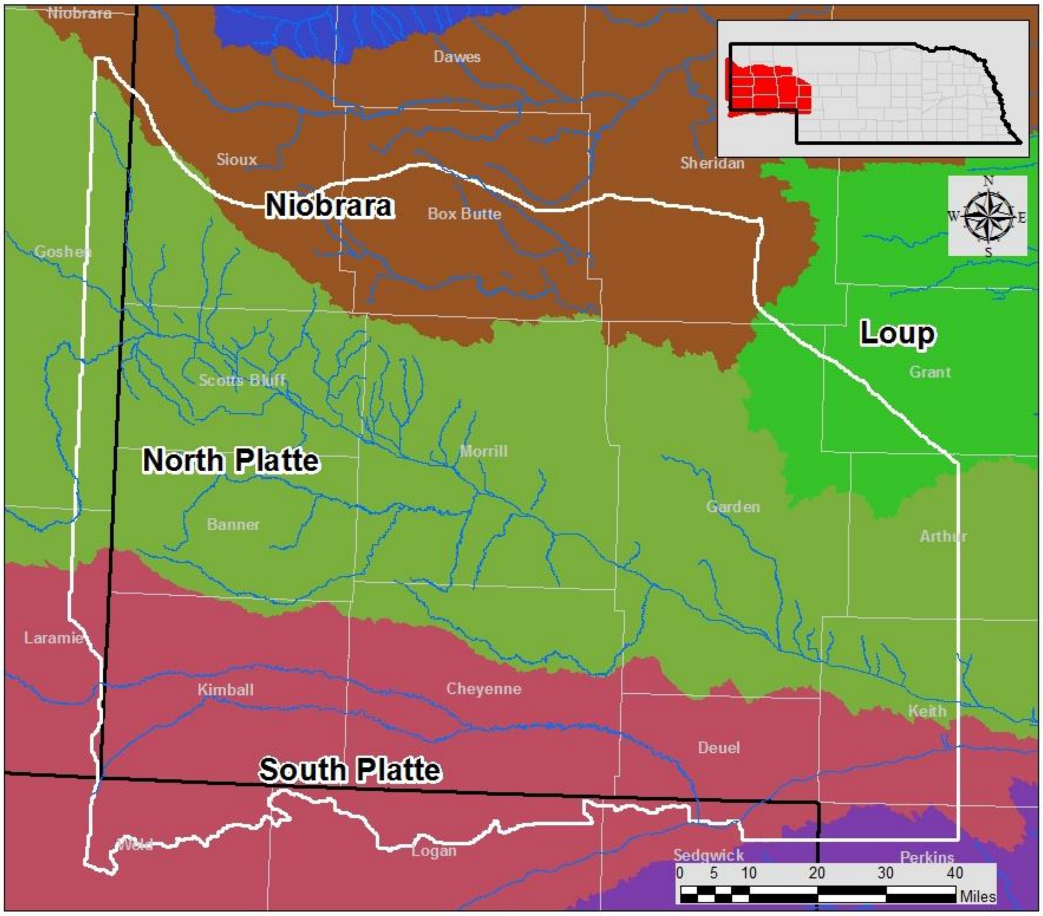
The Western Water Use Model: Regionalized Soil Water Balance Model 2013 Extension Report



Prepared By:
The Flatwater Group, Inc.

30 June 2016

1. Introduction

1.1. Authorization

The Flatwater Group, Inc. (TFG) has prepared this report as authorized in the contract between the North Platte Natural Resources District (NPNRD) and TFG originally dated 26 January 2010.

1.2. Purpose and Scope

The NPNRD, in conjunction with the South Platte Natural Resources District (SPNRD) and the Nebraska Department of Natural Resources (DNR), have developed the Western Water Use Management (WWUM) Model for evaluating management actions aimed at achieving the goals of the districts' Integrated Management Plans (IMPs) using the period of record May 1953 through December 2010. The WWUM model consists of a surface water operations model, a ground water flow model, and a regionalized soil water balance (RSWB) model. Results from the three models are integrated to analyze actions related to the goals identified in the IMPs.

This report focuses on the improvements made to the RSWB and extension of the temporal domain from January 2011 through April 2014. This report also discusses the changes to the general methodologies described in the original RSWB documentation [1], details the development of additional input files over the extended domain, and presents select summaries of pumping, recharge, and other water balance parameters. A copy of the completed historical extension, the source code for the programs which constitute this model and the inputs necessary to run the model are included.

2. Changes to Model Construction

Since the completion of the original WWUM model (2010) several improvements have been made to enhance the usability and calibration of the model. The major changes to each program of the model are described below.

2.1. Irrigation Application and Demand (IAD)

The purpose of the IAD is the identification and implementation of available irrigation records and the development of irrigation estimates when necessary. The program then partitions the applied water to specific crops in each cell and accumulates the irrigation on a headgate or certificate basis. Further detail is available in section 4.1 of the RSWB documentation [1].

Over the course of developing the model extension the following changes were made to the IAD:

- Additional quality control files were created to track the pumping on a parcel by parcel level
- Implemented a technique for distributing irrigation water within a parcel with no NIR[1] for integrating irrigated fallow into the model
    - Irrigation is partitioned to the cells uniformly per acre
    - Volumes were provided from the irrigated data sets
    - Necessary for simulating the effect of irrigating fallow from the
- Improved the process for identifying whether an individual parcel had a specified pumping volume of 0.0 AF or was not included in the data set necessitating that the irrigation volume be estimated within the IAD
- Corrected an error in which the program was not processing the last irrigated land use record
- Corrected a unit transfer error for metered comingled pumping

2.2. Water Supply Partitioning Program (WSPP)

The WSPP program incorporates the defined levels of irrigation from the IAD with precipitation and partitions the total on field applied water between evapotranspiration (ET), deep percolation (DP), runoff (RO), and change in soil water content (ΔSWC). Throughout the process adjustments are made to the water balance parameters to account for differing levels of irrigation and non-idealized conditions experienced in the field. Further detail on the WSPP program is available in section 4.2 of the RSWB documentation [1].

Over the course of developing the model extension the following changes were made to the WSPP:

- The introduction of scenario specific controls
    - Switch turning all irrigation water on or off
    - Switch turning all ground water pumping on or off

[1] Net Irrigation Requirement

- Implementation of a technique to partition applied irrigation water on irrigated fallow
    - As with any other irrigated crop in the model, the irrigation water is partitioned between ET, RO, DP, and ΔSWC.
    - To account for the additional wetting of the soil surface, an ET gain was calculated as a percentage of potential ET gain on irrigated pasture
        - 5% was used
    - Upon determining the ET gain, the remaining applied water was partitioned according to the techniques laid out in section 4.2 of the RSWB documentation [1].

2.3. Make Well and Compile Well

The Make Well and Compile Well programs combine the various sources of pumping into a single groundwater exchange file. Further detail is available in sections 4.3 & 4.4 of the RSWB documentation [1].

No substantial changes were made to the Make Well or Compile Well programs.

2.4. Make Recharge and Compile Recharge

The Make Recharge program divides the direct runoff from the field into indirect ET, indirect recharge, and runoff contributions to stream flow. Then the Make Recharge program with the Compile Recharge code combines all sources of recharge into a single .RCH file for inclusion into the ground water model. Further detail is available in sections 4.5-4.6 of the RSWB documentation [1].

No substantial changes were made to the Make Recharge or Compile Recharge programs.

2.5. WSPP Report

The WSPP Report compiles all of the information developed in the WSPP and Make Recharge files into sets of water balance summaries. Summary files can be organized by crops, irrigation source, or model area.

The previous version of WSPP Report created individual summary (example: regional ground water corn summary, regional surface water corn summary, regional groundwater wheat summary, etc…) where each summary was contained within its own file.

The output was changed such that when the model is subdivided, summaries for all of the sections are contained within a single file which sums to the whole (example: the Regional Crop Irrigation Source summary would take the place of all the files listed in the example above).

3. Model Inputs

The extension and calibration of the model required the creation of several new input files to represent the conditions experienced during the extension.

3.1. Climate 2011-2013

Climate data was acquired for the years 2011-2013 for each of the National Weather Service and Cooperative Network (NWS/Coop) weather stations identified in section 5.3 of the RSWB documentation [1]. Upon review of the weather data, it became apparent that the Bridgeport weather station ceased collection operations in the middle of 2011. The historical record of surrounding weather stations was reviewed and it was determined that the station at Crescent Lake would be used as a replacement for the extension. The weather data at each of the weather stations (Table 1) was reviewed for quality and completeness then prepared into .WEA file for inclusion in the CropSim Model. The CropSim model was run from the beginning of the historical record through 2013 with the results being spatially distributed across the model domain as described in section 5.4 of the RSWB documentation [1]. Figures 1 – 6 show the distribution of precipitation and corn NIR for the years 2011-2013.

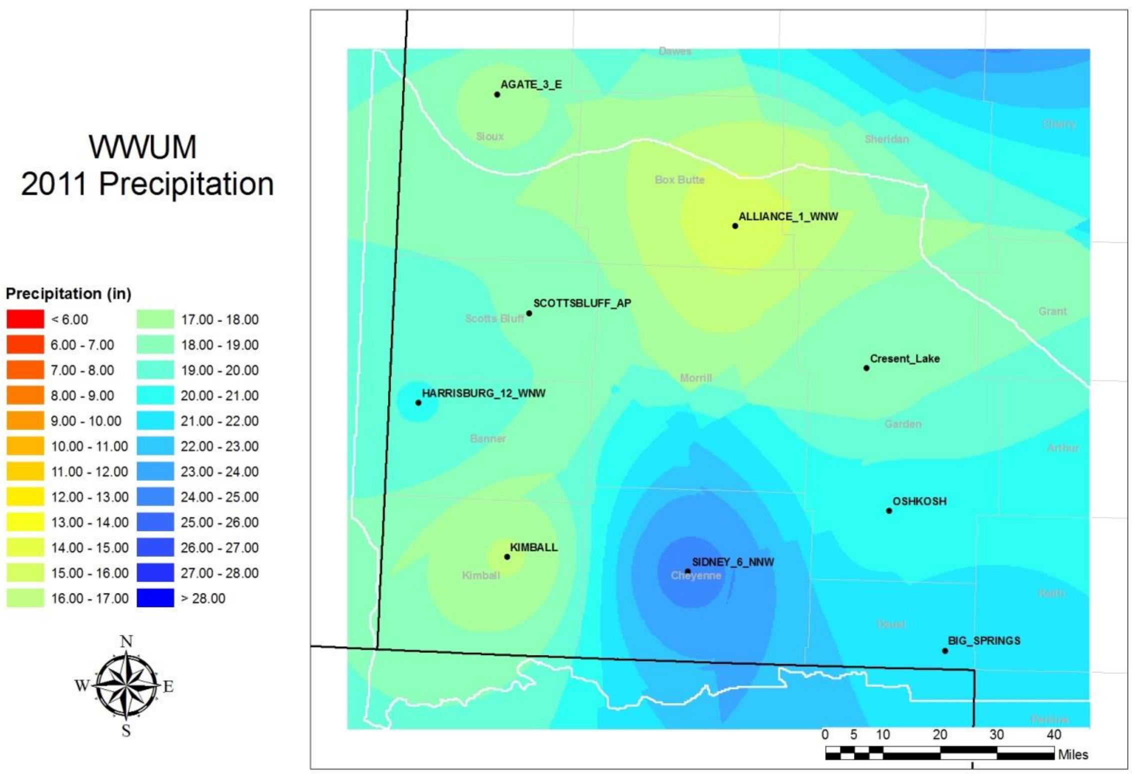


Figure 1. Annual 2011 precipitation (in).

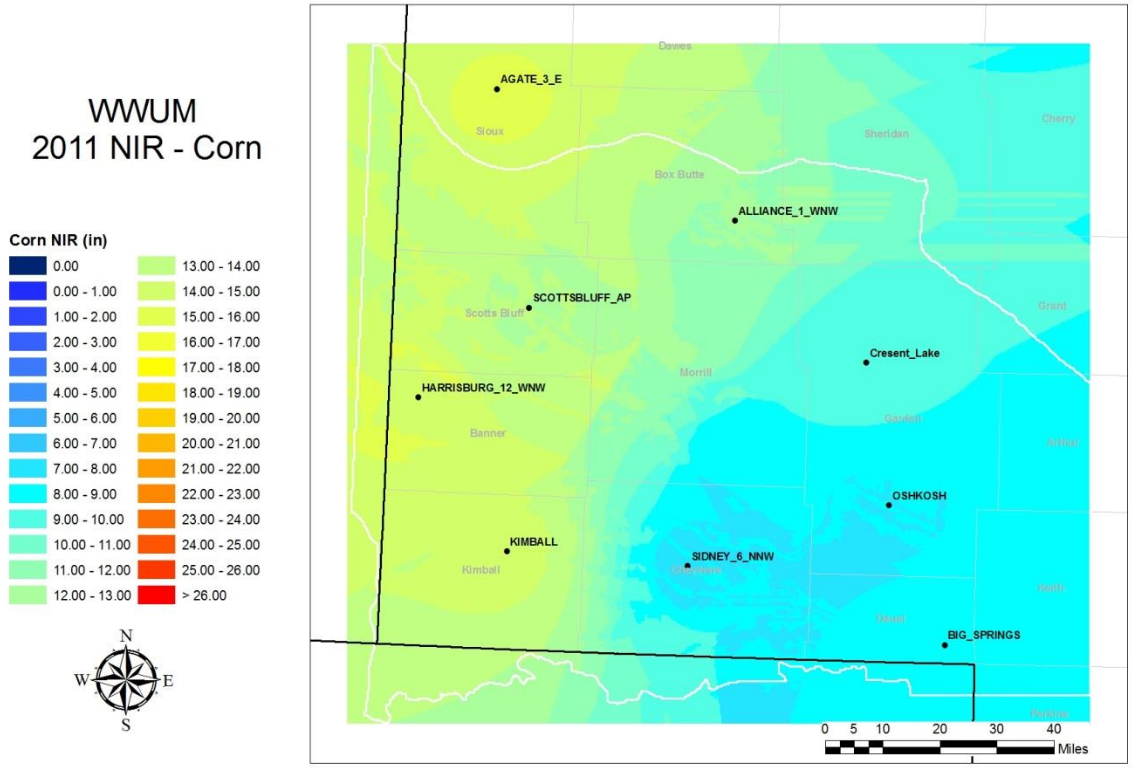


Figure 2. Annual 2011 net irrigation requirement - corn (in).

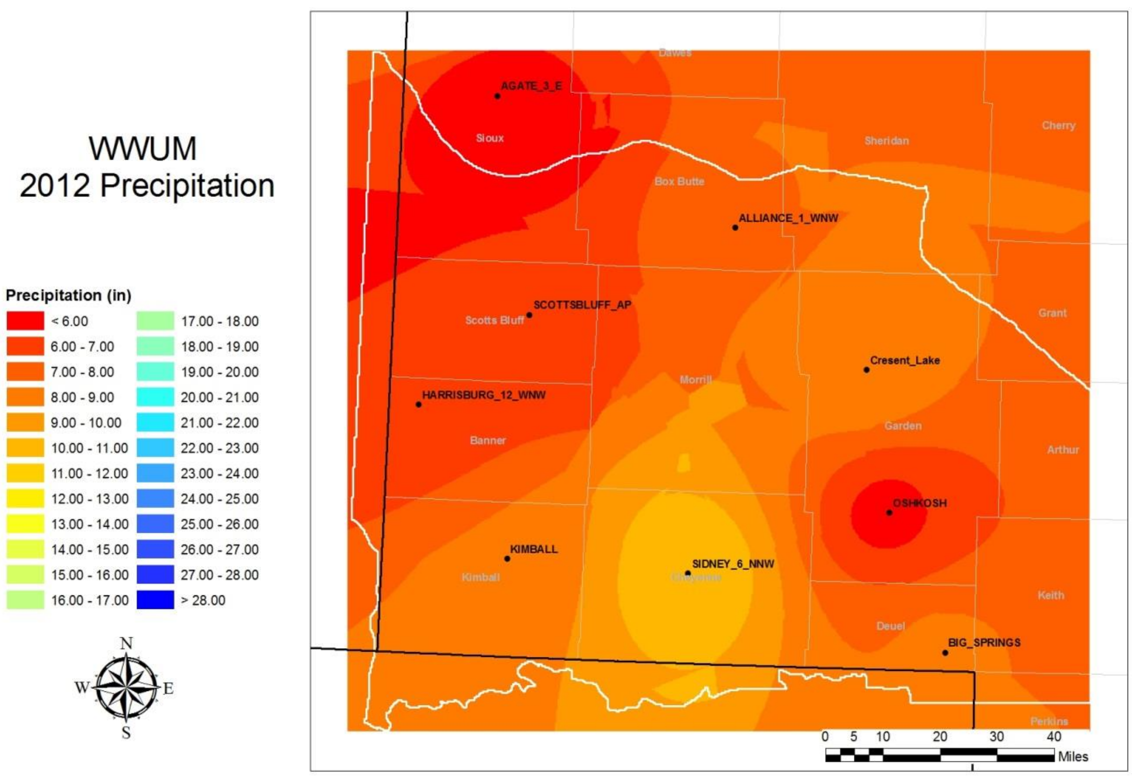


Figure 3. Annual 2012 precipitation (in)

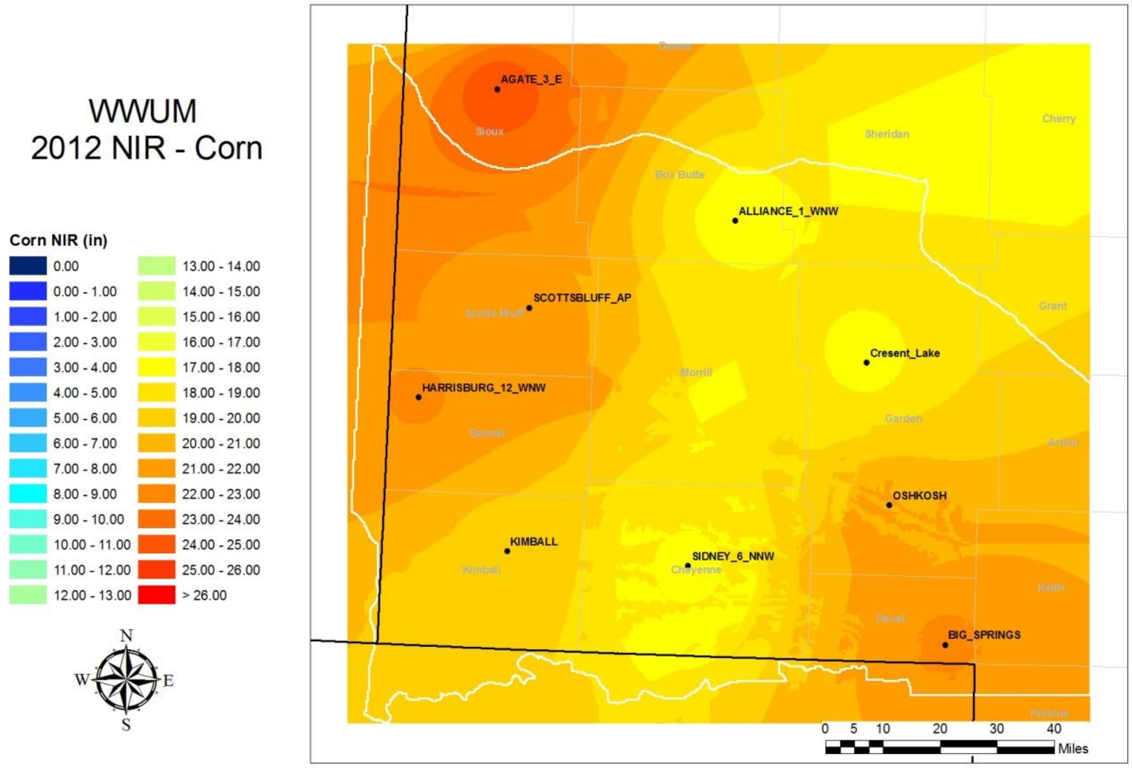


Figure 4. Annual 2012 net irrigation requirement - corn (in).

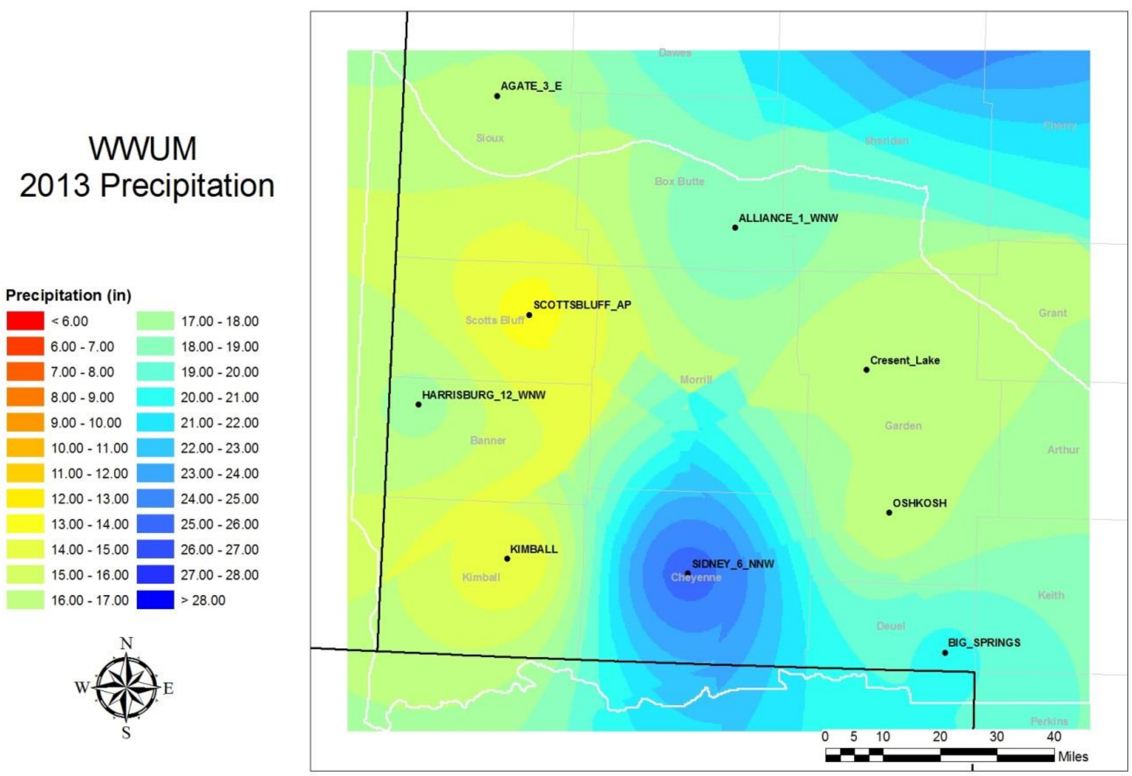


Figure 5. Annual 2013 precipitation (in).

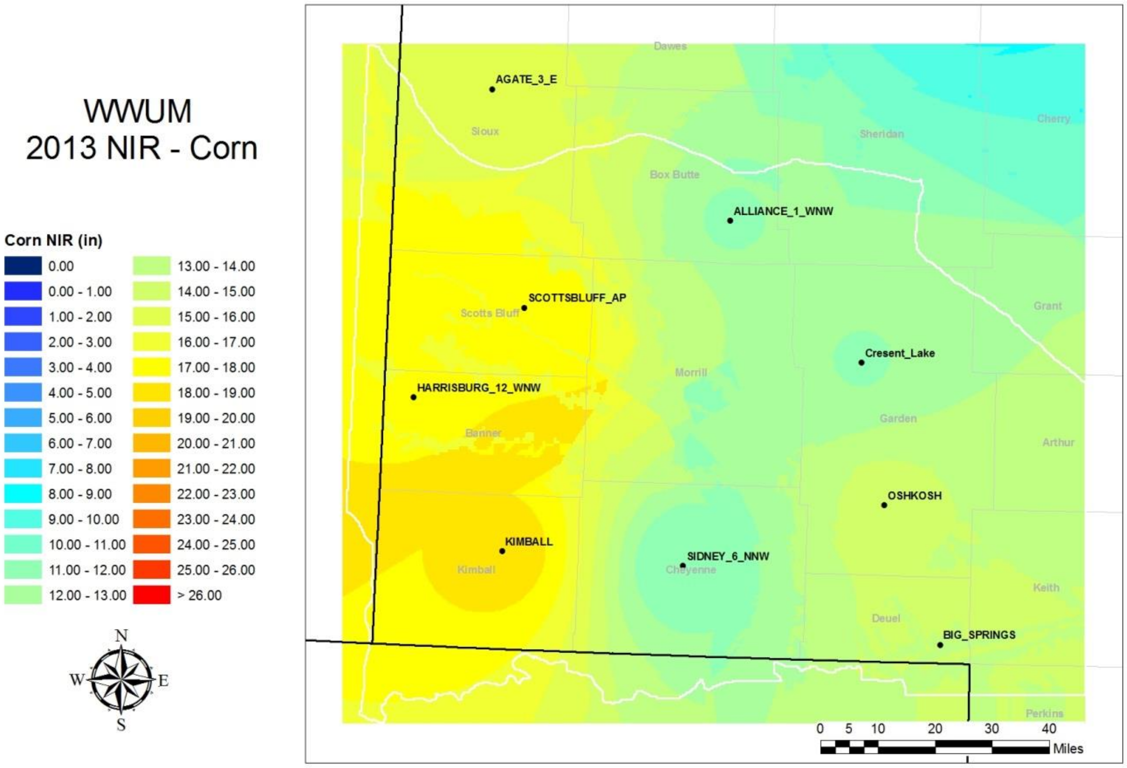


Figure 6. Annual 2013 net irrigation requirement - corn (in).

3.2. Climate 2014

The creation of the climate files occurred (January 2014) prior to the defined end of the simulation period (April 2014). This necessitated the creation of an estimate for the climatic conditions during the 2014 year. Previous professional experience creating estimates of average conditions had shown that simply using the average values from the existing spatially distributed water balance parameters tended to skew recharge and runoff to the high side and distort the water balance.

Table 1. Median precipitation for estimating average conditions at WWUM weather stations.

Station	Code	Median Precipitation Year
Agate 3E	AGAT	1972
Alliance 1WNW	ALI1	1993
Big Springs	BIGS	2010
Chadron 1NW	CHAD	1968
Crescent Lake	CRSC	1983
Gordon 6 N	GORD	1954
Harrison	HARR	2003
Harrisburg 12 WNW	HRSB	1962
Kimball	KMBL	1993
Oshkosh	OSHK	1988
Scottsbluff AP	SCTB	1977
Sidney 6NNW	SDN6	1962

Methodology was developed to use the results from the median precipitation year at each weather station. These results were then combined spatially using the same inverse weighted distance technique depicted in section 5.4 of the RSWB documentation [1]. The data years used for this process listed in Table 1 and the resultant precipitation and corn NIR is shown in Figures 7 – 8. The effect of this is that model did not realize the same variability as using the historical record. Rather, the effect of a normal amount precipitation was used to estimate watershed reactions for the final four months of the simulation. Historical conditions in 2014 tended to be wetter than normal. This probably caused the RSWB to under predict recharge in the region. The effect on pumping was minimal as the simulation ended prior to the typical irrigation season.

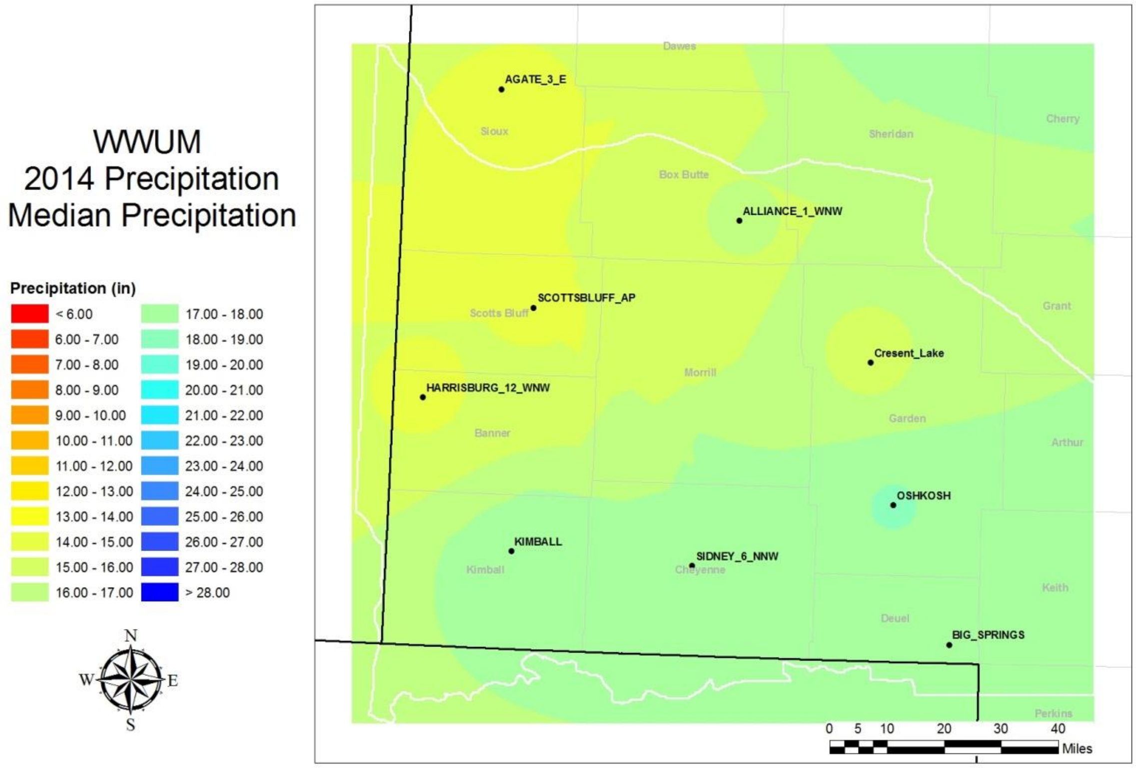


Figure 7. Annual 2014 precipitation (in) using median precipitation conditions.

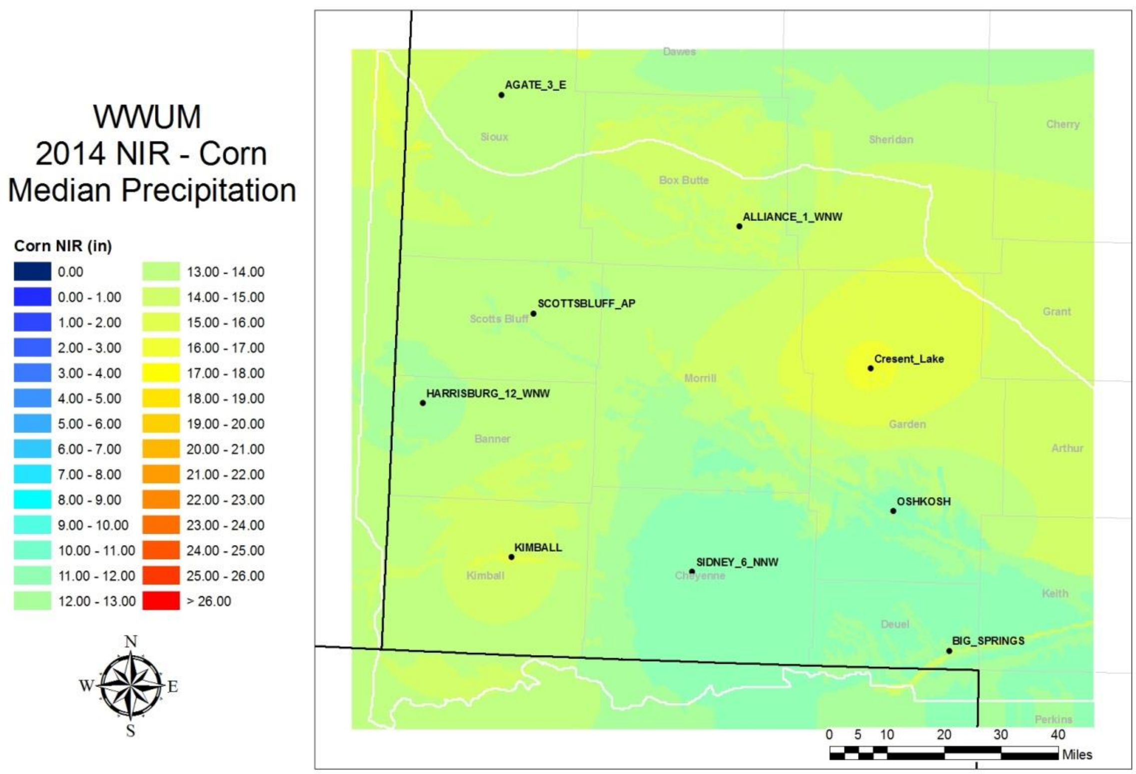


Figure 8. Annual 2014 net irrigation requirement - corn (in) using median precipitation conditions.

4. Operational Regions

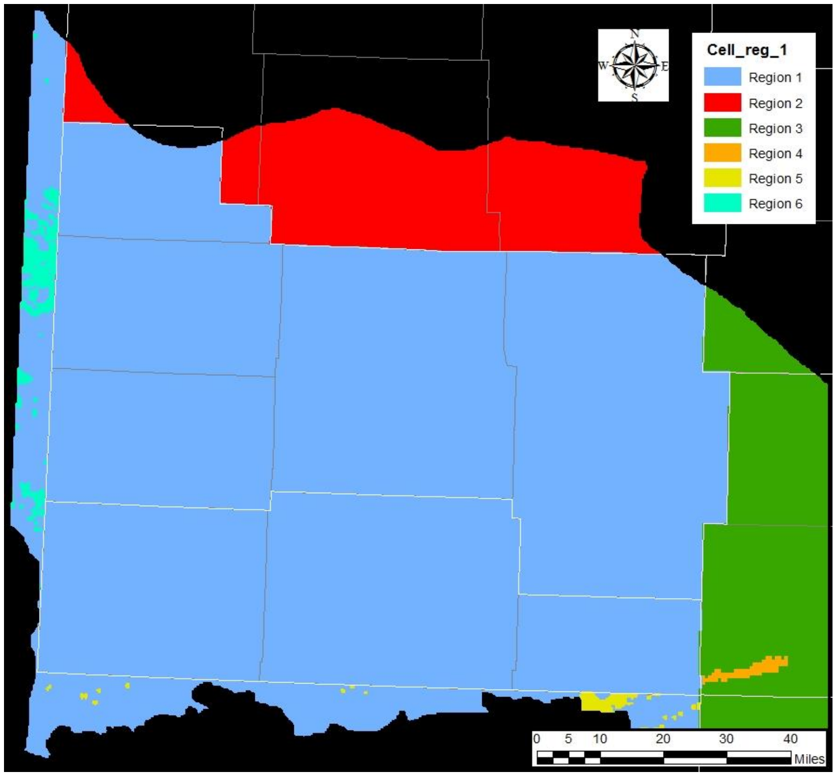


Figure 9. Operational regions in the WWUM model.

4.1. Region 1

Region 1 is the active area in the WWUM domain located in the NPNRD or SPNRD. Region 1 also includes the dryland portion of Colorado and Wyoming within the active WWUM domain. For more information on region 1 see Section 5.5 of the RSWB documentation [1].

The following changes were made to Region 1:

- New parcel land use for dryland and irrigated areas was developed by ARI and provided to TFG fro 2011-2013. This information was overlaid with the model grid to create the parcel land use files for each year, with the remaining area being assigned dryland pasture. The parcel land use was then converted to the cell land use format. The 2014 land use files were copied from 2013.
    - The land use files for the extension included a new category to the model, irrigated fallow
- During the extension, the issue with high pumping volumes was also addressed. Higher than expected pumping rates on alfalfa, irrigated pasture, and small spring grains in the original model were lowered by changing the NIR adjustment factor. Iterative testing found that moving the value from 0.95 to 0.80 brought the estimated pumping volumes for these crops closer to field observations and metered data. These changes were made to coefficient zones 1-6.
- With the new identified NIR target and land use, the parcel NIR was calculated for the years 2011-2013 and provided to the ARI and WWG.

- New volumes of surface water deliveries and comingled pumping were provided by WWG and ARI at the headgate and certificate level respectively. This information was divided among the parcels serviced by the headgate or certificate as described in section 5.5 of the RSWB documentation [1].
    - This information was developed for the SPNRD and NPNRD separately. For the NPNRD, the Pumpkin Creek area parcels were included in the same file as the rest of the NPNRD rather than being provided in a separate file.
- New metered pumping data for the extension was provided by NPRND and SPNRD
    - The metered pumping data set included the application of irrigation water on fallow
- In addition to the extension period, metered pumping volumes for the years 2007-2008 in SPNRD were also incorporated.
- Adjusted the methodology for distributing metered pumping to account for non-irrigation season pumping
- All irrigation was simulated in 2014. This approach was adopted as the irrigation season typically would occur after the end of the modeled period.
- New canal recharge was developed by WWG and incorporated into the .RCH file.

4.2. Regions 2-6

Regions 2-6 are comprised of the Upper Niobrara White NRD, Western COHYST region, Western Canal in the Twin Platte NRD, Colorado irrigated cells, and Wyoming irrigated lands respectively. More information is available in section 5.5 of the RSWB documentation [1] describing details for these areas.

For each of these areas, the pumping and recharge files were copied from existing files from 2000-2010. The representative year was chosen based upon the relative amount of precipitation which occurred in each year, with 2014 being chosen to be represented by an average year. Table 2 shows the years which were copied as representative years for the extension. These areas tend to be on the periphery of the model domain and are not expected to have a significant influence on results for region 1.

Table 2. Regions 2-6 representative years

Simulation Year	Representative Year
2011	2010
2012	2002
2013	2004
2014	2004

5. Results

This section presents selected results from the updated and extended RSWB model. Table 3 provides an overall summary of key water balance terms; both as the depth over the entire model domain and as a percentage of total applied water. Tables 4-7 provide additional detail for the parameters listed on Table 3.[2]

Table 3. Long term water balance results for the WWUM model regions 1-3.

Parameter	Depth (in)	Percent of Total Available Water
Precipitation	16.40	90.9%
Ground Water Application†	NA	4.1%
Surface Water Application†	NA	5.0%
Total Applied Water†	**NA**	**100.0%**
Total ET	16.00	88.7%
Direct ET	**15.70**	**87.0%**
Indirect ET	0.30	1.7%
Total Recharge	1.34	7.4%
Direct Recharge	**1.18**	**6.5%**
Indirect Recharge	0.16	0.9%
Runoff	**1.14**	**6.3%**
Runoff Contributions to Streamflow	0.68	3.8%
Change in Soil Water Content	**0.03**	**0.1%**

†The depth of applied irrigation is not reported as the results in Table 3 are on model wide basis which includes unirrigated areas. Presenting the depth over this area would prove counter-productive. However, the depth of irrigation on ground water only lands can be seen in Table 5.
Bold terms indicate the field water balance
Underlined terms indicate the final partitioned balance

[2] The results were derived from WWUM Run028.

Table 4. Annual average precipitation for counties in the WWUM model domain (in).

Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
1953	18.59	16.44	14.05	17.84	18.59	17.83	17.77	18.68	19.11	15.04	18.56	13.96	14.63	15.07
1954	12.99	13.36	12.06	12.98	13.00	12.60	12.68	13.00	13.66	11.39	12.94	13.98	11.81	13.75
1955	15.99	18.17	16.14	18.68	16.32	16.15	15.80	16.13	18.27	17.54	16.11	17.90	15.85	18.05
1956	14.85	13.18	14.31	12.42	15.59	13.99	14.81	15.68	13.43	11.83	16.16	11.43	14.57	12.47
1957	19.76	24.15	21.89	22.99	19.26	20.26	20.17	19.09	26.90	20.79	18.78	22.27	21.41	21.68
1958	21.81	15.39	14.61	20.42	21.93	20.96	20.54	22.09	19.44	18.44	21.96	14.29	15.71	14.81
1959	15.15	13.67	18.03	13.86	16.12	14.76	15.61	16.13	16.95	15.01	16.79	13.58	17.63	16.59
1960	14.07	11.35	12.66	13.45	13.74	13.99	14.00	13.82	14.47	12.73	13.68	9.78	13.34	11.43
1961	21.46	17.09	16.07	20.46	20.83	20.99	20.75	21.01	22.89	17.94	20.63	14.33	17.03	14.51
1962	19.18	17.23	16.40	18.12	18.08	19.52	18.83	18.30	19.03	19.12	17.76	17.30	16.63	18.31
1963	17.38	13.93	19.99	17.02	17.52	17.38	18.12	17.45	15.91	16.66	17.68	14.28	20.67	14.68
1964	10.43	9.66	8.85	11.46	11.06	10.43	10.09	10.98	10.83	11.84	11.18	8.37	9.92	8.76
1965	24.58	19.90	21.10	23.89	22.53	25.25	24.49	22.71	18.97	23.08	21.67	19.69	22.45	19.39
1966	17.74	14.13	15.19	18.11	18.08	17.24	17.41	18.04	18.60	15.63	18.12	12.23	16.43	12.00
1967	17.18	16.50	18.83	17.79	15.88	17.82	17.78	15.90	17.74	16.98	15.34	16.37	19.16	17.46
1968	17.59	13.36	16.93	18.56	15.16	18.63	18.11	15.22	15.09	16.51	14.04	12.88	18.21	13.68
1969	18.21	14.14	15.22	16.92	17.96	17.70	17.90	18.04	15.16	14.91	17.89	13.70	16.12	12.74
1970	14.67	12.14	14.75	18.06	15.45	14.32	14.60	15.09	14.26	13.54	15.24	11.76	15.18	12.15
1971	19.22	15.76	17.73	16.40	20.05	18.23	18.87	20.14	14.57	16.19	20.61	16.76	17.83	17.32
1972	17.90	15.93	18.06	16.80	17.06	17.92	18.08	17.17	16.27	16.29	16.84	18.39	17.82	17.26
1973	20.04	18.48	21.02	17.46	19.81	20.38	20.54	20.04	20.45	21.36	20.20	17.94	21.72	18.22
1974	10.78	9.59	12.64	11.31	10.53	10.87	11.29	10.47	12.06	9.95	10.42	8.90	12.84	10.11
1975	17.44	12.45	12.62	14.52	19.41	15.53	16.35	19.47	13.84	12.63	20.37	12.23	13.33	10.87
1976	12.48	11.03	14.08	10.31	11.98	12.90	13.16	12.16	12.01	13.10	12.18	10.13	14.78	11.07
1977	17.80	14.45	17.89	16.04	19.19	16.68	17.71	19.15	14.97	14.83	19.90	14.69	18.32	15.35

Table 4. Annual average precipitation for counties in the WWUM model domain (in).

Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
1978	14.98	16.17	21.33	16.39	13.84	16.60	16.48	13.80	17.55	20.01	13.50	18.14	21.03	17.87
1979	18.35	16.71	18.89	18.24	18.35	18.39	18.70	18.33	18.46	18.13	18.42	16.42	19.68	14.31
1980	13.80	11.63	11.44	11.30	15.27	12.67	13.12	15.37	12.60	12.02	16.10	11.66	11.48	12.34
1981	19.85	16.77	15.37	18.63	19.53	19.08	19.22	19.65	19.47	15.26	19.42	14.64	16.26	13.78
1982	19.67	21.08	18.76	18.19	20.67	19.46	19.26	20.80	22.49	21.96	21.34	21.12	18.60	20.92
1983	18.22	17.43	16.55	16.82	17.68	18.29	18.10	17.84	17.29	17.54	17.62	16.47	17.17	16.43
1984	14.77	16.11	13.50	12.83	15.36	14.33	14.51	15.49	15.79	14.28	15.85	14.40	13.85	14.15
1985	17.75	13.95	12.97	14.21	17.04	17.04	17.19	17.37	16.41	13.11	17.10	12.40	13.71	11.92
1986	16.11	19.78	16.84	17.37	14.65	16.90	16.29	14.69	18.32	17.26	13.94	20.98	16.37	19.81
1987	19.91	18.19	16.34	17.80	21.10	18.90	19.02	21.22	18.80	18.78	21.75	20.54	16.13	16.36
1988	17.40	16.02	13.66	17.31	17.38	17.09	16.74	17.43	17.57	16.25	17.30	15.23	14.51	13.80
1989	10.98	12.91	9.45	12.62	12.15	10.21	10.41	11.99	16.21	9.80	12.39	10.55	9.52	10.44
1990	13.83	18.58	15.68	17.65	14.17	14.44	14.03	13.95	22.26	17.74	14.01	17.18	15.67	15.72
1991	16.31	13.78	13.12	13.61	15.78	15.90	15.74	16.02	11.95	13.69	15.77	14.53	13.36	15.95
1992	21.59	15.92	13.71	17.56	20.35	21.10	20.50	20.79	16.74	17.44	20.15	15.58	15.05	14.05
1993	21.89	19.16	17.91	20.62	21.13	21.61	21.08	21.30	17.96	19.86	20.80	22.44	17.76	20.92
1994	18.54	13.42	13.31	17.24	15.99	18.76	18.01	16.25	12.68	14.33	14.90	14.98	13.72	13.90
1995	19.85	17.82	19.03	19.75	19.12	20.27	19.96	19.15	16.17	19.97	18.79	17.61	20.04	17.87
1996	19.57	15.47	19.93	18.49	21.63	18.48	19.53	21.48	15.77	18.03	22.53	16.02	20.90	15.00
1997	16.22	19.99	15.33	18.36	15.66	16.28	15.94	15.60	21.97	15.74	15.17	19.57	15.17	17.80
1998	17.18	18.95	18.99	18.74	16.88	18.07	17.70	16.82	20.16	20.67	16.71	17.71	19.85	17.29
1999	16.62	15.78	16.69	18.00	17.75	16.66	16.42	17.59	16.11	19.37	18.04	16.36	17.15	16.75
2000	16.01	14.28	18.66	14.45	16.02	16.09	16.66	16.09	15.16	15.93	16.31	14.50	19.05	16.13
2001	18.36	14.22	15.73	20.90	18.55	18.47	18.00	18.34	14.89	18.60	18.18	13.51	17.35	12.61
2002	10.37	9.32	6.79	10.30	12.88	9.08	9.20	12.73	7.64	9.91	13.72	8.79	7.23	8.62
2003	14.64	16.04	13.27	15.47	13.70	15.51	14.65	13.78	17.09	16.93	13.30	12.77	14.35	13.75
2004	18.61	16.16	17.22	17.00	19.01	18.47	18.60	19.11	17.56	18.50	19.40	13.64	18.54	14.03

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Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
2005	17.84	21.63	19.42	21.37	15.74	19.50	18.47	15.65	20.52	21.03	14.55	20.67	19.61	19.52
2006	14.42	14.60	11.33	14.51	13.92	14.88	14.00	14.00	12.10	15.99	13.65	13.56	12.41	11.85
2007	18.12	13.26	10.41	17.51	19.14	16.90	16.62	19.17	15.55	14.62	19.38	10.66	11.87	10.36
2008	18.20	14.82	13.99	16.27	18.62	17.87	17.52	18.75	13.15	17.88	18.90	14.76	15.44	13.05
2009	23.69	21.00	20.55	26.20	25.00	23.28	22.87	24.74	21.56	24.28	25.07	20.14	21.28	20.85
2010	19.10	17.44	19.70	19.33	18.08	20.25	19.64	18.16	18.54	22.23	17.77	16.57	20.95	16.84
2011	20.12	19.07	19.66	22.72	21.79	19.44	19.06	21.15	18.01	19.03	21.61	19.12	20.89	18.30
2012	7.36	6.89	6.79	9.81	7.92	7.52	7.84	7.61	8.21	8.21	7.96	6.45	7.24	6.46
2013	17.33	15.88	17.22	22.47	19.76	16.93	16.81	18.72	15.53	18.01	19.51	14.89	18.52	15.29
Ave.	17.13	15.60	15.75	16.98	17.16	17.00	16.94	17.16	16.61	16.49	17.15	15.11	16.31	14.96

Table 5. Average depth of ground water pumped per county on ground water only lands (in)‡.

Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
1953	20.53	23.70	0.12	19.67	20.79	20.58	-	20.64	18.12	22.01	-	21.84	-	22.41
1954	24.90	26.10	0.15	22.98	25.22	25.98	-	25.62	24.07	28.57	-	22.39	-	25.09
1955	26.50	24.33	0.13	21.33	23.38	26.46	-	24.94	24.12	25.47	-	21.43	-	22.72
1956	24.33	26.60	0.11	23.99	22.98	24.17	-	22.90	23.99	24.94	-	24.63	-	25.17
1957	19.00	15.28	0.09	14.36	17.22	18.13	-	17.60	12.49	18.40	13.46	16.33	-	16.27
1958	15.14	24.61	0.11	15.85	13.88	14.17	-	13.82	18.11	20.14	10.17	21.76	-	23.20
1959	26.67	29.68	0.12	23.70	22.29	25.64	-	21.59	23.54	27.75	17.54	25.62	-	26.02
1960	26.35	31.38	21.83	23.77	23.62	25.16	-	22.39	24.44	26.91	18.60	27.28	23.33	28.79
1961	18.98	24.65	20.83	17.11	19.98	18.50	-	18.84	16.16	24.63	15.52	23.28	23.28	23.52
1962	21.26	21.57	20.38	17.52	18.04	18.54	-	17.16	17.81	18.63	13.69	19.56	21.11	20.38
1963	28.42	29.18	19.84	23.91	26.69	26.40	-	25.30	24.41	28.04	21.25	24.34	23.41	25.38
1964	31.15	32.59	26.67	25.97	25.41	27.36	-	24.43	26.92	26.69	19.60	29.51	28.57	30.39
1965	19.01	18.47	16.75	16.76	17.80	15.25	-	17.03	19.67	18.45	13.19	16.37	14.27	15.96
1966	20.92	25.98	17.45	16.44	13.17	17.52	-	13.70	18.64	19.93	10.84	22.11	17.97	23.86
1967	23.78	19.10	17.73	19.18	22.03	21.02	-	20.57	18.62	22.29	16.05	19.71	18.40	19.86
1968	23.44	24.57	18.73	19.20	22.33	20.84	-	22.10	21.84	22.35	19.04	24.29	17.78	25.40
1969	22.81	26.45	21.37	22.57	19.44	21.69	-	18.60	23.43	26.05	14.30	25.89	22.68	28.80
1970	26.87	26.20	20.29	18.36	21.44	24.99	-	20.77	20.22	25.92	16.17	24.83	23.56	26.94
1971	23.03	19.91	17.76	22.59	20.64	21.83	-	20.07	22.29	23.73	16.93	20.14	21.39	20.74
1972	21.43	21.22	16.96	18.93	16.91	18.86	-	18.02	18.48	21.15	15.12	17.87	18.29	19.45
1973	25.96	21.48	18.53	20.76	19.78	22.31	-	20.73	17.43	20.44	18.13	20.33	22.27	21.12
1974	32.54	28.47	19.92	25.26	21.52	26.40	22.79	23.14	21.31	25.01	19.70	25.65	23.22	27.63
1975	23.85	25.92	25.43	23.91	17.38	23.14	18.61	18.39	22.86	27.38	15.36	27.42	24.97	28.73
1976	25.03	25.01	20.58	28.16	20.91	23.60	20.00	21.57	22.10	24.21	19.39	25.82	21.03	25.94
1977	20.15	21.41	16.81	19.70	14.07	20.96	15.52	14.71	18.09	22.95	12.70	21.49	16.78	23.11

Table 5. Average depth of ground water pumped per county on ground water only lands (in)‡.

Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
1978	26.31	21.37	16.67	22.77	22.00	25.99	20.09	22.43	17.83	20.97	19.82	18.80	18.20	19.71
1979	18.88	19.32	13.34	19.81	15.39	17.35	15.01	15.32	15.75	18.09	13.88	17.96	15.88	21.19
1980	23.66	24.10	22.88	22.06	16.09	21.99	20.08	15.51	19.70	23.21	14.41	23.90	26.79	24.57
1981	16.85	18.44	17.19	15.49	13.37	14.40	14.80	13.41	12.36	20.00	12.78	19.72	19.70	20.85
1982	15.78	13.71	15.11	13.32	11.94	13.95	12.64	11.85	10.51	12.81	10.68	15.09	17.70	15.82
1983	17.20	17.82	16.40	16.22	14.75	15.19	14.60	14.07	15.26	17.35	13.60	20.32	19.01	19.33
1984	20.63	17.44	18.37	18.94	16.32	19.60	17.68	15.97	16.37	18.42	15.35	19.26	19.62	19.16
1985	20.39	24.32	23.92	21.00	17.54	19.59	18.86	16.99	17.62	24.34	16.89	27.93	24.13	27.89
1986	21.21	16.85	18.84	16.82	17.29	18.75	18.47	17.18	15.79	18.11	16.54	16.33	22.51	17.64
1987	17.72	18.90	20.59	16.89	13.29	16.85	15.14	13.14	13.79	17.19	12.30	18.89	24.03	21.17
1988	19.63	20.79	22.16	17.07	14.94	18.27	17.21	14.35	17.20	18.40	13.70	22.44	24.34	24.12
1989	23.13	24.03	27.86	20.53	16.74	24.48	21.10	15.77	17.79	24.35	15.32	26.38	29.40	26.01
1990	22.19	18.62	19.26	14.73	17.14	21.08	18.27	16.46	11.45	17.15	15.72	19.27	20.77	20.58
1991	18.69	20.31	22.12	15.38	15.72	18.23	14.33	14.79	20.45	17.35	13.82	21.45	23.45	19.62
1992	13.33	18.46	21.37	12.47	8.34	11.12	10.24	7.95	13.94	13.63	6.64	19.14	21.85	20.51
1993	12.71	13.38	18.07	9.23	9.35	9.74	11.02	9.28	14.19	12.57	8.72	14.50	20.87	13.35
1994	18.53	17.52	21.65	13.28	14.50	16.01	16.42	14.31	20.43	16.93	13.22	21.13	24.08	20.11
1995	15.67	15.16	19.03	13.64	12.72	14.00	13.89	13.02	18.02	14.53	11.90	18.92	20.09	17.08
1996	11.66	15.40	14.99	12.35	7.74	12.10	11.11	7.35	16.44	14.19	6.83	18.59	16.22	17.31
1997	14.50	13.30	18.95	11.20	11.06	12.78	12.58	11.38	13.63	14.57	10.03	16.19	19.88	15.40
1998	17.90	14.25	19.04	11.23	12.97	14.40	16.05	13.03	13.48	13.56	11.71	19.59	19.45	18.38
1999	14.52	13.84	16.83	9.11	11.01	12.16	15.53	11.11	12.93	10.73	10.09	16.24	17.67	14.44
2000	26.02	20.38	21.28	17.39	19.21	20.23	26.21	19.09	19.92	19.69	17.72	24.76	23.17	22.19
2001	21.17	17.87	16.64	11.18	14.24	14.60	23.01	14.67	18.46	15.16	13.31	19.65	19.07	20.27
2002	28.90	22.33	30.23	18.26	17.62	20.96	31.03	17.69	24.84	22.07	16.12	26.37	31.48	26.94
2003	24.16	16.49	24.78	14.49	16.10	16.93	26.51	16.52	16.86	16.58	15.17	22.91	26.07	22.43

Table 5. Average depth of ground water pumped per county on ground water only lands (in)‡.

Year	Arthur	Banner	Box Butte	Cheyenne	Deuel	Garden	Grant	Keith	Kimball	Morrill	Perkins	Scotts Bluff	Sheridan	Sioux
2004	20.17	16.87	21.37	13.06	13.08	15.44	23.77	13.05	15.87	16.25	11.87	22.58	22.56	22.91
2005	19.02	12.43	17.42	11.65	15.84	13.58	20.92	15.38	13.86	12.90	14.35	17.21	19.78	17.02
2006	22.38	17.03	23.97	15.67	17.72	18.28	-	17.20	17.77	18.05	-	22.57	25.39	23.56
2007	17.12	19.28	24.32	12.50	10.92	15.09	-	10.98	15.75	17.51	-	24.70	26.02	24.75
2008	17.43	16.02	21.26	12.25	13.05	15.69	-	13.44	15.26	14.51	-	20.00	21.21	20.80
2009	13.69	10.09	13.61	6.90	9.50	9.88	-	11.01	8.62	9.41	-	13.00	15.03	13.33
2010	15.30	9.75	15.68	9.06	11.82	10.98	-	11.25	9.71	10.89	-	9.90	17.87	13.90
2011	15.10	10.77	15.69	8.01	10.64	10.49	-	10.61	11.06	11.40	-	13.06	17.87	12.15
2012	31.32	17.44	30.23	16.49	19.62	20.65	-	25.57	17.07	20.02	-	20.09	31.48	20.36
2013	19.62	12.37	21.37	11.09	13.86	13.93	-	16.47	11.32	13.60	-	15.57	22.56	14.60
Ave.	20.91	20.35	17.45	17.22	16.73	18.64	9.72	16.61	17.83	19.58	12.02	20.99	18.87	21.55

‡These depths include the results of both simulated and metered pumping for the domain of the WWUM. Metered data from the SPNRD was included for the years 2007 through 2013. Metered data from the NPNRD was included for the years 2009-2013. For years when metered data was available, fields which did not have a defined volume of applied ground water were simulated.

Table 6. Annual field water balance results for the WWUM model domain (AF).

Year	Precipitation	Surface Water	Ground Water	Total Applied Water	Direct ET	Direct DP	Direct RO	Surface Losses	Soil Water Balance
1953	9,842,768	560,124	60,638	10,463,530	9,199,541	419,731	747,073	30,694	66,492
1954	7,528,915	446,010	97,667	8,072,592	7,746,768	260,615	475,837	26,705	(437,332)
1955	10,153,235	422,024	100,617	10,675,877	8,985,701	380,212	763,845	25,647	520,471
1956	7,849,324	487,814	84,581	8,421,719	8,036,111	271,067	497,466	28,176	(411,101)
1957	12,880,473	511,752	57,553	13,449,778	10,609,035	1,312,334	1,174,970	28,071	325,367
1958	10,849,711	552,144	70,723	11,472,578	10,215,761	714,660	686,859	30,848	(175,550)
1959	8,990,724	539,691	119,215	9,649,630	8,193,183	367,702	508,363	32,418	547,964
1960	7,600,683	525,769	168,751	8,295,203	8,140,945	421,190	473,802	33,228	(773,962)
1961	11,115,187	444,838	159,695	11,719,720	9,480,379	916,717	849,712	28,703	444,208
1962	10,728,273	484,080	133,852	11,346,204	9,591,302	1,189,358	725,773	29,238	(189,466)
1963	9,772,674	572,877	194,515	10,540,065	8,690,995	587,472	585,301	36,567	639,729
1964	6,101,201	596,476	227,881	6,925,559	6,907,700	443,425	489,227	38,856	(953,649)
1965	13,007,406	498,898	137,024	13,643,327	10,221,601	1,134,609	913,107	30,149	1,343,861
1966	9,504,100	594,184	153,702	10,251,987	9,518,740	697,059	692,882	35,617	(692,312)
1967	10,169,610	500,955	175,465	10,846,029	9,409,272	989,331	624,410	31,542	(208,526)
1968	9,509,596	564,851	220,525	10,294,971	8,786,846	611,813	681,096	36,762	178,455
1969	9,300,875	617,403	258,668	10,176,946	8,660,891	462,538	615,739	40,773	397,004
1970	8,413,875	601,474	258,997	9,274,346	8,562,004	663,094	647,697	39,764	(638,213)
1971	10,073,276	545,217	256,675	10,875,168	9,386,707	521,299	613,793	36,890	316,479
1972	10,018,801	553,267	231,321	10,803,389	9,080,217	455,913	592,571	35,887	638,802
1973	11,524,046	587,714	271,117	12,382,877	9,910,034	1,120,384	740,867	38,927	572,666
1974	6,318,089	620,782	363,252	7,302,122	7,670,773	437,739	533,284	44,053	(1,383,726)
1975	8,343,910	623,104	429,307	9,396,321	8,107,234	380,289	597,765	46,122	264,911
1976	7,074,382	621,496	477,607	8,173,484	7,460,212	389,389	570,648	47,910	(294,675)
1977	9,510,361	566,661	404,970	10,481,992	9,153,777	435,183	663,428	42,444	187,160

Table 6. Annual field water balance results for the WWUM model domain (AF).

Year	Precipitation	Surface Water	Ground Water	Total Applied Water	Direct ET	Direct DP	Direct RO	Surface Losses	Soil Water Balance
1978	10,160,704	532,433	427,003	11,120,139	9,213,017	562,124	677,304	40,911	626,783
1979	10,448,485	550,288	358,345	11,357,118	9,813,616	525,523	616,263	39,522	362,193
1980	7,283,255	599,061	493,275	8,375,591	7,966,887	618,155	530,684	46,096	(786,231)
1981	10,210,161	536,495	406,289	11,152,944	9,528,664	506,709	683,834	39,841	393,895
1982	11,918,813	501,994	338,692	12,759,499	10,594,577	724,493	938,870	33,960	467,599
1983	10,178,419	589,272	422,111	11,189,803	9,309,120	1,238,063	763,808	40,737	(161,926)
1984	8,521,398	614,949	527,693	9,664,040	8,724,094	541,080	617,437	43,481	(262,052)
1985	8,677,695	659,516	665,143	10,002,355	7,913,305	448,393	623,779	49,514	967,363
1986	10,333,813	570,285	520,964	11,425,062	10,266,965	1,030,398	894,419	40,785	(807,505)
1987	10,872,921	502,028	521,045	11,895,994	10,154,492	693,793	720,638	37,561	289,510
1988	9,563,304	580,935	575,614	10,719,853	9,185,021	913,904	920,427	42,881	(342,381)
1989	6,764,238	535,763	747,137	8,047,138	6,785,033	303,043	588,592	45,575	324,895
1990	9,832,267	415,897	574,904	10,823,067	9,845,741	475,764	575,437	35,164	(109,038)
1991	8,445,302	476,744	642,802	9,564,847	8,551,305	459,219	602,317	40,293	(88,287)
1992	10,318,834	439,290	519,082	11,277,206	9,684,051	637,202	658,786	34,684	262,483
1993	11,849,628	461,196	433,596	12,744,420	10,822,741	635,719	649,398	32,396	604,166
1994	9,039,059	574,410	606,281	10,219,750	8,598,771	883,660	617,052	42,392	77,875
1995	11,123,735	493,864	548,605	12,166,204	9,833,856	2,468,726	881,963	37,185	(1,055,525)
1996	10,558,407	567,886	468,839	11,595,132	9,591,065	600,645	696,422	38,538	668,461
1997	10,292,084	540,453	509,690	11,342,227	9,641,178	981,070	937,851	36,192	(254,064)
1998	10,943,994	578,421	540,673	12,063,088	10,249,364	592,418	606,704	38,862	575,740
1999	10,055,165	522,554	466,627	11,044,347	10,194,933	1,052,695	691,125	34,429	(928,836)
2000	9,242,687	628,279	743,056	10,614,022	8,554,280	659,202	684,497	46,023	670,021
2001	9,991,995	551,265	596,291	11,139,551	9,454,654	949,130	621,448	36,535	77,783
2002	5,525,196	427,851	972,784	6,925,831	6,270,326	354,882	468,398	40,714	(208,489)
2003	8,909,484	413,600	815,102	10,138,185	9,434,753	549,766	564,301	36,505	(447,141)

Table 6. Annual field water balance results for the WWUM model domain (AF).

Year	Precipitation	Surface Water	Ground Water	Total Applied Water	Direct ET	Direct DP	Direct RO	Surface Losses	Soil Water Balance
2004	10,162,687	381,530	765,020	11,309,237	9,949,669	352,126	573,813	34,227	399,402
2005	11,643,804	431,000	621,841	12,696,645	10,632,622	1,039,105	785,709	31,070	208,139
2006	8,165,683	490,645	817,578	9,473,906	8,591,961	380,925	533,465	38,056	(70,500)
2007	8,794,627	475,046	765,376	10,035,049	8,884,655	793,688	597,233	36,250	(276,777)
2008	9,438,955	481,515	680,240	10,600,710	9,727,161	395,671	602,040	34,334	(158,496)
2009	13,460,118	476,567	421,279	14,357,964	11,787,550	1,162,957	853,149	27,924	526,384
2010	11,233,134	523,557	474,779	12,231,471	10,557,038	1,753,283	830,510	29,709	(939,068)
2011	11,631,786	560,309	478,211	12,670,306	11,527,046	640,225	702,067	30,589	(229,622)
2012	4,534,642	644,968	874,202	6,053,812	5,595,020	294,994	399,942	41,044	(277,188)
2013	10,351,719	460,284	626,824	11,438,827	9,500,113	363,496	735,760	29,410	810,049
Ave.	9,617,372	531,635	427,562	10,576,570	9,158,367	691,236	670,671	36,711	19,585

Column Notes:

Surface Water is the gross volume of surface water applied at the farm head gate as irrigation
Ground Water is the gross volume of water pumped for irrigation
Total Applied Water is the sum of precipitation, surface water, and ground water
Direct ET is the estimate of evapotranspiration from applied water; it does not consider evapotranspiration related to transmission losses[3]
Direct DP is the estimate of recharge resulting from applied water; it does not consider recharge from transmission losses[3]
Direct RO is the estimate of runoff at the field boundaries
Surface Losses evaporative losses related to the application of irrigation
Soil Water Balance is the change in soil water moisture content

[3] Transmission losses refer to volumes of water which originate as runoff but do not become streamflow.

Table 7. Annual runoff balance (AF).

Year	Direct Runoff	Indirect Recharge	Indirect ET	Runoff Contributions to Streamflow
1953	747,073	95,627	210,805	440,641
1954	475,837	62,830	120,112	292,895
1955	763,845	97,241	227,459	439,145
1956	497,466	67,424	124,520	305,522
1957	1,174,970	146,335	378,634	650,001
1958	686,859	89,810	179,425	417,624
1959	508,363	68,856	128,054	311,453
1960	473,802	66,321	116,451	291,029
1961	849,712	106,950	281,576	461,187
1962	725,773	96,405	195,698	433,670
1963	585,301	86,976	136,906	361,420
1964	489,227	65,369	117,745	306,113
1965	913,107	118,741	254,433	539,932
1966	692,882	90,363	188,604	413,915
1967	624,410	90,709	159,240	374,461
1968	681,096	90,568	172,101	418,427
1969	615,739	82,462	150,669	382,607
1970	647,697	86,366	170,501	390,831
1971	613,793	88,356	141,847	383,591
1972	592,571	83,209	136,037	373,325
1973	740,867	105,400	192,819	442,647
1974	533,284	73,177	129,960	330,147
1975	597,765	77,950	158,698	361,117
1976	570,648	82,795	133,749	354,105
1977	663,428	89,577	172,255	401,596
1978	677,304	103,165	166,862	407,276
1979	616,263	91,714	150,727	373,822
1980	530,684	74,923	129,507	326,255
1981	683,834	94,797	186,538	402,499
1982	938,870	128,833	237,319	572,719
1983	763,808	112,025	197,354	454,429
1984	617,437	87,927	150,616	378,894
1985	623,779	88,311	153,630	381,838
1986	894,419	123,917	230,406	540,095
1987	720,638	106,394	178,613	435,631
1988	920,427	127,857	262,424	530,146
1989	588,592	80,330	179,546	328,717

Table 7. Annual runoff balance (AF).

Year	Direct Runoff	Indirect Recharge	Indirect ET	Runoff Contributions to Streamflow
1990	575,437	88,238	159,524	327,675
1991	602,317	92,634	148,432	361,250
1992	658,786	96,993	179,152	382,641
1993	649,398	97,716	156,124	395,557
1994	617,052	91,141	145,032	380,878
1995	881,963	121,708	252,402	507,852
1996	696,422	101,425	175,306	419,691
1997	937,851	126,731	280,414	530,705
1998	606,704	95,262	146,370	365,072
1999	691,125	104,662	166,812	419,651
2000	684,497	105,098	178,428	400,971
2001	621,448	95,673	148,372	377,404
2002	468,398	73,210	118,326	276,862
2003	564,301	91,819	143,882	328,600
2004	573,813	95,734	143,657	334,422
2005	785,709	126,014	203,358	456,337
2006	533,465	87,602	121,565	324,298
2007	597,233	90,769	158,290	348,174
2008	602,040	97,099	140,341	364,600
2009	853,149	123,684	230,941	498,525
2010	830,510	128,819	221,627	480,064
2011	702,067	115,835	165,316	420,916
2012	399,942	66,462	90,394	243,086
2013	735,760	110,568	207,331	417,861
Ave.	670,671	95,982	175,135	399,554

Column Notes:

Direct RO is the estimate of runoff occurring at the field boundaries

The remaining terms present the results of further partitioning of the Direct RO water:

Indirect DP is the volume of transmission loss water resulting in additional recharge

Indirect ET is the volume of transmission loss water resulting in additional evapotranspiration

Runoff contributions to streamflow indicate the portion of Direct RO which results in streamflow at the gauge at the end of the runoff zone

6. References

[1] The Flatwater Group, Inc., "The Western Water Use Model: Regional Soil Water Balance Model," 2016.