Appendix E

Net Irrigation Requirement[1]

Background

The net irrigation water requirement (INET) is the net amount of water that must be applied by irrigation to supplement stored soil water and precipitation and supply the water required for the full yield of an irrigated crop. INET does not include irrigation water that is not available for crop water use such as irrigation water that percolates through the crop root zone or that runs off of the irrigated field. INET as used in this application is the annual amount of water and is expressed in units of acre-inches of water per acre of irrigated land for a year. Since corn is the most widely irrigated crop in Nebraska, the net irrigation requirement was simulated for corn grown on fine sandy loam soil. The soil used in the simulations holds about 1.75 inches of available water per foot of soil depth. The soil used for the simulations represents an average condition of soils across Nebraska.

Procedure

The net irrigation requirement can be computed using several methods. Early methods relied on the difference between the evapotranspiration (ET) required for full crop yields minus the amount of precipitation during the irrigation season that is estimated to be effective in meeting crop water requirements. This method was generally applied on a monthly basis and did not consider precipitation or soil water rewetting during the portion of the year when crops were not growing, or the effects of individual precipitation events. This method has given way to daily calculations of the soil water balance of irrigated crops.

A computer simulation model (CROPSIM) developed at the University of Nebraska-Lincoln by Dr. Derrel Martin was used to compute the daily water balance for irrigated corn and INET for an array of weather stations across the state. Computations with the CROPSIM program for data from selected weather stations were used to generate the map of net irrigation water requirements for corn grown on a fine sandy loam soil.

The CROPSIM model maintains a daily soil water balance including the following terms:

$$D_i = D_{i-1} + ET_c + DP + RO - P - I_{net}$$

where D_i is the available soil water depletion on day i, inches
D_{i-1} is the depletion on the previous day, inches
ET_c is the daily evapotranspiration rate, inches/day
DP is the daily deep percolation from the root zone, inches/day
RO is the daily run off from the irrigated land due to rainfall, inches/day
P is the daily precipitation, inches/day
I_{net} is the net irrigation that is applied on day i, inches/day.

[1] Prepared by Derrel Martin, Professor of Irrigation and Water Resources Engineering, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE. 68583-0726.

The daily soil water depletion is maintained in the model. Irrigations are applied on days when the depletion reaches a specified amount for the crop root zone. Irrigations were applied when more than half of the available water in the top four feet of the root zone was depleted. This is a common management practice used to schedule irrigation. The net irrigation applied each irrigation resembles practices typical of center pivot irrigation. This involved applying a gross irrigation of one inch each application which equaled a net irrigation of 0.85 inches per irrigation. Irrigations did not begin until the corn crop had begun vegetative growth. Irrigations were continued for the year until the corn crop had reached a growth stage where water stress has minimal affects on yield. This stage generally matches a hard-dent growth stage for corn.

The CROPSIM program depends on evapotranspiration (ET) to compute the soil water depletion and determine dates for irrigation. The ET for corn was computed in the model using a reference crop evapotranspiration (ETr) that represents the amount of energy available from the environment to evaporate water. The reference crop evapotranspiration is multiplied by a crop coefficient (Kc) to compute the water use of corn:

$$ETc = Kc\ ETr$$

A tall reference crop often considered to be alfalfa about 20 inches in height was used for the reference crop evapotranspiration. The Standardized Penman-Monteith method developed by the ASCE-EWRI[2] task force was used as the basis for computing ETr. Since climatic data needed for the Penman-Monteith method are not available dating back to 1950, the Hargreaves[3] method was calibrated to the Penman-Monteith method for a period of about 20 years for selected weather stations that are part of the Automated Weather Data Network operated by the High Plains Climate Center at the University of Nebraska-Lincoln. The calibrated Hargreaves method provides daily estimates of reference crop ET for the CROPSIM model to simulate corn ET and net irrigation requirements for the period from 1950 through 2004. The fifty-five year period was used to include climatic variations that are expected in the Great Plains. The Hargreaves method was calibrated for each month using the ASCE Hourly method for an alfalfa (tall) reference crop. Data were used from the 23 automated weather data network stations listed in Table 1. The automated weather stations were selected to provide statewide coverage and a period long enough to represent climatic variations across the state. The location of the automated weather data network (AWDN) stations are shown in Figure 1. The map shows that the AWDN stations are well distributed across the state.

[2] ASCE-EWRI. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Environmental and Water Resources Institute of the American Society of Civil Engineers, Standardization of Reference Evapotranspiration Task Committee. ASCE. Reston, NY.
[3] Hargreaves, G.H. and R,G. Allen. 2003. History and evaluation of Hargreaves evapotranspiration equation. Journal of Irrigation and Drainage Engineering. ASCE. 129(1): 53-63.

Table 1. Automated weather data network stations used to calibrate the Hargreaves method to the sum-of-hourly for daily reference ET for a tall reference crop (i.e., alfalfa). The date the system first became operational and the latitude, longitude and elevation of the stations are also listed.

Station	Latitude degrees North	Longitude, degrees west	Elevation, meters	Month	Day	Year
AINSWORTH	42.550	-99.817	765	6	4	1984
ALLIANCEWEST	42.017	-103.133	1213	5	29	1988
BEATRICE	40.300	-96.933	376	1	1	1990
CENTRALCITY	41.150	-97.967	517	9	4	1986
CHAMPION	40.400	-101.717	1029	5	20	1981
CLAY CENTER(SC)	40.567	-98.133	552	7	14	1982
CONCORD(NE)	42.383	-96.950	445	7	16	1982
DICKENS	40.950	-100.967	945	5	21	1981
ELGIN	41.933	-98.183	619	1	1	1988
GORDON	42.733	-102.167	1109	10	18	1984
GUDMUNDSENS	42.067	-101.433	1049	10	5	1982
HOLDREGE	40.333	-99.367	707	5	29	1988
LEXINGTON	40.767	-99.733	728	8	5	1986
MCCOOK	40.233	-100.583	792	5	21	1981
MEADTURFFARM	41.167	-96.467	366	7	29	1986
MITCHELL FARMS	41.933	-103.700	1098	7	11	1996
NEBRASKA CITY	40.533	-95.800	328	6	29	1998
ONEILL	42.467	-98.750	625	7	17	1985
ORD	41.617	-98.933	625	7	10	1983
SCOTTSBLUFF	41.883	-103.667	1208	1	1	1991
SIDNEY	41.217	-103.017	1317	12	1	1982
WESTPOINT	41.850	-96.733	442	5	15	1982
YORK	40.867	-97.617	490	4	22	1996

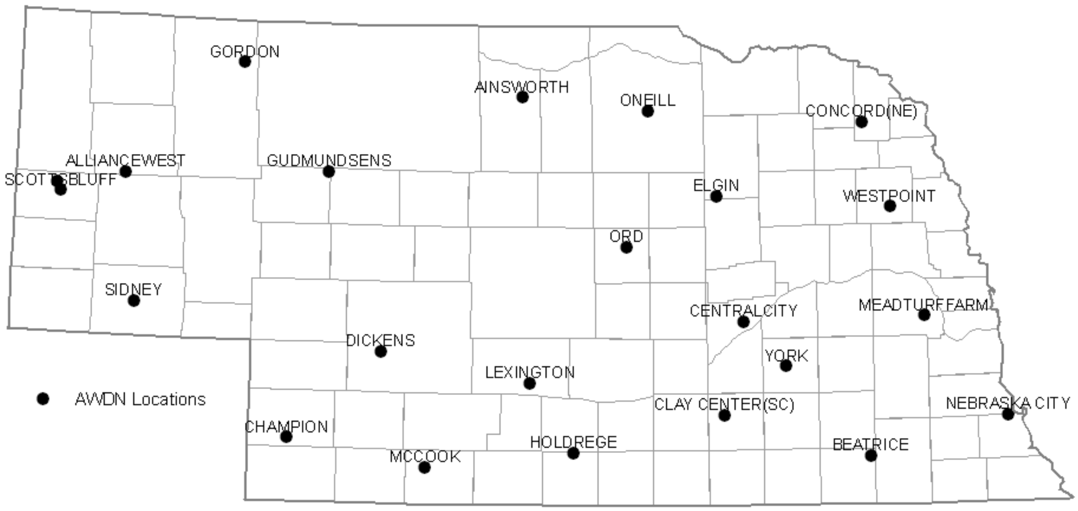

Figure 1. Location of automated weather stations used to calibrate the Hargreaves method.

The daily reference crop ET for alfalfa was calibrated using the following equation:

$$ETr = \left[a + b\ Long^2 \right] Hg^c$$

where ETr is daily reference crop ET for alfalfa as computed with the ASCE method, and
Long is the longitude, degrees
Hg is the Hargreaves factor,
and a, b and c are empirical coefficients.

The Hargreaves factor is computed as:

$$Hg = \frac{(Ta + 17.8)\sqrt{T\max - T\min}\ \ Ra}{\lambda}$$

where Ta is the average daily temperature, °C,
Tmax is the maximum daily temperature, °C,
Tmin is the minimum daily temperature, °C,
Ra is the extraterrestrial radiation, $MJ/m^2/day$,
8 is the heat of vaporization = 2.45 MJ/Kg of water.

Daily data from the AWDN stations were used to compute daily ETr values with the Penman-Monteith method. The Hargreaves factor was compute for each day as well. The results of the computations were separated by month and the coefficients for the calibrated Hargreaves method (*i.e.*, a, b and c) were computed from the regression analysis for all 23 AWDN stations. The results of the calibration are listed in Table 2. The coefficients of determination (r^2) for the monthly values are reasonably good for all months.

Table 2. Parameters and coefficient of determination for calibration of Hargreaves method to Sum-of-Hourly calculations for ASCE Penman-Monteith.

Month	a	b	c	r^2
January	-2.97117E-03	6.68252E-07	1.0400	0.68
February	-2.10020E-03	4.71103E-07	1.0746	0.74
March	-1.99470E-04	1.60011E-07	1.1419	0.76
April	3.42244E-04	2.06925E-08	1.2499	0.76
May	1.48641E-04	1.16248E-08	1.3282	0.65
June	1.13210E-04	8.14170E-10	1.4143	0.66
July	6.58766E-05	5.44612E-09	1.4072	0.66
August	4.65366E-05	2.19358E-08	1.3122	0.62
September	3.90011E-04	7.01456E-08	1.1518	0.62
October	9.59964E-04	1.20508E-07	1.0839	0.65
November	-1.08578E-03	3.78426E-07	1.0814	0.68
December	-4.57939E-03	8.95039E-07	1.0180	0.66

Simulation of crop water use for the period from 1950 through 2004 required a different set of weather stations since AWDN data are not available before 1980. Sixty-two cooperator or National Weather Service stations were selected for the simulation. Stations that were selected included measurements for at least the maximum daily air temperature, the minimum daily air temperature and daily precipitation (rain and snow). Some stations also included evaporation measurements from evaporation pans. These data were not used in the simulation. Weather stations were selected to represent the state as indicated by the climate zones shown in Figure 2. Only stations that included daily weather data starting before 1949 were selected for analysis. The High Plains Climate Center has developed data management routines to estimate values for days when data are missing or appear to be incorrect. Therefore, none of the stations have missing data and no procedures were developed to correct these data which are referred to as National Weather Station (NWS) stations in this report.

The CROPSIM model uses a set of parameters to describe how corn develops during the year and to represent typical management practices for a region. To simulate corn growth the state wad divided into four management zones as shown in Figure 3. The management zones in Figure 3 generally align with the Climate Zones in Figure 2 except for the North Central Climate Zone. This zone was divided approximately in half to represent management practices for that region. Some important parameters for the management zones are included in Table 3. The data show that the amount of growing degree days required for crop development increases as one progresses from management zone 1 east to management zone 4. Planting is also generally delayed as one progresses west from zone 3. A slightly later planting date was used for management zone 4 since this region receives more rain in the spring that can delay planting compared to zone 3. Other parameters used to simulate crop growth and management are listed in Table 2. These values were held constant across all four management zones.

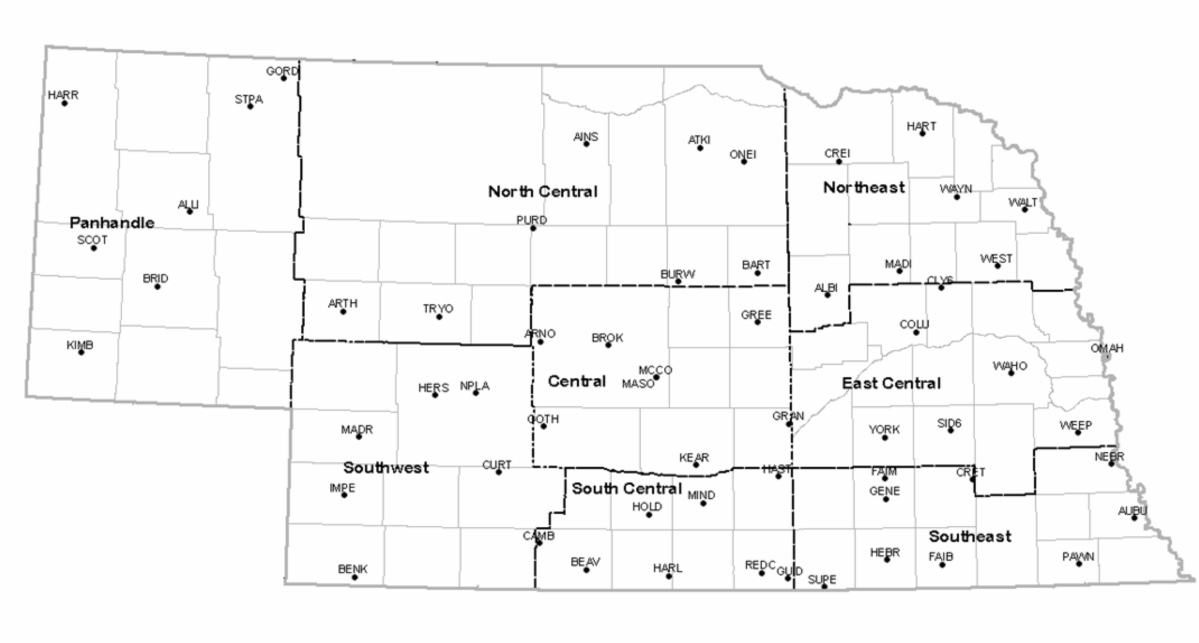

Figure 2. Location of National Weather Service stations used in simulations and Climatic Zones for Nebraska. Specific information for the NWS stations is included in Table 4.

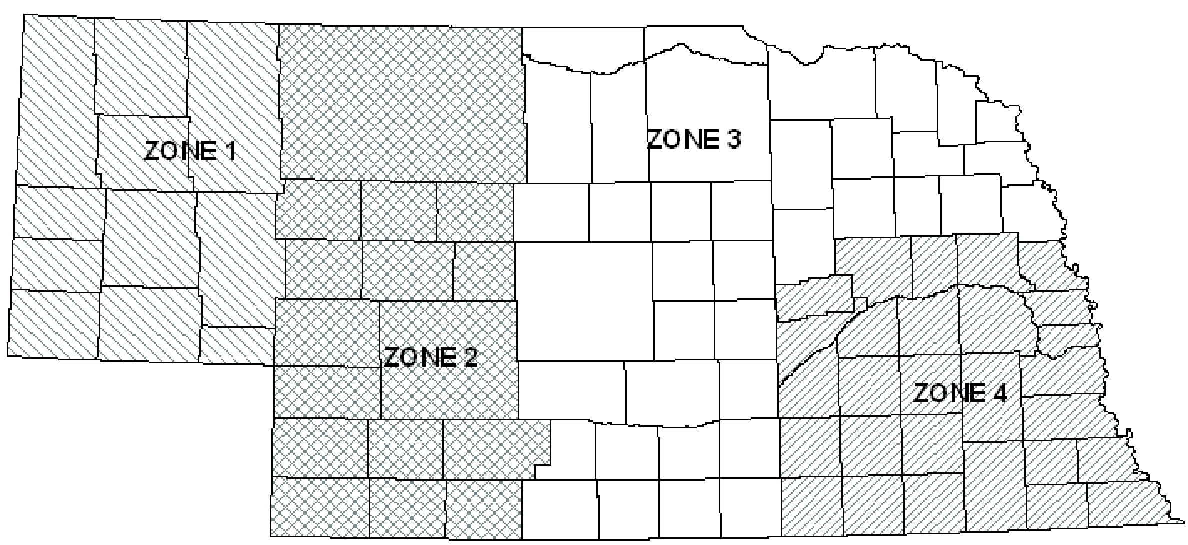

Figure 3. Location of management zones for the CROPSIM model.

Table 3. Parameters used in simulation of crop growth with the CROPSIM model.

Management Zone	Growing Degree Days for Specific Growth Stages					
	Planting Date	Begin of Flowering	Begin of Ripening	Yield Formation	Effective Cover	Physiological Maturity
Zone 1	5/5	1200	1700	2160	1050	2400
Zone 2	5/1	1300	1800	2500	1200	2750
Zone 3	4/25	1350	1850	2600	1250	2850
Zone 4	5/1	1400	1850	2700	1300	2950
Minimum Depth of Crop Root Zone, inches					6	
Maximum Depth of Crop Root Zone, inches					72	
Growing Degree Days for Start of Root Growth					200	
Growing Degree Days for Start of Vegetative Growth					450	
Depth of Soil Profile Used for Irrigation Management, inches					48	

Runoff was simulated using the curve number method originally developed by the USDA Natural Resources Conservation Service. The method was modified to adjust curve numbers based on the soil water content at the time of precipitation. The soil water content adjustment of curve numbers, and melting and infiltration of snow was based on routines in the SWAT[4] model. The fine sandy loam soil has been characterized as being in hydrologic group B in the curve number method.

Results

The net irrigation requirement and the amount of evapotranspiration for fully irrigated corn and non-irrigated corn grown on fine sandy loam was simulated at sixty-two NWS stations across Nebraska for the period from 1949 through 2004. Data for 1949 were not included in the analysis as there is usually a stabilization period following the initial conditions used for the soil water content for the first year of simulation for a site. The difference in the evapotranspiration for fully irrigated corn and non-irrigated corn is the consumptive irrigation requirement (CIR). The CIR is the amount of consumptive use of water due to irrigating for full crop yield. Results of the simulations for the NWS stations are summarized in Table 4. The net irrigation requirement was used to develop contour lines for the net irrigation map across the state (Figure 4). The results generally show that irrigation requirements increase in a southeast-northwest pattern.

[4] Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol. Process. 19(3):563-572.

Table. 4. Results of simulations for ET, CIR and net irrigation for NWS weather stations used in the analysis.

Site	ET Full Yield, Inches/Year	ET Non Irrigated, Inches/Year	CIR, Inches /Year	Net Irrigation, Inches/Year	Latitude, Degrees	Longitude, Degrees	Elevation, Meter	Climate Division	Station Code	Station Name
AINS	29.86	20.48	9.38	10.45	42.55	-99.85	765	2	c250050	AINSWORTH
ALBI	29.65	23.03	6.63	8.41	41.68	-98.00	546	3	c250070	ALBION
ALLI	28.81	15.65	13.15	13.97	42.10	-102.88	1217	1	c250130	ALLIANCE 1 WNW
ARNO	32.07	19.75	12.32	13.09	41.42	-100.18	838	4	c250355	ARNOLD
ARTH	30.12	17.93	12.19	13.21	41.57	-101.68	1067	2	c250365	ARTHUR
ATKI	29.28	20.88	8.40	9.67	42.53	-98.97	643	2	c250420	ATKINSON
AUBU	28.70	24.84	3.86	6.00	40.37	-95.73	283	8	c250435	AUBURN 5 ESE
BART	30.14	22.11	8.03	9.58	41.82	-98.53	652	2	c250525	BARTLETT 4 S
BEAV	33.37	21.01	12.36	13.21	40.12	-99.82	658	7	c250640	BEAVER CITY
BENK	31.25	17.78	13.47	14.37	40.05	-101.53	922	6	c250760	BENKELMAN
BRID	30.01	15.67	14.34	14.85	41.67	-103.10	1117	1	c251145	BRIDGEPORT
BROK	30.75	20.51	10.23	11.30	41.40	-99.67	762	4	c251200	BROKEN BOW 2 W
BURW	30.67	20.59	10.08	11.16	41.77	-99.13	663	2	c251345	BURWELL 4 SE
CAMB	31.23	19.77	11.46	12.16	40.27	-100.17	689	7	c251415	CAMBRIDGE
CLY6	29.59	22.88	6.71	8.07	40.50	-97.93	530	8	c251680	CLAY CENTER 6 ESE
COLU	28.05	22.67	5.38	7.11	41.47	-97.33	442	5	c251825	COLUMBUS 3 NE
CREI	29.63	22.06	7.58	9.16	42.45	-97.90	497	3	c251990	CREIGHTON
CRET	28.67	23.78	4.89	6.80	40.62	-96.93	437	8	c252020	CRETE
CURT	31.22	19.38	11.84	13.15	40.67	-100.48	829	6	c252100	CURTIS 3 NNE
FAIB	29.92	24.67	5.25	7.09	40.13	-97.17	415	8	c252820	FAIRBURY
FAIM	29.64	22.83	6.81	8.30	40.63	-97.58	500	8	c252840	FAIRMONT
GENE	28.27	23.16	5.11	6.91	40.52	-97.58	497	8	c253175	GENEVA
GORD	28.79	16.89	11.90	13.20	42.88	-102.20	1128	1	c253355	GORDON 6 N

GOTH	30.89	20.18	10.70	11.39	40.93	-100.15	788	4	c253365	GOTHENBURG
GRAN	28.70	21.27	7.43	8.89	40.95	-98.30	561	4	c253395	GRAND ISLAND WSO AP
GREE	30.87	22.15	8.73	10.20	41.53	-98.53	616	4	c253425	GREELEY
GUID	29.48	22.43	7.05	8.72	40.07	-98.32	498	7	c253485	GUIDE ROCK
HARL	30.17	20.70	9.47	10.35	40.08	-99.20	610	7	c253595	HARLAN COUNTY LAKE
HARR	28.11	16.25	11.87	13.85	42.68	-103.88	1478	1	c253615	HARRISON
HART	28.72	22.05	6.67	8.35	42.60	-97.25	418	3	c253630	HARTINGTON
HAST	29.93	23.08	6.85	8.55	40.65	-98.38	591	7	c253660	HASTINGS 4 N
HEBR	29.51	23.75	5.77	7.46	40.17	-97.58	451	8	c253735	HEBRON
HERS	30.51	18.47	12.04	13.21	41.10	-100.97	900	6	c253810	HERSHEY 5 SSE
HOLD	30.09	22.02	8.07	9.41	40.43	-99.35	707	7	c253910	HOLDREGE
IMPE	29.85	18.30	11.56	12.67	40.52	-101.63	999	6	c254110	IMPERIAL
KEAR	29.72	21.70	8.03	9.37	40.72	-99.00	649	4	c254335	KEARNEY 4 NE
KIMB	30.38	16.60	13.78	14.51	41.27	-103.65	1451	1	c254440	KIMBALL
MADI	29.19	22.81	6.39	8.27	41.82	-97.45	511	3	c255080	MADISON 2 W
MADR	31.45	18.73	12.72	13.77	40.85	-101.53	975	6	c255090	MADRID
MASO	30.30	21.65	8.65	9.83	41.22	-99.30	689	4	c255250	MASON CITY
MCCO	29.05	19.31	9.74	11.14	40.20	-100.62	771	6	c255310	MCCOOK
MIND	29.60	21.79	7.80	9.20	40.50	-98.95	658	7	c255565	MINDEN
NEBR	28.48	24.88	3.60	5.61	40.68	-95.88	329	8	c255810	NEBRASKA CITY
NPLA	29.45	18.64	10.81	12.13	41.12	-100.67	847	6	c256065	NORTH PLATTE WSO ARP
OMAH	27.31	23.98	3.33	5.39	41.30	-95.88	304	5	c256255	OMAHA EPPLEY AIRFIEL
ONEI	30.20	21.30	8.90	10.15	42.45	-98.63	607	2	c256290	ONEILL
PAWN	29.13	24.66	4.48	6.63	40.12	-96.15	369	8	c256570	PAWNEE CITY
PURD	31.79	19.67	12.12	12.98	42.07	-100.25	820	2	c256970	PURDUM
REDC	31.29	22.46	8.83	10.35	40.10	-98.52	524	7	c257070	RED CLOUD
SCOT	29.43	14.72	14.72	15.36	41.87	-103.60	1202	1	c257665	SCOTTSBLUFF AP

SID6	29.43	15.99	13.44	14.14	41.20	-103.02	1317	1	c257830	SIDNEY 6 NNW
STPA	28.30	21.10	7.20	8.64	41.27	-98.47	541	4	c257515	ST PAUL 4 N
SUPE	29.68	23.05	6.63	8.27	40.02	-98.05	482	8	c258320	SUPERIOR
TRYO	30.53	18.30	12.23	13.34	41.55	-100.95	990	2	c258650	TRYON
WAHO	29.47	25.01	4.47	6.68	41.22	-96.62	387	5	c258905	WAHOO
WALT	29.22	23.18	6.05	7.93	42.15	-96.48	372	3	c258935	WALTHILL
WAYN	28.91	22.50	6.41	8.05	42.23	-97.00	445	3	c259045	WAYNE
WEEP	28.49	24.41	4.08	6.17	40.87	-96.13	335	5	c259090	WEEPING WATER
WEST	28.30	23.30	5.00	7.09	41.83	-96.70	399	3	c259200	WEST POINT
YORK	28.78	23.19	5.59	7.31	40.87	-97.58	491	5	c259510	YORK

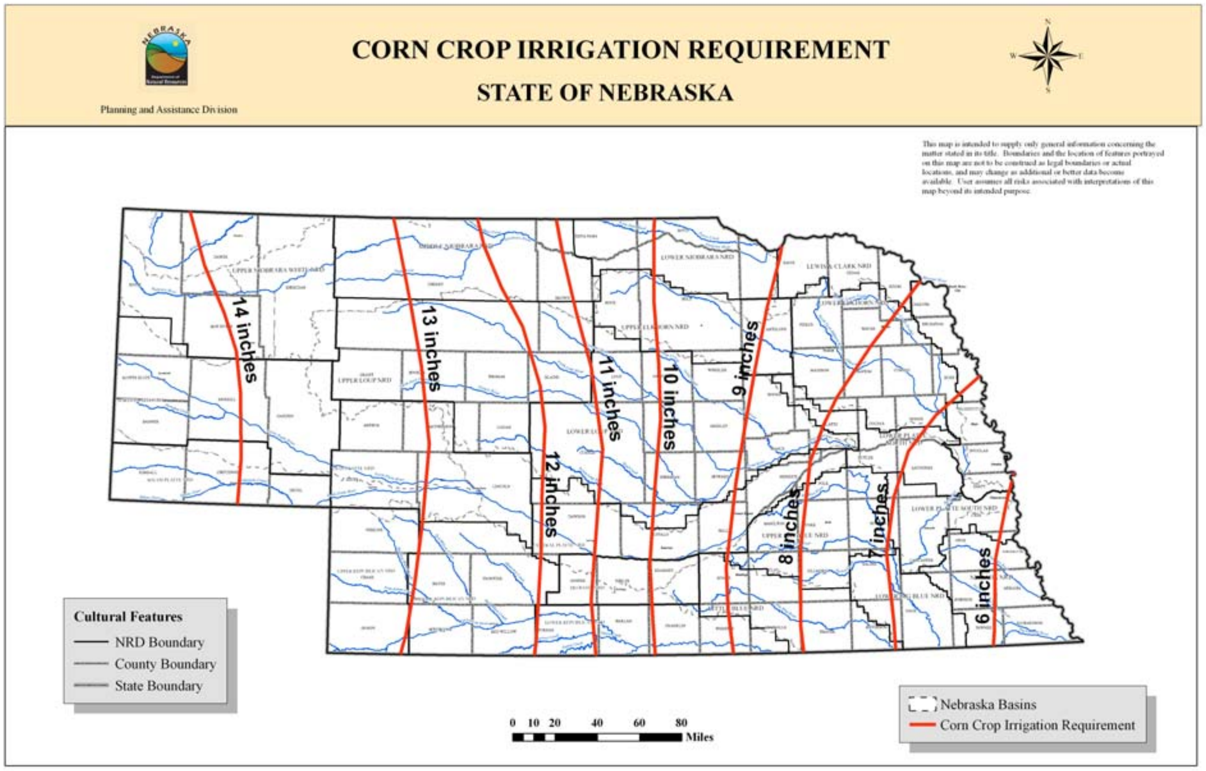

Figure 4. Map of net irrigation requirements (inches/year) for corn grown on fine sandy loam.