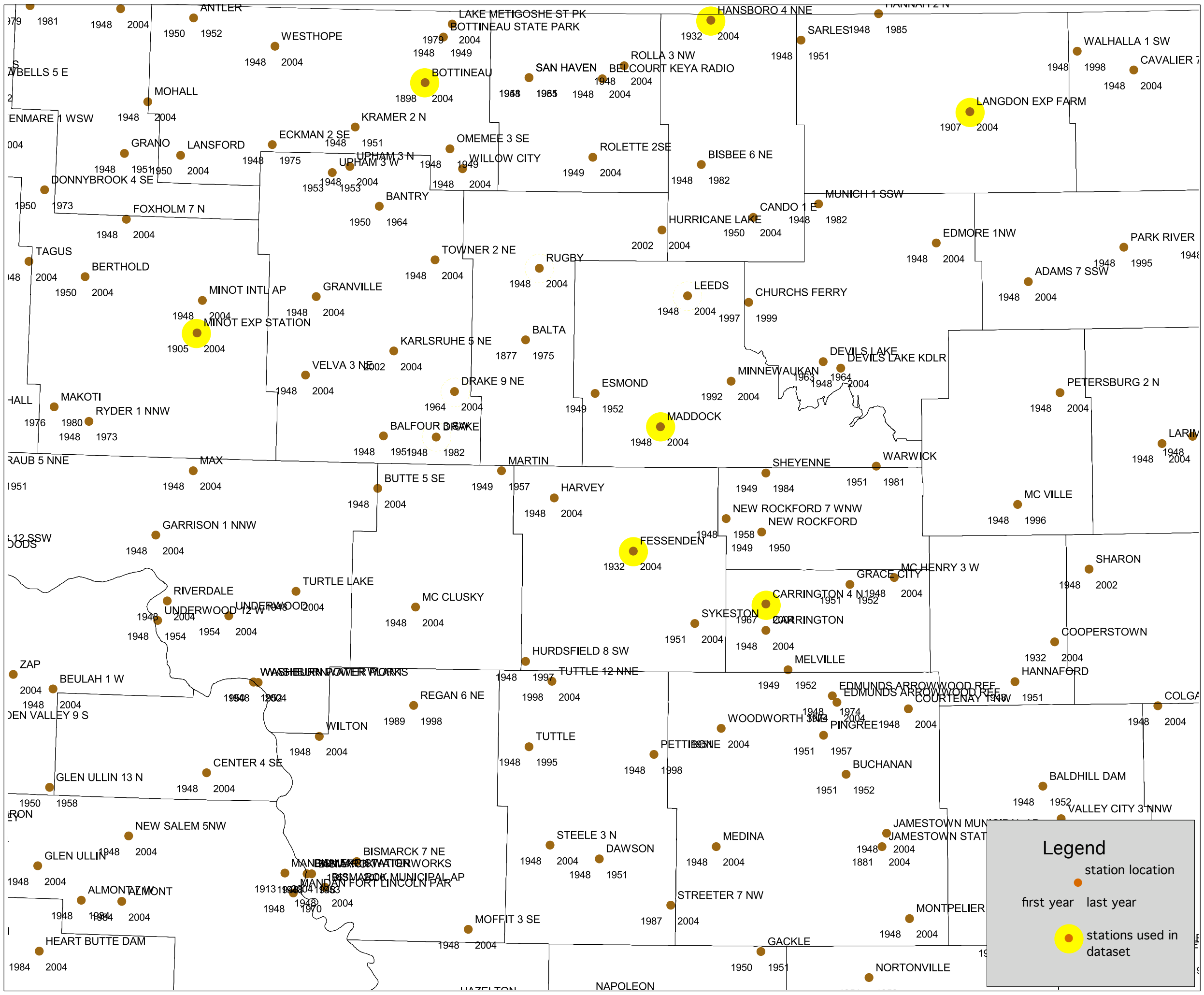


Figure 66. Location of stations used in Fessenden composite climate dataset.

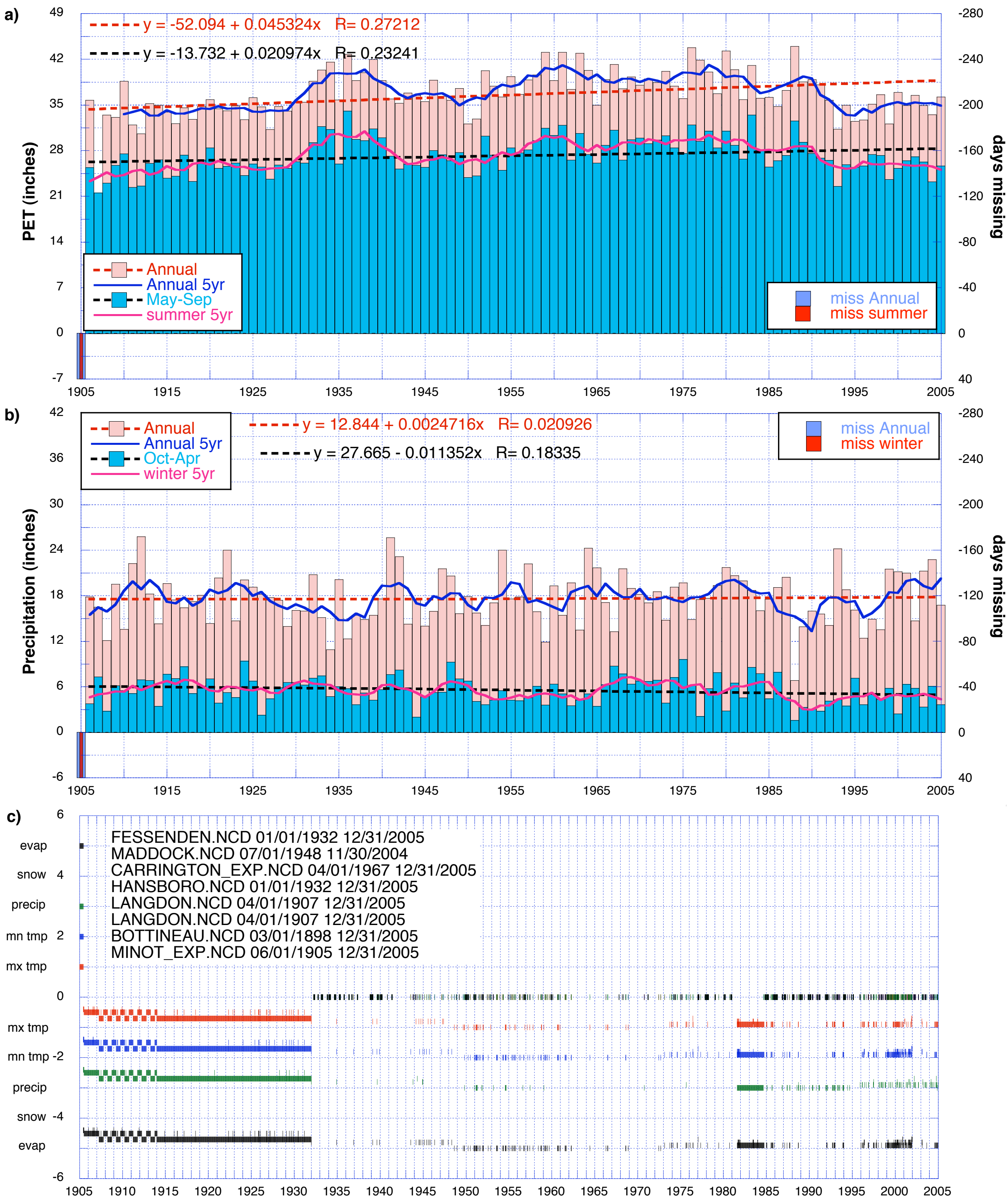


Figure 67. Fessenden from Fessenden composite climate dataset. a) Annual and growing season PET from maximum and minimum temperature using Penman-Monteith (FAO-56) using Harvey NDAWN calibrations. b) Annual and winter precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

NDAWN automated weather stations

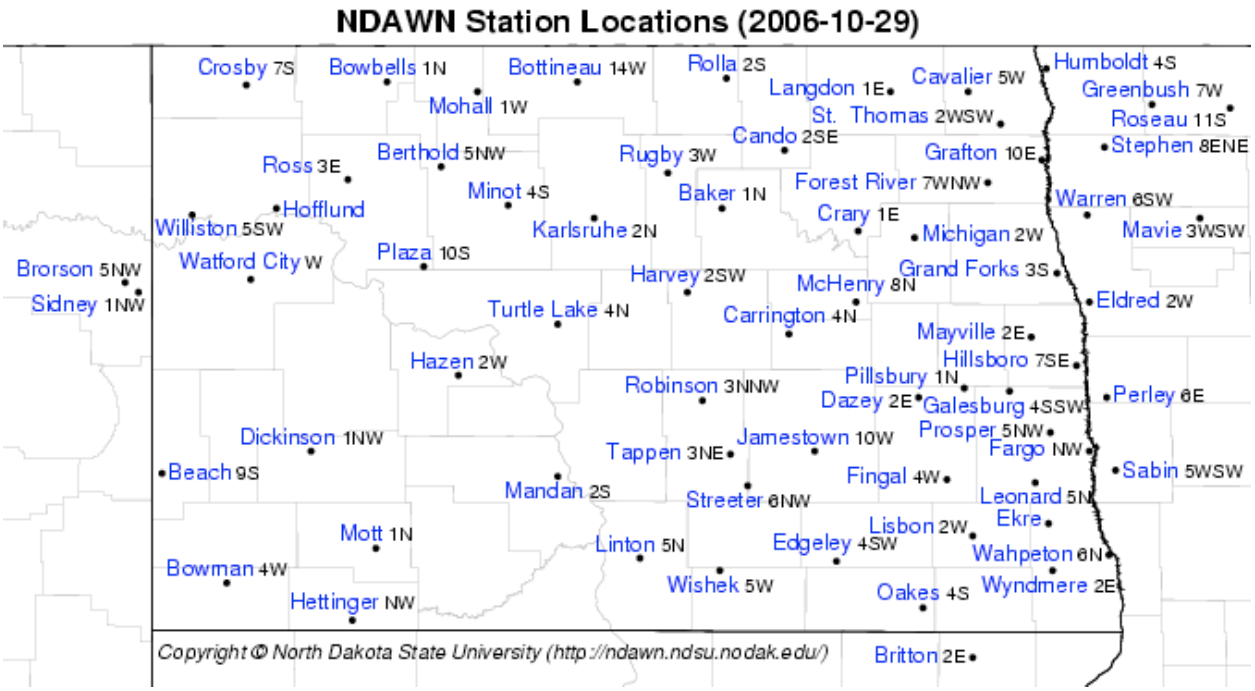


Fig. 68. Location of NDAWN automated weather stations operating in 2006. A few stations have been discontinued and are not shown on map. NDAWN began in 1990. Sites with at least 10 years of record near Trappers Coulee aquifer are Baker, Carrington, Harvey, Minot, and Langdon.

ARB observer dataset

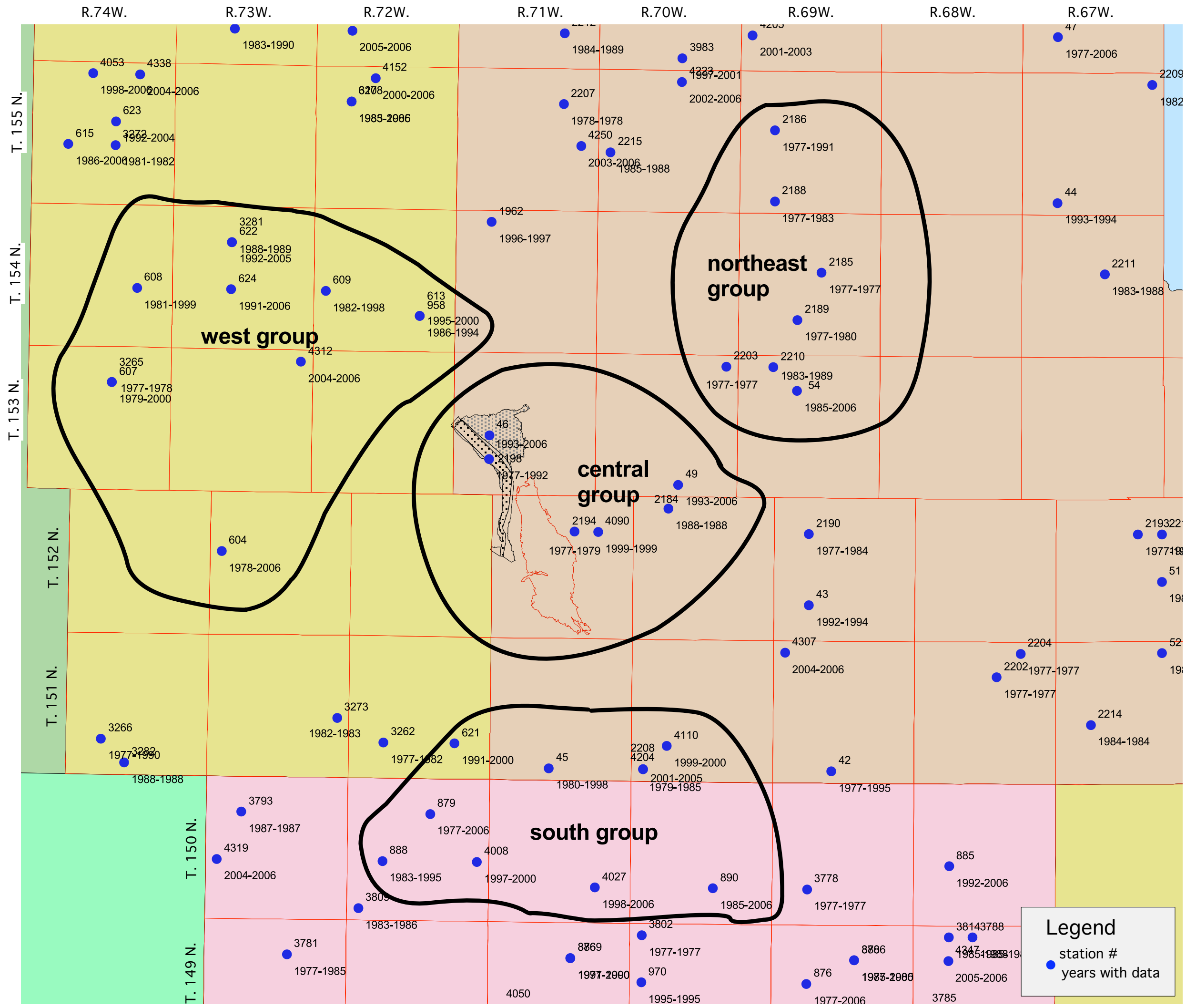


Figure 69. Location of North Dakota Atmospheric Resource Board Observers near Trappers Coulee aquifer. By compositing observers within the four groups shown, complete data sets are developed.

ARB West Group

a)

b)

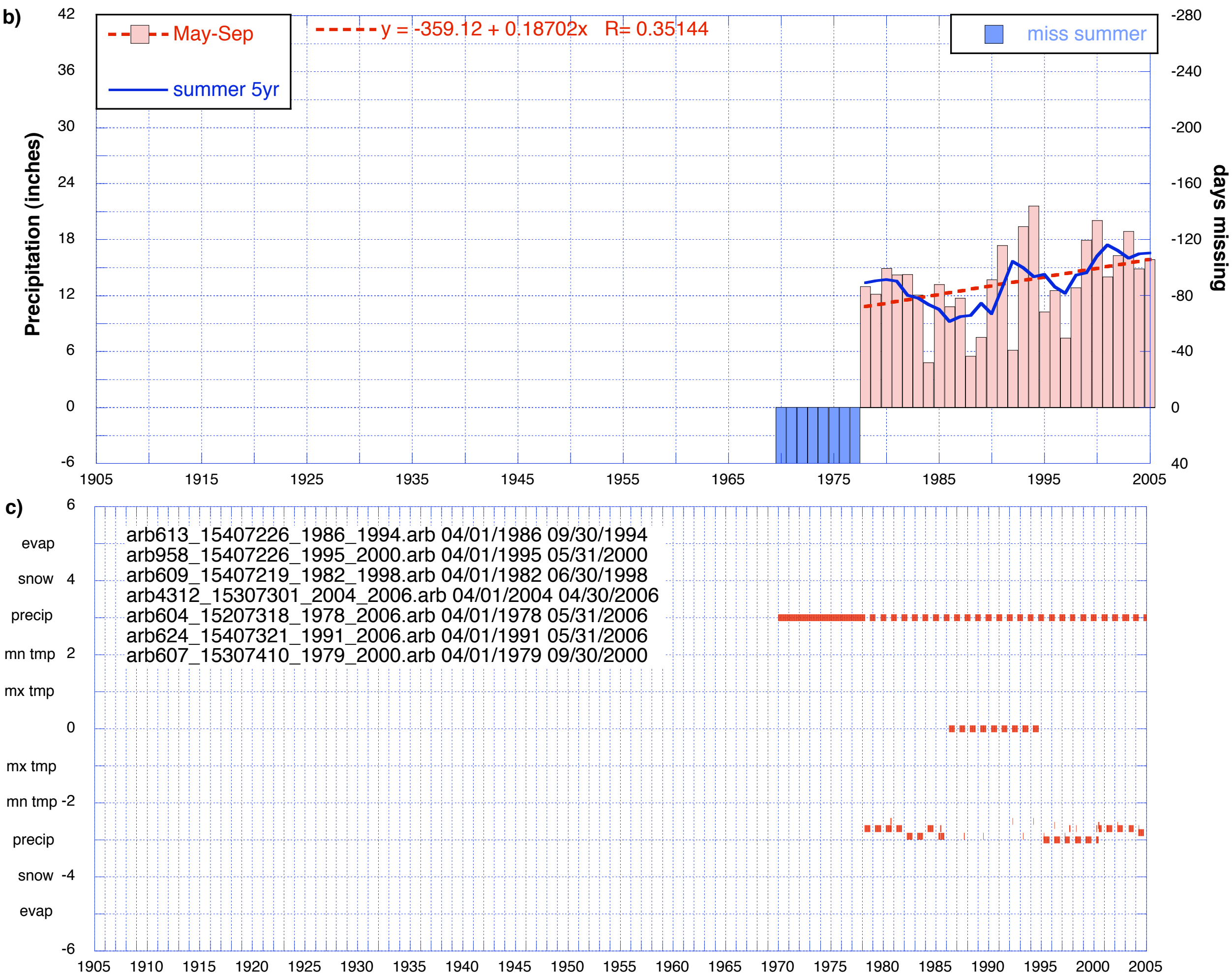


Figure 70. ARB 613 from ARB West Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

a)

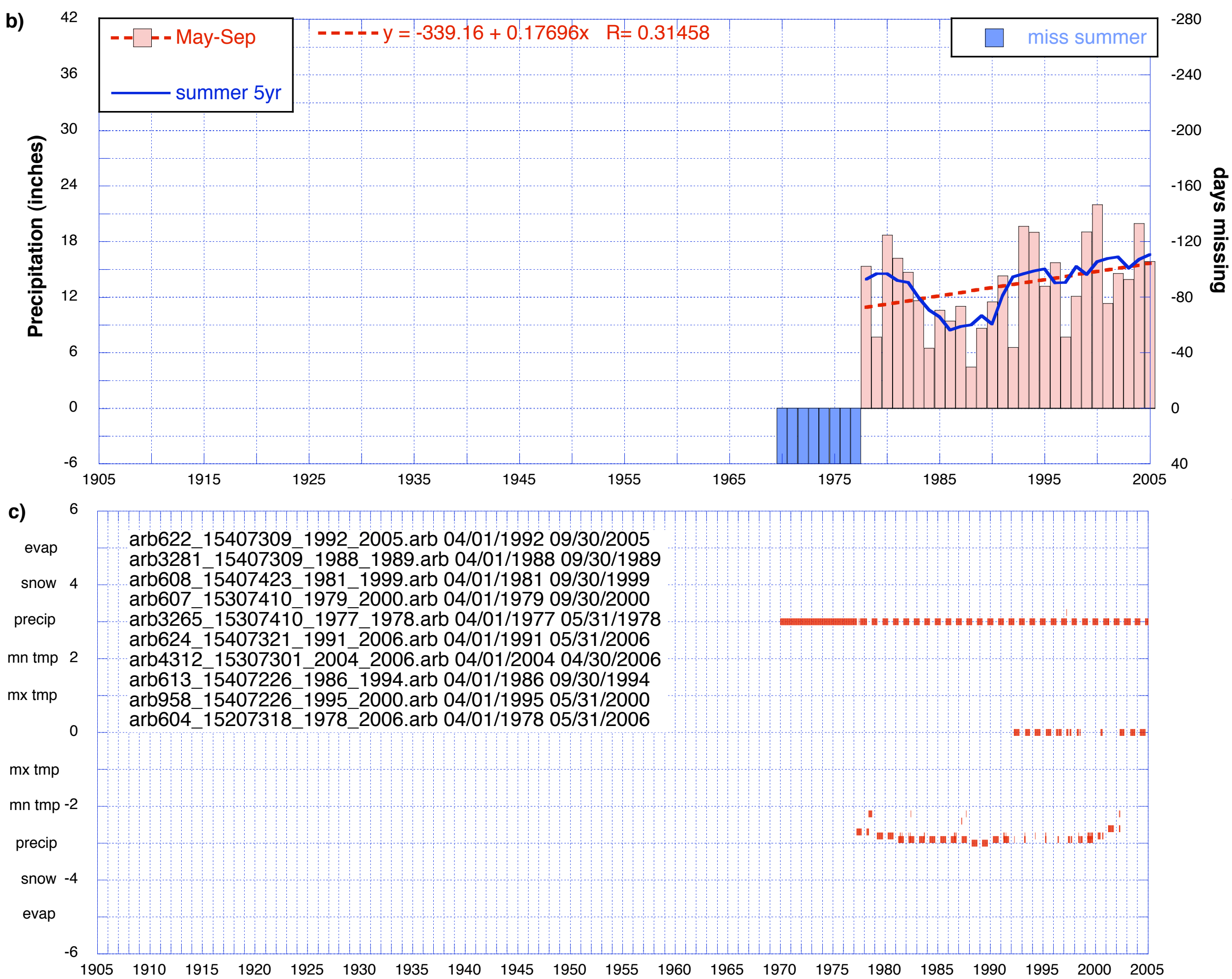


Figure 71. ARB 622 from ARB West Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

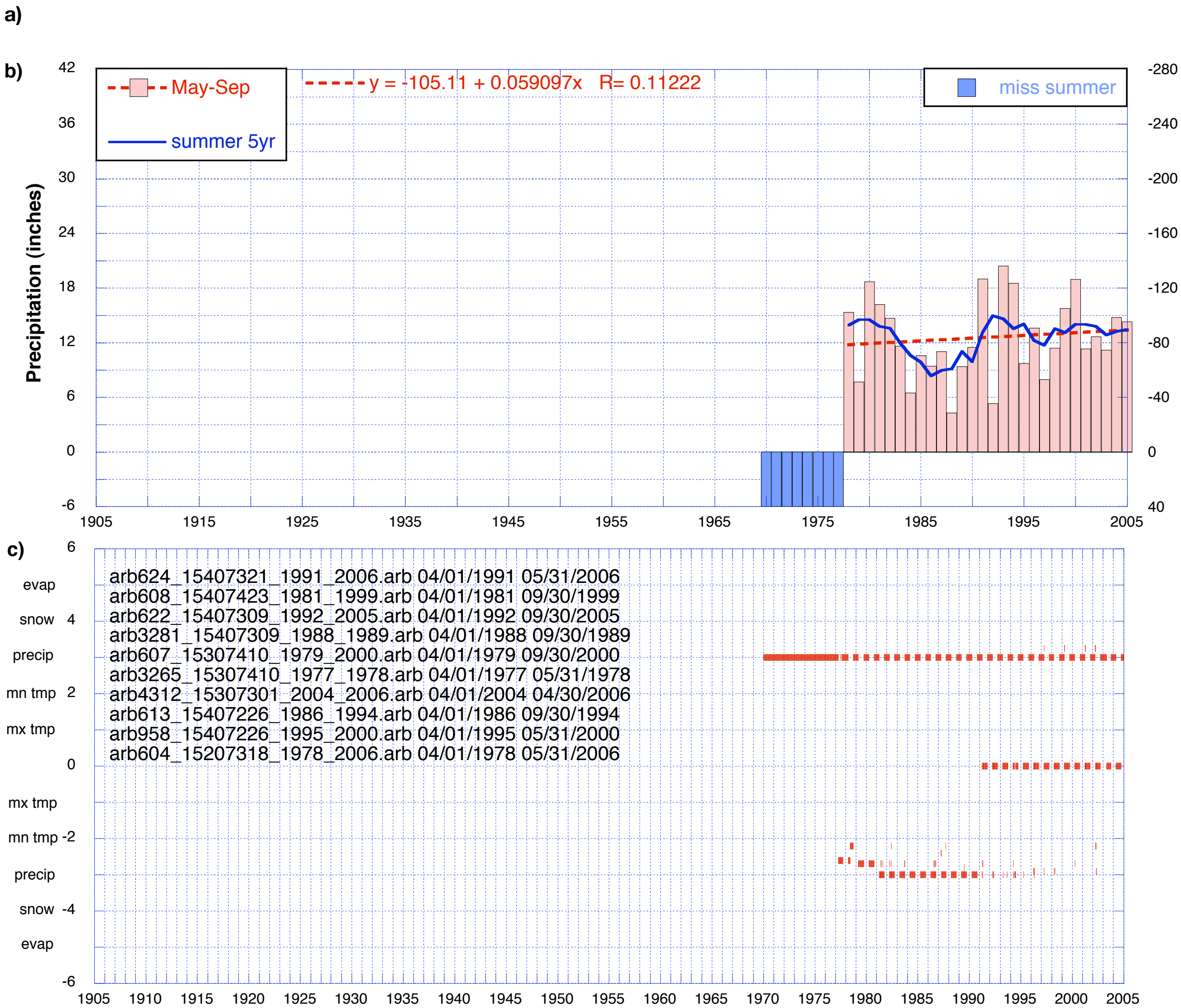


Figure 72. ARB 624 from ARB West Group composite climate dataset. a) PET -no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

ARB Central Group

a)

b)

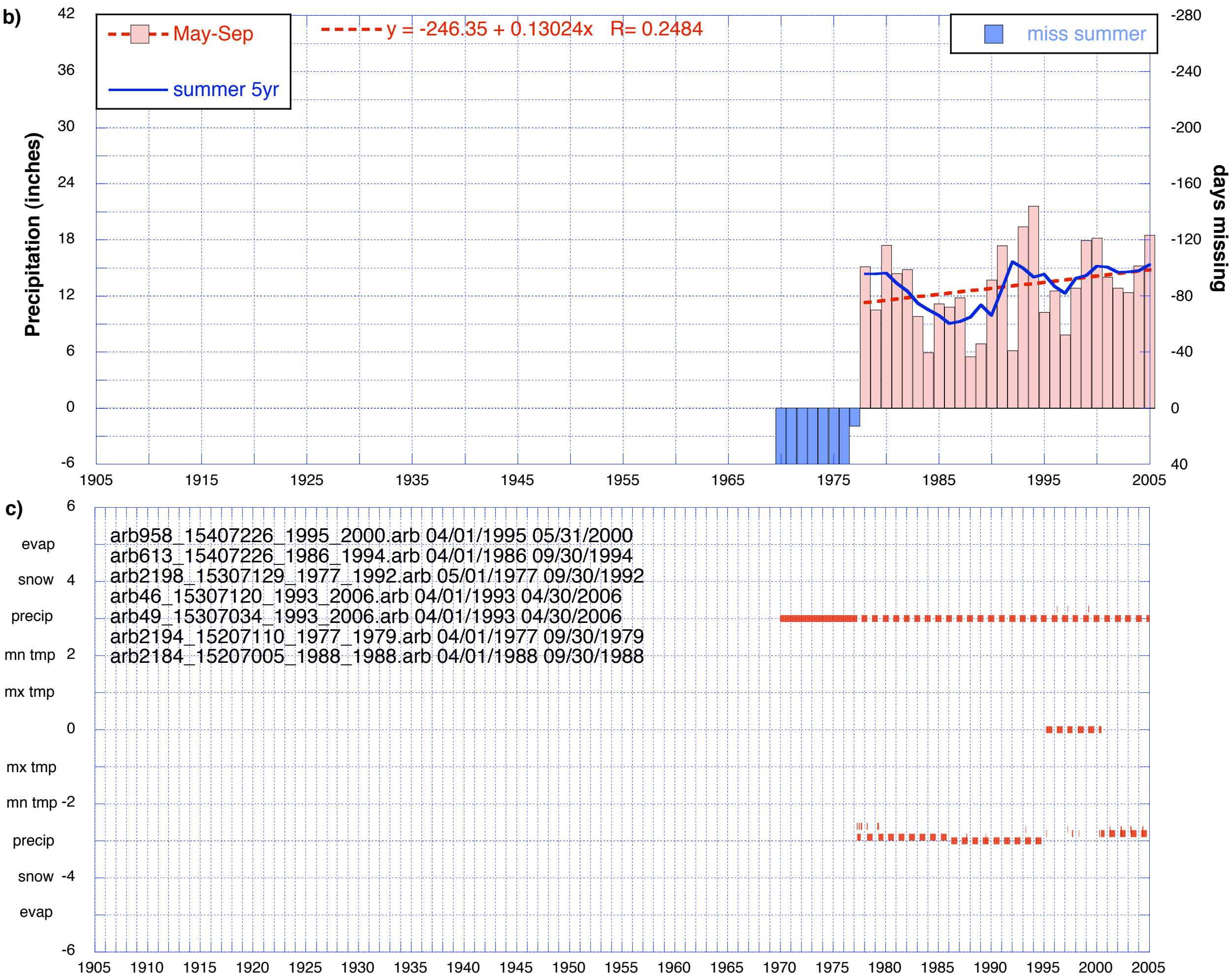


Figure 73. ARB 958 from ARB Central Group composite climate dataset. This set includes ARB sites 613 and 958 from ARB West Group. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

a)

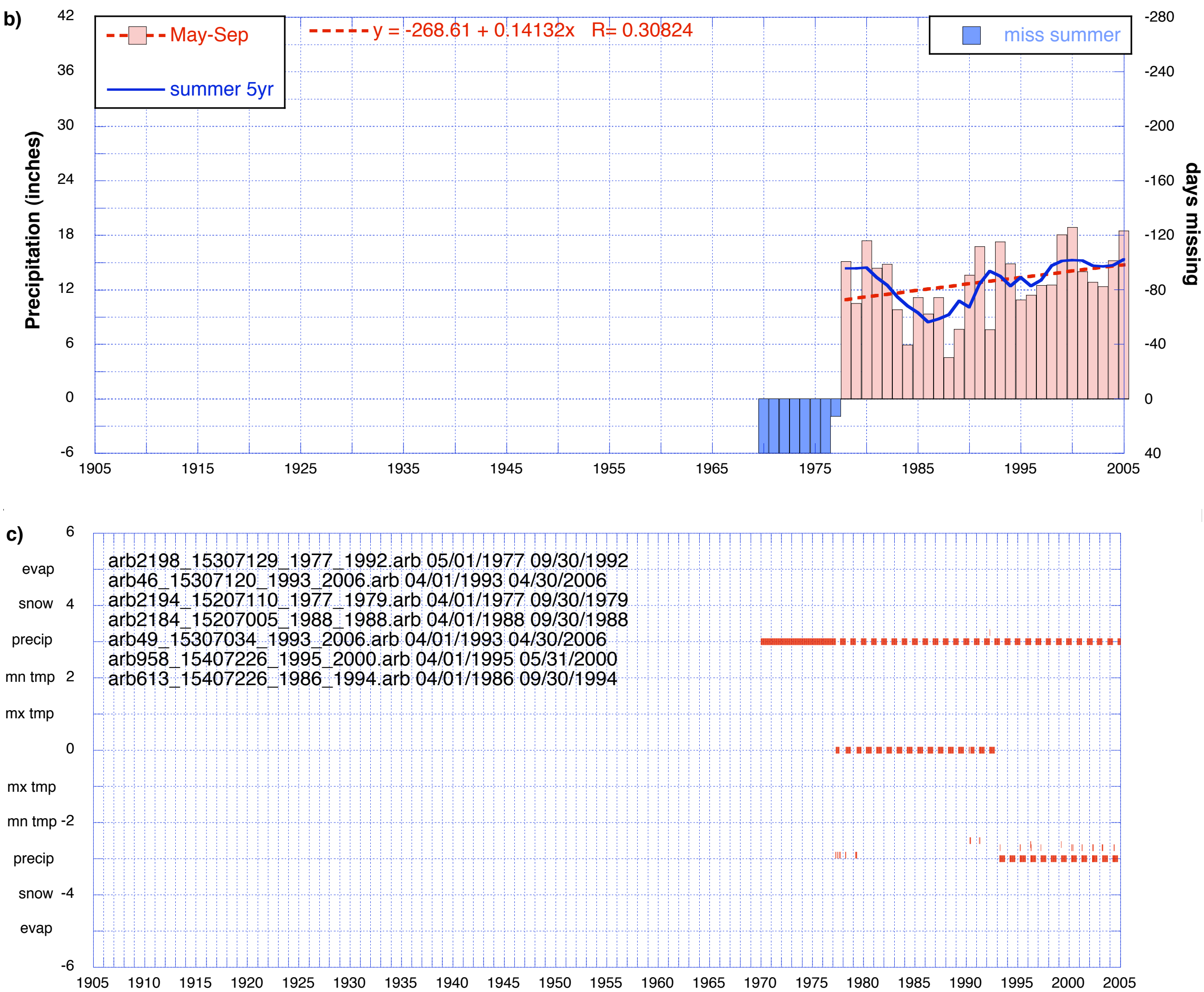


Figure 74. ARB 2198 from ARB Central Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

ARB Northeast Group

a)

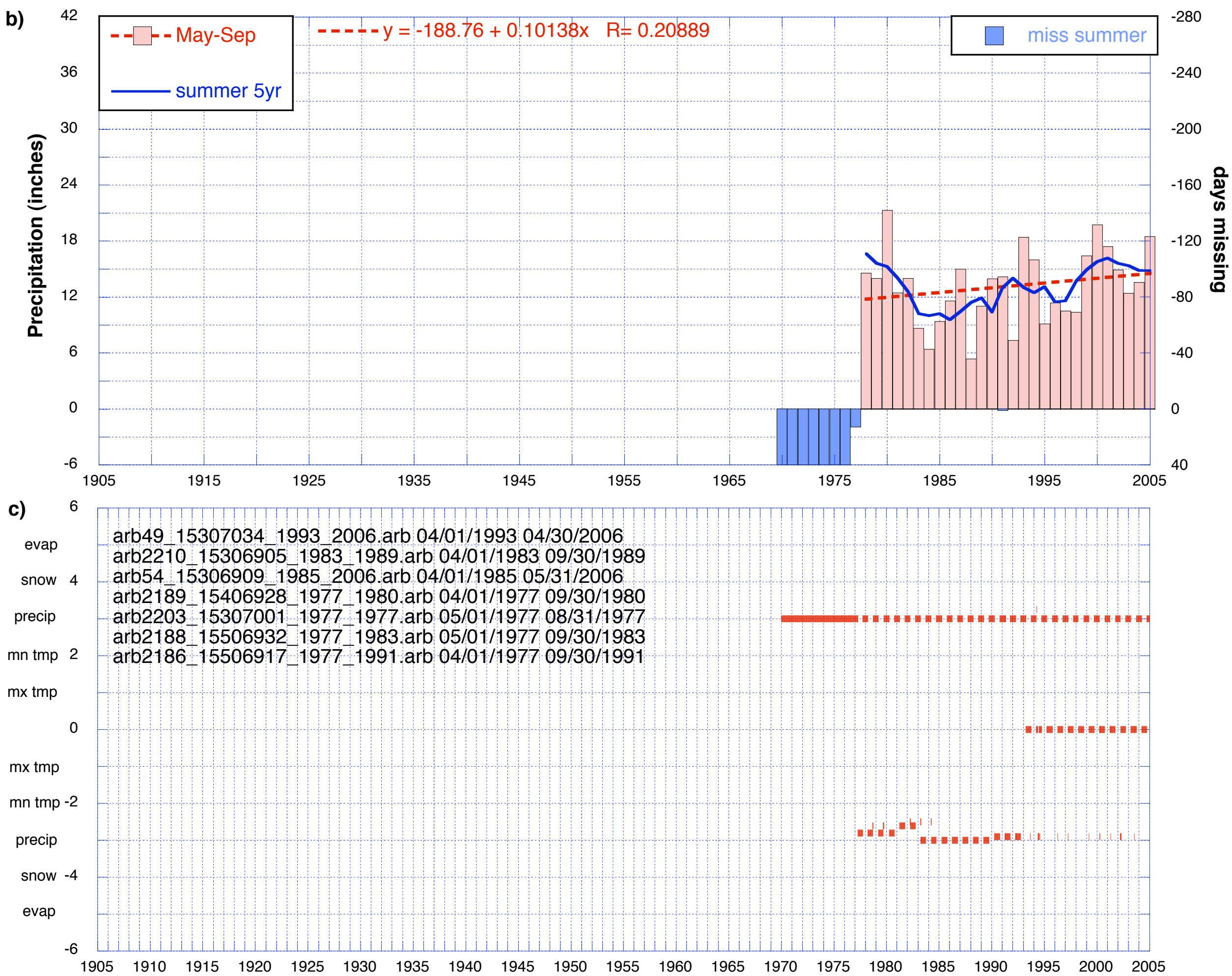
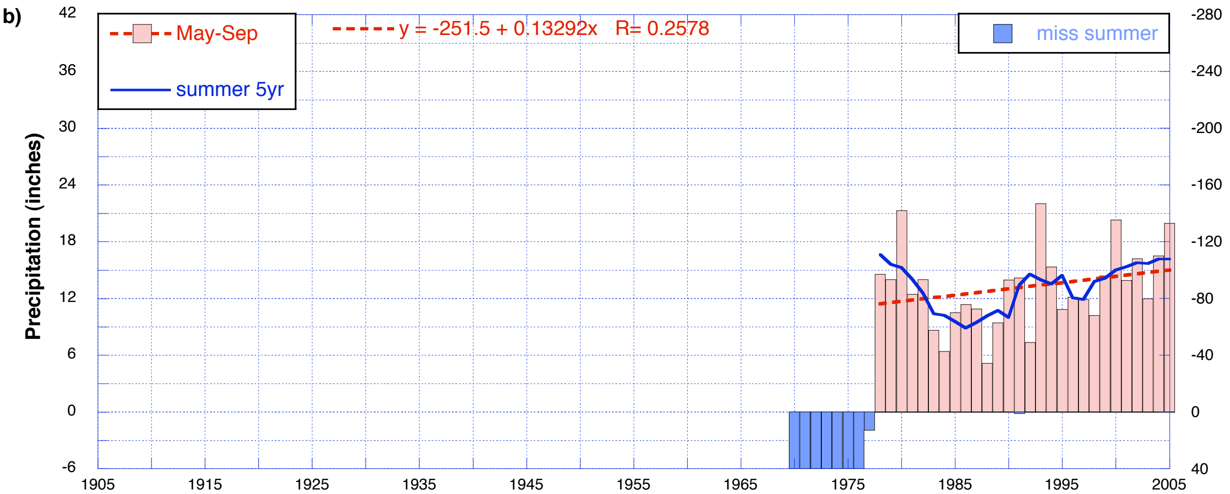


Figure 75. ARB 49 from ARB Northeast Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

a)



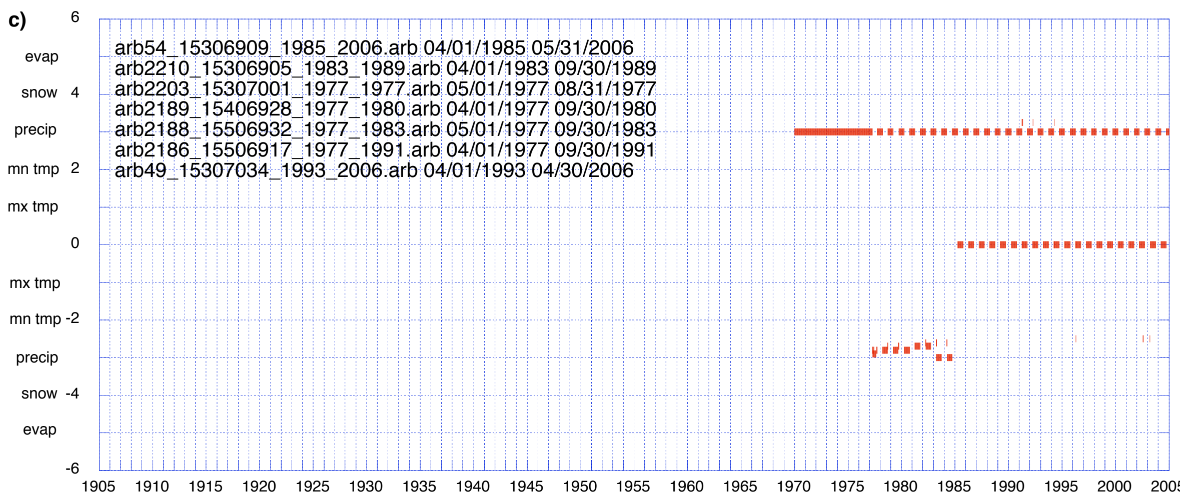


Figure 76. ARB 54 from ARB Northeast Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

ARB South Group

a)

b)

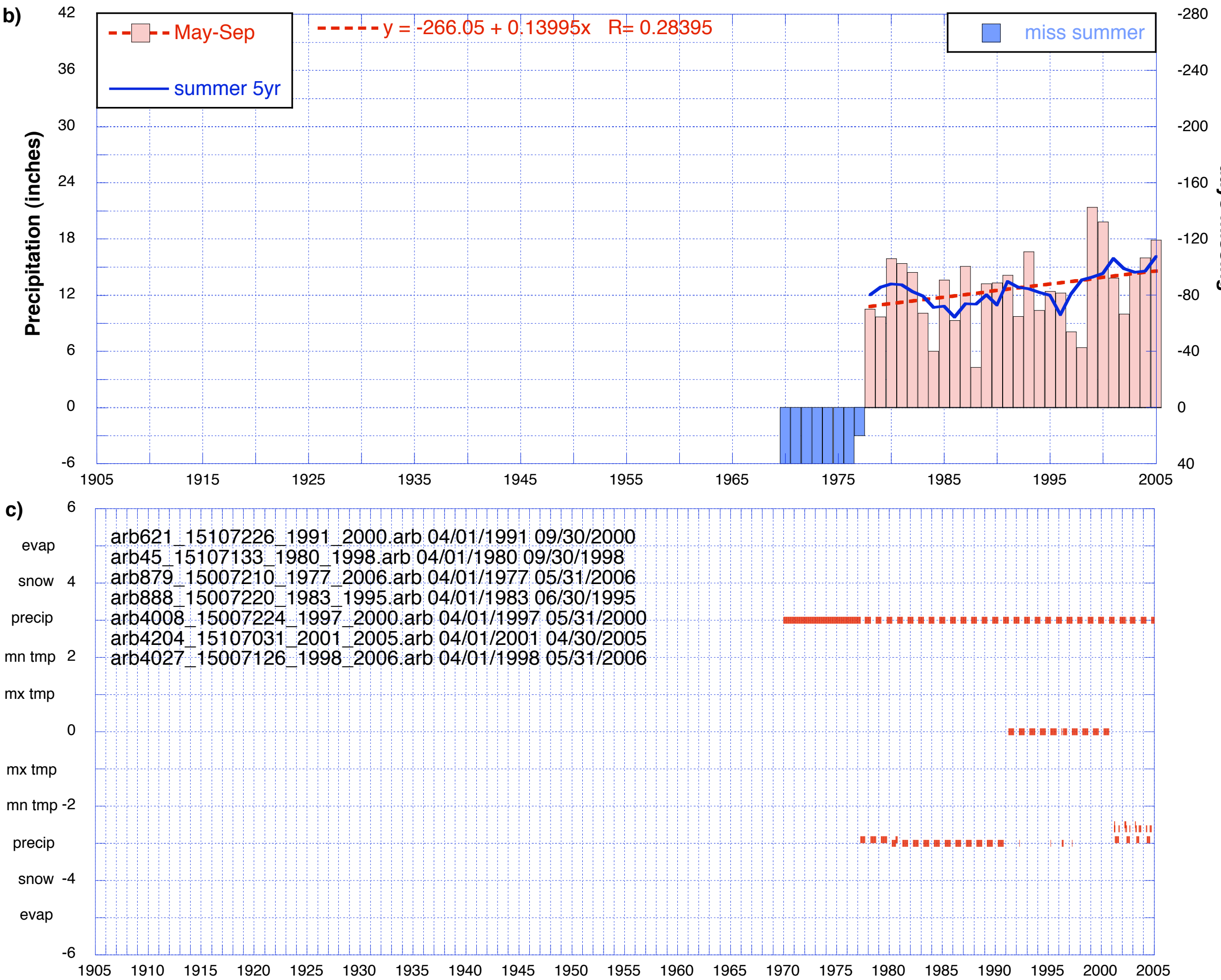


Figure 77. ARB 621 from ARB South Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

a)

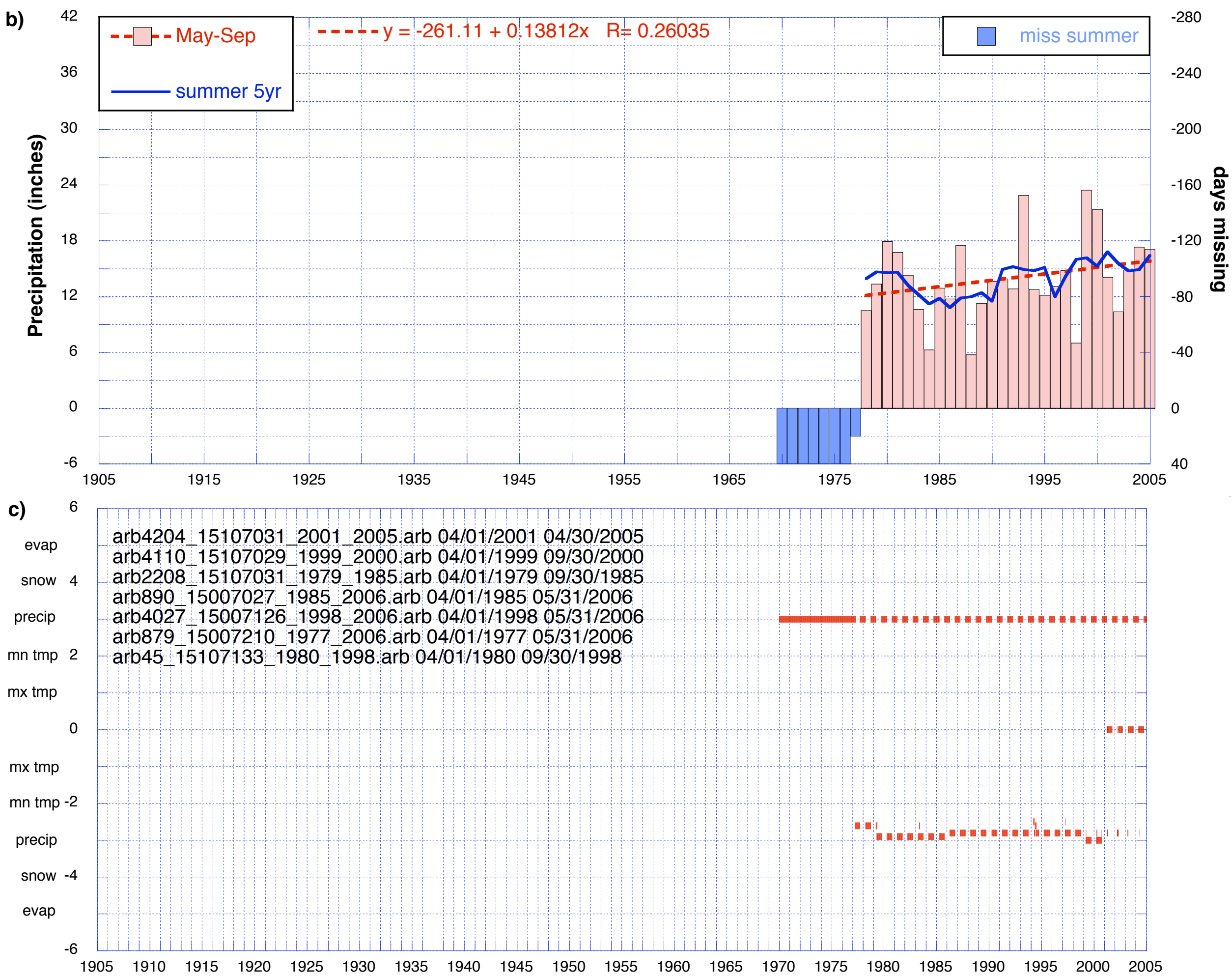


Figure 78. ARB 4204 from ARB South Group composite climate dataset. a) PET - no data. b) Growing season precipitation. c) Stations used to construct dataset showing missing data and station used to replace missing day.

The variability within both the ARB datasets and the NCDC datasets is considerable. Figure 79 is a comparison of the datasets generated from the four ARB groups. Growing season precipitation, within this small area, varies annually from 2 inches to over 10 inches. Variability between the five-year moving average exceeds 3 inches. Mean precipitation for each dataset is listed in the legend. The Granville group is presented in figure 80. The Towner group is presented in figure 81. The Rugby group is presented in figure 82. The Maddock group is presented in figure 83. The long-term stations group (most distant) is presented in figure 84. The ARB CG-2198 dataset is included in figures 80 through 84 for comparison. The average data for the NCDC datasets for each group are presented in table 4.

This analysis shows a great deal of both spatial and temporal variability between sites. It appears most of the variability across this rather large area is stochastic and not climatic. The tracks of three consecutive storm events occurring on 8/9/2005, 8/11/2005, and 8/17/2005 are shown in figure 85. As can be seen, convective storms can locally deliver large amounts of precipitation, sometimes along long narrow tracks. The monthly and annual precipitation totals are the summation of all of the storm tracks for a given period. The relatively random nature, at least over large time periods (several weeks), of these tracts introduces a large random component into the precipitation data. On time scales of days to weeks tracks can tend to repeat because of patterns of atmospheric stability or recycling of local soil moisture.

The moisture that is the source of precipitation is a combination of moisture transported into the region by Gulf and Pacific air masses and recycling of soil moisture by evapotranspiration. There are general patterns to the data representing variations in climate through time (teleconnections such as ENSO, PDO, AMO, etc. to regional soil moisture feed backs), but there is a lot of randomness. Even 50 years of record from one station is not climate. To determine climate, many stations are going to need to be averaged. Even if the climate for the next 100 years was the same as the last 100 years, the precipitation for the next 100 years will likely be very different than the last 100 years.

There is also significant spatial variability in PET. For the set of NCDC climate stations near the Trappers Coulee aquifer, average 1949-2005 growing season PET from temperature data ranged from 26.82 to 28.52 inches (table 4). The range in values of 1.70 inches is greater than the range of 1.07 inches for average growing season precipitation (table 4). The differences reflect spatial climatic trends, difference in land use near the thermometer, differences in rainfall (how much solar radiation gets partitioned to latent heat), topography, and cloudiness. The differences are large enough to impact recharge and irrigation water use calculations, but there are no criteria to indicate which station is better.

The method of calculating PET from temperature data is going to underestimate the variability. The temperature-based methods to estimate PET are going to smooth the amount of natural variability. This will result in a significant error between drought and pluvial periods. It may be possible to make some improvement by developing dewpoint and wind speed corrections based on wet and dry years.

Comparisons of Growing Season Precipitation at Selected Stations

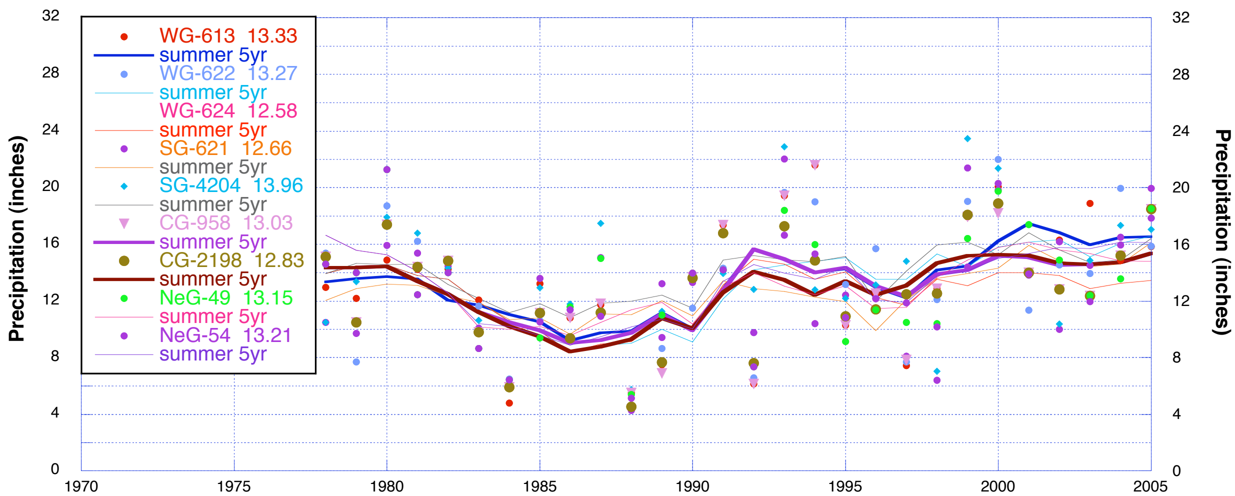


Figure 79. Variability of growing-season precipitation (May-Sep.) at ARB observers near Trappers Coulee aquifer. WG- = West Group, SG = South Group, CG = Central Group, and NeG = Northeast Group.

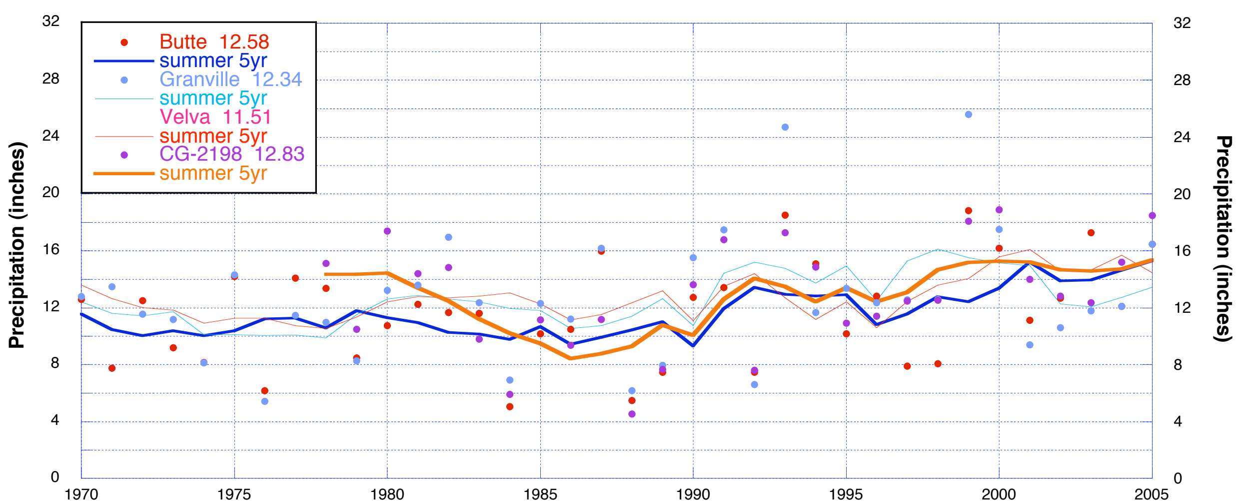


Figure 80. Variability of growing-season precipitation (May-Sep.) at NCDC observers in Granville Group compared to ARB CG-2198 near Trappers Coulee aquifer.

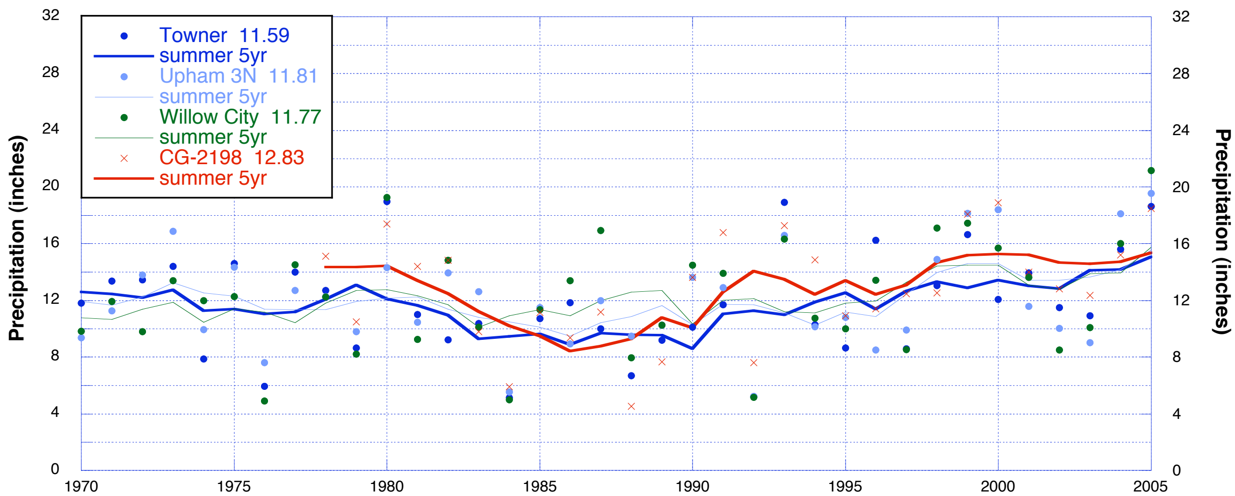


Figure 81. Variability of growing-season precipitation (May-Sep.) at NCDC observers in Towner Group compared to ARB CG-2198 near Trappers Coulee aquifer.

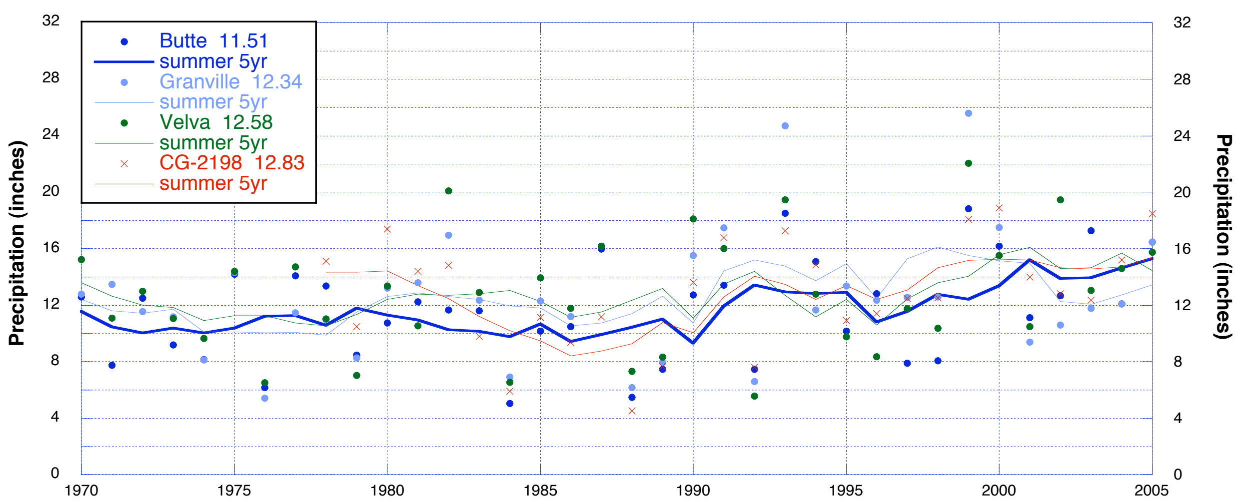


Figure 82. Variability of growing-season precipitation (May-Sep.) at NCDC observers in Rugby Group compared to ARB CG-2198 near Trappers Coulee aquifer.

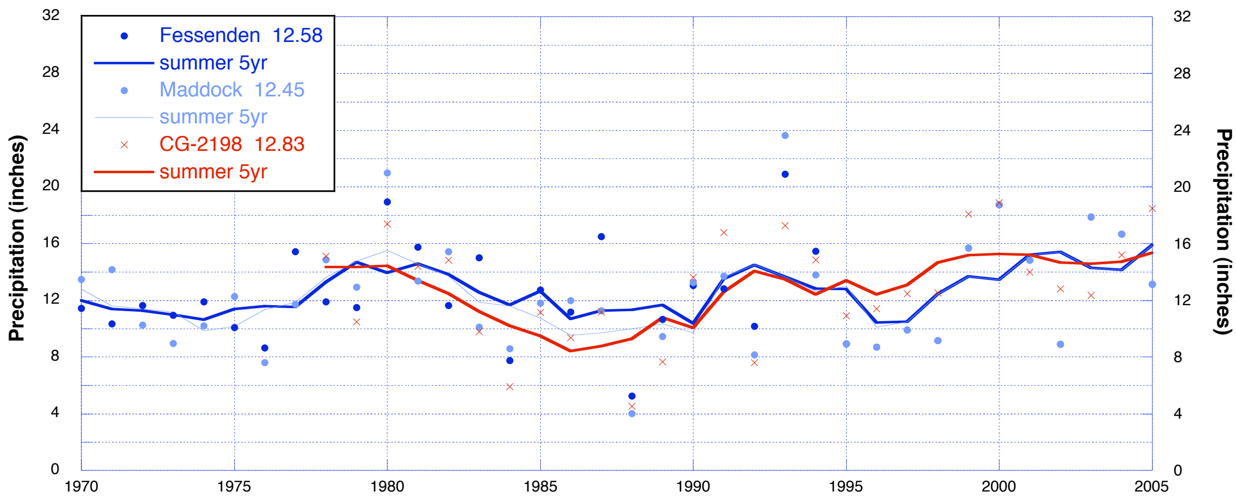


Figure 83. Variability of growing-season precipitation (May-Sep.) at NCDC observers in Maddock Group compared to ARB CG-2198 near Trappers Coulee aquifer.

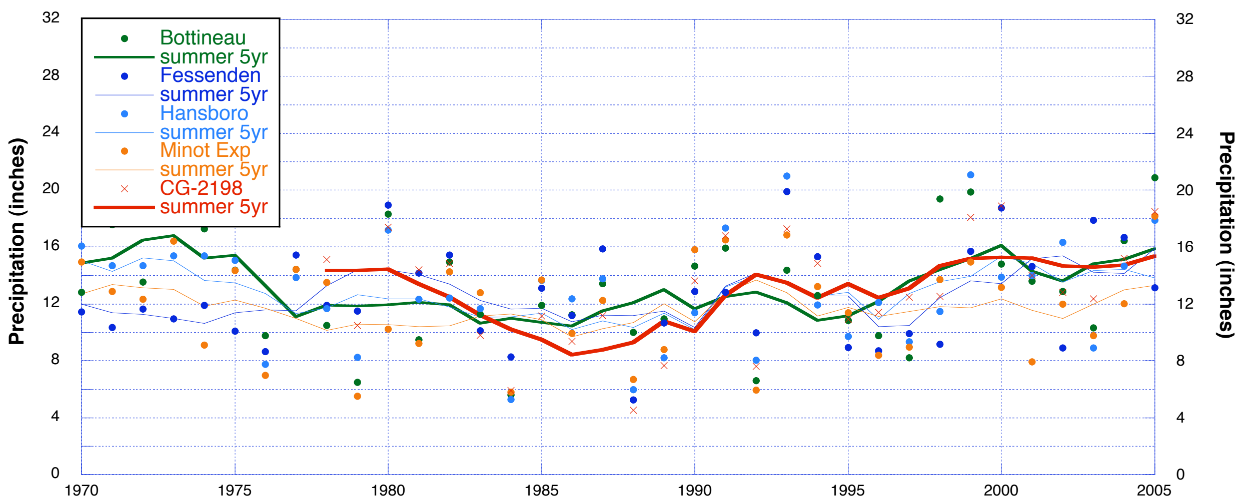


Figure 84. Variability of growing-season precipitation (May-Sep.) at NCDC observers at stations with long period of record compared to ARB CG-2198 near Trappers Coulee aquifer.

TOWNER SET	PRECIP Oct-Apr inches	std.dev	May-Sep inches	std.dev	Annual inches	std.dev	PET Oct-Apr inches	std.dev	May-Sep inches	std.dev	Annual inches	std.dev
Towner	5.16	2.21	11.59	3.53	16.75	3.74	10.1	1.27	28.52	1.84	38.61	2.44
Upham 3N	5.12	2.05	11.81	3.62	16.93	3.92	10.46	1.3	28.41	2.17	38.87	2.73
Willow City	4.58	1.84	11.77	3.72	16.36	3.9	9.68	1.27	27.3	2.09	36.98	2.75
GRANVILLE SET												
Granville	5.13	2.29	12.34	3.97	17.47	4.61	10.02	1.25	27.9	2.13	37.92	2.63
Butte	4.8	2.16	11.51	3.49	16.31	3.86	9.63	1.41	27.59	2.24	37.22	2.91
Velva	5.81	2.5	12.58	3.77	18.39	4.2	10.38	1.31	27.77	2.4	38.15	2.94
RUGBY SET												
Rugby	5.23	2.31	12.57	3.66	17.8	4	9.32	1.31	27.22	1.95	36.54	2.56
Leeds	6	2.2	12.37	3.43	18.37	3.87	9.05	1.19	26.82	1.98	35.86	2.48
Drake 9NE	4.65	2.1	11.83	3.26	16.48	3.69	9.63	1.27	27.34	2.05	36.97	2.72
MADDOCK SET												
Maddock	5.02	1.82	12.45	3.73	17.5	3.86	9.48	1.35	27.77	2.32	37.25	2.98
Fessenden	5.28	1.98	12.58	3.57	17.88	3.7	9.81	1.43	27.8	2.36	37.64	3.13

Table 4. Comparison of average precipitation and average PET at each station set for each climate dataset from 1950 to 2005.

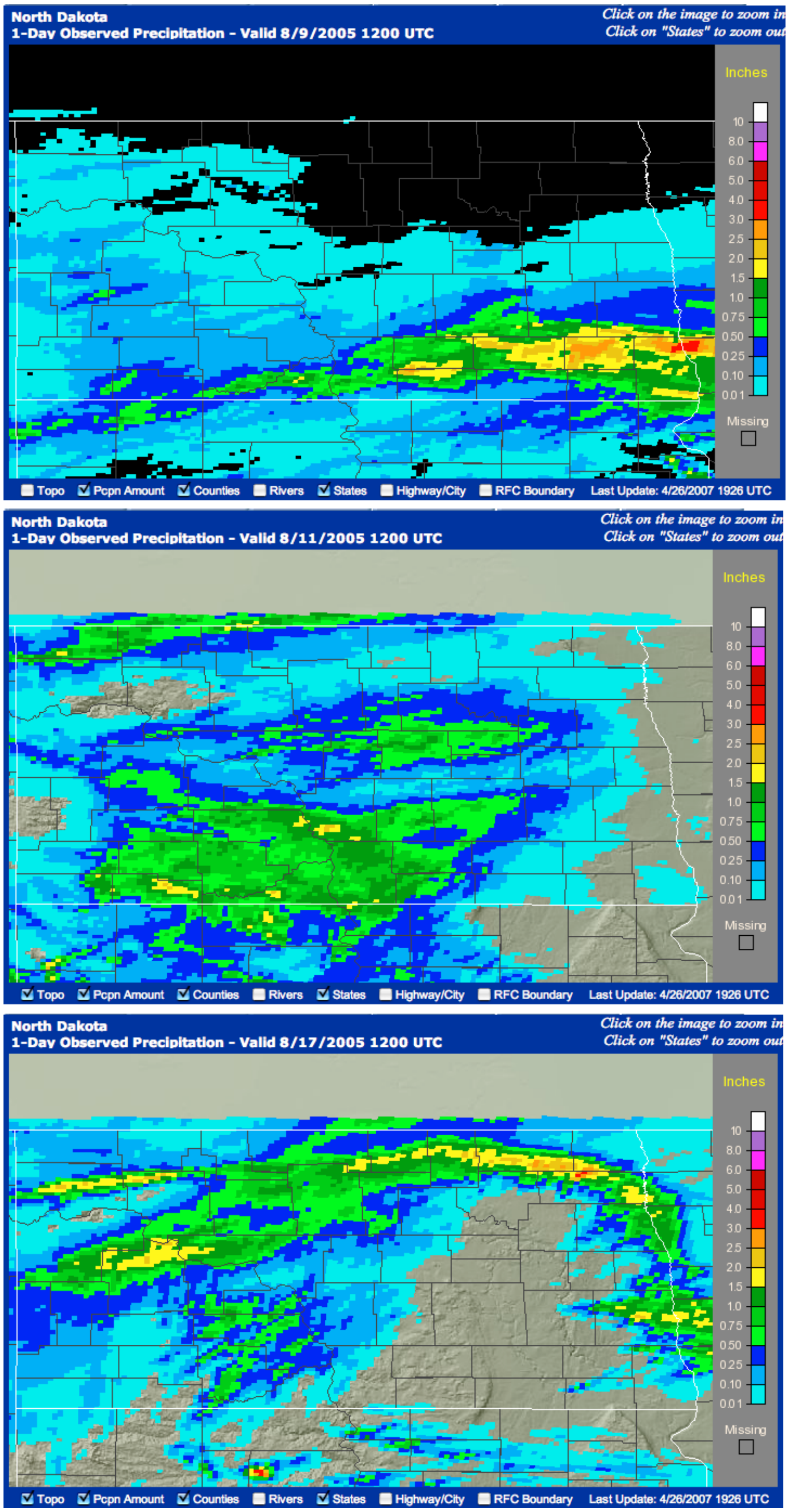


Figure 85. Total North Dakota precipitation from three consecutive storms occurring on 8/9/2005, 8/11/2005, and 8/17/2005. The precipitation data are quality-controlled, multi-sensor (radar and rain gauge) precipitation estimates obtained from National Weather Service (NWS) River Forecast Centers (RFCs). Maps obtained from http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php.

Simulation of Recharge, Evapotranspiration, and Irrigation Water Use

The modeling of ground-water flow requires the following datasets that are a function of climate:

- recharge
- evapotranspiration from groundwater (ET_{gw})
- irrigation water use

To calculate these datasets, the Versatile Soil Moisture Budget Model (VB2000, also referred to as VB2K) as described by Baier (2000) and Dyer (1984) was used. The model was originally developed for use in the Canadian Prairie Provinces. It does a daily accounting of soil moisture by dividing the soil into a maximum of ten layers for which porosity, specific retention, and residual soil moisture (permanent wilting point), which are available in the SSURGO dataset, are specified. The year is divided into crop growth stages for which root depth and fraction of ET that occurs from each layer are specified. The rooting depth data for various crop types and crop coefficients are from Stegman and others (1972 and 1977). Besides the soils data, VB2K input consists of daily climate data consisting of maximum temperature, minimum temperature, precipitation, and PET for this project.

Both recharge and actual evapotranspiration (AET) are modeled as if the aquifer can be characterized by one soil type and one crop, the "big corn plant" model. In doing this, the budget model parameters become fitting parameters and will not necessarily be physically realistic for the modeled soil type. There are several assumptions made in the application of a budget model:

- A significant part (most) of the area is not coupled and is separated from the coupled area. That is, the water table is sufficiently deep that a change in its position does not significantly affect hydrologic processes within the root zone and/or land surface.

- The uncoupled area is predominately coarse textured soils or loams over coarse textured soils. These conditions best fit the bucket model of a budget model as field capacity is a close approximation to the way the soil drains.

- Some fraction of runoff can be considered to represent depression focused recharge and/or finger flow and routed to the model as recharge. To account for this, VB2000 was modified to allow a specified fraction of spring snow melt and precipitation to occur as direct recharge.

- Generally, except when field capacity is exceeded, the gradient from the water table is going to be upward. The water content at field capacity is often approximated by a 1⁄3 bar tension, which is 11.3 feet of water. With a 3-foot-thick root zone, the base of the root zone could only drain to field capacity if the water table is 14.3 feet below land surface. Even with the water table 33.9 feet below the base of the root zone, the equilibrium tension at the base of the root zone is only 1 bar. The permanent wilting point of most plants is 15 bars. The water table in most (all?) of the water table aquifers in North Dakota is less than 30 feet below land surface. Therefore, during the growing season, except for the periods following significant precipitation events, the gradient from the water table is going to be upward if live vegetation is present. With coarse textured sediments between the water table and the base of the root zone, unsaturated hydraulic conductivities would be small, and therefore the amount of water moving upward to the root zone would be a very small part of the root zone budget. With sandy soils, the height of the capillary fringe is 1 to 3 feet. Therefore, the primary factor in determining groundwater recharge is determining the amount of water removed from the root zone by evapotranspiration.

PET from groundwater (ET_{gw}) is: ET_{gw} = PET-AET+recharge. This equation accounts for the part of PET that is satisfied by evapotranspiration from the unsaturated zone above the water table. This simplification avoids the problem of having to express recharge as a function of water table depth where recharge would equal precipitation at land surface. In the numerical model simulations, ETgw is used for evapotranspiration (maximum ET flux [L/T]).

Calibration datasets

To develop recharge datasets for calibration, ARB precipitation central group datasets 958c and 2198c, west group dataset 613w, northeast group dataset 2210ne, and south group dataset 4204s were combined with the NCDC Drake9NE dataset. For comparison ARB central group dataset 958c was combined with the NCDC Rugby dataset. The Drake 9NE dataset was also combined with the Carrington NDAWN dataset. Long-term recharge datasets were also created using the Fessenden, Hansboro, Bottineau, and Minot climate datasets.

For each recharge dataset calculated, graphs are presented showing annual water year and October to May precipitation, annual water year and June to September PET, recharge, AET, and $ET_{gw,}$ and annual irrigation water use in inches. For select VB2K model runs, plots of the output are presented for the simulation period of 1951 to 2005. The model as implemented must start on January 1. The upper plot is of monthly values of recharge (descending green bars), PET (pink bars), precipitation (blue bars), and AET(dark green line). The lower plot shows fraction of saturation for the soil profile versus depth in centimeters. The layers in in the budget model show as bands of uniform water content.

VB2K run **drake2198c**. The climate stations used to generate the dataset are given in table 5. Figure 86 shows plots of annual and seasonal precipitation, PET, recharge, AET, ET_{gw}, and irrigation water use in inches. Figure 87 shows plots of monthly recharge, precipitation, PET, and AET compared to plots of fraction of saturation for the simulated soil profile.

VB2K run **drake613w**. The climate stations used to generate the dataset are given in table 6. Figure 88 shows plots of annual and seasonal precipitation, PET, recharge, AET, ET_{gw}, and irrigation water use.

VB2K run **drake**. The climate stations used to generate the dataset are given in table 7. Figure 89 shows plots of annual and seasonal precipitation, PET, recharge, AET, ET_{gw}, and irrigation water use.

VB2K run **rugby01**. The climate stations used to generate the dataset are given in table 8. Figure 90 shows plots of annual and seasonal precipitation, PET, recharge, AET,PET_{gw}, and irrigation water use. Figure 91 shows plots of monthly recharge, precipitation, PET, and AET compared to plots of fraction of saturation for the simulated soil profile.

VB2K run **drake2210ne**. The climate stations used to generate the dataset are given in table 9. Figure 92 shows plots of annual and seasonal precipitation, PET, recharge, AET, ET_{gw}, and irrigation water use.

VB2K run **drake4204s**. The climate stations used to generate the dataset are given in table 10. Figure 93 shows plots of annual and seasonal precipitation, PET, recharge, AET, ET_{gw}, and irrigation water use. Figure 94 shows plots of monthly recharge, precipitation, PET, and AET compared to plots of fraction of saturation for the simulated soil profile.

VB2K run **maddock02**. Not presented.

VB2K run **drake_carr93**. The climate stations used to generate the dataset are given in table 11. Figure 95 shows plots of annual and seasonal precipitation, PET, recharge, AET, PET_{gw}, and irrigation water use.

VB2K run **fessenden100a**. The climate stations used to generate the dataset are given in table 12. Figure 96 shows plots of annual and seasonal precipitation, PET, recharge, AET, PET_{gw}, and irrigation water use.

VB2K run **hansboro100**. The climate stations used to generate the dataset are given in table 13. Figure 97 shows plots of annual and seasonal precipitation, PET, recharge, AET, PET_{gw}, and irrigation water use.

VB2K run **bottineau_100**. The climate stations used to generate the dataset are given in table 14. Figure 98 shows plots of annual and seasonal precipitation, PET, recharge, AET, PET_{gw}, and irrigation water use.

VB2K run **minot100a**. The climate stations used to generate the dataset are given in table 15. Figure 99 shows plots of annual and seasonal precipitation, PET, recharge, AET, PET_{gw}, and irrigation water use.

drake2198c

Climate station	Date starts	Date ends
arb2198_15307129_1977_1992COMP_02.daily2	01/01/1970	12/31/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004
DRAKE.NCD	07/01/1948	07/31/1982
HARVEY.NCD	07/01/1948	11/30/2004
FESSENDE.NCD	01/01/1932	12/31/2004
RUGBY.NCD	07/01/1948	12/31/2004

Table 5. Climate stations used to build VB2K input climate dataset “arb2198_15307129_1977_1992COMP_02COMP_01.daily.vb2k” for VB2K model run drake2198c.

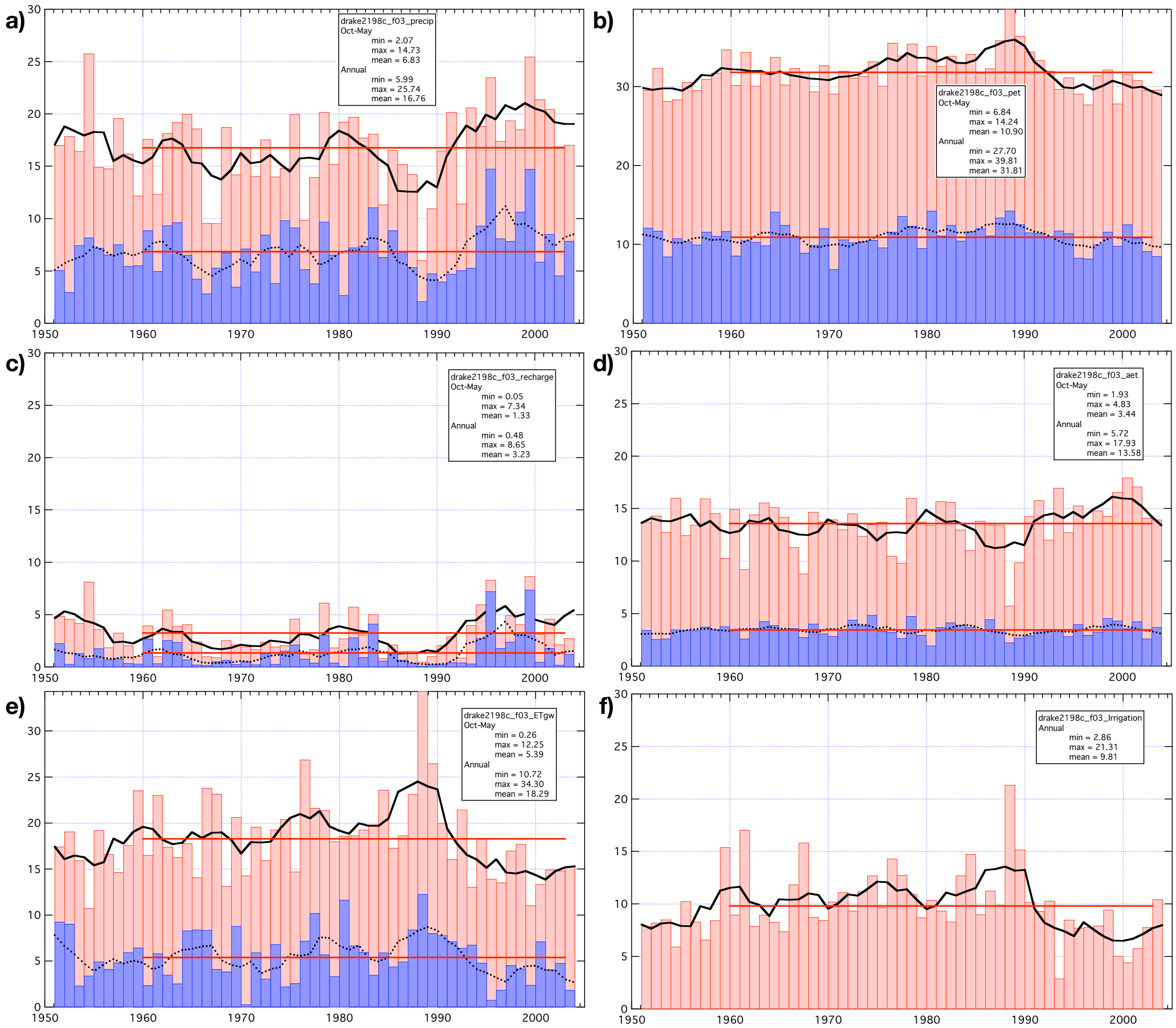


Figure 86. Plots of water-year and Oct.-May output from VB2K run drake2198c. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

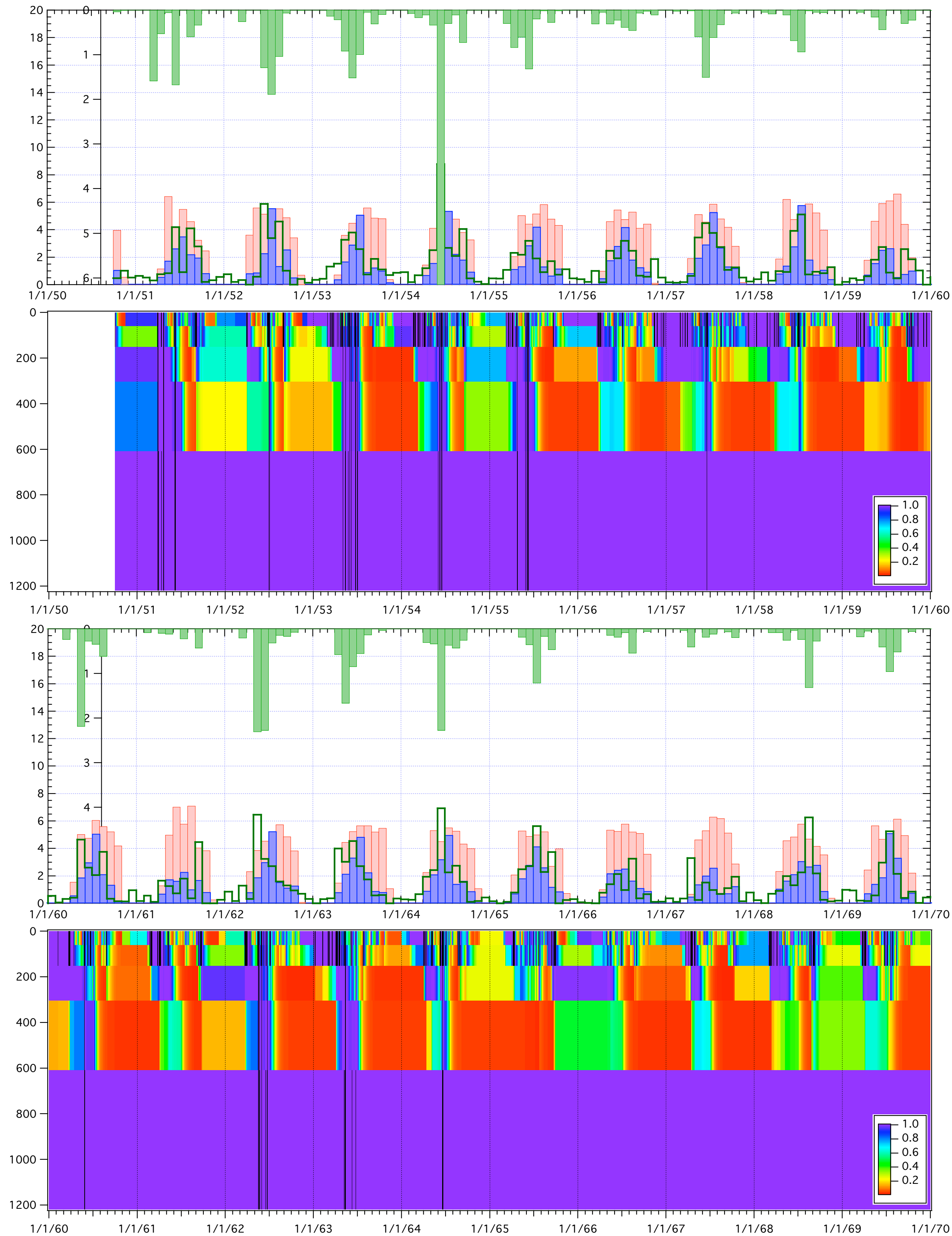


Figure 87. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake2198c.

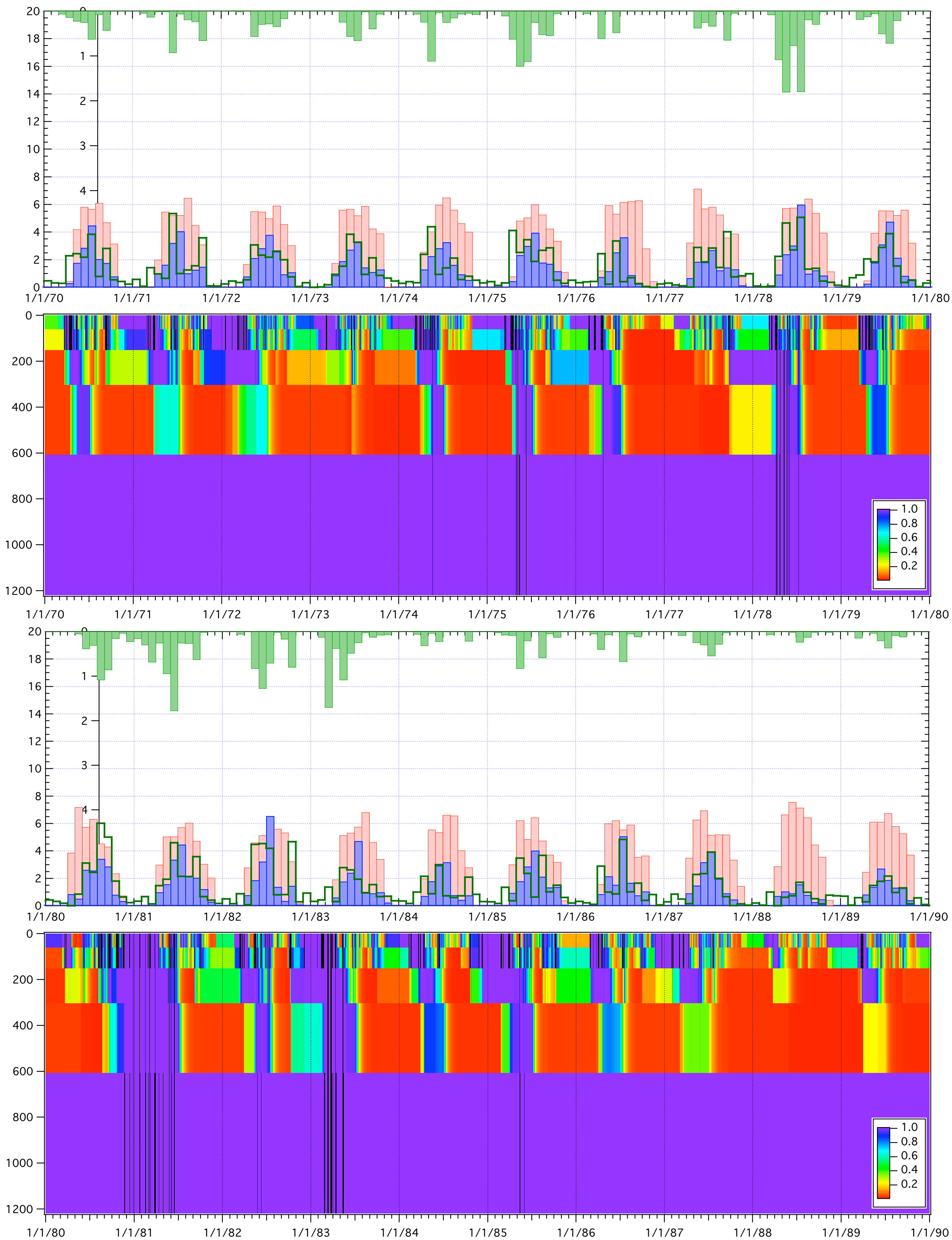


Figure 87 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake2198c.

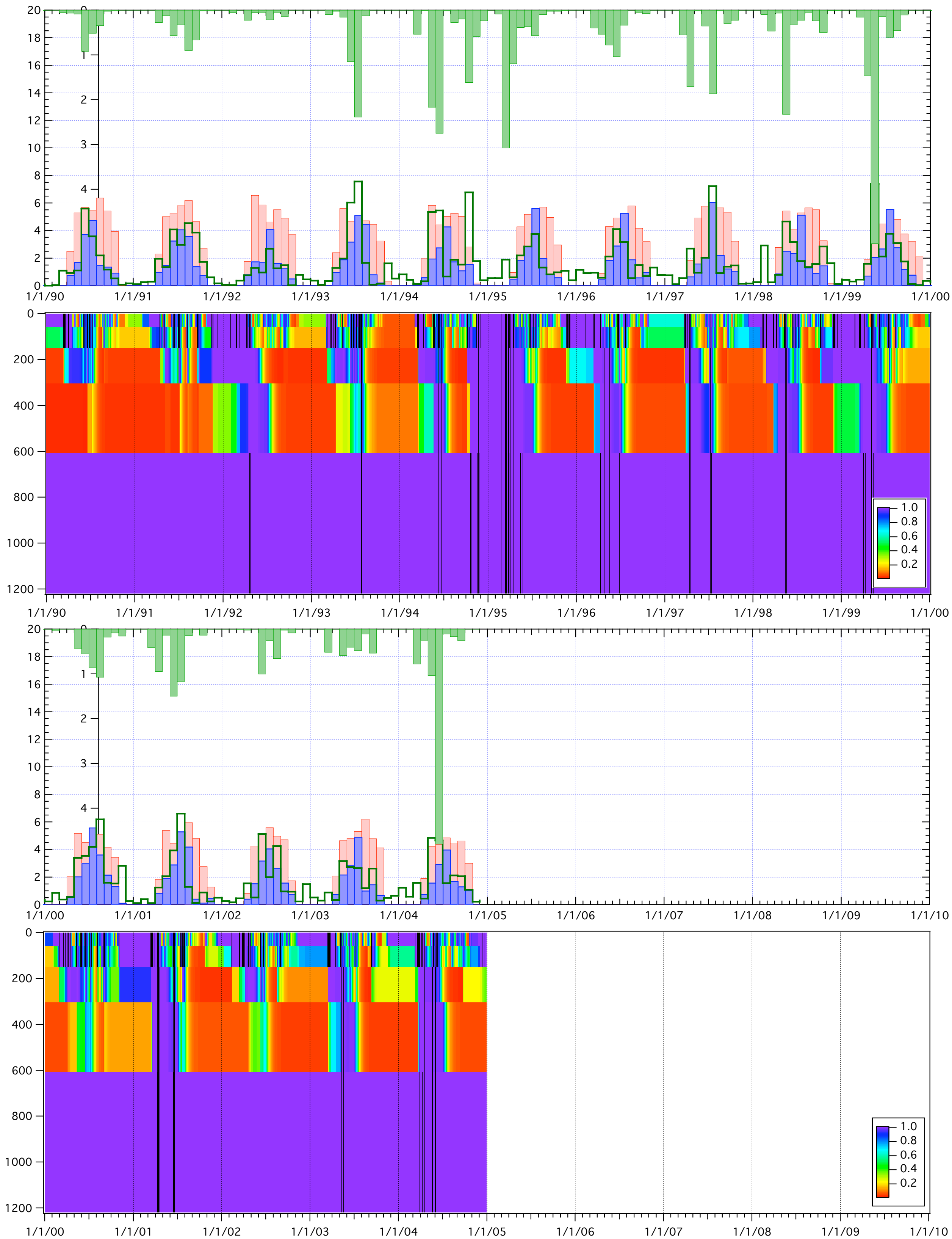


Figure 87 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake2198c.

drake613w

Climate station	Date starts	Date ends
arb613_15407226_1986_1994COMP_01.daily2	01/01/1970	12/31/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004
DRAKE.NCD	07/01/1948	07/31/1982
HARVEY.NCD	07/01/1948	11/30/2004
FESSENDE.NCD	01/01/1932	12/31/2004
RUGBY.NCD	07/01/1948	12/31/2004

Table 6. Climate stations used to build climate VB2K input climate dataset "arb613_15407226_1986_1994COMP_01COMP_01.daily.vb2k" for VB2K model run drake613w.

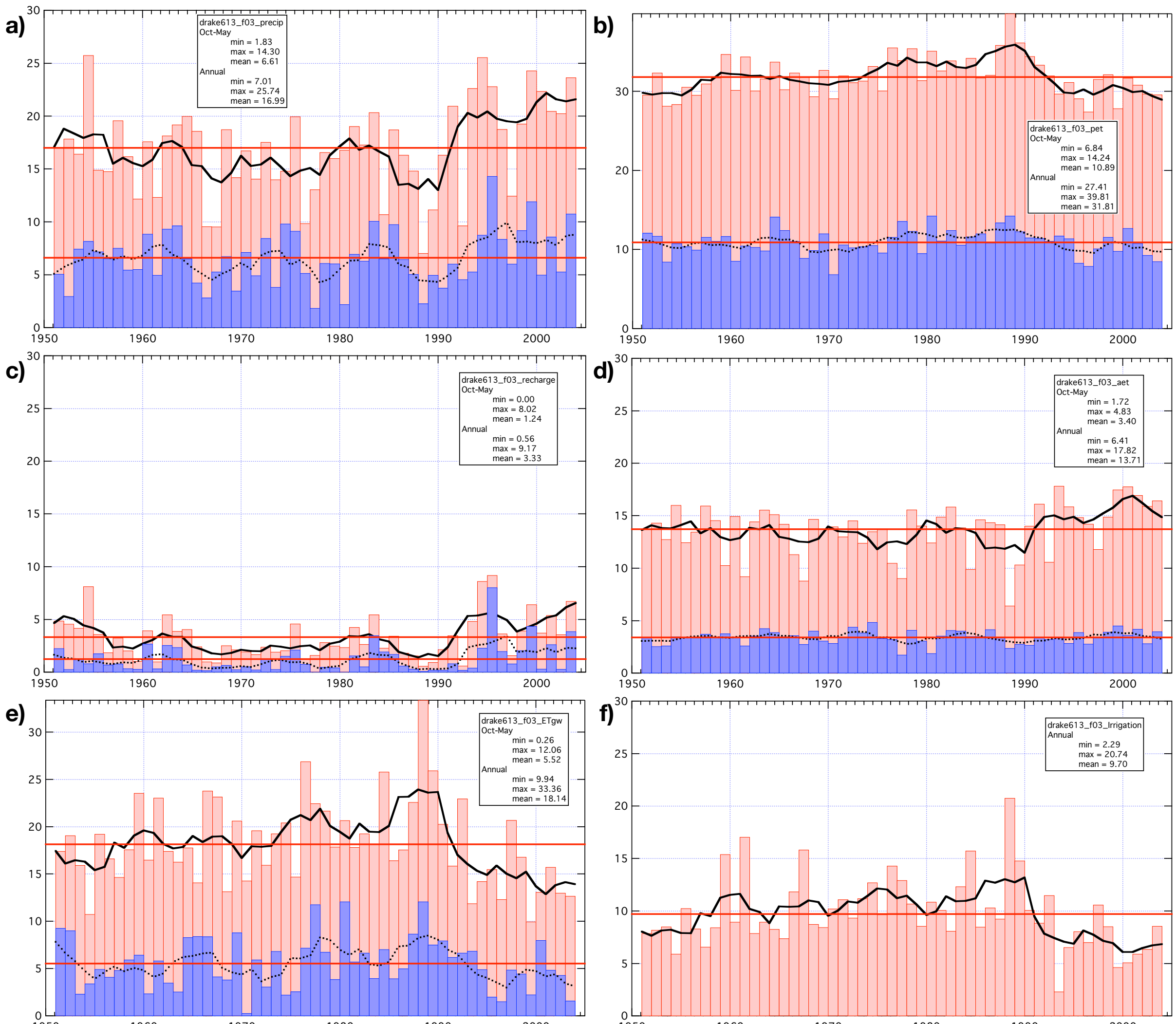


Figure 88. Plots of water-year and Oct.-May output from VB2K run drake613w. **a**) precipitation, **b**) PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

drake

Climate station	Date starts	Date ends
arb958_15407226_1995_2000COMP_01.daily2	01/01/1970	12/31/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004
DRAKE.NCD	07/01/1948	07/31/1982
HARVEY.NCD	07/01/1948	11/30/2004
FESSENDE.NCD	01/01/1932	12/31/2004

Table 7. Climate stations used to build VB2K input climate data “drake_arb958_COMP_01.daily.vb2k” for VB2K model run drake.

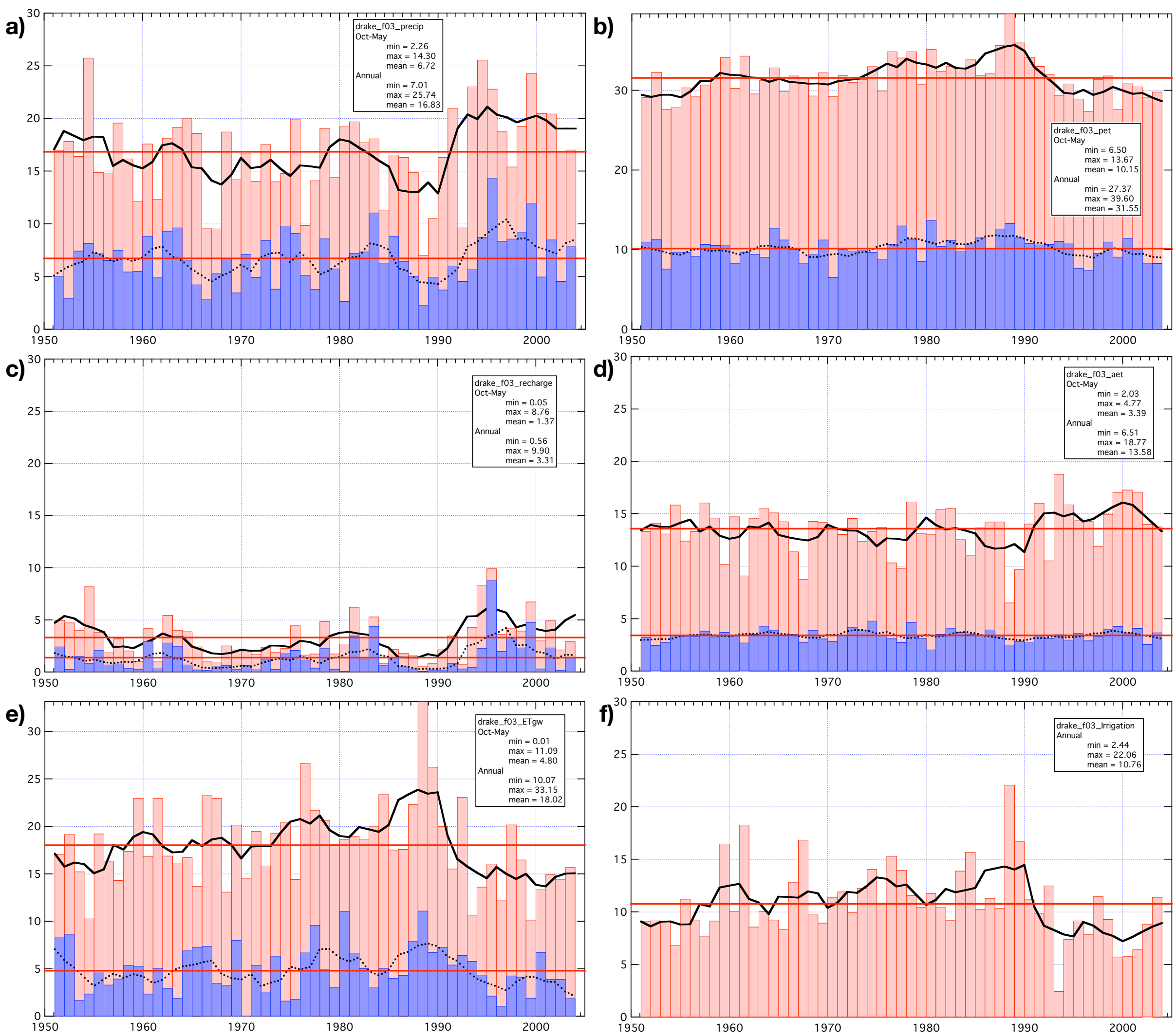


Figure 89. Plots of water-year and Oct.-May output from VB2K run drake. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

rugby01

Climate station	Date starts	Date ends
arb958_15407226_1995_2000COMP_01.daily2	01/01/1970	12/31/2004
RUGBY.NCD	07/01/1948	12/31/2004
BALTA.NCD	08/01/1877	08/31/1975
TOWNER.NCD	07/01/1948	12/31/2004
GRANVILL.NCD	07/01/1948	02/29/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004

Table 8. Climate stations used to build VB2K input climate dataset rugby_arb958_COMP_01.daily.vb2k” for VB2K model run rugby01.

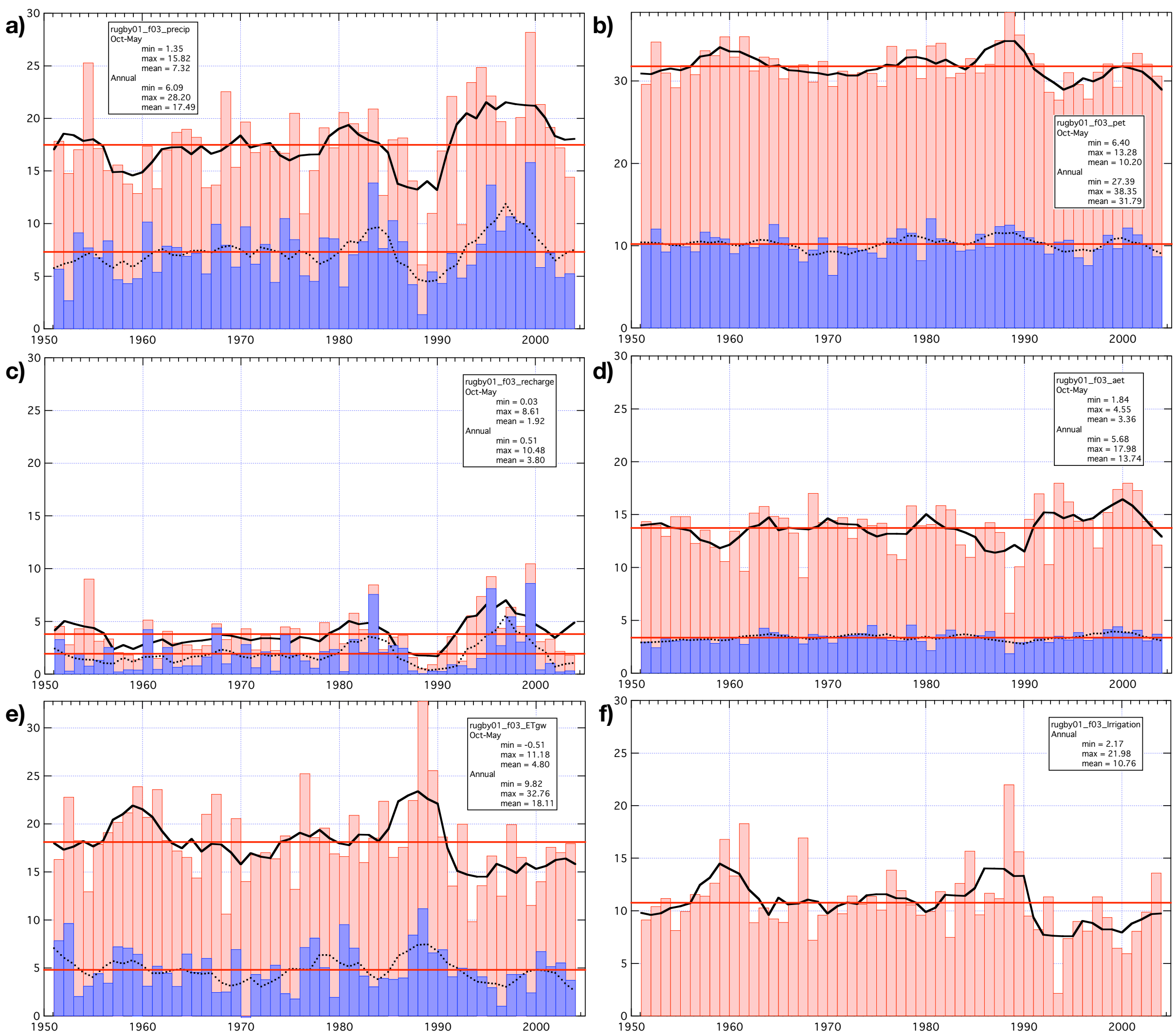


Figure 90. Plots of water-year and Oct.-May output from VB2K run rugby01. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

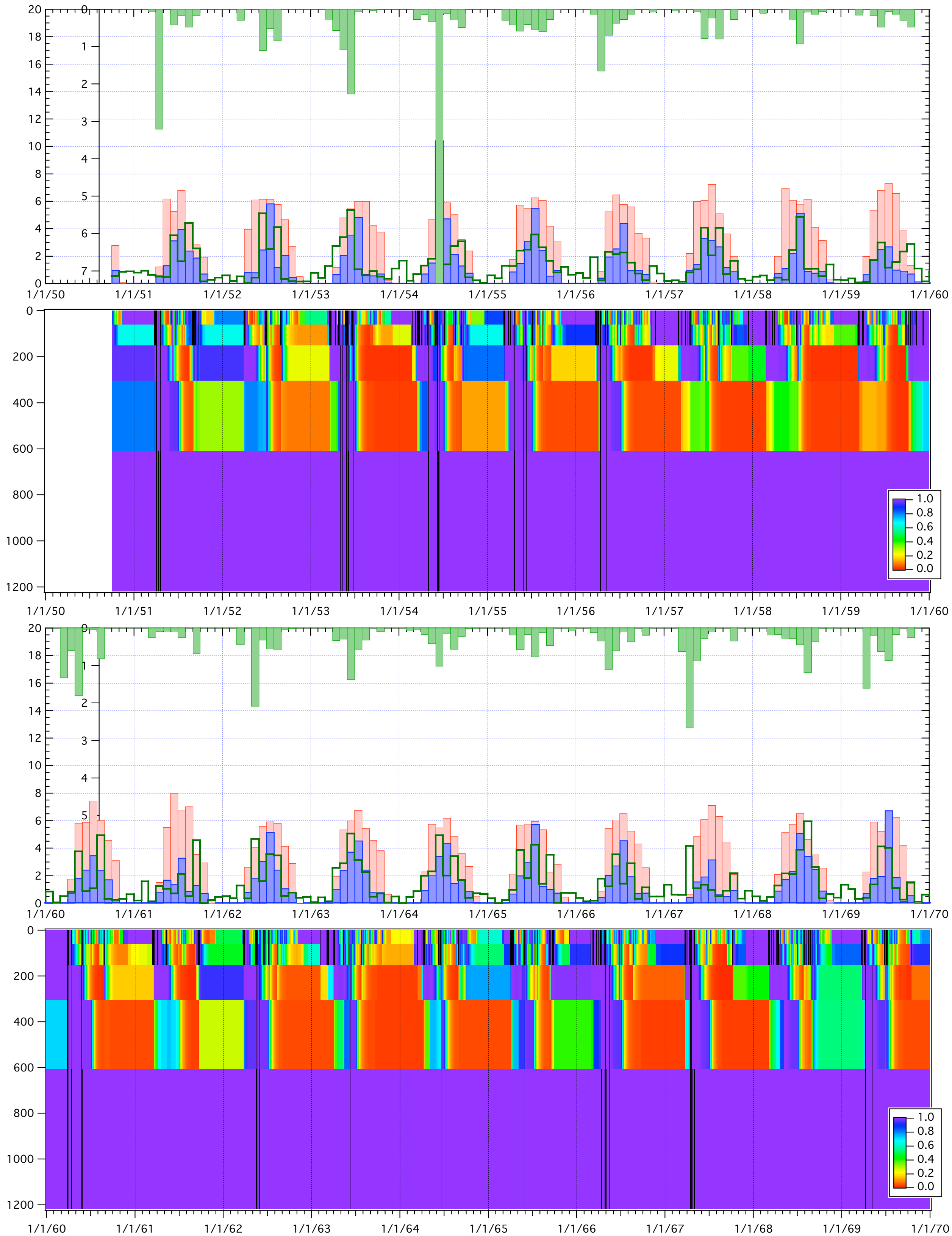


Figure 91. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run rugby01.

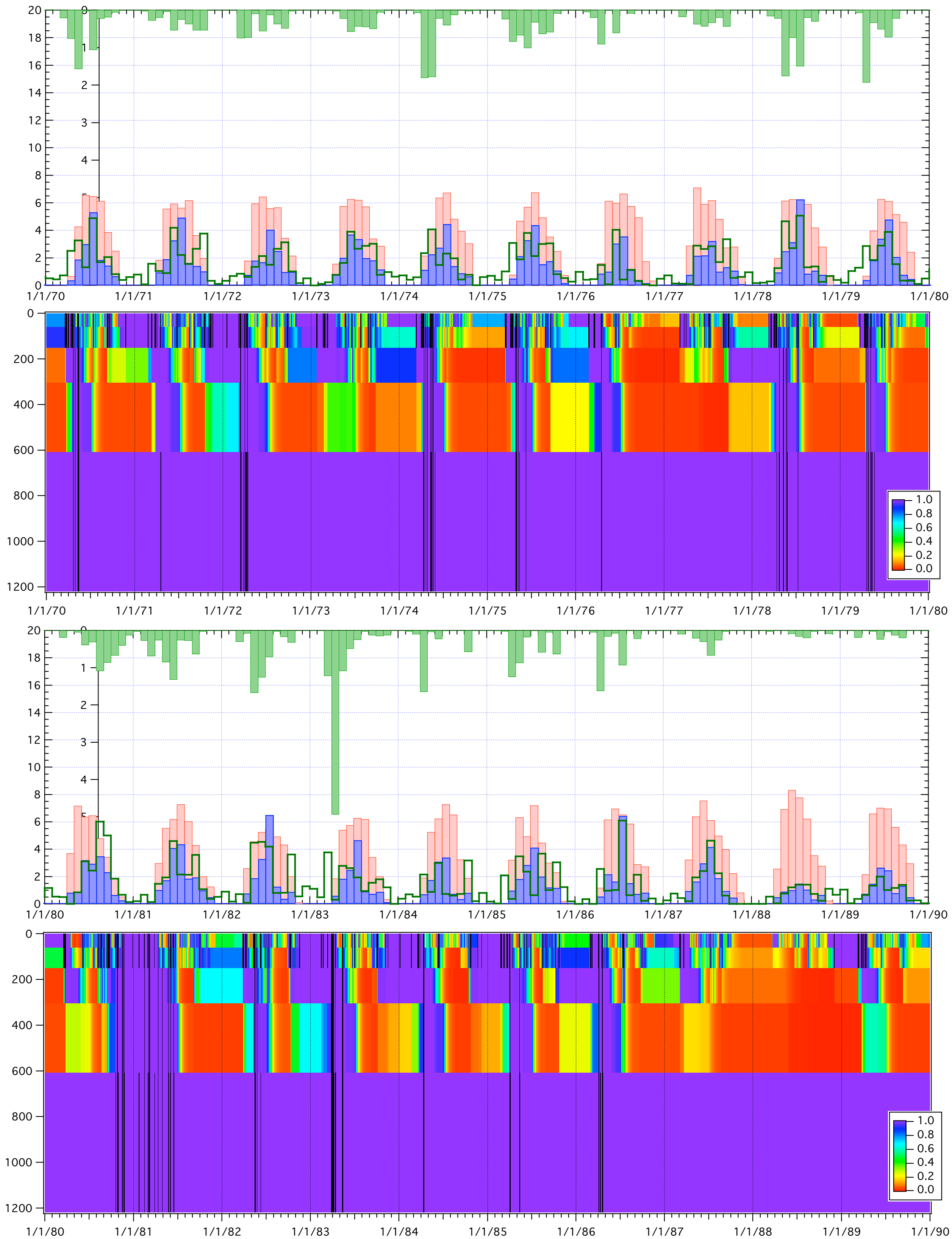


Figure 91 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run rugby01.

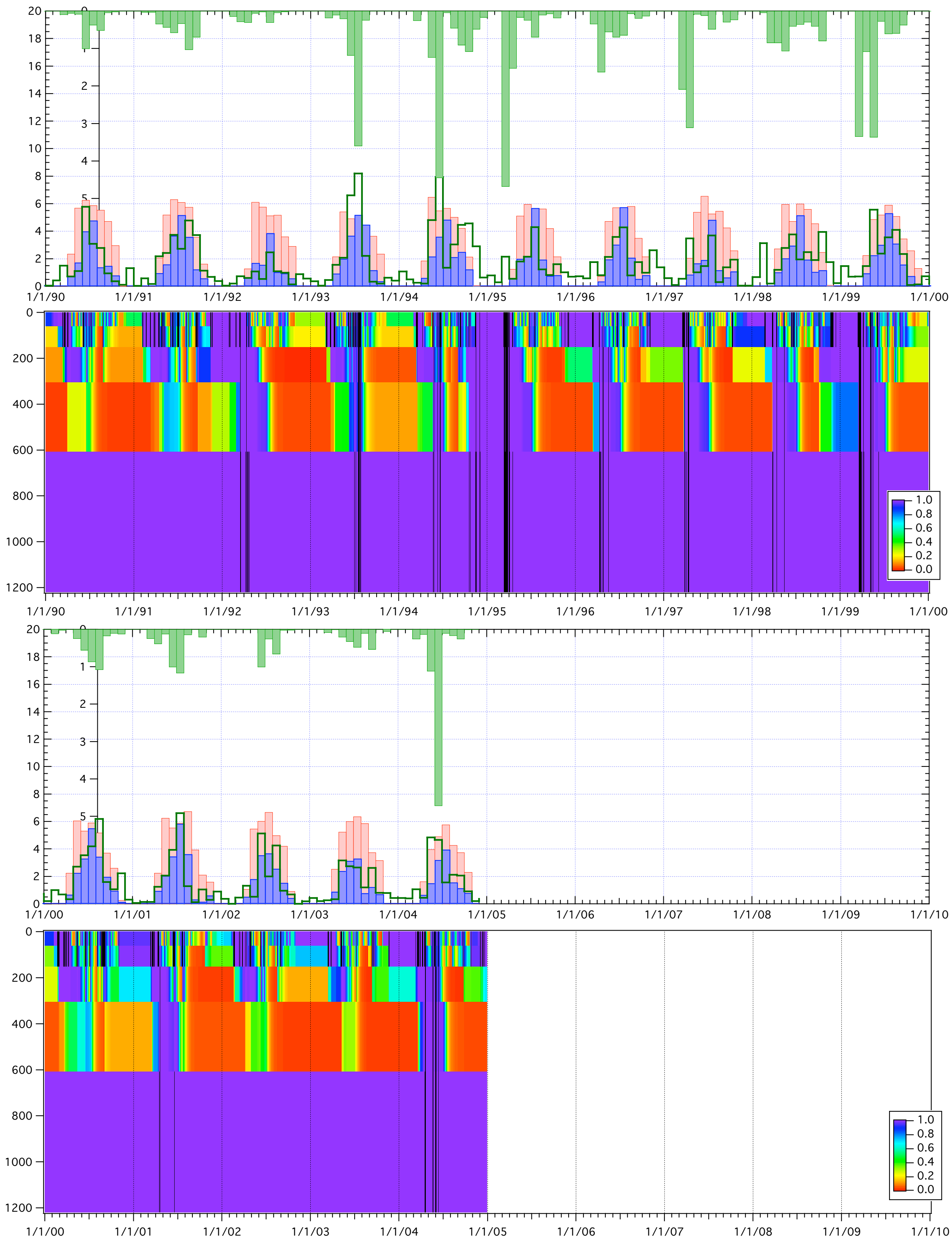


Figure 91 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run rugby01.

drake2210ne

Climate station	Date starts	Date ends
arb2210_15306905_1983_1989COMP_01.daily2	01/01/1970	12/31/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004
DRAKE.NCD	07/01/1948	07/31/1982
HARVEY.NCD	07/01/1948	11/30/2004
FESSENDE.NCD	01/01/1932	12/31/2004
RUGBY.NCD	07/01/1948	12/31/2004

Table 9. Climate stations used to build VB2K input climate dataset "arb2210_15306905_1983_1989COMP_01COMP_01.daily.vb2k" for VB2K model run drake2210ne.

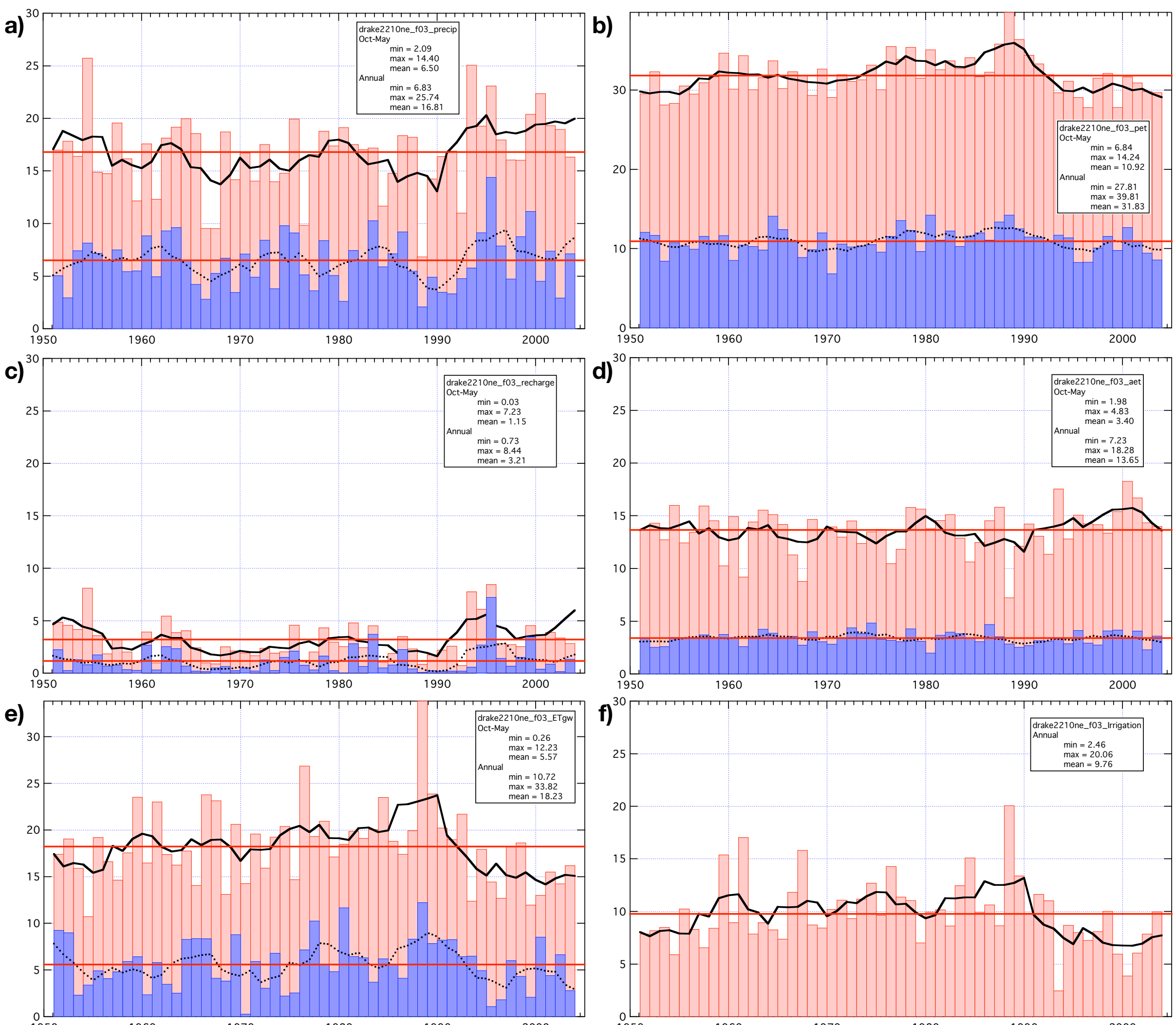


Figure 92. Plots of water-year and Oct.-May output for VB2K run drake2210ne. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

drake4204s

Climate station	Date starts	Date ends
arb4204_15107031_2001_2004COMP_01.daily2	01/01/1970	12/31/2004
DRAKE9NE.NCD	08/01/1964	12/31/2004
DRAKE.NCD	07/01/1948	07/31/1982
HARVEY.NCD	07/01/1948	11/30/2004
FESSENDE.NCD	01/01/1932	12/31/2004
RUGBY.NCD	07/01/1948	12/31/2004

Table 10. Climate stations used to build VB2K input climate dataset "arb4204_15107031_2001_2004COMP_01COMP_01.daily.vb2k" for VB2K model run drake4204s.

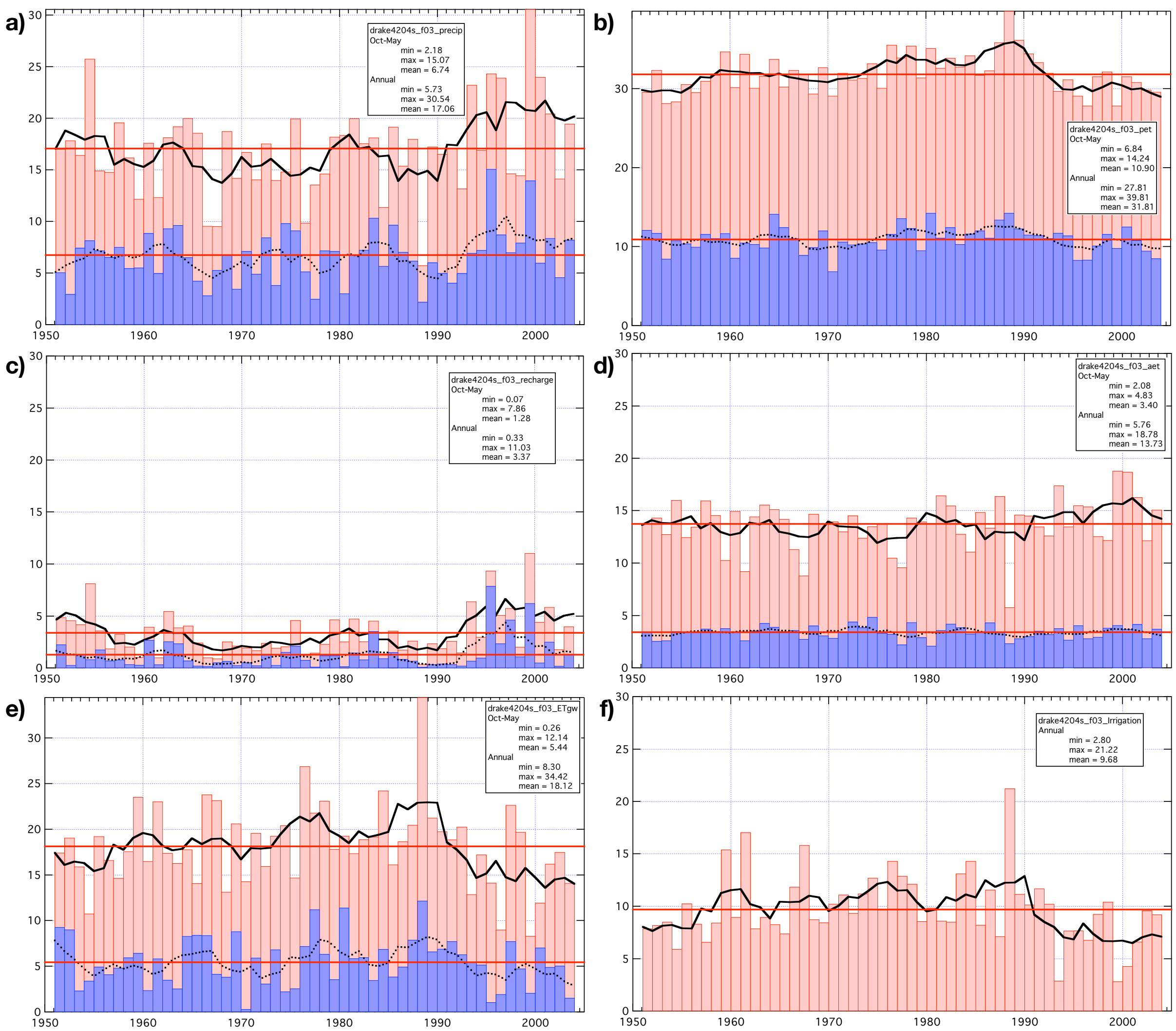


Figure 93. Plots of water-year and Oct.-May output from VB2K run drake4204s. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e**) ETgw, and **f)** irrigation water use per acre. All data in inches per year.

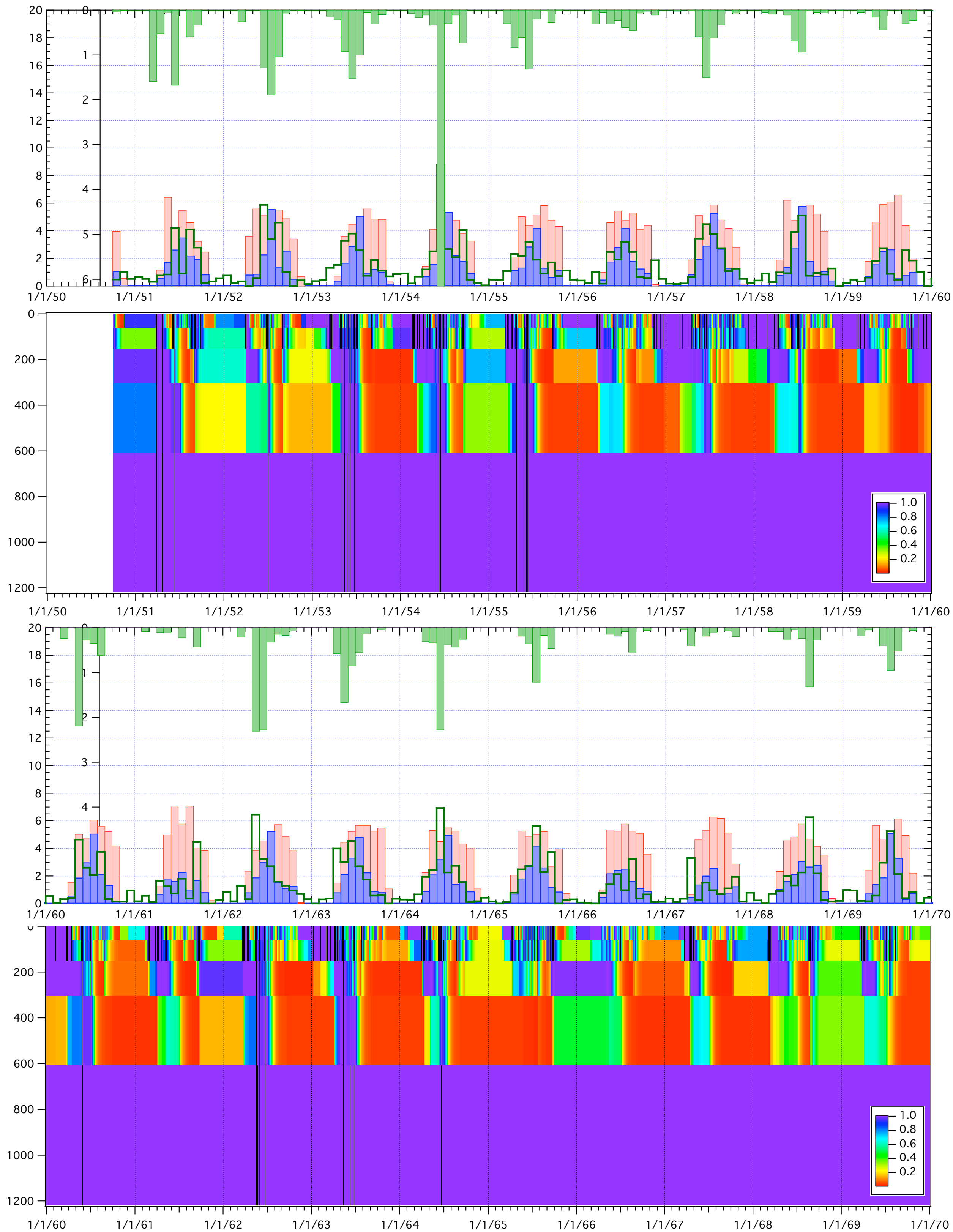


Figure 94. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake4204s.

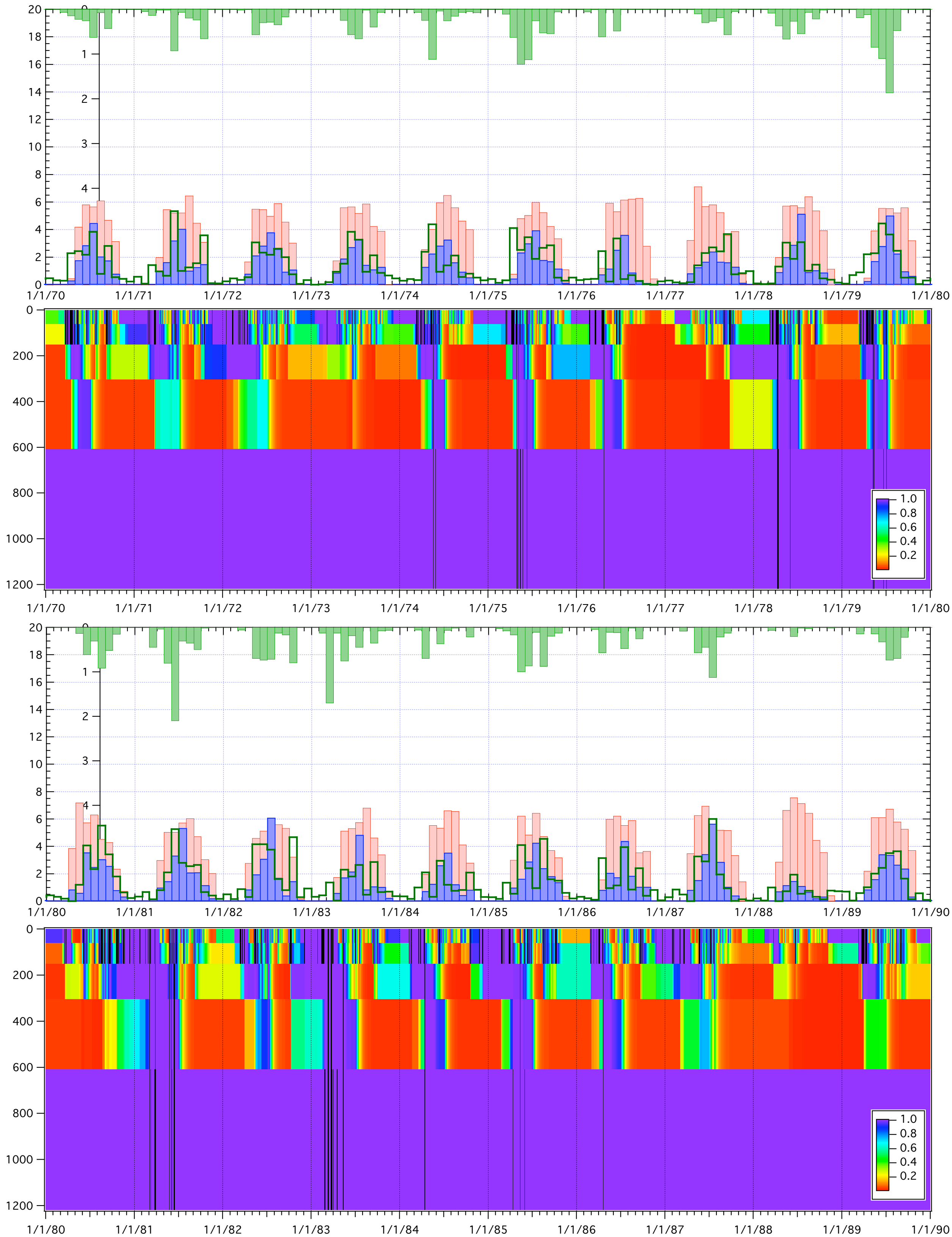


Figure 94 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake4204s.

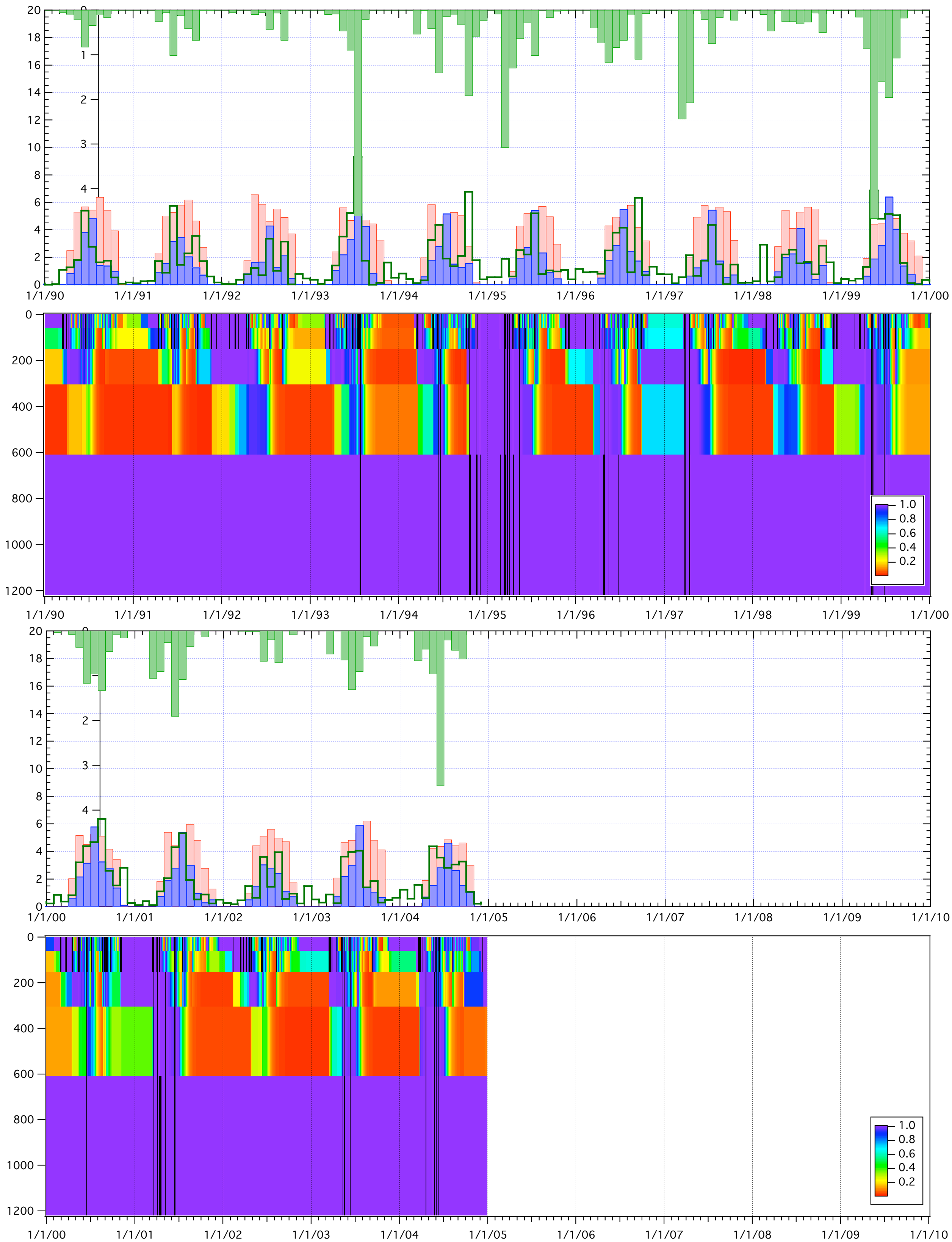


Figure 94 continued. Comparison of climate (PET and precipitation) and VB2K output of recharge and AET (upper column charts, units are inches) and soil moisture saturation with depth (lower plots, units are centimeters) over time for VB2K run drake4204s.

drake_carr93

Station	Start of Record	End of Record	max. temp.	min. temp.	precip.	snow	evap.
carrington.csv	04/24/1990	05/22/2006	Off	Off	Off	Off	On
DRAKE9NE.NCD	08/01/1964	12/31/2005	On	On	On	On	No data
RUGBY.NCD	07/01/1948	11/30/2005	On	On	On	On	No data
DRAKE.NCD	07/01/1948	07/31/1982	On	On	On	On	No data

Table 11. Climate stations used to build VB2K input climate dataset carringtonCOMP_02x093drake.daily.vb2k for VB2K model run drake_carr93.

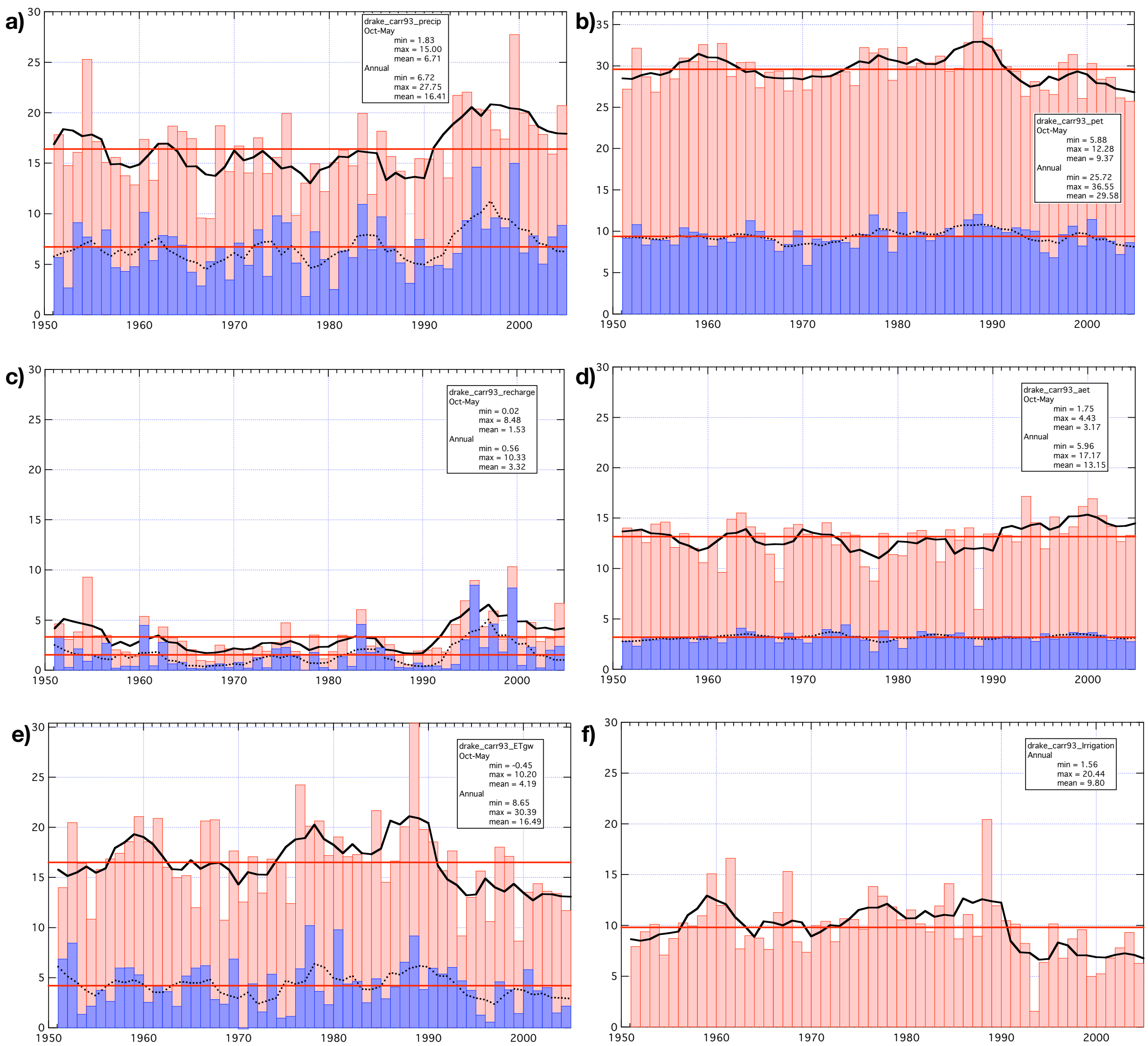


Figure 95. Plots of water-year and Oct.-May output from VB2K run drake_carr93. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

fessenden100a

Station	Start of Record	End of Record	max. temp.	min. temp.	precip.	snow	evap.
FESSENDEN.NCD	1932-01-01	2005-12-31	On	On	On	On	No data
MADDOCK.NCD	1948-07-01	2004-11-30	On	On	On	On	No data
CARRINGTON_EXP.NCD	1967-04-01	2005-12-31	On	On	On	On	On
HANSBORO.NCD	1932-01-01	2005-12-31	On	On	On	On	No data
LANGDON.NCD	1907-04-01	2005-12-31	On	On	On	On	On
BOTTINEAU.NCD	1898-03-01	2005-12-31	On	On	On	On	No data
MINOT_EXP.NCD	1905-06-01	2005-12-31	On	On	On	On	On

Table 12. Climate stations used to build VB2K input climate dataset “FESSENDENCOMP_01.daily.vb2k” for VB2K model run fessenden100a.

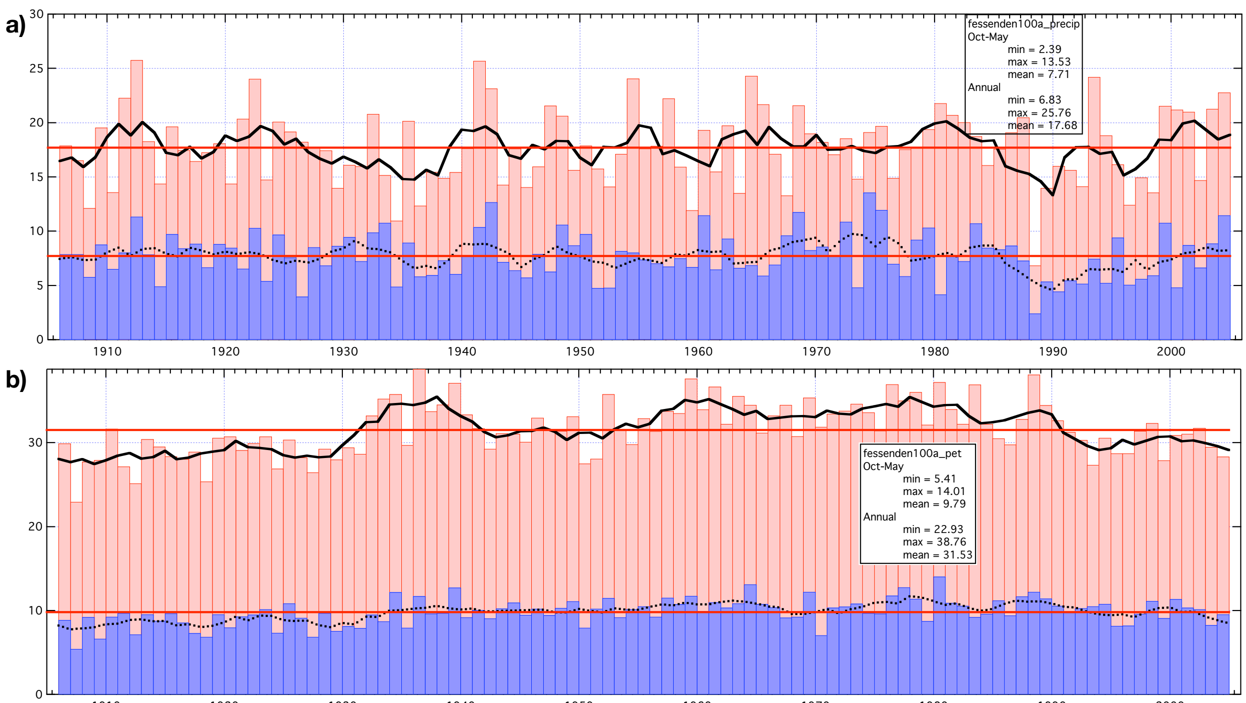


Figure 96. Long-term stress period VB2K run fessenden100a. a) precipitation, b) PET, c) recharge, d) AET, e) ETgw, and f) irrigation water use per acre. All data in inches per year.

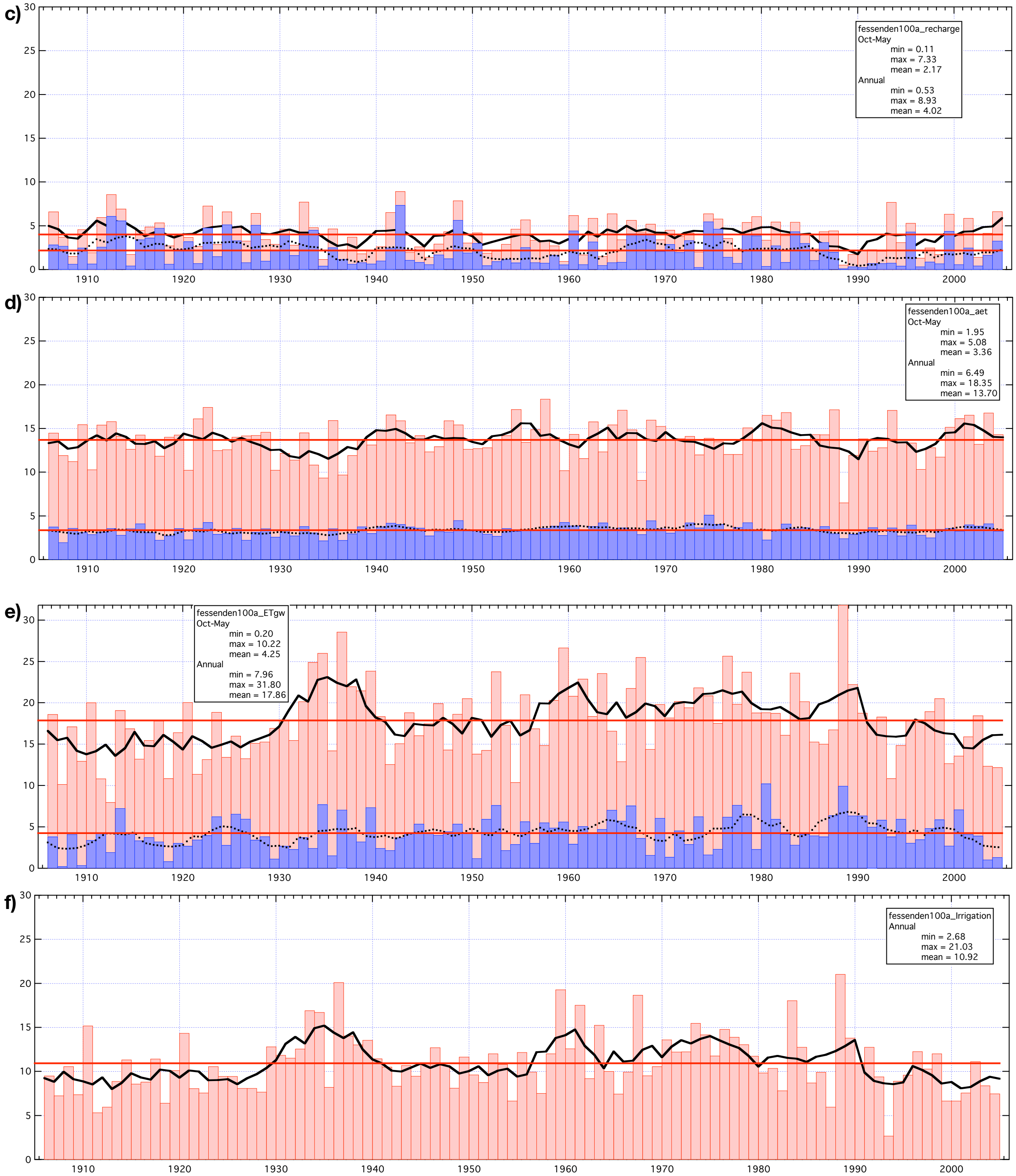


Figure 96 continued. Long-term stress period VB2K run fessenden100a. a) precipitation, b) PET, c) recharge, d) AET, e) ETgw, and f) irrigation water use per acre. All data in inches per year.

hansboro100

Station	Start of Record	End of Record	max. temp.	min. temp.	precip.	snow	evap.
HANSBORO.NCD	1932/1/1	2005/12/31	On	On	On	On	No data
LANGDON.NCD	1907/4/1	2005/12/31	On	On	On	On	On
BOTTINEAU.NCD	1904/3/1	2005/12/31	On	On	On	On	No data
MINOT_EXP.NCD	1905/6/1	2005/12/31	On	On	On	On	On

Table 13. Climate stations use to build VB2K input climate dataset “HANSBOROCOMP_01.daily.vb2k” for model run hansboro100.

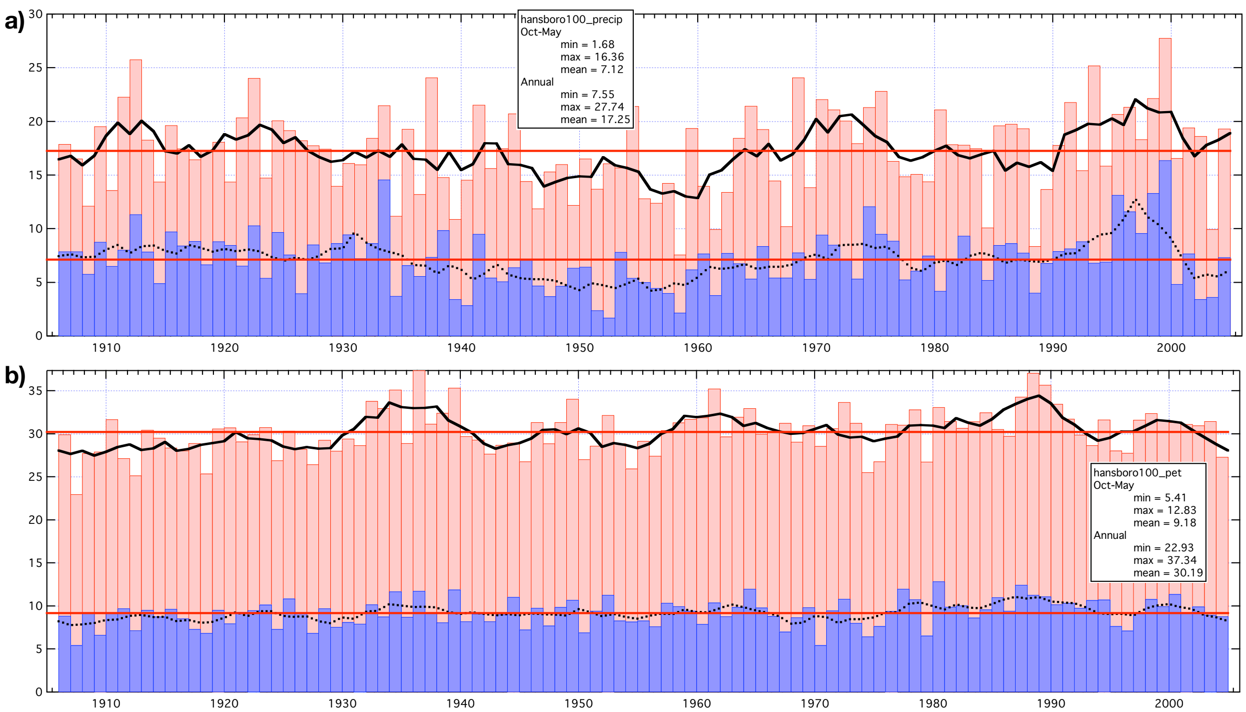


Figure 97. Long-term stress period VB2K run hansboro100. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

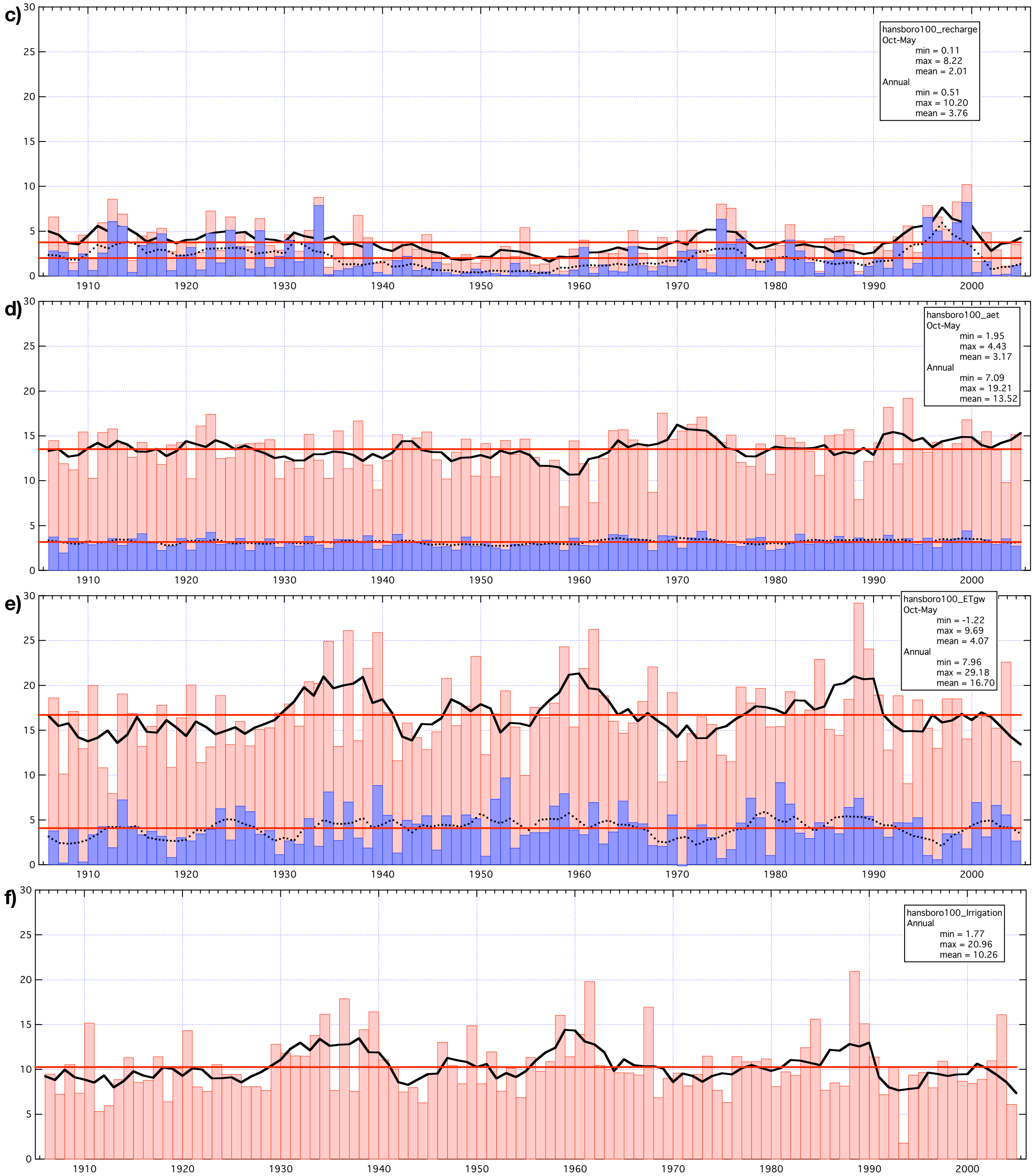


Figure 97 continued. Long-term stress period VB2K run hansboro100. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

bottineau_100

Station	Start of Record	End of Record	max. temp.	min. temp.	precip.	snow	evap.
BOTTINEAU.NCD	1904/3/1	2005/12/31	On	On	On	On	No data
MINOT_EXP.NCD	1905/6/1	2005/12/31	On	On	On	On	On

Table 14. Climate stations used to build VB2K input climate dataset “BOTTINEAUCOMP_01.daily.vb2k” for model run bottineau_100.

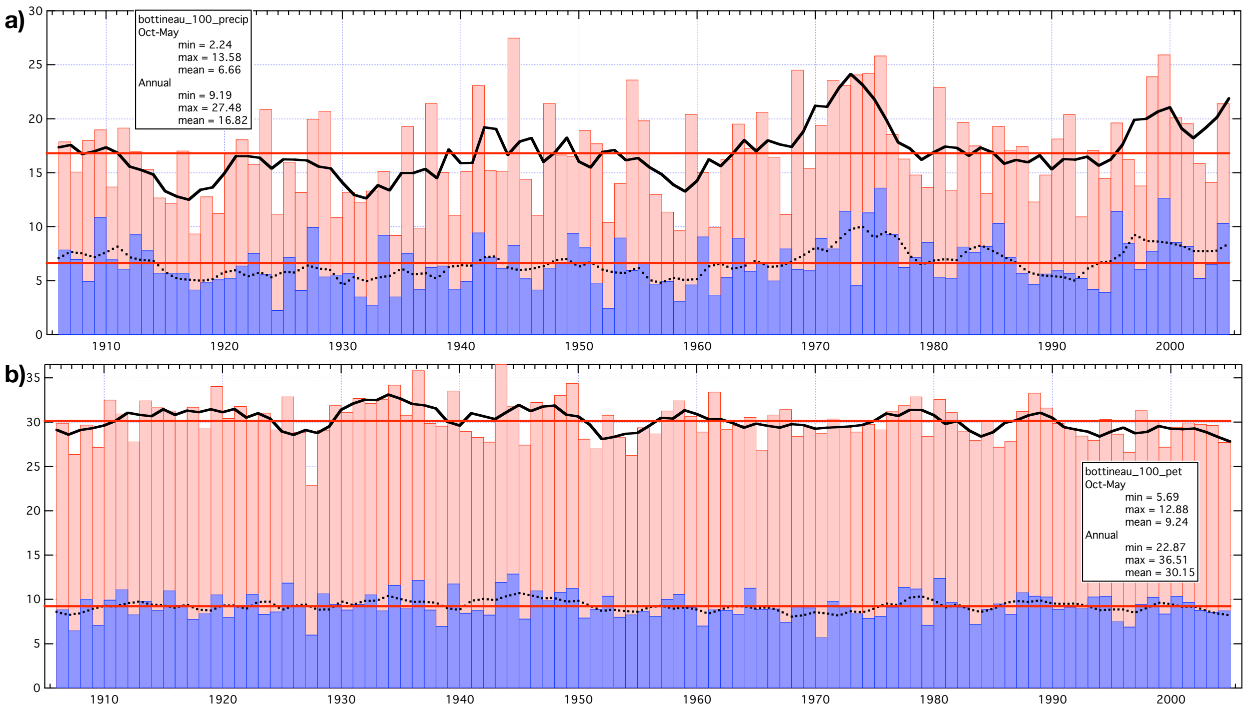


Figure 98. Long-term stress period VB2K run bottineau_100. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

Figure 98 continued. Long-term stress period VB2K run bottineau_100. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

minot100a

Station	Start of Record	End of Record	max. temp.	min. temp.	precip.	snow	evap.
MINOT_EXP.NCD	1905/6/1	2005/12/31	On	On	On	On	On
BOTTINEAU.NCD	1904/3/1	2005/12/31	On	On	On	On	No data

Table 15. Climate stations used to build VB2K climate dataset "MINOT_EXPCOMP_01.daily.vb2k" for model run minot100a.

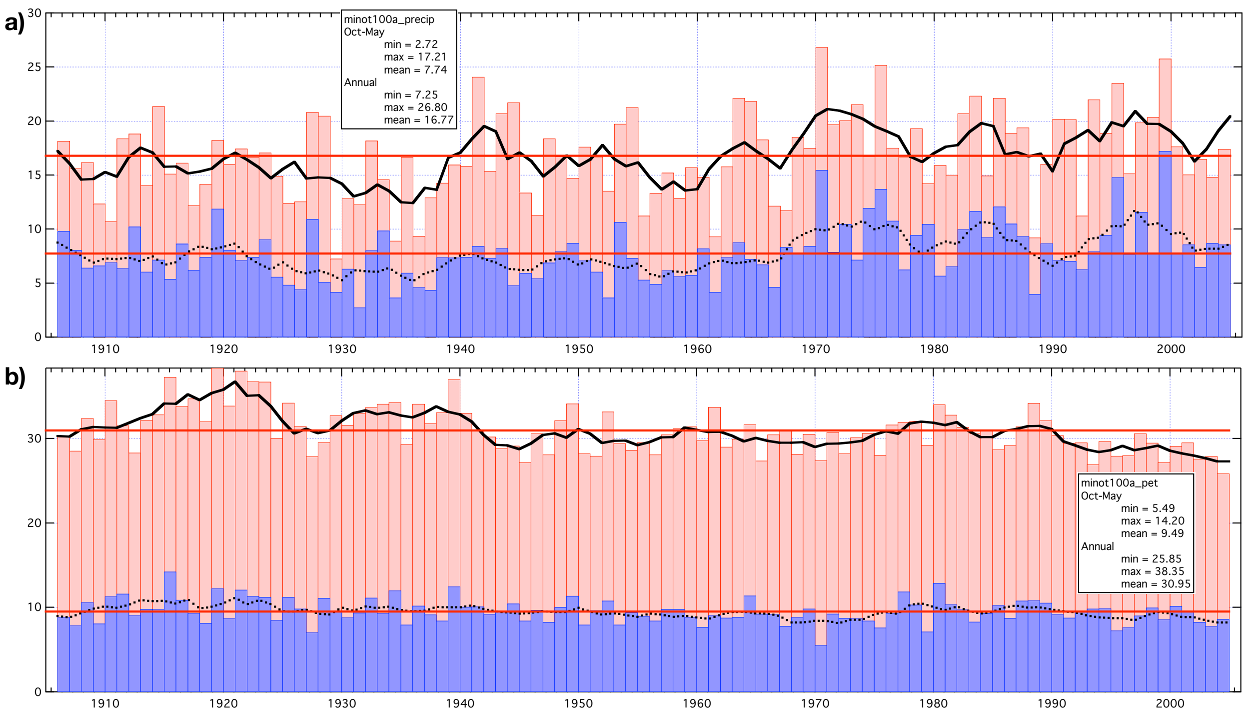


Figure 99. Long-term stress period VB2K run minot100a. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

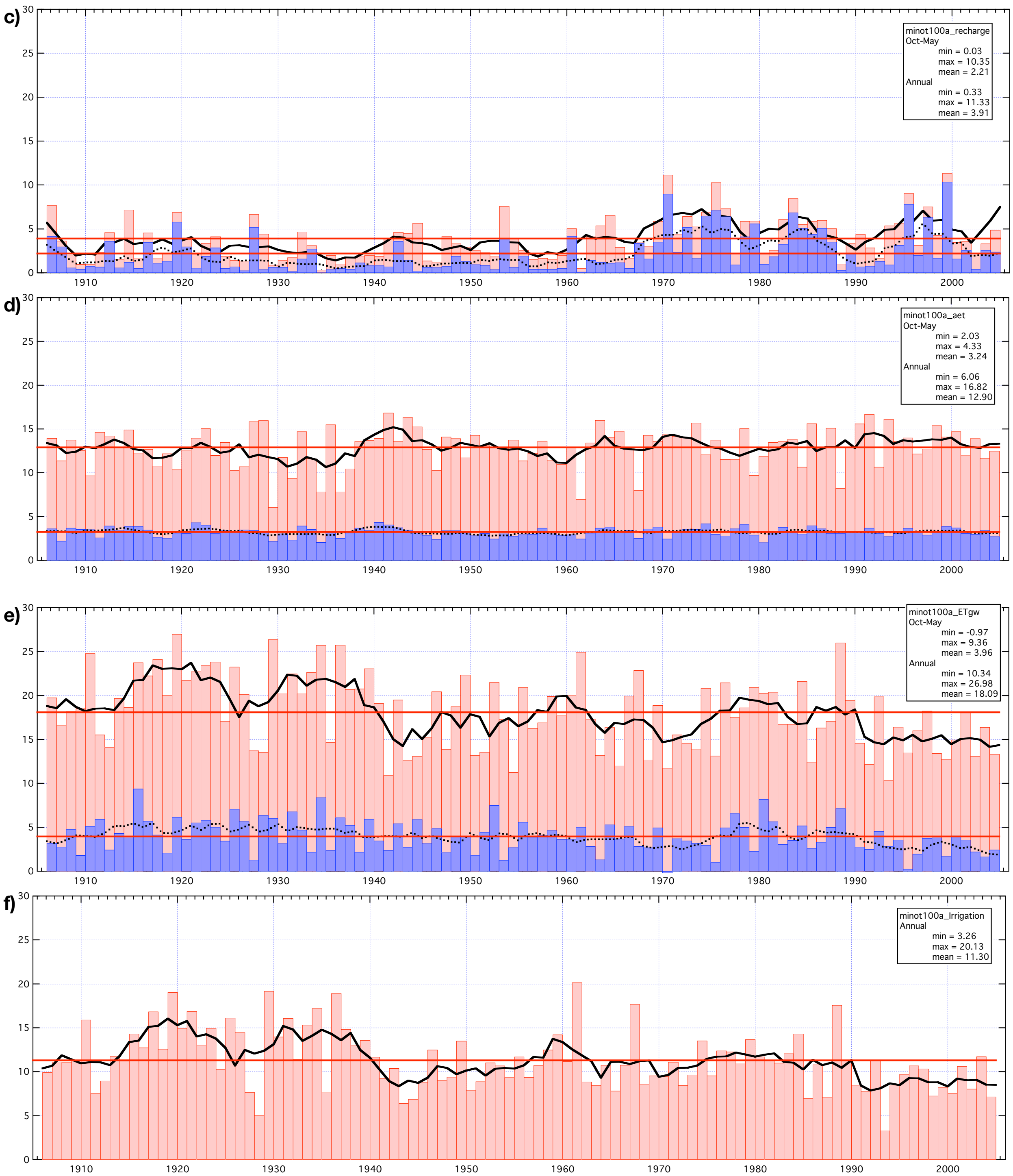


Figure 99 continued. Long-term stress period VB2K run minot100a. **a)** precipitation, **b)** PET, **c)** recharge, **d)** AET, **e)** ETgw, and **f)** irrigation water use per acre. All data in inches per year.

Simulation Dataset Comparisons

The results of the simulations are summarized in table 16. Estimates of irrigation water use for the 1950 to 2004 simulations ranges 9.68 to 10.76 inches per year. This appears reasonable, but possibly underestimated, when compared to the 1975 to 2004 average water use of 11.2 inches per year observed at Karlsruhe (fig. 42b). Figure 100 shows a comparison of the climate (precipitation and PET) and simulated recharge, PET_{gw}, and irrigation water use for the drake2198c, drake613w, drake, drake4204s, and drake2210ne VB2K model run. Further comparisons are shown in figure 101, which has the results of the simulations with the rugby, maddock, and drake2198c VB2K model run. There is significant variability of recharge and irrigation water use using the three nearest NCDC stations to determine PET. The results of the long-term simulations with Bottineau, Minot, Fessenden, and Hansboro climate datasets are compared with drake2198c VB2K model run in figure 102.

The recharge datasets used as input to MODFLOW simulations, and the associated climate datasets used in the VB2K runs to generate them, are given in tables 17 and 18.

VB2K model run	Year	Rech. Oct-May	Annual	ET_{gw} Oct-May	Annual	Irrig.	Prec. Oct-May	Annual	PET Oct-May	Annual	AET Oct-May	Annual
drake2198c	1950-2004	1.33	3.23	5.39	18.29	9.81	6.83	16.76	10.90	31.81	3.44	13.58
drake613w	1950-2004	1.24	3.33	5.52	18.14	9.70	6.61	16.99	10.89	31.81	3.40	13.71
drake	1950-2004	1.37	3.31	4.80	18.02	10.76	6.72	16.83	10.15	31.55	3.39	13.58
rugby01	1950-2004	1.92	3.80	4.80	18.00	10.76	7.32	17.49	10.20	31.79	3.36	13.74
drake2210ne	1950-2004	1.15	3.21	5.57	18.23	9.76	6.50	16.81	10.92	31.83	3.40	13.65
drake4204s	1950-2004	1.28	3.37	5.44	18.12	9.68	6.74	17.06	10.90	31.81	3.40	13.73
drake_carr93	1950-2005	1.53	3.32	4.19	16.49	9.80	6.71	16.41	9.37	29.58	3.17	13.15
fessenden100a	1906-2005	2.17	4.02	4.25	17.86	10.92	7.71	17.68	9.79	31.53	3.36	13.70
hansboro100	1906-2005	2.01	3.76	4.07	16.70	10.26	7.12	17.25	9.18	30.19	3.17	13.52
bottimeau_100	1906-2005	1.47	3.34	4.05	16.67	10.24	6.66	16.82	9.24	30.15	3.28	13.51
minot100a	1906-2005	2.21	3.91	3.96	18.09	11.30	7.74	16.77	9.49	30.95	3.24	12.90

Table 16. Comparison of climate, recharge, and ETgw from VB2K runs used in ground-water flow simulations. All units are inches. Rech. = Recharge, Irrig. = Irrigation, and Prec. = Precipitation.

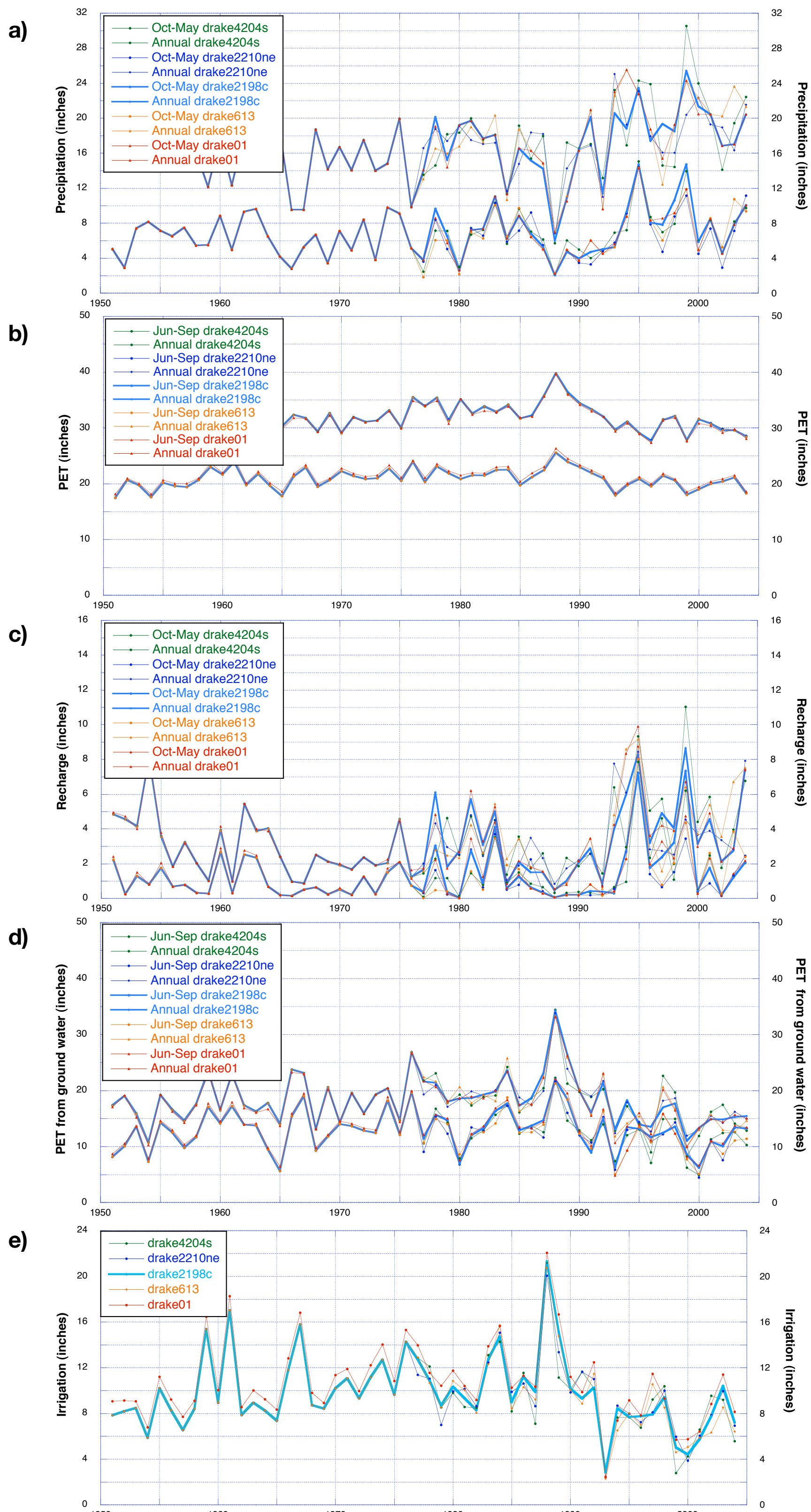


Figure 100. Comparison of **a)** precipitation, **b)** PET, **c)** recharge, **d)** PET from groundwater, and **e)** irrigation water use for VB2K model runs generated with Drake 9NE NCDC composite and ARB composite climate datasets.

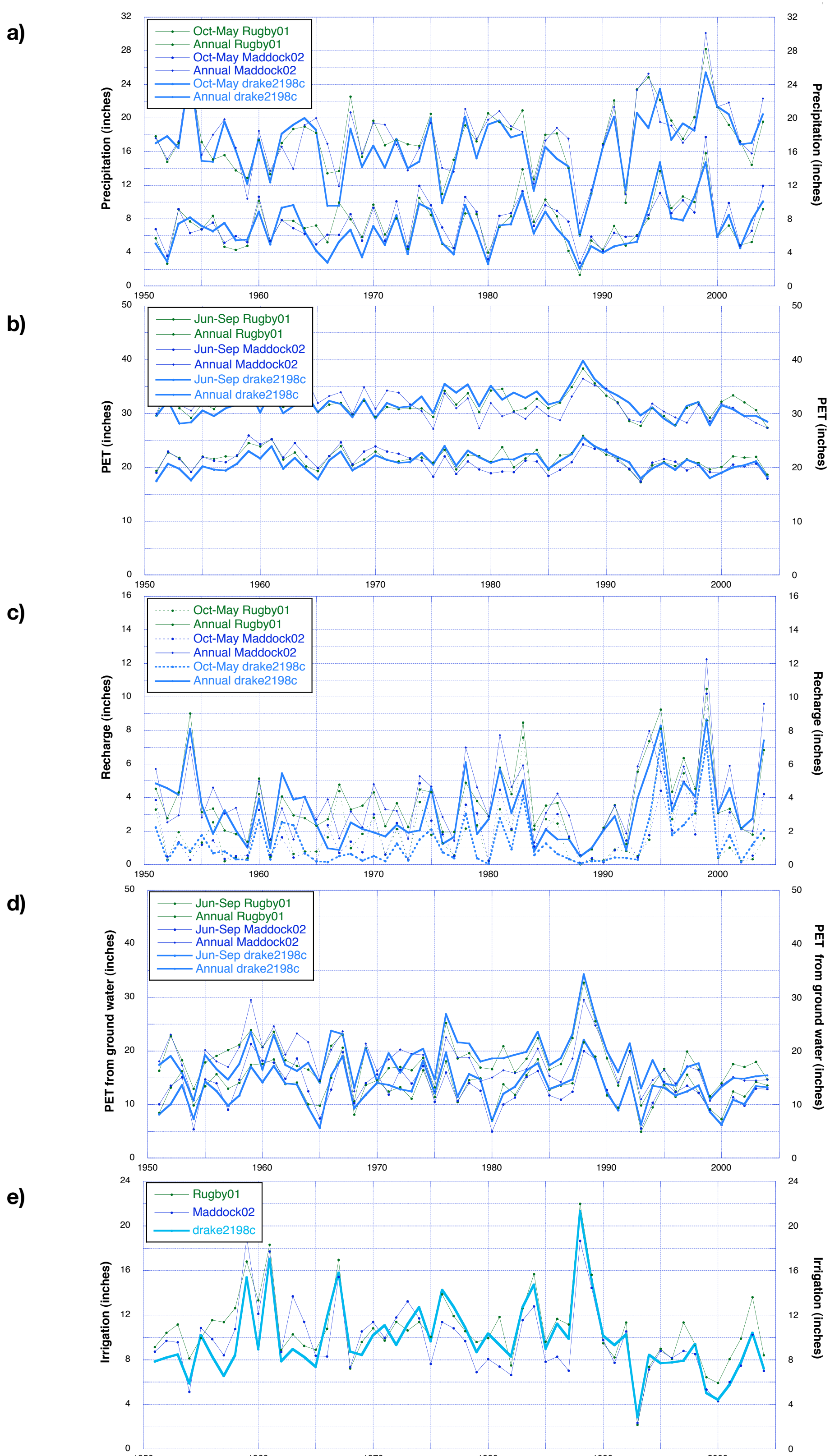


Figure 101. Comparison of **a)** precipitation, **b)** PET, **c)** recharge, **d)** PET from groundwater, and **e)** irrigation water use from VB2K model runs rugby01, maddock02, and drake2198c.

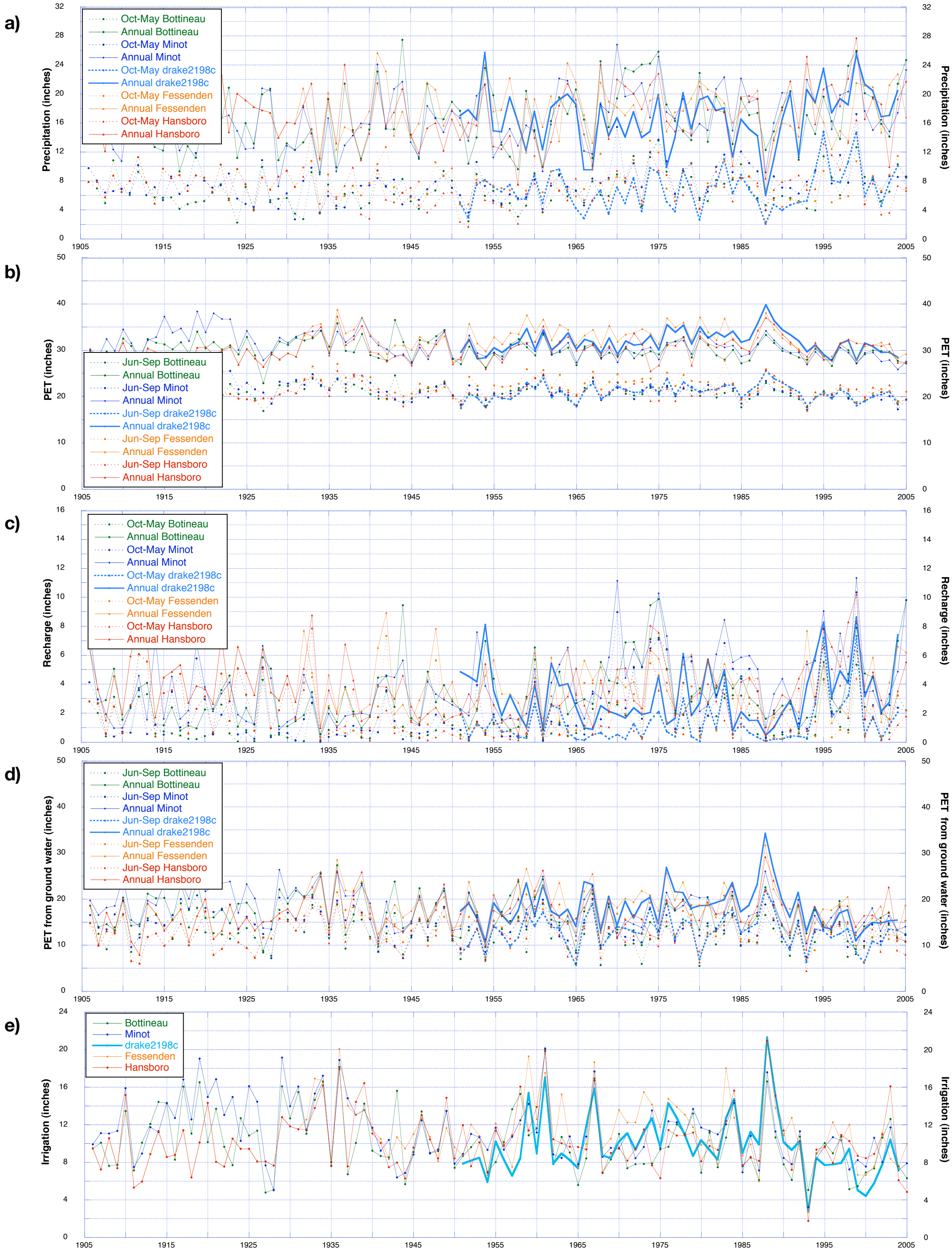


Figure 102. Comparison of **a)** precipitation, **b)** PET, **c)** recharge, **d)** PET from groundwater, and **e)** irrigation water use from VB2K model runs bottineau_100, minot100a, drake2198c, fessenden100a, and hansboro100a.

The VB2K output files containing monthly total recharge, ETgw, and irrigation water use were used to generate the numerical model input data for recharge, ET, and wells, respectively. Table 17 lists VB2K output files of monthly data (_ _ _ _.monthly) and the VB2K climate input files (_ _ _ _ .daily.vb2k) used in the model calibration runs. Table 18 shows the files for the 100-year simulations.

RECHARGE DATA (from VB2K)	/modeling/trappersCoulee/climate/dataSets02/ monthlyData/	
bottineau05_f03.monthly	BOTTINEACOMP_01.daily.vb2k	
drake2198c_f03.monthly	arb2198_15307129_1977_1992COMP_02COMP_01.daily.vb2k	
drake2210ne_f03.monthly	arb2210_15306905_1983_1989COMP_01COMP_01.daily.vb2k	
drake4204s_f03.monthly	arb4204_15107031_2001_2004COMP_01COMP_01.daily.vb2k	
drake613_f03.monthly	arb613_15407226_1986_1994COMP_01COMP_01.daily.vb2k	
drake_f03.monthly	drake_arb958_COMP_01.daily.vb2k	
hansboro_f03.monthly	HANSBOROCOMP_02.daily.vb2k	
langdon_f03.monthly	LANGDONCOMP_01.daily.vb2k	
maddock02_f03.monthly	maddock_arb958_COMP_02.daily.vb2k	
minot_f03.monthly	MINOTEXPCOMP_01.daily.vb2k	
rugby01_f03.monthly	rugby_arb958_COMP_01.daily.vb2k	

Table 17. Table shows the name of the recharge dataset (recharge, ETgw, and irrigation water use) used as input to MODFLOW simulations and the associated climatic dataset that was used in the VB2K run.

RECHARGE DATA (from VB2K)	/modeling/trappersCoulee/recharge2006/	
bottineau_100-2005.monthly	BOTTINEAUCOMP_01.daily.vb2k	
drake-carr93-093carr-2005.monthly	carringtonCOMP_02x093drake.daily.vb2k	
fessenden100a-2006.monthly	FESSENDENCOMP_01.daily.vb2k	
hansboro100-2006.monthly	HANSBOROCOMP_01.daily.vb2k	
minot100a-2006.monthly	MINOT_EXPCOMP_01.daily.vb2k	

Table 18. Table shows the name of the recharge dataset (recharge, ETgw, and irrigation water use) used as input to MODFLOW simulations and the associated climatic dataset that was used in the VB2K run.

Simulation of Ground-Water Flow

Numerical Model

Because of the hydrologic complexity of the Trappers Coulee aquifer and the large percentage of the inflow to the aquifer already appropriated, it was necessary to develop a numerical model of the aquifer using MODFLOW to evaluate the effects of the proposed pumping. MODFLOW is a numerical model that simulates flow in three dimensions by solving a finite-difference approximation of the partial differential equations describing ground-water flow through porous media. The model solves a budget of the aquifer routing water between specified source (recharge) and sinks (evapotranspiration, spring flow, and wells) based on the hydraulic properties specified for the aquifer.

MODFLOW is a finite-difference ground-water flow model developed by the U.S. Geological Survey. The version used for this study was MODFLOW-2000 (MF2K) version 16. MF2K is documented in Harbaugh and others (2000). The solvers PCG2 and GMG are documented in Hill (1990) and Wilson and Naff (2004), respectively. The stream package SFR1 and lake package LAK are documented in Prudic and others (2004) and Merritt and Konikow (2000). It was compiled from source code using the IBM xlf v8.1 compiler to run on an Apple Macintosh Computer running OS 10.4.x operating system. Pre- and post-processing of model data was done using ArcView 3.2a, Surfer 8.0, and Igor 5.0.

A flow chart of the modeling process is shown in figure 103.

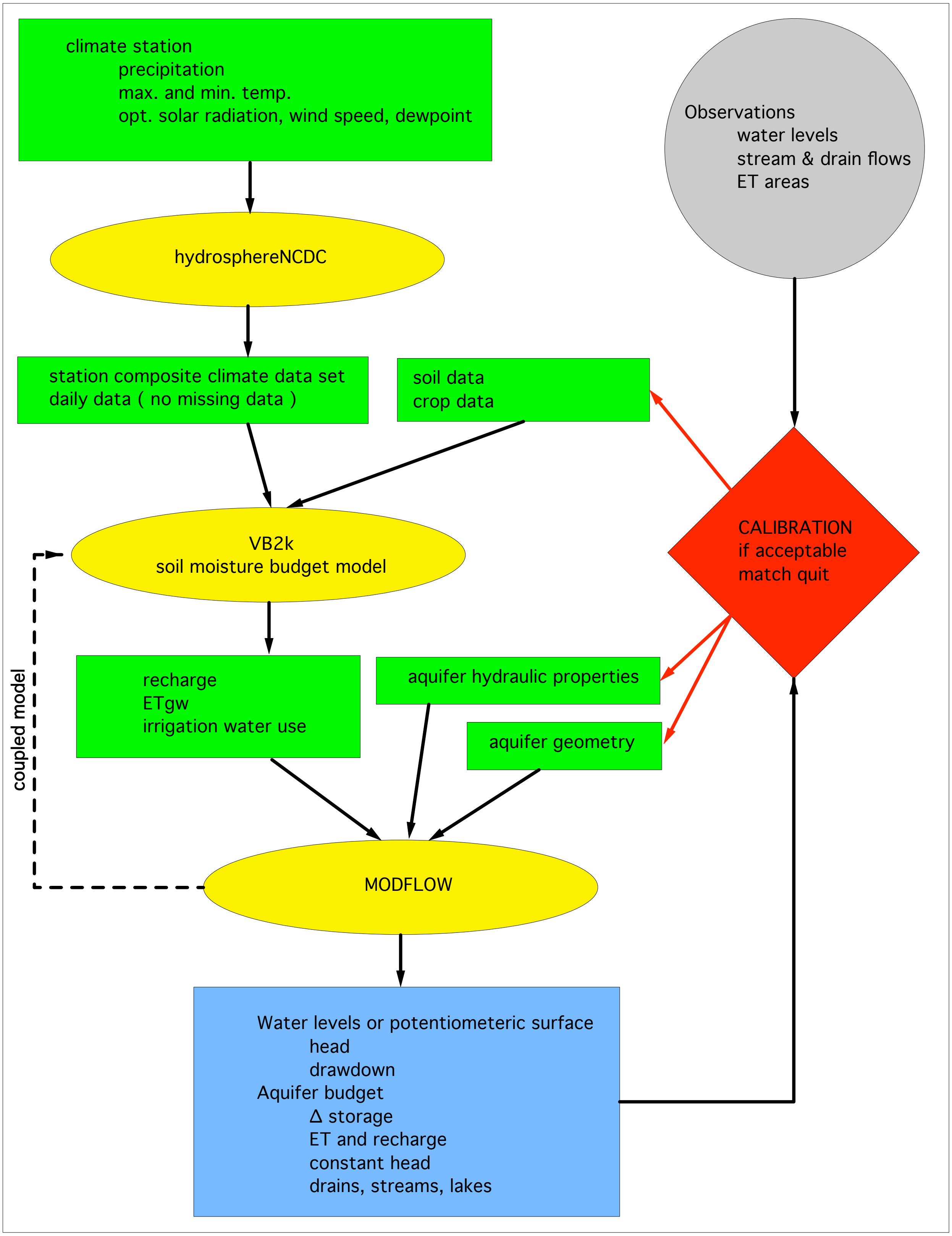


Figure 103. Flow chart of modeling process showing input and output.

Model Discretization and Boundaries

The hydrogeologic features simulated in the model are the Trappers Coulee meltwater channel, the outwash plain to the north of the meltwater channel, and the Fox Hills Formation into which the meltwater channel is incised (fig. 104). Surface water features included in the simulation are Trappers Coulee and Long Lake. The extent and orientation of the model grid are shown in figure 104. The model consists of 158 rows, 282 columns, and 3 layers. The active grid for layer 1 is shown in figure 105. This layer includes Long Lake and its associated outwash. The active nodes in layer 2 include the Trappers Coulee meltwater channel, the associated outwash plain and the Fox Hills aquifer. Except for the southeast end of the model, the model boundary is assumed to be a ground-water divide in the Fox Hills aquifer based on surface topography (fig. 106). The active Layer 3 initially had the same extent as layer 2 and represented the Fox Hills aquifer. It was set inactive to avoid severe instability issues in the model.

ZONEBUDGET (Harbaugh, 1990) is used to analyze the model output. The budget zones for layers 1 and 2 are shown in figures 107 and 108 respectively.

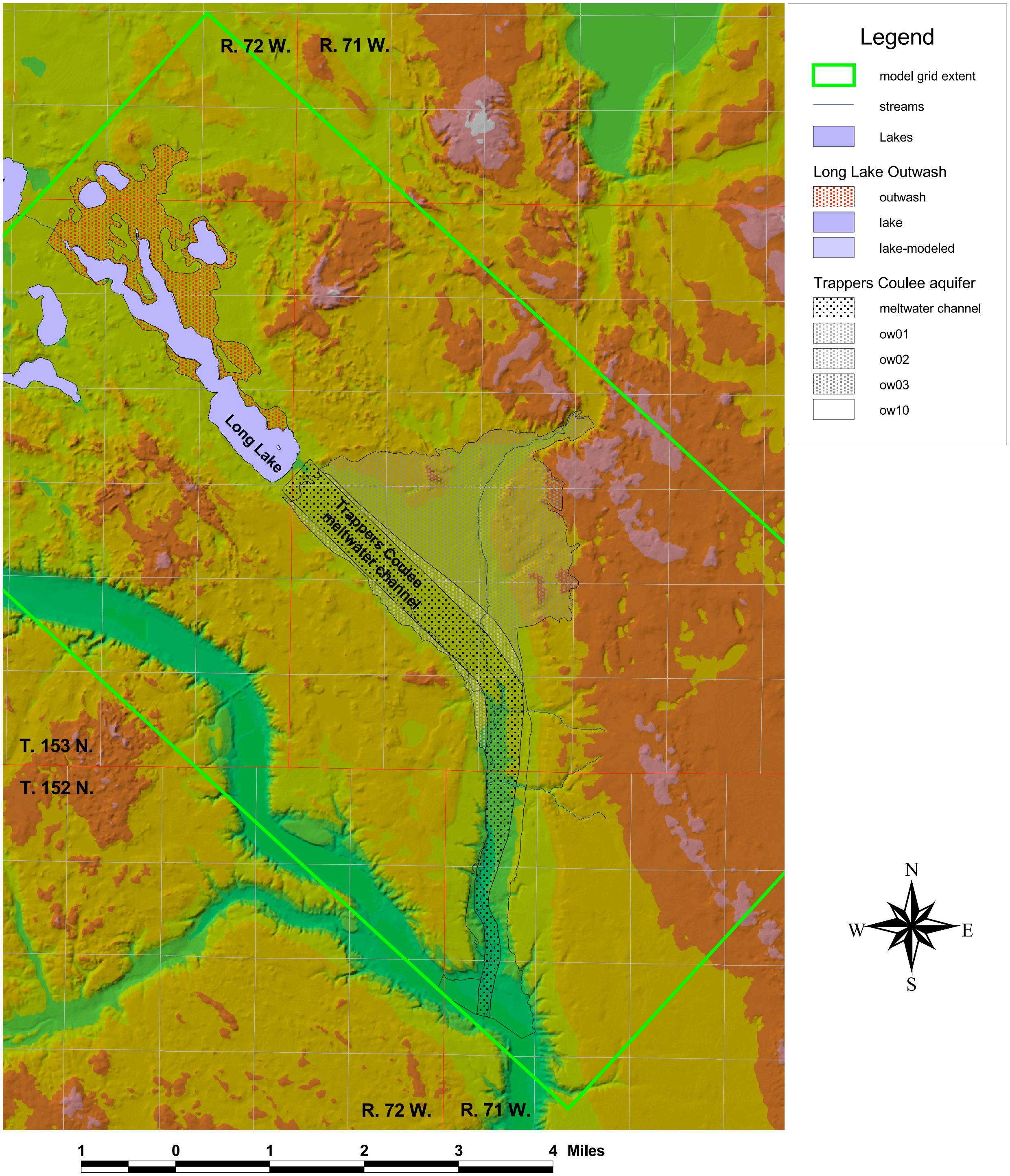


Figure 104. Location of outwash and surface hydrology simulated in Trappers Coulee model.

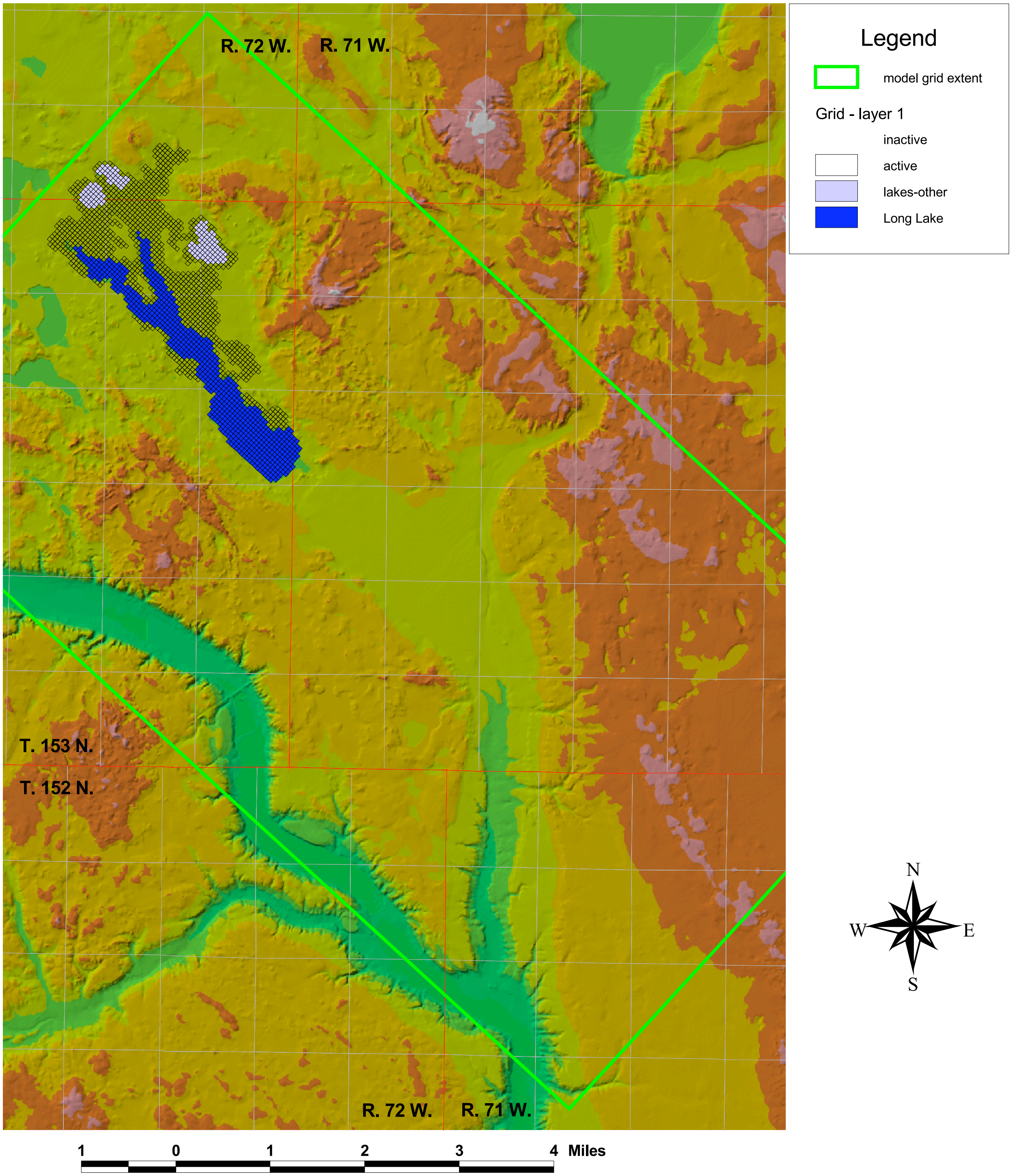


Figure 105. Layer 1 active grid.

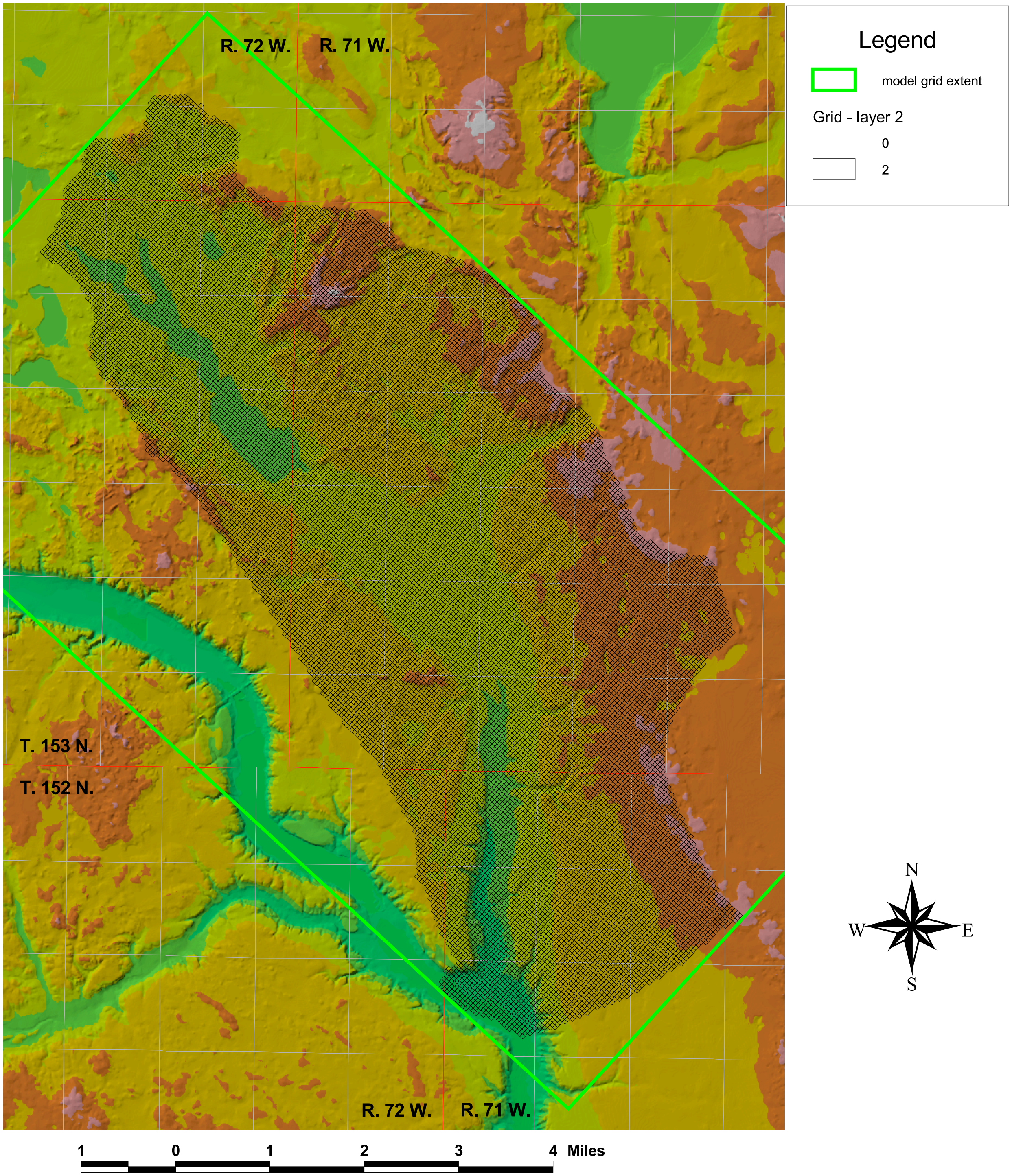


Figure 106. Layer 2 active grid.

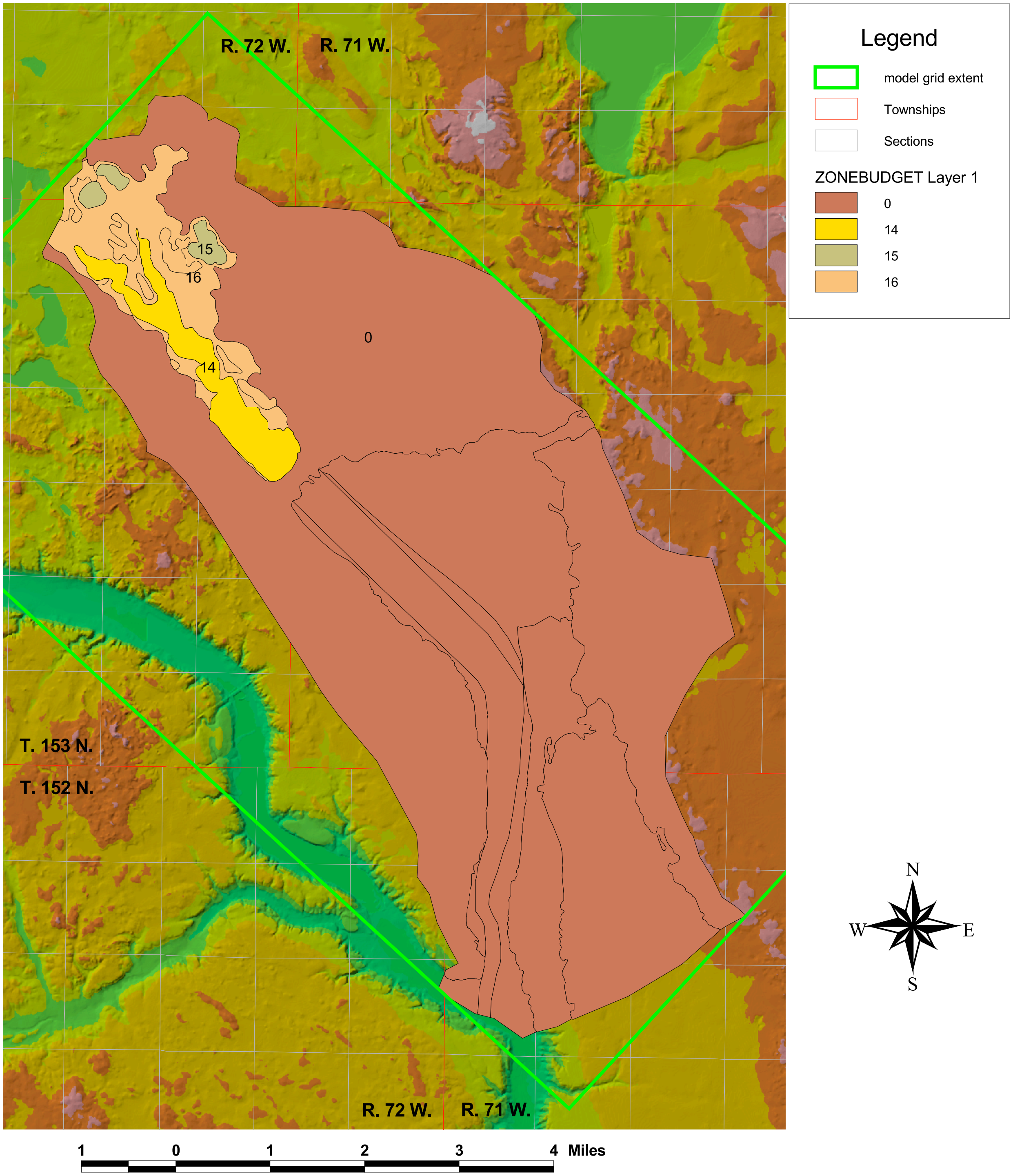


Figure 107. Layer 1 budget zones used by ZONEBUDGET. File “esmond/model02outwash/GRID10/zone_budget/arcview/ZBDG001_tc10_v01a.shp”.

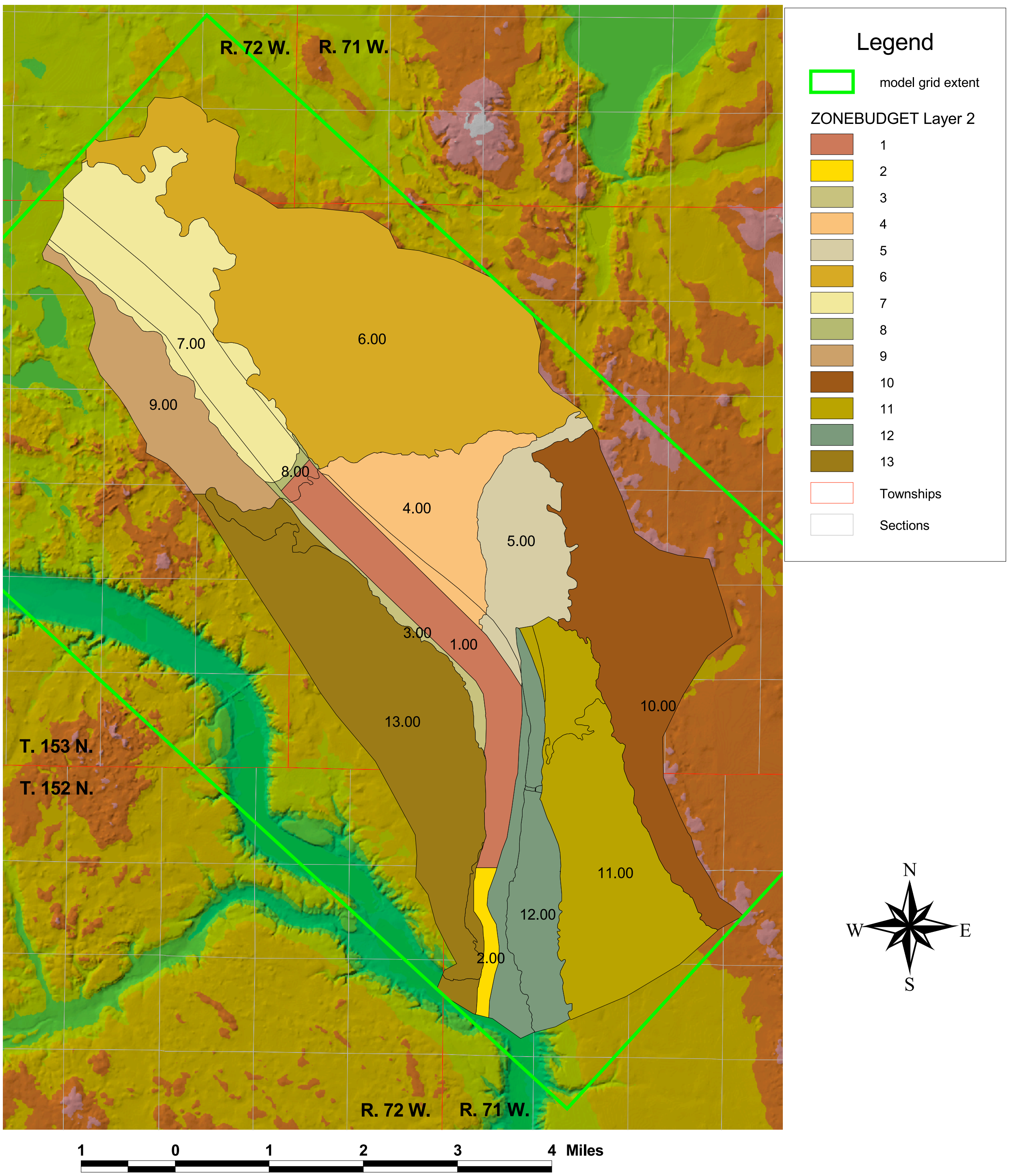


Figure 108. Layer 2 budget zones used by ZONEBUDGET. File “esmond/model02outwash/GRID10/zone_budget/arcview/ZBDG002_tc10_v01.shp”.

Model Parameters

Parameter Zones

Hydraulic parameters for each layer in the model may be represented as either continuously varying surfaces or as a set of zones, each with a unique value. This model of the Trappers Coulee aquifer represents hydraulic conductivity and recharge variability using zones. A set of parameter zones was also developed for each layer (figs. 109 and 110). These zones are based on soil parent material, topography, and test drilling. The zones were developed prior to determining the layer structure of the model. In the final model, layer 1 only included the area around Long Lake and the Esmond aquifer. Therefore, most of the zones shown in figure 109 are irrelevant to the model. Various combinations of these zones are used to define a hydraulic property zone. This allows rapid assignment of hydraulic properties to a facies or other hydrogeologic unit and the creation of the MODFLOW data values array. "c0" is the meltwater channel, "ow__" are outwash zones associated with the meltwater channel, "es__" is the esmond aquifer, and "fh__" is the Fox Hills aquifer.

Hydraulic Conductivity

Hydraulic conductivity for layers 1 and 2 are shown respectively in figures 111 and 112. The initial model included the outwash on the north side of the meltwater channel in layer 1 and the upper part of the meltwater channel in layer 1. A stable solution could never be achieved. Trying to do this was plagued with several issues. The saturated zone in the outwash is thin and many of the nodes may go dry requiring use of the WETDRY flow package option. Because the water level elevation in the meltwater channel is lower than the bottom of the outwash, steep water table gradients may exist in nodes along the boundary between the meltwater channel and the aquifer. These problems are exacerbated by the very large changes in hydraulic conductivity that occur when water levels in the model oscillate between layer 1, composed of outwash with a large hydraulic conductivity, and the underlying Fox Hills Formation of layer 2, with its smaller hydraulic conductivity. This is further compounded by the thin outwash near Trappers Coulee where additional highly nonlinear conditions are introduced into the model by the drain package used to simulate Trappers Coulee and the ET package (Mehl, 2006). Except near Trappers Coulee, there is little discharge from the outwash by ET. Recharge entering the outwash area either flows laterally in the outwash in a thin saturated zone or leaks into the underlying Fox Hills aquifer where it flows laterally to either the meltwater channel or the vicinity of Trappers Coulee. The meltwater channel and outwash were removed from layer 1 by making the cells inactive. The outwash area was approximated by assigning a large hydraulic conductivity (5 feet per day) to the Fox Hills aquifer in layer 2 where it underlies the outwash. Figures 113 through 115 show different versions of the hydraulic conductivity zonation that were used for layer 2.

Storage Coefficient

A specific yield of 0.22 was used for all active grid cells in the transient simulations. Specific storage was set to 0.000020.

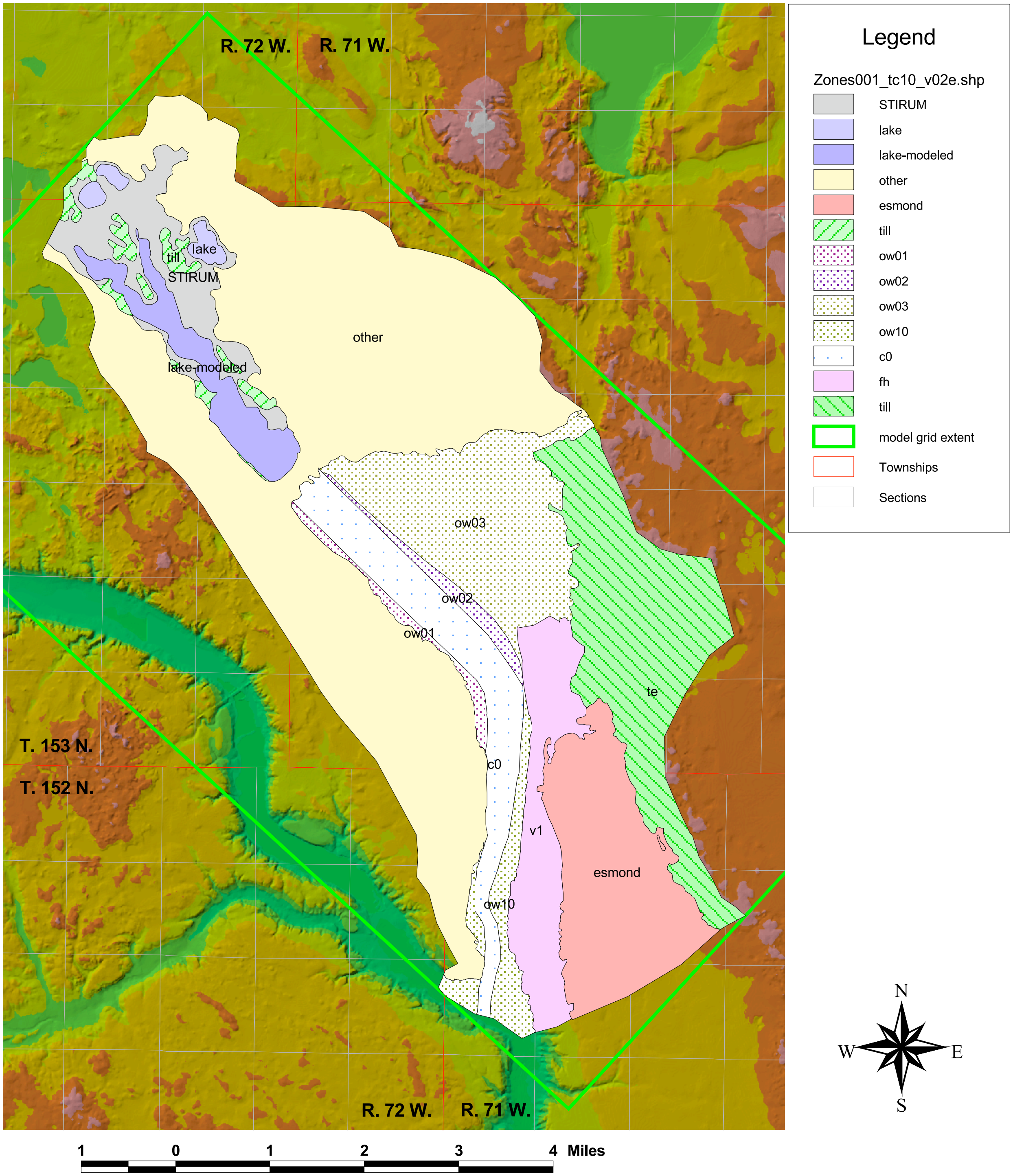


Figure 109. Layer 1 hydraulic property zones. Different combinations of property zones were used to assign various hydraulic properties or multipliers to arrays. File "esmond/model02outwash/GRID10/zone/zones/zones001_tc10_v02e.shp".

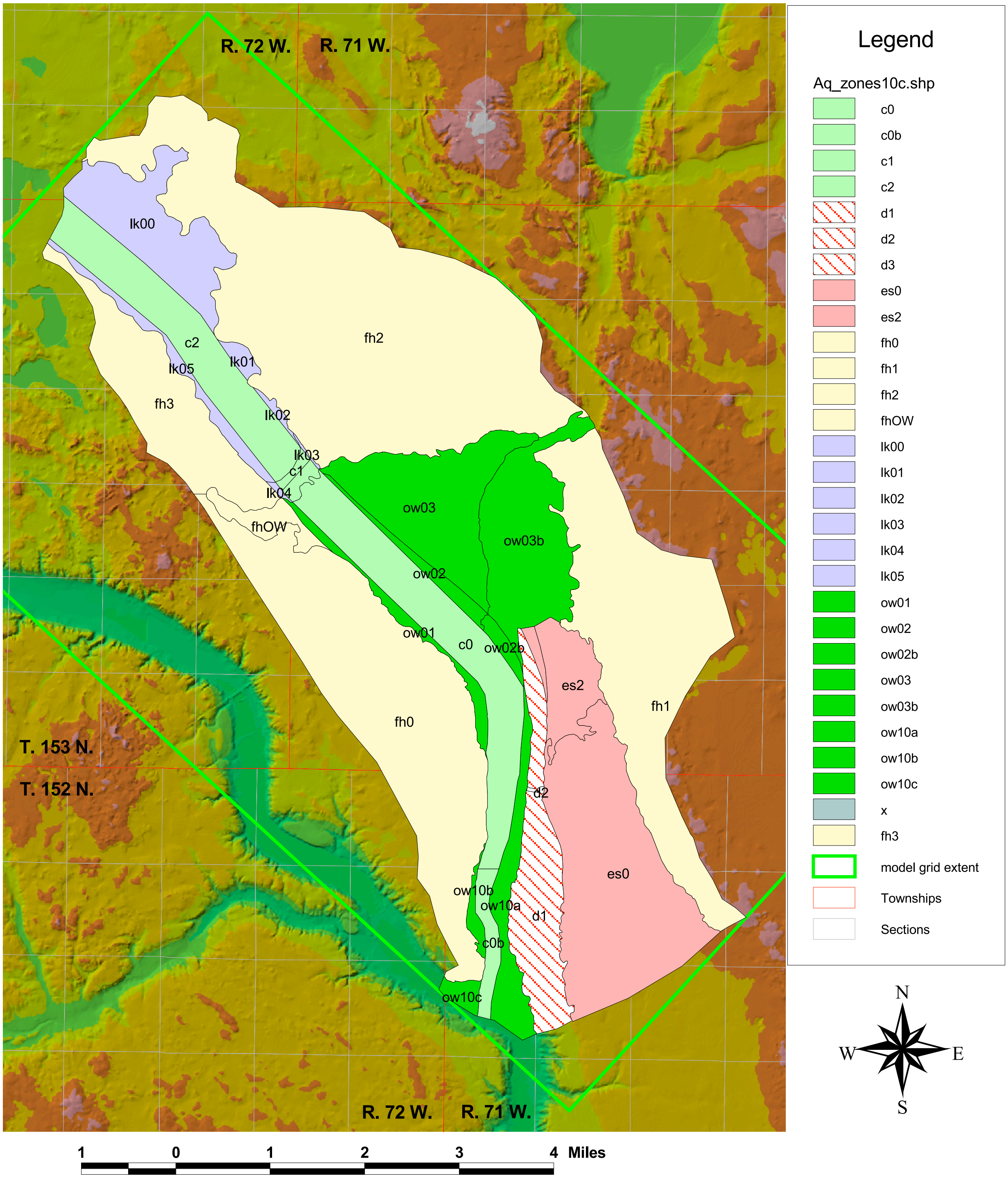


Figure 110. Layer 2 hydraulic property zones. Different combinations of property zones were used to assign various hydraulic properties or multipliers to arrays. File “esmond/model02outwash/GRID10/zone/zones/aq_zones10c.shp”.

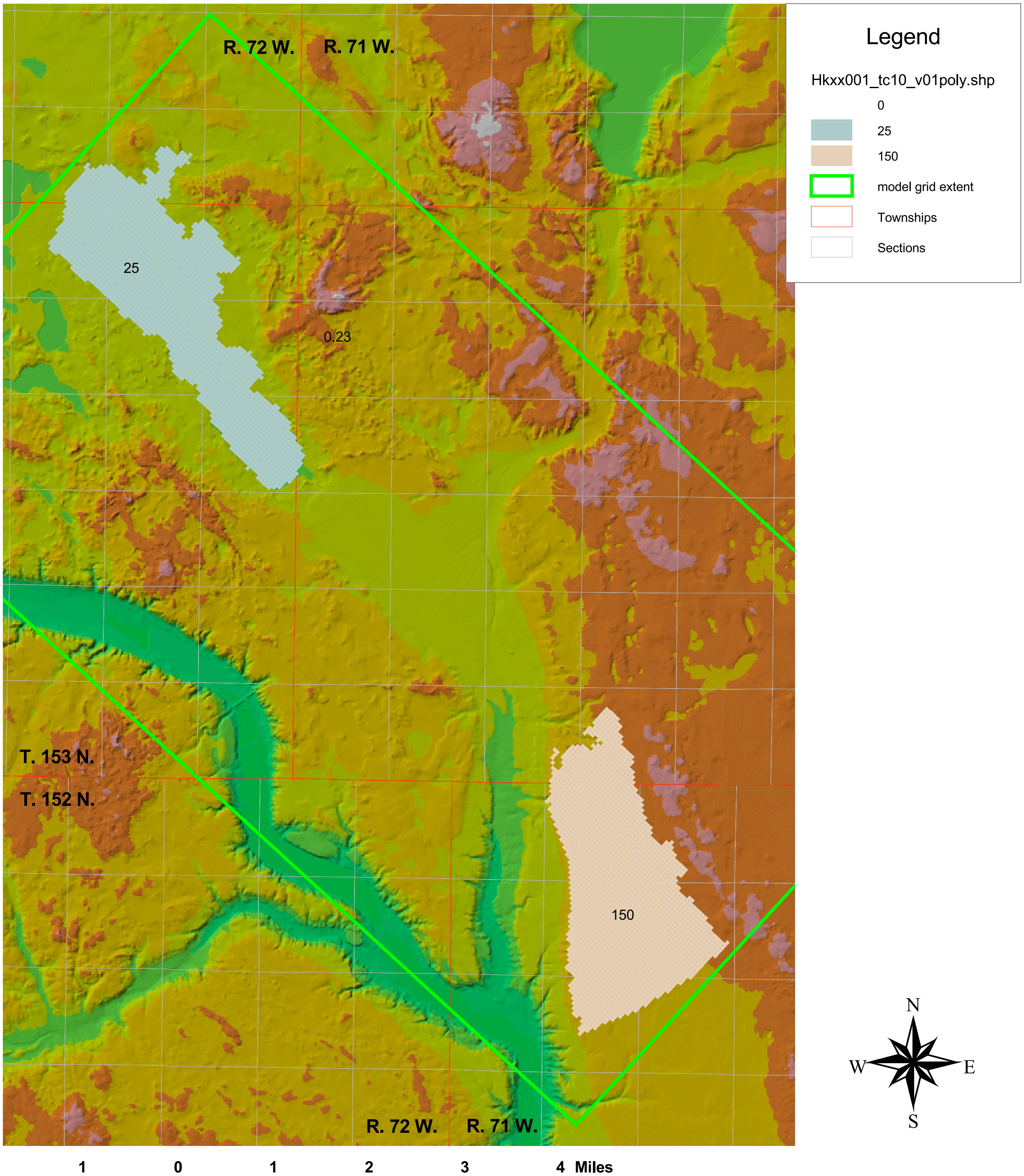


Figure 111. Layer 1 hydraulic conductivity (feet per day) for GRID10. File "Volumes/G5data2/esmond/model02outwash/GRID10/hy/HKxx001_tc10_v01.mf".

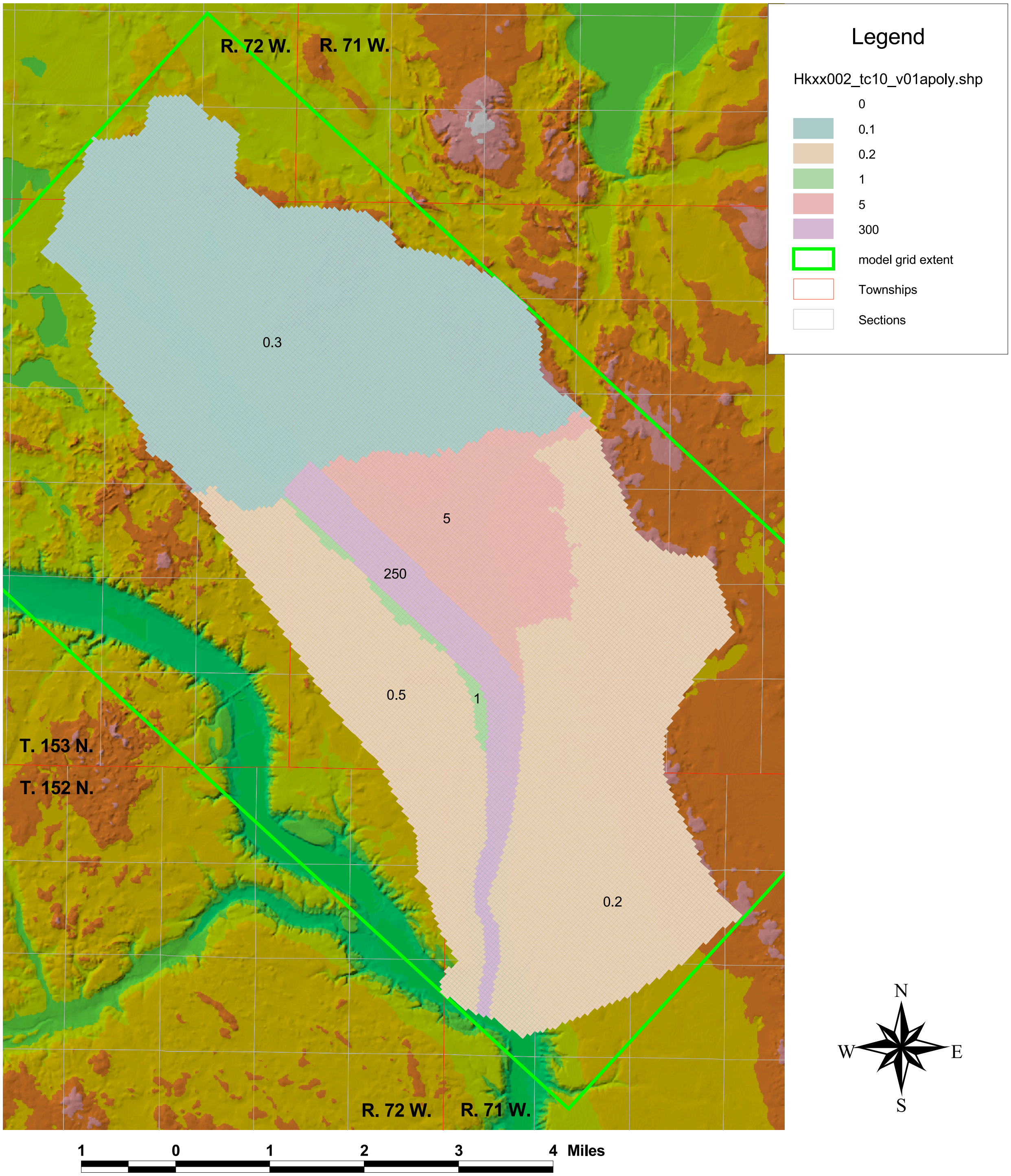


Figure 112. Layer 2 hydraulic conductivity (feet per day) for GRID10. File “Volumes/G5data2/esmond/model02outwash/GRID10/hy/HKxx002_tc10_v01a.mf”.

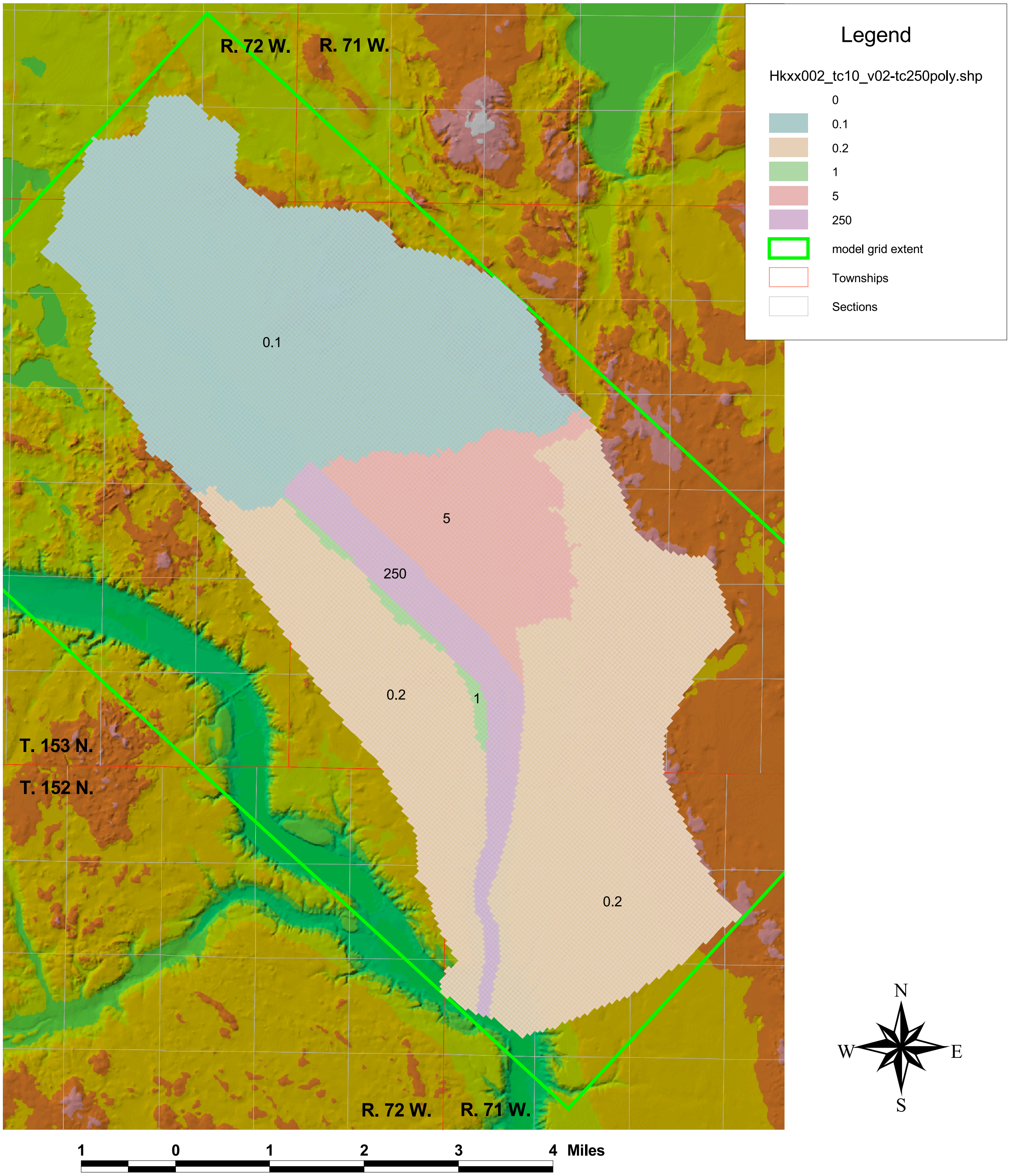


Figure 113. Layer 2 hydraulic conductivity (feet per day) for GRID10. File "Volumes/G5data2/esmond/model02outwash/GRID10/hy/HKxx002_tc10_v02-tc250.mf".

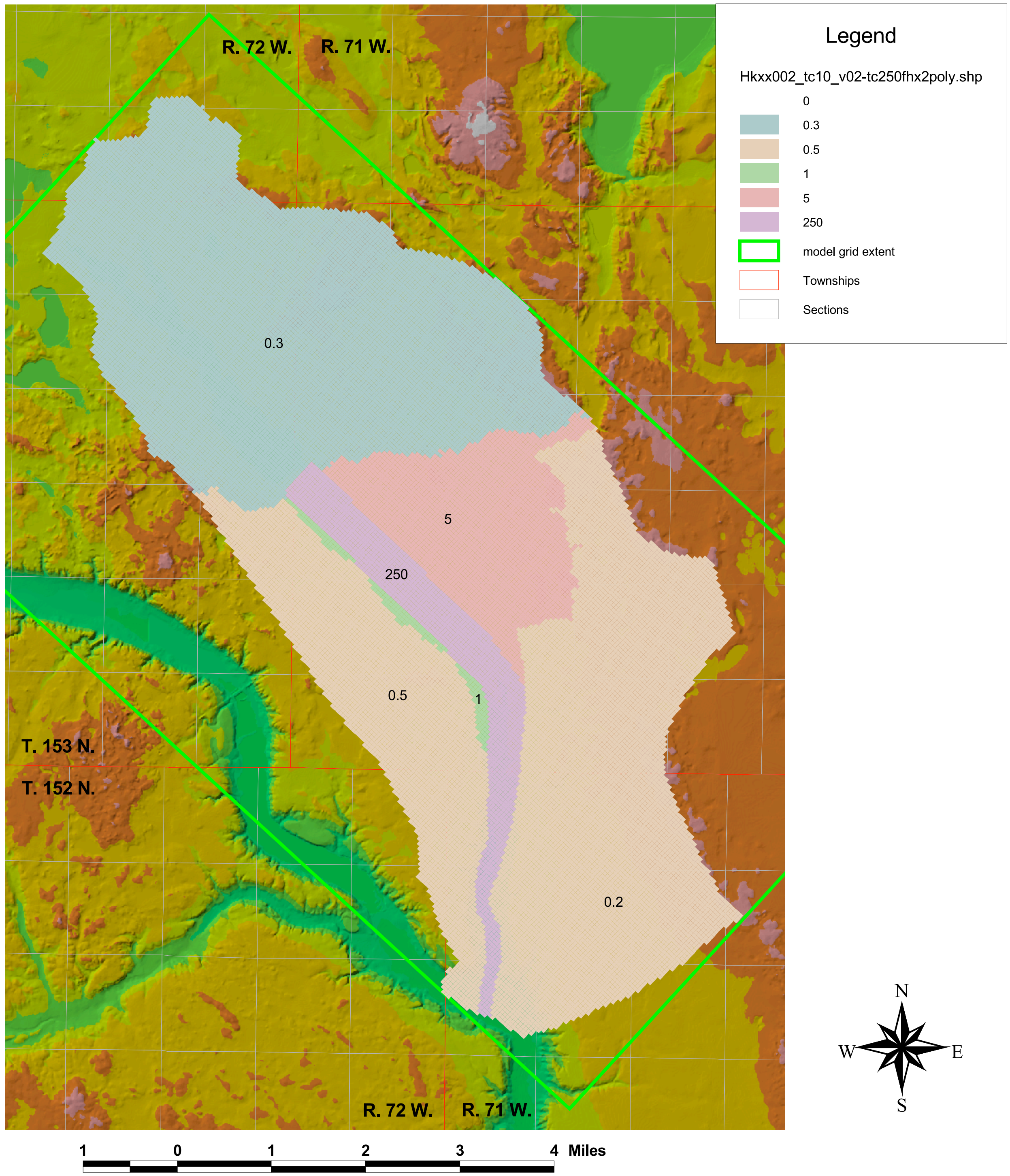


Figure 114. Layer 2 hydraulic conductivity (feet per day) for GRID10. File "Volumes/G5data2/esmond/model02outwash/GRID10/hy/HKxx002_tc10_v02-tc250fhx2.mf".

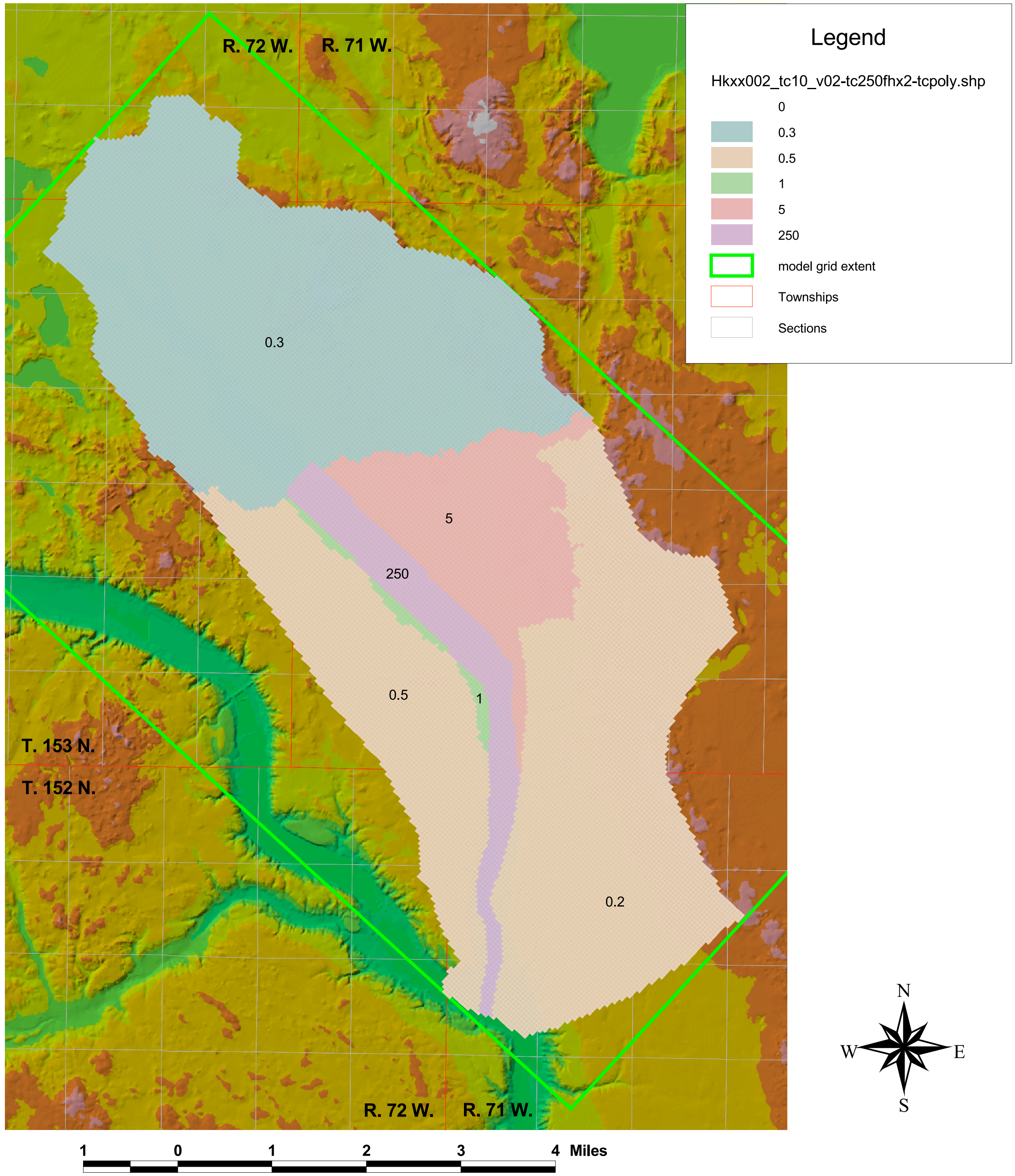


Figure 115. Layer 2 hydraulic conductivity (feet per day) for GRID10. File "Volumes/G5data2/esmond/model02outwash/GRID10/hy/HKxx002_tc10_v02-tc250fhx2-tc.mf".

Model Stress

Evapotranspiration

Land surface data for the ET package (EVT) was generated from USGS 10-meter DEMs. Elevations in the DEMs were to the nearest foot. The ArcView 3 Spatial Analyst command “Summarize by Zone” was used to determine the maximum and minimum elevation, and range of elevation in each model cell. The maximum elevation was used to generate the land surface array. The extinction depth was set to the elevation range plus 4 feet to account for root depth plus capillary rise. In the steady-state simulations an ET rate of 29 inches per year was used. For transient simulations, PET (ETgw from VB2K) for each monthly stress period is from the recharge dataset generated by VB2K.

Streams and Lakes

Initially it was attempted to simulate Long Lake using the lake package. Under normal to wet conditions, Long Lake discharges to the lake to the northwest, which then discharges by stream flow to the southwest. It became apparent that the Trappers Coulee aquifer did not extend under Long Lake and ground-water discharge was not the main component of inflow into the lake. The lake was then simulated using constant head nodes (fig. 116).

Trappers Coulee and its tributaries were digitized from USGS 7.5” DRGs (stream shown in fig. 104). Elevations were assigned where it crossed an elevation contour. Head water and tributary junction elevations were estimated. Stream width and streambed conductance values were assigned to each point with an elevation. A combination of ArcView 3 and a custom Python script were then used to generate the drain package. The length of the stream segment within a node was calculated, conductance and width of the stream in the node were interpolated from the data and the node conductance was calculated. The average stream elevation in the node was also calculated. The location and elevation of the drain nodes used to represent Trappers Coulee and its tributaries are shown in figure 117.

Recharge

The recharge multiplier array is shown in figure 118. Areas of outwash are assigned a multiplier of 1.0. This includes the areas of Fox Hills aquifer overlain by outwash north of the meltwater channel and by the Esmond aquifer. The areas of Fox Hills aquifer overlain by till were considered to have 23 percent of the recharge of the Fordville soils developed on outwash.

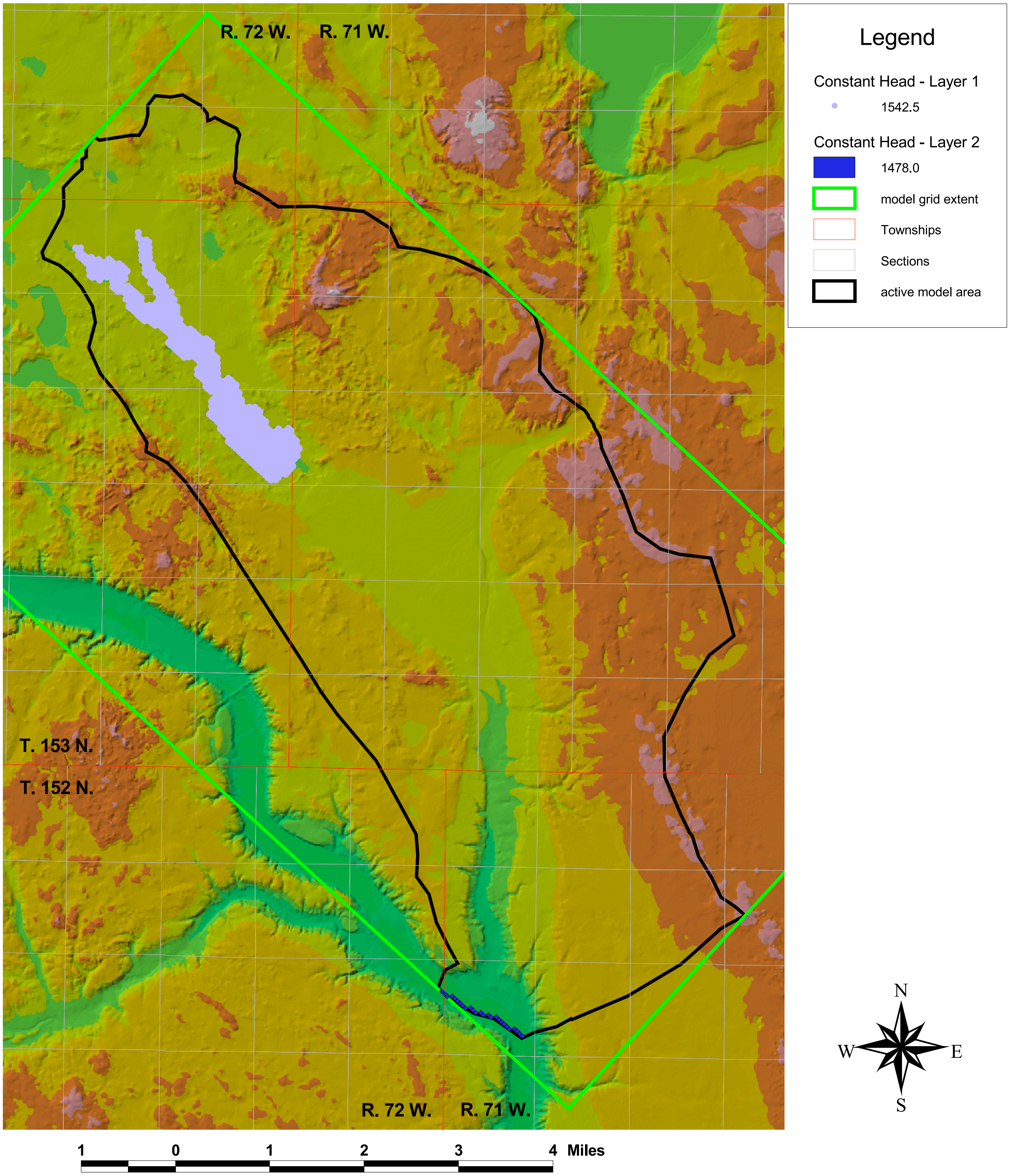


Figure 116 Location of constant head nodes used to simulate Long Lake and Sheyenne River.

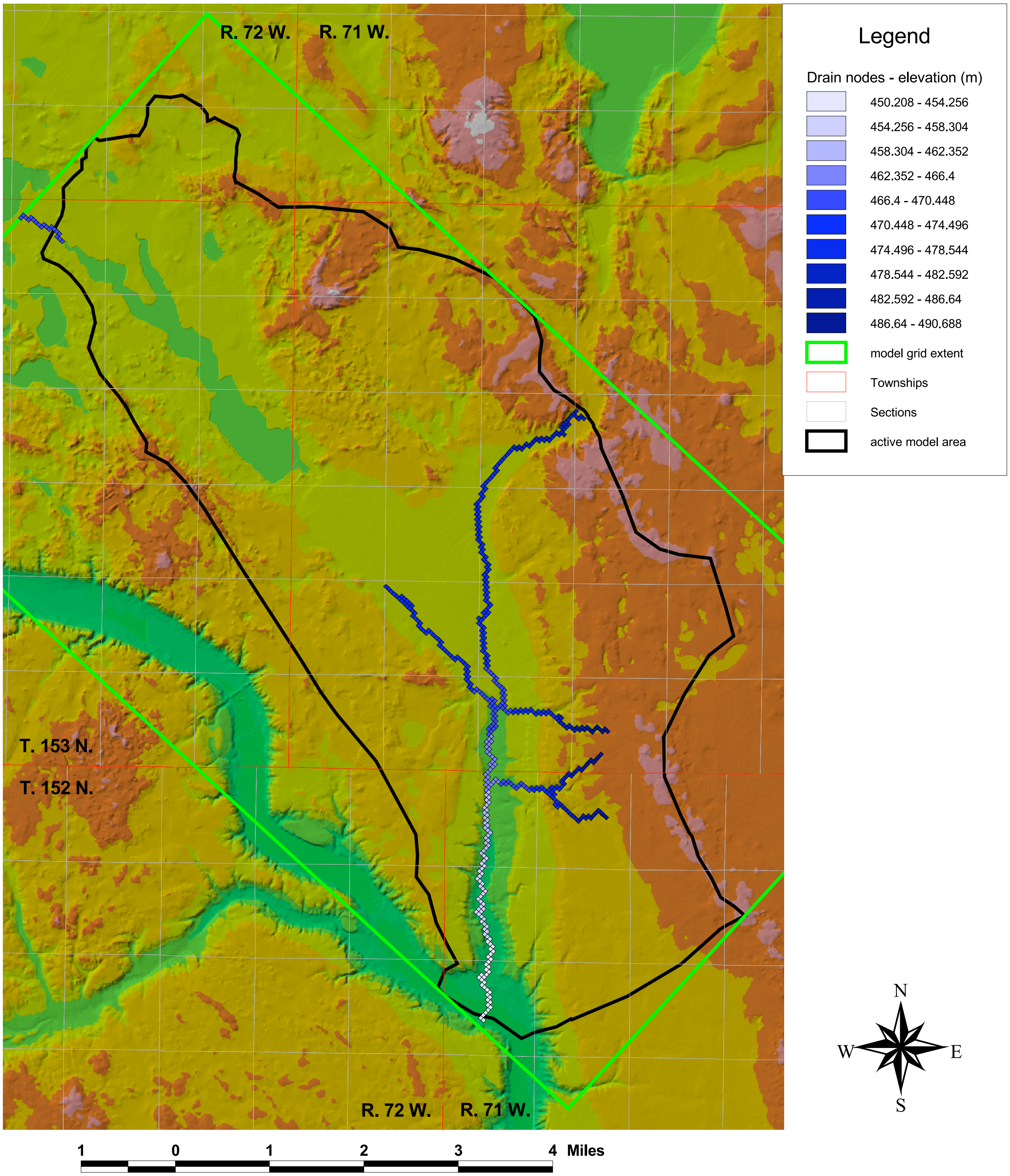


Figure 117 Location of drain package nodes used to simulate aquifer discharge to Trappers Coulee. Drain nodes were assigned to all model nodes from digitized streams. Those drain nodes outside the active model nodes are inactive.

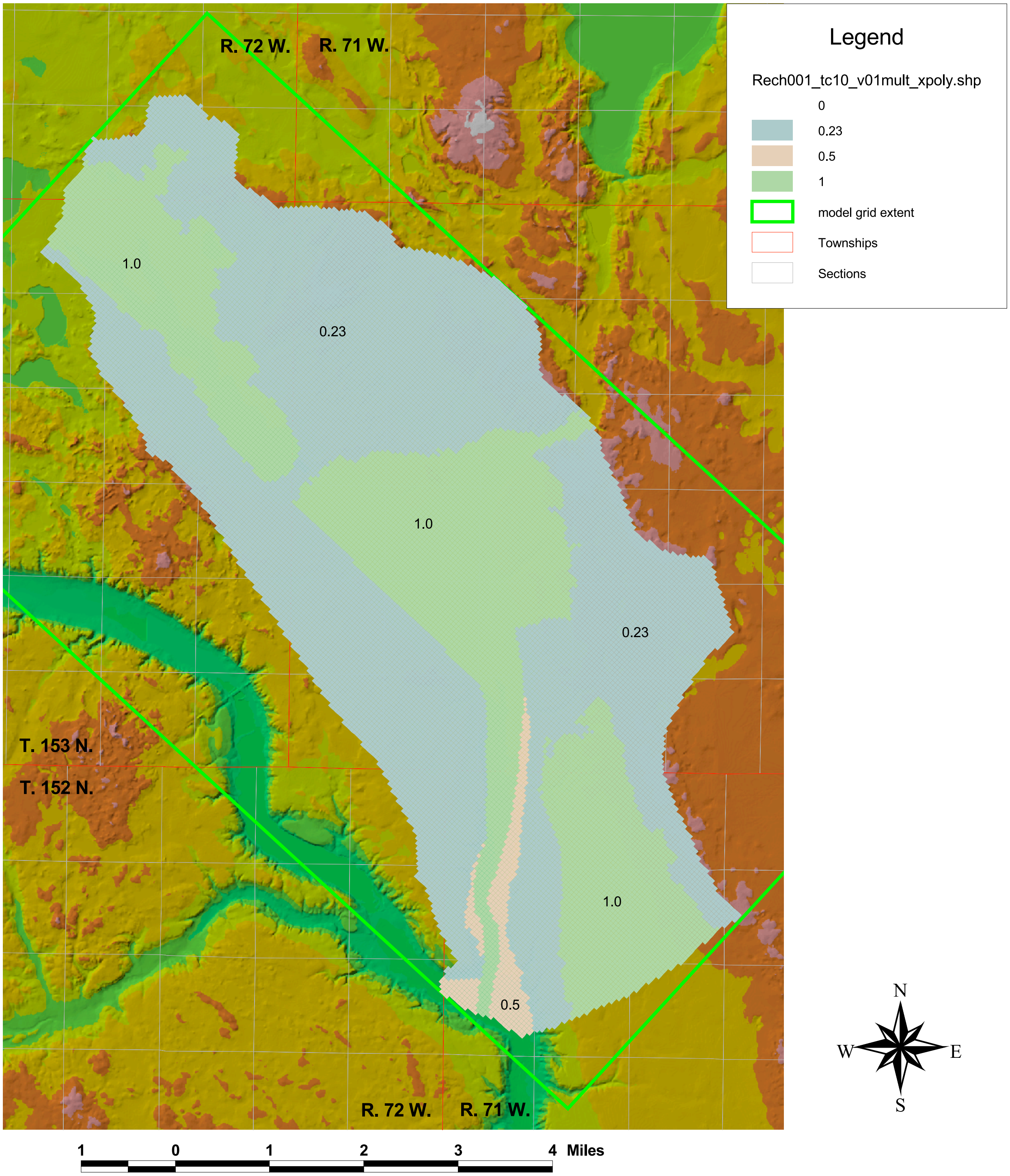


Figure 118. Recharge multiplier array. File "/esmond/model02outwash/GRID10/run_tc10B21_INPUT/input/arcviewMf/RECH001_tc10_v01mult_XPOLY.shp"

Model Calibration

Steady-State Simulation

Steady-state simulation run B21hh was considered an acceptable match to observations. A contour map of simulated water table elevations is shown in figure 119. Observed to simulated water levels are compared for 11/25/1981 (table 19), 12/07/1998 (table 20), and 12/07/2004 (table 21). The water table gradient is too steep in the UTC aquifer in this simulation. A solution to this would be to increase the hydraulic conductivity of the aquifer and this is supported by the specific capacity data for the three irrigation wells. Prior to the recent pluvial, the gradient in the UTC aquifer is not known, but would be expected to be flatter than the present gradient. Though providing a better match to the observed water table gradient, the problem is that increasing the hydraulic conductivity lowers the water table in the upper reach of the aquifer unacceptably. Reducing the width of the channel at the elbow between the UTC and LTC aquifer (fig. 115) helped by increasing water levels in the UTC, but did not eliminate the problem. As can be seen with the present Buffalo Coulee and Sheyenne River valleys, there can be significant changes in channel cross-sectional area over short distances. This issue of cross-sectional area of the meltwater channel is complicated by the simulation of the cross-section as a rectangle. If the aquifer were simulated as being incised into impermeable material, then the bottom of the cross-section could be varied by adjusting the bottom elevation of the nodes given a sufficiently fine node spacing to resolve the channel. To simulate a V-shaped, U-shaped, or more complex geometry of the channel incised into the Fox Hills, there are two options. The first is to use many layers. Besides the greatly increased complexity and computational requirements, if the water table fluctuates across layers, then WETDRY option must be used, which decreases stability, particularly under transient conditions. The other option is to use the Hydrologic Unit Flow package (HUF). This was experimented with and had significant stability problems. Assuming large hydraulic conductivity outwash overlying small conductivity Fox Hills aquifer, for an unconfined aquifer, the HUF package calculates the transmissivity for the node based on where the water table falls within the outwash or underlying Fox Hills. When the water table fluctuates across the contact, large changes in transmissivity occur, causing the model to oscillate. The addition of adaptive dampening to the GMG solver may allow stable solutions using HUF in this scenario and should be explored.

At observation well 152-071-07ABBB1, the model underestimates the water level by 4.4 feet (tables 20 and 21). This well is near Trappers Coulee (fig. 120). Simulated elevation for the observation well is 1501.85 feet, which is very similar to the drain node elevation of 1501.41 feet. The stream elevation defined at this point is a little over 2 feet too low based on observed water levels at 152-071-06CDDC. This is well within the expected error for an elevation estimated from a topographic map with 10-foot contour intervals. If a more precise fit is required, then the only alternative would be to survey the stream. The remaining 2 feet of error likely result from the drain node conductance being too high.

Drain node elevations in the SE1⁄4 Section 28, Township 153 North, Range 57 West and near observation well 153-071-29DDAA are shown figure 121. Simulated discharge by evapotranspiration for layers 2 and 1 are shown in figures 123 and 124 respectively. In the model, there is no discharge to the stream (fig. 122) or by ET (fig. 123) at this location. No discharge through the culvert on Trappers Coulee along the south side of Section 28 was observed in November, 2006. Therefore the model is consistent with observation. However, significant ET would be expected in the model in this area based on the soil classification and CIR photography (figs. 11, 12, and 29), again indicating the models underestimation of water levels in this area. This points to the hydraulic conductivity in the LTC aquifer being too high and/or the cross-sectional area of the meltwater channel being too large possibly as a result of the rectangular profile. The other possibility is that surface water flow in Trappers Coulee from the north provides a sufficient quantity of water to the meltwater channel to maintain water levels near land surface in the SW1⁄4 Section 28 where the bend in the meltwater channel occurs.

Figure 125 shows the budget for the meltwater channel derived from ZONEBUDGET. The simulated stream discharge of 647 acre-feet per year at gaging site 152-071-06CDDC is very close to measured base flow (fig. 31). Total outflow from the aquifer (stream, ET, and underflow) is about 1000 acre-feet per year. The direct recharge of 307 acre-feet per year accounts for less than a third of the aquifer budget. Almost half of the water in the aquifer comes from the adjoining outwash area as subsurface flow through either outwash or the underlying Fox Hills aquifer. The budget for the outwash area is shown in figure 126.

Long Lake has a surface area of 685 acres. Net ET (PET - precipitation) should be over 12 inches per year or over 685 acre-feet per year. Simulated lake discharge through the constant head nodes used to simulate the lake is 160 acre-feet per year. This would indicate that groundwater is not a large part of the lake budget. The lake was largely dry on 8/13/1990 (fig. 127), but had filled significantly by two weeks later. The composite central ARB dataset "arb2198_" indicates 2.01 inches of precipitation fell during this period, of which 1.16 inches fell in the 5 days prior to the 8/28/1990 photo. This would indicate that surface water runoff is a dominant part of the budget for Long Lake. If this is the case, then what role does runoff play in the budget of the Trappers Coulee aquifer? Does this mean that recharge to the aquifer is greater than estimated in the steady-state model or that total recharge to the Trappers Coulee aquifer is correct, but much of it comes from runoff and very little comes from the Fox Hills?

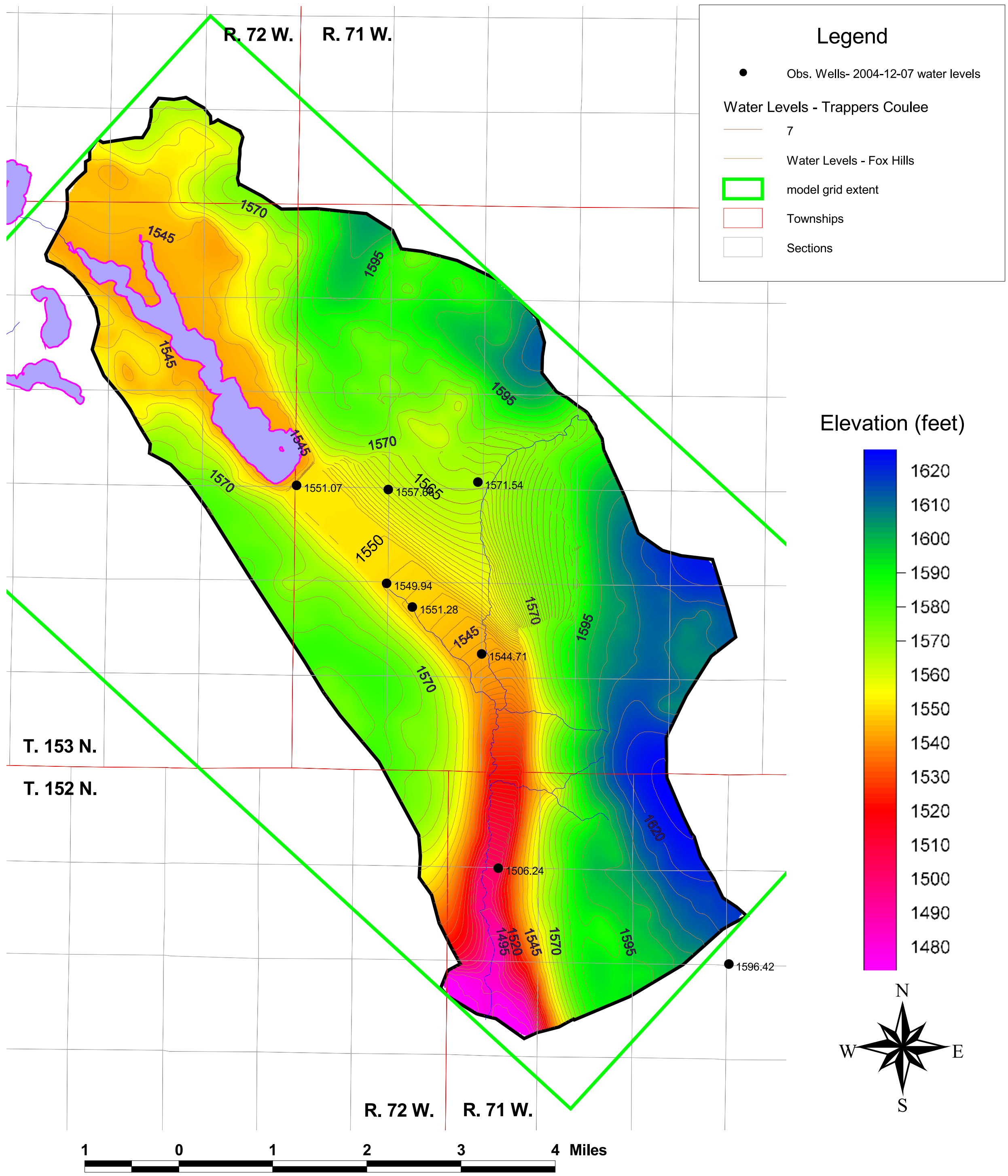


Figure 119. Water table elevations (feet) from steady-state simulation, run B21hh.

Aquifer	location	layer	WL (B21hh) (feet)	WL 11/25/1981 (feet)	model error (feet)
Fox Hills	15307203DDD	2	1544.58	1549.01	-4.43
Fox Hills	15307119AAAA1	2	1560.42		
Outwash	15307117DDD1	2	1566.43	1570.58	-4.15
Trappers Coulee	15307118CCCC1	2	1551.67		
Trappers Coulee	15307130AAAA1	2	1550.04	1547.61	2.43
Trappers Coulee	15307129DDAA1	2	1543.31		
Trappers Coulee	15207107ABBB1	2	1501.85		
Trappers Coulee	15207106CDDC	2	1501.35		
Fox Hills	15207105CCCC1	2	1559.73		
Esmond	15207105DDDD1	2	1604.56		

Table 19. Comparison of simulated steady-state heads from run B21hh and 11/25/1981 observed water levels. Wells listed in a northwest to southeast down gradient direction of the Trappers Coulee aquifer.

Aquifer	location	layer	WL (B21hh) (feet)	WL 12/07/1998 (feet)	model error (feet)
Fox Hills	15307203DDD	2	1544.58		
Fox Hills	15307119AAAA1	2	1560.42	1557.66	2.76
Outwash	15307117DDD1	2	1566.43	1568.81	-2.38
Trappers Coulee	15307118CCCC1	2	1551.67	1551.23	0.44
Trappers Coulee	15307130AAAA1	2	1550.04	1549.46	0.58
Trappers Coulee	15307129DDAA1	2	1543.31	1544.61	-1.30
Trappers Coulee	15207107ABBB1	2	1501.85	1506.27	-4.42
Trappers Coulee	15207106CDDC	2	1501.35		
Fox Hills	15207105CCCC1	2	1559.73		
Esmond	15207105DDDD1	2	1604.56		

Table 20. Comparison of simulated steady-state heads from run B21hh and 12/07/1998 observed water levels. Wells listed in a northwest to southeast down gradient direction of the Trappers Coulee aquifer.

Aquifer	location	layer	WL (B21hh) (feet)	WL 12/07/2004 (feet)	model error (feet)
Fox Hills	15307203DDD	2	1544.58		
Fox Hills	15307119AAAA1	2	1560.42	1557.66	2.76
Outwash	15307117DDD1	2	1566.43	1571.54	-5.11
Trappers Coulee	15307118CCCC1	2	1551.67	1551.07	0.60
Trappers Coulee	15307130AAAA1	2	1550.04	1549.94	0.10
Trappers Coulee	15307129DDAA1	2	1543.31	1544.71	-1.40
Trappers Coulee	15207107ABBB1	2	1501.85	1506.24	-4.39
Trappers Coulee	15207106CDDC	2	1501.35		
Fox Hills	15207105CCCC1	2	1559.73		
Esmond	15207105DDDD1	2	1604.56		

Table 21. Comparison of simulated steady-state heads from run B21hh and 12/07/2004 observed water levels. Wells listed in a northwest to southeast down gradient direction of the Trappers Coulee aquifer.

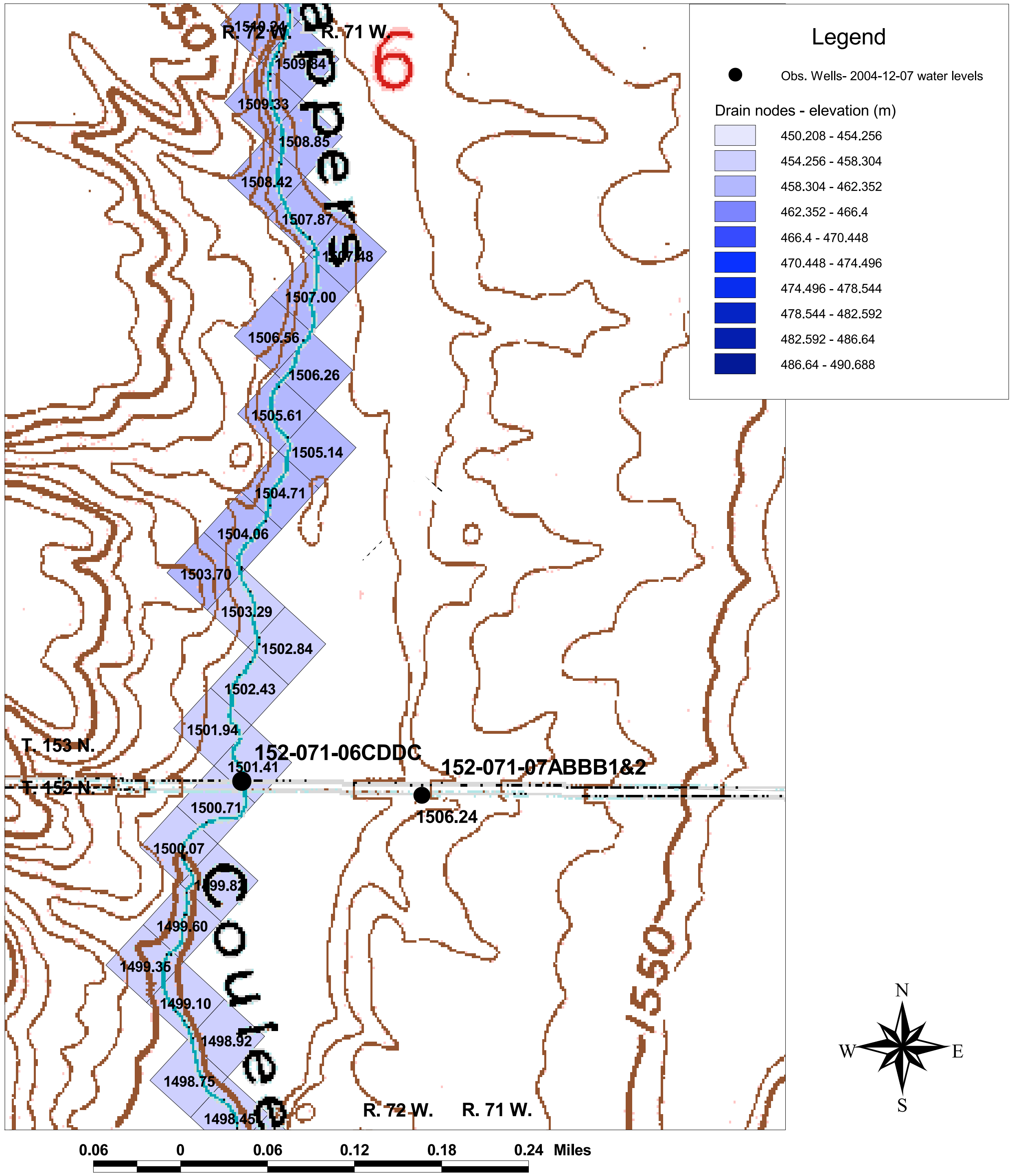


Figure 120. Shows drain node elevations (feet) in Trappers Coulee and observed water level elevation in 15207107ABBB1 on 12/07/04. Topography from USGS Esmond 7.5-Minute Quadrangle Map. At NDSWC stream gage site 15207106CDDC the bottom of stream elevation is approximately 1504 feet. The water level at 15207107ABBB is approximately 2 feet higher than in the stream at 15207106CDDC (see figure 21).

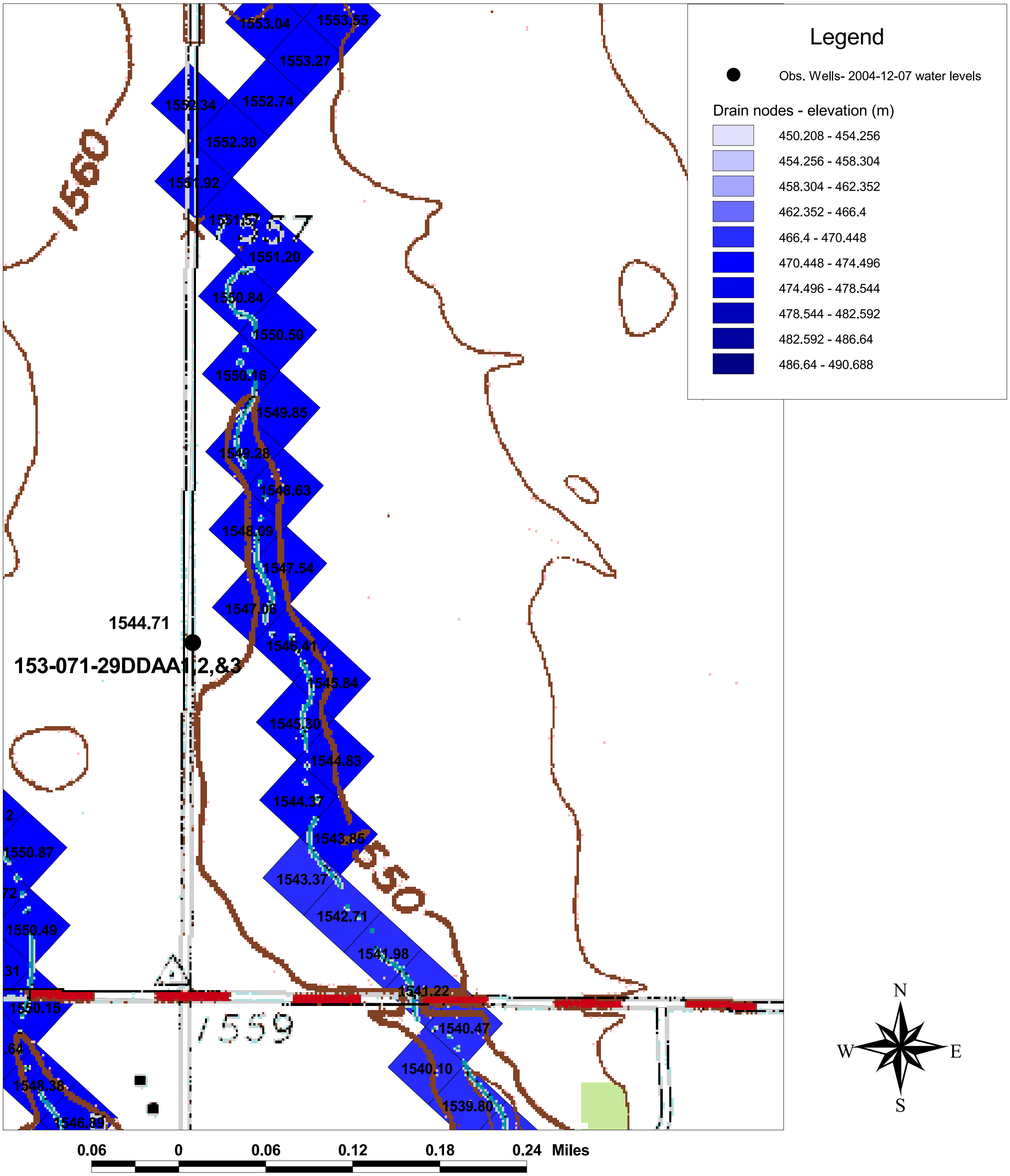


Figure 121. Shows drain node elevations (feet) in Trappers Coulee near NDSWC observation wells at 15307129DDAA (see figure 20). Observed water level in 15307129DDAA1 on 12/07/04 is shown. Topography from USGS Esmond 7.5-Minute Quadrangle Map.

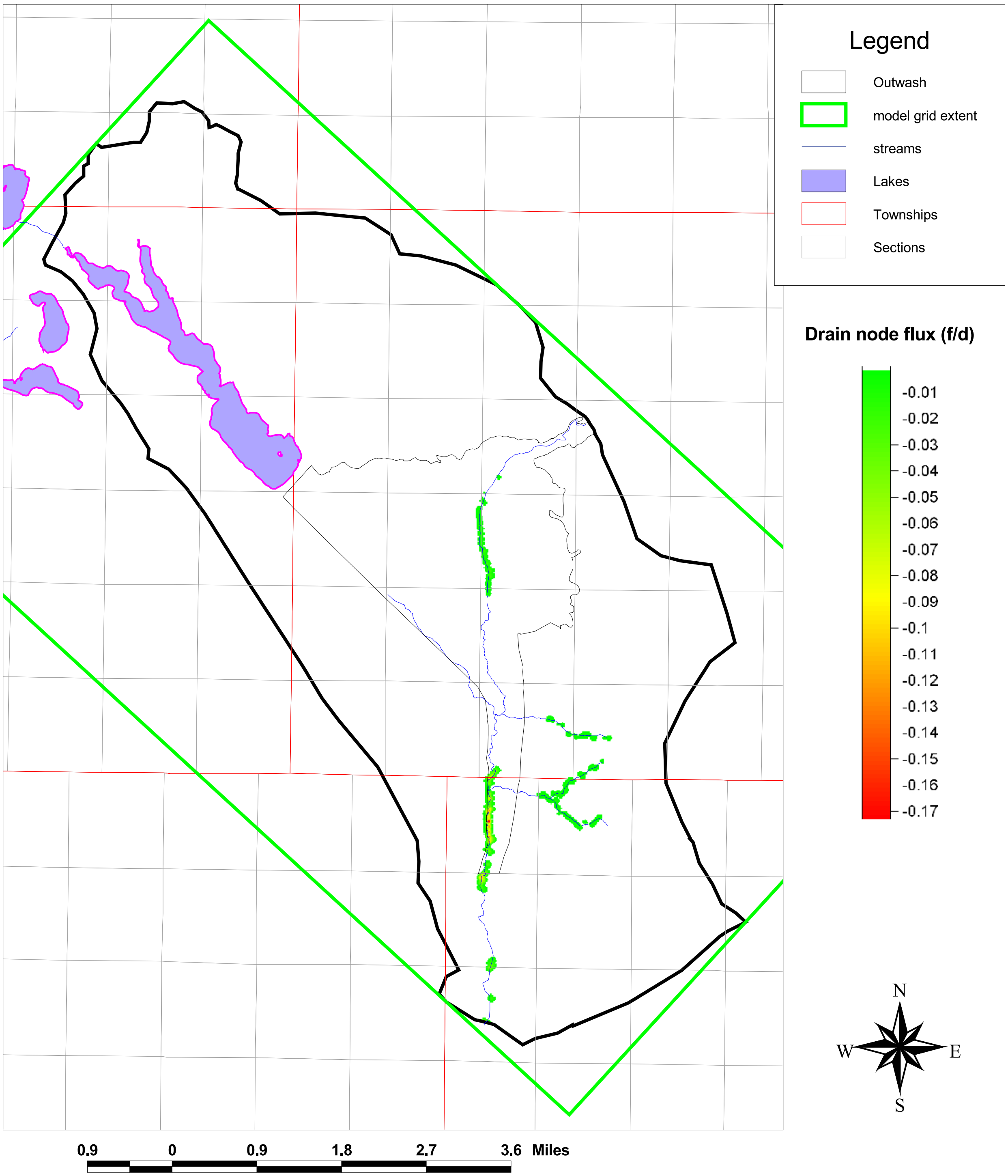


Figure 122. Flow from drain (feet per day) nodes in layer 2, steady-state model run B21hh.

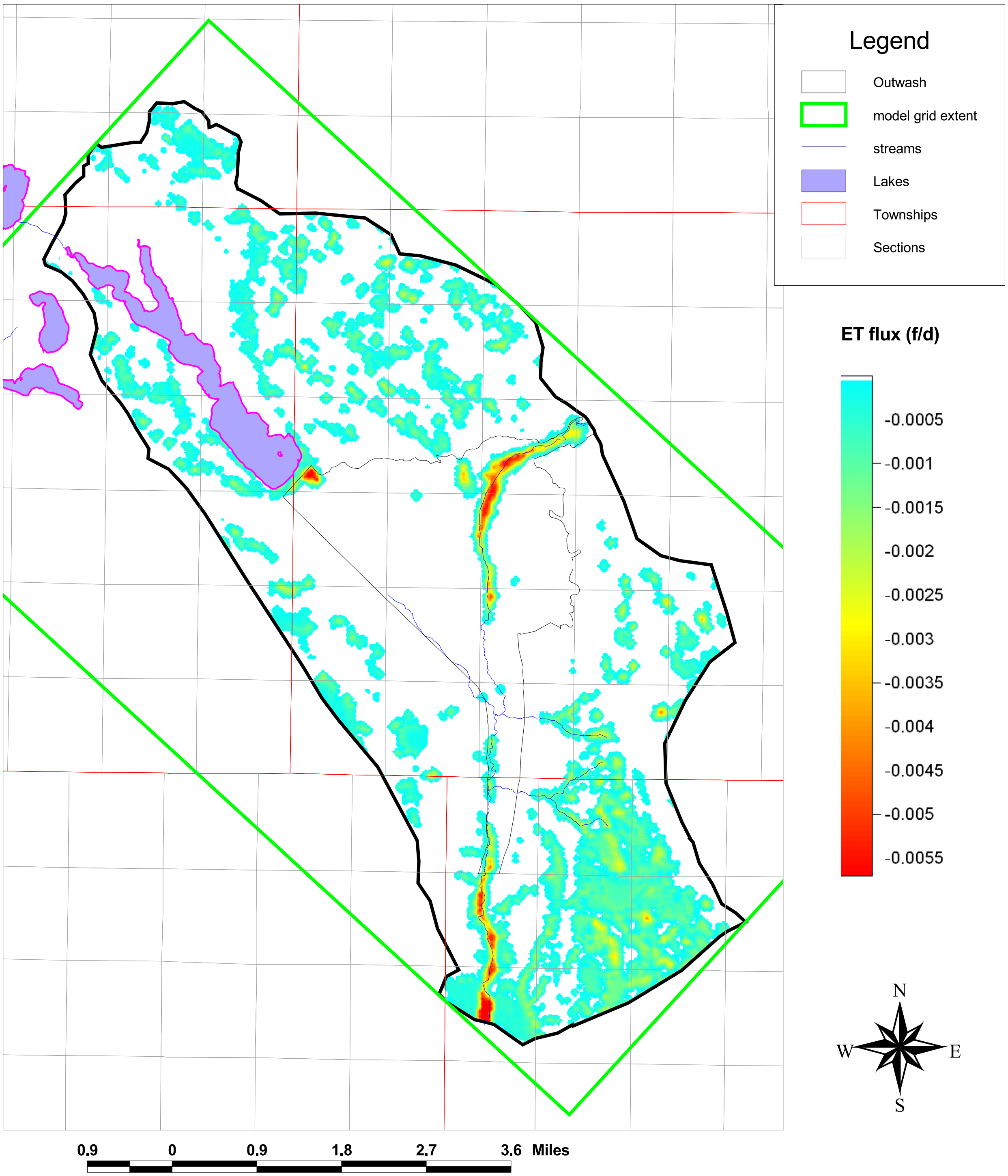


Figure 123. Discharge by evapotranspiration (feet per day) in layer 2, steady-state model run B21hh.

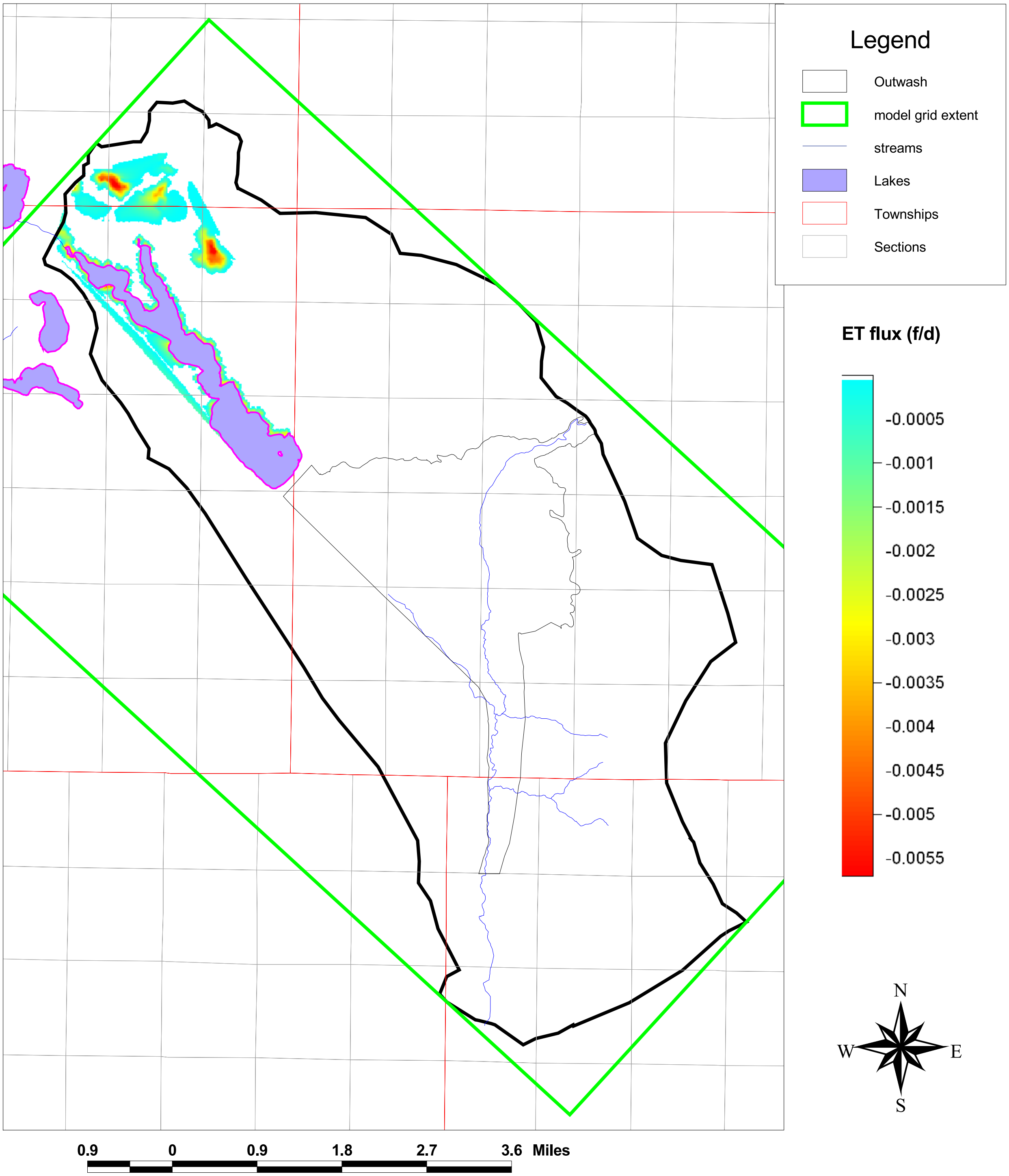


Figure 124. Discharge by evapotranspiration (feet per day) in layer 1, steady-state model run B21hh.

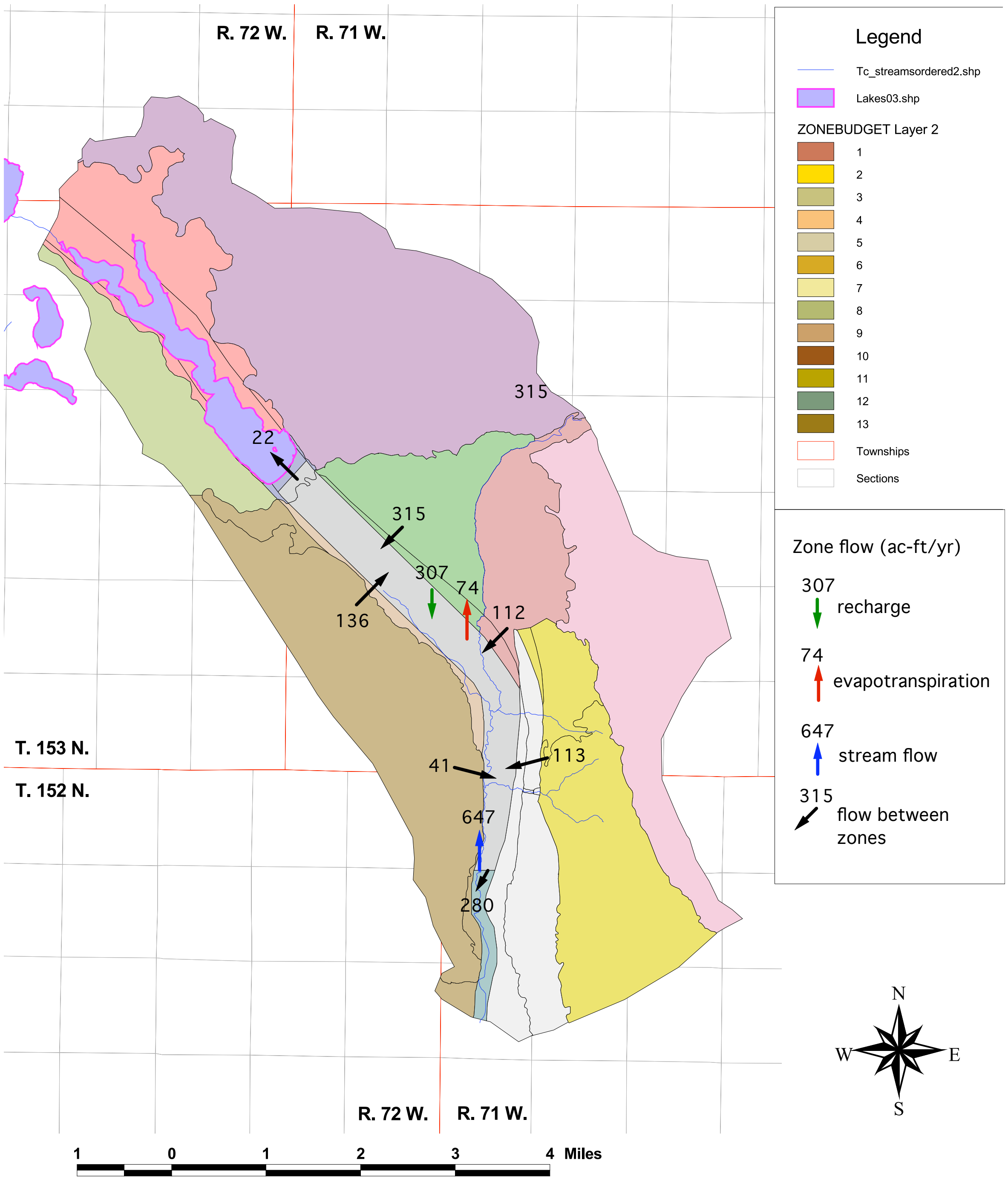


Figure 125. Hydrologic budget of the Trappers Coulee meltwater trench (ZONEBUDGET zone 01). Simulation tc10B21hh.

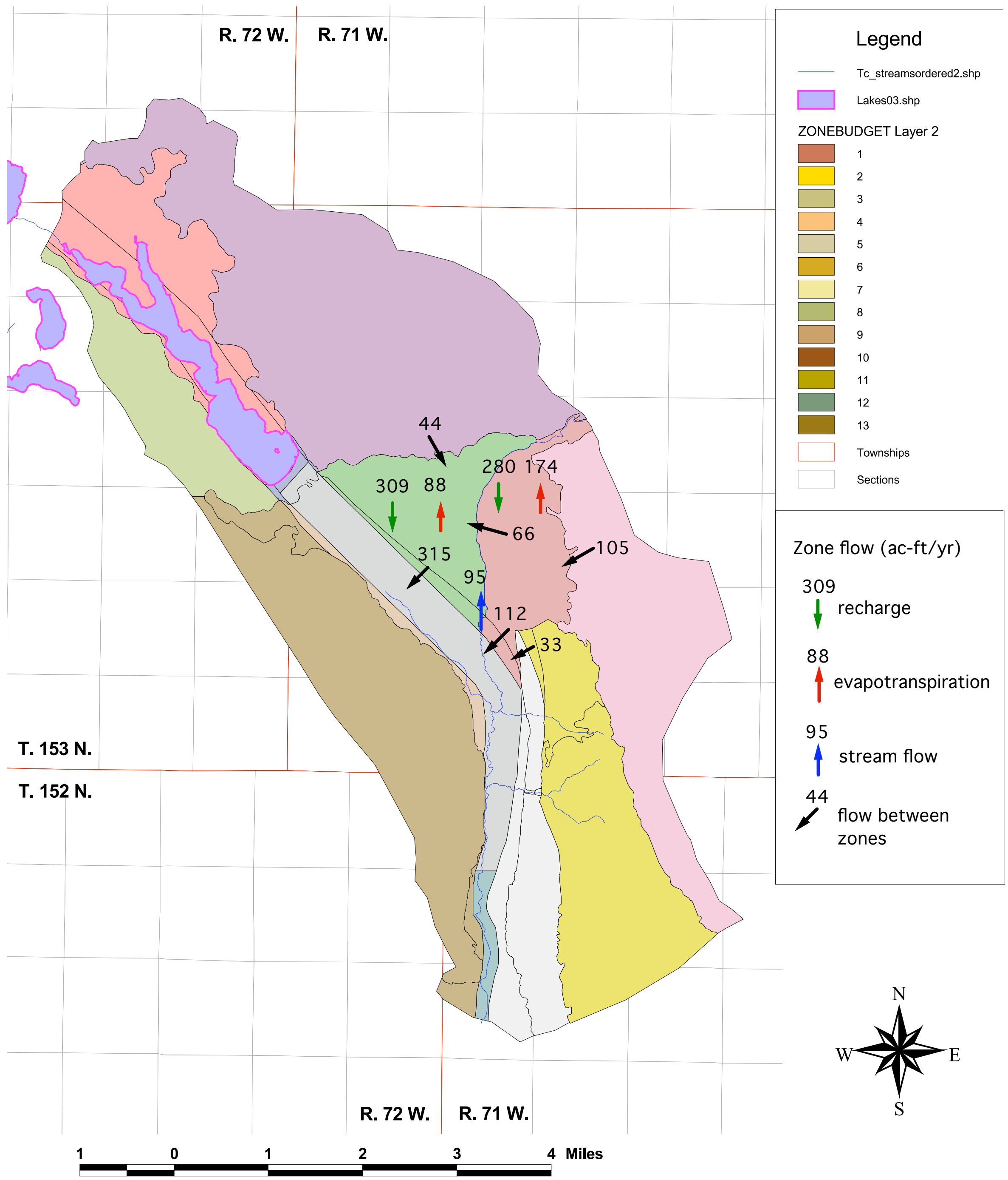


Figure 126. Hydrologic budget of the outwash plain of the Trappers Coulee aquifer (ZONEBUDGET zones 04 and 05). Simulation tc10B21hh.

Long Lake Aerial Photos

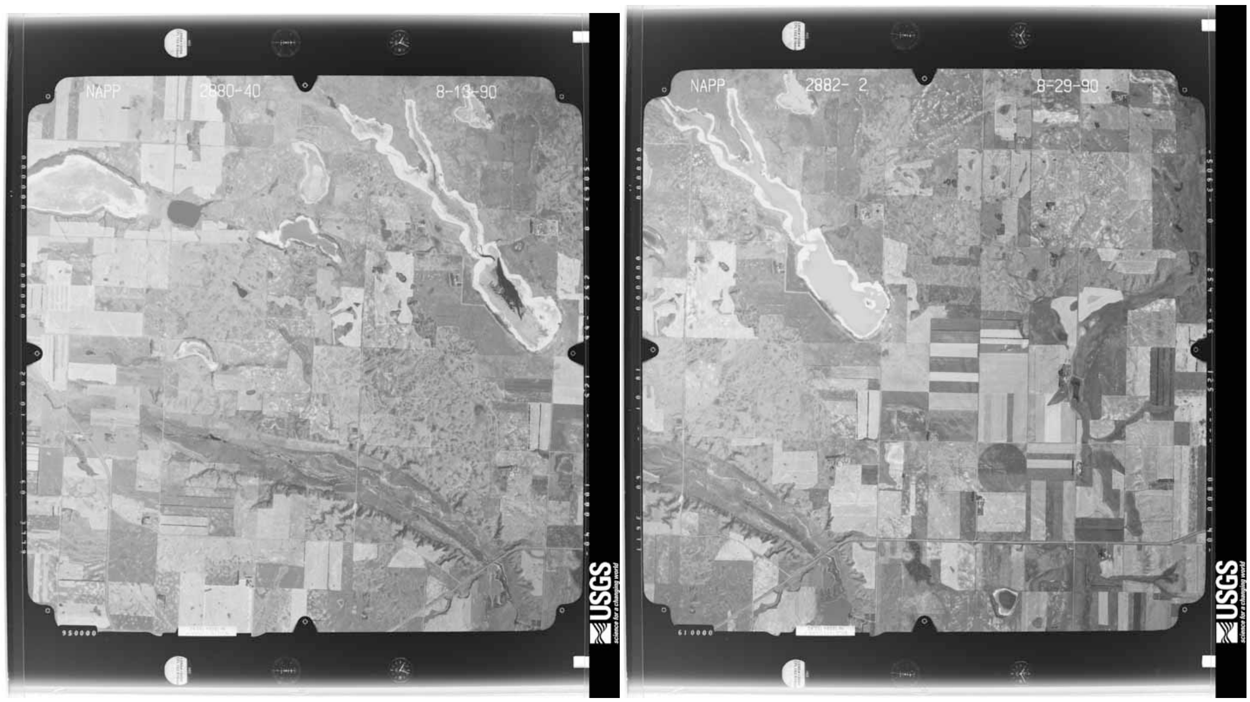


Figure 127. USGS National Aerial Photography Program photos from http://edcsns17.cr.usgs.gov/EarthExplorer/ showing Long Lake on 8/13/90 (left) and on 8/29/90 (right).

Transient Simulation

In the transient simulation, each year of simulation consists of 12 stress periods each 1 month long. The monthly recharge data file generated by the VB2K post-processing program is used to create the recharge, ET, and well packages. The well package generator can either multiply the monthly irrigation water use in the recharge data file by the number of acres irrigated by a specified well node or scale reported use to the fraction of estimated use for that month.

Figures 128 through 136 show simulated water levels from 1951 through 2005 at 153-071-30AAAA1 using different climatic data sets and comparing the no-irrigation case to the case of irrigation based on reported use. Figures 128 through 136 also include observed water levels at observation wells 153-071-20CCC and -30AAAA1. Note that figure 129 uses a slightly different starting head file than the other runs in this set. In most of these cases, the simulations using reported use fit the data quite well for the period prior to the late 1990s. There is some tendency to under-predict drawdown resulting from the 1988 to 1992 drought. Based on these results, it would appear that the model has significant predictive power. However, these simulations fail horribly to predict the effect of the increased pumping beginning in 1998. The better the model fits the 1988 to 1992 drought, the worse it does in predicting the effect of the increased pumping. The best fits of simulated to observed water levels are for the non-pumping scenarios. Why does the model fail to reproduce the water levels of this recent pluvial? One possible factor is that the irrigation has increased soil moisture sufficiently that increased pumping from summer rains increased summer recharge largely offsetting the amount of water pumped. Another possibility is that in reality, recharge to the outwash area is rapidly transmitted to the meltwater channel. The model's treatment of the outwash area as Fox Hills would greatly reduce the rate of transmission thereby definitely dampening the effect of climate variability on recharge in the simulation. Even though the average recharge from this outwash area is correct (steady-state model works), the variability between drought and pluvials is greatly smoothed. Another possibility is that runoff has played a significant role in recharge during this period that did not occur in the period from 1950 to 1994. Given the much greater runoff production during this period in the Sheyenne River valley (fig. 33), this seems plausible.

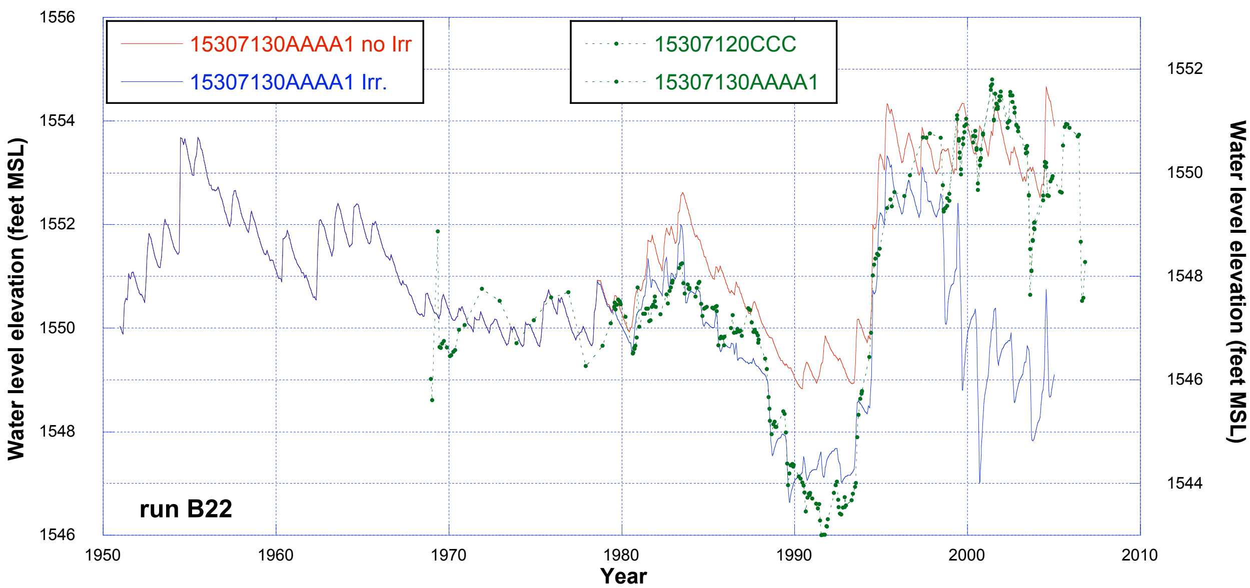


Figure 128. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B22 (drake_f03.monthly) using reported water use and no irrigation use.

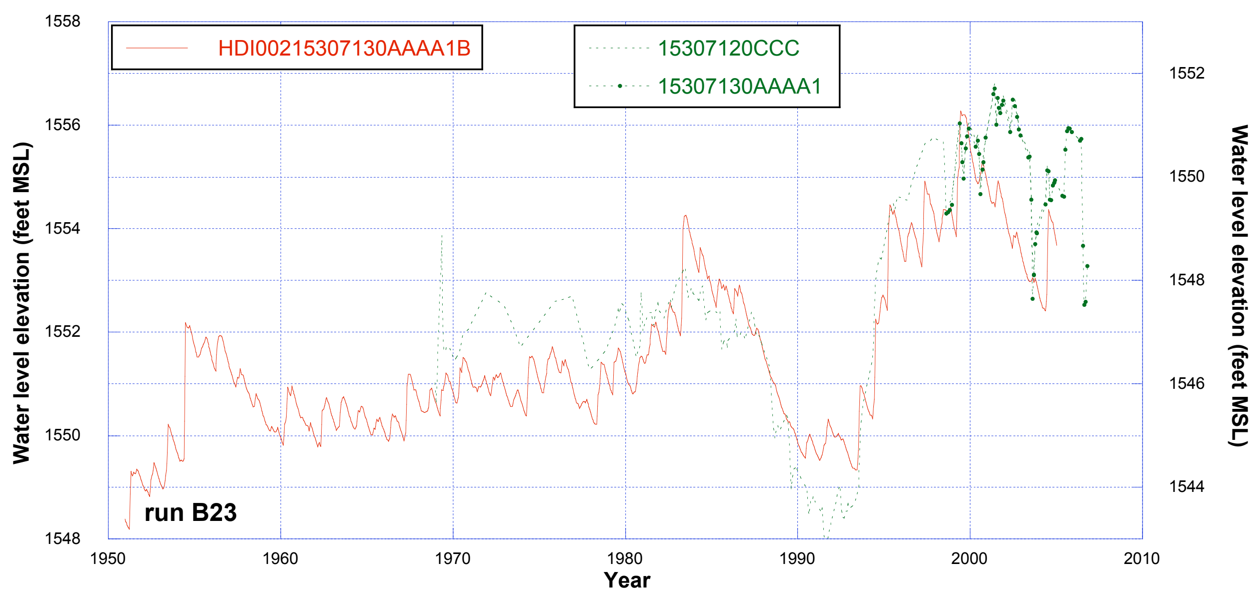


Figure 129. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B23 (rugby01_f03.monthly) with no irrigation.

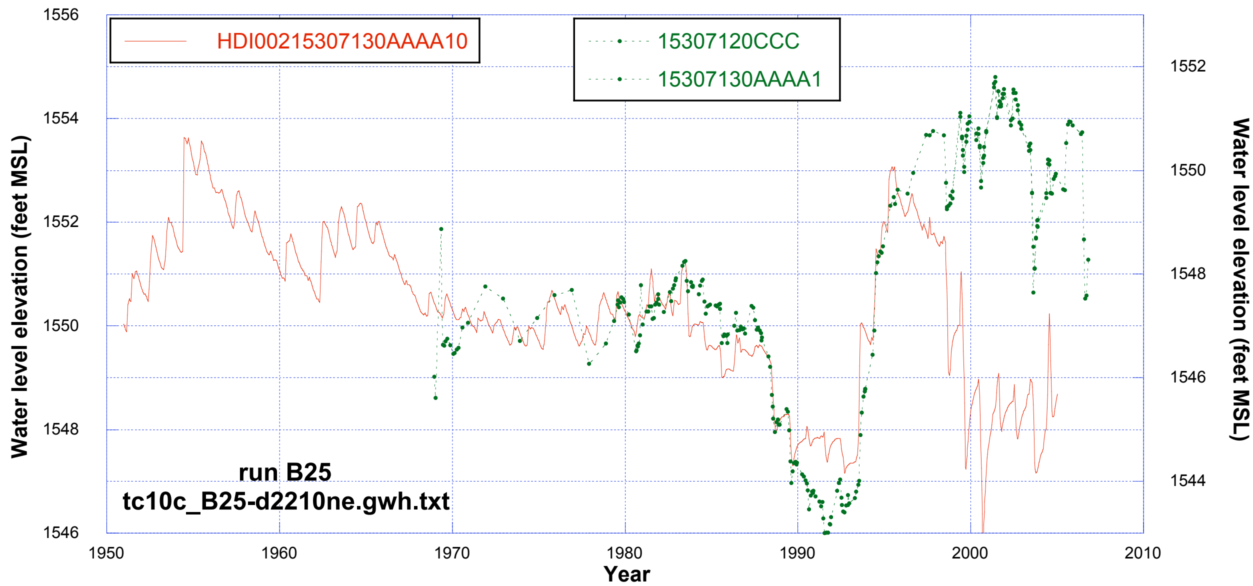


Figure 130. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (drake2210ne_f03.monthly) using reported water use.

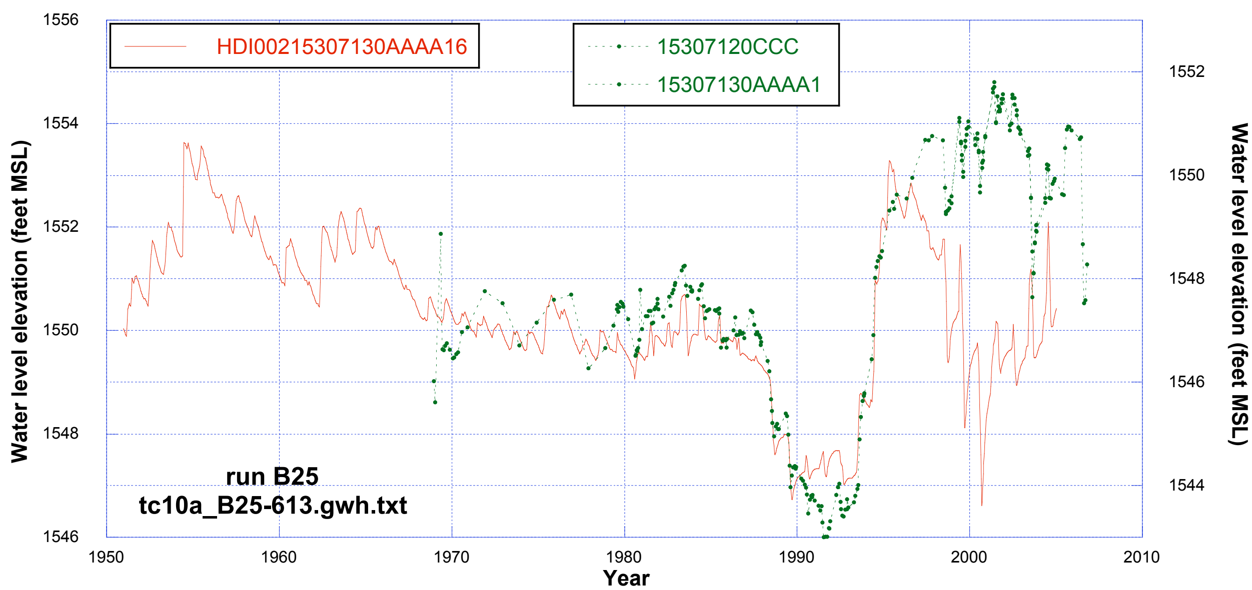


Figure 131. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (drake613_f03.monthly) using reported water use.

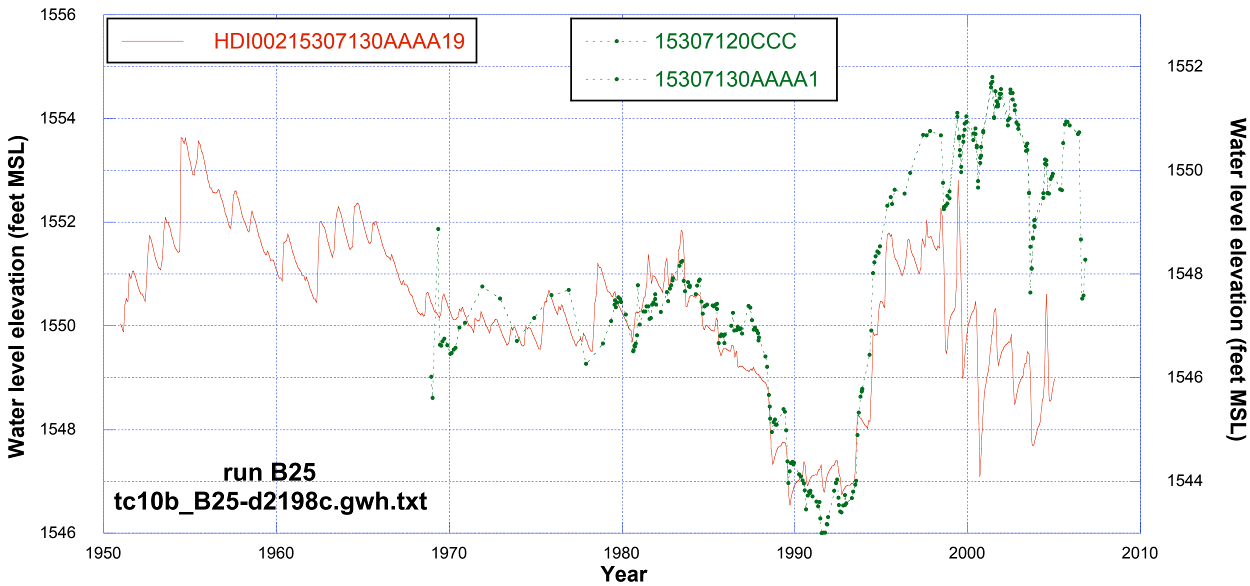


Figure 132. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (drake2198c_f03.monthly) using reported water use.

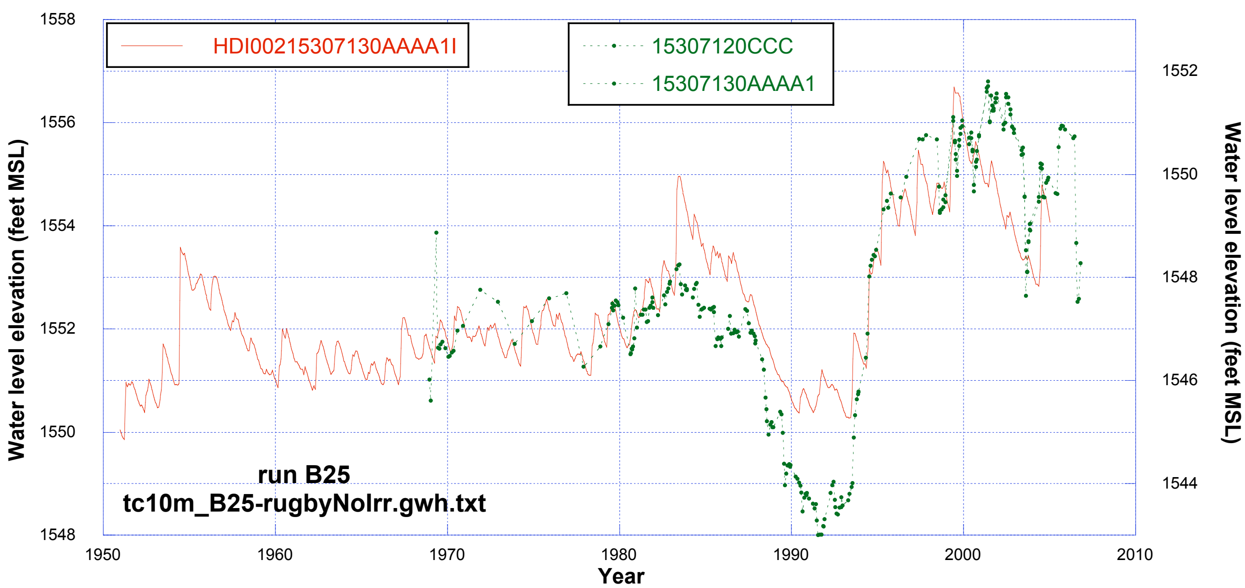


Figure 133. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (rugby01_f03.monthly) with no irrigation.

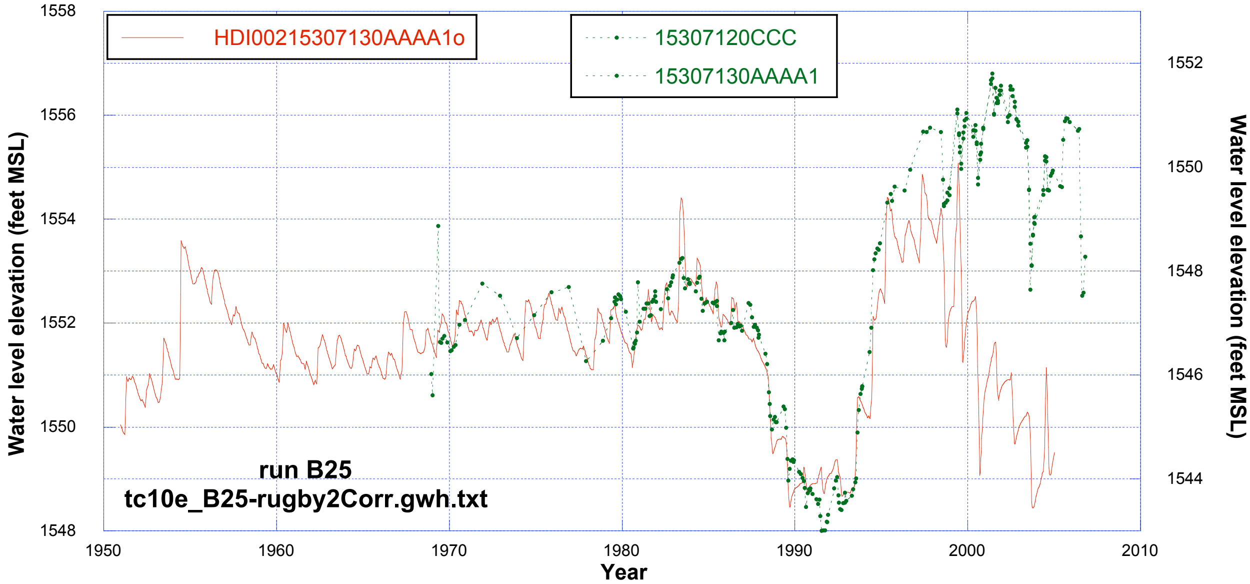


Figure 134. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (rugby01_f03.monthly) using reported water use.

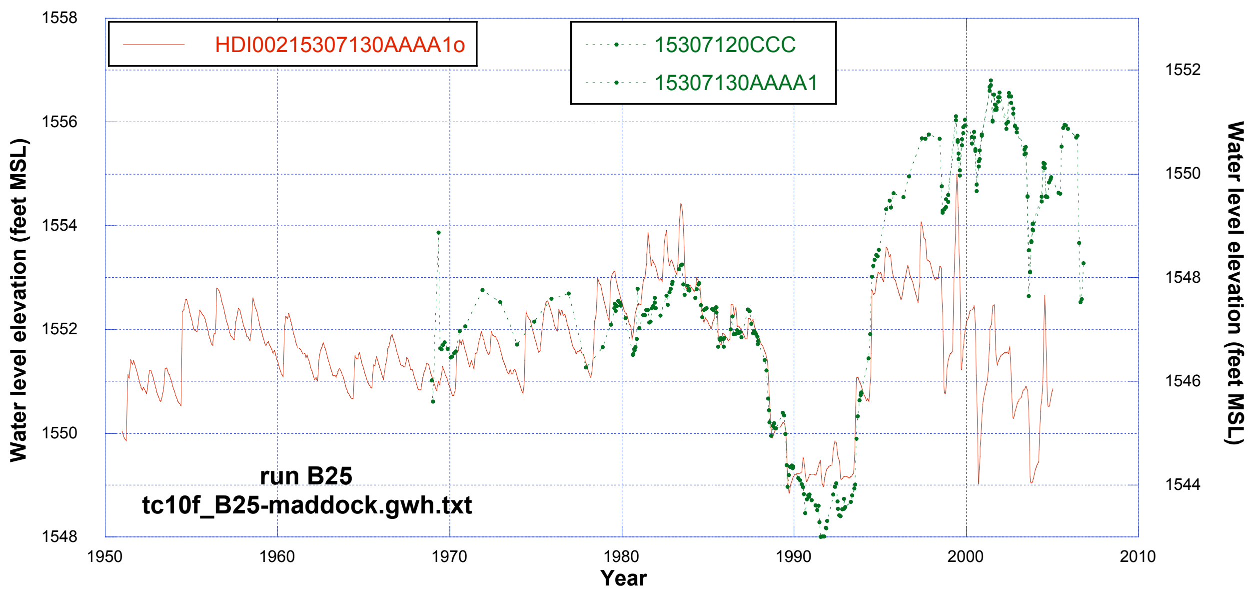


Figure 135. Comparison of observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC) with simulated water levels from run B25 (maddock02_f03.monthly) using reported water use.

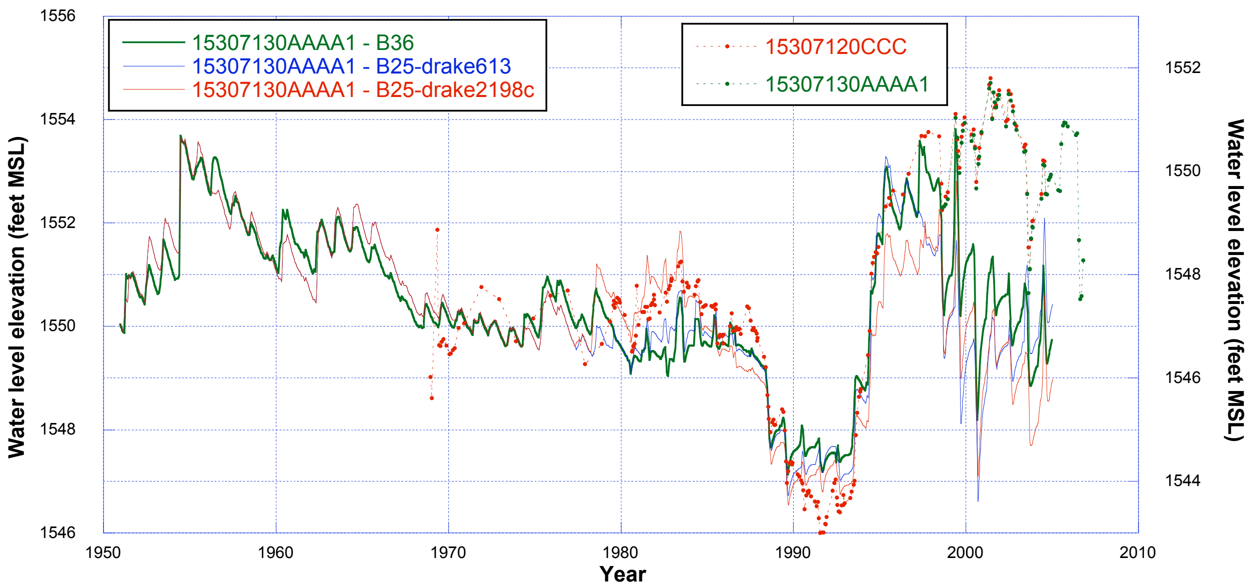


Figure 136. Comparisons of simulated water levels at observation well 153-071-30AAAA1 using reported water use and drake613_f03.monthly, drake2198c_f03.monthly, and drake-carr93-093carr.monthly (B36) climate datasets to observed water levels at 153-071-20CCC and 153-071-30AAA1 (replacement well for 153-071-20CCC).

Climate and Pumping Scenarios

In this section the effect of long-term stress upon the aquifer is evaluated. The five long-term climate datasets (55 to 100 years in length) used are drake_carr93, fessenden, hansboro, bottineau, and minot (summarized in table 16). The monthly recharge datasets were revised so that the dates start on January 1, 2006, otherwise the datasets are identical.

Pumping scenarios were developed using the permit information shown in table 22. The most senior permit application to review in the area is water permit application #5173 held by Victor Wolf. The applicant requested 480 acre-feet of water per year to irrigate two quarters of land at a total of 318.88 acres. Irrigation of 135 or 270 acres, using either one or two wells, was considered for the pumping scenarios. The following irrigation scenarios were created: 1) no irrigation, 2) permitted irrigation, 3) permitted+wolf1, 4) permitted+wolf1-270, and 5) permitted+wolf2 (table 22). The maximum pumping rate for an irrigation well is limited to the maximum rate specified for that well. The locations of point(s) of diversion for these permits are shown in figure 1.

Permit No.	Layer	Row	Column	Location	Acres Irrigated	PumpFrac	First Year Irrigated	Max Rate (gpm)
2534	2	85	154	153-071-29BBD	270	1	1998	900
2589	2	79	146	153-071-20CCDB2	285	1	1998	900
3029	2	76	164	153-071-29ACAA2	285	1	1975	900
5173 - wolf1	2	82	133	153-071-19DDB	135	1	2007	810
5173 - wolf1-270	2	82	133	153-071-19DDB	270	1	2007	900
5173 -wolf2	2	82	133	153-071-19DDB	135	1	2007	810
	2	81	118	153-071-19BAC	135	1	2007	810

Table 22. Irrigation wells and node location used to generate pumping scenarios. Permitted case is permits 2534, 2589, and 3029. Three different scenarios, wolf1, wolf1-270, and wolf2, were used to evaluate the effect of water permit application 5173.

Observation Wells

Figure 137 compares the simulated response to permitted pumping (irrigation scenario 2) at 153-071-30AAAA1 for the five climate data sets.

For each of the climate scenarios, effect on water levels is examined at the Fox Hills aquifer observation well 153-0-071-19AAAA1 and UTC aquifer observation wells 153-071-18CCCC1, 153-071-30AAAA1 and 153-071-29DDAAA1 (locations shown in Fig. 16). For the drake-carr93 climate dataset, simulated water levels are shown in figures 138 to 141. For the bottineau climate dataset, simulated water levels are shown in figures 142 to 145. For the minot climate dataset, simulated water levels are shown in figures 146 to 149. The simulated responses to the no irrigation and permitted pumping scenarios are the only ones shown for the minot climate dataset. For the fessenden climate dataset, simulated water levels are shown in figures 150 to 153. For the hansboro climate dataset, simulated water levels are shown in figures 154 to 157.

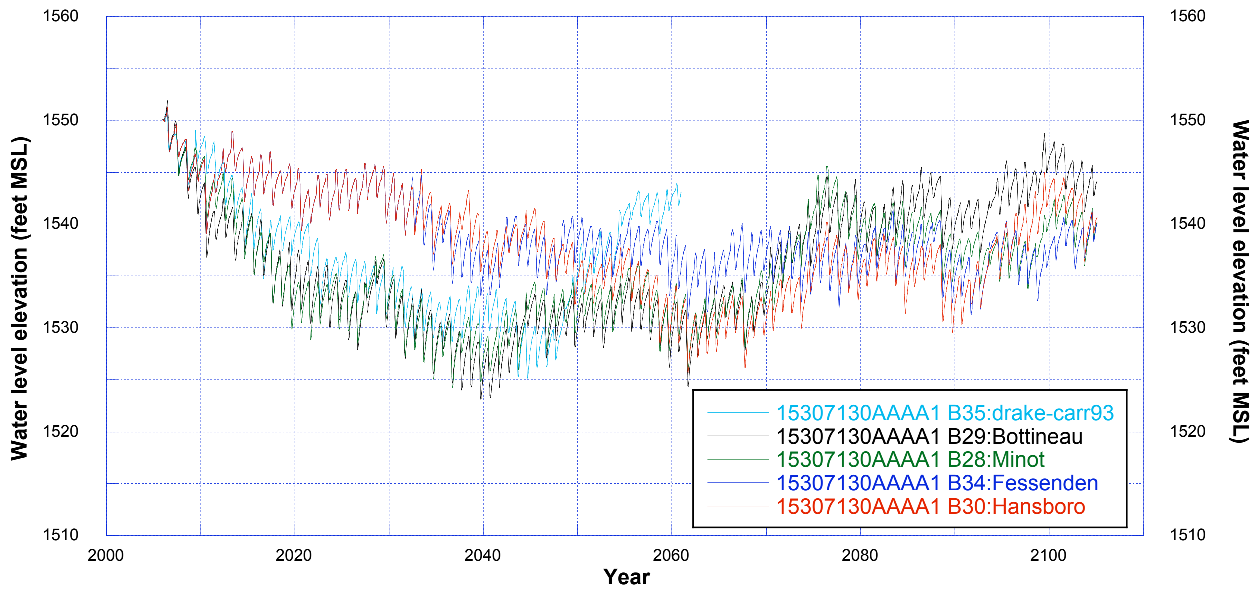


Figure 137. Comparisons effects of climate on simulated water levels at observation well 153-071-30AAAA1 using permitted irrigation.

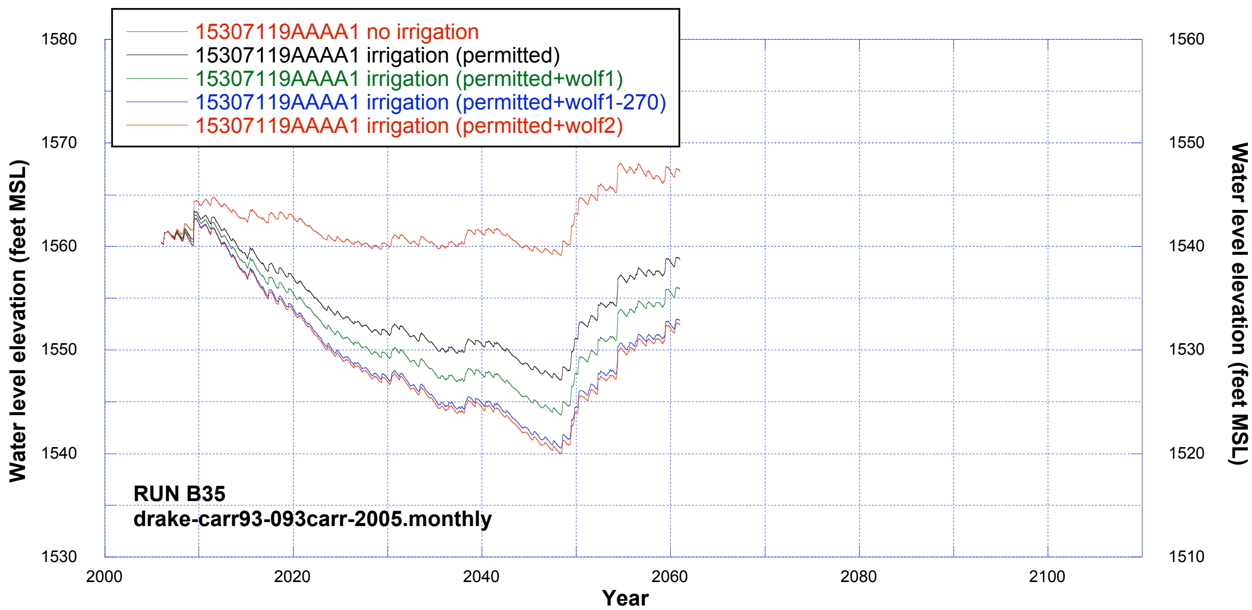


Figure 138. Comparisons of simulated water levels at observation well 153-071-19AAAA1 (Fox Hills aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

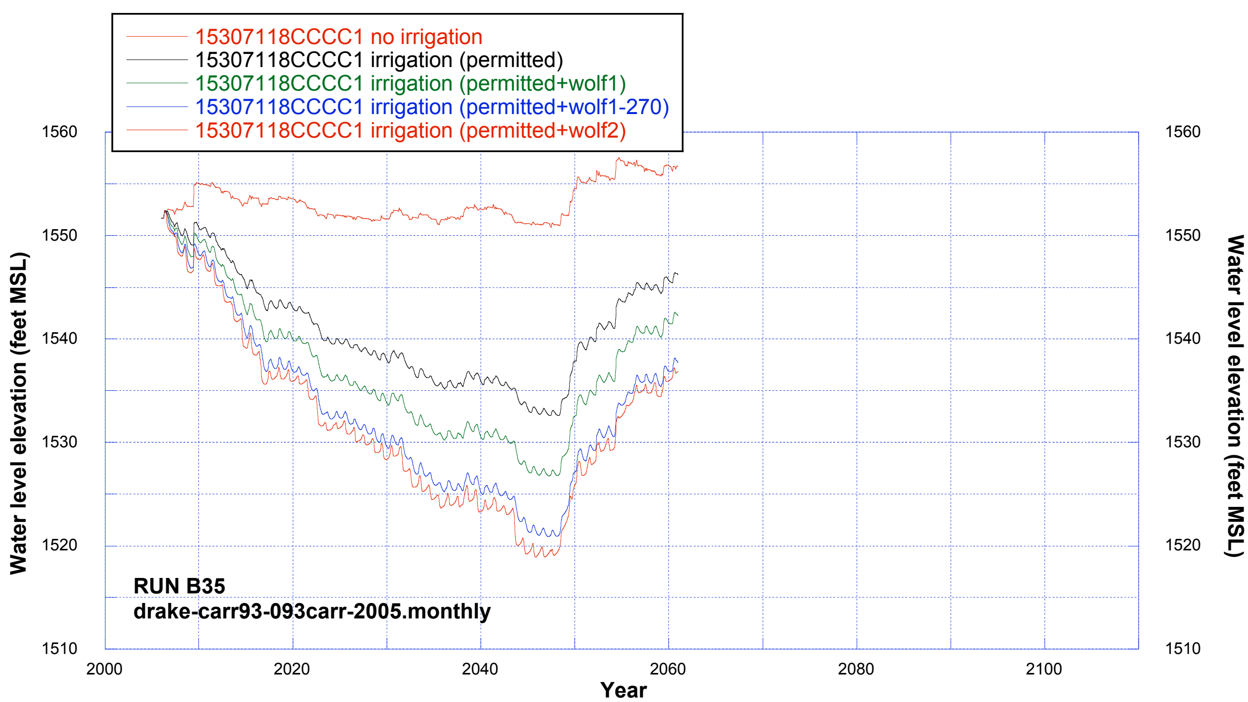


Figure 139. Comparisons of simulated water levels at observation well 153-071-18CCCC1 (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

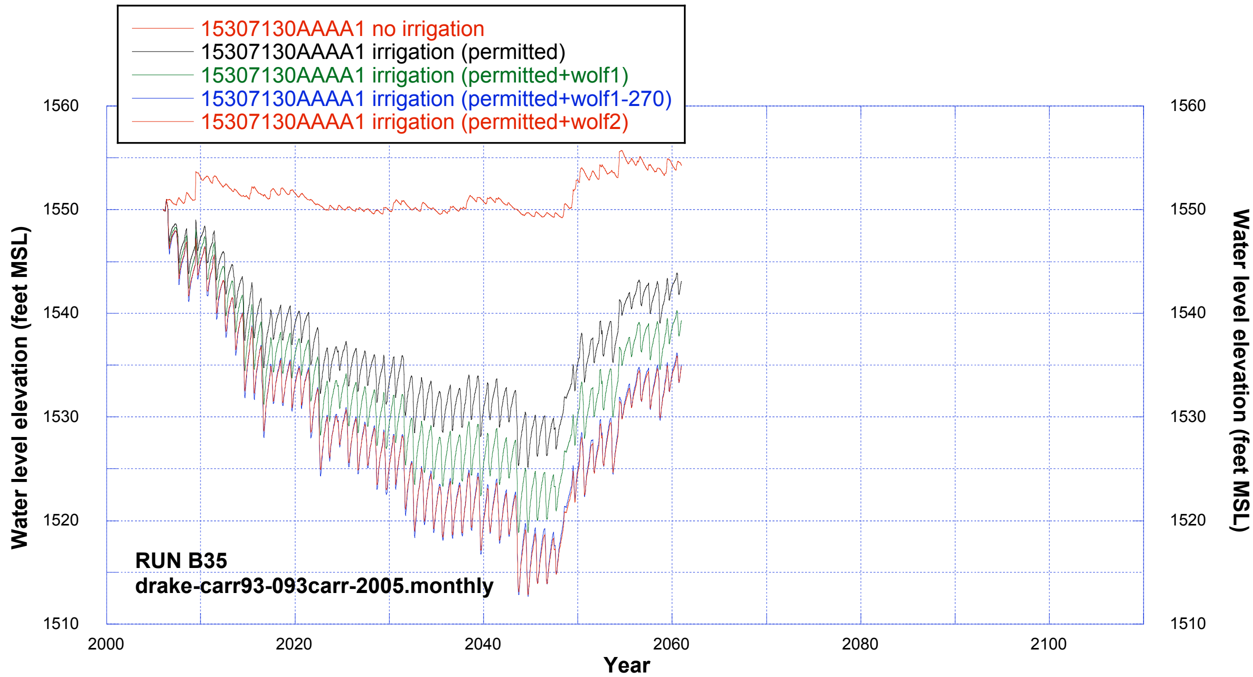


Figure 140. Comparisons of simulated water levels at observation well 153-071-30AAAA1 (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

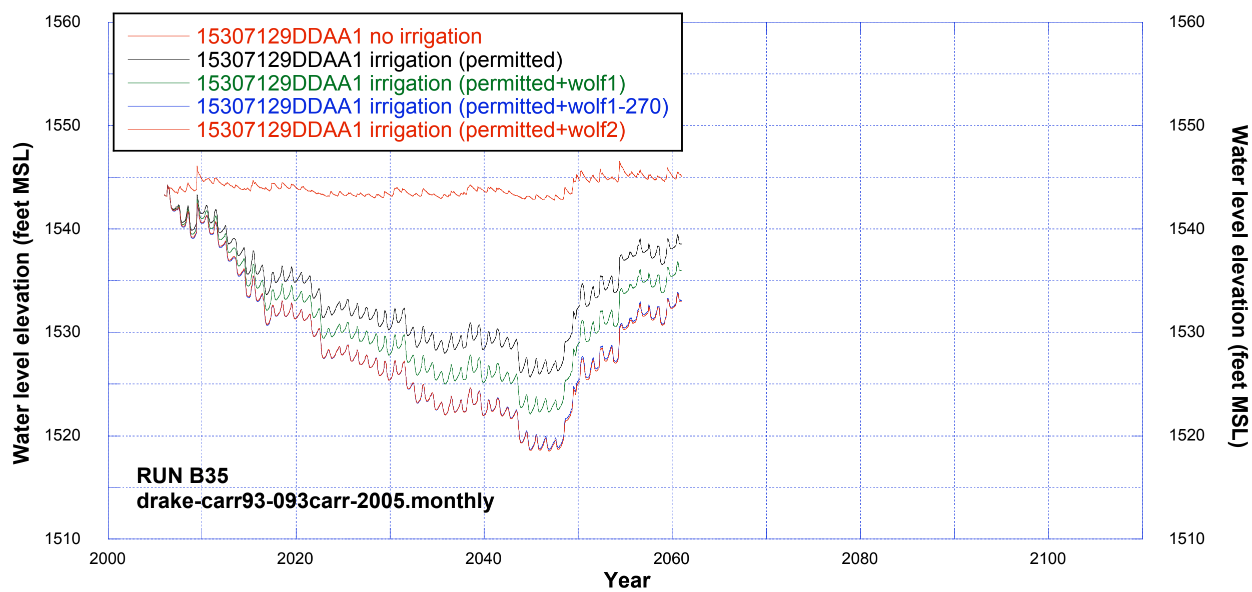


Figure 141. Comparisons of simulated water levels at observation well 153-071-29DDAA1 (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

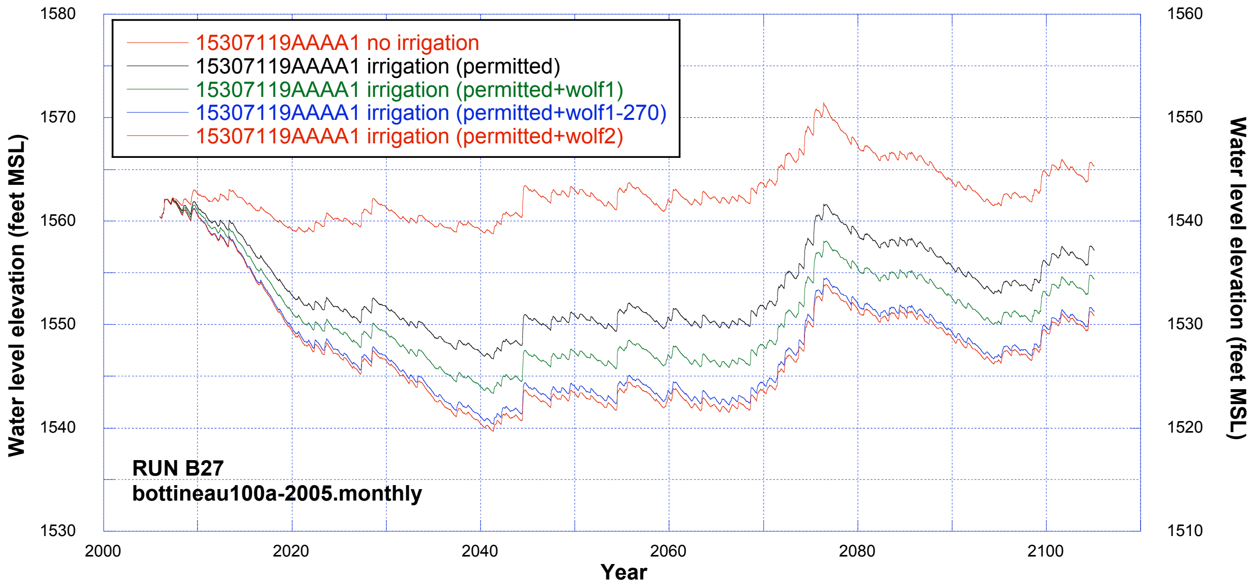


Figure 142. Comparisons of simulated water levels at observation well 153-071-19AAAA1 (Fox Hills aquifer) using bottineau100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

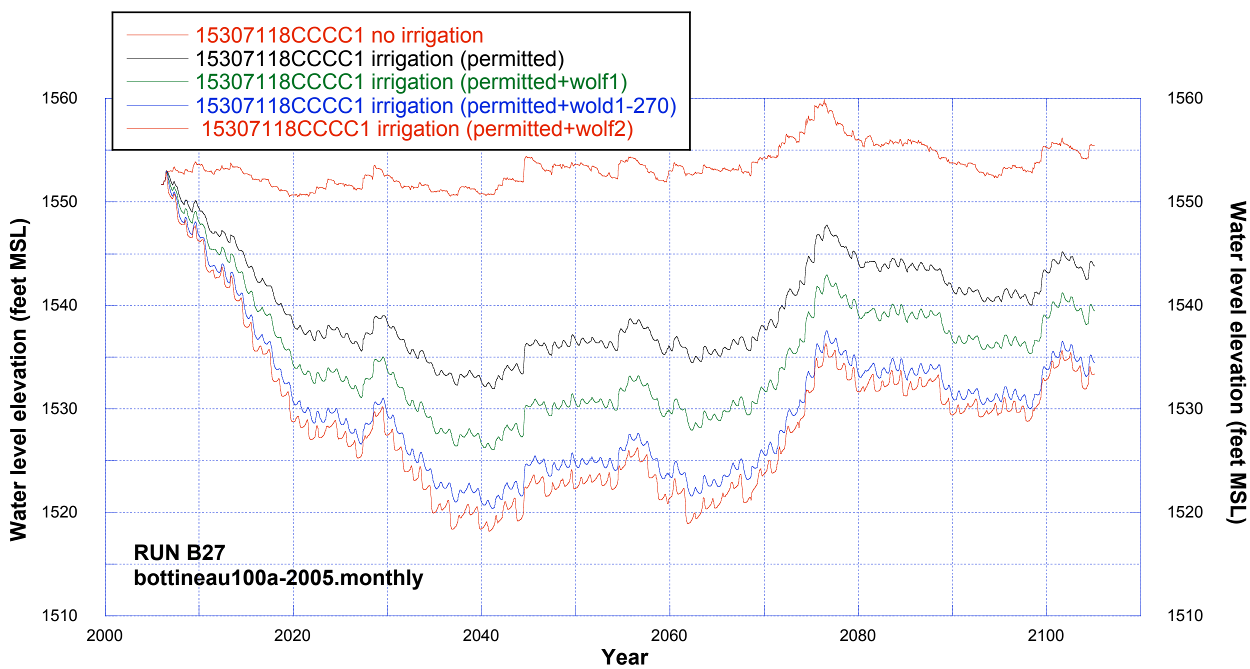


Figure 143. Comparisons of simulated water levels at observation well 153-071-18CCCC1 (Trappers Coulee aquifer) using bottineau100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

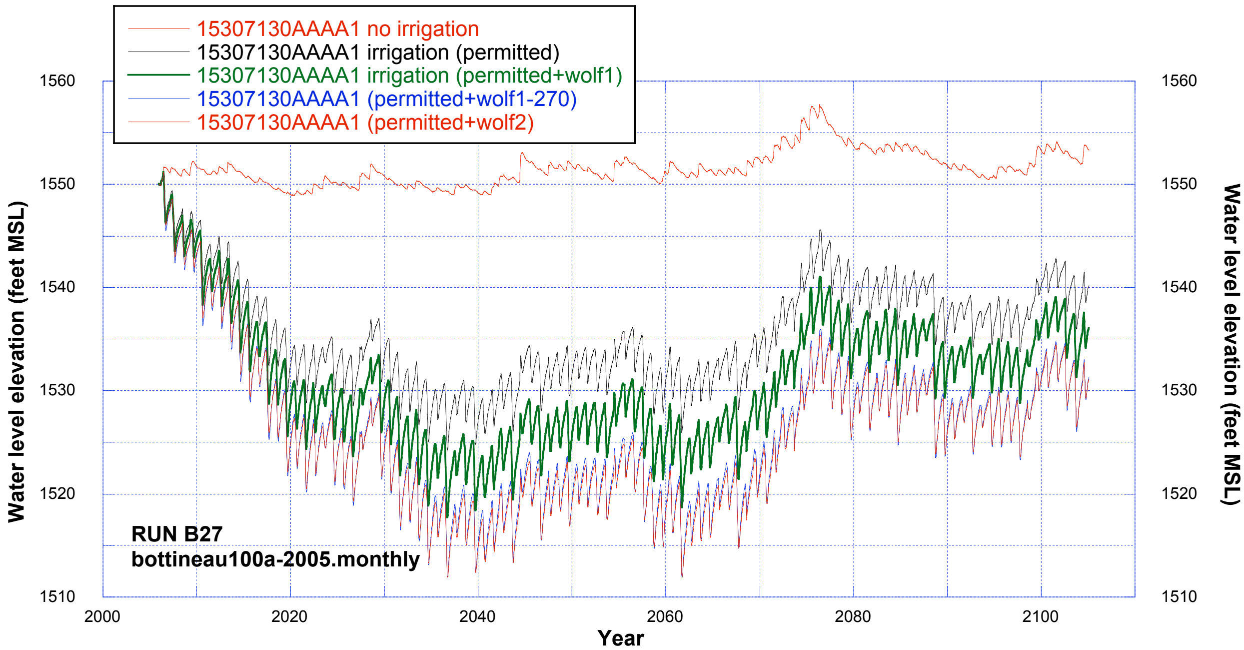


Figure 144. Comparisons of simulated water levels at observation well 153-071-30AAAA1 (Trappers Coulee aquifer) using bottineau100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

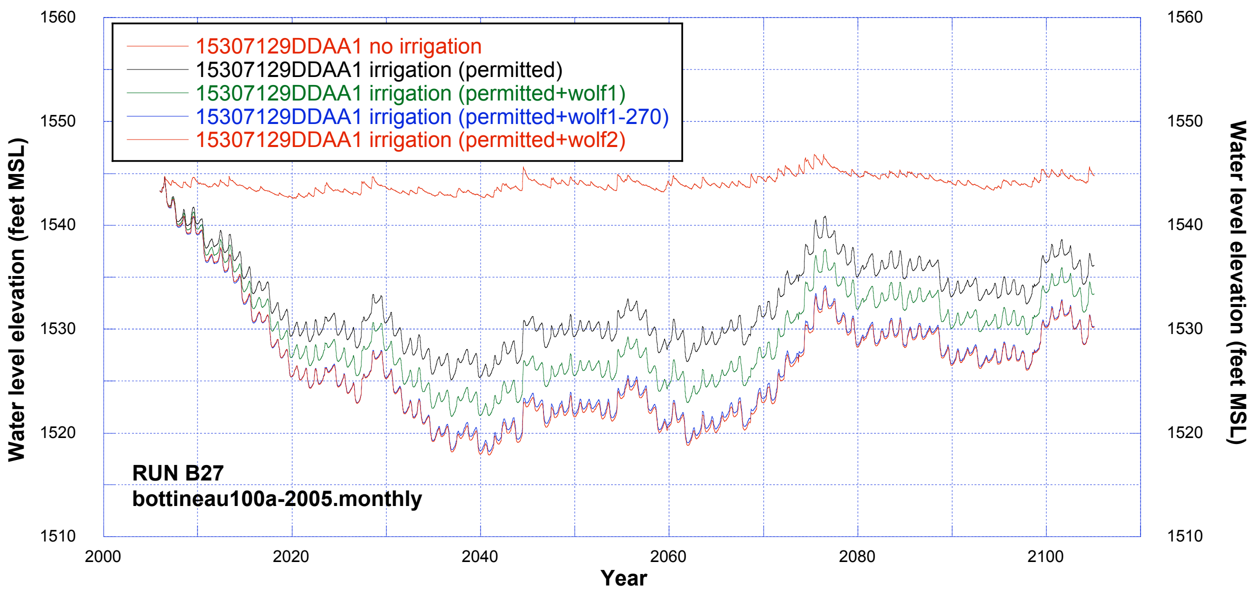


Figure 145. Comparisons of simulated water levels at observation well 153-071-29DDAA1 (Trappers Coulee aquifer) using bottineau100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

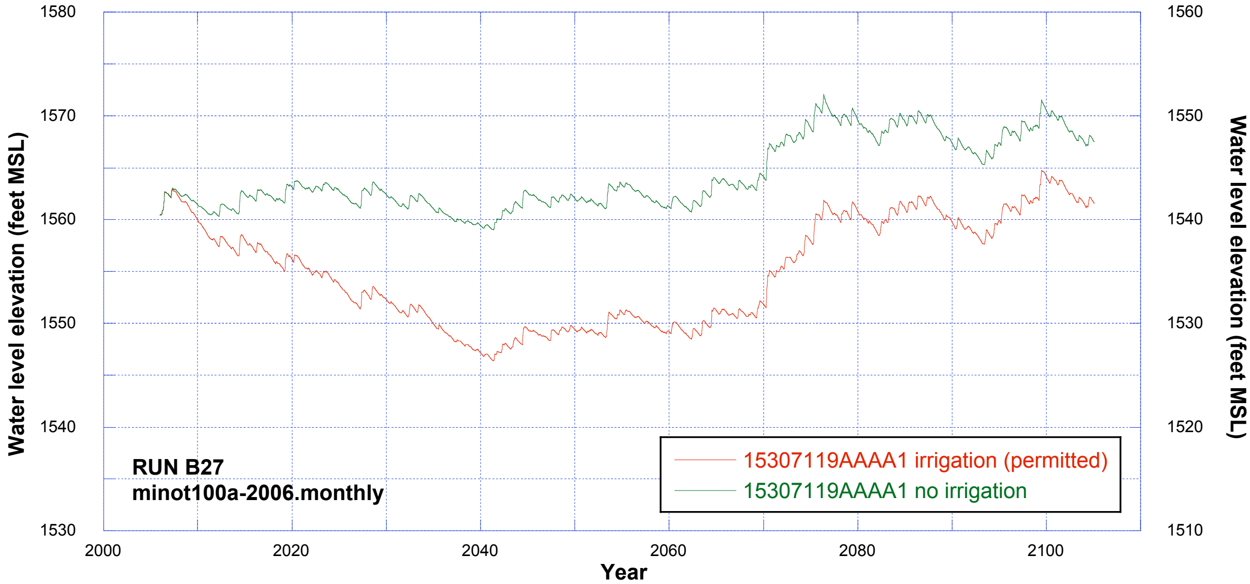


Figure 146. Comparisons of simulated water levels at observation well 153-071-19AAAA1 (Fox Hills aquifer) using minot100a-2005.monthly recharge dataset for cases of no irrigation and permitted irrigation.

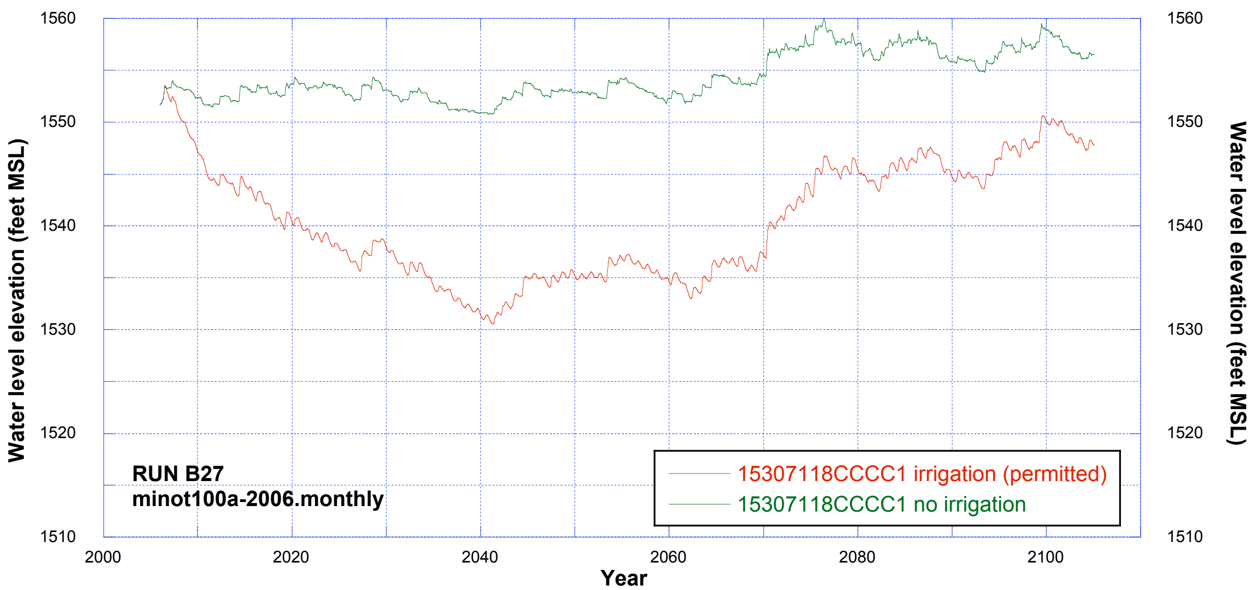


Figure 147. Comparisons of simulated water levels at observation well 153-071-18CCCC1 (Trappers Coulee aquifer) using minot100a-2005.monthly recharge dataset for cases of no irrigation and permitted irrigation.

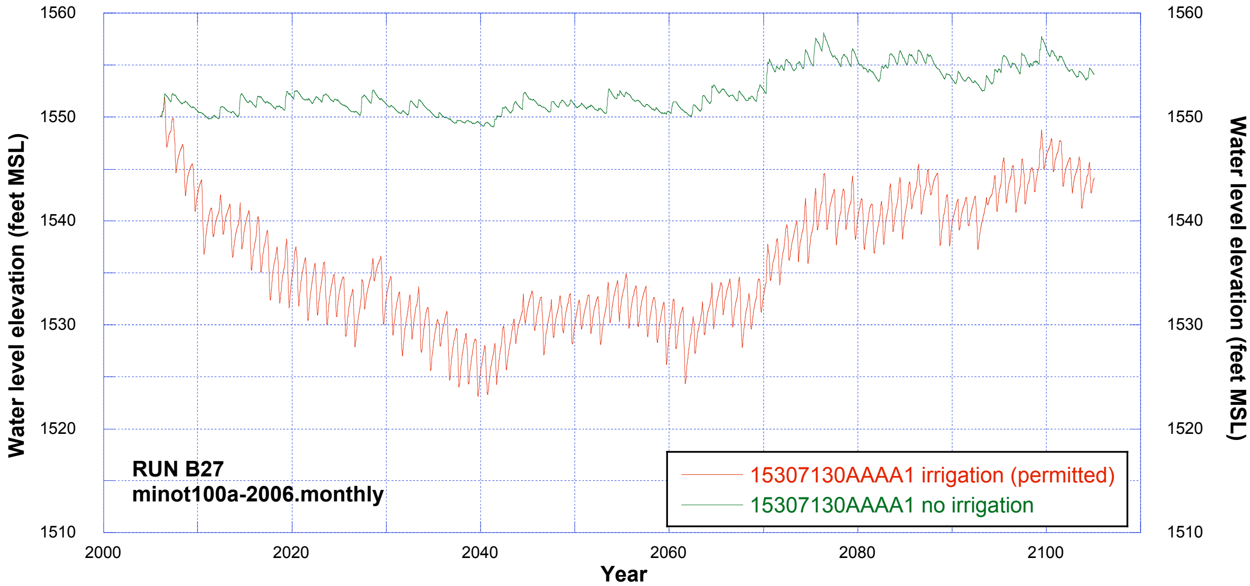


Figure 148. Comparisons of simulated water levels at observation well 153-071-30AAAA1 (Trappers Coulee aquifer) using minot100a-2005.monthly recharge dataset for cases of no irrigation and permitted irrigation.

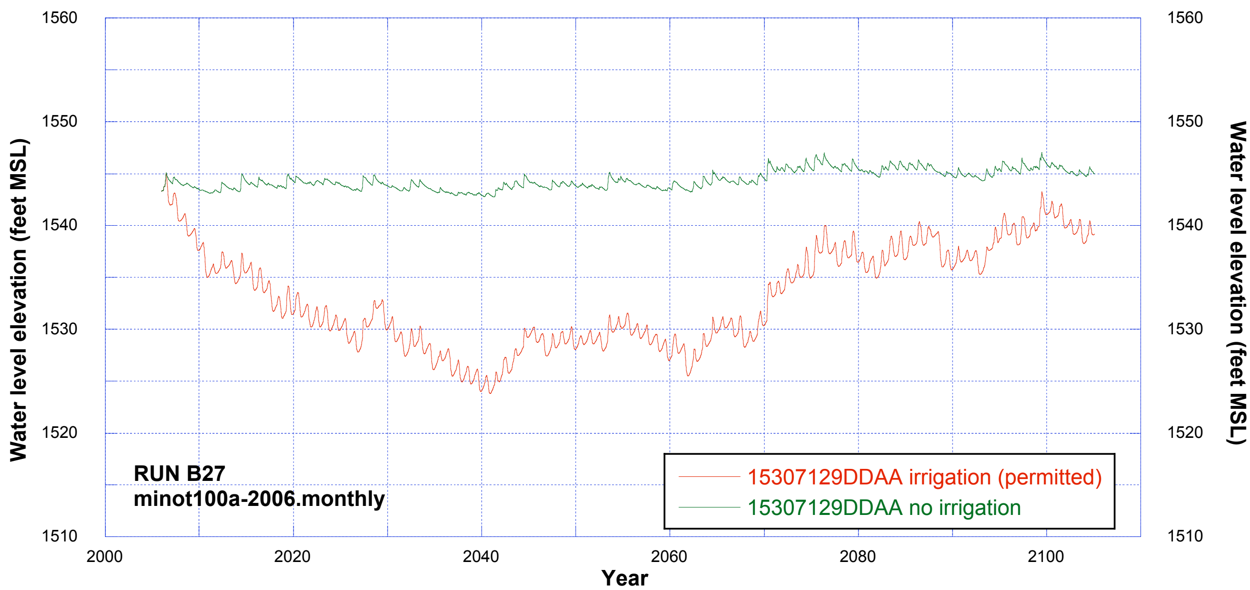


Figure 149. Comparisons of simulated water levels at observation well 153-071-29DDAA1 (Trappers Coulee aquifer) using minot100a-2005.monthly recharge dataset for cases of no irrigation and permitted irrigation.

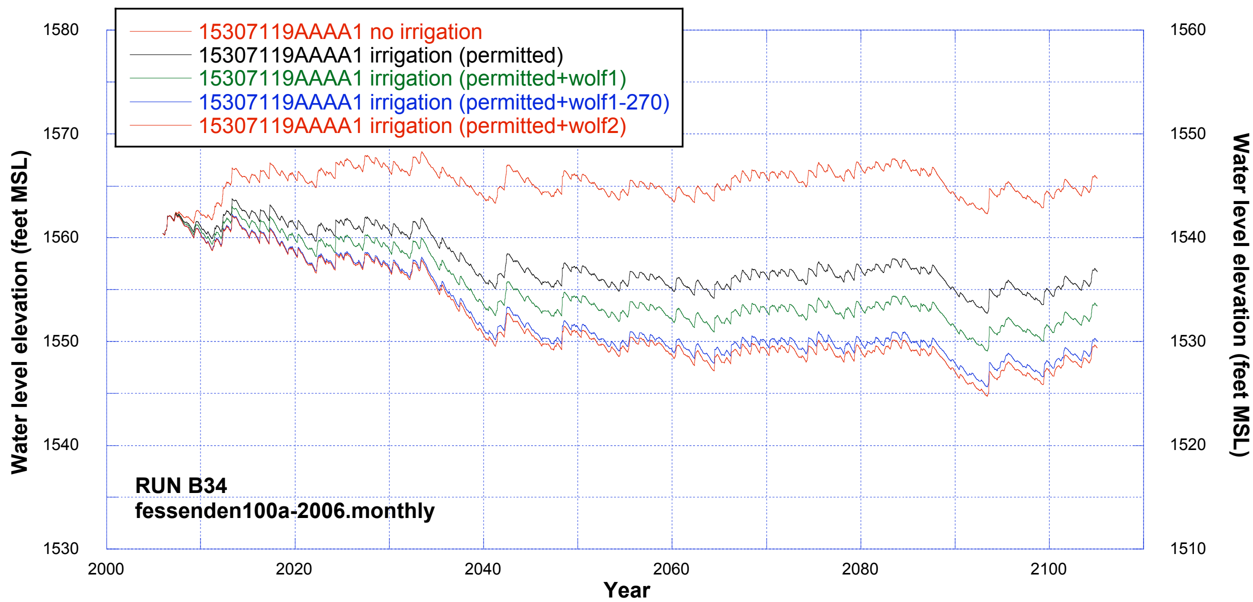


Figure 150. Comparisons of simulated water levels at observation well 153-071-19AAAA1 (Fox Hills aquifer) using fessenden100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

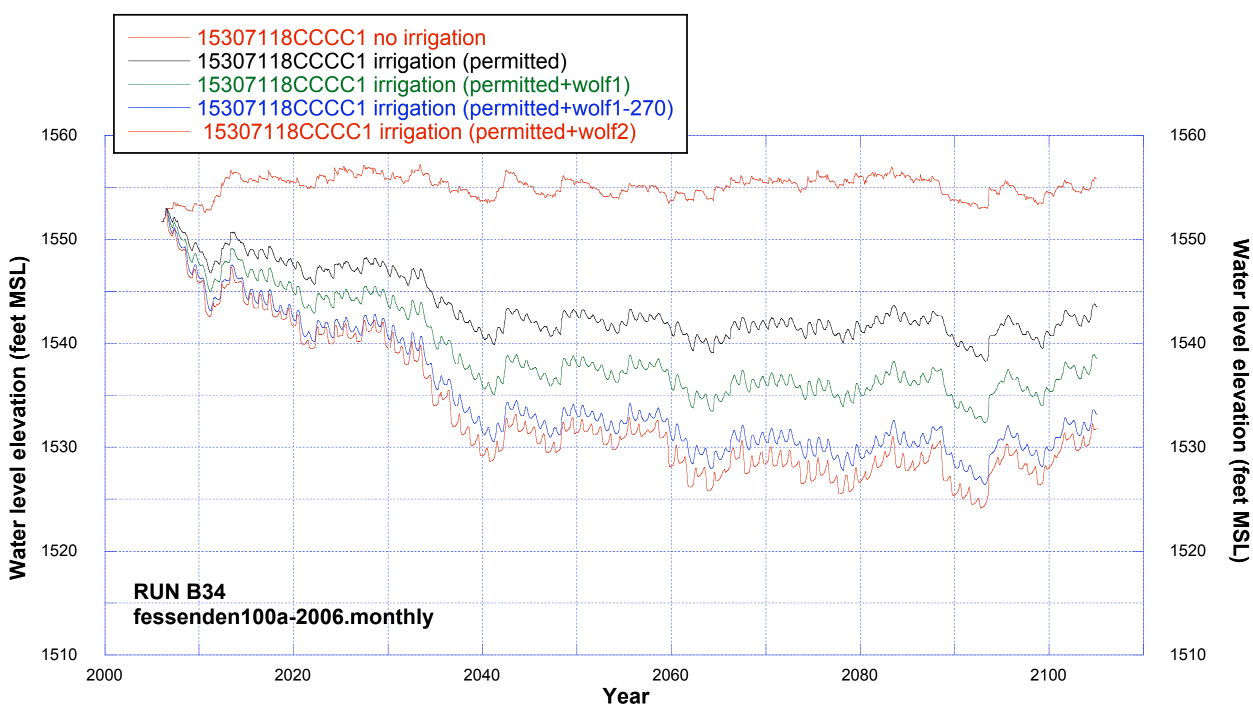


Figure 151. Comparisons of simulated water levels at observation well 153-071-18CCCC1 (Trappers Coulee aquifer) using fessenden100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

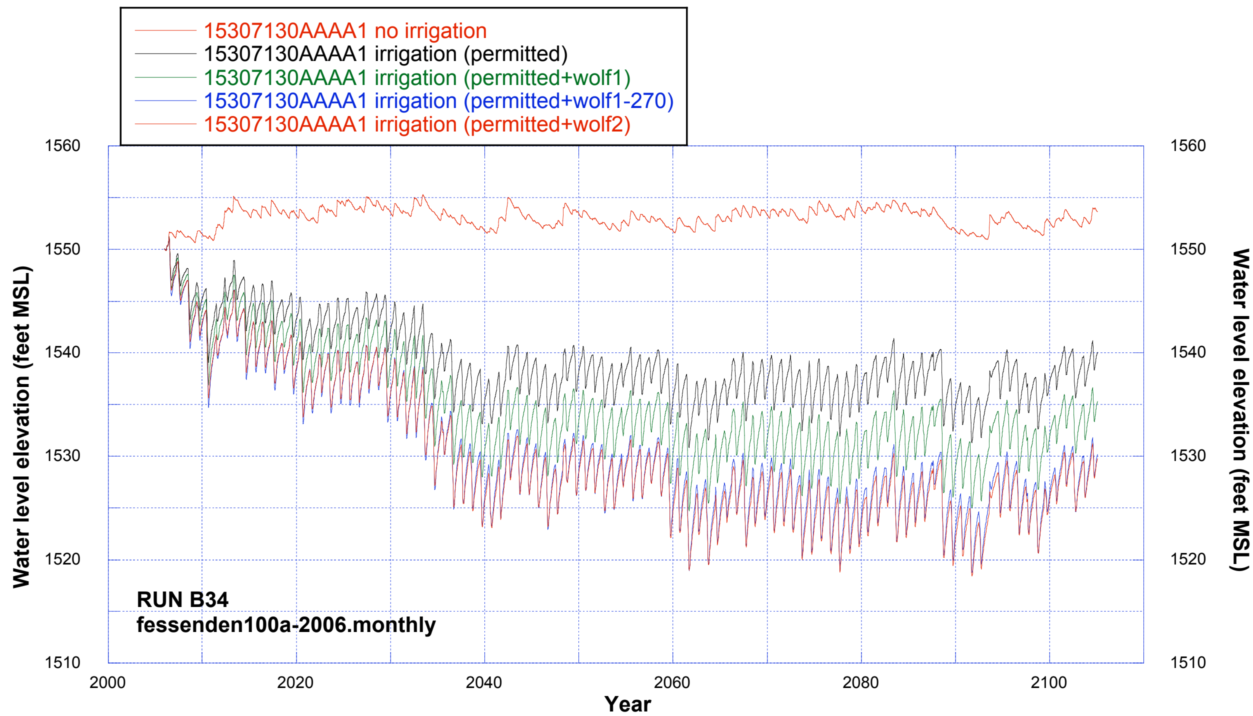


Figure 152. Comparisons of simulated water levels at observation well 153-071-30AAAA1 (Trappers Coulee aquifer) using fessenden100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

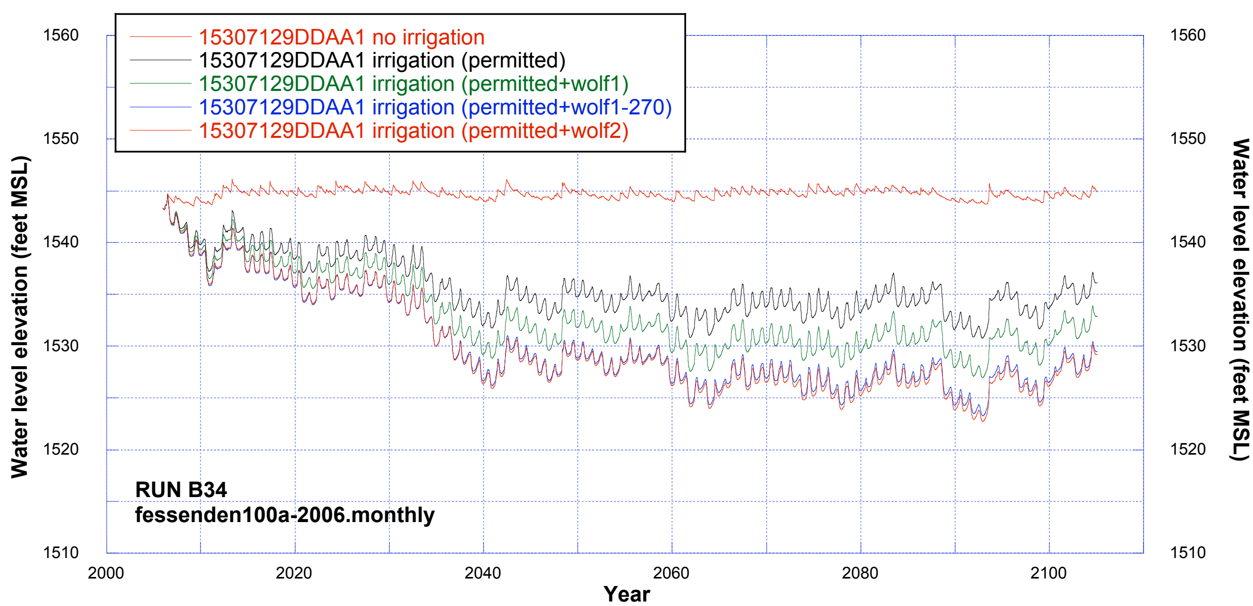


Figure 153. Comparisons of simulated water levels at observation well 153-071-29DDAA1 (Trappers Coulee aquifer) using fessenden100a-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

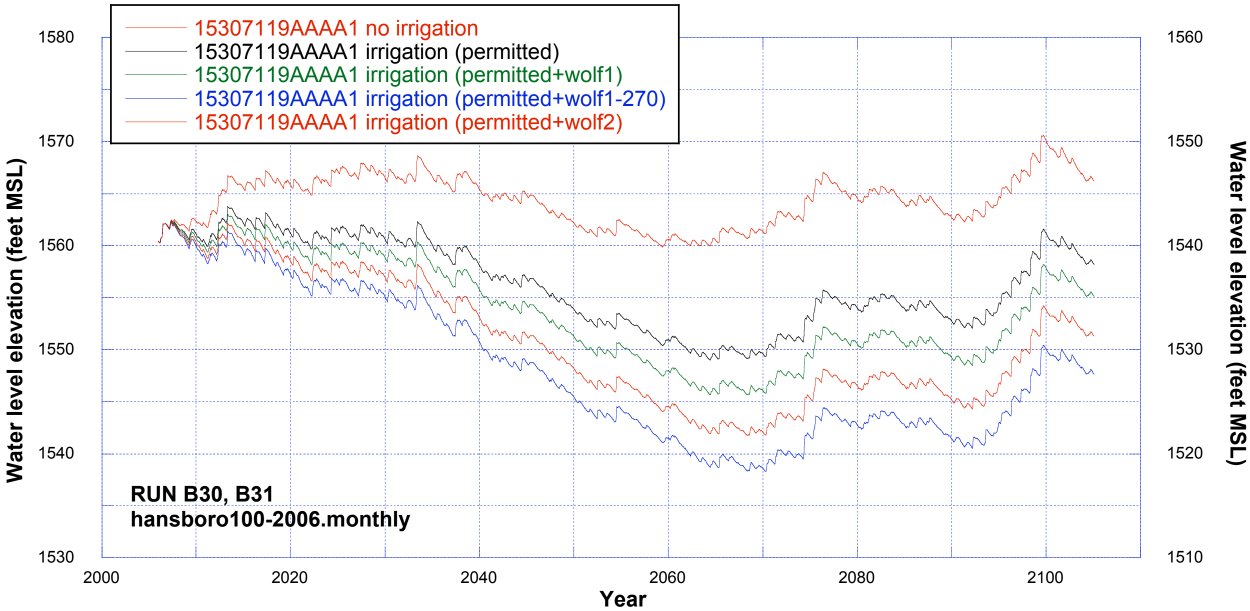


Figure 154. Comparisons of simulated water levels at observation well 153-071-19AAAA1 (Fox Hills aquifer) using hansboro100-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

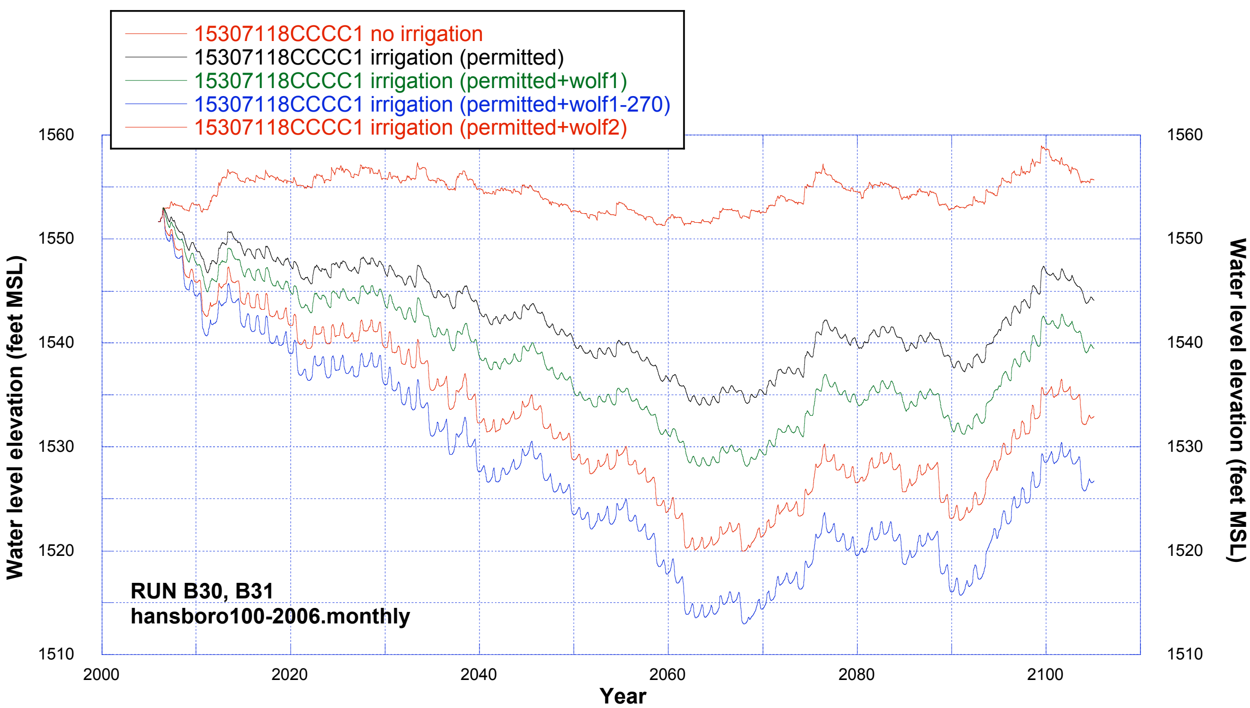


Figure 155. Comparisons of simulated water levels at observation well 153-071-18CCCC1 (Trappers Coulee aquifer) using hansboro100-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

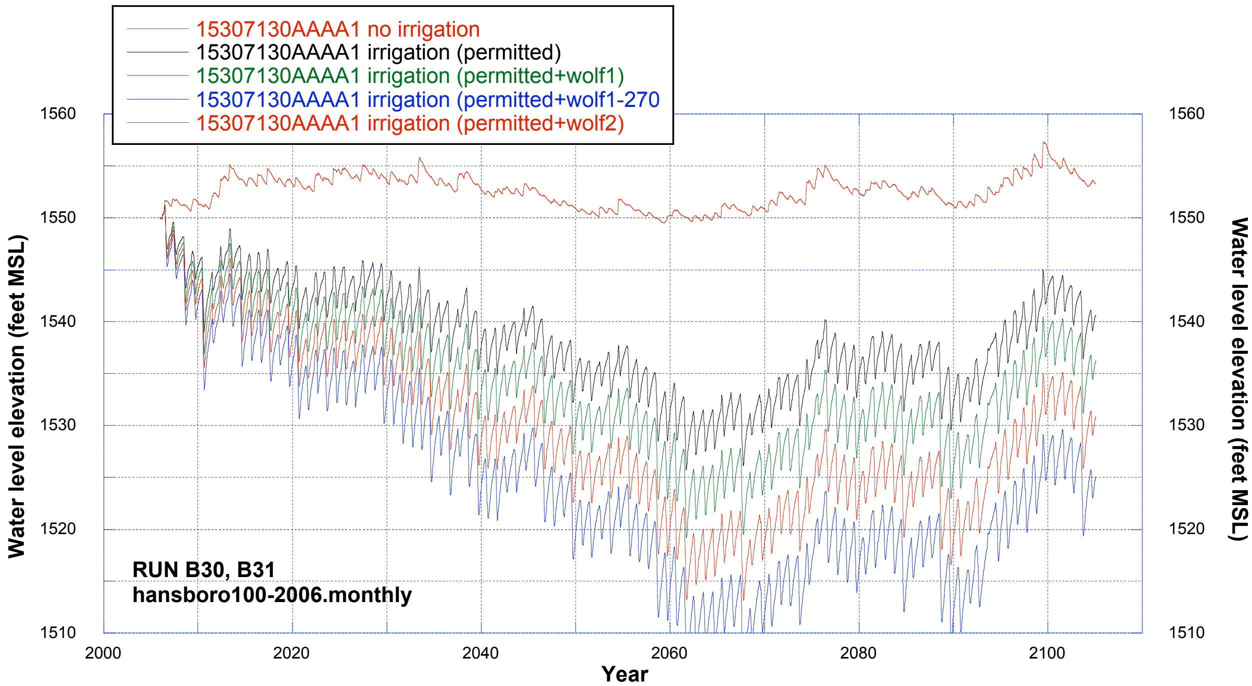


Figure 156. Comparisons of simulated water levels at observation well 153-071-30AAAA1 (Trappers Coulee aquifer) using hansboro100-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

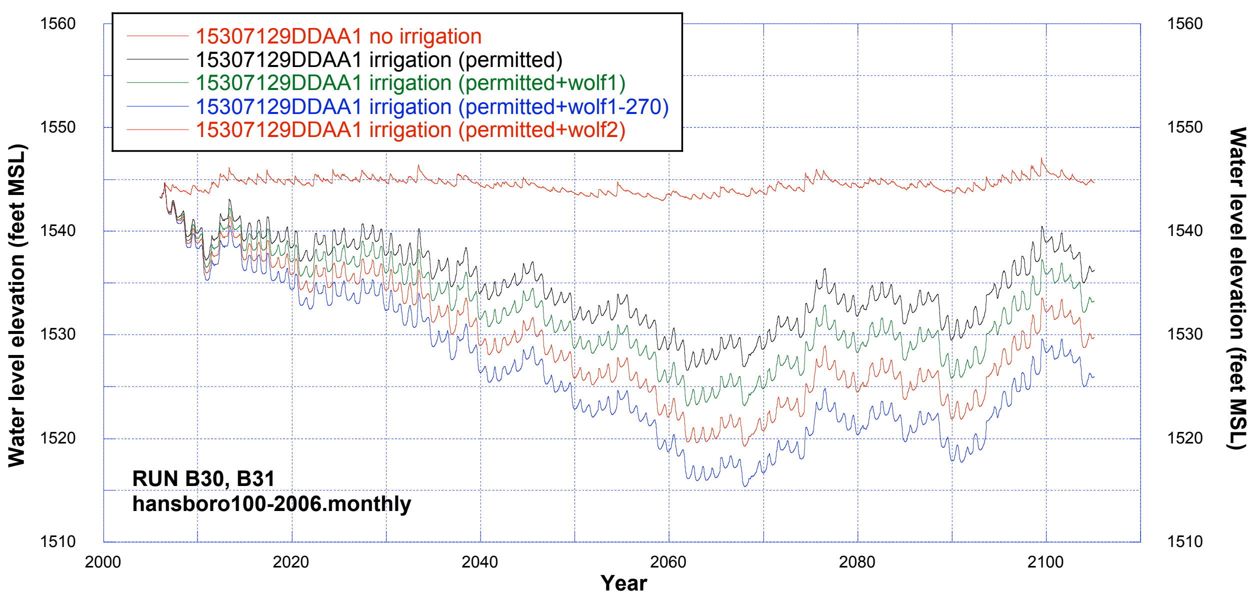


Figure 157. Comparisons of simulated water levels at observation well 153-071-29DDAA1 (Trappers Coulee aquifer) using hansboro100-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

Irrigation Wells

The primary concern is what impact additional pumping will have upon existing irrigation wells. To examine the drawdown at the irrigation wells, the drake-carr93 climate dataset was chosen as in it represents a likely response. Hydrographs for the irrigation well nodes plus a new well in the center of the SE1⁄4 Section 19 are shown in figures 158 to 161. The screened intervals are presented in table 23.

location	top screen	bottom screen	bottom	elevation	elev. top screen	elev. bottom screen	saturated thickness
153-071-29BBD	49	79	82	1560	1511	1481	72
153-071-20CCDB2	71	91	93	1565	1494	1474	78
153-071-29ACAA2	65	85	85	1565	1500	1480	65

Table 23. Screened interval and saturated thickness at the three irrigation wells completed in the Trappers Coulee aquifer. Units in feet.

The simulated water levels for the irrigation well nodes are <u>not</u> the actual water levels that would occur in a pumping well. The water level for a pumping well node represents a well of an effective radius r_e determined by the node size instead of the actual well radius, where $r_e = (\Delta x+\Delta y)/9.62$ (Planert, 1997). For the Trappers Coulee model with a uniform node size of 200 feet, r_e = 41.6 feet. Also, the simulated well's pumping rate is the average rate to pump a specified volume of water in the length of the stress period (1 month) and therefore may be less than the actual pumping rate of the well.

Since this is an unconfined aquifer, a determination of the water level in an irrigation well at the node center from the drawdown requires the application of the Dupuit-Forchheimer correction. To evaluate the impact on decreases in saturated thickness on the difference between node and well, drawdown was evaluated with an analytical solution. The results are presented in Table 24. Irrigation well 153-071-20CCDB2 was chosen for the analysis. Beginning of irrigation season saturated thicknesses were determined from figure 158 for the period 2045 to 2047. For these saturated thicknesses, drawdown was calculated at the effective node radius of 41.6 feet and a well radius of 0.5 feet using the hydraulic properties specified in the model. In this case, the actual well drawdown increased from 7.1 feet at the beginning of development to 17.8 feet for the permited+wolf-270 case above the well node drawdown.

Given the assumptions of the model, the present level of development is sustainable, even with a slightly drier climate. However, for either the permitted+wolf1-270 or permitted+wolf2 case there are times when the existing irrigation wells would have drawdowns into the well screens and possible reductions in well yield.

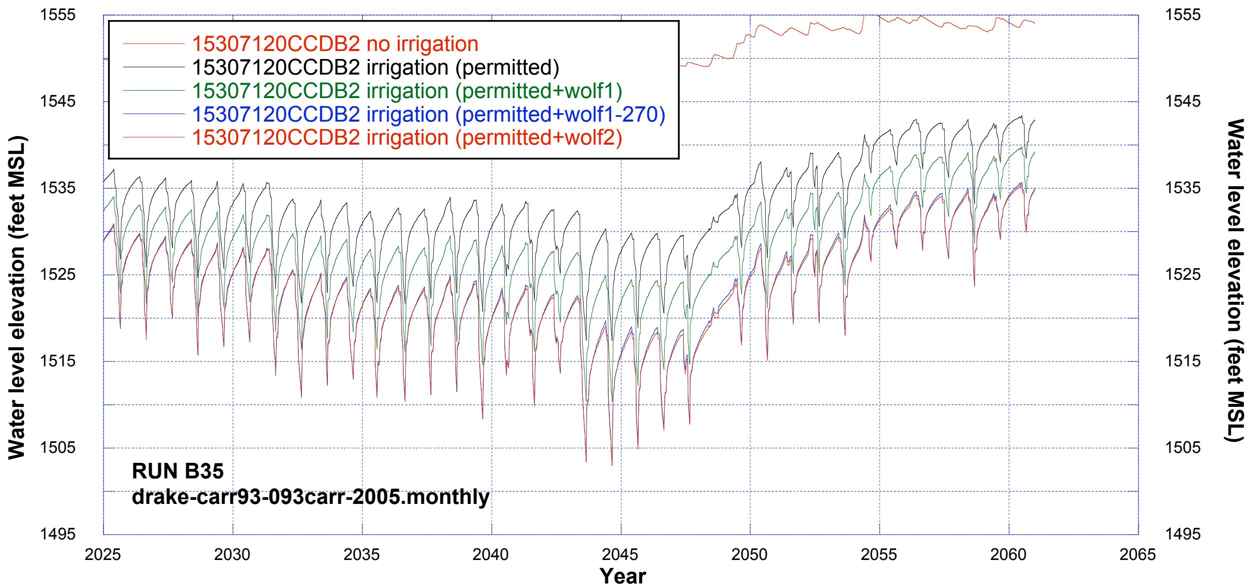


Figure 158. Simulated water levels at irrigation well 153-071-20CCDB2 (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

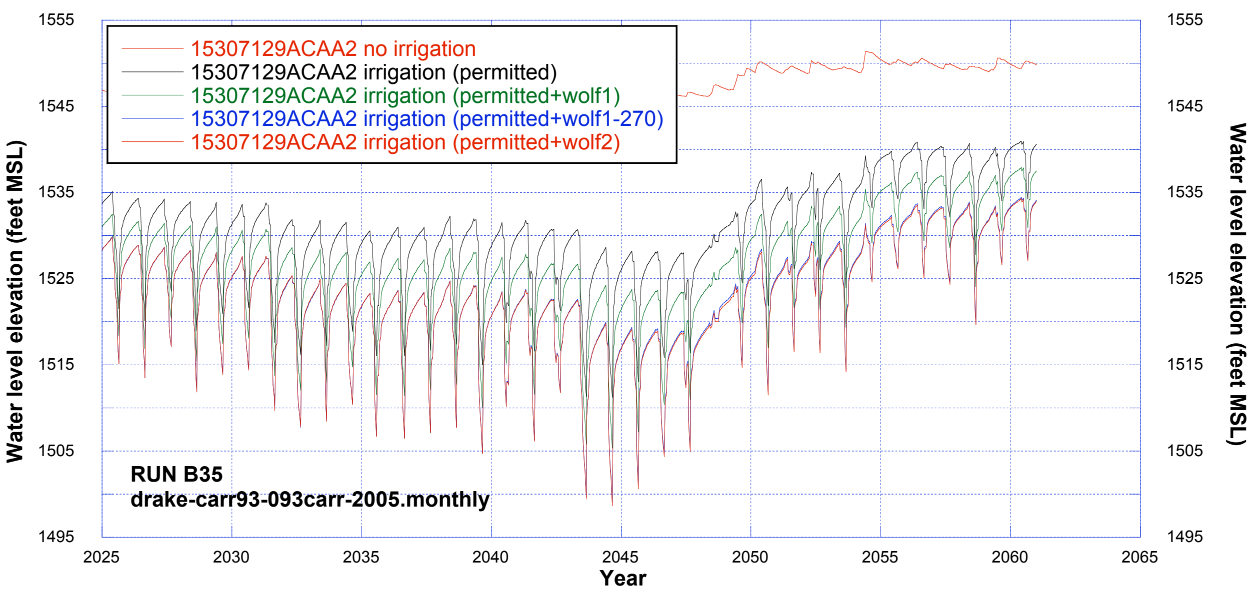


Figure 159. Simulated water levels at irrigation well 153-071-29ACAA2 (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

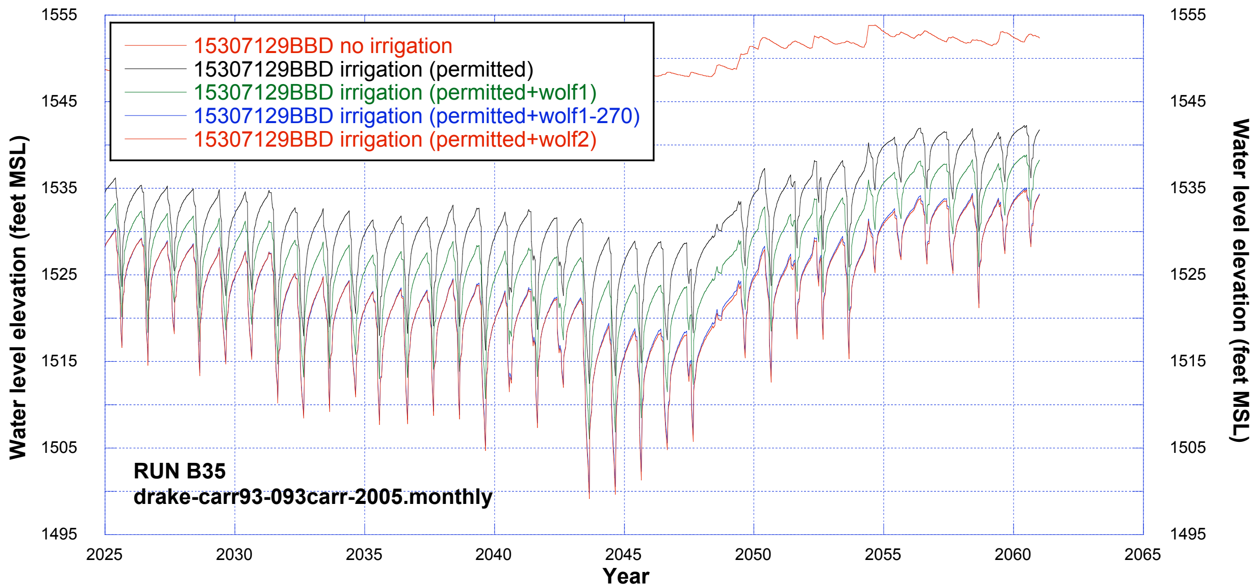


Figure 160. Simulated water levels at irrigation well 153-071-29BBD (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

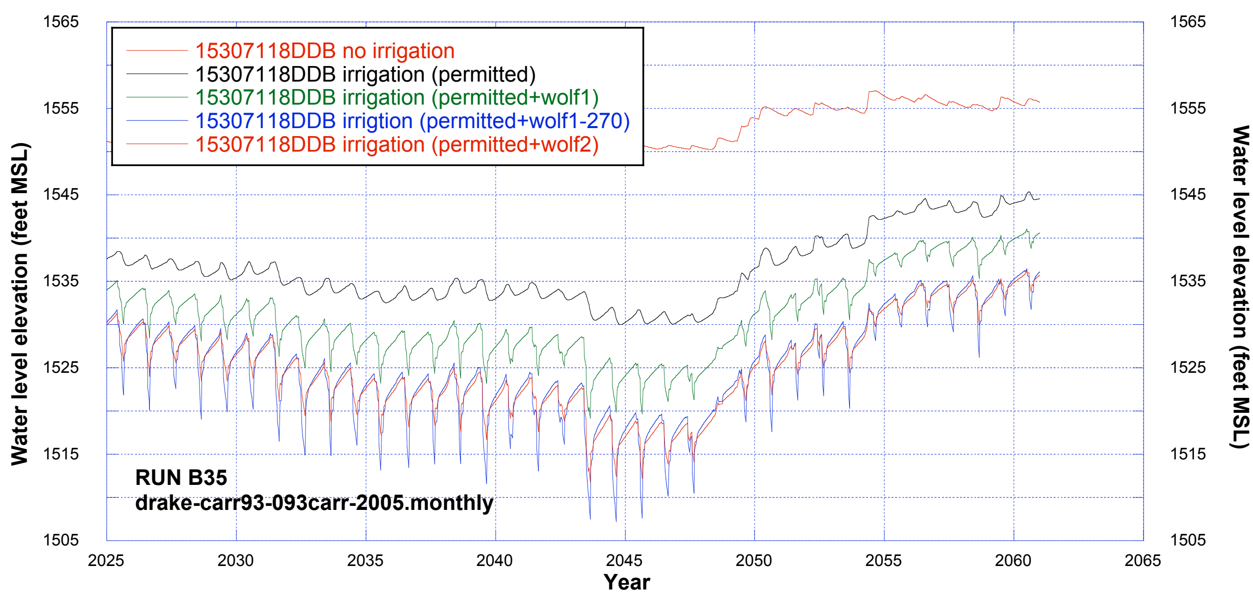


Figure 161. Simulated water levels at proposed irrigation well 153-071-18DDB (Trappers Coulee aquifer) using drake-carr93carr-2005.monthly recharge dataset for cases of no irrigation, permitted irrigation, and additional irrigation.

Scenario	saturated thickness	r = 41.6 feet	r = 0.5 feet	well correction (feet)
no irrigation	78	5.705	12.799	7.1
permitted	58	7.61	18.454	10.8
+wolf1	51	8.687	22.451	13.8
+wolf1-270	46	9.713	27.522	17.8

Table 24. Analytical solution using Theis equation with Dupuit-Forchheimer correction for drawdown at irrigation well 153-071-20CCDB2 after 20 days of pumping assuming saturated thickness at start of irrigation season is the same as shown in figure 158 for period 2045 to 2047.

Summary and Conclusions

The conceptual model of the Trappers Coulee aquifer is significantly flawed. Though the model can reproduce water levels prior to the mid-1990s, including the 1988 to 1992 drought, reasonably well, the model tends to underestimate the impact of the 1988-1992 drought. The model fails miserably to reproduce the water levels with the increased irrigation during the recent pluvial. This is likely due either to a failure to route recharge from the adjacent largely unsaturated area rapidly enough to the meltwater channel and/or to surface water runoff being a very significant part of total recharge. Analysis of Sheyenne River runoff in the vicinity of the study area indicates it was two to three times as great during the pluvial as during the period from 1940 to 1993. The thinly saturated outwash area was modeled as a single layer combining outwash with the underlying Fox Hills Formation. Though this may represent average recharge to the meltwater channel well, it likely does not capture the variability. Attempts to model the outwash and Fox Hills aquifer as two separate layers failed because the model instability could not be overcome.

However, an indication the model captures some of the characteristics of the system is that it provides reasonable estimates of stream flow in Trappers Coulee, a gaining stream as it flows across the aquifer. Because, in the model, much of the recharge to the meltwater channel occurs as inflow from the Fox Hills aquifer over long flow paths, much of the effect of climate variability on recharge is dampened out. Matching water levels in the meltwater channel during calibration likely results in a reasonable total average recharge to the system. The accuracy of the steady-state recharge estimate for the UTC aquifer is dependent only on the accuracy of the estimates of hydraulic conductivity and channel geometry.

The tendency of the model to underestimate water levels at the division between the UTC and LTC while at the same time overestimating the gradient in UTC must be due either to a significant restriction in the aquifer near the division or to Trappers Coulee providing significant recharge to the aquifer that is able to maintain heads near land surface in the upper part of the LTC. If Trappers Coulee is a source of significant recharge, then the model is conservative in its estimates of the impact of additional appropriation on the UTC.

The modeling indicates that the primary sources of water to the UTC meltwater channel are direct recharge and recharge from the outwash area on the north side of the meltwater channel. That the Fox Hills aquifer underlying the outwash area is not the means of transmittal of this water to the meltwater channel is indicated by the fact that the water at NDSWC observation well 153-071-19AAAA1 has low TDS (388 mg/l) and is almost pure sodium-bicarbonate water, which is not characteristic of the bulk of the water in the UTC. This interpretation is supported by the water quality data where the characteristic sodium-bicarbonate water of the Fox Hills Formation is observed only in the stagnant flow area at the start of the aquifer and in wells near the base of the Trappers Coulee aquifer. The Fox Hills aquifer likely contributes less than 20% of the inflow into the UTC. Therefore, given the small regional hydraulic conductivity of the Fox Hills aquifer and the confined response, it is unlikely that water level declines within the UTC would induce significant additional flow out of the Fox Hills.

The model indicates that the long-term response to the presently permitted appropriation would be on average a 10- to 15-foot decline in water levels, with more drawdown during drought periods. An additional 135 acres of irrigation results in about 5 additional feet of drawdown. Addition of another quarter would double this. The present permitted level of development is sustainable over the long-term in all five climate scenarios evaluated. The addition of 270 acres of irrigation would result in drawdown into the screens of the existing irrigation wells during drought periods and possible reduction in well yields in the drake-carr93, minot, and bottineau scenarios.

The UTC aquifer presently has 60 to 80 feet of available drawdown with the irrigation wells ranging between 65 and 78 feet. If the long-term equilibrium drawdown does not reduce this too much, then the aquifer has the capability to survive long periods of drought with the large amount of water in storage. Trappers Coulee has not been considered as a source of recharge to the aquifer. However, some additional recharge should occur to the aquifer from stream infiltration as water levels decline due to pumping.

The amount of recharge to the aquifer will depend on future weather and climate. Local variability in precipitation can have a significant impact on water availability on a multi-decadal scale. Even if it was known what the climate would be for the next century, the stochastic nature of precipitation events will significantly impact the amount of water available for appropriation from the aquifer. The climate of the 20th century is likely a poor guide to the climate of 21st century.

There is some risk to additional appropriation, but most likely the aquifer can sustain at least one and probably two additional quarters of irrigation. There is very large uncertainty about the inflow of surface water from Trappers Coulee into upper part of the LTC and its ability to maintain water levels with increased appropriation from the aquifer. Even if additional appropriation in the end does result in over-appropriation, many years of operation could be sustained before operation would need to cease without unacceptable effect on senior water rights.

Many aquifers in North Dakota have thinly saturated adjoining outwash areas overlying small permeability sediments that contribute significant recharge to the aquifer. Both the total quantity and the variability and time lags in recharge from such areas can be very important to water management. Finding a stable solution to modeling thinly saturated outwash needs to be done. Further work should be done using the Trappers Coulee model to explore solutions to the simulation of thinly saturated outwash areas that are adjacent to significant aquifers.

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