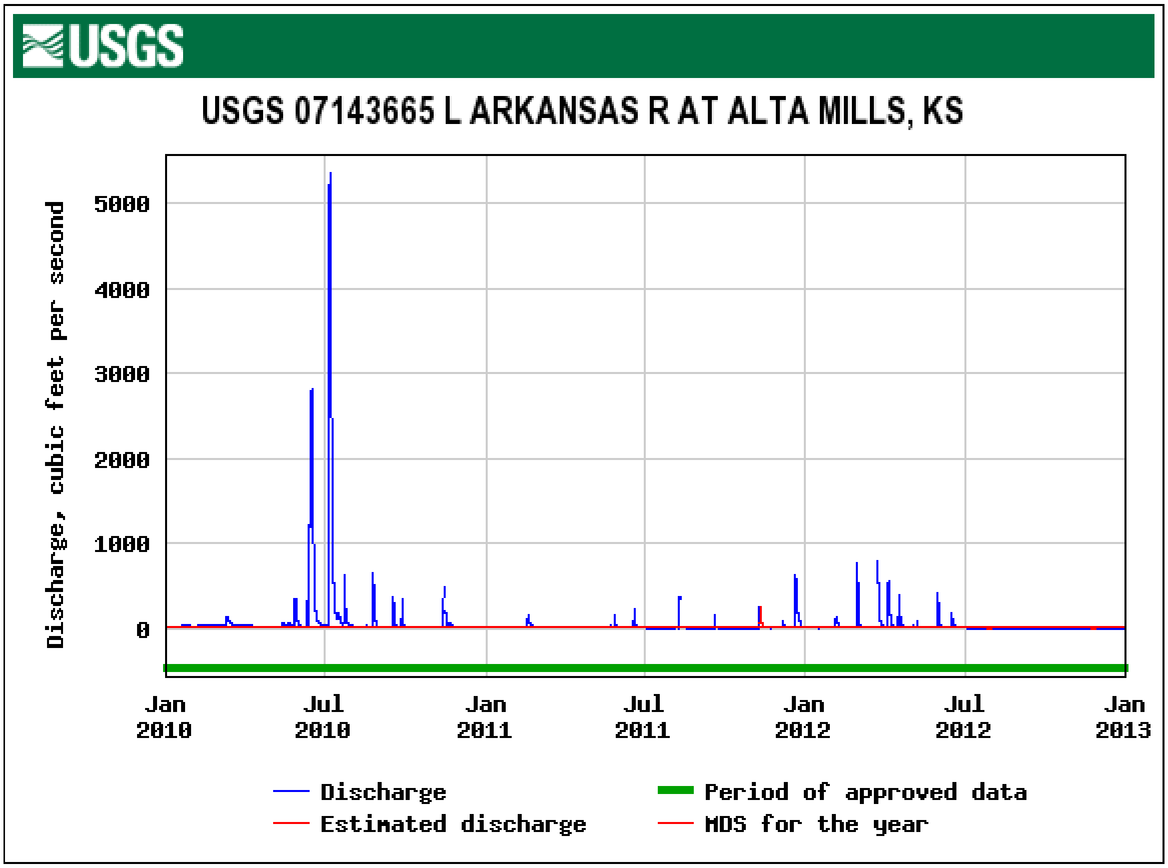
ATTACHMENT F
Historic NOAA PDSI Values for South-Central Kansas

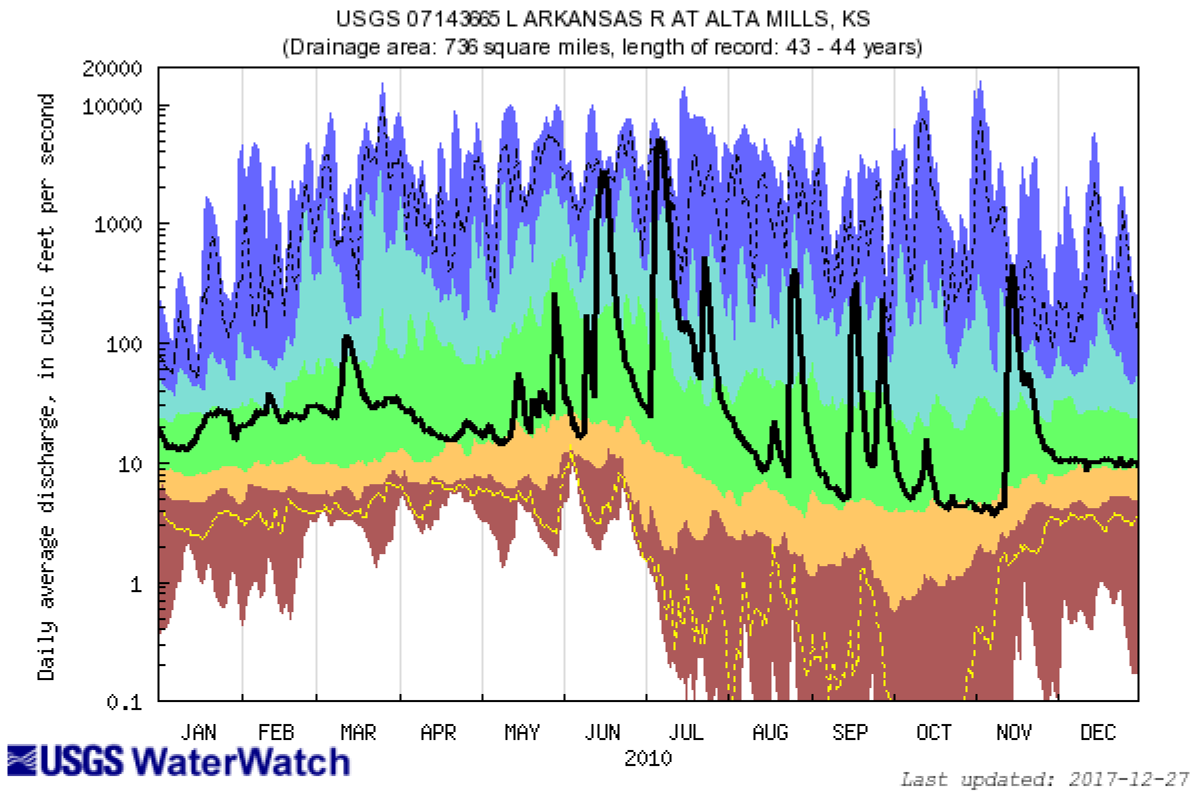
Annual and Seasonal Total PDSI Comparison
South Central Kansas
from
http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp
Annual: 12 month total; Seasonal: 6 month growing season

South Central KS PDSI

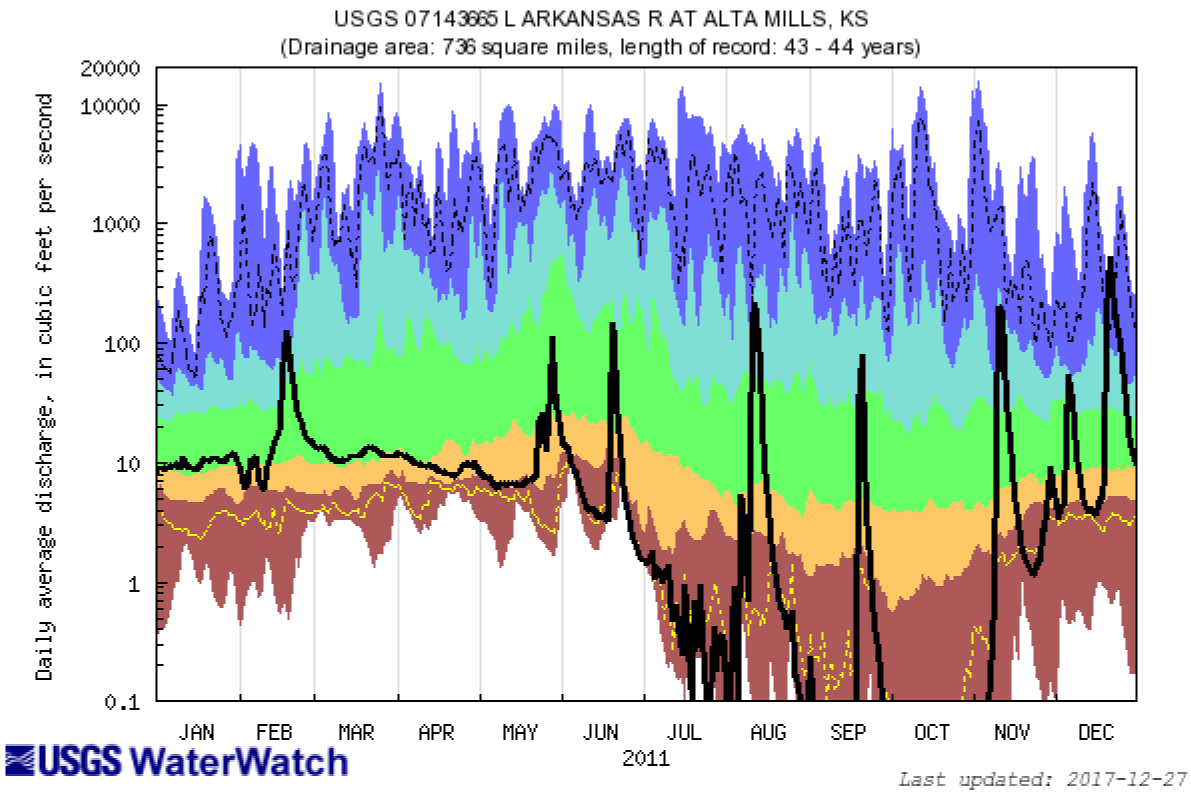
Year	PDSI Date	Annual	Seasonal	Rank		Year	PDSI Date	Annual	Seasonal	Rank
1901	10/01/1901	-11.42	-10.51	27		**1959**	10/01/1959	24.17	10.26	76
1902	10/01/1902	-6.07	11.07	79		**1960**	10/01/1960	32.79	14.66	89
1903	10/01/1903	9.08	0.51	52		**1961**	10/01/1961	25.54	16.45	98
1904	10/01/1904	10.84	12.82	84		**1962**	10/01/1962	36.51	11.75	81
1905	10/01/1905	-2.07	2.33	57		**1963**	10/01/1963	-19.97	-16.03	14
1906	10/01/1906	1.88	5.43	69		**1964**	10/01/1964	-39.35	-23.14	8
1907	10/01/1907	31.04	14.43	88		**1965**	10/01/1965	17.74	15.94	96
1908	10/01/1908	31.72	17.49	101		**1966**	10/01/1966	0.6	-14.77	20
1909	10/01/1909	0.42	-2.88	45		**1967**	10/01/1967	-40.68	-17.15	13
1910	10/01/1910	-2.68	-12.86	23		**1968**	10/01/1968	-22.06	-5.03	40
1911	10/01/1911	-32.23	-15.05	19		**1969**	10/01/1969	23.54	15.47	93
1912	10/01/1912	6.09	5.9	70		**1970**	10/01/1970	-4.93	-5.44	39
1913	10/01/1913	-21.38	-18.06	11		**1971**	10/01/1971	-16	-6.85	34
1914	10/01/1914	-16.79	-8.3	33		**1972**	10/01/1972	1.21	0.24	50
1915	10/01/1915	16.52	24.99	113		**1973**	10/01/1973	31.25	19.28	103
1916	10/01/1916	33.66	3.93	63		**1974**	10/01/1974	42.67	13.96	86
1917	10/01/1917	-21.66	-12.6	24		**1975**	10/01/1975	19.04	2.2	56
1918	10/01/1918	-25.84	-8.39	32		**1976**	10/01/1976	-7.17	-1.42	49
1919	10/01/1919	15.94	0.93	53		**1977**	10/01/1977	-4.21	4.89	66
1920	10/01/1920	-17.25	-3.33	44		**1978**	10/01/1978	-3.62	-2.45	47
1921	10/01/1921	7.62	0.98	54		**1979**	10/01/1979	-0.3	3.6	61
1922	10/01/1922	3.64	4.76	65		**1980**	10/01/1980	4.65	-8.53	30
1923	10/01/1923	3.21	12.62	83		**1981**	10/01/1981	-18.43	2.34	58
1924	10/01/1924	19.62	-4.25	41		**1982**	10/01/1982	15.04	5	68
1925	10/01/1925	-24.24	-15.98	15		**1983**	10/01/1983	1.89	1.95	55
1926	10/01/1926	-19.67	-6.62	35		**1984**	10/01/1984	-2.85	-6.15	36
1927	10/01/1927	20.43	14.7	90		**1985**	10/01/1985	23.1	14.4	87
1928	10/01/1928	29.81	16.26	97		**1986**	10/01/1986	32.84	15.13	91
1929	10/01/1929	34.48	16.8	100		**1987**	10/01/1987	49.16	27.03	115
1930	10/01/1930	-4.03	-5.58	38		**1988**	10/01/1988	15.71	-8.52	31
1931	10/01/1931	-0.64	-3.84	43		**1989**	10/01/1989	-11.11	8.04	71
1932	10/01/1932	1.59	0.28	51		**1990**	10/01/1990	-2.27	-4.21	42
1933	10/01/1933	-30.98	-23.76	7		**1991**	10/01/1991	-30.85	-21.19	10
1934	10/01/1934	-51.12	-28.65	3		**1992**	10/01/1992	5.03	10.19	75
1935	10/01/1935	-31.22	-8.85	29		**1993**	10/01/1993	49.15	22.36	109
1936	10/01/1936	-32.46	-23.9	6		**1994**	10/01/1994	-13	-8.88	28
1937	10/01/1937	-37.5	-17.38	12		**1995**	10/01/1995	18.33	15.58	94
1938	10/01/1938	-13	4.15	64		**1996**	10/01/1996	-9.62	2.56	59
1939	10/01/1939	-19.56	-15.27	18		**1997**	10/01/1997	40.74	25.03	114
1940	10/01/1940	-37.18	-15.8	16		**1998**	10/01/1998	46.39	13.33	85
1941	10/01/1941	11.97	12.36	82		**1999**	10/01/1999	43.75	24.22	111
1942	10/01/1942	36.66	18.96	102		**2000**	10/01/2000	33.25	16.62	99
1943	10/01/1943	4.9	-6.06	37		**2001**	10/01/2001	14.9	-2.59	46
1944	10/01/1944	15.88	15.4	92		**2002**	10/01/2002	-28.5	-11.21	26
1945	10/01/1945	38.71	15.73	95		**2003**	10/01/2003	16.77	2.73	60
1946	10/01/1946	-16.75	-11.65	25		**2004**	10/01/2004	6.66	8.11	72
1947	10/01/1947	16.61	4.98	67		**2005**	10/01/2005	26.18	9.19	73
1948	10/01/1948	9.34	10.98	78		**2006**	10/01/2006	-23.46	-15.41	17
1949	10/01/1949	43.07	21.45	107		**2007**	10/01/2007	17.68	19.57	104
1950	10/01/1950	-8.23	-1.81	48		**2008**	10/01/2008	30.75	20.35	105
1951	10/01/1951	15.79	24.26	112		**2009**	10/01/2009	44.76	21.4	106
1952	10/01/1952	17.74	-13.28	21		**2010**	10/01/2010	31	9.37	74
1953	10/01/1953	-43.52	-26.01	4		**2011**	10/01/2011	-23.89	-22.09	9
1954	10/01/1954	-51.82	-29.92	2		**2012**	10/01/2012	-23.04	-13.08	22
1955	10/01/1955	-60.51	-25.6	5		**2013**	10/01/2013	-3	11.37	80
1956	10/01/1956	-59.2	-37.8	1		**2014**	10/01/2014	5.74	3.79	62
1957	10/01/1957	-12.15	22.04	108		**2015**	10/01/2015	6.97	10.45	77
1958	10/01/1958	43.22	22.98	110						

ATTACHMENT G
Streamflows For Arkansas & Little Arkansas Rivers 2011-2012

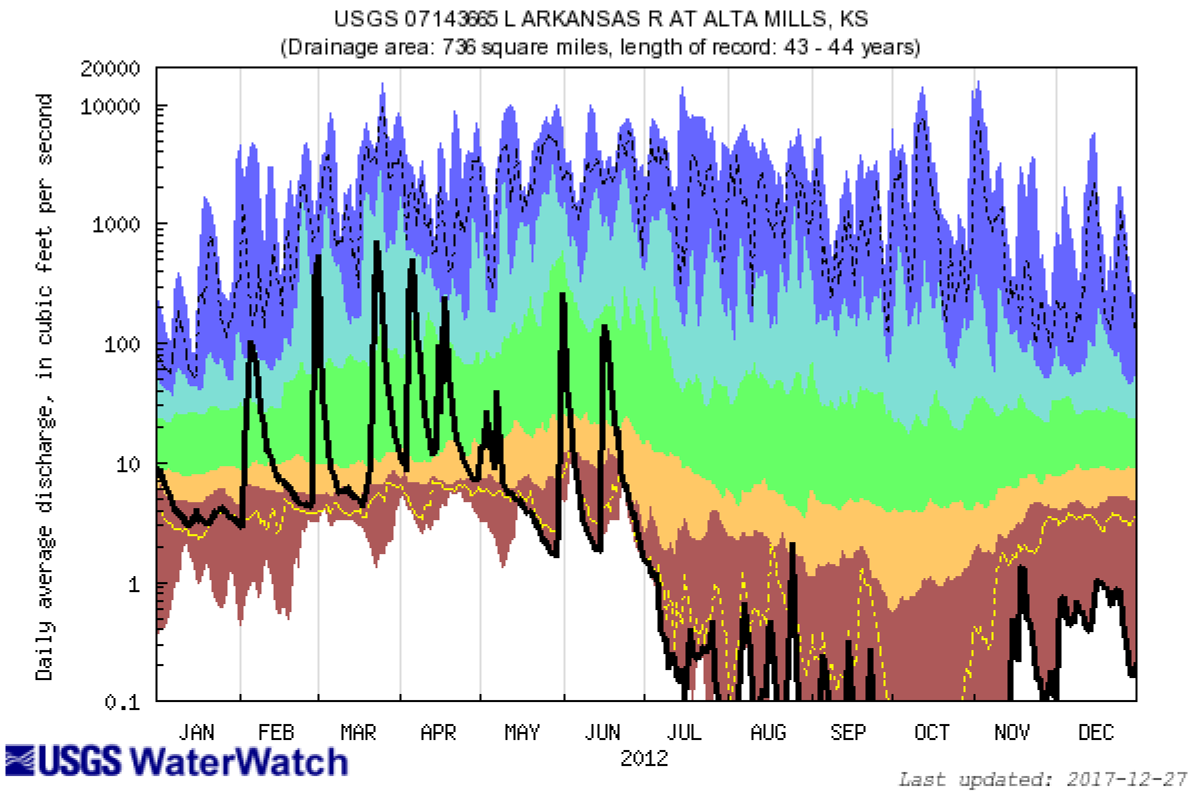

USGS
USGS 07143665 L ARKANSAS R AT ALTA MILLS, KS
Discharge, cubic feet per second
5000
4000
3000
2000
1000
0
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Discharge
Estimated discharge
Period of approved data
MDS for the year



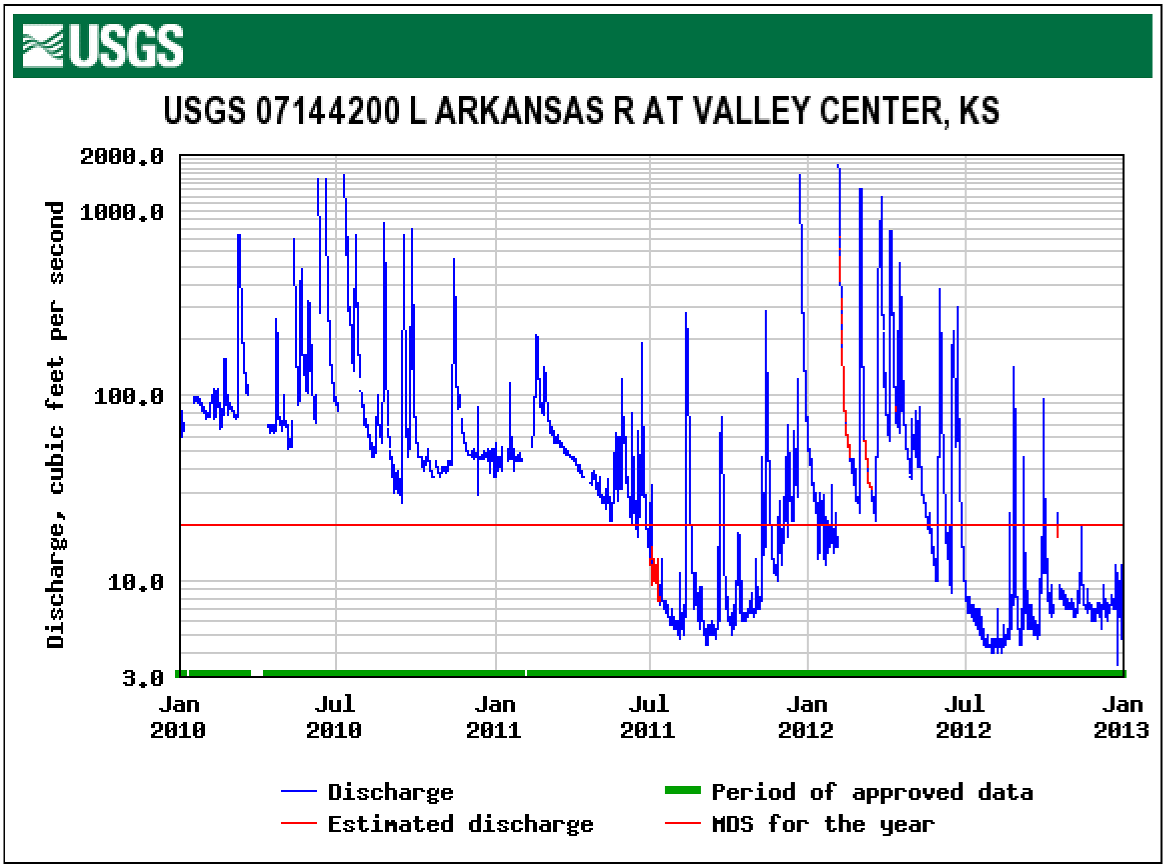
Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		



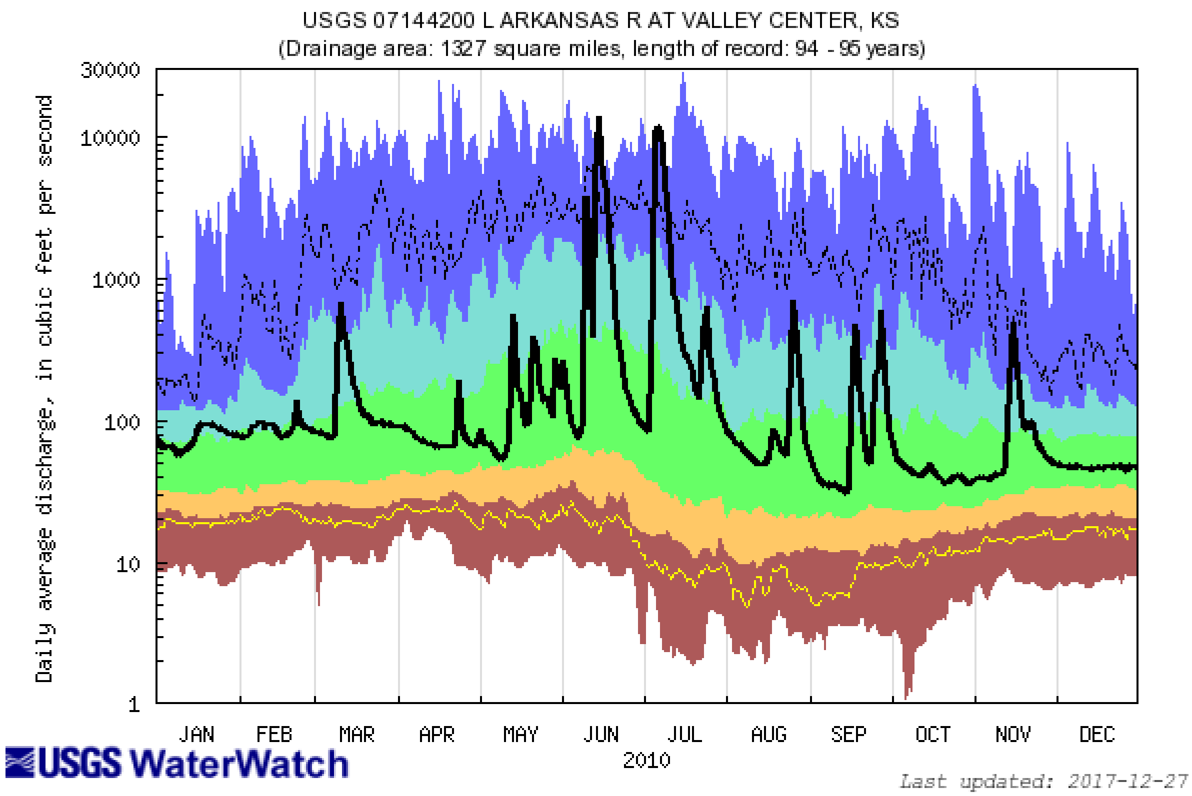
Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

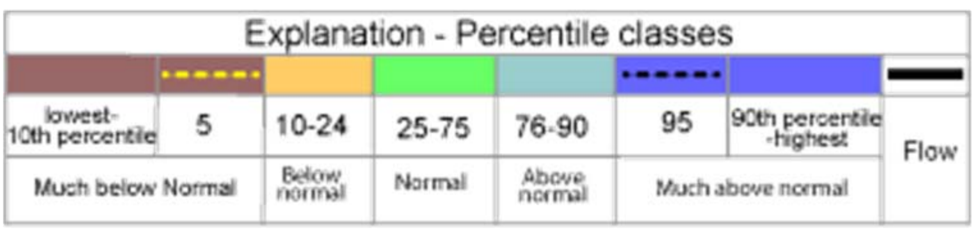


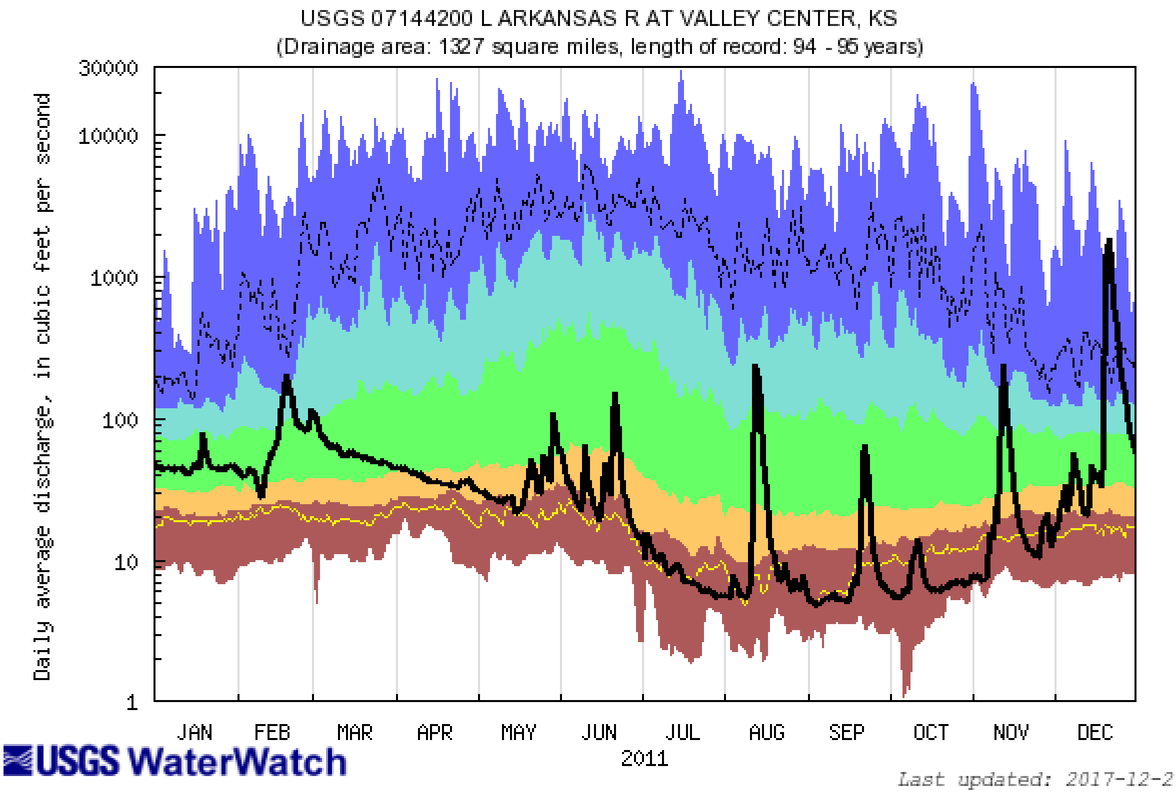
Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		



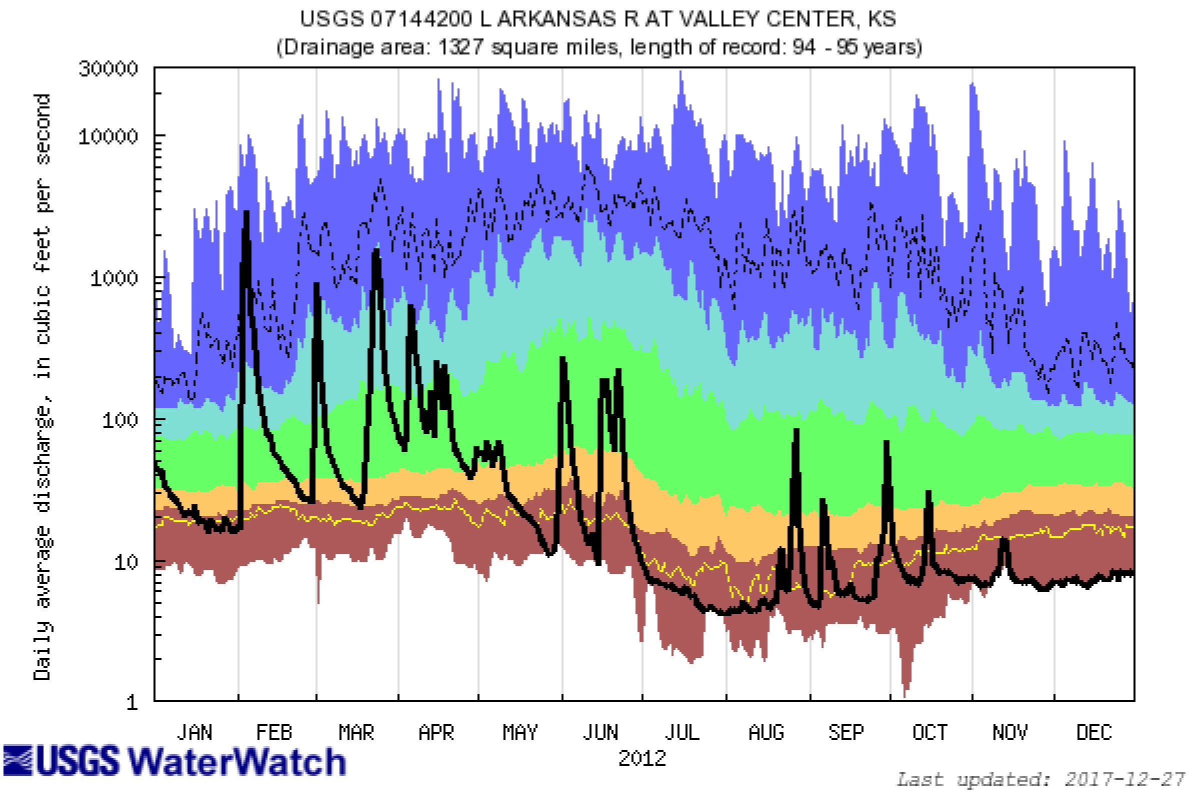
USGS
USGS 07144200 L ARKANSAS R AT VALLEY CENTER, KS
Discharge, cubic feet per second
2000.0
1000.0
100.0
10.0
3.0
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Discharge
Estimated discharge
Period of approved data
MDS for the year


USGS 07144200 L ARKANSAS R AT VALLEY CENTER, KS
(Drainage area: 1327 square miles, length of record: 94 - 95 years)
Daily average discharge, in cubic feet per second
30000
10000
1000
100
10
1
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
2010
USGS WaterWatch
Last updated: 2017-12-27

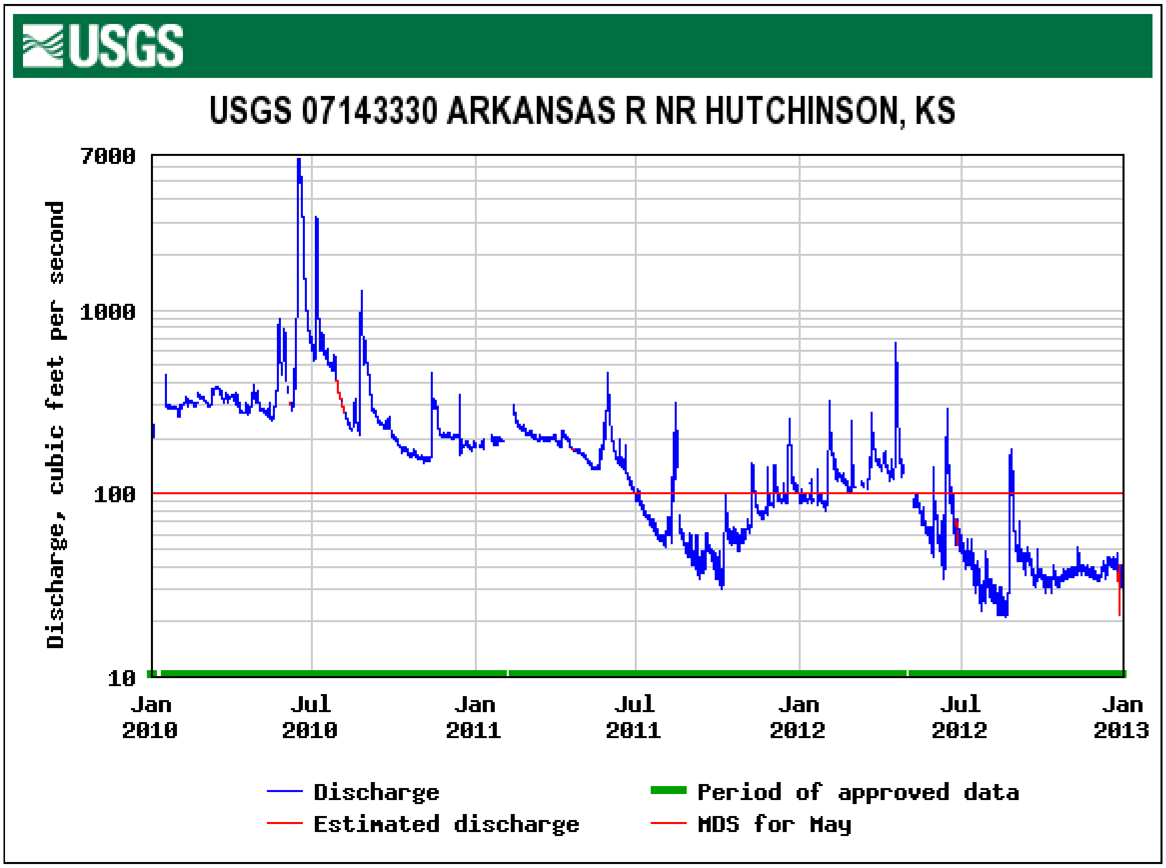

Explanation - Percentile classes
lowest-10th percentile
5
10-24
25-75
76-90
95
90th percentile -highest
Flow
Much below Normal
Below normal
Normal
Above normal
Much above normal

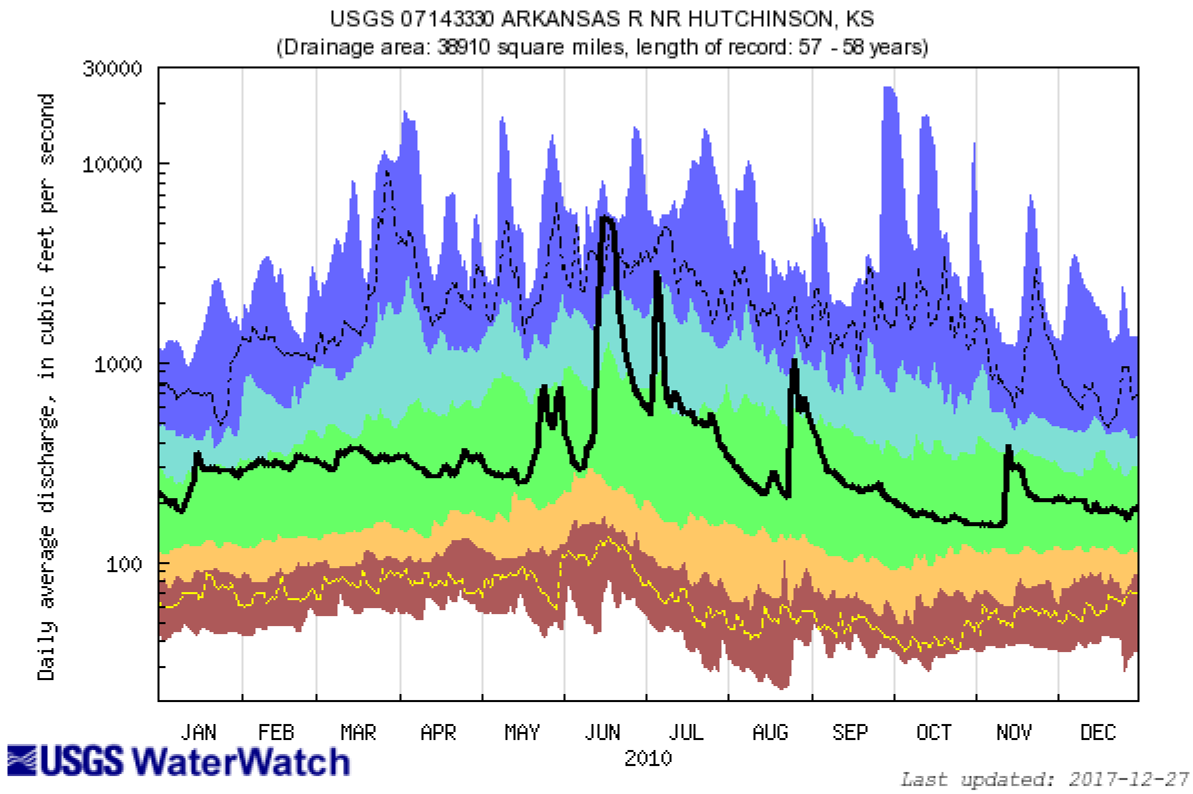


Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		



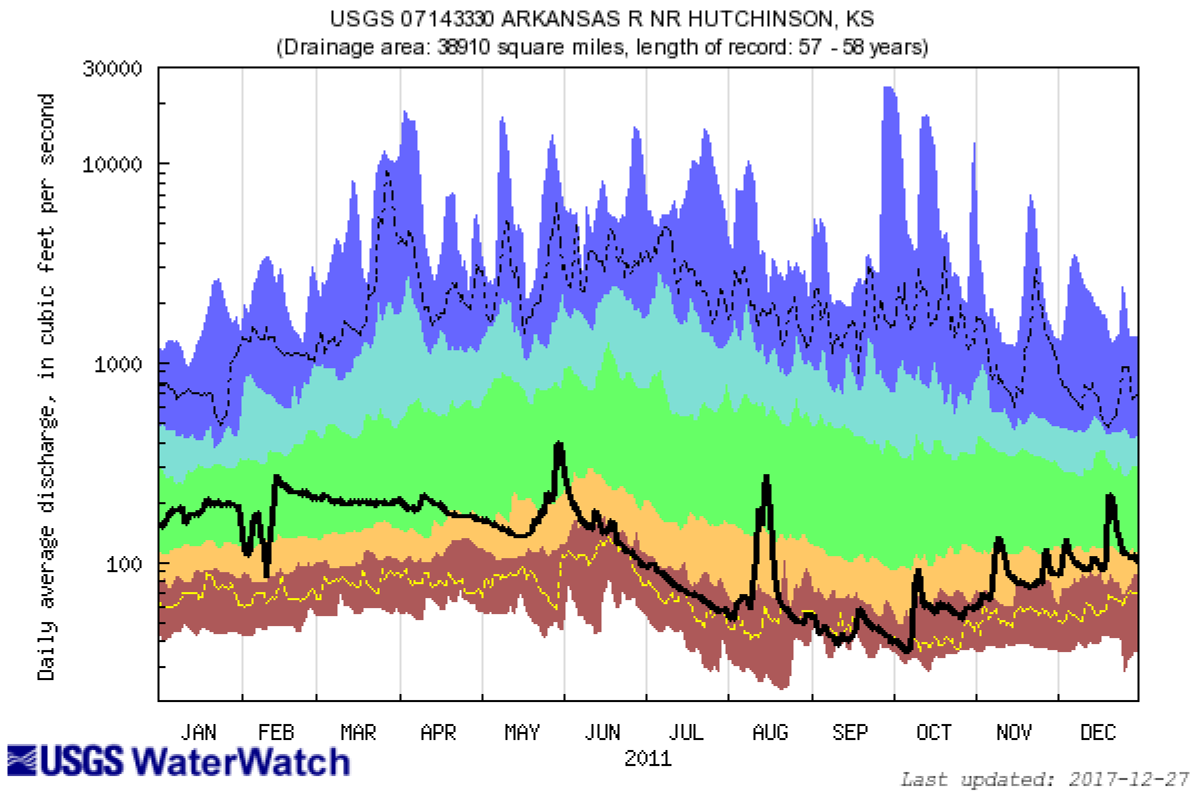
Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		


USGS
USGS 07143330 ARKANSAS R NR HUTCHINSON, KS
Discharge, cubic feet per second
7000
1000
100
10
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Discharge
Estimated discharge
Period of approved data
MDS for May

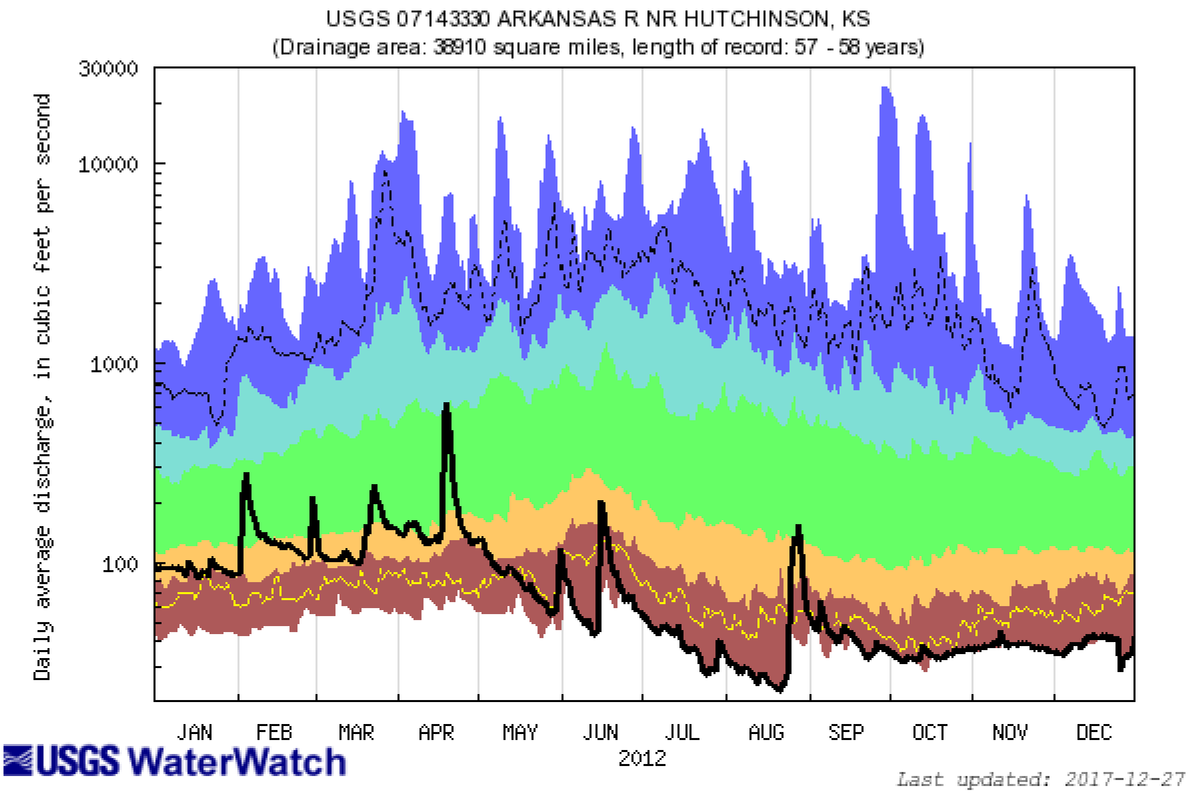


Explanation - Percentile classes

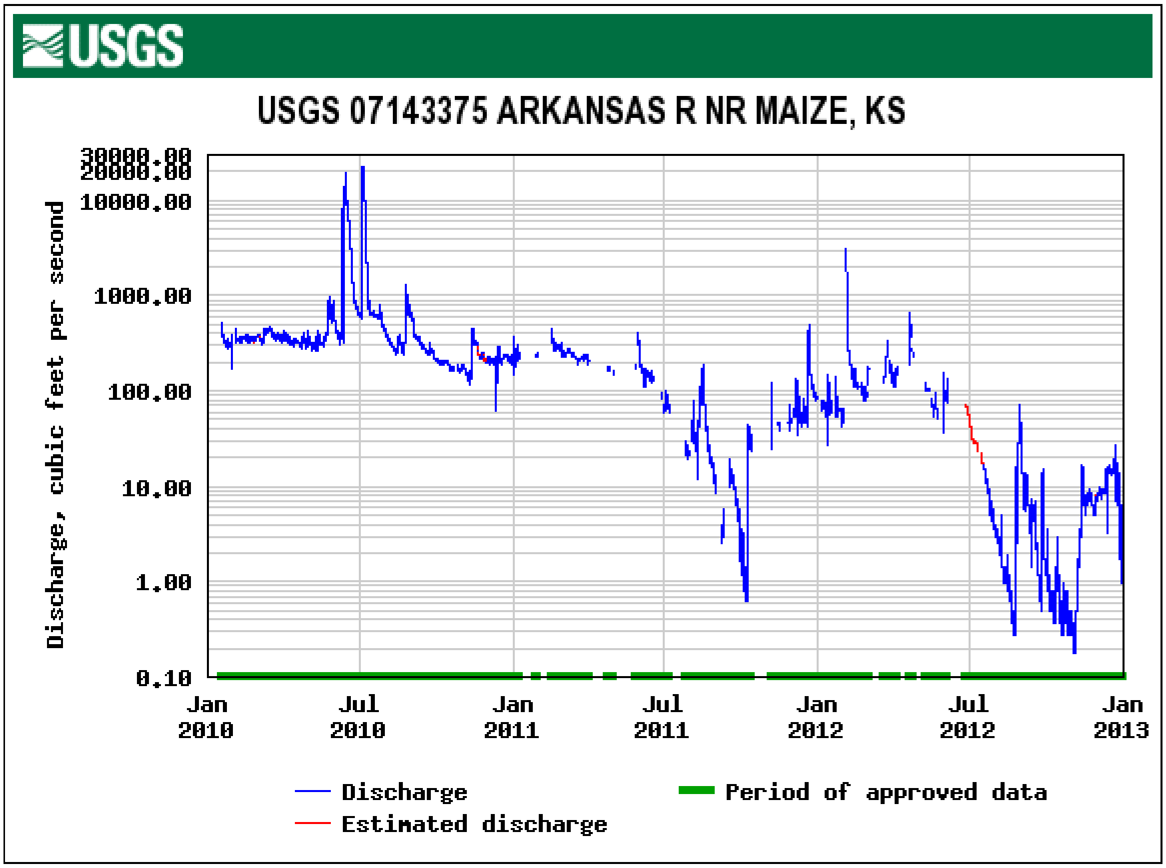
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

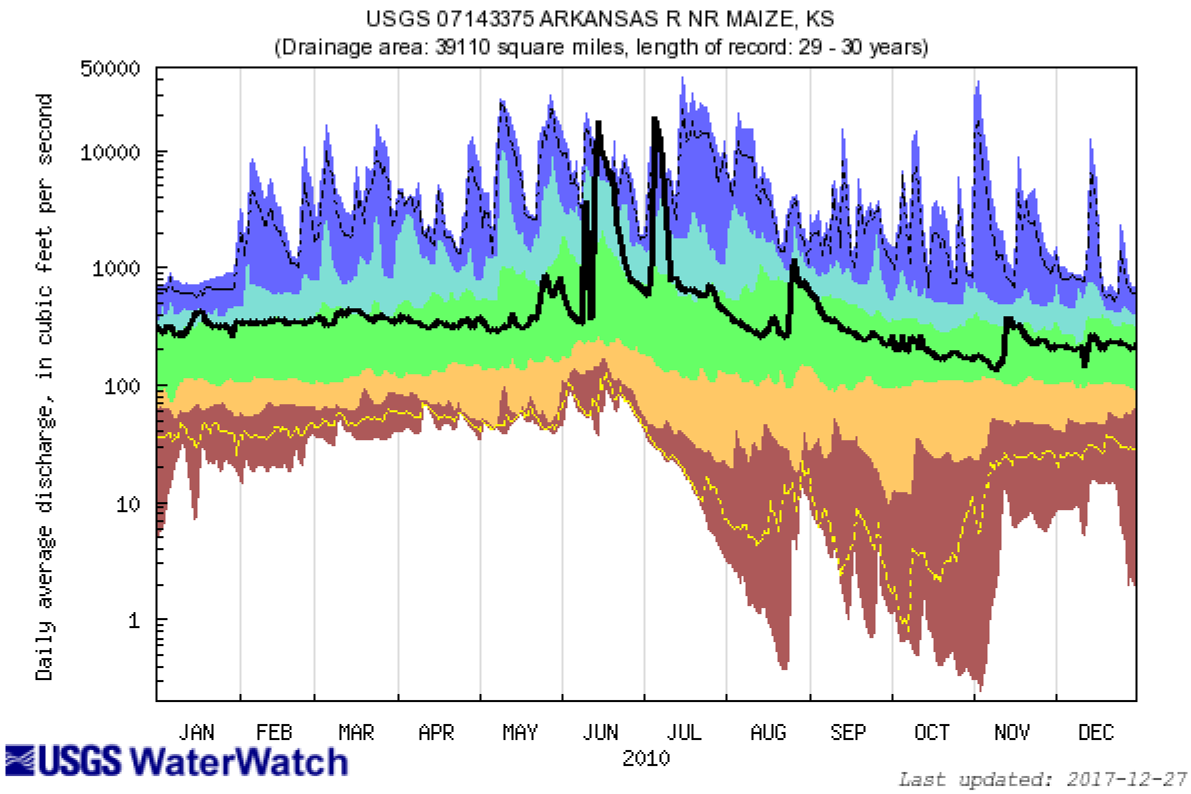


Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

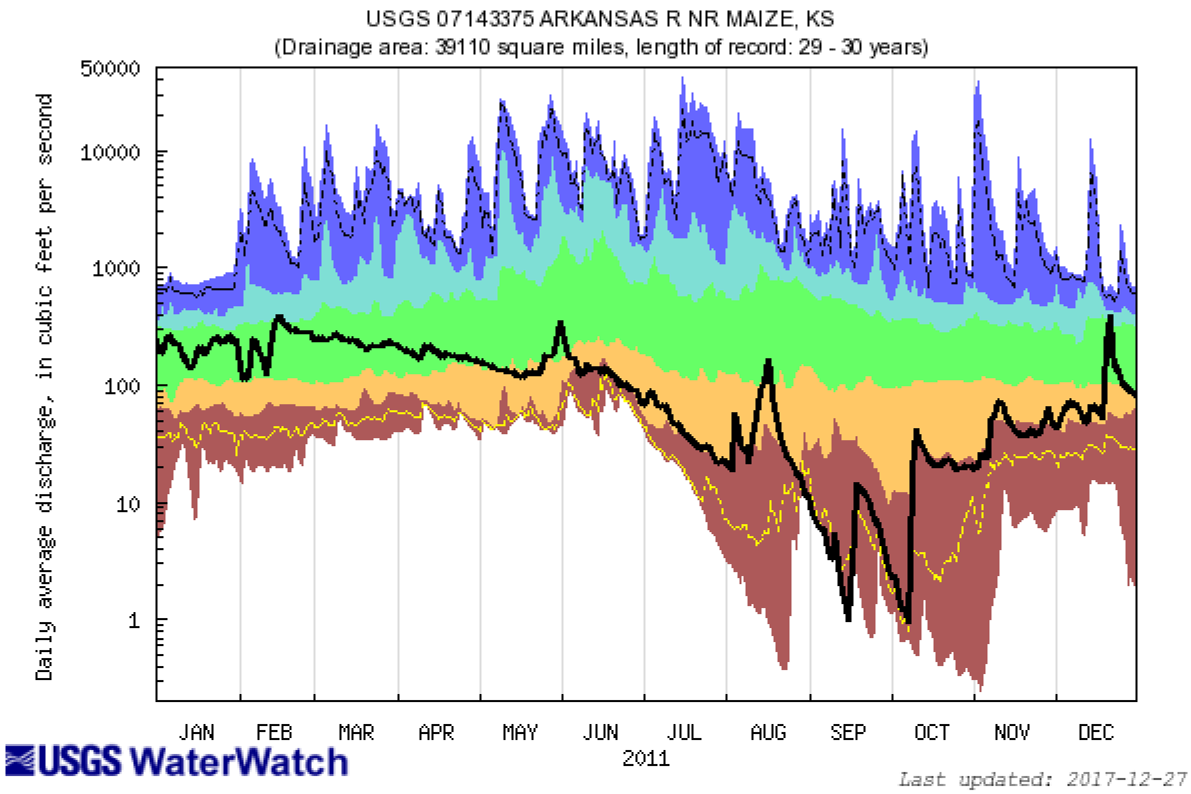


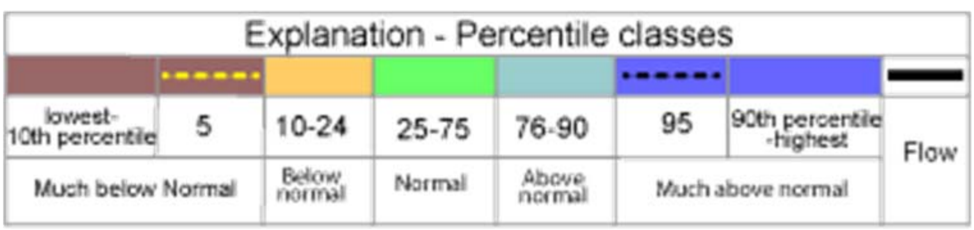
Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

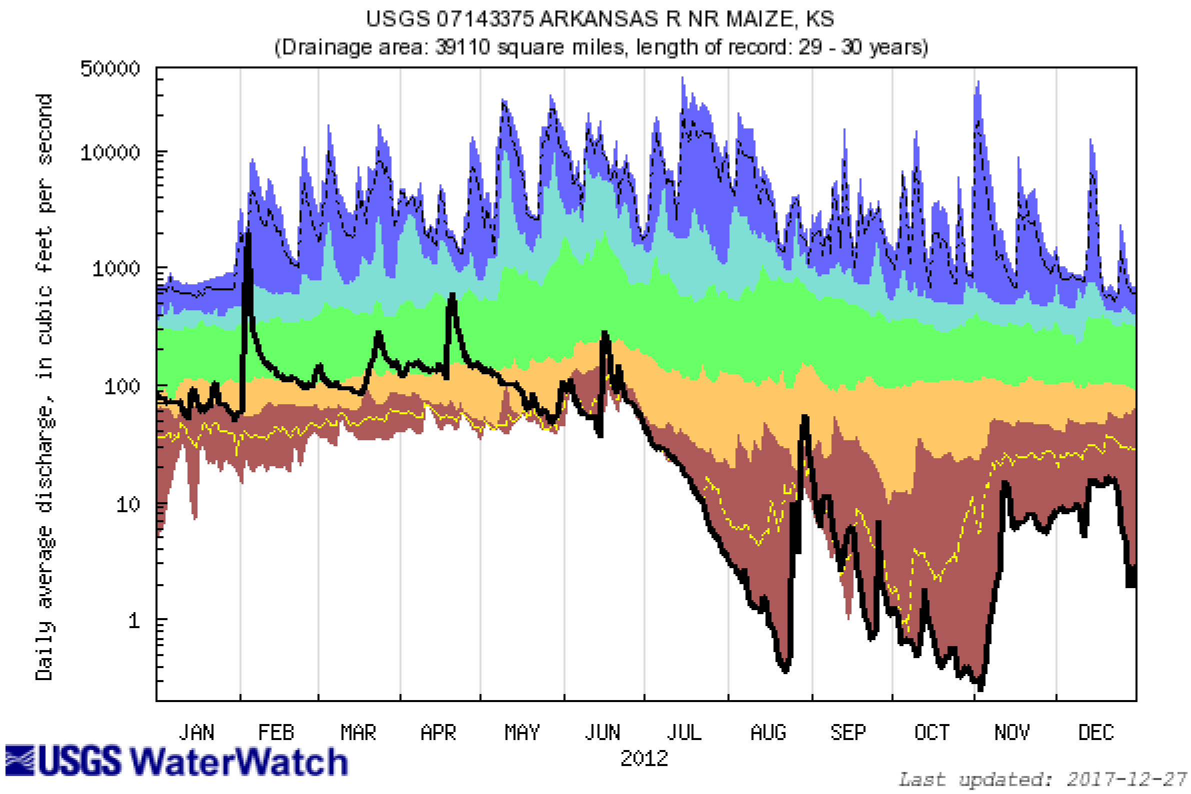

USGS
USGS 07143375 ARKANSAS R NR MAIZE, KS
Discharge, cubic feet per second
30000.00
20000.00
10000.00
1000.00
100.00
10.00
1.00
0.10
Jan 2010
Jul 2010
Jan 2011
Jul 2011
Jan 2012
Jul 2012
Jan 2013
Discharge
Estimated discharge
Period of approved data



Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		


USGS 07143375 ARKANSAS R NR MAIZE, KS
(Drainage area: 39110 square miles, length of record: 29 - 30 years)
Daily average discharge, in cubic feet per second
50000
10000
1000
100
10
1
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
2011
USGS WaterWatch
Last updated: 2017-12-27


Explanation - Percentile classes
lowest-10th percentile
5
10-24
25-75
76-90
95
90th percentile -highest
Flow
Much below Normal
Below normal
Normal
Above normal
Much above normal

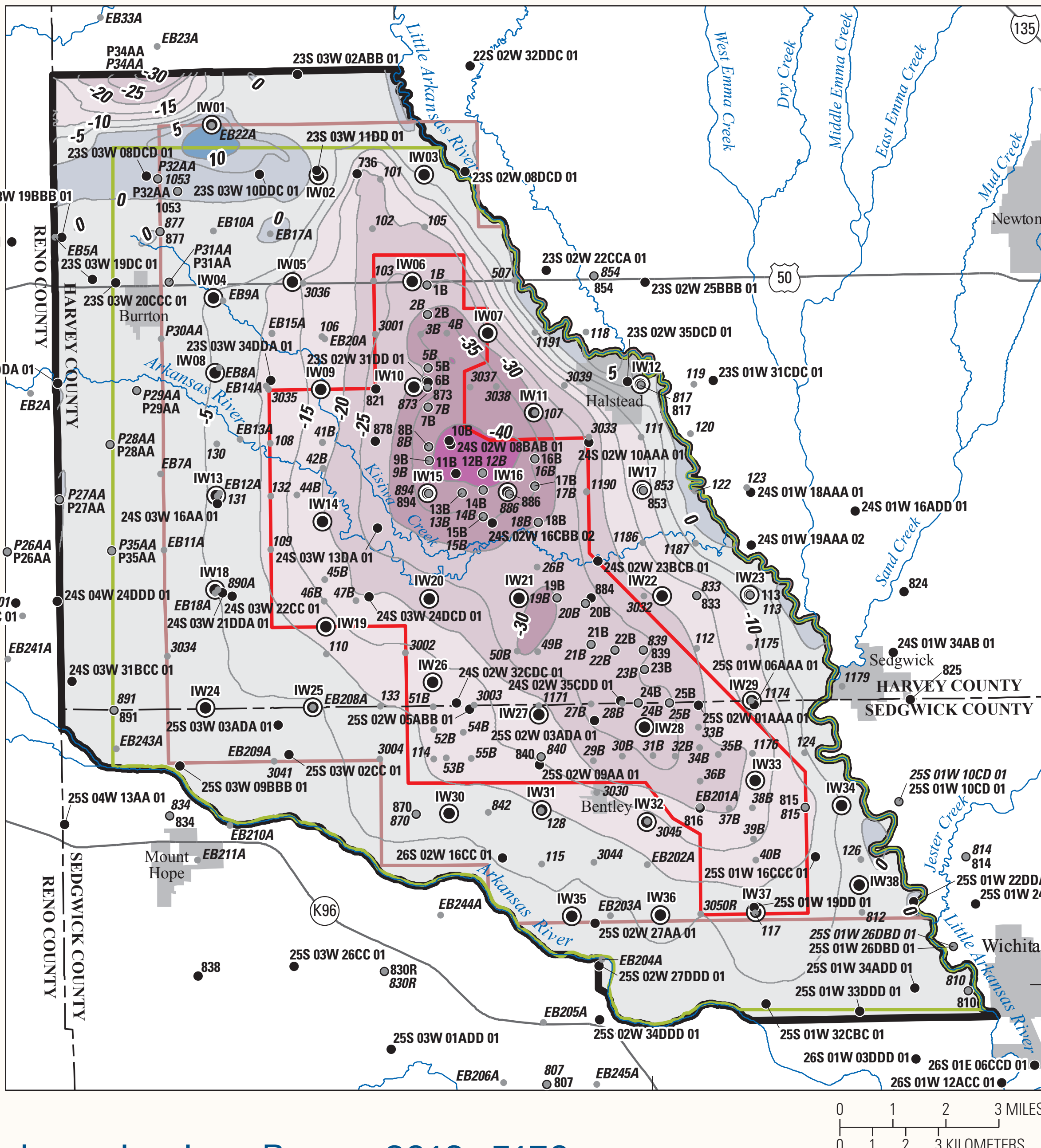


Explanation - Percentile classes							
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

ATTACHMENT H
USGS SIR 2013-5170, Revised 1993 Groundwater Levels

USGS
science for a changing world

Revised Shallow and Deep Water-Level and Storage-Volume Changes in the *Equus* Beds Aquifer near Wichita, Kansas, Predevelopment to 1993



Scientific Investigations Report 2013–5170

U.S. Department of the Interior
U.S. Geological Survey

EXPLANATION
(cover illustration)

Area of water-level change:

- Decline of 40 feet or more
- Decline of 30 to less than 40 feet
- Decline of 20 to less than 30 feet
- Decline of 10 to less than 20 feet
- Decline of zero to less than 10 feet
- Rise of zero to 10 feet
- Rise of greater than 10 feet

-25 **Line of equal water-level change in the shallow layer of the *Equus* Beds aquifer, predevelopment to 1993. Contour interval 5 feet.**

Boundary of study area

Boundary of pre-2012 study area

Boundary of basin storage area

Boundary of central part of the study area

IW35 **Index monitoring well and identifier**

EB245A **Monitoring well in the shallow layer of the *Equus* Beds aquifer, 1993**—Well identifier shown in *italic* type

807 **Monitoring well in the shallow layer of the *Equus* Beds aquifer, predevelopment, and identifier**

Front cover illustration: Static water-level changes in the shallow layer of the *Equus* Beds aquifer, predevelopment to 1993. (Fig. 6 from this report.)

Back cover photograph: Aerial photograph of city of Wichita Aquifer Storage and Recovery phase II facility (photograph by Tom Mason, city of Wichita, February 1, 2012).

Revised Shallow and Deep Water-Level and Storage-Volume Changes in the *Equus* Beds Aquifer near Wichita, Kansas, Predevelopment to 1993

By Cristi V. Hansen, Jennifer L. Lanning-Rush, and Andrew C. Ziegler

Scientific Investigations Report 2013–5170

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Hansen C.V., Lanning-Rush J.L., and Ziegler A.C., 2013, Revised shallow and deep water-level and storage-volume changes in the *Equus* Beds Aquifer near Wichita, Kansas, predevelopment to 1993: U.S. Geological Survey Scientific Investigations Report 2013–5170, 18 p., http://pubs.usgs.gov/sir/2013/5170/.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Acknowledgments

The authors acknowledge the invaluable assistance of Tim Boese and Daniel Clement of the *Equus* Beds Groundwater Management District Number 2 and of Tara Lanzrath and Andrew Lyon of Kansas Department of Agriculture, Division of Water Resources for providing expertise and consensus in evaluating which wells and water levels to use for the 1993 water-level altitude map of the deep layer of the *Equus* Beds aquifer.

The authors acknowledge the assistance of Debra Ary and Michael Jacobs of the city of Wichita and Tim Boese of Groundwater Management District Number 2 for providing water-level data and for their technical reviews, which contributed to improved technical and editorial clarity of the report.

Technical reviews by U.S. Geological Survey employees Brian Klager, Brian Kelly, and Geoffrey Delin also contributed to improved technical and editorial clarity of the report.

Revised Shallow and Deep Water-Level and Storage-Volume Changes in the *Equus* Beds Aquifer near Wichita, Kansas, Predevelopment to 1993

By Cristi V. Hansen, Jennifer L. Lanning-Rush, and Andrew C. Ziegler

Abstract

Beginning in the 1940s, the Wichita well field was developed in the *Equus* Beds aquifer in southwestern Harvey County and northwestern Sedgwick County to supply water to the city of Wichita. The decline of water levels in the aquifer was noted soon after the development of the Wichita well field began. Development of irrigation wells began in the 1960s. City and agricultural withdrawals led to substantial water-level declines. Water-level declines enhanced movement of brines from past oil and gas activities near Burrton, Kansas and enhanced movement of natural saline water from the Arkansas River into the well field area. Large chloride concentrations may limit use or require the treatment of water from the well field for irrigation or public supply. In 1993, the city of Wichita adopted the Integrated Local Water Supply Program (ILWSP) to ensure an adequate water supply for the city through 2050 and as part of its effort to effectively manage the part of the *Equus* Beds aquifer it uses. ILWSP uses several strategies to do this including the *Equus* Beds Aquifer Storage and Recovery (ASR) project. The purpose of the ASR project is to store water in the aquifer for later recovery and to help protect the aquifer from encroachment of a known oilfield-brine plume near Burrton and saline water from the Arkansas River.

As part of Wichita's ASR permits, Wichita is prohibited from artificially recharging water into the aquifer in a Basin Storage area (BSA) grid cell if water levels in that cell are above the January 1940 water levels or are less than 10 feet below land surface. The map previously used for this purpose did not provide an accurate representation of the shallow water table. The revised predevelopment water-level altitude map of the shallow part of the aquifer is presented in this report.

The city of Wichita's ASR permits specify that the January 1993 water-level altitudes will be used as a lower baseline for regulating the withdrawal of artificial recharge credits from the *Equus* Beds aquifer by the city of Wichita. The 1993 water levels correspond to the lowest recorded levels and largest storage declines since 1940. Revised and new water-level maps of shallow and deep layers were developed to better represent the general condition of the aquifer. Only static water levels were used to better represent the general condition of the aquifer and comply with Wichita's ASR permits. To ensure adequate data density, the January 1993 period was expanded to October 1992 through February 1993. Static 1993 water levels from the deep aquifer layer of the *Equus* Beds aquifer possibly could be used as the lower baseline for regulatory purposes.

Previously, maps of water-level changes used to estimate the storage-volume changes included a combination of static (unaffected by pumping or nearby pumping) and stressed (affected by pumping or nearby pumping) water levels from wells. Some of these wells were open to the shallow aquifer layer and some were open to the deep aquifer layer of the *Equus* Beds aquifer. In this report, only static water levels in the shallow aquifer layer were used to determine storage-volume changes.

The effects on average water-level and storage-volume change from the use of mixed, stressed water levels and a specific yield of 0.20 were compared to the use of static water levels in the shallow aquifer and a specific yield of 0.15. This comparison indicates that the change in specific yield causes storage-volume changes to decrease about 25 percent, whereas the use of static water levels in the shallow aquifer layer causes an increase of less than 4 percent. Use of a specific yield of 0.15 will result in substantial decreases in the amount of storage-volume change compared to those reported previously that were calculated using a specific yield of 0.20. Based on these revised water-level maps and computations, the overall decline and change in storage from predevelopment to 1993 represented a loss in storage of about 6 percent (-202,000 acre-feet) of the overall storage volume within the newly defined study area.

Introduction

Beginning in the 1940s, the Wichita well field was developed in the *Equus* Beds aquifer in southwestern Harvey County and northwestern Sedgwick County to supply water to the city of Wichita, the largest city in Kansas (Williams and Lohman, 1949; Gibson, 1998; U.S. Census Bureau, 2012).

In addition to supplying drinking water for Wichita, the other primary use of water from the *Equus* Beds aquifer is crop irrigation in this agriculturally dominated part of south-central Kansas (Rich Eubank, Kansas Department of Agriculture, Division of Water Resources, oral commun., 2008). The decline of water levels in the aquifer was noted soon after the development of the Wichita well field began (Williams and Lohman, 1949). Large-scale development of irrigation wells began in the 1960s. City and agricultural withdrawals have led to substantial declines. As water levels in the aquifer decline, the volume of water stored in the aquifer decreases and less water is available to supply future needs. Water-level declines enhanced movement of brines from past oil and gas activities near Burrton, Kansas and enhanced movement of natural saline water from the Arkansas River into the well field area. Further movement into the well field area of these waters with large chloride concentrations may limit use or may require treatment of water from the well field area for irrigation or public supply (Ziegler and others, 2010). Since 1940, the U.S. Geological Survey (USGS), in cooperation with the city of Wichita, has monitored changes in water levels and the resulting changes in storage volume in the *Equus* Beds aquifer as part of Wichita's effort to effectively manage this resource

In 1993, the city of Wichita adopted the Integrated Local Water Supply Program (ILWSP) to ensure an adequate water supply for the city through 2050 and as part of its effort to effectively manage the part of the *Equus* Beds aquifer it uses (City of Wichita, [2007?] and 2008; Warren and others, 1995). ILWSP uses several strategies to do this including: (1) greater reliance on other sources of water from outside the study area (for example, Cheney Reservoir on the North Fork of the Ninnescah River (fig. 1), the Bentley Wellfield southwest of the Arkansas River, and Wichita's Local Wellfield at the confluence of the Arkansas and Little Arkansas Rivers (locations not shown on figures), (2) encouraging conservation, and (3) developing the *Equus* Beds Aquifer Storage and Recovery (ASR) project with a designed artificial-recharge capacity of as much as 100 million gallons a day (City of Wichita, [2007?] and 2008). The purpose of the ASR project is to store and later recover groundwater and to help protect the part of the aquifer used by the city from the encroachment of a known oilfield-brine plume near Burrton and encroachment of saline water from the Arkansas River (Ziegler and others, 2010). In 2007, the city of Wichita began using the Phase I facilities of the *Equus* Beds ASR project to increase the long-term sustainability of the *Equus* Beds aquifer through large-scale artificial recharge (City of Wichita, [2007?]). The ASR project uses water from the Little Arkansas River—either pumped from the river directly or from wells in the riverbank that obtain their water from the river by induced infiltration—as the source of artificial recharge to the *Equus* Beds aquifer (City of Wichita, [2007?]). For Phase I (operational in 2007), the water pumped directly from the Little Arkansas River is treated to reduce sediment and remove atrazine before being recharged to the aquifer through recharge basins; water pumped from wells in the riverbank does not receive additional treatment before being recharged to the aquifer through recharge basins or wells (Debra Ary, city of Wichita, written commun., 2012). Phase II recharge facilities withdraw water from the Little Arkansas River and treat the water using ultrafiltration membranes and advanced oxidation techniques. The treated water can then be recharged into spreading basins or recharge wells throughout the area and stored in the aquifer for future use. The Phase II facilities began operation in April 2013.

The previously published maps of August 1940 (predevelopment) and 1993 water-level altitudes (Aucott and Myers, 1998; Hansen and Aucott, 2001) are no longer appropriate for use as baselines for computing changes in water levels and storage volume because they were made using a single set of wells in which some were open to the shallow layer of the *Equus* Beds aquifer and some were open to the deep layer. This requires that new predevelopment and 1993 water-level altitude maps be created that only include wells that are from a single aquifer layer. In addition, estimates of the predevelopment 1993 static water-level altitude at the Phase I and II monitoring sites are needed as part of the accounting of ASR recharge-credits.

Purpose and Scope

The purpose of this report is to (1) document measured and interpolated predevelopment water levels in the shallow layer of the *Equus* Beds aquifer, (2) document measured and interpolated 1993 static water levels in the shallow and deep aquifer layers for the set of wells used for regulating the withdrawal of ASR recharge credits from the *Equus* Beds aquifer by the city of Wichita, (3) document changes in the set of wells used for calculating the 1993 water-level and storage-volume changes, (4) document the change in method used to calculate storage volume changes in the *Equus* Beds aquifer, (5) compare average water-level differences for 1993 calculated using measured and interpolated water-levels from the current (2013) set of wells with previously published average water-level changes, and (6) compare the differences in water-level changes and storage volumes using static water levels from the shallow aquifer layer. Maps of related measured and interpolated groundwater levels and water-level changes are presented. Comparison of average water-level changes and storage-volume changes for several subareas are presented in tabular form. Information in this report can be used to document and improve understanding of the effects of climate, water use, and water-resource management practices on water supplies in the *Equus* Beds aquifer, which is an important source of water for the city of Wichita and the surrounding area.

Description of Study Area

The current study area covers approximately 189 square miles (mi^2) and is located northwest of Wichita, Kansas in Harvey and Sedgwick Counties (fig. 1). It is mostly bounded on the southwest by the Arkansas River and on the east by the Little Arkansas River. The land surface in the study area typically slopes gently toward the major streams from an altitude of about 1,510 feet (ft) above the North American Vertical Datum of 1988 (NAVD88) in the northwest to a low of about 1,325 ft in the southeast. The study area represents about one-seventh of the 1,400-mi^2 *Equus* Beds aquifer and about one-third of the pumpage from the aquifer occurs in the study area (Kansas Department of Agriculture, 2011). Pumpage from the *Equus* Beds aquifer in the study area is dominated by irrigation and city use (Hansen and Aucott, 2010). Pumpage from the study area in 2011 (latest year for which pumpage is available) was about 45,500 acre-feet (acre-ft) for irrigation and about 21,900 acre-ft for the city of Wichita (Kansas Department of Agriculture and Kansas Geological Survey, 2013).

The current study area is an expansion of the 165-mi^2 study area first used by Aucott and Myers (1998). In 2012, the study area of Aucott and Myers (1998) (referred to as the "pre-2012 study area" in this report) was expanded north to the northern boundary of township 23 south, west to the eastern Reno County line, southwest of the Arkansas River in a small area south of Bentley, and south to the southern boundary of township 25 south (fig. 1). This current study area includes all the ASR Phase I and II wells and the ASR basin storage area (BSA) west of the Little Arkansas River.

The approximately 141-mi^2 BSA is defined by Wichita's ASR permits as the recharge-credit accounting area and is used by the city of Wichita, Groundwater Management District Number 2 (GMD2), and Kansas Department of Agriculture, Division of Water Resources (DWR) to estimate the location of artificially recharged water in the aquifer and to determine where and how much of it can be withdrawn for use by Wichita (Kansas Department of Agriculture, 2005).

The central part of the study area (fig. 1), which covers about 55 mi^2 or less than one-third of the study area, is the historic center of pumping in the study area. The central part of the study area includes wells used to supply water to the city of Wichita and many wells used for irrigation (Kansas Department of Agriculture and Kansas Geological Survey, 2013). Pumpage from the central part of the study area in 2011 was about 12,100 acre-ft for irrigation and about 21,300 acre-ft was for the city of Wichita (Kansas Department of Agriculture and Kansas Geological Survey, 2013).

Hydrogeology of the Study Area

The *Equus* Beds aquifer is the easternmost extension of the High Plains aquifer in Kansas (Stullken and others, 1985; Hansen and Aucott, 2001). The *Equus* Beds aquifer covers about 1,400 mi^2 in Kansas, or about 5 percent of the approximately 30,900 mi^2 covered by the High Plains aquifer in Kansas (fig. 1). The *Equus* Beds aquifer is an important source of water because of the generally shallow depth to the water table, the large saturated thickness, and generally good water quality.

The *Equus* Beds aquifer primarily consists of Quaternary-age alluvial deposits, locally known as the *Equus* beds, with some dune sand and loess (Myers and others, 1996). The alluvial deposits are as thick as 250 ft in the study area (Leonard and Kleinschmidt, 1976). The *Equus* beds primarily consist of sand and gravel interbedded with clay or silt, but locally may consist primarily of clay with thin sand and gravel layers (Lane and Miller, 1965a; Myers and others, 1996). The middle part of the *Equus* beds generally has more fine-grained material than the lower and upper parts (Lane and Miller, 1965b, Myers and others, 1996). Approximately north of U.S. Highway 50 (fig. 1) and south of the Little Arkansas River in the study area, an area of dune sands is underlain by thick clay layers that restrict the downward movement of water in the *Equus* Beds aquifer and create the confined to semiconfined conditions in the deep aquifer layer in this part of the area (Kelly and others, 2013). The approximately 700-ft-thick Permian-age Wellington Formation underlies the *Equus* beds in the study area and forms the bedrock confining unit below them (Bayne, 1956; Myers and others, 1996). Total storage volume (the amount of water available for use) of the *Equus* Beds aquifer in the pre-2012 study area was estimated at about 2,100,000 acre-ft by Hansen (2007). Using the groundwater flow model of Kelly and others (2013), the total storage volume was estimated at about 2,776,000 acre-ft for the pre-2012 area and about 3,192,000 acre-ft for the current study area (Brian Kelly, written commun., June 10, 2013).

Near the Arkansas River and in the western part of the study area, the water table in the *Equus* Beds aquifer can be less than 10 ft below land surface. Farther from the Arkansas River and near the Little Arkansas River, the water table can be at a greater depth (as much as 50 ft below land surface in January 2012), depending on the altitude of the land surface and the amount of water-level decline that has been caused by groundwater withdrawals. The saturated thickness of the *Equus* Beds aquifer within the study area ranges from about 75 ft near the Little Arkansas River to almost 250 ft near the Arkansas River where the lowest areas of the underlying bedrock surface occur (Spinazola and others, 1985). The *Equus* Beds aquifer is considered to be an unconfined aquifer, but the presence of clay layers has resulted in semiconfined conditions in some areas (Spinazola and others, 1985; Stramel, 1967). These semiconfined conditions may have resulted in the substantial water-level and water-quality differences in the shallow and deep parts of the *Equus* Beds aquifer in some parts of the study area (Stramel, 1956; Whittemore, 2007, 2012; and Ziegler and others, 2010). These substantial differences, along with a need to monitor the long-term effects of artificial recharge on the shallow and deep aquifer layers, led to development of separate potentiometric-surface maps of the shallow and deep layers of the aquifer.

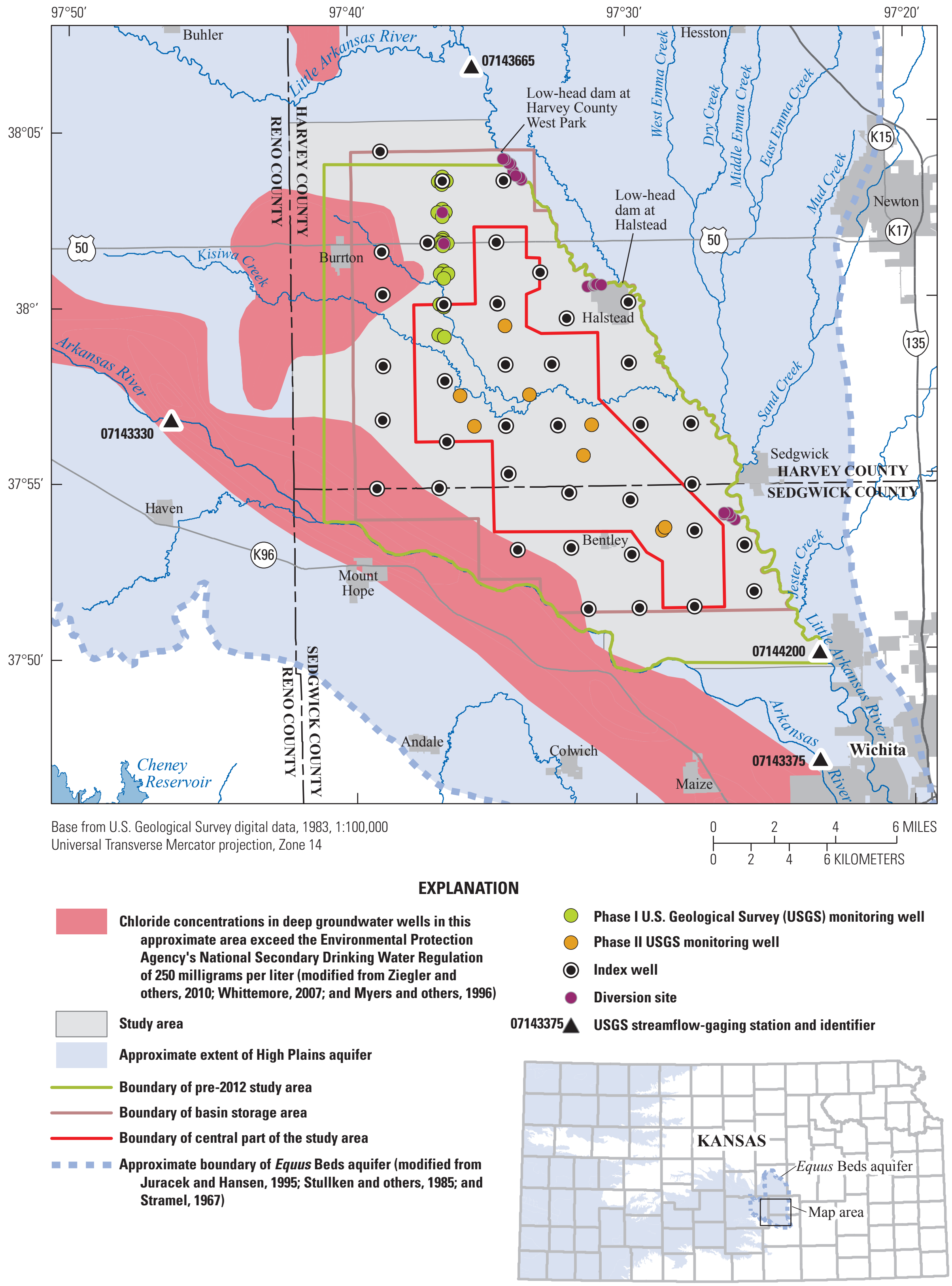


Figure 1. Location of study area near Wichita, south-central Kansas (modified from Aucott and Myers, 1998).

Previous Studies

The *Equus* Beds aquifer has been extensively studied because of its importance as a source of water for cities, agriculture, and industry. As noted by Kelly and others (2013), previous studies include those by Williams and Lohman (1949), Stramel (1956, 1962a, 1962b, 1967), Petri and others (1964), Sophocleous (1983), Spinazola and others (1985), Pruitt (1993), Myers and others (1996), Aucott and Myers (1998), Aucott and others (1998), Ziegler and others (1999, 2010), Hansen and Aucott (2001, 2004, 2010), and Hansen (2007, 2009a, 2009b, 2011a, 2011b, 2012). In addition, Burns and McDonnell Engineering, Inc. (Kansas City) has worked with the city of Wichita to determine the location and amount of the ASR recharge credits the city of Wichita is allowed to pump from the aquifer as part of the annual accounting required by DWR.

Methods

Aquifer Layers

Wells used in this report were divided into two groups to describe differences between the water levels in the shallow and deep layers of the aquifer. For the purposes of this report, wells completed and screened in the *Equus* Beds aquifer were assigned to either the shallow or deep aquifer layer based on the layer in which the bottom of the well's casing or screened interval occurred. These layer assignments were based on *Equus* Beds GMD2 aquifer zone designations and on well completion and screen depths. GMD2 has identified as many as four aquifer zones (designated AA, A, B, and C, in order of descending depth) within the *Equus* Beds aquifer where there are competent clay layers separating them (Tim Boese, *Equus* Beds Groundwater Management District Number 2, written commun., 2009). The A, B, and C zones are similar to the upper, middle, and lower aquifer units defined by Myers and others (1996); the AA zone is of more limited areal extent and would be considered part of the upper aquifer unit. GMD2 monitoring wells generally are in clusters (closely spaced wells screened to different depths) with each well screened in a different aquifer zone. For this report, wells designated by GMD2 as completed in zones A or C were assigned to the shallow or deep aquifer layers, respectively; no wells designated as completed in zone AA were used in this study. A few wells designated by GMD2 as being in zone B that were deemed to be in the same zone as the nearby BSA deep index wells were used to supplement the interpretation of the deep 1993 potentiometric map.

The city of Wichita also measures water levels in clusters of monitoring wells. The shallower well in each city well cluster was assumed to be in and assigned to the shallow aquifer layer; the deeper well in each cluster was assumed to be in and assigned to the deep aquifer layer. Ziegler and others (2010) used a depth of 80 ft as the dividing point between the shallow and deep layers of the *Equus* Beds aquifer. An analysis of the GMD2 and city of Wichita well clusters in the study area by Hansen (2011b) indicated about 90 percent of the GMD2 zone A wells and shallower wells in city well clusters were completed and screened to a depth of 80 ft or less, and about 90 percent of the GMD2 zone C wells and deeper wells in city well clusters were completed and screened to a depth of greater than 80 ft. This indicates that, when no other information was available, the use of the 80 ft depth as the dividing point between shallow and deep aquifer layers was reasonable when assigning the city of Wichita monitoring wells not in clusters into either the shallow or deep layer of the *Equus* Beds aquifer. Examination of well and screen depth and of water-level hydrographs lead in a few cases to assigning more than one well in a cluster to the same aquifer layer. Most of these cases were where both wells measured less than 80 ft deep and both wells were assigned to the shallow aquifer layer.

Water Levels

The city of Wichita's historic monitoring wells have been used for monitoring water levels in the *Equus* Beds aquifer for years, many since the late 1930s (Stramel, 1956). All of the historic monitoring wells are measured at least quarterly by the city of Wichita personnel; many of the historic wells in the central part of the study area are measured monthly by city personnel. Some of the historic wells in the central part of the study area were replaced in 2009 through 2010 as part of Phase II of the ASR project. The GMD2 monitoring wells were installed for GMD2 beginning in 1978, or are existing wells used by GMD2 to monitor the *Equus* Beds aquifer. Some of the GMD2 wells only are measured annually during the last 3 months of the year after the irrigation season has ended; other wells are measured by GMD2 on a quarterly or monthly frequency.

Groundwater levels measured from August 1937 through August 1940 in 51 city of Wichita historic monitoring wells and 41 other wells in Harvey and Sedgwick Counties were used to represent predevelopment conditions in the study area. A range of years was used because of the limited amount of data available for either January 1940, the period mentioned in the ASR regulations as the highest baseline water levels (Kansas Department of Agriculture, 2005), or August 1940, the period that previously was used by Aucott and Myers (1998) to represent the time before substantial pumpage began in the study area. Other than the city of Wichita's public-supply wells, some of which began pumping in September 1940, groundwater development in the study area was limited mostly to small-capacity wells; therefore, water levels measured before September 1940 were used. Most of the predevelopment water levels used in this report were the first water level measured at each well.

For the 1993 water-level altitude maps, the use of water levels for January 1993 is specified in the ASR permits; in addition, the water levels also are specified to be static water levels (Kansas Department of Agriculture, 2005). Static water levels are those unaffected by pumping; for example, no pumping in the previous 24 hours from wells within 300 ft of the measured well. Inspection of water-level data and hydrographs indicated many wells in the study area either were not measured in January 1993, or their January 1993 water levels were affected by pumping. To ensure the use of static water levels and increase the areal density of data, the period used to represent the static 1993 water levels was expanded from just January 1993 to October 1, 1992 (after the end of the irrigation pumping season) through February 1993 (before the beginning of the irrigation pumping season). If the January 1993 water level was noted as affected by pumping, or inspection of the well's hydrograph indicated the January 1993 water level was affected by pumping, it was not used. If the hydrograph indicated another water level in the October 1, 1992, through February 28, 1993, period was not affected by pumping, then that water level was used instead of the January 1993 water level. The October 1992 through February 1993 period is hereinafter referred to as 1993 in this report. DWR, GMD2, and USGS personnel examined and evaluated the water-level and construction data and hydrographs of the wells in the deep layer of the *Equus* Beds aquifer to arrive at a consensus of the set of wells and water levels to use for the deep static 1993 water-level-altitude map that possibly could be used for regulating the withdrawal of ASR artificial recharge credit water from the *Equus* Beds aquifer by the city of Wichita.

Groundwater levels measured from October 12, 1992, through February 1, 1993, at 124 city of Wichita historic monitoring or public-supply wells and 20 GMD2 monitoring wells were used to represent static water-level conditions in 1993 in the shallow layer of the *Equus* Beds aquifer in the study area. Water levels in the historic monitoring wells were measured by city of Wichita personnel, water levels in the GMD2 monitoring wells were measured by GMD2 personnel, and water levels from wells that were not part of either of these monitoring networks were measured by the USGS. All agencies used standard water-level measurement techniques that are similar to USGS methods described in Cunningham and Schalk (2011). The historic monitoring well data are on file, in paper and electronic form, with the city of Wichita's Public Works and Utilities Department in Wichita, Kansas; the GMD2 monitoring well data collected by GMD2 are stored in the Kansas Geological Survey's (KGS) Water Information Storage and Retrieval Database (WIZARD) (Kansas Geological Survey, 2012); and well data collected by the USGS are stored in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2012). All the measured water-level data used in this report also are stored in NWIS.

Predevelopment and 1993 water levels for the ASR Phase I and II wells were interpolated from rasters generated from the measured water levels and the contours created from these measured data. A raster is an areal grid of cells with a value assigned to each cell. Each grid cell in the raster used for this report had an area of 10 meters by 10 meters. The BSA index (IW) wells were installed in 2001 and 2002 as part of Phase I of the ASR project to monitor the effects of artificial recharge on the water quality and water levels in the *Equus* Beds aquifer across the study area and to determine if there are water-quality differences between the shallow and deep layers of the aquifer. The Phase II compliance-monitoring wells were installed to provide additional monitoring of the effects of artificial recharge within the central part of the study area. As part of Phase II of the ASR project, some of the historic public-supply wells and their associated monitoring wells were replaced with new wells.

Data Quality and Limitations

The data used in this report were collected for other purposes; most of the data were collected by the city of Wichita and GMD2 personnel. The quality of the water-level data for each well was evaluated by examining hydrographs of the all the water levels available for the well. If a water level looked questionable, it was not used. Because the water-level altitude maps are to represent static—not pumping—water-level conditions, water levels that were noted as being from pumping wells or near pumping wells or whose hydrographs indicated that the water levels were affected by pumping were excluded from use.

Water-Level Altitudes

The predevelopment and 1993 water-level altitudes depicted in the water-level altitude maps of the shallow and deep layers of the *Equus* Beds aquifer were calculated by subtracting the depth to water below land surface in a well from the altitude of land surface at the well. Land-surface altitudes are those stored for the wells in NWIS or WIZARD or determined from Light Detection and Ranging (lidar) (Data Access and Support Center, 2013a, 2013b) or from the National Elevation Dataset (NED) (U.S. Geological Survey, 2009). The land-surface altitudes referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) were converted to the North America Vertical Datum of 1988 (NAVD 88); all water-level altitudes are referenced to NAVD 88.

The predevelopment water-level-altitude contours of the shallow layer of the *Equus* beds aquifer were modified from the 1940–44 water-table contours and measured data from plate 1 of Williams and Lohman (1949). Examination of the wells used for these maps indicated that most of the wells were in the shallow aquifer and the water-level altitude contours were revised as needed. Historic wells that were previously determined to be in the deep layer of the *Equus* Beds aquifer or other wells that were greater than 80 ft deep were removed from the analysis. Comparison of the water levels displayed on plate 1 of Williams and Lohman (1949) with the data stored in NWIS indicated that many of the water levels were older than 1940; measurements from 1937 through 1939 were not uncommon and generally were the wells' first measured water levels. The predevelopment contours and measured water levels were brought into ArcGIS (Environmental Systems

Research Institute, 2012) and were compared to the NED land surface; the contours were revised where needed to remain below the land surface. These predevelopment contours and measured water levels were used as input to create a raster of the predevelopment water-level surface of the shallow aquifer layer. The water-level altitudes of the raster cells that contain measured wells were modified, if needed, to ensure they exactly matched the measured water levels. The completed raster was used to interpolate the predevelopment water-level altitudes at ASR Phase I and II wells in the shallow layer of the *Equus* Beds aquifer. Only 164 wells used in this report had predevelopment and 1993 measurements. For those wells that had a shallow static 1993 water level used in this report that did not have a measured predevelopment water level, the well's predevelopment water level was estimated as described in the "Water Levels" section of this report.

For wells that were in existence in January 1993, no October 1992 through February 1993 water levels were interpolated. The measured 1993 static water-level altitudes of the wells were entered into ArcGIS, plotted on the water-level altitude map of their assigned aquifer layer, and converted to a raster using ArcGIS Spatial Analyst's "Topo to Raster" command (*http://resources.arcgis.com/en/help/main/10.1/index.html#//009z0000006s000000*). Each layer's raster was then converted to contour data using the ArcGIS Spatial Analyst's "Contour" command (*http://resources.arcgis.com/en/help/main/10.1/index.html#//009z000000ts000000*) and plotted with the well data. Where needed, the machine-generated water-level altitude contours were modified to match the well data. Further constraints on the water-level altitude contours were that (1) all water-level altitude contours would remain below land surface; (2) the 1993 static water-level altitude contours of the deep aquifer layer would remain below those of the 1993 static contours of the shallow aquifer layer, except where the measured water levels from well clusters indicated otherwise or at gaining streams; and (3) the 1993 static water-level altitude contours of the shallow layer would remain below those of the predevelopment contours, unless data indicated otherwise. A new raster was generated from the measured points and revised contours.

After the shallow predevelopment and shallow and deep static 1993 water-level altitude contours and associated rasters were considered to appropriately represent their respective surfaces, they were used to interpolate the water-level altitudes at the ASR Phase I and II monitoring sites. This was done by intersecting the location of each well with the raster of the appropriate aquifer layer and applying the water-level altitude of the raster at that location to the well. Using the same method, a predevelopment water-level altitude was estimated for all wells with measured 1993 water levels used in this report that did not have a measured predevelopment water level. For wells in the shallow *Equus* Beds aquifer layer without a measured predevelopment water level, one was interpolated from the predevelopment water-level altitude map of the shallow aquifer layer that was based on measured values. For the ASR Phase I and Phase II monitoring wells, predevelopment water levels were interpolated only for those wells in the shallow aquifer layer; however, 1993 water-level altitudes were interpolated for Phase I and II wells in the shallow and deep aquifer layers of the *Equus* Beds aquifer.

Water-surface altitudes from four streamflow-gaging stations and two low-head dams (fig 1) were used as additional data points to manually adjust contours in the shallow aquifer layer. Median water-surface altitudes for October 1, 1992, through January 31, 1993, were obtained from NWIS (U.S. Geological Survey, 2012) for the streamflow-gaging stations; the altitudes of the tops of the low-head dams (Trudy Bennett, U.S. Geological Survey, written commun. 2009) were used as the surface-water altitude at the low-head dams.

Water-Level Difference and Change

Only 176 well clusters used in this report had measured 1993 water levels in the shallow and deep wells in the cluster. At these well clusters, the measured water level from the well open to the deep aquifer layer was subtracted from the measured water level from the well open to the shallow layer in the same well cluster to determine the water-level difference between the aquifer layers. All wells used to develop the water-level-altitude change maps of predevelopment to 1993 and between the shallow and deep *Equus* Beds aquifer layers in 1993 were historic or GMD2 monitoring wells. Only 164 of the wells used in this report had measured predevelopment water levels. If a predevelopment water-level measurement did not exist for a well in the study area, one was estimated from the raster of the predevelopment water-level altitude map as described in the previous "Water Levels" section of this report.

The water-level difference and change maps in this report were developed using a different method than that used in the past. In the past, only the water-level changes measured or estimated at wells were used to develop the maps because water-level altitude maps were not always created for each time period. The method used in this report involved the subtraction of water-level altitude rasters developed from measured water-level altitudes for either separate time periods or for separate aquifer layers. The areal data density generally is greater for a single water-level altitude map than in sets of wells measured at two different time periods or in well clusters with static water levels in separate wells open to the shallow and deep *Equus* Beds aquifer layers. This allows for a water-level-altitude change map that is more consistent with the water-level altitude maps and potentially more accurate than one based only on wells with measured water-level altitudes. The results of the raster subtractions were converted to contour maps and the contours revised where necessary to honor the actual measured data and to make hydrologic sense.

The measured differences were determined from well clusters that had static 1993 water levels in wells in the shallow and deep aquifer layers. The measured and interpolated differences were determined from water-level altitudes in well clusters where either both wells in the cluster had measured static 1993 water-level altitudes or one or more wells in the cluster was missing a measured static 1993 water-level altitude. Where a 1993 static water-level altitude value was missing, one was interpolated for the well from the appropriate aquifer layer's 1993 static water-level altitude raster. The raster differences were determined by subtracting the raster of the 1993 static water-level altitude of the deep aquifer layer from the raster of the 1993 static water-level altitude of the shallow aquifer layer. The resulting raster of water-level altitude differences was summed and then divided by the number of cells in the raster to calculate the average water-level difference.

The average water-level change from predevelopment to 1993 was computed at wells with measured water levels in 1993 and measured or interpolated predevelopment water levels instead of using the average water-level altitude change of the resulting raster subtraction. Similarly, the average water-level change between the shallow and deep *Equus* Beds aquifer layers used water levels at well clusters where the water level from the deep well was subtracted from the water level in the shallow well in the cluster.

In previous studies (Aucott and Myers, 1998; Hansen and Aucott, 2001), the map of water-level changes from August 1940 to January 1993 included a combination of static and stressed water levels from wells, some of which were open to the shallow aquifer layer and some open to the deep aquifer layer. To better represent the general condition in the aquifer, only static water levels from the shallow aquifer layer were used in this study for determining water-level changes and aquifer storage-volume changes.

Specific Yield

Specific yield is the ratio of (1) the volume of water which a rock or soil, after being saturated, will yield by gravity to (2) the volume of rock or soil (Lohman and others, 1972). The specific yield of the *Equus* Beds aquifer has been estimated by many investigators using a variety of methods including aquifer tests, laboratory analyses of samples, lithologic descriptions from drillers' logs, water-balance equations, and parameter estimation for groundwater models. Estimates of specific yield from these methods have ranged from less than 0.1 to more than 0.3 with most estimates in the range of 0.15 to 0.2 (Williams and Lohman, 1949; Stramel, 1956, 1967; Kansas Water Resources Board, 1960; Bayne and Ward, 1969; Lohman, 1972; Gutentag and others, 1984; Reed and Burnett, 1985; Spinazola and others, 1985; Stullken and others, 1985; Hansen, 1991; Cederstrand and Becker, 1998; David Stous and Patrick Higgins, Burns and McDonnell Engineering Consultants, written commun., 2000; and Kelly and others, 2013). A specific yield of 0.2 previously was used by Stramel (1956), who was the first to compute changes in storage volume in the *Equus* Beds aquifer. A specific yield of 0.2 continued to be used by scientists in Kansas through 2011. For this report, a value of 0.15 was used because it was within the range of most estimates and matched that used by a recent groundwater flow model of the *Equus* Beds aquifer (Kelly and others, 2013). The specific yield of 0.15 from the groundwater flow model was a product of the model calibration; that is, it was determined to produce simulated water levels that better matched observed water levels than did the specific yield of 0.20. Specific yield can be used with the aquifer volume to estimate the amount of water available from storage in the aquifer, referred to as storage in this report.

Aquifer Storage Volume

Aquifer storage volume was previously estimated by Hansen (2007) as the estimated average thickness of the aquifer of 100 ft multiplied by the area of the pre-2012 study and the estimated specific yield of 0.2. This resulted in an estimate of total aquifer storage volume of 2,100,000 acre-ft (Hansen, 2007). In this report, the aquifer storage volume was estimated using the recently published groundwater flow model of Kelly and others (2013). The model multiplies the predevelopment thickness of the aquifer by the area of each cell, sums the volume of all the cells within a specified area, and then multiplies the result by the specific yield of 0.15 that was used by the model.

Aquifer Storage-Volume Change

Aquifer storage-volume change for the purposes of this report is defined as the change in aquifer thickness multiplied by the area of the aquifer containing the change multiplied by the specific yield of the aquifer. The change in aquifer storage volume is estimated in this manner instead of the computing the difference between two total aquifer storage volumes because of the large uncertainty in the total aquifer storage volume and because the amount of storage-volume change to date (2013) is small compared to the total aquifer storage volume. For example, the -255,000 acre-ft of storage-volume change from August 1940 to January 1993 estimated by Aucott and Myers (1998) is the largest recorded storage-volume change to date; however, it only represents about 12 percent of the 2,100,000 acre-ft of total storage volume of the *Equus* Beds aquifer in the pre-2012 study area as estimated by Hansen (2007).

In recent reports (Aucott and Myers, 1998; Aucott and others, 1998; Hansen and Aucott, 2001, 2004, 2010; Hansen, 2007, 2009a, 2009b, 2011a, 2011b, 2012), change in storage volume in the *Equus* Beds aquifer was computed using computer-generated Thiessen polygons (Thiessen, 1911) that were based on the measured water-level changes at wells and the manually drawn lines of equal water-level change. Thiessen polygons apportion the water-level change at each well and the estimated value at points representing the lines of equal water-level change to the area around the wells and points. The volume of storage change was computed by summing the area of each Thiessen polygon multiplied by the water-level-change value associated with the Thiessen polygon, and then multiplied by the specific yield. To determine the storage-volume change since August 1940 in the whole study area and in the central part of the study area, the computation was done for the Thiessen polygons within each of these areas.

The calculation of storage-volume change for this report uses a different method than was done in previous reports. In this report, the storage-volume change was calculated by subtracting the raster of the water-level altitudes at the beginning of the change period from the raster of the water-level altitudes at the end of the period. The resulting water-level change raster was converted to contours, plotted with the measured water-level changes at the wells, and the contours modified where needed to conform to the measured water-level changes and to make hydrologic sense. The revised contours and the measured water-level changes were used to create a new water-level change raster. The area of each cell in the revised raster was multiplied by the water-level change for that cell; the resulting value for each cell multiplied by a specific yield value of 0.15 yields the estimated storage-volume change in each raster cell. Storage-volume changes can be summed for all the cells within a particular area to get the storage-volume change for that area.

Water-Level Altitude Maps

A water-level-altitude surface of an aquifer or of a layer within an aquifer indicates the height of the water surface above a datum (for example, NAVD 88) and the direction of flow within the aquifer or aquifer layer. Where an aquifer is unconfined, the water-level altitude surface is the same as the water-table. In general, water moves horizontally and vertically from areas of higher water-level altitudes towards lower water-level altitudes. Water moves perpendicularly to the water-level altitude contours in the horizontal direction. Where the water-level altitudes in the shallow aquifer layer are above those in the deep layer, water tends to move downward from the shallow layer into the deep layer. Where the water-level altitudes are higher in the deep aquifer layer than the shallow layer, the water tends to move upward from the deep layer into the shallow layer. Where an aquifer layer is confined or semiconfined, the water-level altitude in the deep aquifer layer may differ substantially from the water table in the shallow aquifer layer.

Previously published water-level altitude maps for August 1940 and January 1993 (Williams and Lohman, 1949; and Aucott and Myers, 1998) were based on a mix of stressed and static water-level measurements made in Wichita's historic monitoring wells, some of which were open to the shallow layer and some to the deep layer of the *Equus* Beds aquifer. In this report, the number of wells has been expanded to include other wells, especially monitoring wells measured by GMD2 for the 1993 water-level altitude map. In addition, efforts were made to include only static water levels and for each map to include only wells from a single layer.

Shallow Aquifer Layer, Predevelopment

An aquifer is considered to be in a predevelopment condition if large-scale pumpage from the aquifer has not yet begun. Large-scale pumpage from the *Equus* Beds aquifer in the study area began in September 1940 with the city of Wichita's pumpage from the aquifer in the central part of the study area (fig. 1). Large-scale pumpage for irrigation, the other major use of water in the study area, did not begin until the 1960s and 1970s with the adoption of rolling sprinkler irrigation systems. For the purposes of this report, water levels before September 1940 are considered to represent predevelopment conditions, especially in the central part of the study area.

Examination of the available predevelopment water levels indicated most were in the shallow part of the aquifer. A predevelopment water-level altitude map of the shallow aquifer layer was constructed using the measured water levels from the wells in the shallow aquifer layer (fig. 2, *link to figure 2*). The water-level altitude contours shown in figure 2 (*link to figure 2*) are a modification of the contours published by Williams and Lohman (1949), which are considered to represent predevelopment conditions in and near the study area. Except in the northern part of the study area, the contours are similar to those used by Aucott and Myers (1998). Most wells used by Aucott and Myers (1998) were open to the shallow aquifer layer; however, in the northern part of the study area (north of U.S. Highway 50), they were open to the deep aquifer layer.

Figure 2 (*link to figure 2*) shows that in predevelopment time, water in the aquifer generally flowed from west to east and discharged to the Little Arkansas River and possibly to the Arkansas River. The large area of higher water-level altitudes in the northern part of the study area indicates an area of recharge associated with the porous dune sand deposits in this part of the study area (Kelly and others, 2013). Water-level altitudes in the study area range from about 1,470 ft in the northwest to about 1,330 ft in the southeast.

As part of the city of Wichita's ASR permits, the city is prohibited from artificially recharging water into the aquifer in a BSA grid cell if water levels in that cell are above the January 1940 water levels or are less than 10 ft below land surface (Kansas Department of Agriculture, 2005). The map previously used for this purpose was the August 1940 water-level altitude map of Aucott and Myers (1998). As noted above, some of the wells used to construct this map were completed in the deep aquifer layer, especially in the northern part of the study area; water levels in the shallow aquifer layer in this area can be more than 30 ft higher than those in the deep aquifer layer. Therefore, the use of water levels from the deep part of the *Equus* Bed aquifer in the northern part of the study area would not provide an accurate representation of the shallow water table in this area. The revised predevelopment water-level altitude map of the shallow part of the aquifer that is presented in this report (fig. 2, *link to figure 2*) uses only water levels from wells open to the shallow part of the aquifer. This will enable the city of Wichita, DWR, and GMD2 to better manage the aquifer and meet regulatory requirements.

The raster created from the predevelopment map of the shallow aquifer was used to interpolate the predevelopment water-level altitudes for the ASR Phase I and II monitoring wells that are open to the shallow part of the aquifer. The water-level altitudes at the IW wells can be used as surrogates for the water levels in the BSA cells; however, as the IW wells were not installed until 2001–02, water-level altitudes, interpolated from the predevelopment map, must be used. The locations and names of these wells are shown on figure 2 (*link to figure 2*); the interpolated water-level altitudes for these wells are shown in table 1 (*link to table 1*). These interpolated water-level altitudes can be used for determining water-level changes since predevelopment at these wells and those water-level changes can be used to estimate the storage-volume changes since predevelopment.

Deep Aquifer Layer, 1993

The ASR permits (Kansas Department of Agriculture, 2005) specify that the January 1993 water-level altitudes will be used as a lower baseline for regulating withdrawals by the city of Wichita of artificial recharge credits from the *Equus* Beds aquifer. January 1993 is used as the lower baseline because Aucott and Myers (1998) reported January 1993 was when record to near-record low water levels were measured in most wells. To better represent the general condition of the aquifer and to comply with Wichita's ASR permits, only static (unaffected by pumping) water levels were used for this report. The January 1993 time period was expanded to October 1992 through February 1993 to ensure the use of static water levels and increase the areal density of data because water levels were not measured in many wells in January 1993 and some of the measured water levels were affected by pumping.

The ASR permits do not specify which aquifer layer to use as the lower baseline for regulating the withdrawal of recharge credits by the city of Wichita. After much consultation and discussion among personnel of the city of Wichita, GMD2, DWR, and USGS, the possibility exists of using the deep aquifer layer for this lower baseline. Using the deep aquifer layer for regulatory purposes would be helpful to stakeholders, in part, because most irrigation, city public-supply, and artificial recharge wells are open to the deep layer of the aquifer. However, there are technical issues with using water levels from the deep aquifer layer to determine storage changes, especially in the more confined parts of the aquifer. Storage changes compared to predevelopment are computed using shallow water-level maps and are the most appropriate for assessing the depth to water below land surface and the overall storage changes in the aquifer.

Measured water levels from October 1992 to February 1993 were used to generate a static water-level altitude surface of the deep layer of the *Equus* Beds aquifer (fig. 3, *link to figure 3*) from which the 1993 water levels for the deep IW wells were interpolated. Use of the October 1992 to February 1993 period also allowed the selection of the water level from each well that best represented static conditions. Water-level measurements were excluded from use if the hydrographs indicated that the measured wells or nearby wells were pumping or had recently been pumped for all measurements in the October 1992 through February 1993 period. For wells in the deep aquifer layer without measured 1993 water levels, water-level altitudes were interpolated from a raster of the map of static 1993 water-level altitudes in the deep *Equus* Beds aquifer layer and are shown in table 1 (*link to table 1*).

Water-level altitudes in 1993 in the deep *Equus* Beds aquifer layer indicate that groundwater generally moved from west to east. However, between the central part of the study area and the Little Arkansas River pumping from municipal and irrigation wells intercepted some groundwater flow and also diverted water from the Little Arkansas River.

Shallow Aquifer Layer, 1993

Comparison of the shallow static water-level altitude maps for predevelopment and 1993 (figs. 2 and 4, *link to figures 2* and *4*) shows that groundwater during both time periods generally moved from the west to east. However, between the central part of the study area and the Little Arkansas River the direction of flow had changed by 1993. In this area, the direction of flow was from east to west in 1993, as water that formerly discharged to the Little Arkansas River was pumped out of the aquifer by wells in or near the central part of the study area. Interpolated static 1993 water levels for wells in the shallow aquifer layer without 1993 water levels are shown in table 1 (*link to table 1*).

Water-Level Altitude Differences and Storage-Volume Changes

By comparing water-level altitude differences between the shallow and deep aquifer layers or changes between two time periods, the vertical and horizontal areas affected by water-level differences or changes can be determined. This difference or change also can be used to estimate the storage-volume of the aquifer within which water-level differences or changes have occurred.

Difference between Shallow and Deep Aquifer Layers, 1993

Examination of 2011 water-level altitude maps of the shallow and deep aquifer layers (Hansen, 2011b and 2012) and figures 3 and 4 (*link to figures 3* and *4*) for 1993 show generally similar patterns of water-level altitudes. The only exception is in the area north of U.S. Highway 50 where semi-confined conditions exist in the deep aquifer layer that lies beneath thick clay-rich layers that are overlain by dune sands. The map of the shallow aquifer layer (fig. 4, *link to figure 4*) indicates an area of recharge that is not shown on the map of the deep aquifer layer (fig. 3, *link to figure 3*).

Differences between the shallow and deep aquifer water-level altitudes in 1993 were less than 5 ft in about two-thirds of the study area, indicating that unconfined conditions likely existed in those areas (fig. 5). The greatest differences were in the extreme northwestern part of the study area, centered near the IW01 cluster, where positive differences were as much as 60 ft. A positive value indicated that the water level in the deep aquifer layer was below the water level in the shallow aquifer layer and the vertical component of groundwater flow was downward. Near the IW09 well cluster was an area with positive differences of more than 10 feet; an area with positive differences of more than 15 ft was near and south of the IW26 well cluster (fig. 5). There are several small areas where water-level differences were negative, but one of these areas in the western part of the study area is notably larger than the others. Where water-level differences were large and positive the deep *Equus* Beds aquifer layer was probably semiconfined, because water levels in the deep aquifer layer were substantially below those in the shallow aquifer layer. Areas with negative values indicated the water levels in the deep aquifer layer were above those in the shallow aquifer layer indicating water may have been moving from the deep aquifer layer upward into the shallow aquifer layer. None of the negative areas had differences as great as 5 ft, indicating only minor flow from the deep to the shallow aquifer layer (fig. 5).

Table 2 shows the average differences between the static water-level altitudes in the shallow and deep *Equus* Beds aquifer layers in the four parts of the study area (fig. 1) using three different methods. Except in the pre-2012 study area, the average differences using measured and interpolated values are smaller than the differences from measured values only (table 2). The average differences from the raster are larger than the average measured differences and the average measured and interpolated differences (table 2), but are all within an average difference of 1.10 ft.

Change in Shallow Aquifer Layer, Predevelopment to 1993

As noted by Kelly and others (2013), most of the water-level and storage-volume changes occur in the shallow layer of the *Equus* Beds aquifer. This is because most of the water that comes out of storage is from the unconfined part of the aquifer, which is typically the shallow aquifer layer. If the shallow and deep aquifer layers are unconfined, the water levels in both layers will be similar and use of specific yield to estimate the storage-volume change is appropriate. However, if the shallow aquifer layer is unconfined and the deep layer is semiconfined to confined, use of specific yield is appropriate for estimating the storage-volume change only for the shallow aquifer layer and storage coefficient for the deep aquifer layer.

Table 2. Comparison of computations of average differences between static water-level altitudes in the shallow and deep aquifer *Equus* Beds aquifer layers, 1993, for various parts of the study area.

[Positive values indicate the water levels in the deep aquifer layer are below those in the shallow aquifer layer.]

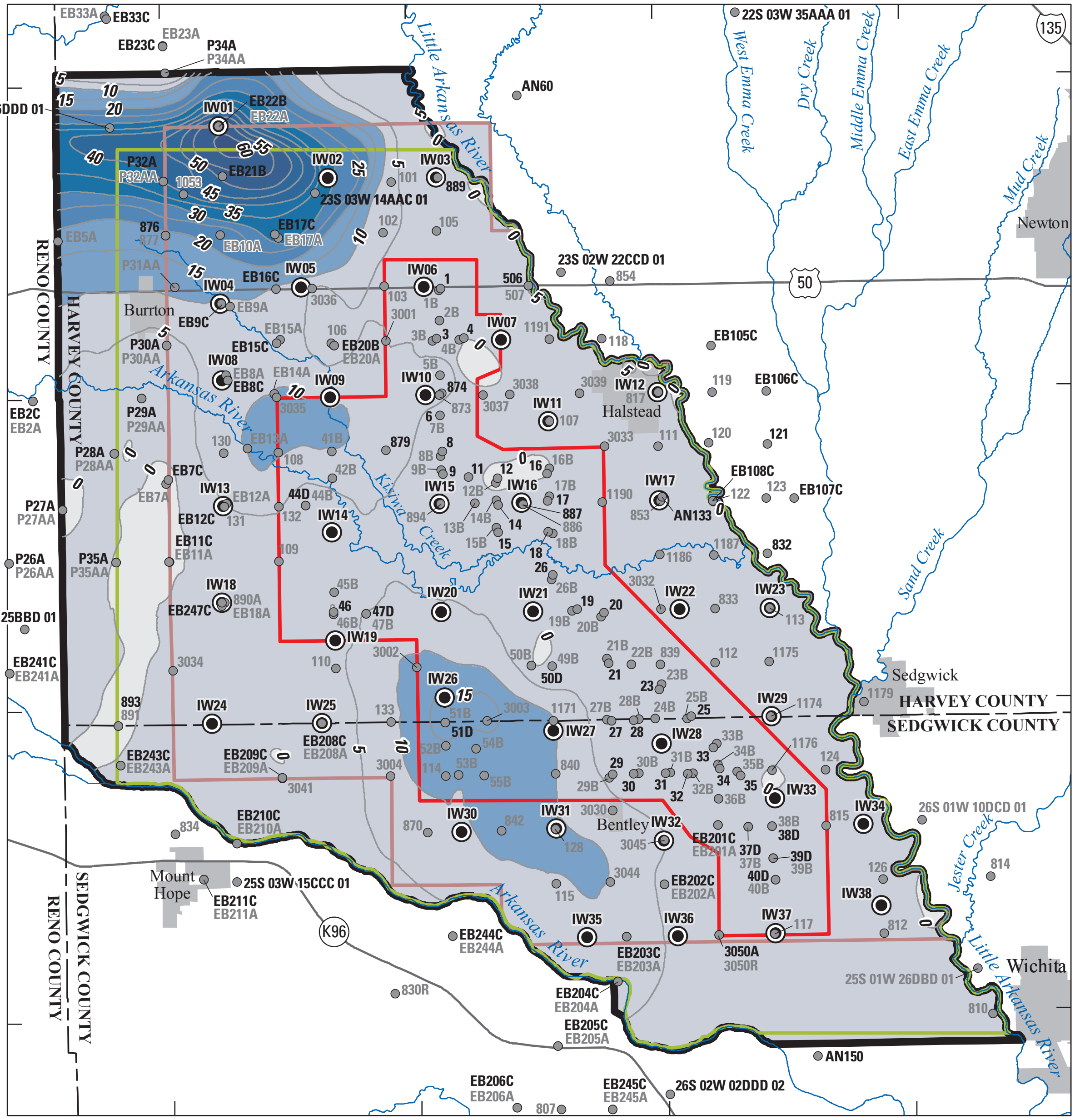
Area	Average differences between static water-level altitudes in shallow and deep *Equus* Beds aquifer layers, 1993 (feet)		
	Measured at wells	Measured and interpolated at wells	Raster
Study area	5.81	5.38	6.41
Pre-2012 study area	4.53	4.94	5.44
Basin storage area	5.11	5.07	6.16
Central part of study area	3.74	3.26	4.04

Kelly and others (2013) used a specific yield of 0.15 for the *Equus* Beds aquifer where it was unconfined. Kelly and others (2013) used a storage coefficient of 0.0005 for the semiconfined to confined parts of the *Equus* Beds aquifer. Therefore, although water-level changes in the deep aquifer layer may be larger than those in the shallow aquifer layer in confined to semiconfined areas, the contribution of the deep aquifer layer to the amount of storage-volume change will be small. Kelly and others (2013) state:

> "Use of groundwater level changes that do not include storage changes that occur in confined or semi-confined part of the aquifer will slightly underestimate storage changes; however, use of specific yield and groundwater level changes to estimate storage change in confined or semi-confined parts of the aquifer will overestimate storage changes. Using only changes in shallow groundwater levels will provide more accurate storage changes for the measured groundwater levels method."

Thus, the use of water-level changes in the shallow layer of the *Equus* Beds aquifer is more appropriate for determining storage-volume changes than the use of water-level changes in the deep aquifer layer, which includes semiconfined conditions in part of the area.

The static shallow predevelopment to 1993 water-level change map shows that water-level declines occurred in most of the study area (fig. 6). Almost the entire central part of the study area and the northwest corner of the study area had declines of 10 ft or more and most of the central part of the study area had declines of 20 ft or more. Declines of more than 30 ft occurred in two areas in the central part of the study area. An area of more than 40 ft of decline from predevelopment to 1993 occurs on the eastern edge of the central part of the study area (fig. 6). This pattern of decline is similar to the pattern of August 1940 to January 1993 shown by Hansen and



Base from U.S. Geological Survey digital data, 2012, 1:24,000
Universal Transverse Mercator projection, Zone 14
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

0 1 2 3 MILES
0 1 2 3 KILOMETERS

EXPLANATION

Area of water-level difference—Positive values indicate water levels in the deep aquifer layer are below those in the shallow aquifer layer and vertical flow is downward. Negative values indicate water levels in the deep aquifer layer are above those in the shallow aquifer layer and vertical flow is upward

- -10 to less than zero feet
- Zero to less than 10 feet
- 10 to less than 20 feet
- 20 to less than 30 feet
- 30 to less than 40 feet
- 40 to less than 50 feet
- 50 to less than 60 feet
- More than 60 feet

10 **Line of equal water-level altitude difference between shallow and deep *Equus* Beds aquifer layers, 1993. Contour interval 5 feet**

Boundary of study area

Boundary of pre-2012 study area

Boundary of basin storage area

Boundary of central part of the study area

IW35 **Index monitoring well and identifier**

EB245C EB245A **Monitoring well in the *Equus* Beds aquifer**—Well identifier shown in black type indicates deep layer; well identifier shown in gray type indicates shallow layer. Datum is North American Vertical Datum of 1988

Figure 5. Difference between the shallow and deep static water-level altitudes of the *Equus* Beds aquifer, 1993.

Aucott (2001) that was constructed using a combination of stressed and unstressed January 1993 water levels. Pumping for municipal and irrigation purposes probably are the main reason for water-level declines in the central part of the study area. The area of water-level declines in the northwestern corner of the study area and the area of water-level rises of 10 ft near the IW01 well cluster (fig. 6) were not reported by Hansen and Aucott (2001) because they were outside the pre-2012 study area and probably because they used wells open to the deep aquifer layer in these areas. These areas of water-level rise and decline in the northwestern part of the study area may be associated with heterogeneity of the aquifer material within the dune sand area because there is little pumpage from the *Equus* Beds aquifer in this area (Kansas Department of Agriculture and Kansas Geological Survey, 2013).

Estimates of total storage volume made using the recently published groundwater flow model of the *Equus* Beds aquifer (Kelly and others, 2013) and comparisons of average water-level and storage-volume changes for the method used in previous reports (for example, Aucott and Myers, 1998; Hansen, 2012) are shown in table 3. The method used in this report and the effect on storage-volume change of using a specific yield of 0.15 instead of the previously used specific yield of 0.20 are also shown in table 3. Changing the specific yield from 0.20 to 0.15 has a greater effect on the amount of storage-volume change than does the change from the use of mixed, stressed water-level altitudes to the use of static water-level altitudes from a single aquifer layer. For example, the use of mixed, stressed water-level altitudes with a specific yield of 0.20 for the pre-2012 study area resulted in a storage-volume change of -255,000 acre-ft. Retaining the 0.20 specific yield, but using static water-level altitudes in the shallow *Equus* Beds aquifer layer, caused the storage-volume change to increase by only 2 percent to -261,000 acre-ft. Changing the specific yield to 0.15 resulted in storage-volume change that was 25 percent less for use of the mixed, stressed water-level altitudes (table 3). The storage-volume change determined using the static, shallow water-level altitudes and a specific yield of 0.15 (-196,000 acre-ft) was about 23 percent less than the storage-volume change determined using the mixed, stressed water-level altitudes and a specific yield of 0.20 (-255,000 acre-ft). Even in the central part of the study area, where many city public-supply wells are located, the effect on the storage-volume change from using mixed, stressed water-level altitudes to static water-level altitudes in the shallow aquifer layer was an increase in storage-volume change of less than 4 percent (table 3). This indicates that use of static water-level altitudes in the shallow aquifer layer will not result in large changes in storage-volume calculations compared to those reported in previous reports. Instead, use of a specific yield of 0.15 will result in substantial decreases in the amount of storage-volume change compared to those reported in previous

Table 3. Total aquifer storage volume and comparison of computations of average water-level and storage-volume changes from previously published mixed stressed water-level change map and from static water-level change maps of the shallow layer of the *Equus* Beds aquifer, predevelopment to 1993, for various parts of the study area.

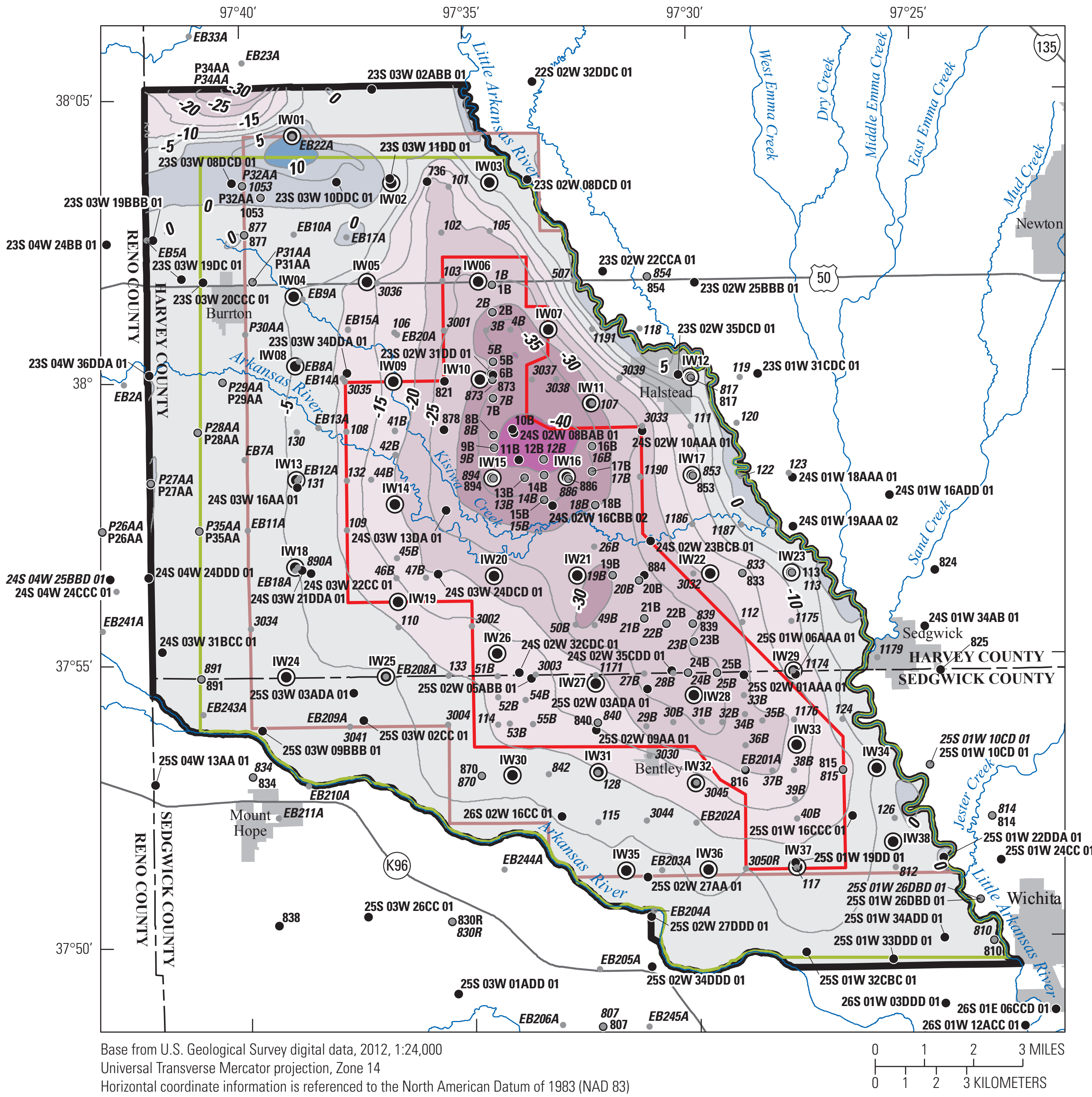
[NA, not applicable]

Area and type of water levels used for water-level change map	Total aquifer storage volume, predevelopment, from model (acre-feet)	Average water-level change, predevelopment to 1993 (feet)			Storage-volume changes, predevelopment to 1993 (acre-feet)		Storage-volume changes, predevelopment to 1993 (percent)
	Specific yield 0.15	Measured	Measured and interpolated	Raster	Specific yield 0.20	Specific yield 0.15	Specific yield 0.15
Mix of shallow and deep stressed water levels							
Study area	NA	-23.33	-16.73	NA	-259,000	-194,000	NA
Pre-2012 study area	NA	-23.97	[2]-16.07	NA	[1]-255,000	-192,000	NA
Basin storage area	NA	-24.58	-17.40	NA	-250,000	-187,000	NA
Central part of study area	NA	-30.65	[2]-24.09	NA	[3]-154,000	-116,000	NA
Shallow static water levels							
Study area	3,192,000	-21.07	-15.16	-11.19	-270,000	-202,000	-6
Pre-2012 study area	2,776,000	-22.56	-16.17	-12.36	-261,000	-196,000	-7
Basin storage area	2,400,000	-25.87	-17.33	-13.97	-251,000	-188,000	-8
Central part of study area	1,025,000	-31.01	-24.56	-22.99	-160,000	-120,000	-12

[1] Storage-volume change previously reported by Aucott and Myers (1998).

[2] Storage-volume change previously reported by Hansen (2012a).

[3] Storage-volume change previously reported by Hansen and Aucott (2001).



Base from U.S. Geological Survey digital data, 2012, 1:24,000
Universal Transverse Mercator projection, Zone 14
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

EXPLANATION

Area of water-level change:

- Decline of 40 feet or more
- Decline of 30 to less than 40 feet
- Decline of 20 to less than 30 feet
- Decline of 10 to less than 20 feet
- Decline of zero to less than 10 feet
- Rise of zero to 10 feet
- Rise of greater than 10 feet

-25 — **Line of equal water-level change in the shallow layer of the *Equus* Beds aquifer, predevelopment to 1993. Contour interval 5 feet.**

Boundary of study area

Boundary of pre-2012 study area

Boundary of basin storage area

Boundary of central part of the study area

IW35 **Index monitoring well and identifier**

EB245A **Monitoring well in the shallow layer of the *Equus* Beds aquifer, 1993**—Well identifier shown in *italic* type

807 **Monitoring well in the shallow layer of the *Equus* Beds aquifer, predevelopment, and identifier**

Figure 6. Static water-level changes in the shallow layer of the *Equus* Beds aquifer, predevelopment to 1993.

reports that were calculated using a specific yield of 0.20. Because the value of specific yield has such a large effect on storage-volume calculations and there is substantial range in values, more information on the distribution of specific yield in the study area would improve the accuracy of the estimates of storage-volume change.

Dividing the estimated storage-volume change by the estimated total predevelopment aquifer storage volume yields the percent of aquifer storage volume that has been lost. Approximately 12 percent of storage volume had been lost from August 1940 to January 1993 using the storage-volume change of -255,000 acre-ft from Aucott and Myers (1998) and the estimated aquifer storage volume of 2,100,000 acre-ft from Hansen (2007) for the pre-2012 study area. Table 3 shows that this previous estimate, which was made using a specific yield of 0.2, mixed, stressed water levels and an average aquifer thickness, may have overestimated the percentage of storage volume change and underestimated the amount of total aquifer storage volume. Based on the revised water-level maps and the methods used in this report, there was only a 7 percent loss of aquifer storage volume in the pre-2012 study area from predevelopment to 1993. The overall decline and change in storage from predevelopment to 1993 represented a loss in storage of about 6 percent of the overall storage volume in the newly defined study area. Even in the central part of the study area, where the declines were greatest, the loss of storage volume from predevelopment to 1993 was only 12 percent of the total aquifer volume. These revised estimates of storage changes in shallow and deep layers can be used by Wichita, GMD2, and DWR to manage, regulate, and preserve the water supply in this aquifer.

Summary

Beginning in the 1940s, the Wichita well field was developed in the *Equus* Beds aquifer in southwestern Harvey County and northwestern Sedgwick County to supply water to the city of Wichita. The decline of water levels in the aquifer was noted soon after the development of the Wichita well field began. Development of irrigation wells began in the 1960s. City and agricultural withdrawals have led to substantial water-level declines. Water-level declines enhanced movement of brines from past oil and gas activities near Burrton, Kansas and enhanced movement of natural saline water from the Arkansas River to migrate into the well field area. Further movement into the well field area of these waters with large chloride concentrations may limit use or require treatment of water from the well field area for irrigation or public supply. As water levels in the aquifer decline, the volume of water stored in the aquifer decreases and less water is available to supply future needs. In 1993, the city of Wichita adopted the Integrated Local Water Supply Program (ILWSP) to ensure an adequate water supply for the city through 2050 and as part of its effort to effectively manage the part of the *Equus* Beds aquifer it uses. The ILWSP uses several strategies to do this including the *Equus* Beds Aquifer Storage and Recovery (ASR). The purpose of the ASR project is to store water and later recover groundwater and to help protect the aquifer from the encroachment of a known oilfield-brine plume near Burrton and saline water from the Arkansas River.

As part of the Wichita's ASR permits, Wichita is prohibited from artificially recharging water into the aquifer in a Basin Storage area (BSA) grid cell if the water levels in that cell are above the January 1940 water levels or are less than 10 feet below land surface. The map previously used for this purpose was a previously published August 1940 water-level altitude map, which used water levels from wells in the deep and shallow *Equus* Beds aquifer layers, and did not provide an accurate representation of the shallow water table. The revised predevelopment water-level altitude map of the shallow part of the aquifer is presented in this report. A raster of the predevelopment map was used to interpolate predevelopment water levels for wells in the shallow layer of the *Equus* beds aquifer.

The city of Wichita's ASR permits specify that the January 1993 water-level altitudes will be used as a lower baseline for regulating withdrawals by the city of Wichita of artificial recharge credits (water) from the *Equus* Beds aquifer. The city of Wichita is prohibited from withdrawing artificial recharge credits from the aquifer if water levels estimated in the BSA cells are below the lowest January 1993 water levels. To better represent the general condition of the aquifer and to comply with Wichita's ASR permits, only static (unaffected by pumping) water levels were used. To ensure an adequate density of static water levels, the January 1993 period was expanded to October 1992 through February 1993. Static water levels from the deep aquifer layer of the *Equus* Beds aquifer possibly could be used as the lower baseline for the city of Wichita's ASR permits because most city public-supply wells and artificial recharge wells, respectively, pump water from and inject water into the deep layer of the aquifer.

The 1993 water-level altitudes in the shallow and deep aquifer layers indicate that water generally flows from west to east across the study area but that pumping wells in the central part of the study area were intercepting some of the east to west flow and were also drawing water from the Little Arkansas River. Water-level altitudes in 1993 in the shallow *Equus* Beds aquifer layer were less than 5 feet above those in the deep aquifer layer in about two-thirds of the study area. Water-level altitude as much as 60 feet higher in the shallow aquifer layer than in the deep aquifer layer occurred locally in the northwest part of the study area, indicating downward flow and semiconfined conditions in this part of the study area. Small areas where water-level altitudes were less than 5 feet lower in the shallow deep than the deep shallow aquifer layer indicate only minor flow upward from the deep to shallow aquifer layer. A comparison of average water-level altitude differences between the shallow and deep *Equus* Beds aquifer layers in 1993 shows those determined by the use of rasters were greater than those from either well clusters with measured water levels or wells clusters with measured and interpolated water levels.

Previously, maps of water-level changes used to estimate the storage-volume changes included a combination of static and stressed water levels from wells, some of which were open to the shallow part of the aquifer and some open to the deep part of the aquifer. In this report only static water levels in the shallow aquifer layer were used. This change was made because the use of water-level changes in the shallow layer of the *Equus* Beds aquifer is more appropriate for determining storage-volume changes than use of water-level changes in the deep aquifer layer, which includes semiconfined conditions in part of the area. The map of static water-level changes in the shallow aquifer layer from predevelopment to 1993 shows declines of 20 feet or more in most of the central part of the study area with declines of 40 feet or more along the eastern edge of the central part of the study area. Pumping for municipal and irrigation purposes probably are the main reason for these water-level declines. A small area of water-level rises in the northwestern part of the study area may be associated with heterogeneity of the aquifer material within the dune sand area because there is little pumpage from this area.

The effects on average water-level and storage-volume change from the use of mixed, stressed water levels and a specific yield of 0.20 (used in previous studies) were compared to the use of static water levels in the shallow aquifer and a specific yield of 0.15. This comparison indicates that the change in specific yield causes storage-volume changes to decrease about 25 percent, whereas the use of static shallow aquifer layer causes an increase of less than 4 percent. Use of a specific yield of 0.15 resulted in substantial decreases in the estimated amount of storage-volume change compared to those reported in previous reports that were calculated using a specific yield of 0.20. Based on these revised water-level maps and computations, the overall decline and change in storage from predevelopment to 1993 represented a loss in storage of about 6 percent (-202,000 acre-feet) of the overall storage volume within the newly defined study area. These revised estimates of storage changes in shallow and deep layers can be used by Wichita, *Equus* Beds Groundwater Management District Number 2 and Kansas Department of Agriculture, Division of Water Resources to manage, regulate, and preserve the water supply in this aquifer.

References Cited

Aucott, W.R., and Myers, N.C., 1998, Changes in groundwater levels and storage in the Wichita well field area, south-central Kansas, 1940–98: U.S. Geological Survey Water-Resources Investigations Report 98–4141, 20 p.

Aucott, W.R., Myers, N.C., and Dague, B.J., 1998, Status of ground-water levels and storage in the Wichita well field area, south-central Kansas, 1997: U.S. Geological Survey Water-Resources Investigations Report 98–4095, 15 p.

Bayne, C.K., 1956, Geology and ground-water resources of Reno County, Kansas: Kansas Geological Survey Bulletin 120, 130 p. (Also available at *http://www.kgs.ku.edu/General/Geology/Reno/index.html.*)

Bayne, C.K., and Ward, J.R., 1969, Saturated thickness and specific yield of Cenozoic deposits in Kansas: Kansas Geological Survey Map M-5A, 1 sheet, scale 1:500,000.

Cederstrand, J.R., and Becker, M.F., 1998, Digital map of specific yield for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 98–414, scale 1:1,000,000. (Also available at *http://pubs.er.usgs.gov/publication/ofr98414.*)

City of Wichita, [2007?], Wichita area future water supply—a model program for other municipalities: Wichita, Kansas, accessed July 9, 2013, at *http://www.wichita.gov/Government/Departments/PWU/UtilitiesDocuments/WICHITA%20AREA%20FUTURE%20WATER%20SUPPLY.pdf.*

City of Wichita, 2008, City of Wichita, KS meeting the demands of a growing community: Transformations, Alliance for Innovation newsletter, v. 2, no. 3, p. 6.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods, 1–A1, 151 p.

Data Access and Support Center, 2013a, LiDAR 2011: Data Access and Support Center accessed May 28, 2013, at *http://www.kansasgis.org/catalog/index.cfm*.

Data Access and Support Center, 2013b, Metadata for LiDAR data for Harvey and Sedgwick Counties, Kansas: Data Access and Support Center accessed May 28, 2013, at *http://data.kansasgis.org/requests/USGS_2012/*.

Environmental Systems Research Institute, 2012, ArcGIS version 10.1: Redlands, Calif., Environmental Systems Research Institute software documentation [on-line documentation and instructions included with software].

Gibson, Campbell, 1998, Population of the 100 largest cities and other urban places in the United States—1790–1990: U.S. Census Bureau, Population Division Working Paper No. 27 accessed January 10, 2010, at *http://www.census.gov/population/www/documentation/twps0027/twps0027.html*.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

Hansen, C.V., 1991, Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas: U. S. Geological Survey Water-Resources Investigations Report 87–4230, 100 p., 4 pl., scales 1:500,000 and 1:1,000,000. (Also available at *http://pubs.er.usgs.gov/publication/wri874230*.)

Hansen, C.V., 2007, Status of ground-water levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2003–January 2006: U.S. Geological Survey Scientific Investigations Report 2006–5321, 34 p. (Also available at *http://pubs.usgs.gov/sir/2006/5321/*.)

Hansen, C.V., 2009a, Status of ground-water levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, July 2008: U.S. Geological Survey Scientific Investigations Map 3075, map scale 1:84,480. (Also available at: *http://pubs.usgs.gov/sim/3075/*.)

Hansen, C.V., 2009b, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2009: U.S. Geological Survey Scientific Investigations Map 3087, map scale 1:84,480. (Also available at *http://pubs.usgs.gov/sim/3087/*.)

Hansen, C.V., 2011a, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, July 2010: U.S. Geological Survey Scientific Investigations Map 3159, map scale 1:84,480. (Also available at *http://pubs.usgs.gov/sim/3159/*.)

Hansen, C.V., 2011b, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2011: U.S. Geological Survey Scientific Investigations Map 3192, map scale 1:84,480. (Also available at *http://pubs.usgs.gov/sim/3192*.)

Hansen, C.V., 2012, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, July 2011: U.S. Geological Survey Scientific Investigations Map 3208, map scale 1: 84,480. (Also available at *http://pubs.usgs.gov/sim/3208*.)

Hansen, C.V., and Aucott, W.R., 2001, Status of ground-water levels and storage volume in the Wichita well field area, south-central Kansas, 1998–2000: U.S. Geological Survey Water-Resources Investigations Report 00–4267, 27 p.

Hansen, C.V., and Aucott, W.R., 2004, Status of ground-water levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2000–January 2003: U.S. Geological Survey Water-Resources Investigations Report 03–4298, 36 p. (Also available at *http://pubs.usgs.gov/wri/wrir034298/*.)

Hansen, C.V., and Aucott, W.R., 2010, Status of groundwater levels and storage volume in the *Equus* Beds aquifer near Wichita, Kansas, January 2006 to January 2010: U.S. Geological Survey Scientific Information Report 2010–5231, 42 p. (Also available at *http://pubs.usgs.gov/sir/2010/5231/*.)

Juracek, K.E., and Hansen, C.V., 1995, Digital maps of the extent, base, top, and 1991 potentiometric surface of the High Plains aquifer in Kansas: U.S. Geological Survey Open-File Report 95–758, map scales 1:500,000 and 1:1,000,000.

Kansas Department of Agriculture, 2005, In the matter of the city of Wichita's applications to operate an aquifer storage and recovery project in Harvey and Sedgwick Counties, Kansas—applications to appropriate water, file nos. 45,567; 45,568; 45,569; 45,570; 45,571; 45,572; 45,573; 45,574; 45,575; 45,576; and 46,081: Topeka, Kansas, Kansas Department of Agriculture, Division of Water Resources, August 8, 2005, 21 p.

Kansas Department of Agriculture, 2011, Wichita well field sees improved water levels: DWR Currents, April 14, 2011, unnumbered pages, accessed February 13, 2012, at *http://www.ksda.gov/dwr/content/314/cid/1773*.

Kansas Department of Agriculture and Kansas Geological Survey, 2013, Water Information Management and Analysis System (WIMAS): Kansas Department of Agriculture, Division of Water Resources database, accessed March 13, 2013, at *http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm*.

Kansas Geological Survey, 2012, WIZARD water-level database: Kansas Geological Survey database accessed February 3, 2012, at *http://www.kgs.ku.edu/Magellan/WaterLevels/index.html*.

Kansas Water Resources Board, 1960, Section 4, Lower Arkansas Unit, *in* State Water Plan Studies Part A—preliminary appraisal of Kansas water problems: Topeka, Kansas, 177 p.

Kelly, B.P., Pickett, L.L., Hansen, C.V., and Ziegler, A.C., 2013, Simulation of groundwater flow, effects of artificial recharge, and storage volume changes in the *Equus* Beds aquifer near the city of Wichita, Kansas well field, 1939–2008: U.S. Geological Survey Scientific Investigations Report 2013–5042, 90 p. (Also available at *http://pubs.er.usgs.gov/publication/sir20135042*.)

Lane, C.W., and Miller, D.E., 1965a, Geohydrology of Sedgwick County, Kansas: Kansas Geological Survey Bulletin 176, 100 p. (Also available at *http://www.kgs.ku.edu/General/Geology/Sedgwick/index.html*.)

Lane, C.W., and Miller, D.E., 1965b, Logs of wells and test holes in Sedgwick County, Kansas: Kansas Geological Survey Special Distribution Publication 22, 175 p.

Leonard, R.B., and Kleinschmidt, M.K., 1976, Saline water in the Little Arkansas River Basin area, south-central Kansas: Kansas Geological Survey Chemical Quality Series 3, 24 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms—Revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p. (Also available at *http://pubs.usgs.gov/wsp/wsp_1988/.)*

Myers, N.C., Hargadine, G.D., and Gillespie, J.B., 1996, Hydrologic and chemical interaction of the Arkansas River and the *Equus* Beds aquifer between Hutchinson and Wichita, south-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 95–4191, 100 p. (Also available at *http://pubs.er.usgs.gov/publication/wri954191*.)

Petri, L.R., Lane, C.W., and Furness, L.W., 1964, Water resources of the Wichita area, Kansas: U.S. Geological Survey Water-Supply Paper 1499–I, 69 p.

Pruitt, T., 1993, Arkansas River water management improvement study—Modeling of chloride transport in the *Equus* Beds aquifer: U.S. Department of the Interior, Bureau of Reclamation Technical Report, 96 p.

Reed, T.B., and Burnett, R.D., 1985, Compilation and analyses of aquifer performance tests in eastern Kansas: U.S. Geological Survey Open-File Report 85–200, 125 p.

Sophocleous, M.A., 1983, Water quality modeling of the *Equus* beds aquifer in south-central Kansas: Kansas Geological Survey Open-File Report 83–1, 75 p.

Spinazola, J.M., Gillespie, J.B., and Hart, R.J., 1985, Ground-water flow and solute transport in the *Equus* beds area, south-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 85–4336, 68 p. (Also available at *http://pubs.er.usgs.gov/publication/wri854336*.)

Stramel, G.J., 1956, Progress report on the ground-water hydrology of the *Equus* beds area, Kansas: Kansas Geological Survey Bulletin 119, part 1, 59 p.

Stramel, G.J., 1962a, A review of the geology and hydrology of the Wichita well field: Wichita, Kans., city of Wichita Water Department, 29 p.

Stramel, G.J., 1962b, A preliminary review of artificial recharge potential in the area between Hutchinson and Wichita, Kansas: Wichita, Kans., city of Wichita Water Department, 21 p.

Stramel, G.J., 1967, Progress report on the ground-water hydrology of the *Equus* beds area, Kansas 1966: Kansas Geological Survey Bulletin 187, part 2, 27 p.

Stullken, L.E., Watts, K.R., and Lindgren, R.J., 1985, Geohydrology of the High Plains aquifer, western Kansas: U.S. Geological Survey Water-Resources Investigations Report 85–4198, 86 p. (Also available at *http://pubs.er.usgs.gov/publication/wri854198*.)

Thiessen, A.H., 1911, Precipitation averages for large areas: Monthly Weather Review, v. 39, p. 1082–1084.

U.S. Census Bureau, 2012, Intercensal estimates of the resident population for incorporated places and minor civil division—April 1, 2000 to July 1, 2010 (SUB-EST00INT-TOT):: U.S. Census Bureau, Population Division, accessed July 9, 2013 at *http://www.census.gov/popest/data/intercensal/cities/cities2010.html*.

U.S. Geological Survey, 2009, National Elevation Dataset (NED): Sioux Falls, South Dakota, U.S. Geological Survey Earth Observation and Science (EROS) Center, accessed March 9, 2011, at *http://nationalmap.gov/elevation.html*.

U.S. Geological Survey, 2012, National Water Information System (NWISWeb): U.S. Geological Survey database accessed February 10, 2012, at *http://waterdata.usgs.gov/ks/nwis/*.

Warren, D.R., Blain, G.T., Shorney, F.L., and Klein, L.J., 1995, IRP—A case study from Kansas: Journal of the American Water Works Association, v. 87, no. 6, p. 57–71.

Whittemore, D.O., 2007, Fate and identification of oil-brine contamination in different hydrogeologic settings: Applied Geochemistry, v. 22, no. 10, p. 2099–2114.

Whittemore, D.O., 2012, Distribution and change in salinity in the *Equus* Beds Aquifer in the Burrton Intensive Groundwater Use Control Area; Kansas Geological Survey Open File Report 2012–1, 35 p.

Williams, C.C., and Lohman, S.W., 1949, Geology and ground-water resources of a part of south-central Kansas, with special reference to the Wichita municipal water supply: Kansas Geological Survey Bulletin 79, 455 p.

Ziegler, A.C., Christensen, V.G., and Ross, H.C., 1999, Baseline water-quality and preliminary effects of artificial recharge on groundwater, south-central Kansas, 1995–98: U.S. Geological Survey Water-Resources Investigations Report 99–4250, 74 p.

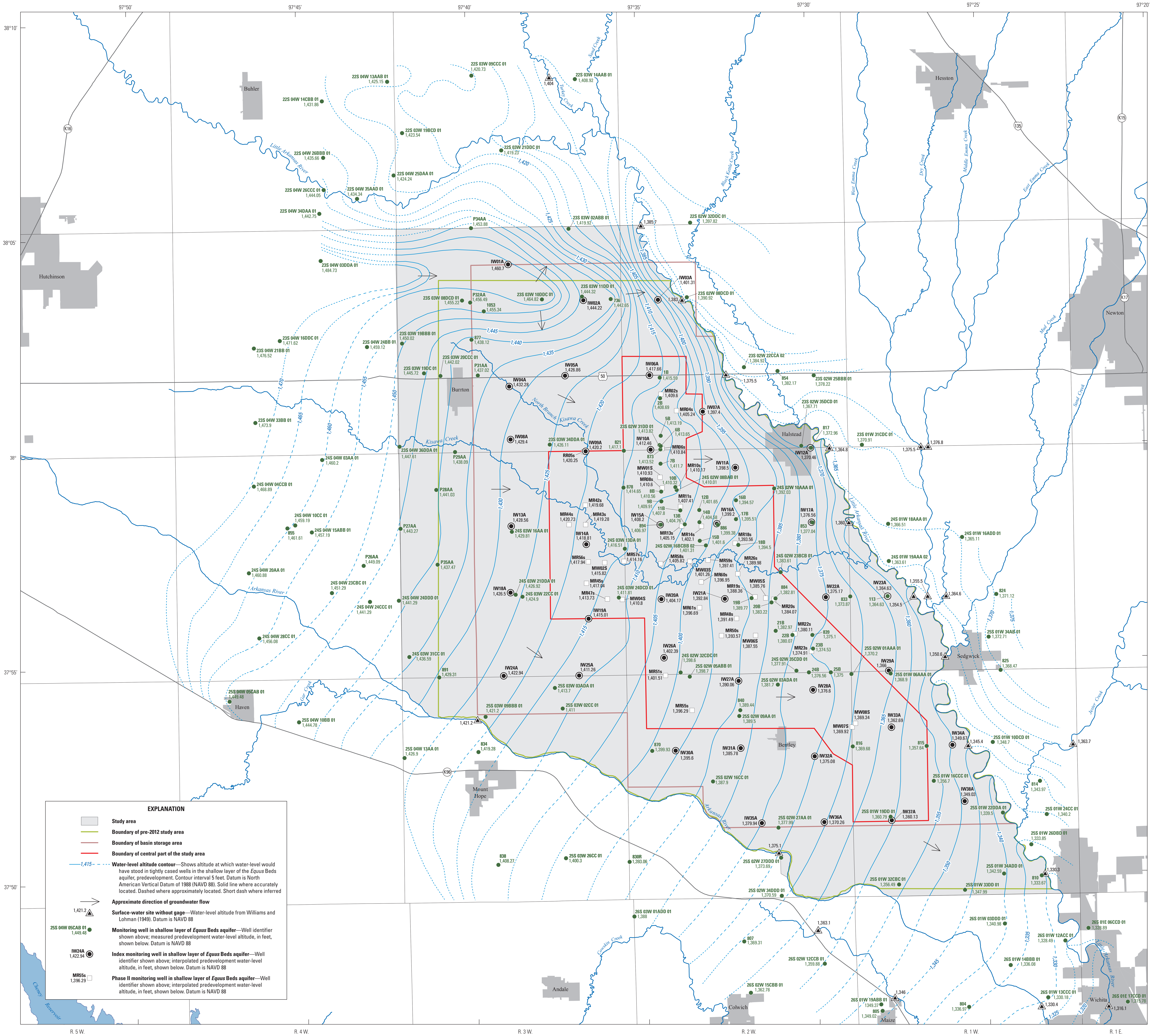
Ziegler, A.C., Hansen, C.V., and Finn, D.A., 2010, Water quality in the *Equus* Beds aquifer and the Little Arkansas River before implementation of large-scale artificial recharge, south-central Kansas, 1995–2005: U.S. Geological Survey Scientific Investigations Report 2010–5023, 143 p. (Also available at *http://pubs.usgs.gov/sir/2010/5023/*.)

Publishing support provided by:
Rolla Publishing Service Center

For additional information concerning this publication, contact:
Director, USGS Kansas Water Science Center
4821 Quail Crest Place
Lawrence, KS 66049
(785) 842–9909

Or visit the Kansas Water Science Center Web Site at:
http://ks.water.usgs.gov

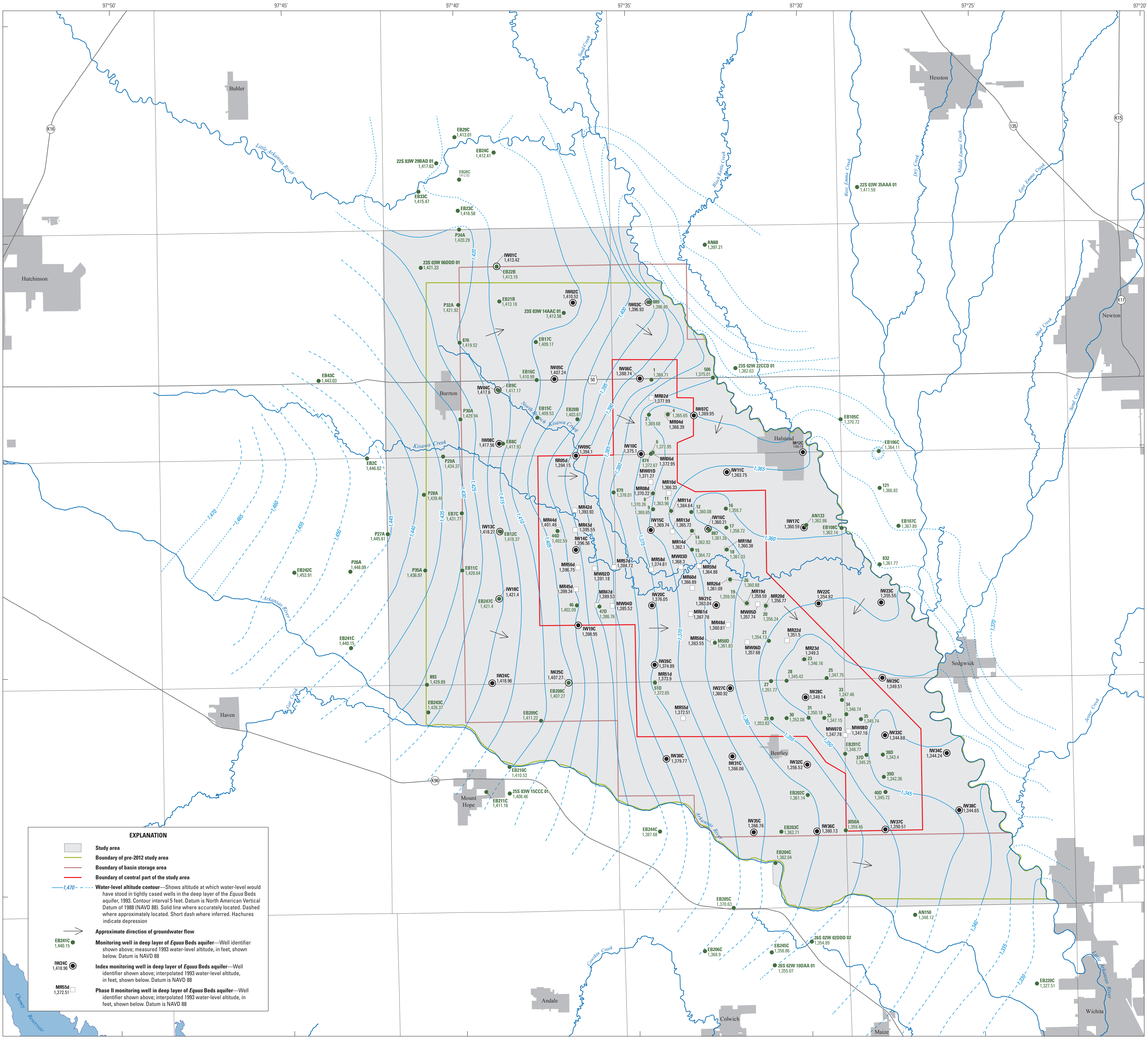
Hansen and others—**Revised Shallow and Deep Water-Level and Storage-Volume Changes in the *Equus* Beds Aquifer near Wichita, Kansas**—Scientific Investigations Report 2013–5170



Base from U.S. Geological Survey digital data, 2012, 1:24,000
Universal Transverse Mercator projection, zone 14
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

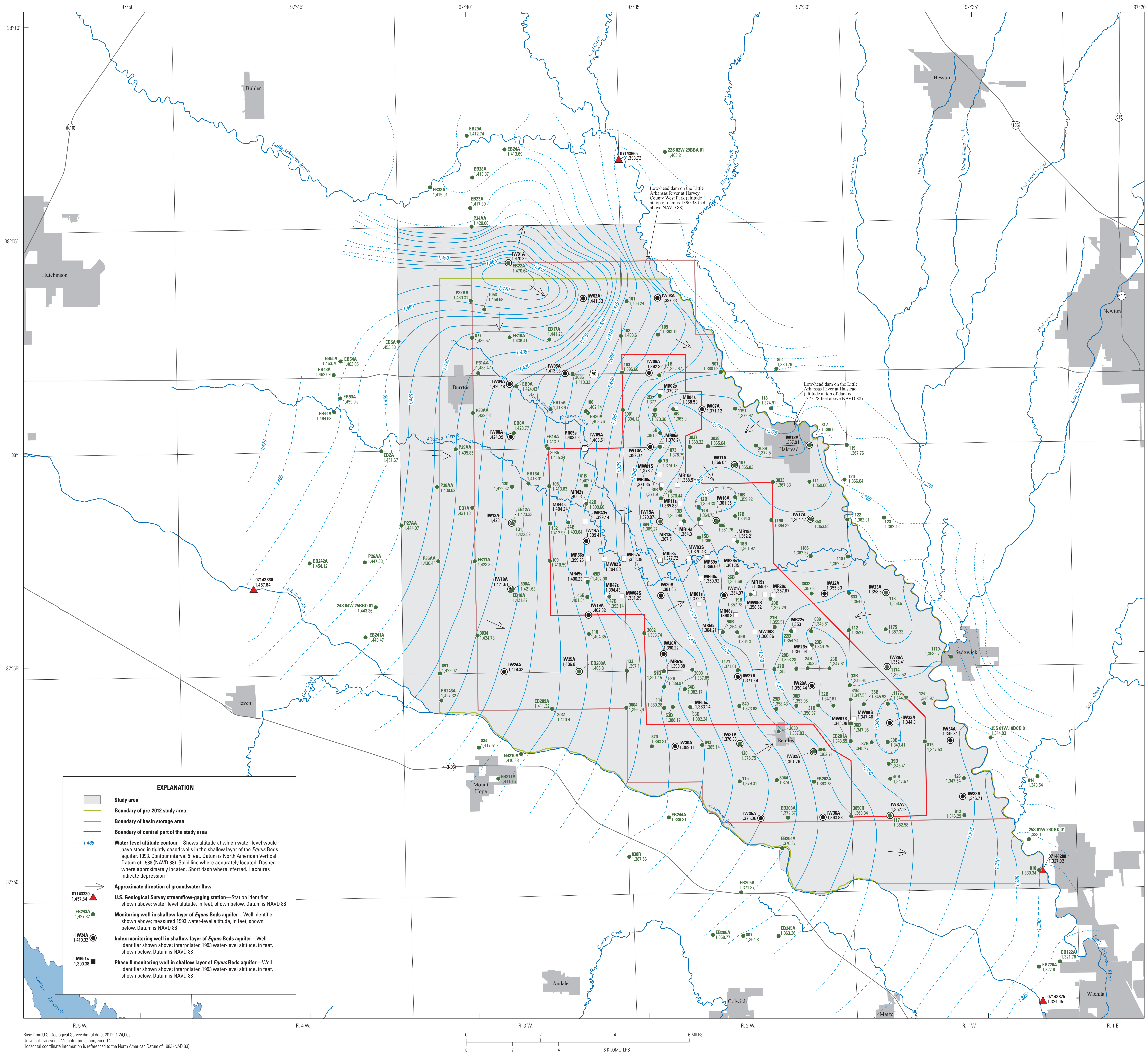
0 2 4 6 MILES
0 2 4 6 KILOMETERS

Figure 2. Predevelopment water-level altitudes in the shallow layer of the *Equus* Beds aquifer.



Base from U.S. Geological Survey digital data, 2012, 1:24,000
Universal Transverse Mercator projection, zone 14
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Figure 3. Static water-level altitudes in the deep layer of the *Equus* Beds aquifer, 1993.

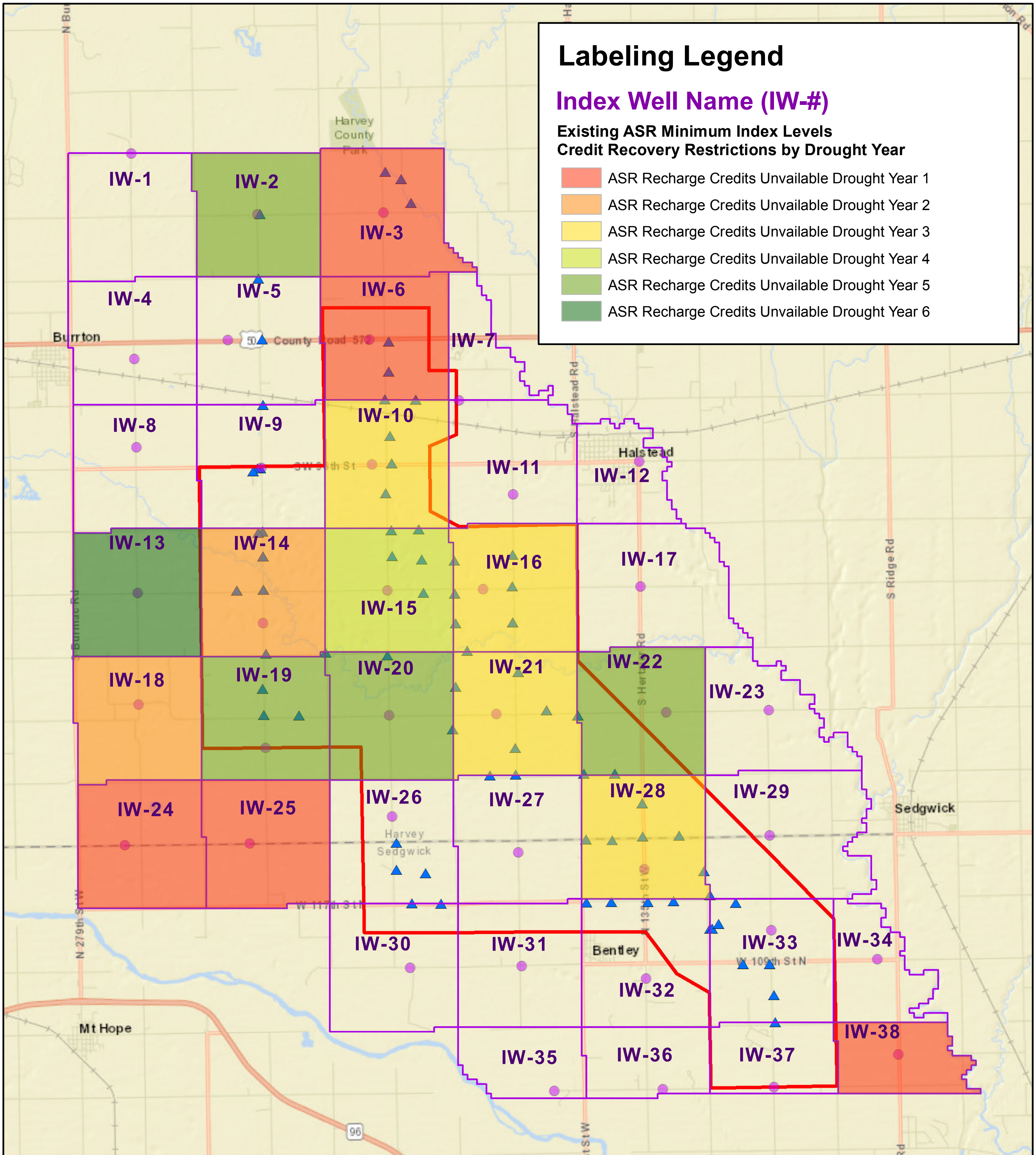


Base from U.S. Geological Survey digital data, 2012, 1:24,000
Universal Transverse Mercator projection, zone 14
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

0 2 4 6 MILES
0 2 4 6 KILOMETERS

Figure 4. Static water-level altitudes in the shallow layer of the *Equus* Beds aquifer, 1993.

ATTACHMENT I
Drought Model Simulation Results & Hydrographs



Legend

ASR Index Cells (Numbered)

USGS Central Wellfield Study Area

ASR Index Well Locations

N

1:130,000

0 0.5 1 2
Miles

CITY OF WICHITA

BURNS McDONNELL

Simulated Drought Results
Recovery of ASR Credits
Limited by Existing
Minimum Index
Level Elevations

Modeled Groundwater Elevations at ASR Index Wells During Simulated Drought
Extracted from Lower Model Layer (3) - Equivalent to IW(C) Aquifer Interval

Index Well Name	Initial Heads	Stress Period 1	Stress Period 2	Stress Period 3	Stress Period 4	Stress Period 5	Stress Period 6	Stress Period 7	Stress Period 8	Stress Period 9	Stress Period 10	Existing ASR Minimum Index Level*
IW01C	1436.80	1435.51	1434.33	1432.97	1432.03	1431.01	1430.36	1429.58	1429.14	1430.11	1431.18	1413.42
IW02C	1416.44	1414.55	1413.15	1411.81	1410.86	1409.86	1409.19	1408.43	1407.96	1409.16	1410.31	1410.52
IW03C	1393.89	1392.11	1391.44	1391.10	1390.64	1390.44	1390.10	1390.01	1389.76	1391.32	1391.79	1396.93
IW04C	1429.43	1427.77	1426.70	1425.38	1424.36	1423.10	1422.19	1421.06	1420.35	1420.82	1421.53	1417.60
IW05C	1419.79	1417.04	1415.67	1413.94	1412.73	1411.15	1410.16	1408.85	1408.21	1409.68	1410.78	1407.23
IW06C	1389.71	1388.71	1386.24	1383.58	1382.70	1380.95	1380.94	1380.72	1380.42	1382.78	1384.69	1388.74
IW07C	1381.46	1379.56	1377.80	1375.74	1374.69	1373.49	1373.07	1373.02	1372.79	1375.38	1377.15	1369.95
IW08C	1426.82	1425.15	1424.22	1423.01	1421.91	1420.72	1419.74	1418.75	1418.06	1418.37	1419.22	1417.56
IW09C	1406.62	1406.12	1404.70	1398.16	1400.00	1395.52	1396.49	1395.39	1394.74	1395.42	1397.17	1394.10
IW10C	1383.29	1380.79	1377.93	1373.81	1372.08	1369.35	1368.80	1368.40	1368.08	1372.32	1375.45	1375.09
IW11C	1375.71	1374.25	1372.15	1369.56	1367.89	1366.28	1365.61	1365.35	1365.27	1367.45	1369.79	1363.75
IW12C	1372.80	1371.10	1370.80	1370.97	1370.68	1370.88	1370.61	1370.84	1370.60	1371.91	1371.97	1365.78
IW13C	1424.92	1423.14	1422.20	1420.76	1419.92	1418.76	1418.21	1417.43	1417.21	1419.08	1420.98	1418.27
IW14C	1402.76	1398.40	1396.07	1392.10	1391.00	1388.48	1387.84	1387.08	1386.60	1392.49	1395.75	1396.56
IW15C	1382.13	1379.64	1376.35	1371.05	1369.08	1365.69	1365.00	1364.41	1364.07	1368.98	1372.89	1369.75
IW16C	1373.72	1370.01	1365.87	1360.00	1358.34	1354.50	1354.58	1354.35	1354.11	1359.07	1362.81	1360.21
IW17C	1368.19	1366.63	1365.86	1365.11	1364.33	1363.86	1363.40	1363.28	1363.16	1364.63	1365.37	1360.59
IW18C	1423.66	1421.81	1421.06	1419.81	1419.28	1418.30	1418.00	1417.32	1417.28	1419.01	1420.61	1421.40
IW19C	1405.80	1403.97	1402.34	1400.17	1399.08	1397.66	1396.98	1396.45	1396.07	1398.51	1400.64	1398.95
IW20C	1387.37	1386.22	1384.12	1380.32	1378.30	1375.84	1374.60	1373.79	1373.34	1375.03	1377.85	1376.05
IW21C	1370.45	1367.37	1364.82	1359.25	1357.66	1353.96	1353.24	1352.31	1352.12	1355.65	1358.77	1363.04
IW22C	1362.11	1360.18	1358.79	1356.97	1355.75	1354.63	1354.04	1353.79	1353.82	1355.64	1357.16	1354.92
IW23C	1360.00	1357.82	1357.46	1357.30	1357.08	1357.04	1356.94	1357.05	1356.98	1358.60	1358.81	1355.55
IW24C	1419.62	1418.12	1417.50	1417.45	1416.93	1416.97	1416.53	1416.65	1416.31	1417.80	1418.33	1418.96
IW25C	1408.27	1406.90	1405.97	1405.18	1404.42	1403.93	1403.44	1403.26	1403.00	1404.85	1405.95	1407.27
IW26C	1389.71	1388.05	1386.28	1384.06	1383.07	1381.56	1381.20	1380.84	1380.64	1382.55	1384.16	1374.89
IW27C	1373.52	1372.90	1371.10	1368.37	1366.20	1364.35	1363.35	1363.16	1363.22	1364.60	1366.65	1360.92
IW28C	1356.73	1356.09	1351.91	1347.19	1346.18	1343.80	1345.29	1346.61	1347.37	1350.80	1353.30	1349.14
IW29C	1354.92	1352.61	1351.59	1350.81	1350.76	1350.36	1350.74	1350.98	1351.05	1353.05	1353.51	1349.51
IW30C	1389.81	1387.93	1387.03	1386.85	1386.39	1386.42	1386.13	1386.50	1386.13	1387.80	1388.17	1379.77
IW31C	1379.78	1378.31	1377.29	1377.06	1376.46	1376.53	1376.18	1376.65	1376.33	1378.06	1378.53	1366.06
IW32C	1366.87	1365.23	1363.78	1363.30	1362.89	1362.86	1362.90	1363.54	1363.30	1365.30	1365.86	1356.51
IW33C	1353.74	1351.50	1350.02	1349.23	1349.33	1348.93	1349.59	1350.03	1350.00	1352.14	1352.55	1344.68
IW34C	1347.28	1345.11	1344.76	1344.67	1344.63	1344.62	1344.67	1344.82	1344.75	1346.24	1346.34	1344.24
IW35C	1375.72	1374.78	1373.95	1374.47	1373.77	1374.37	1373.74	1374.44	1373.79	1375.25	1375.37	1366.76
IW36C	1365.95	1364.28	1363.30	1363.61	1363.02	1363.49	1363.04	1363.72	1363.17	1364.87	1365.06	1360.13
IW37C	1355.80	1354.12	1353.14	1353.20	1352.85	1353.08	1352.93	1353.47	1353.11	1354.91	1355.14	1350.51
IW38C	1345.99	1343.83	1343.35	1343.33	1343.19	1343.27	1343.23	1343.47	1343.32	1344.96	1345.10	1344.65

Note: Red highlight indicates elevation below current ASR Minimum Index Level

Existing ASR Minimum Index Levels sourced from joint review process including the City, the Division of Water Resources, Groundwater Management District No. 2, and the United States Geological Survey as revised in 2015

Modeled Groundwater Elevations at ASR Index Wells During Simulated Drought Extracted from Lower Model Layer (3) - Equivalent to IW(C) Aquifer Interval Showing Index Cells within USGS Central Wellfield Study Area

Index Well Name	Initial Heads	Stress Period 1	Stress Period 2	Stress Period 3	Stress Period 4	Stress Period 5	Stress Period 6	Stress Period 7	Stress Period 8	Stress Period 9	Stress Period 10	Existing ASR Minimum Index Level
IW06C	1389.71	1388.71	1386.24	1383.58	1382.70	1380.95	1380.94	1380.72	1380.42	1382.78	1384.69	1388.74
IW10C	1383.29	1380.79	1377.93	1373.81	1372.08	1369.35	1368.80	1368.40	1368.08	1372.32	1375.45	1375.09
IW14C	1402.76	1398.40	1396.07	1392.10	1391.00	1388.48	1387.84	1387.08	1386.60	1392.49	1395.75	1396.56
IW15C	1382.13	1379.64	1376.35	1371.05	1369.08	1365.69	1365.00	1364.41	1364.07	1368.98	1372.89	1369.75
IW16C	1373.72	1370.01	1365.87	1360.00	1358.34	1354.50	1354.58	1354.35	1354.11	1359.07	1362.81	1360.21
IW19C	1405.80	1403.97	1402.34	1400.17	1399.08	1397.66	1396.98	1396.45	1396.07	1398.51	1400.64	1398.95
IW20C	1387.37	1386.22	1384.12	1380.32	1378.30	1375.84	1374.60	1373.79	1373.34	1375.03	1377.85	1376.05
IW21C	1370.45	1367.37	1364.82	1359.25	1357.66	1353.96	1353.24	1352.31	1352.12	1355.65	1358.77	1363.04
IW22C	1362.11	1360.18	1358.79	1356.97	1355.75	1354.63	1354.04	1353.79	1353.82	1355.64	1357.16	1354.92
IW26C	1389.71	1388.05	1386.28	1384.06	1383.07	1381.56	1381.20	1380.84	1380.64	1382.55	1384.16	1374.89
IW27C	1373.52	1372.90	1371.10	1368.37	1366.20	1364.35	1363.35	1363.16	1363.22	1364.60	1366.65	1360.92
IW28C	1356.73	1356.09	1351.91	1347.19	1346.18	1343.80	1345.29	1346.61	1347.37	1350.80	1353.30	1349.14
IW32C	1366.87	1365.23	1363.78	1363.30	1362.89	1362.86	1362.90	1363.54	1363.30	1365.30	1365.86	1356.51
IW33C	1353.74	1351.50	1350.02	1349.23	1349.33	1348.93	1349.59	1350.03	1350.00	1352.14	1352.55	1344.68
IW37C	1355.80	1354.12	1353.14	1353.20	1352.85	1353.08	1352.93	1353.47	1353.11	1354.91	1355.14	1350.51

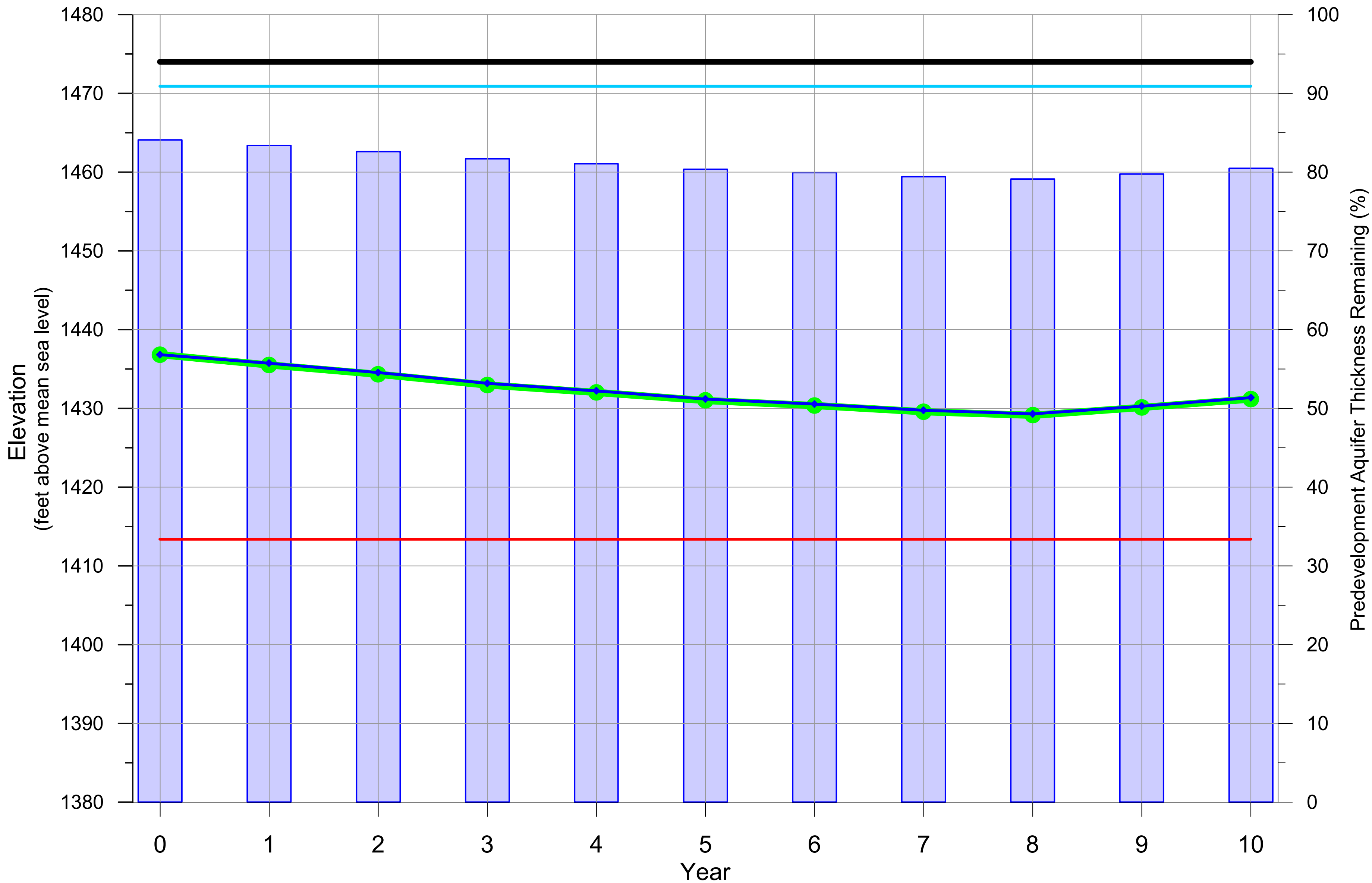
Note: Red text indicates elevation below current ASR Minimum Index Level (1993 Index Level Elevations)

Existing ASR Minimum Index Levels sourced from joint review process including the City, the Division of Water Resources, Groundwater Management District No. 2, and the United States Geological Survey as revised in 2015

Modeled Aquifer Conditions as a Percentage of Predevelopment Aquifer Thickness by ASR Index Well
Extracted from Upper Model Layer (1) - Equivalent to IW(A) Aquifer Interval

		Drought Years								Recovery Years	
Index Well Site Name	**Initial Aquifer Condition (% Full)**	**SP1 Aquifer Condition (% Full)**	**SP2 Aquifer Condition (% Full)**	**SP3 Aquifer Condition (% Full)**	**SP4 Aquifer Condition (% Full)**	**SP5 Aquifer Condition (% Full)**	**SP6 Aquifer Condition (% Full)**	**SP7 Aquifer Condition (% Full)**	**SP8 Aquifer Condition (% Full)**	**SP9 Aquifer Condition (% Full)**	**SP10 Aquifer Condition (% Full)**
IW01A	84%	83%	83%	82%	81%	80%	80%	79%	79%	80%	80%
IW02A	88%	88%	87%	87%	86%	86%	86%	85%	85%	86%	86%
IW03A	96%	95%	94%	94%	94%	94%	93%	93%	93%	94%	94%
IW04A	99%	98%	98%	97%	97%	96%	96%	95%	95%	95%	95%
IW05A	96%	94%	93%	92%	91%	90%	90%	89%	89%	89%	90%
IW06A	86%	85%	84%	83%	82%	81%	81%	81%	81%	82%	83%
IW07A	90%	89%	88%	87%	86%	85%	85%	85%	85%	87%	88%
IW08A	99%	98%	98%	97%	97%	96%	96%	96%	95%	95%	96%
IW09A	95%	94%	94%	91%	92%	90%	91%	90%	90%	90%	91%
IW10A	82%	80%	79%	76%	75%	73%	73%	73%	72%	75%	77%
IW11A	86%	86%	84%	83%	82%	81%	80%	80%	80%	82%	83%
IW12A	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
IW13A	97%	96%	96%	95%	94%	93%	93%	92%	92%	94%	95%
IW14A	93%	91%	90%	89%	88%	87%	87%	86%	86%	89%	90%
IW15A	89%	88%	86%	84%	83%	82%	81%	81%	81%	83%	85%
IW16A	85%	83%	80%	77%	76%	74%	74%	73%	73%	76%	78%
IW17A	91%	90%	89%	88%	88%	87%	87%	87%	86%	88%	89%
IW18A	97%	96%	95%	94%	94%	93%	93%	92%	92%	93%	95%
IW19A	93%	92%	91%	90%	89%	88%	87%	87%	87%	88%	90%
IW20A	93%	92%	91%	90%	89%	88%	87%	87%	87%	87%	89%
IW21A	87%	86%	84%	81%	80%	78%	78%	77%	77%	79%	81%
IW22A	92%	90%	90%	88%	88%	87%	87%	86%	86%	88%	88%
IW23A	97%	95%	95%	95%	95%	95%	95%	95%	95%	96%	96%
IW24A	98%	97%	97%	97%	96%	96%	96%	96%	96%	97%	97%
IW25A	97%	96%	95%	95%	94%	94%	93%	93%	93%	94%	95%
IW26A	94%	93%	93%	92%	91%	90%	90%	90%	90%	91%	92%
IW27A	93%	93%	92%	91%	90%	90%	89%	89%	89%	90%	90%
IW28A	89%	89%	86%	84%	83%	82%	83%	83%	84%	86%	87%
IW29A	91%	90%	89%	88%	88%	88%	88%	88%	88%	90%	90%
IW30A	95%	93%	92%	92%	92%	92%	92%	92%	92%	93%	93%
IW31A	97%	97%	96%	96%	96%	96%	96%	96%	96%	96%	97%
IW32A	95%	94%	94%	93%	93%	93%	93%	94%	93%	95%	95%
IW33A	93%	92%	91%	90%	91%	90%	91%	91%	91%	92%	93%
IW34A	98%	96%	96%	96%	96%	96%	96%	96%	96%	97%	97%
IW35A	96%	95%	95%	95%	94%	95%	94%	95%	94%	96%	96%
IW36A	98%	97%	96%	96%	96%	96%	96%	96%	96%	97%	97%
IW37A	97%	96%	95%	95%	95%	95%	95%	96%	95%	97%	97%
IW38A	96%	93%	93%	93%	93%	93%	93%	93%	93%	95%	95%

Predevelopment groundwater elevations used to calculate aquifer conditions sourced from: "*Revised Shallow and Deep Water-Level and Storage-Volume Changes in the Equus Beds Aquifer near Wichita, Kansas Predevelopment to 1993*" *USGS Scientific Investigations Report 2013-5170 (Hansen C.V., Lanning-Rush J.L., and Ziegler A.C., 2013)*

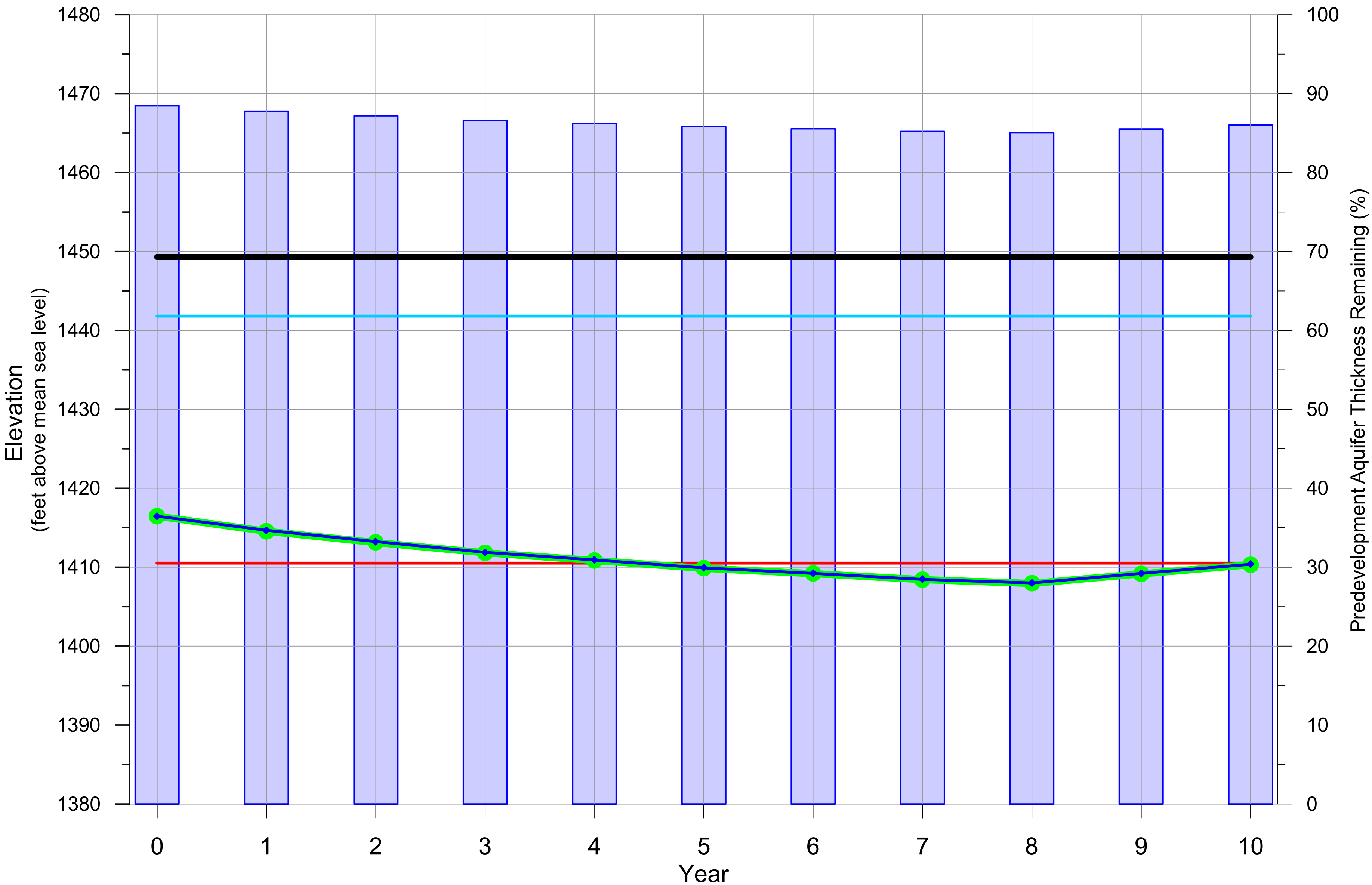


LEGEND

- IW-01A
- IW-01C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 1
Index Well Hydrographs
IW-01A & IW-01C
Stress Periods 1 through 10

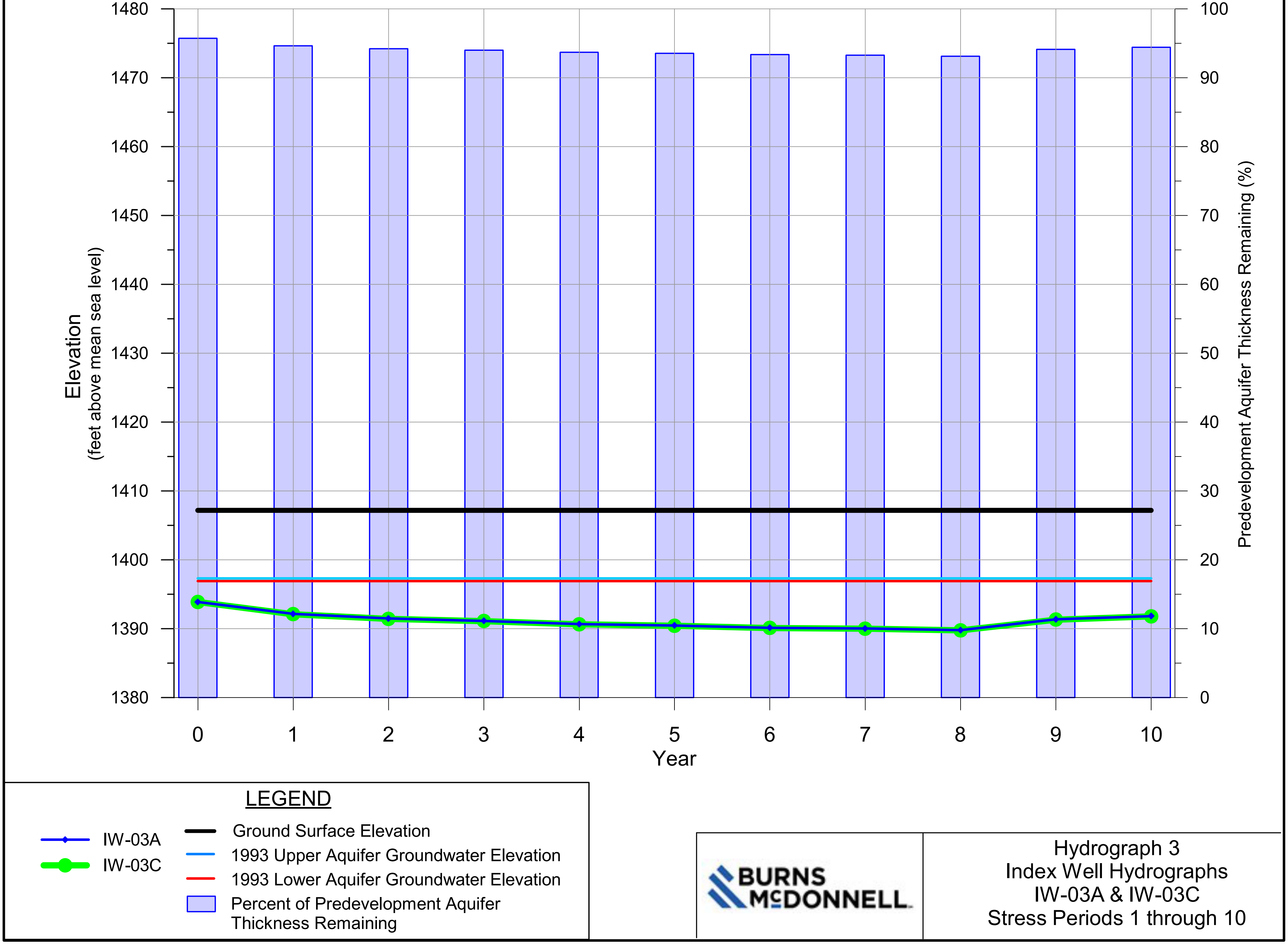


LEGEND

- IW-02A
- IW-02C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

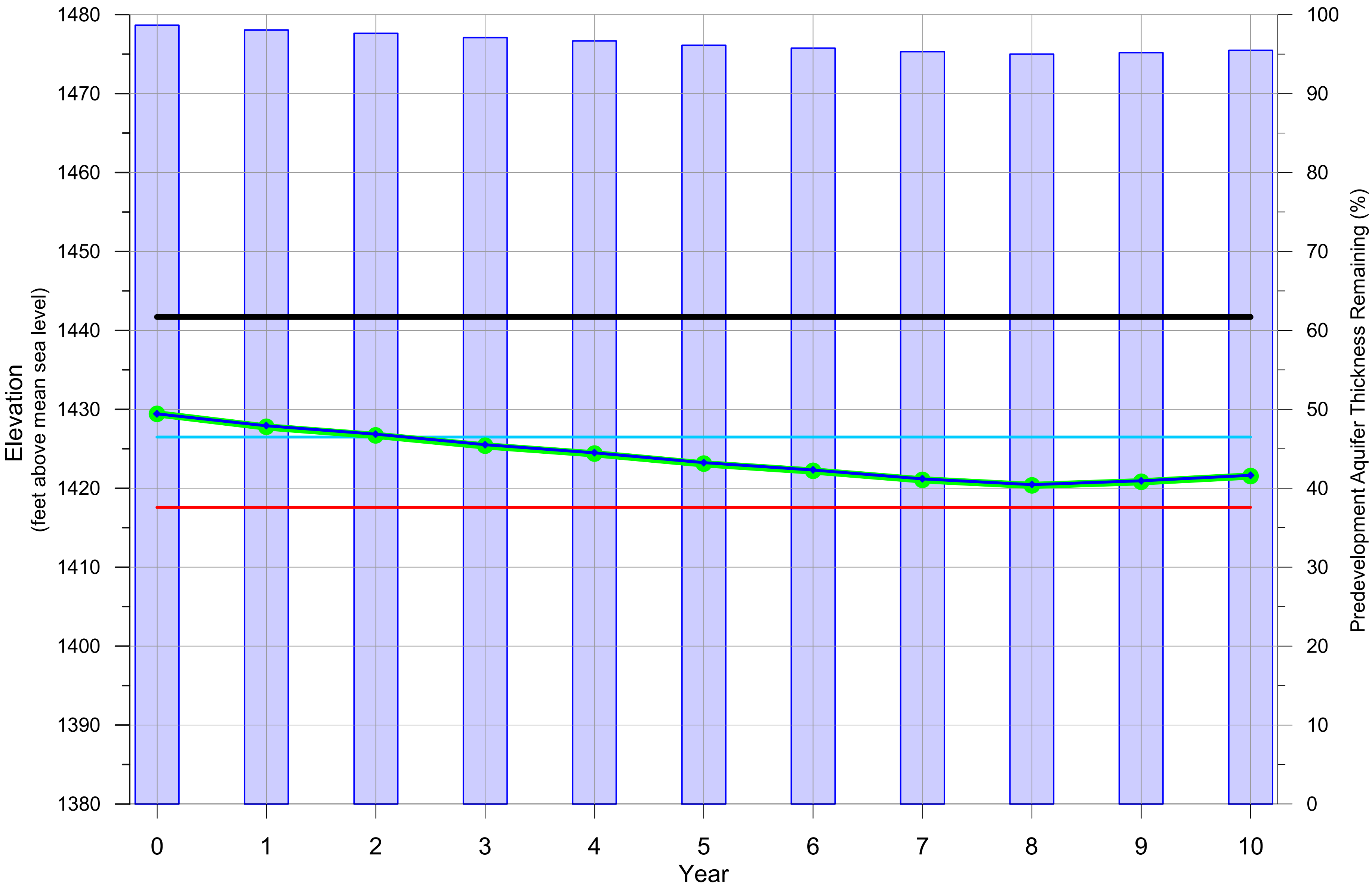
BURNS McDONNELL

Hydrograph 2
Index Well Hydrographs
IW-02A & IW-02C
Stress Periods 1 through 10



BURNS McDONNELL

Hydrograph 3
Index Well Hydrographs
IW-03A & IW-03C
Stress Periods 1 through 10

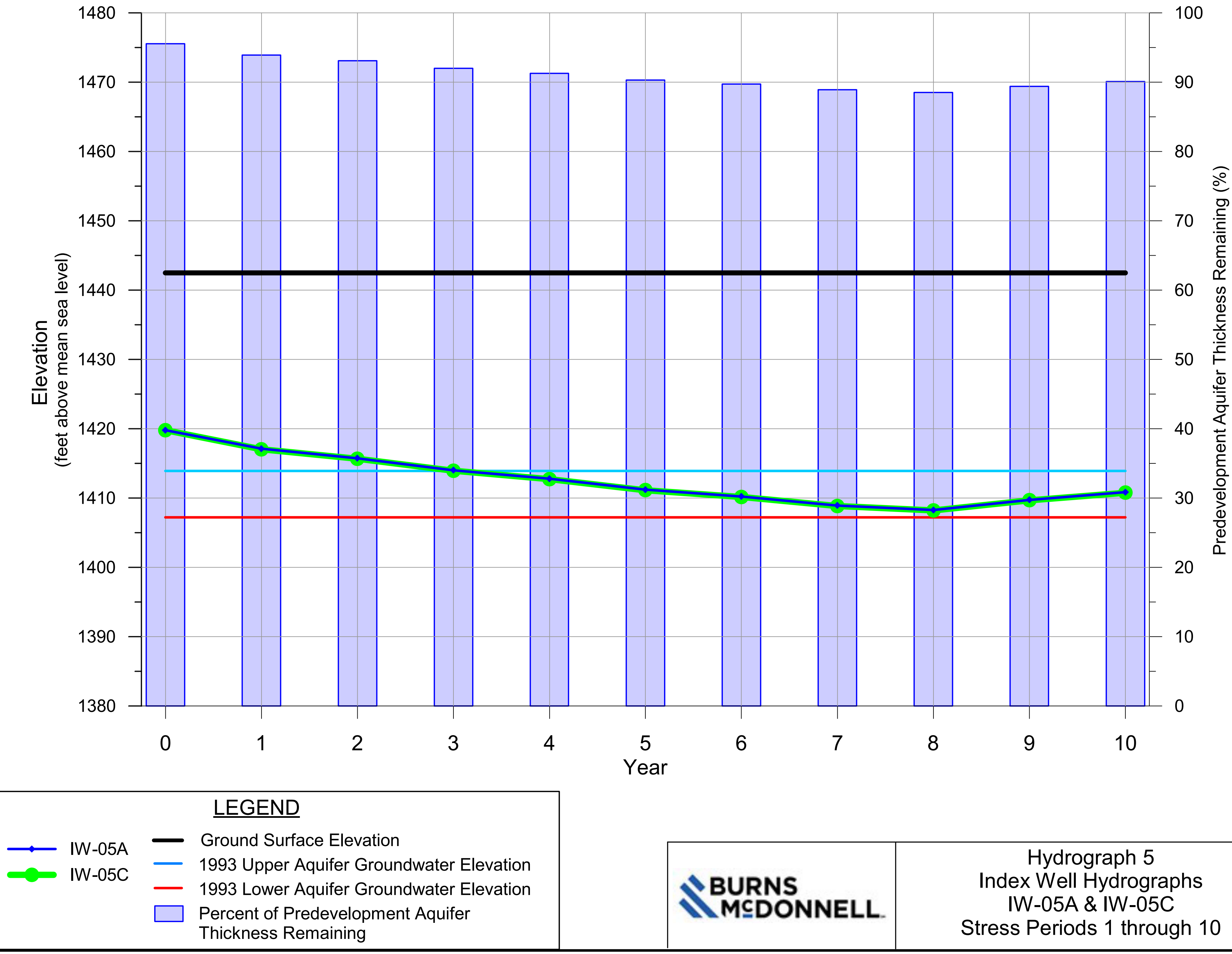


LEGEND

IW-04A
IW-04C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

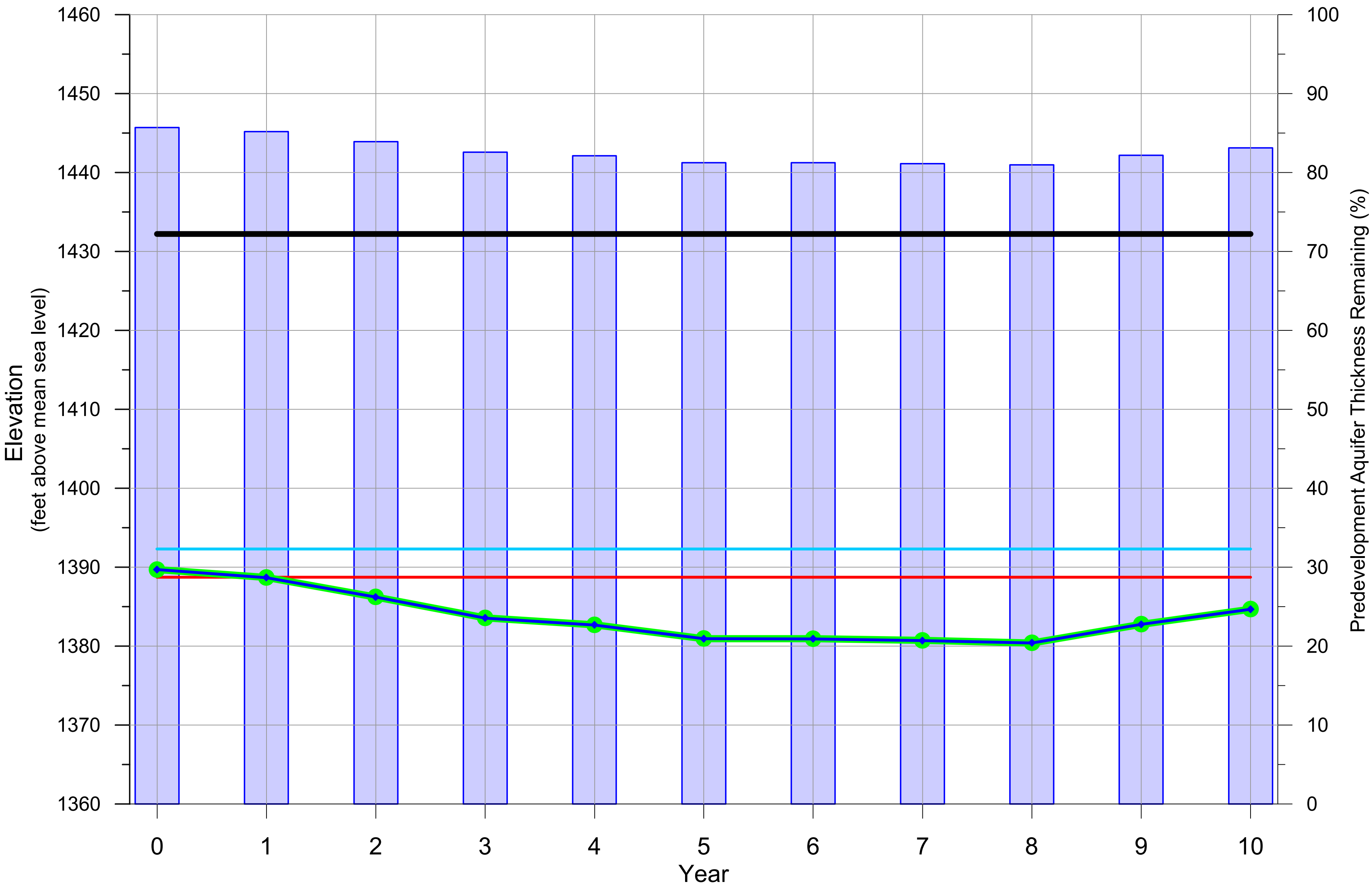
BURNS McDONNELL

Hydrograph 4
Index Well Hydrographs
IW-04A & IW-04C
Stress Periods 1 through 10



BURNS McDONNELL

Hydrograph 5
Index Well Hydrographs
IW-05A & IW-05C
Stress Periods 1 through 10

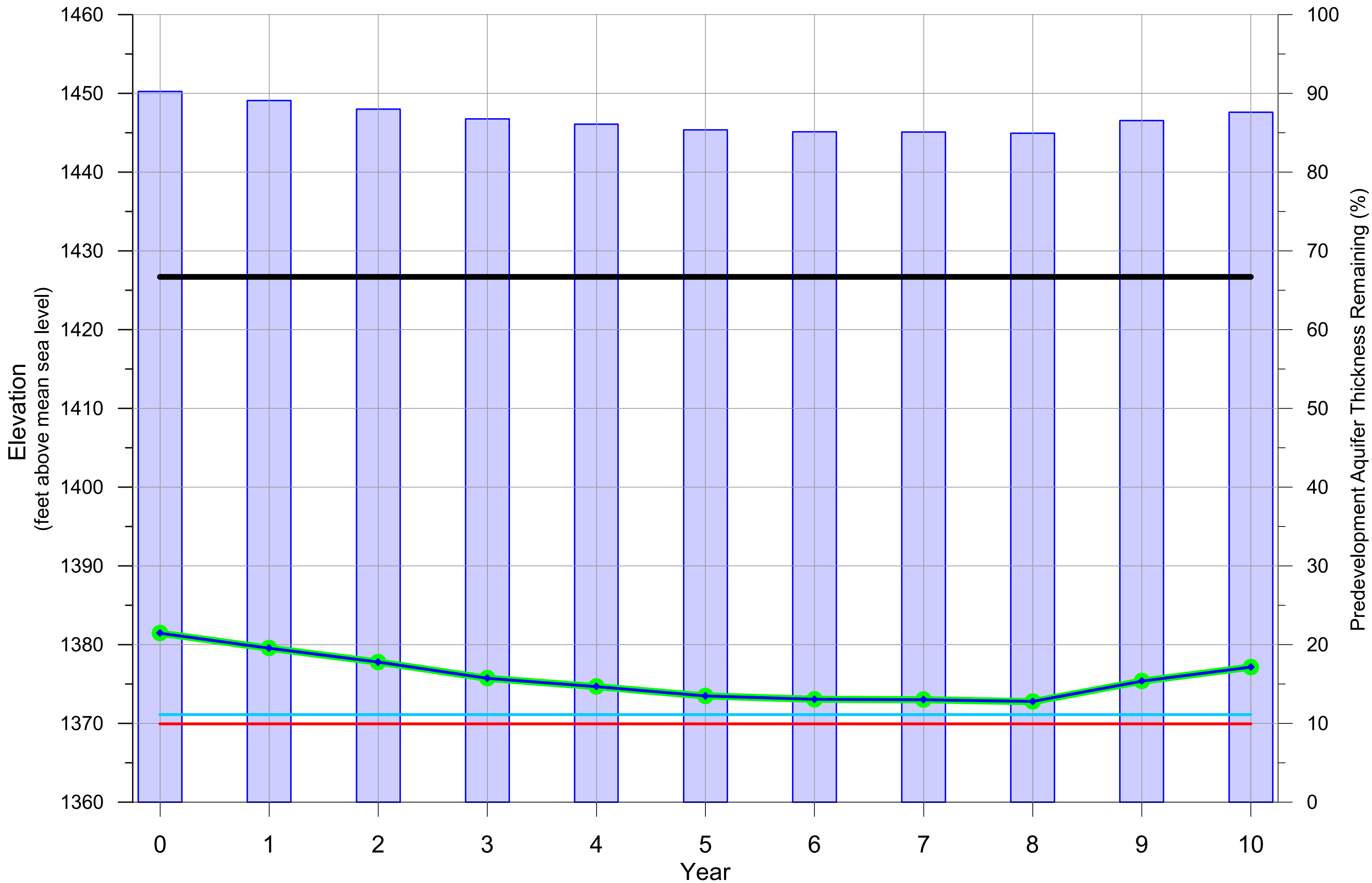


LEGEND

- IW-06A
- IW-06C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 6
Index Well Hydrographs
IW-06A & IW-06C
Stress Periods 1 through 10

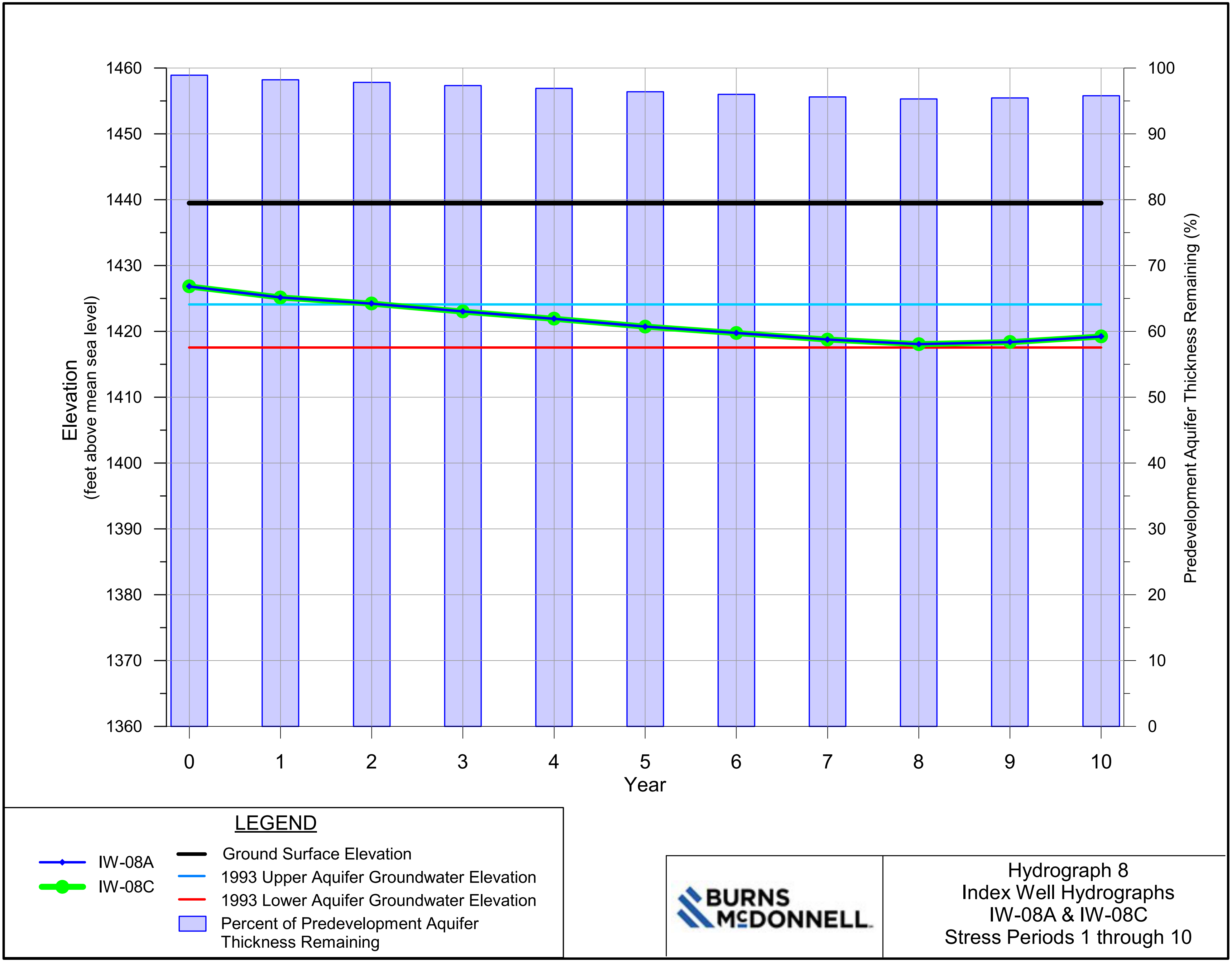


LEGEND

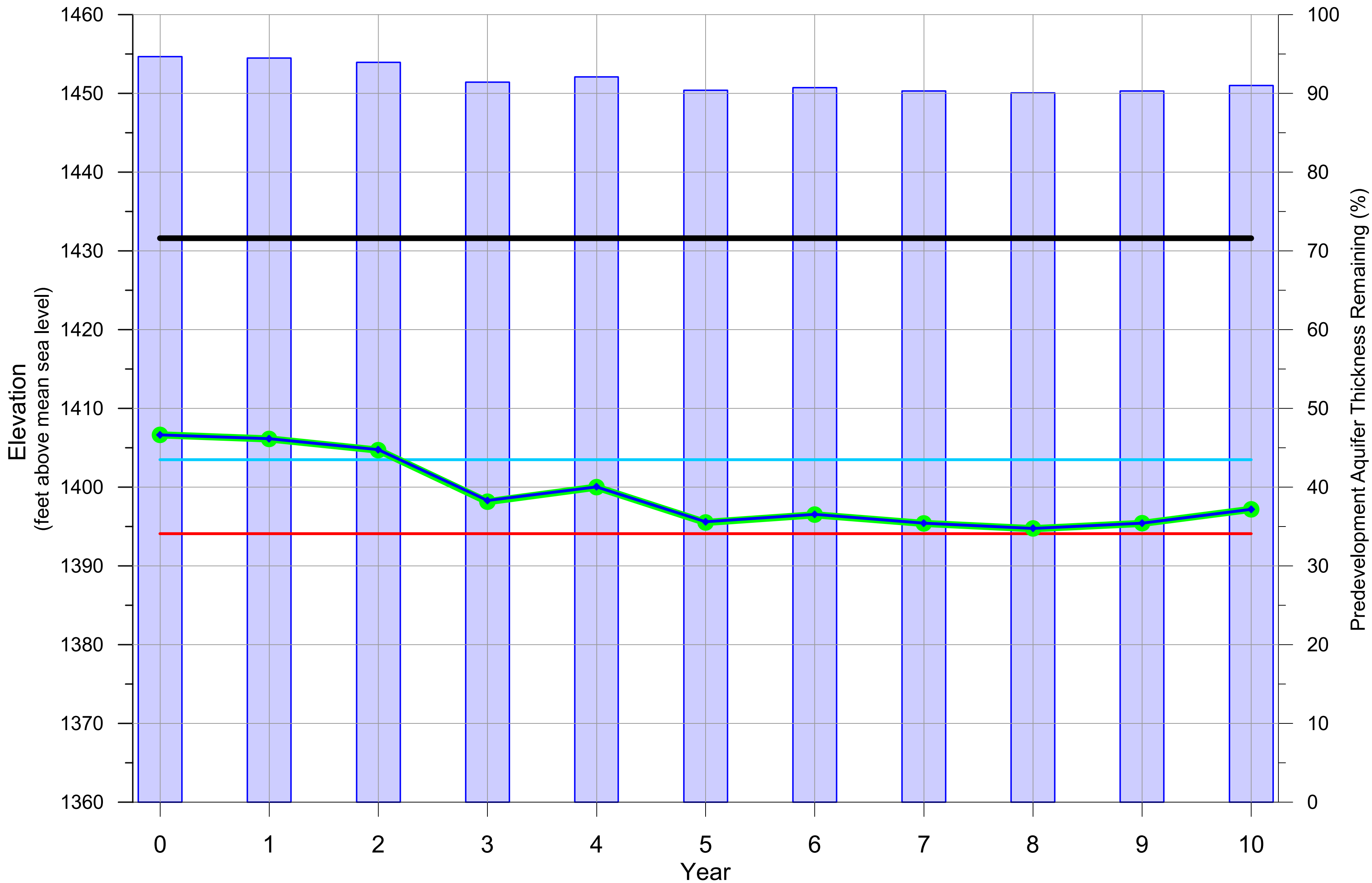
IW-07A	Ground Surface Elevation
IW-07C	1993 Upper Aquifer Groundwater Elevation
	1993 Lower Aquifer Groundwater Elevation
	Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 7
Index Well Hydrographs
IW-07A & IW-07C
Stress Periods 1 through 10



Hydrograph 8
Index Well Hydrographs
IW-08A & IW-08C
Stress Periods 1 through 10

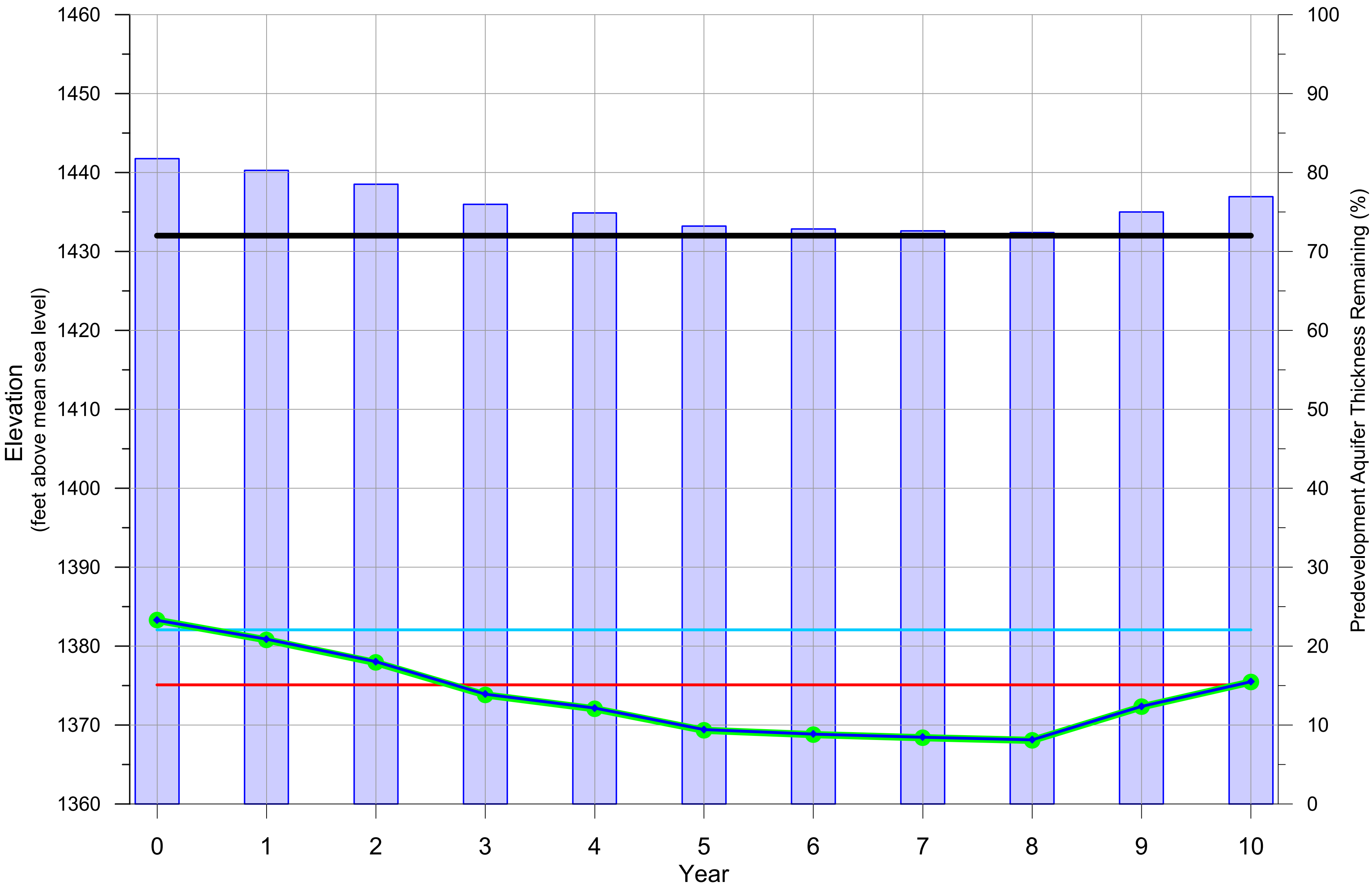


LEGEND

IW-09A
IW-09C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 9
Index Well Hydrographs
IW-09A & IW-09CS
Stress Periods 1 through 10



LEGEND

IW-10A

IW-10C

Ground Surface Elevation

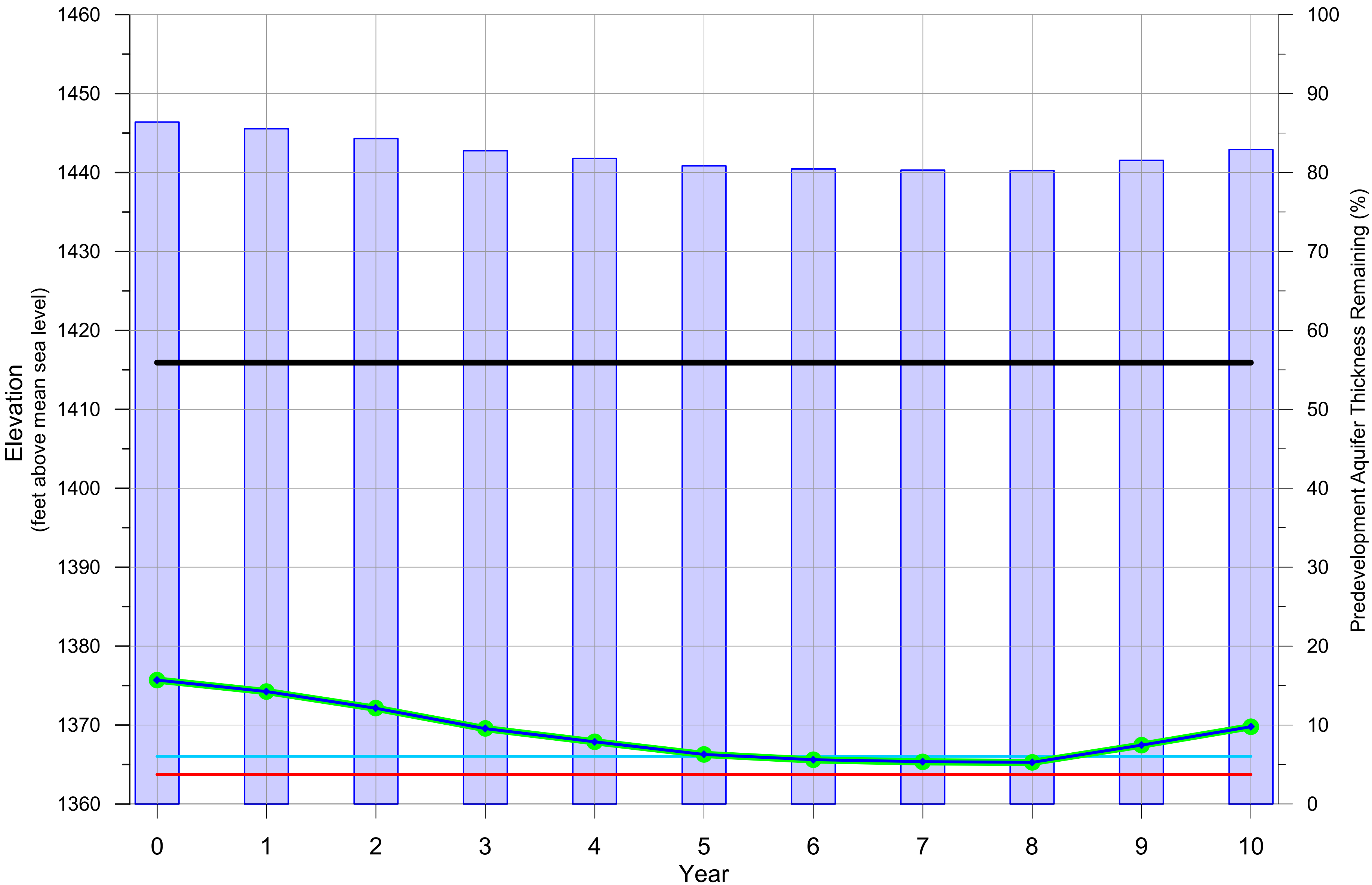
1993 Upper Aquifer Groundwater Elevation

1993 Lower Aquifer Groundwater Elevation

Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 10
Index Well Hydrographs
IW-10A & IW-10C
Stress Periods 1 through 10

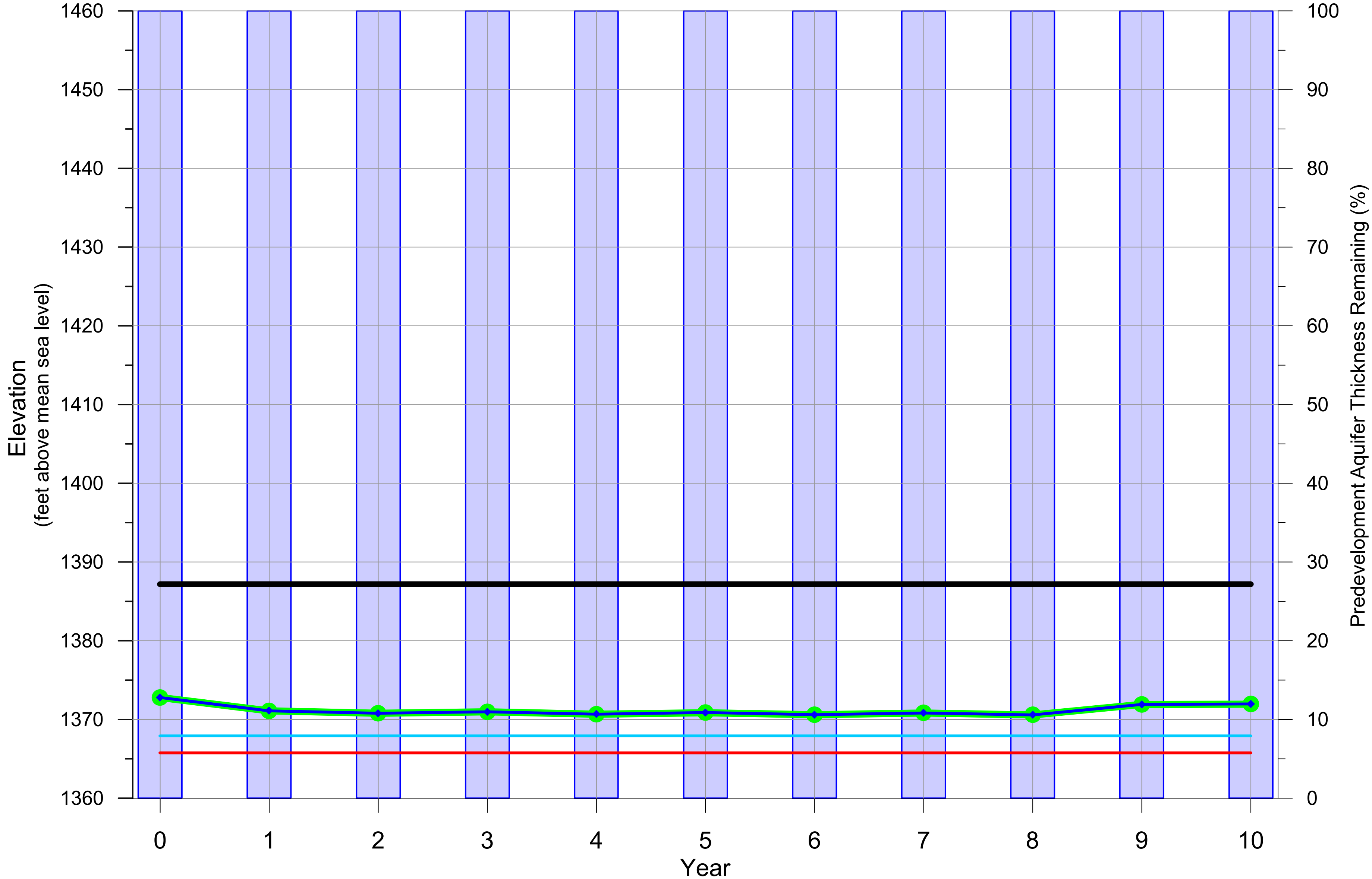


LEGEND

IW-11A
IW-11C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 11
Index Well Hydrographs
IW-11A & IW-11C
Stress Periods 1 through 10

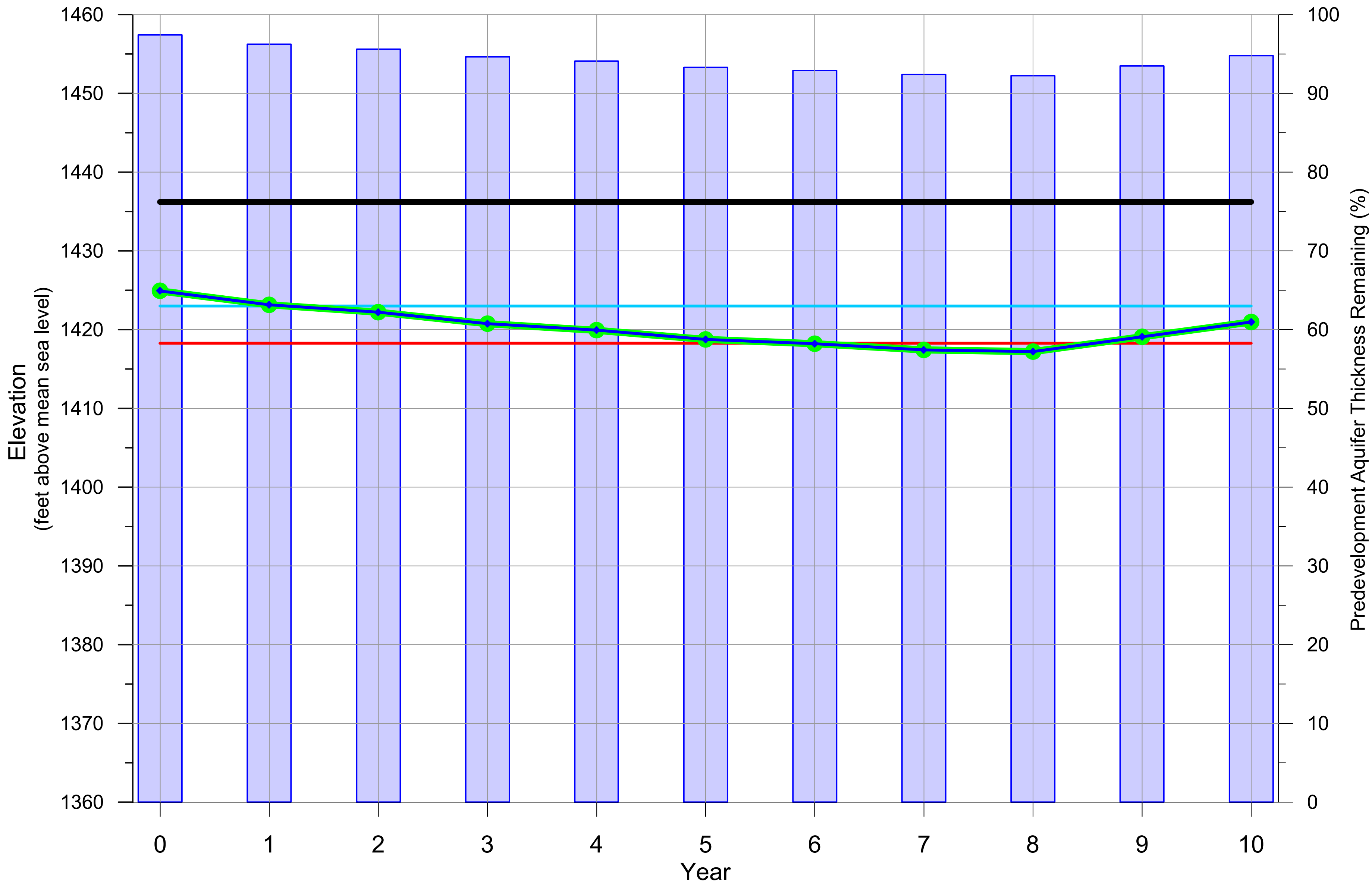


LEGEND

IW-12A
IW-12C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 12
Index Well Hydrographs
IW-12A & IW-12C
Stress Periods 1 through 10

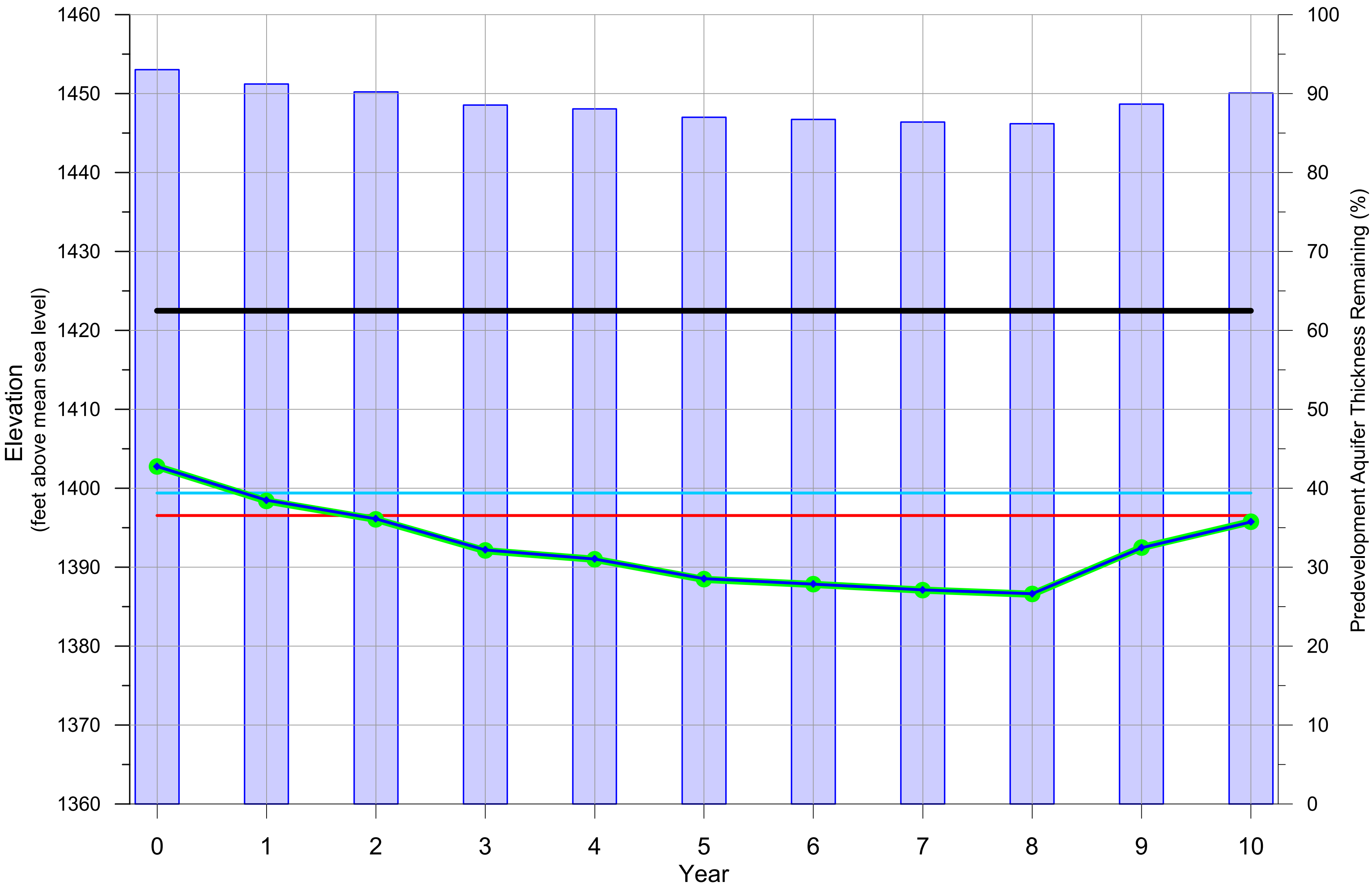


LEGEND

IW-13A
IW-13C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 13
Index Well Hydrographs
IW-13A & IW-13C
Stress Periods 1 through 10

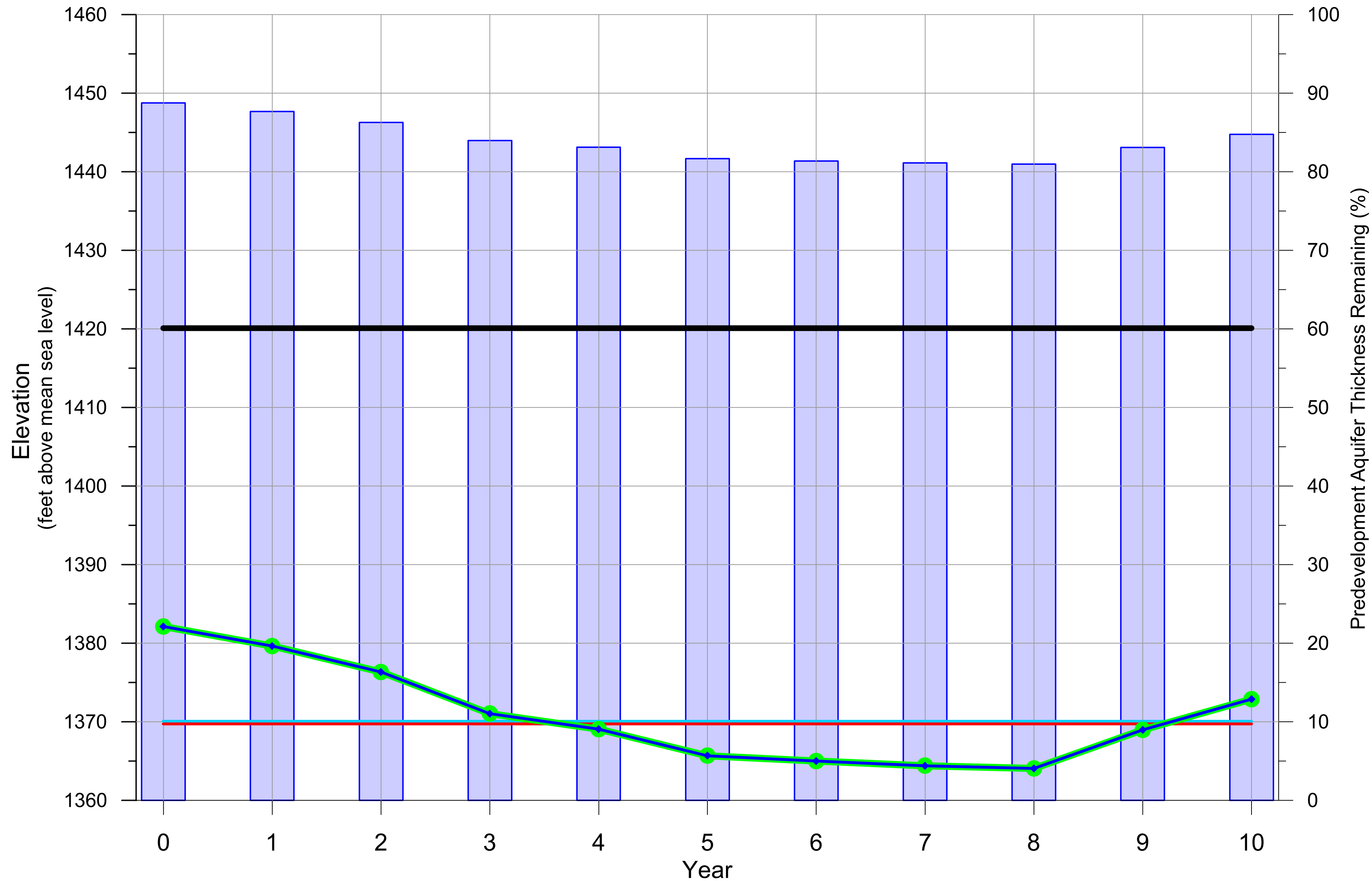


LEGEND

IW-14A
IW-14C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 14
Index Well Hydrographs
IW-14A & IW-14C
Stress Periods 1 through 10

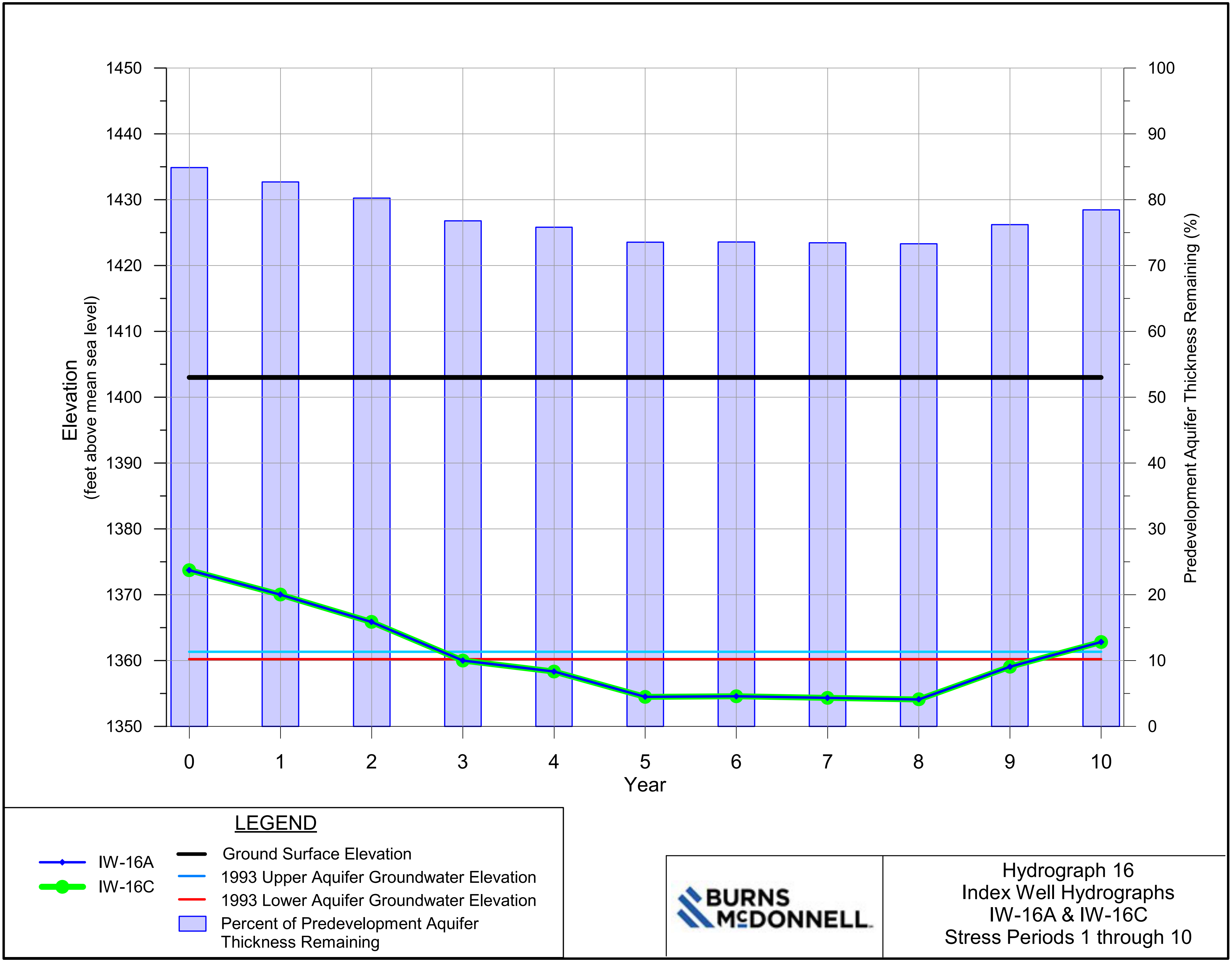


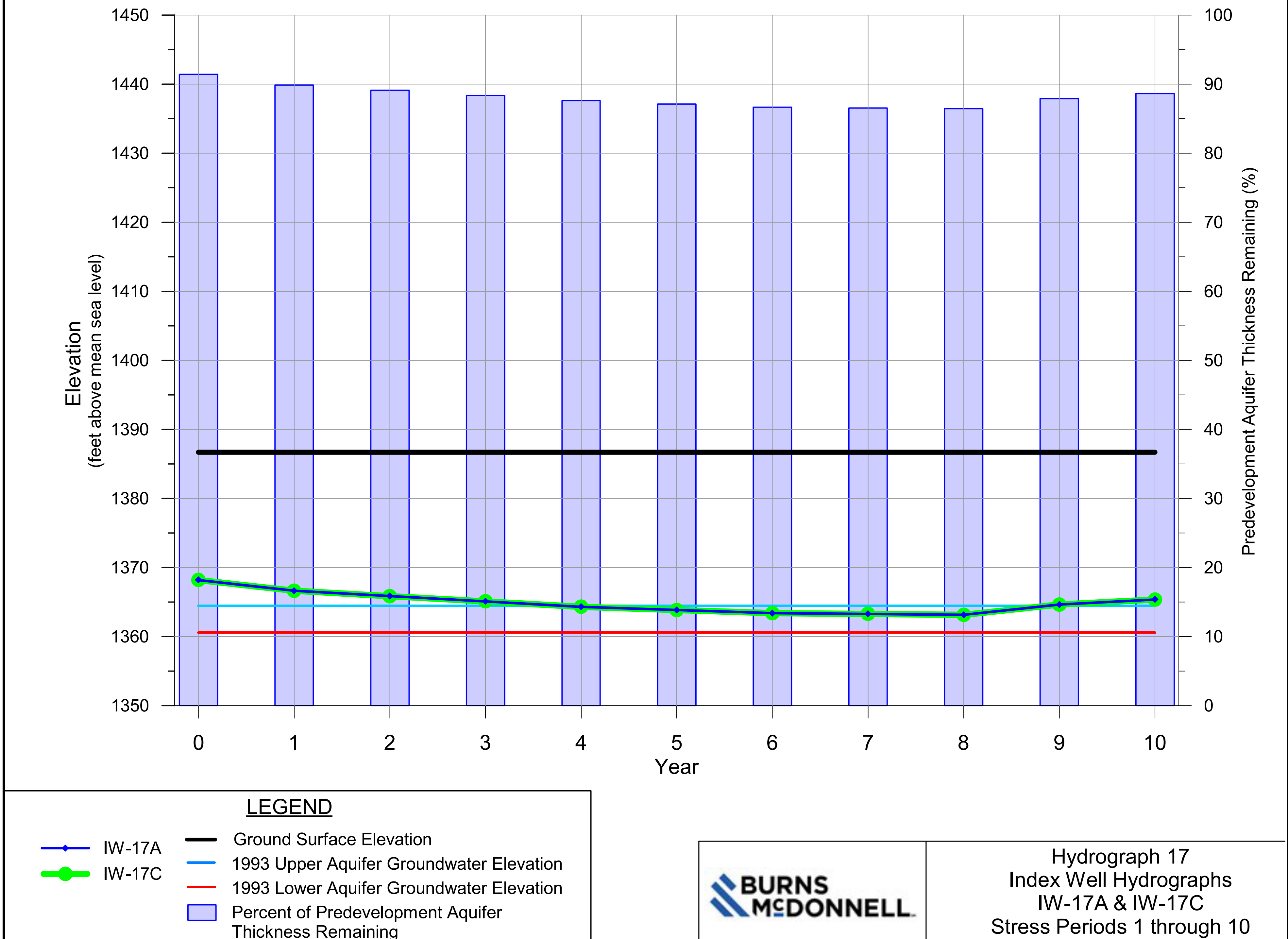
LEGEND

- IW-15A
- IW-15C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

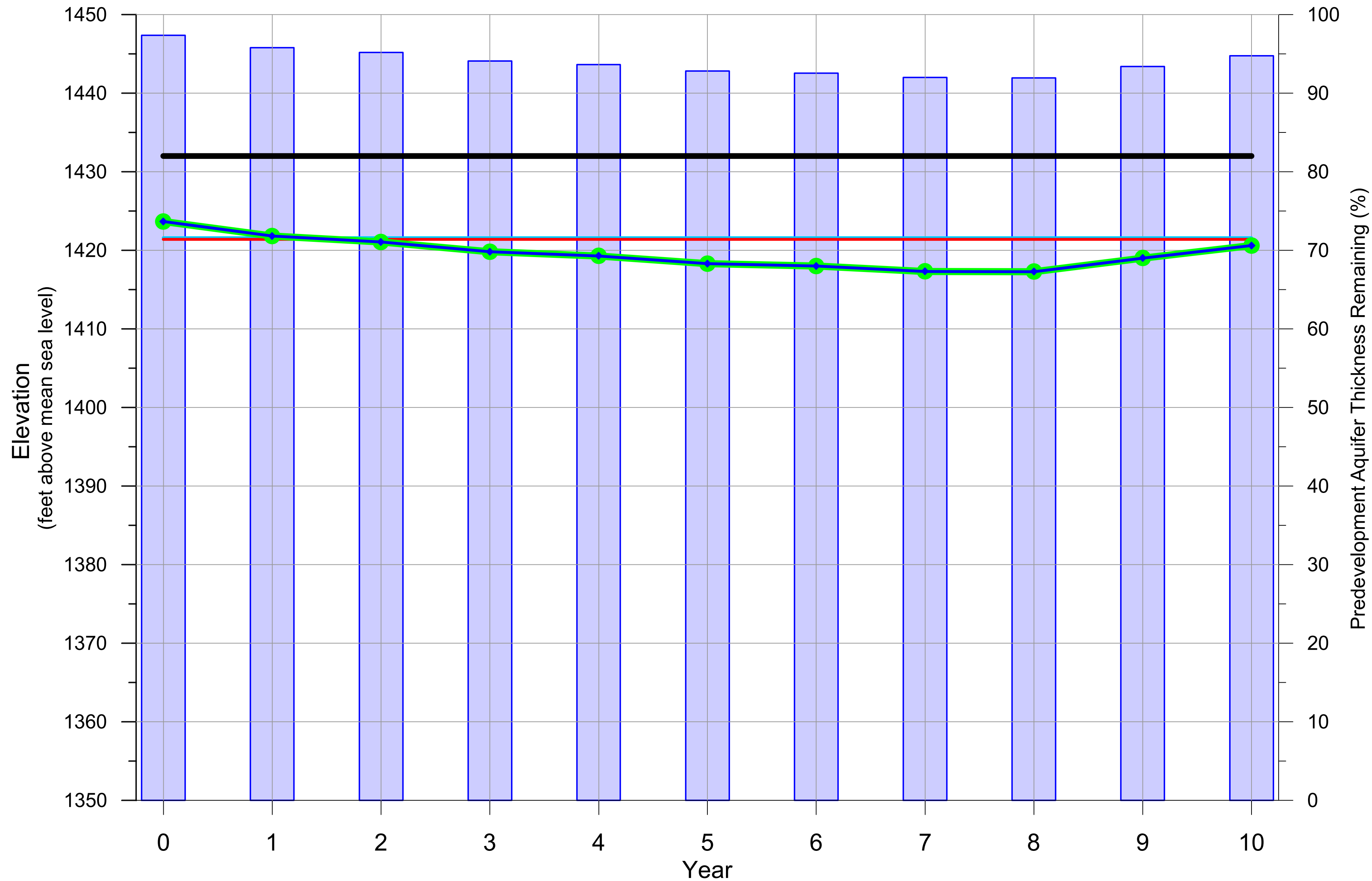
BURNS McDONNELL

Hydrograph 15
Index Well Hydrographs
IW-15A & IW-15C
Stress Periods 1 through 10


1450
1440
1430
1420
1410
1400
1390
1380
1370
1360
1350
Elevation
(feet above mean sea level)
100
90
80
70
60
50
40
30
20
10
0
Predevelopment Aquifer Thickness Remaining (%)
0 1 2 3 4 5 6 7 8 9 10
Year
LEGEND
IW-16A
IW-16C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining
BURNS McDONNELL
Hydrograph 16
Index Well Hydrographs
IW-16A & IW-16C
Stress Periods 1 through 10



Hydrograph 17
Index Well Hydrographs
IW-17A & IW-17C
Stress Periods 1 through 10

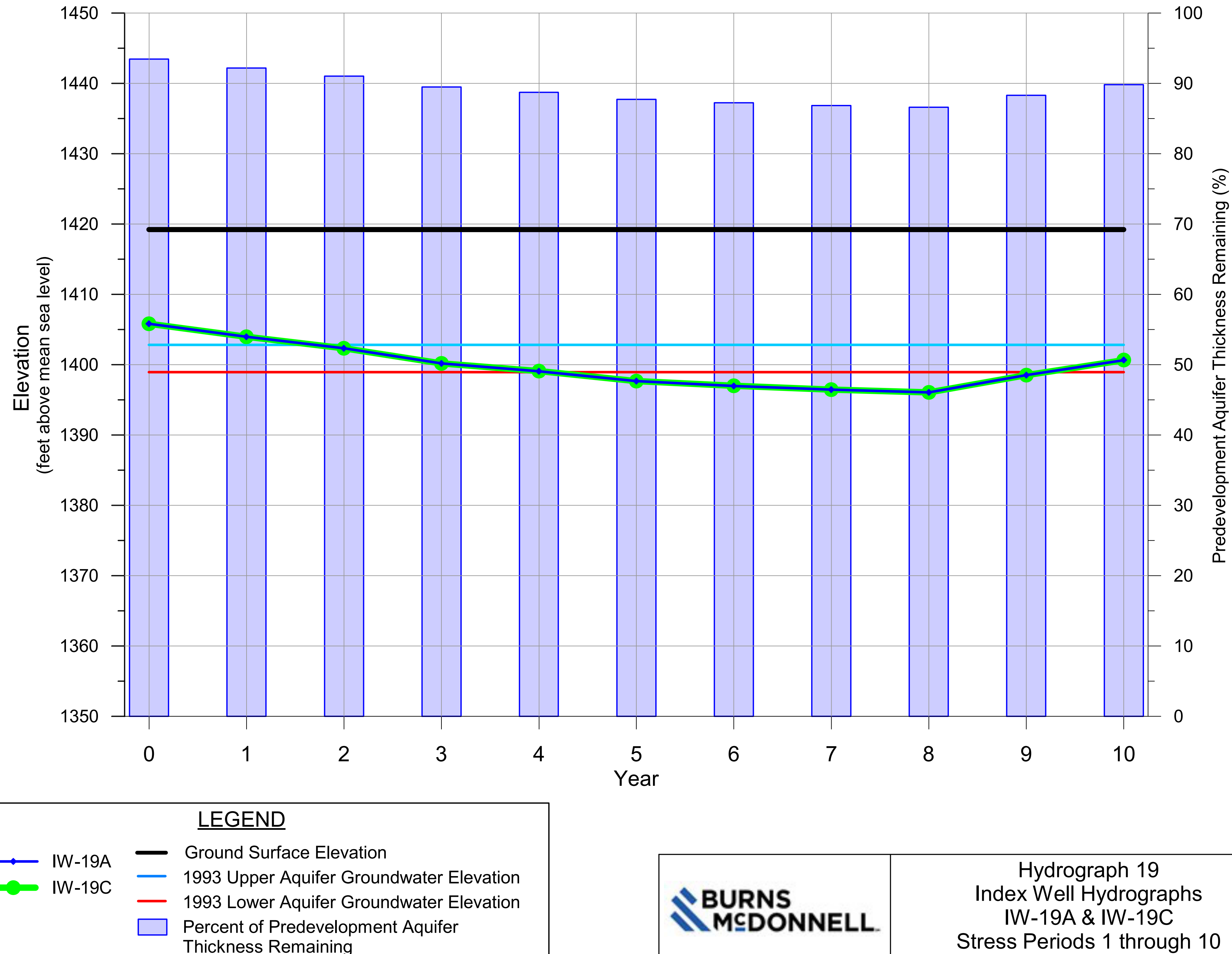


LEGEND

IW-18A
IW-18C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

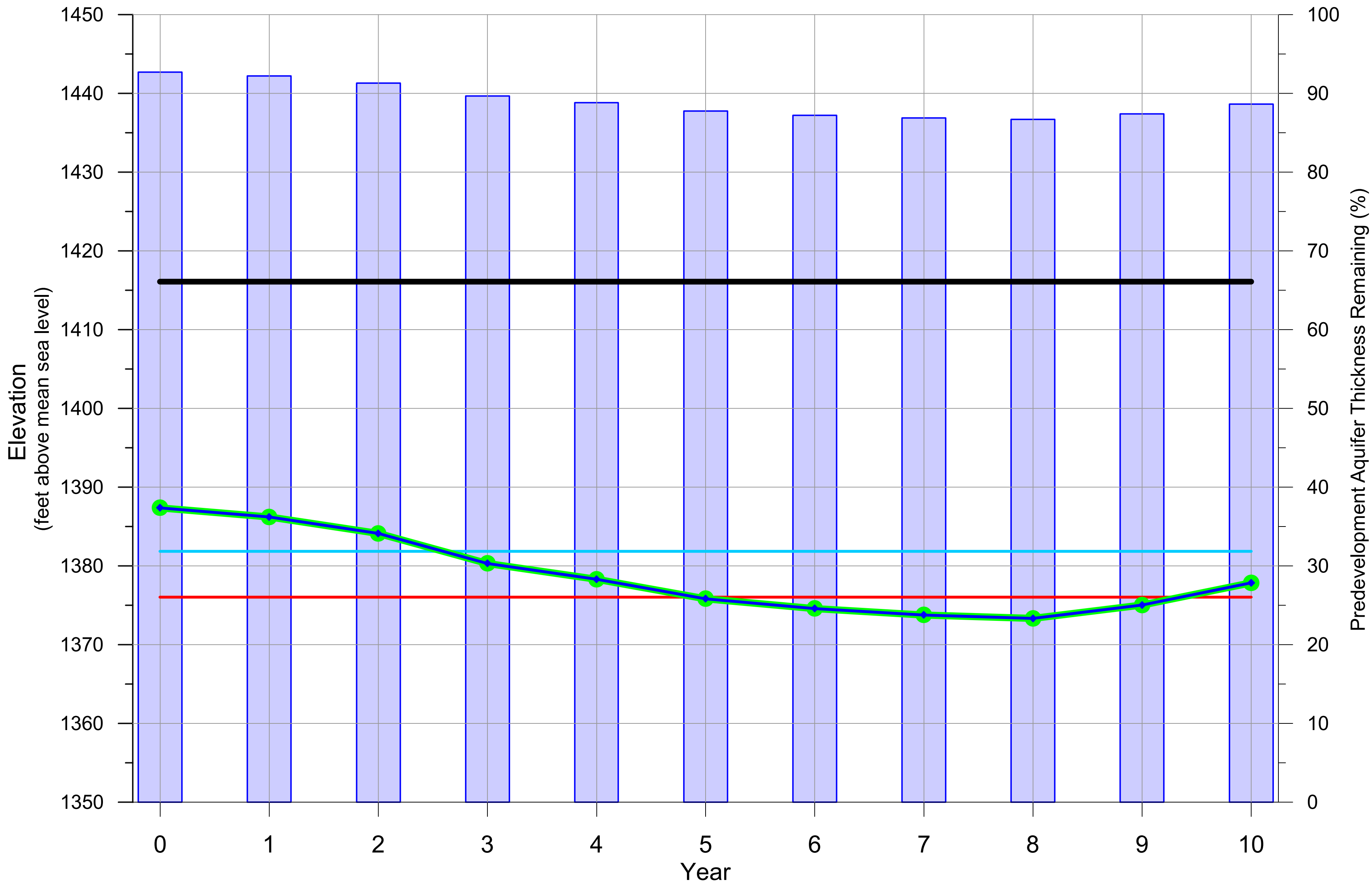
BURNS McDONNELL

Hydrograph 18
Index Well Hydrographs
IW-18A & IW-18C
Stress Periods 1 through 10



BURNS McDONNELL

Hydrograph 19
Index Well Hydrographs
IW-19A & IW-19C
Stress Periods 1 through 10



LEGEND

IW-20A

IW-20C

Ground Surface Elevation

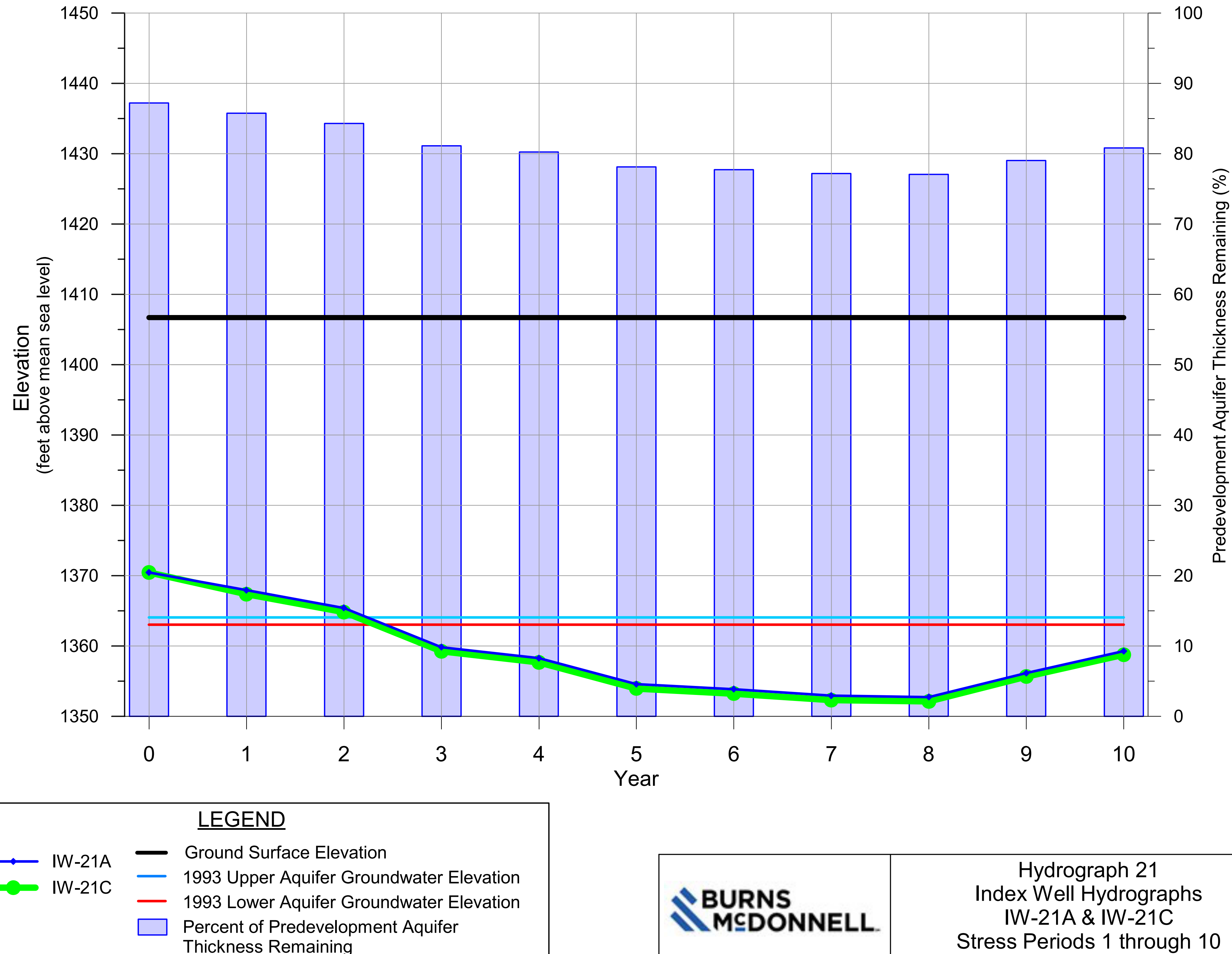
1993 Upper Aquifer Groundwater Elevation

1993 Lower Aquifer Groundwater Elevation

Percent of Predevelopment Aquifer Thickness Remaining

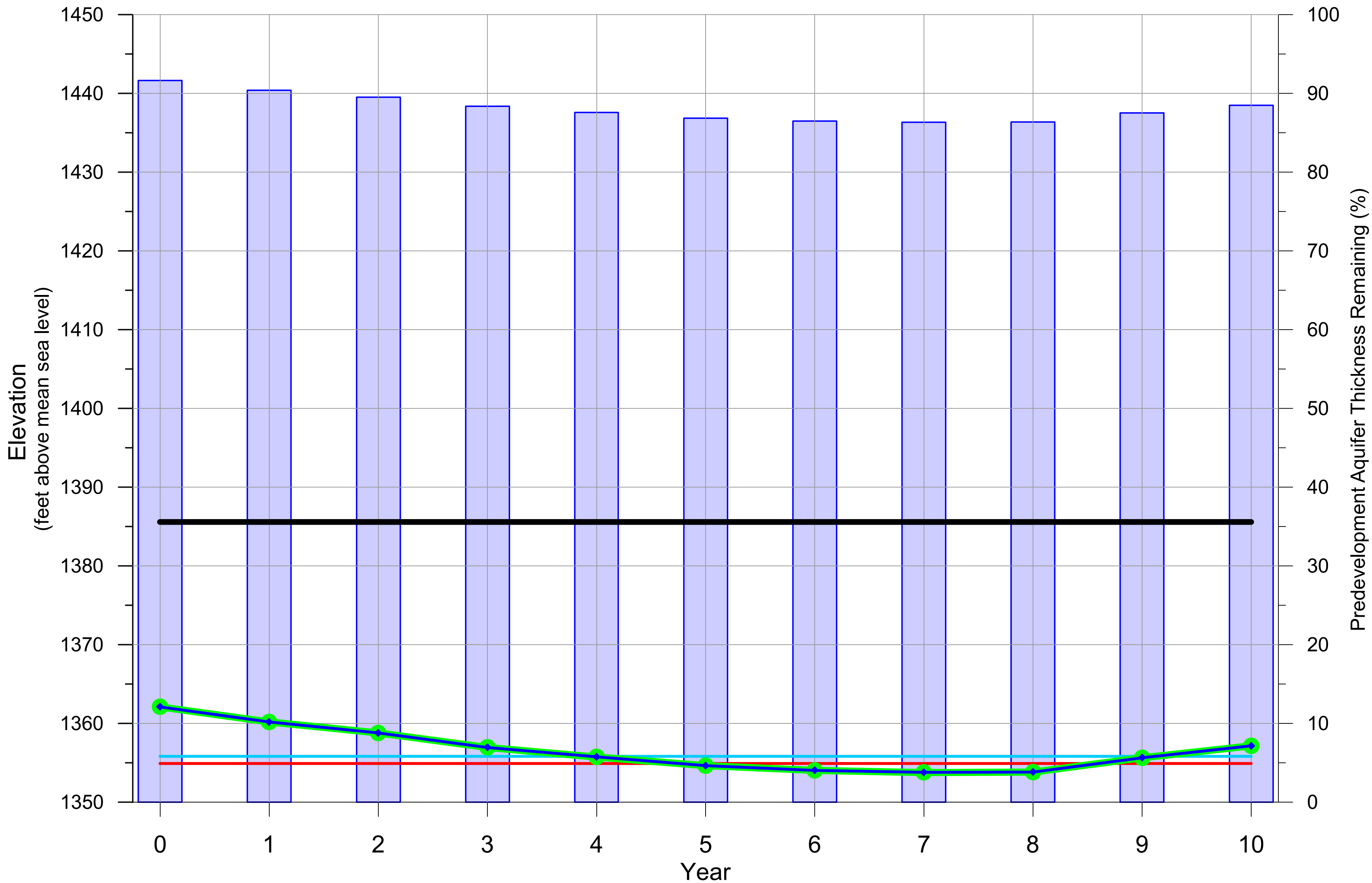
BURNS McDONNELL

Hydrograph 20
Index Well Hydrographs
IW-20A & IW-20C
Stress Periods 1 through 10



BURNS McDONNELL

Hydrograph 21
Index Well Hydrographs
IW-21A & IW-21C
Stress Periods 1 through 10

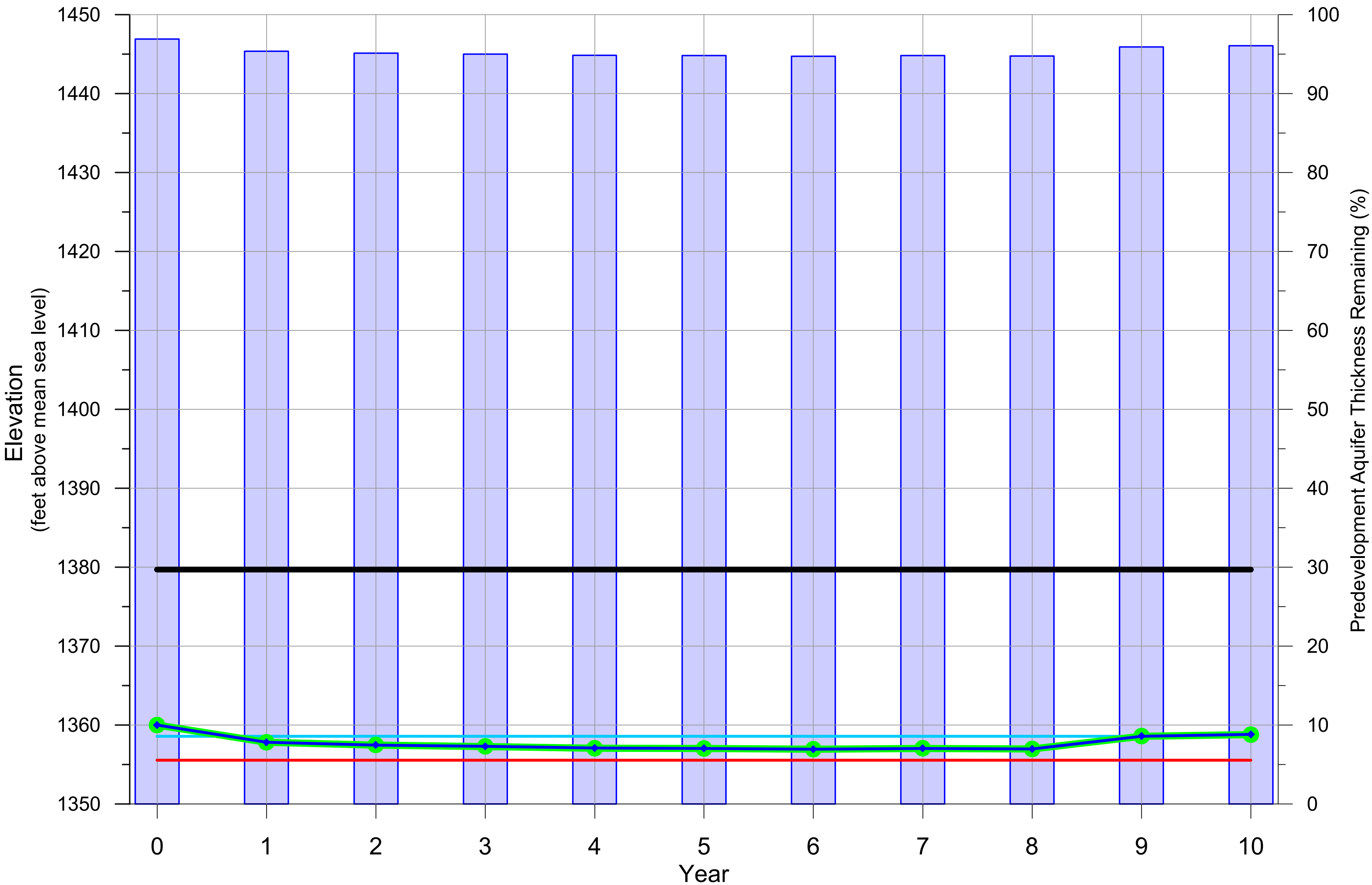


LEGEND

IW-22A
IW-22C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 22
Index Well Hydrographs
IW-22A & IW-22C
Stress Periods 1 through 10

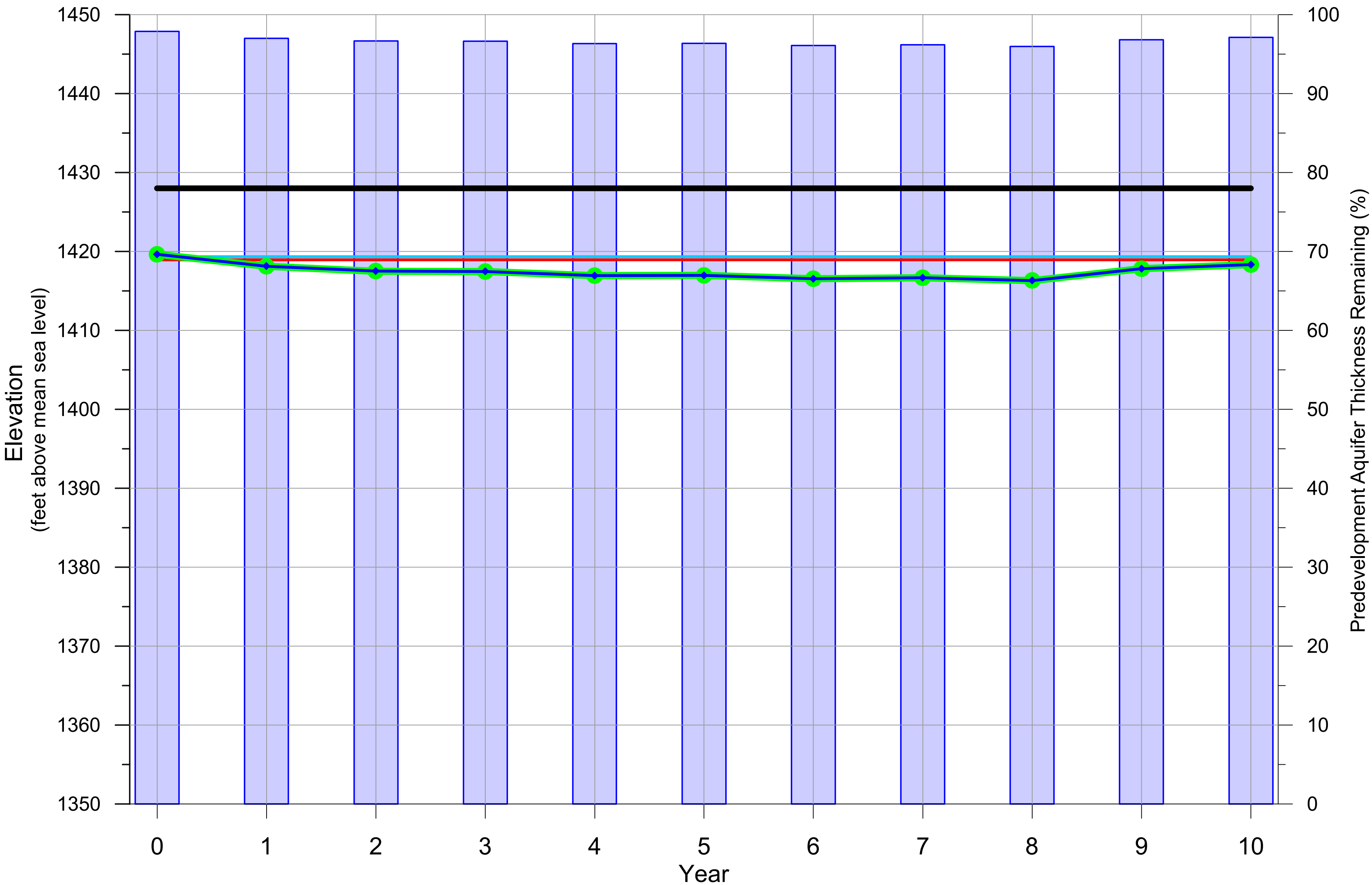


LEGEND

IW-23A
IW-23C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 23
Index Well Hydrographs
IW-23A & IW-23C
Stress Periods 1 through 10

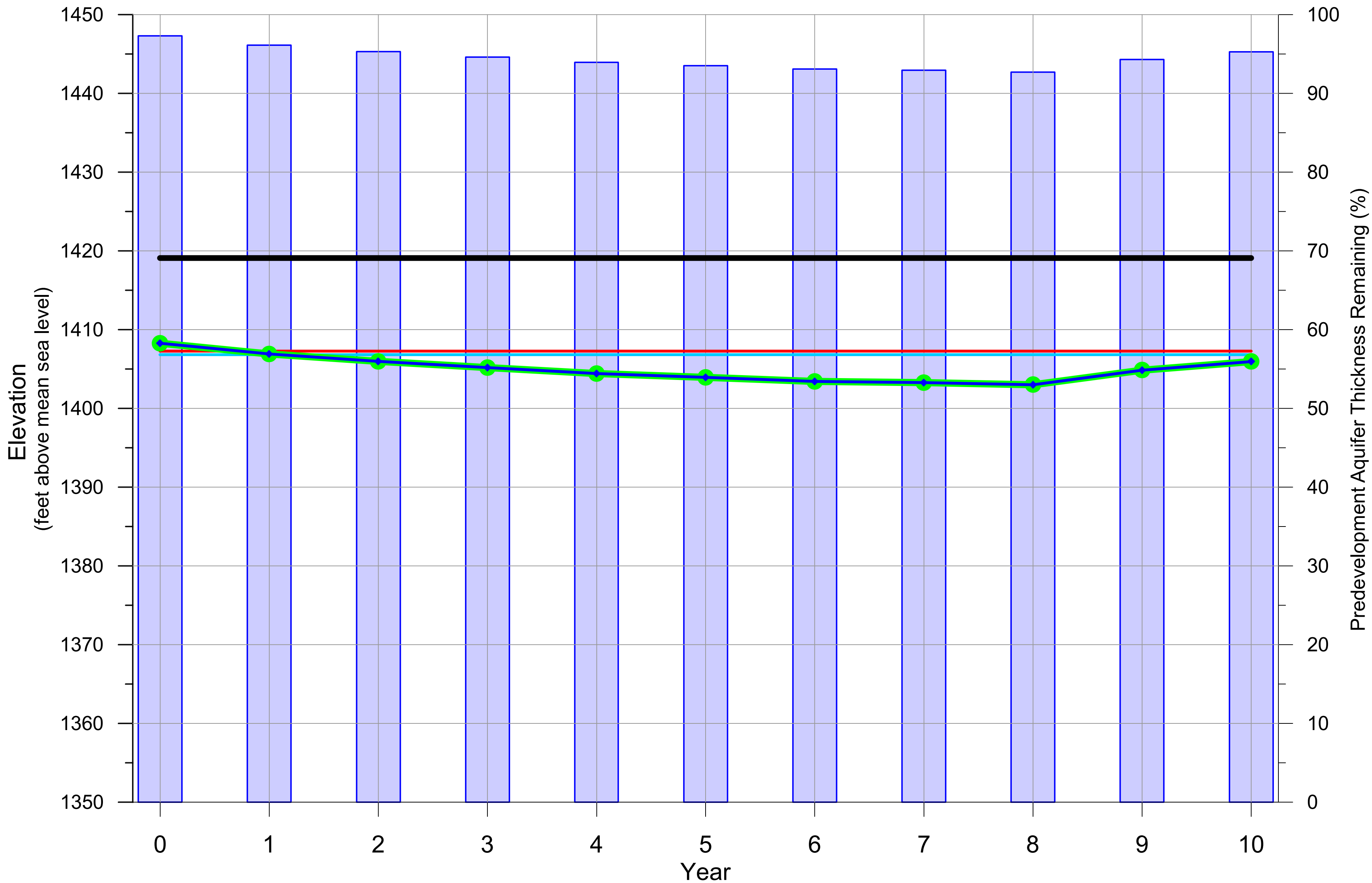


LEGEND

IW-24A
IW-24C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 24
Index Well Hydrographs
IW-24A & IW-24C
Stress Periods 1 through 10

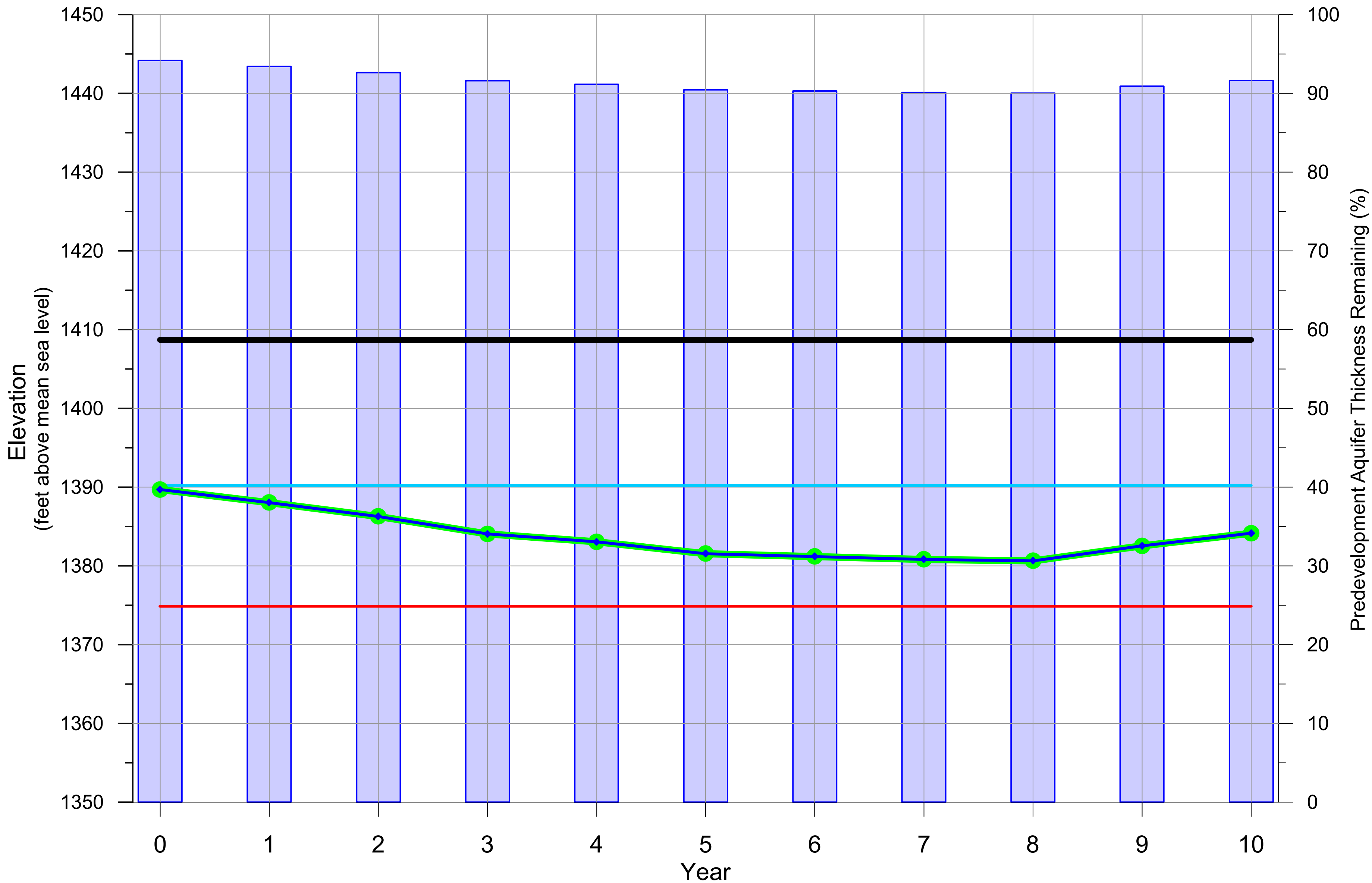


LEGEND

IW-25A
IW-25C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 25
Index Well Hydrographs
IW-25A & IW-25C
Stress Periods 1 through 10

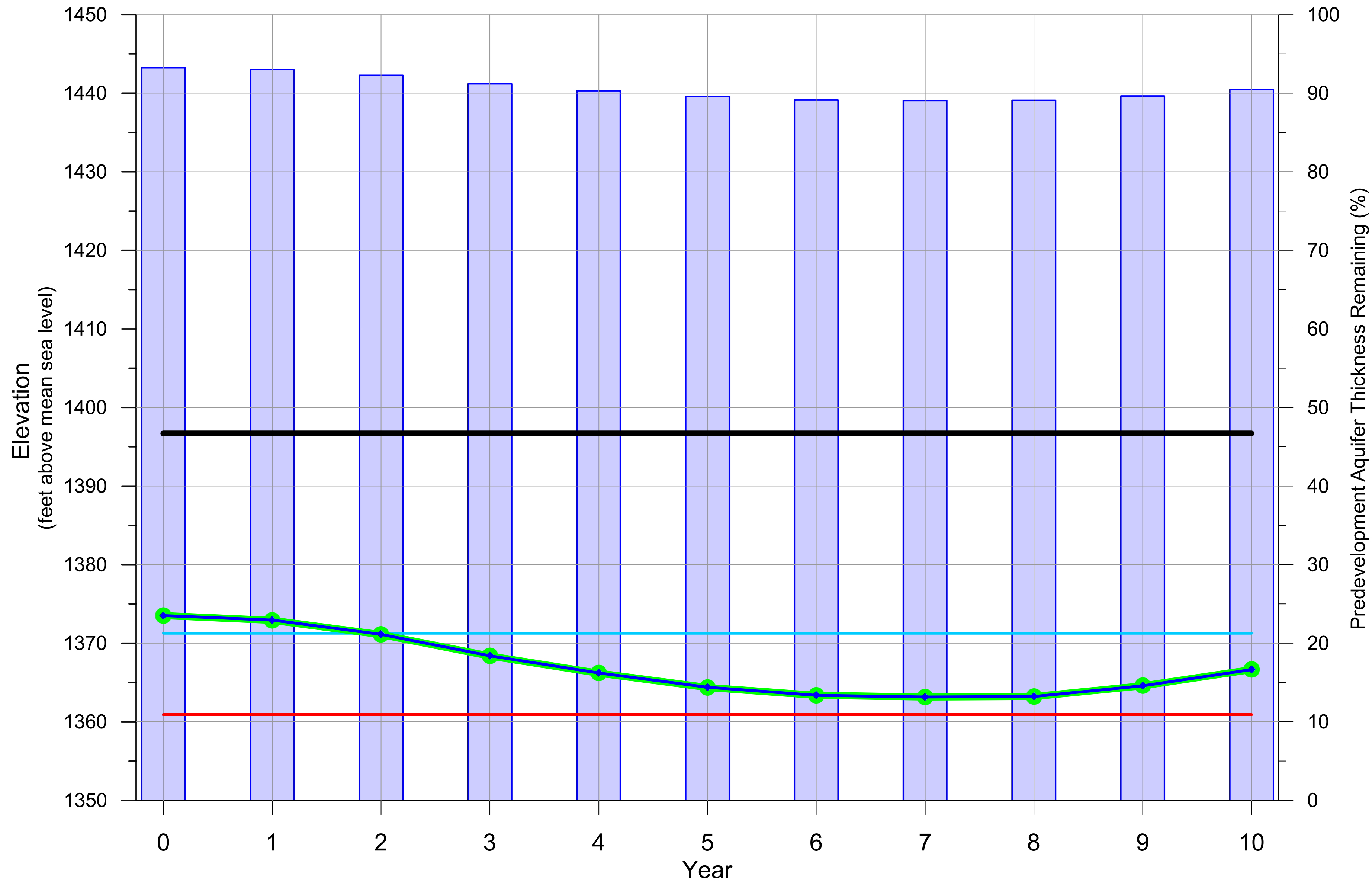


LEGEND

- IW-26A
- IW-26C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 26
Index Well Hydrographs
IW-26A & IW-26C
Stress Periods 1 through 10

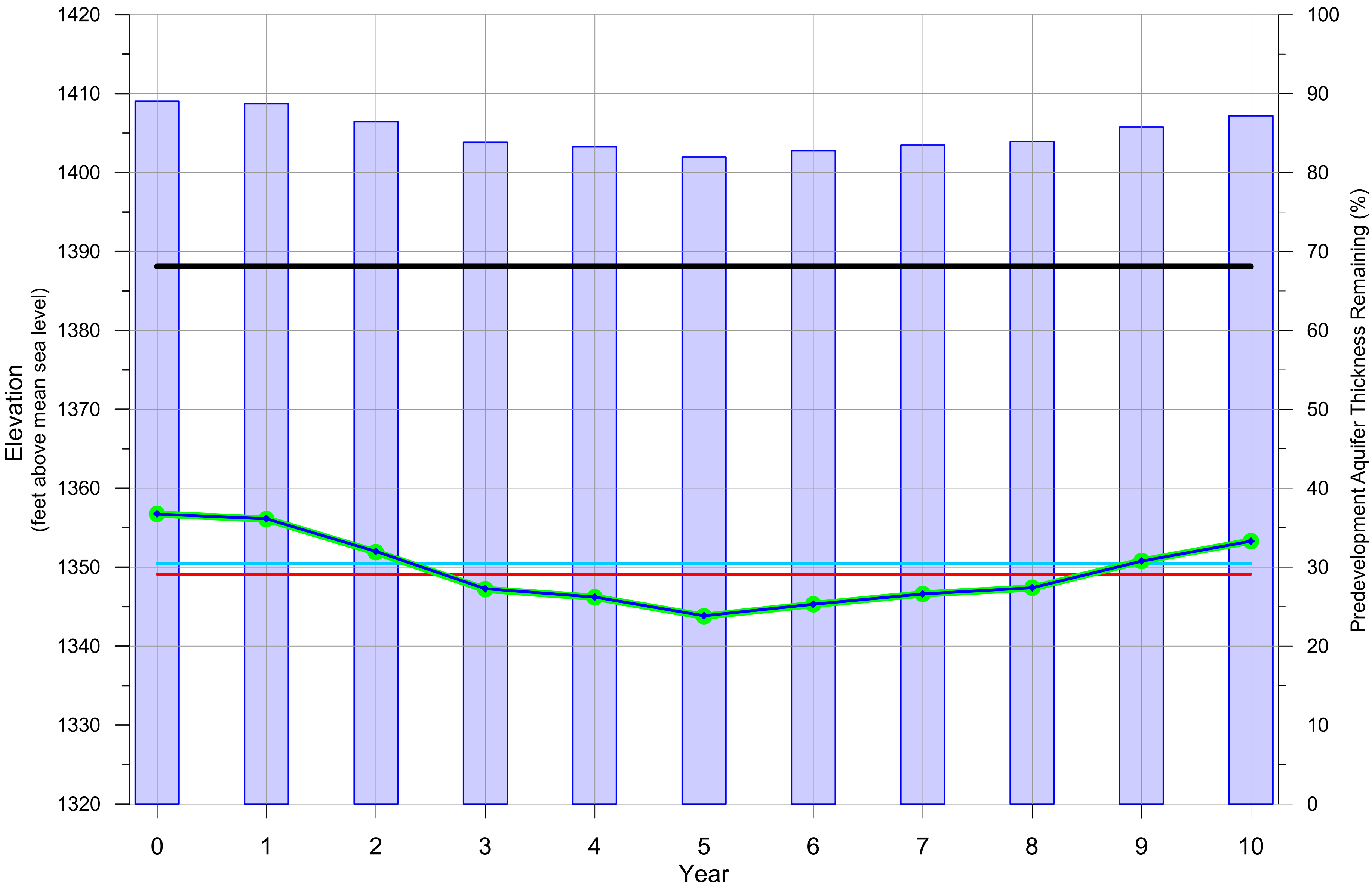


LEGEND

IW-27A
IW-27C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 27
Index Well Hydrographs
IW-27A & IW-27C
Stress Periods 1 through 10

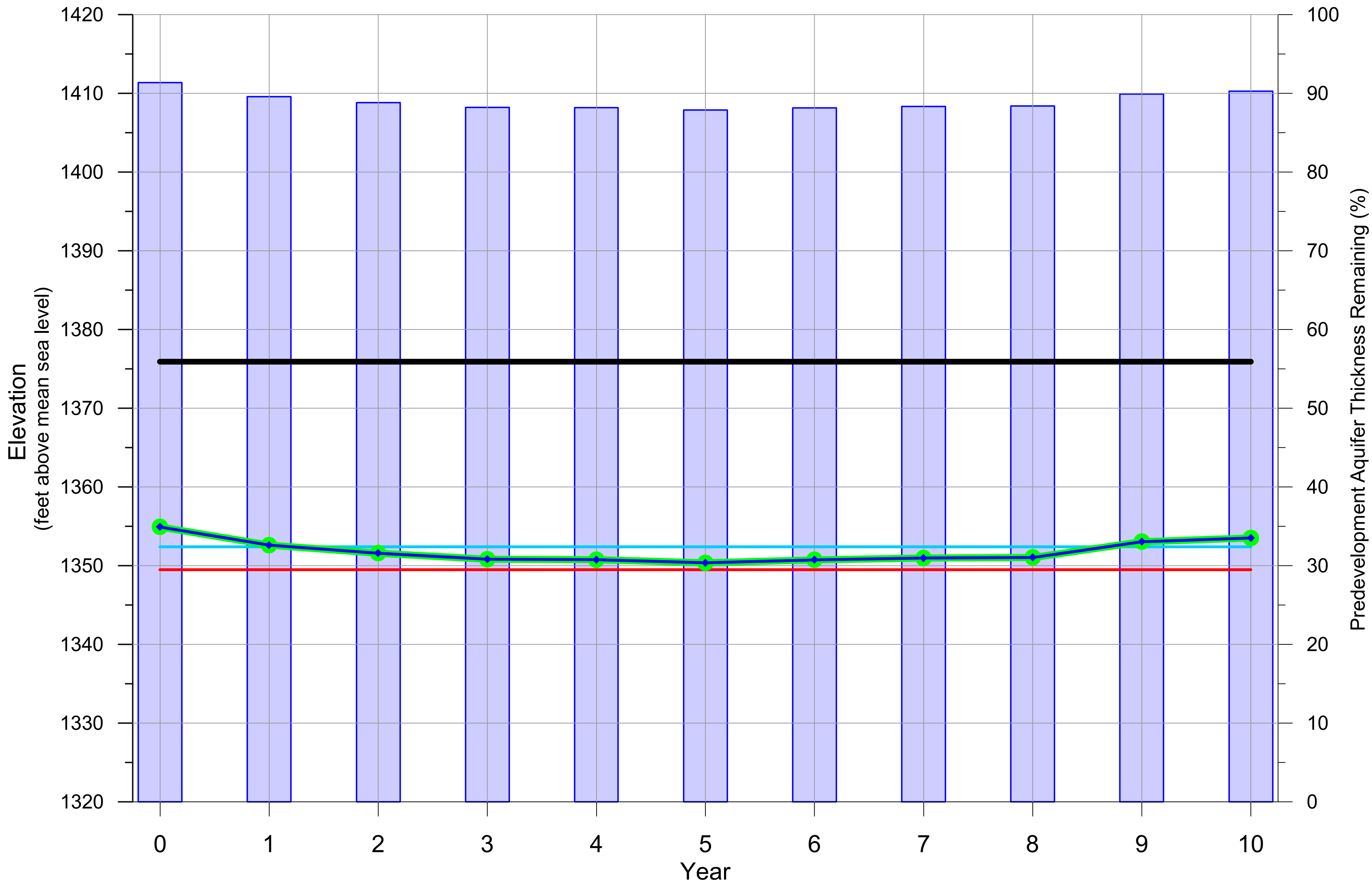


LEGEND

- IW-28A
- IW-28C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 28
Index Well Hydrographs
IW-28A & IW-28C
Stress Periods 1 through 10

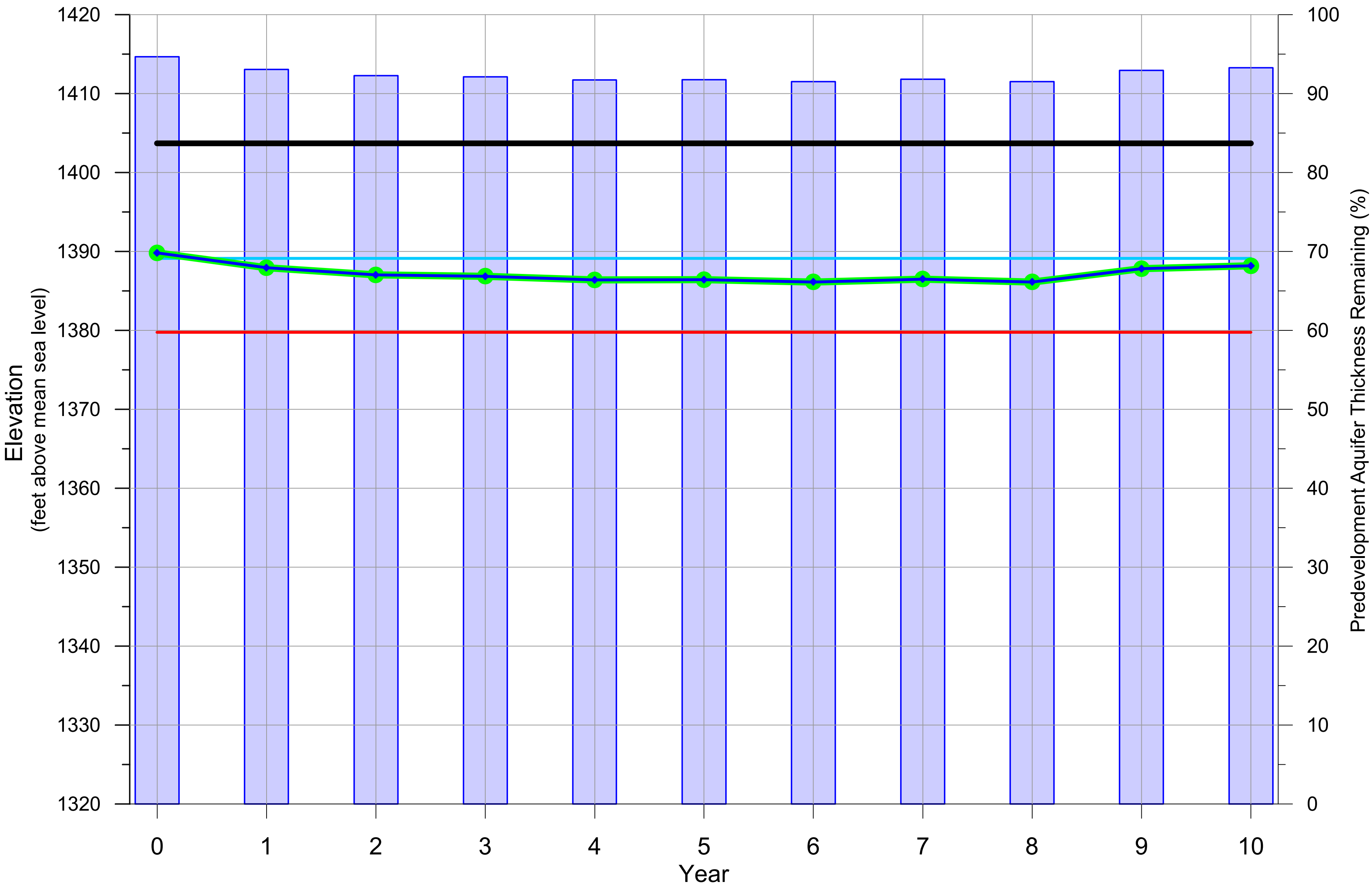


LEGEND

- IW-29A
- IW-29C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 29
Index Well Hydrographs
IW-29A & IW-29C
Stress Periods 1 through 10



LEGEND

IW-30A

IW-30C

Ground Surface Elevation

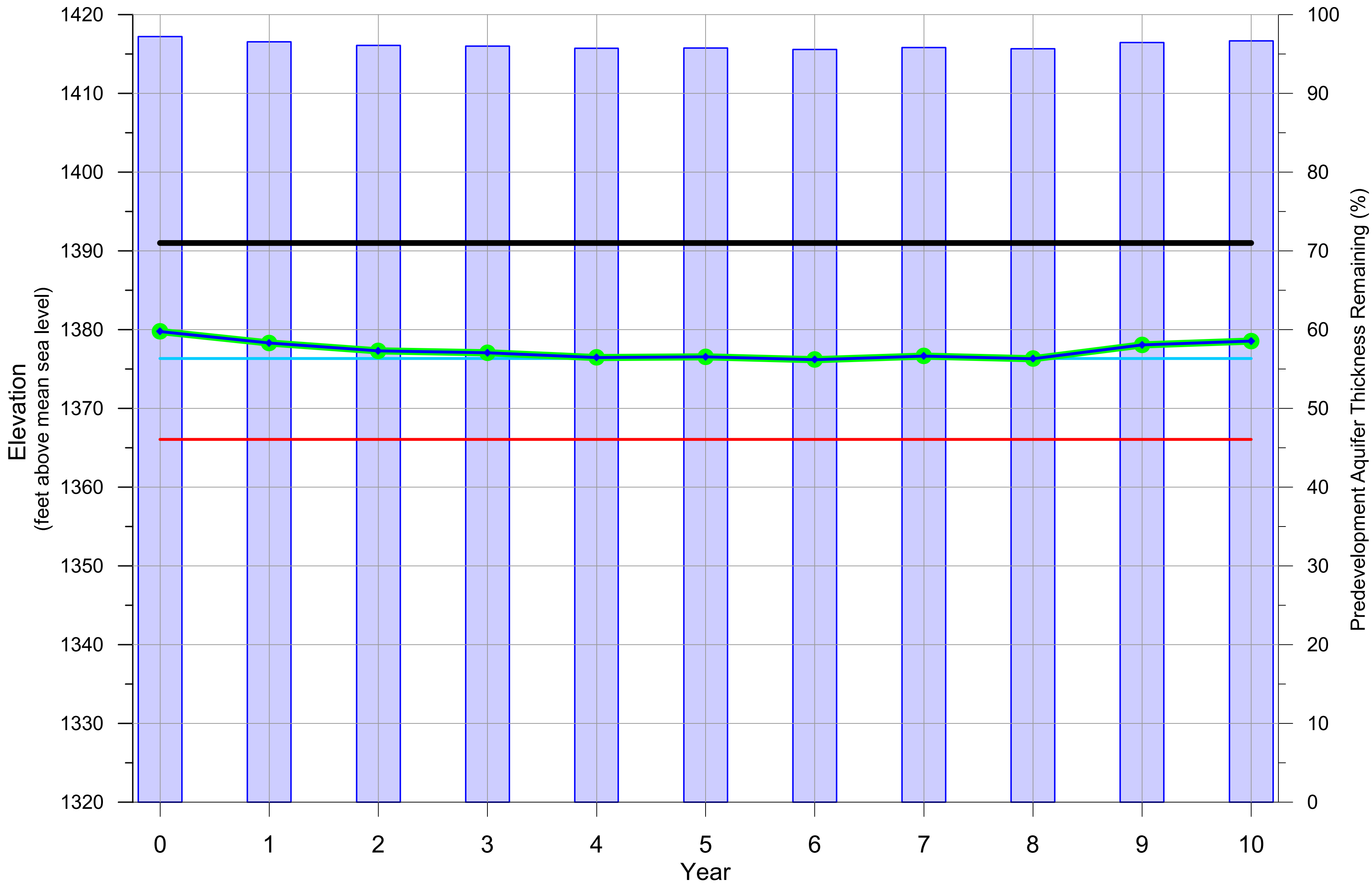
1993 Upper Aquifer Groundwater Elevation

1993 Lower Aquifer Groundwater Elevation

Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 30
Index Well Hydrographs
IW-30A & IW-30C
Stress Periods 1 through 10

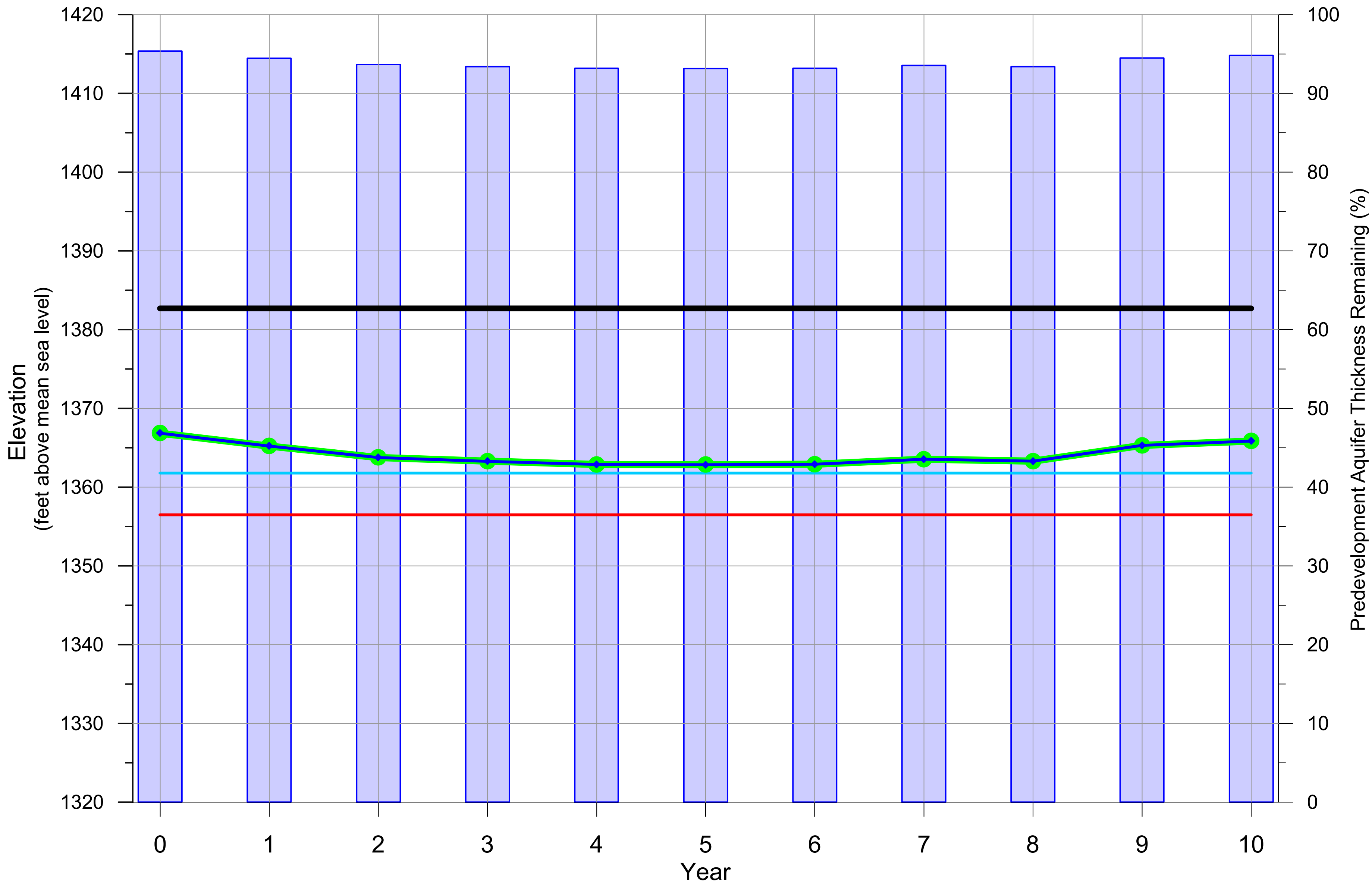


LEGEND

IW-31A
IW-31C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 31
Index Well Hydrographs
IW-31A & IW-31C
Stress Periods 1 through 10

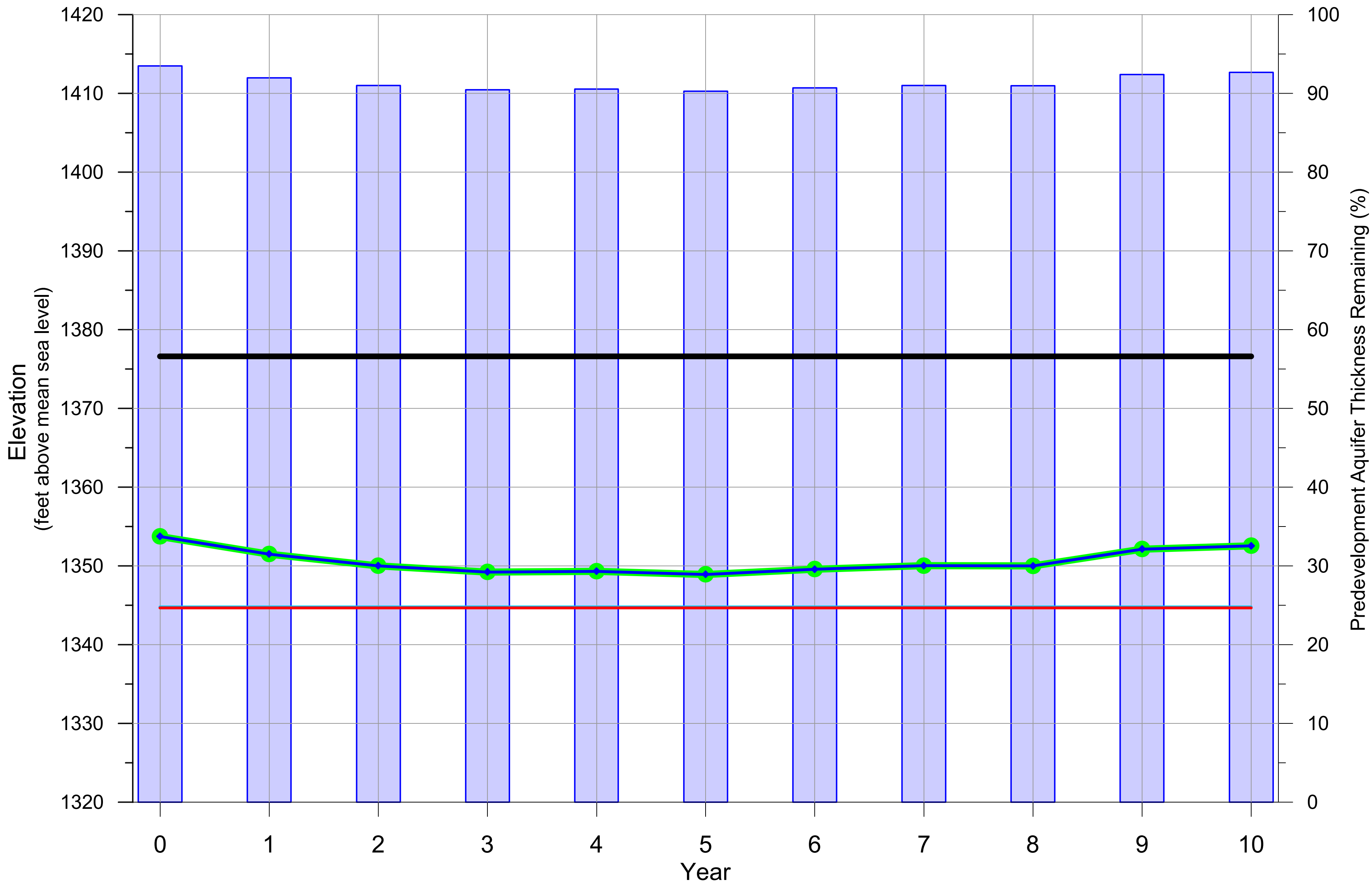


LEGEND

- IW-32A
- IW-32C
- Ground Surface Elevation
- 1993 Upper Aquifer Groundwater Elevation
- 1993 Lower Aquifer Groundwater Elevation
- Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 32
Index Well Hydrographs
IW-32A & IW-32C
Stress Periods 1 through 10



LEGEND

IW-33A

IW-33C

Ground Surface Elevation

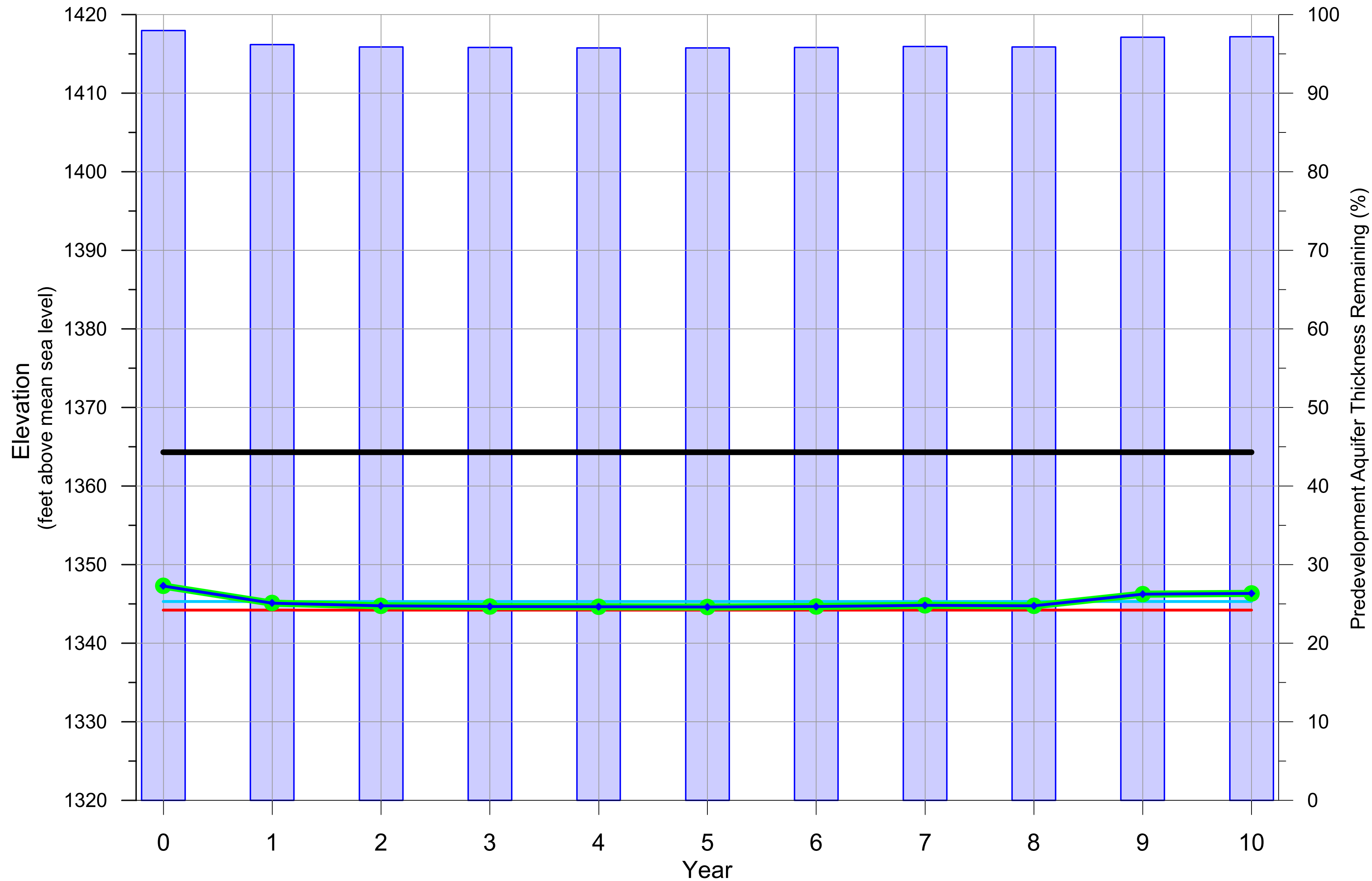
1993 Upper Aquifer Groundwater Elevation

1993 Lower Aquifer Groundwater Elevation

Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 33
Index Well Hydrographs
IW-33A & IW-33C
Stress Periods 1 through 10

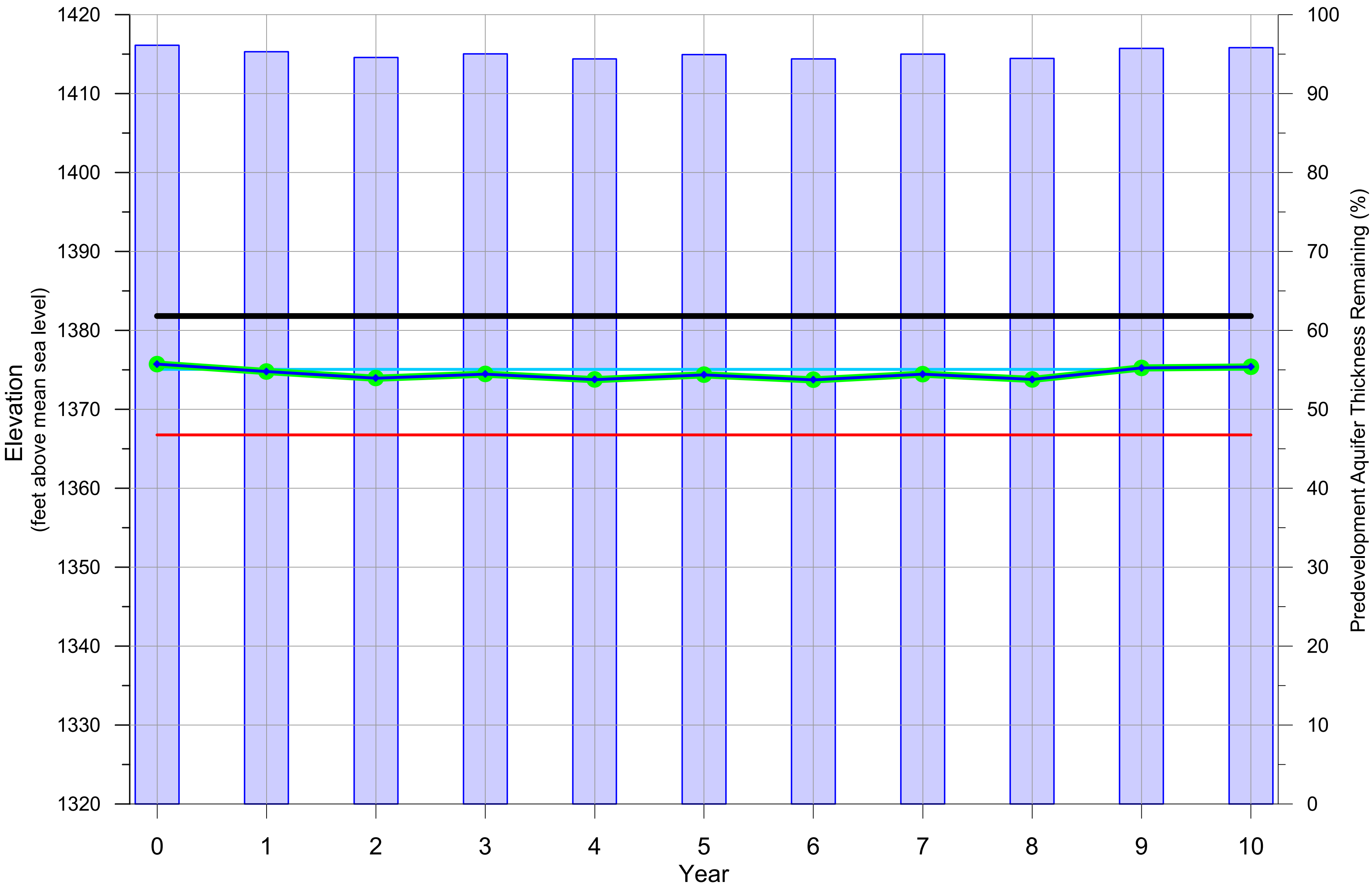


LEGEND

IW-34A
IW-34C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 34
Index Well Hydrographs
IW-34A & IW-34C
Stress Periods 1 through 10

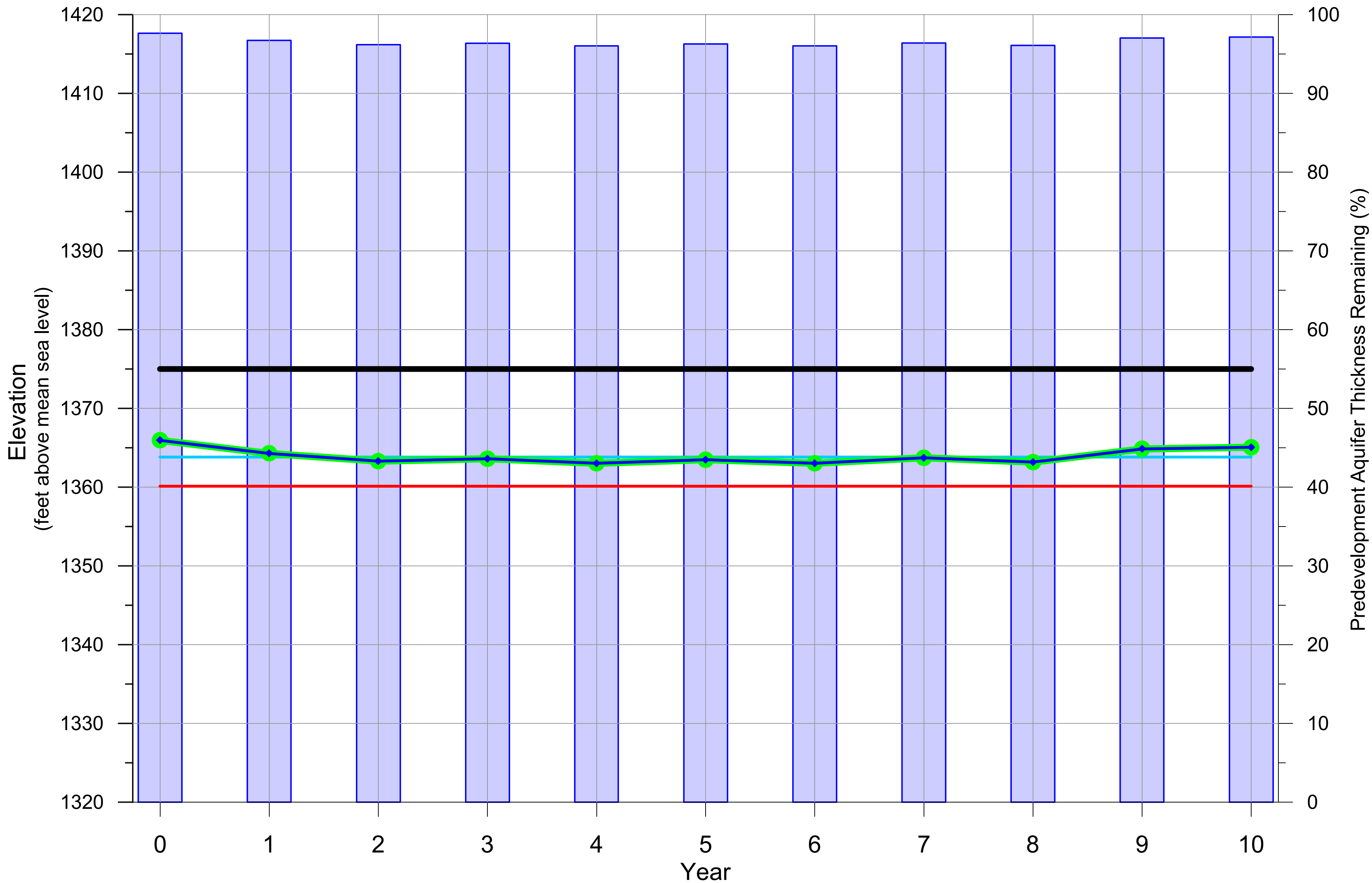


LEGEND

IW-35A
IW-35C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 35
Index Well Hydrographs
IW-35A & IW-35C
Stress Periods 1 through 10



LEGEND

IW-36A

IW-36C

Ground Surface Elevation

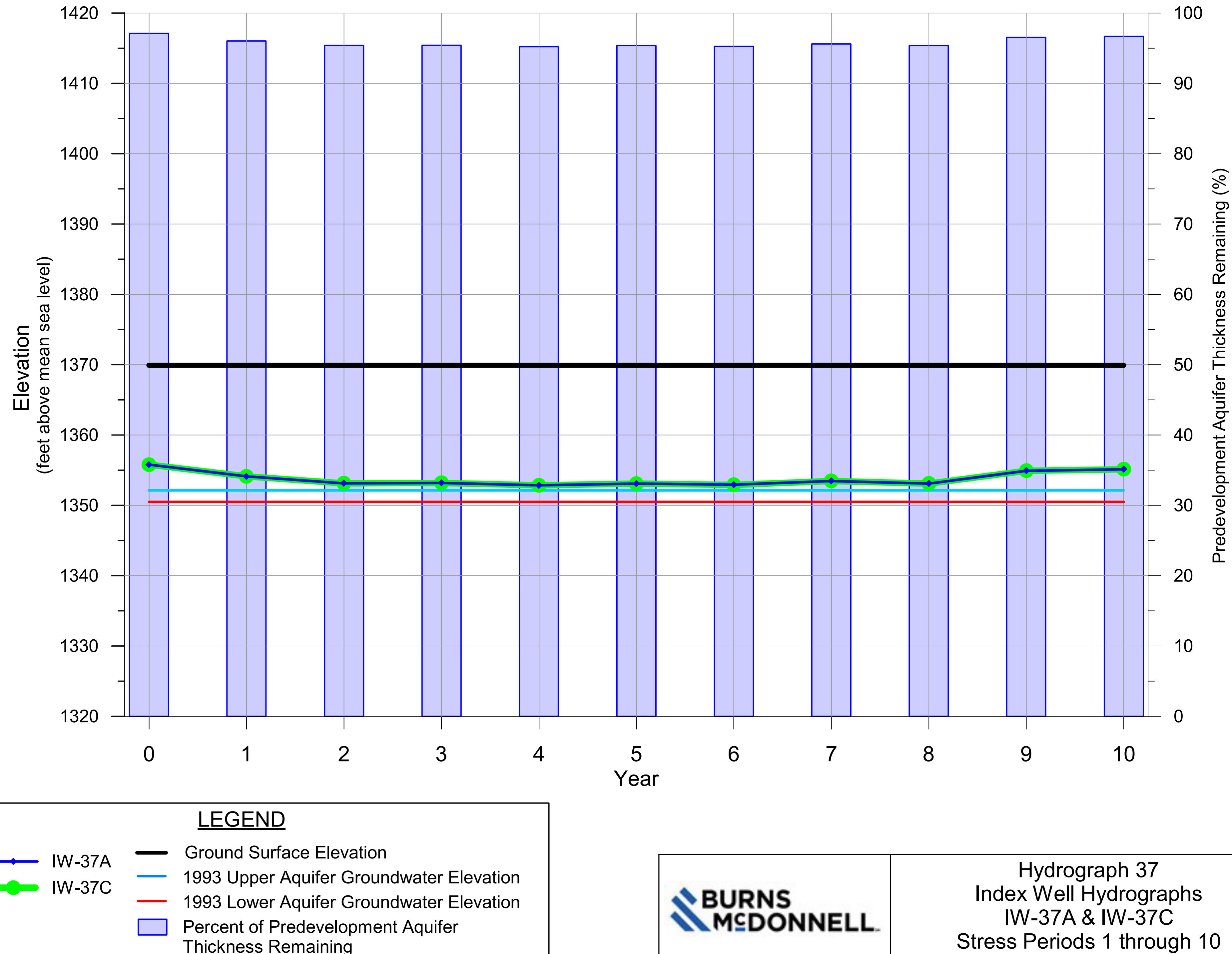
1993 Upper Aquifer Groundwater Elevation

1993 Lower Aquifer Groundwater Elevation

Percent of Predevelopment Aquifer Thickness Remaining

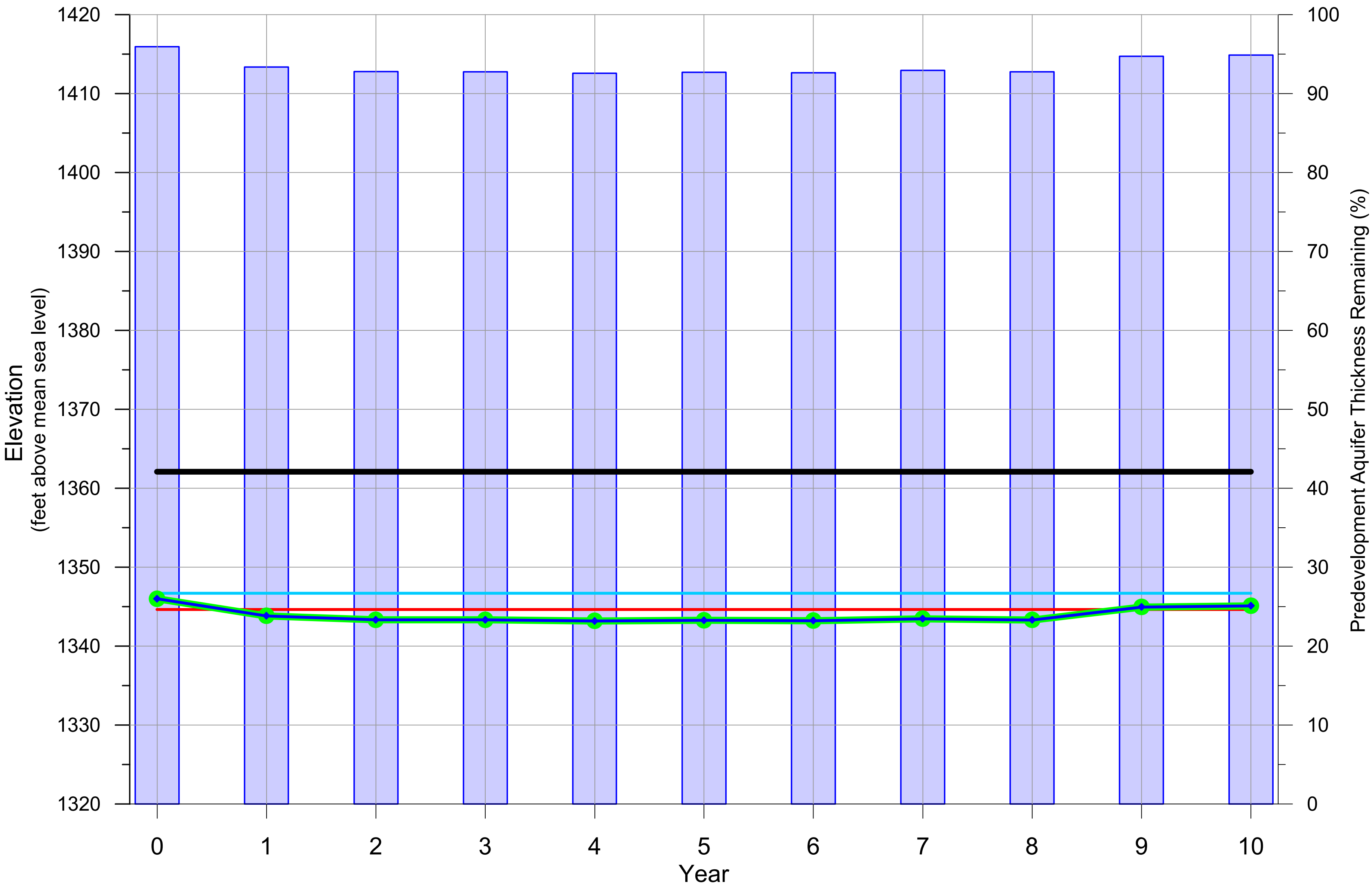
BURNS McDONNELL

Hydrograph 36
Index Well Hydrographs
IW-36A & IW-36C
Stress Periods 1 through 10



BURNS McDONNELL

Hydrograph 37
Index Well Hydrographs
IW-37A & IW-37C
Stress Periods 1 through 10



LEGEND

IW-38A
IW-38C
Ground Surface Elevation
1993 Upper Aquifer Groundwater Elevation
1993 Lower Aquifer Groundwater Elevation
Percent of Predevelopment Aquifer Thickness Remaining

BURNS McDONNELL

Hydrograph 38
Index Well Hydrographs
IW-38A & IW-38C
Stress Periods 1 through 10

ATTACHMENT J
ASR Accounting Simulations

Memorandum

Date: April 27, 2017

To: Scott Macey, City of Wichita

From: Paul McCormick

Subject: ASR Lowered Water Levels Credit Retention

Scott –

We ran several scenarios to evaluate the amount of ASR credits retained at lower water levels. As noted, ASR recharge credit retention varies based on where the water is injected, and whether it is injected via well or recharge basin. Water injected in the western half of the wellfield is typically retained, migrating into the central portion of the basin storage area. Losses from the basin storage area are much higher on the east side of the wellfield, where the water migrates rapidly into the Little Arkansas River.

For this round of evaluation of recharge credit retention under varying water levels, three model runs were completed:

Model Run No. 1

- Water levels start at the 1993 levels.
- Equus Beds Well Field pumped at the 2010 DWR reported rates.
- Phase I diversion wells pumping 928 AF.
- 9,000 AF of water was injected into the Phase I and Phase II wells, RB-2 and RB-36.
- Redevelopment pumping was estimated at 2% of the amount recharged to each well, or 108.3 AF, and applied to each RRW.
- Recharge distribution: RRWs recharged 42%, RB-36 40%, RB-2 18%

ASR Accounting indicates that under these conditions 6,734.3 AF of water would be claimed as recharge credits. This is a retention percentage of 75.7%.

Model Run No. 2

- Water levels start at the 1993 levels.
- Equus Beds Well Field pumped at the 2010 DWR reported rates.
- Phase I diversion wells pumping 928 AF.
- 9,000 AF of water was injected into the Phase I and Phase II wells, and RB-2.
- Redevelopment pumping was estimated at 2% of the amount recharged to each well, or 108.3 AF, and applied to each RRW.
- Recharge distribution: RRWs recharged 82%, RB-2 18%

ASR Accounting indicates that at 1993 water levels 8,587.3 AF of water would be able to be claimed as recharge credit. This is a retention percentage of 95.4%.

Model Run No. 3

- Water levels start at the 2015 levels.
- Year 1,
  - Equus Beds Well Field is pumped 40,000 AF.
- Years 2 through 5,
  - Equus Beds Well Field is pumped at the 2010 DWR reported rates.
  - Phase I diversion wells pumping 928 AF.
  - 9,000 AF of water was injected into the Phase I and II wells, and RB-2.
  - Redevelopment pumping was estimated at 2% of the amount recharged to each well, or 108.3 AF, and applied to each RRW.
  - Recharge distribution: RRWs recharged 82%, RB-2 18%

Pumping 40,000 AF from the well field for one year did not lower the water levels in the basin storage area to the 1993 levels, so the water levels were higher than in Scenario 1. As anticipated, the amount of recharge credits that could be claimed declined each year as water levels rose. ASR Accounting indicates that under Scenario 2, the following amounts of recharge could be claimed as water levels rise during subsequent years:

Recharge Year	Amount Recharged (minus redevelopment pumping) (AF)	Recharge Credit Claimed (AF)	Percentage of Credits Retained
1	8,892.1	8,442.3	94.9%
2	8,892.1	7,792.9	87.6%
3	8,892.1	7,205.2	81.0%
4	8,892.1	6,720.1	75.6%

By year four of recharge, water levels had risen to the same elevation as the starting water levels. The overall average percentage of water able to be claimed as recharge credits was 84.8%.

The attached tables illustrate the results of these scenarios by index cell.

Attachment

cc: Type name(s) for copies of memorandum

Model Run No. 1
1993 Water Levels with 9,000 Acre-Feet Physical Recharge
(Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	0.0	167.6	3.4	81.8	122.3	----	123.7
3	0.0			82.9	0.0	77.6	5.3
4	----			----	----	----	----
5	0.0	335.2	6.7	21.5	108.7	----	241.3
6	0.0	201.1	4.0	27.0	104.7	----	119.4
7	0.0			59.2	4.2	6.1	48.9
8	----			----	----	----	----
9	0.0	335.2	6.7	142.1	83.0	----	387.5
10	0.0	100.6	2.0	210.6	98.2	----	210.9
11	0.0			98.2	10.7	-5.1	92.6
12	0.0			10.0	2.1	2.0	5.9
13	----			----	----	----	----
14	0.0	2165.0	43.3	0.0	430.4	----	1691.3
15	0.0	402.2	8.0	238.0	125.0	----	507.2
16	0.0	301.7	6.0	19.5	49.4	----	265.7
17	0.0			49.4	0.1	6.9	42.4
18	----			----	----	----	----
19	0.0	201.1	4.0	39.6	70.3	----	166.4
20	0.0	201.1	4.0	66.4	0.0	----	263.5
21	0.0	603.3	12.1	6.5	159.0	----	438.7
22	0.0	100.6	2.0	126.3	26.3	----	198.6
23	0.0			19.8	13.2	-52.9	59.4
24	----			----	----	----	----
25	0.0			3.9	23.4	----	-19.5
26	0.0	201.1	4.0	0.0	63.0	----	134.1
27	0.0			46.9	0.0	----	46.9
28	0.0	100.6	2.0	248.7	73.5	----	273.7
29	0.0			669.6	12.7	427.8	229.1
30	0.0			48.8	18.3	----	30.4
31	0.0			5.8	53.9	----	-48.1
32	0.0			776.6	271.0	----	505.6
33	0.0	3584.5	0.0	0.0	2211.7	----	1372.8
34	0.0			849.4	316.9	416.5	116.0
35	0.0			54.2	37.4	0.0	16.7
36	0.0			32.5	288.9	----	-256.3
37	0.0			0.0	556.5	----	-556.5
38	0.0			158.1	102.6	35.0	20.6
Total	**0.0**	**9000.6**	**108.3**	**4193.4**	**5437.5**	**914.0**	**6734.3**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

Model Run No. 2
1993 Water Levels with 9,000 Acre-Feet Physical Recharge
Without Using RB36 (Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	0.0	167.6	3.4	81.9	121.2	----	124.8
3	0.0			84.1	0.0	85.1	-1.0
4	----			----	----	----	----
5	0.0	335.2	6.7	21.6	92.0	----	258.0
6	0.0	448.3	4.0	10.2	235.7	----	218.8
7	0.0			132.4	9.9	30.6	91.8
8	----			----	----	----	----
9	0.0	335.2	6.7	189.9	53.6	----	464.7
10	0.0	224.1	2.0	390.3	214.0	----	398.4
11	0.0			214.0	23.8	-11.0	201.2
12	0.0			22.4	4.7	4.1	13.6
13	----			----	----	----	----
14	0.0	2783.0	43.3	0.0	588.6	----	2151.1
15	0.0	896.6	8.0	297.4	293.0	----	892.9
16	0.0	672.4	6.0	33.9	111.9	----	588.4
17	0.0			111.9	0.1	11.7	100.1
18	----			----	----	----	----
19	0.0	448.3	4.0	94.9	129.0	----	410.2
20	0.0	448.3	4.0	120.2	4.3	----	560.2
21	0.0	1344.9	12.1	14.7	400.1	----	947.4
22	0.0	224.1	2.0	291.9	158.9	----	355.1
23	0.0			69.6	3.8	-13.4	79.3
24	----			----	----	----	----
25	0.0			8.8	50.6	----	-41.8
26	0.0	448.3	4.0	0.0	158.7	----	285.6
27	0.0			140.6	0.2	----	140.4
28	0.0	224.1	2.0	74.6	55.6	----	241.1
29	0.0			54.3	15.1	16.5	22.6
30	0.0			126.3	104.9	----	21.4
31	0.0			81.0	38.0	----	43.0
32	0.0			16.0	4.2	----	11.7
33	0.0	0.0	0.0	15.7	11.0	----	4.7
34	0.0			11.1	4.4	5.4	1.3
35	0.0			21.3	16.4	0.0	4.8
36	0.0			10.5	8.8	----	1.6
37	0.0			1.4	5.5	----	-4.2
38	0.0			1.7	1.2	0.5	0.1
Total	**0.0**	**9000.4**	**108.3**	**2744.2**	**2919.5**	**129.6**	**8587.3**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

Model Run No. 3
40,000 AF Pumped, Year One of 9,000 AF Recharged
(Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	0.0	167.6	3.4	114.1	108.0	----	170.3
3	0.0			63.7	7.0	30.6	26.2
4	----			----	----	----	----
5	0.0	335.2	6.7	29.5	123.3	----	234.6
6	0.0	448.3	4.0	9.3	162.4	----	291.2
7	0.0			161.0	12.3	119.8	28.9
8	----			----	----	----	----
9	0.0	335.2	6.7	0.0	29.5	----	299.0
10	0.0	224.1	2.0	147.3	217.5	----	152.0
11	0.0			217.5	51.9	10.8	154.7
12	0.0			27.5	6.0	12.5	8.9
13	----			----	----	----	----
14	0.0	2783.0	43.3	0.0	205.7	----	2534.0
15	0.0	896.6	8.0	129.5	158.8	----	859.2
16	0.0	672.4	6.0	28.4	135.3	----	559.5
17	0.0			135.3	0.2	33.8	101.4
18	----			----	----	----	----
19	0.0	448.3	4.0	101.7	211.2	----	334.8
20	0.0	448.3	4.0	84.0	78.7	----	449.6
21	0.0	1344.9	12.1	0.0	297.4	----	1035.4
22	0.0	224.1	2.0	264.0	96.6	----	389.5
23	0.0			76.0	4.0	-12.2	84.1
24	----			----	----	----	----
25	0.0			125.3	87.3	----	38.1
26	0.0	448.3	4.0	48.0	102.0	----	390.2
27	0.0			64.2	19.0	----	45.3
28	0.0	224.1	2.0	21.7	87.9	----	155.9
29	0.0			85.1	19.1	17.1	49.0
30	0.0			71.2	109.3	----	-38.2
31	0.0			100.0	43.6	----	56.4
32	0.0			16.9	5.4	----	11.5
33	0.0	0.0	0.0	18.9	9.3	----	9.6
34	0.0			9.2	3.4	4.2	1.6
35	0.0			26.5	17.3	0.0	9.2
36	0.0			11.3	8.1	----	3.1
37	0.0			1.1	4.1	----	-3.0
38	0.0			1.1	0.5	0.2	0.4
Total	**0.0**	**9000.4**	**108.3**	**2189.1**	**2422.0**	**216.9**	**8442.3**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

DRAFT

Model Run No. 3
40,000 AF Pumped, Year Two of 9,000 AF Recharged

(Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	170.3	167.6	3.4	131.0	144.8	----	320.7
3	26.2			88.9	13.0	74.4	27.7
4	----			----	----	----	----
5	234.6	335.2	6.7	29.3	142.4	----	450.0
6	291.2	448.3	4.0	11.3	224.1	----	522.6
7	28.9			277.8	26.0	241.1	39.6
8	----			----	----	----	----
9	299.0	335.2	6.7	1.1	29.3	----	599.3
10	152.0	224.1	2.0	177.4	278.8	----	272.7
11	154.7			278.8	152.9	41.8	238.9
12	8.9			79.1	23.8	48.4	15.9
13	----			----	----	----	----
14	2534.0	2783.0	43.3	0.0	248.7	----	5024.9
15	859.2	896.6	8.0	67.4	251.4	----	1563.8
16	559.5	672.4	6.0	74.0	240.7	----	1059.2
17	101.4			240.7	0.6	120.6	220.8
18	----			----	----	----	----
19	334.8	448.3	4.0	113.1	222.8	----	669.4
20	449.6	448.3	4.0	0.0	113.4	----	780.4
21	1035.4	1344.9	12.1	0.0	410.7	----	1957.6
22	389.5	224.1	2.0	356.9	210.9	----	757.7
23	84.1			163.2	10.9	-32.1	268.6
24	----			----	----	----	----
25	38.1			215.5	204.9	----	48.6
26	390.2	448.3	4.0	106.9	114.9	----	826.5
27	45.3			66.3	36.8	----	74.8
28	155.9	224.1	2.0	49.3	154.4	----	273.0
29	49.0			145.9	39.2	44.4	111.2
30	-38.2			102.3	138.4	----	-74.2
31	56.4			130.3	78.9	----	107.9
32	11.5			30.4	18.3	----	23.6
33	9.6	0.0	0.0	42.7	27.4	----	24.8
34	1.6			27.3	10.6	13.1	5.1
35	9.2			52.0	30.2	0.0	31.0
36	3.1			22.6	19.7	----	6.1
37	-3.0			2.2	13.5	----	-14.3
38	0.4			3.8	2.1	0.8	1.3
Total	**8442.3**	**9000.4**	**108.3**	**3087.7**	**3634.4**	**552.5**	**16235.2**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

DRAFT

Model Run No. 3
40,000 AF Pumped, Year Three of 9,000 AF Recharged
(Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	320.7	167.6	3.4	144.3	173.5	----	455.7
3	27.7			108.6	18.2	111.8	6.4
4	----			----	----	----	----
5	450.0	335.2	6.7	29.7	156.1	----	652.0
6	522.6	448.3	4.0	11.8	289.0	----	689.6
7	39.6			379.8	38.5	338.9	42.1
8	----			----	----	----	----
9	599.3	335.2	6.7	1.7	29.7	----	899.8
10	272.7	224.1	2.0	200.0	325.6	----	369.3
11	238.9			325.6	243.4	71.2	249.8
12	15.9			123.3	40.5	80.6	18.0
13	----			----	----	----	----
14	5024.9	2783.0	43.3	0.0	285.0	----	7479.6
15	1563.8	896.6	8.0	20.7	305.0	----	2168.1
16	1059.2	672.4	6.0	105.0	321.5	----	1509.1
17	220.8			321.5	1.1	197.5	343.7
18	----			----	----	----	----
19	669.4	448.3	4.0	108.4	299.0	----	923.1
20	780.4	448.3	4.0	0.0	150.9	----	1073.8
21	1957.6	1344.9	12.1	0.0	493.8	----	2796.6
22	757.7	224.1	2.0	424.8	300.5	----	1104.2
23	268.6			233.2	16.5	-50.0	535.4
24	----			----	----	----	----
25	48.6			280.7	298.4	----	30.9
26	826.5	448.3	4.0	150.9	132.8	----	1288.8
27	74.8			69.0	64.0	----	79.8
28	273.0	224.1	2.0	80.1	209.2	----	366.0
29	111.2			195.2	54.3	66.9	185.2
30	-74.2			132.8	159.7	----	-101.1
31	107.9			153.9	111.2	----	150.5
32	23.6			42.1	33.9	----	31.7
33	24.8	0.0	0.0	63.7	44.3	----	44.2
34	5.1			44.5	17.7	22.6	9.3
35	31.0			76.3	42.6	0.0	64.7
36	6.1			34.1	33.8	----	6.4
37	-14.3			3.6	23.7	----	-34.4
38	1.3			6.8	4.4	1.6	2.1
Total	**16235.2**	**9000.4**	**108.3**	**3872.0**	**4718.0**	**841.0**	**23440.4**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

DRAFT

Model Run No. 3
40,000 AF Pumped, Year Four of 9,000 AF Recharged

(Acre-Feet)

Index Cell No.	Previous Recharge Credit	Metered Recharge	Metered Recovery	Net Recharge Credit Underflow Entering Index Cell	Net Recharge Credit Underflow Leaving Index Cell	Net Recharge Credit Loss to River	Calculated Recharge Credit
1	----			----	----	----	----
2	455.7	167.6	3.4	156.7	198.6	----	578.1
3	6.4			125.9	22.7	145.6	-36.0
4	----			----	----	----	----
5	652.0	335.2	6.7	30.5	169.4	----	841.5
6	689.6	448.3	4.0	12.7	343.1	----	803.5
7	42.1			466.6	48.7	422.7	37.3
8	----			----	----	----	----
9	899.8	335.2	6.7	1.4	30.5	----	1199.2
10	369.3	224.1	2.0	212.9	362.9	----	441.4
11	249.8			362.9	319.6	94.7	198.4
12	18.0			158.8	53.9	107.2	15.7
13	----			----	----	----	----
14	7479.6	2783.0	43.3	0.0	323.9	----	9895.4
15	2168.1	896.6	8.0	0.0	339.2	----	2717.4
16	1509.1	672.4	6.0	126.2	384.5	----	1917.3
17	343.7			384.5	1.4	260.0	466.8
18	----			----	----	----	----
19	923.1	448.3	4.0	102.3	355.1	----	1114.6
20	1073.8	448.3	4.0	0.0	181.9	----	1336.2
21	2796.6	1344.9	12.1	0.0	557.3	----	3572.1
22	1104.2	224.1	2.0	477.2	370.6	----	1432.8
23	535.4			288.9	21.0	-63.9	867.2
24	----			----	----	----	----
25	30.9			325.6	367.5	----	-11.0
26	1288.8	448.3	4.0	181.9	160.7	----	1754.2
27	79.8			80.1	92.8	----	67.0
28	366.0	224.1	2.0	109.6	254.6	----	443.1
29	185.2			235.8	66.4	85.0	269.7
30	-101.1			160.6	175.6	----	-116.1
31	150.5			172.0	139.3	----	183.2
32	31.7			51.8	49.0	----	34.5
33	44.2	0.0	0.0	81.8	58.6	----	67.3
34	9.3			59.1	23.6	30.0	14.9
35	64.7			97.9	53.1	0.0	109.6
36	6.4			44.5	46.5	----	4.4
37	-34.4			5.0	32.7	----	-62.2
38	2.1			9.4	6.3	2.3	2.9
Total	**23440.4**	**9000.4**	**108.3**	**4522.7**	**5611.1**	**1083.6**	**30160.5**

Calculated recharge credits include negative values to generate the total recharge credit values, but effective recharge credits cannot be less than zero. The effective recharge credit in Index Cells with negative credits is zero.

DRAFT

CREATE AMAZING.

Burns & McDonnell World Headquarters
9400 Ward Parkway
Kansas City, MO 64114
O 816-333-9400
F 816-333-3690
www.burnsmcd.com