Methodologies

Limitations of hydrologic modeling and methods must be considered by the user when considering the results and analyses, and the appropriateness of such for the given task. Historically three broad categories of models have been used to study ground water flow systems, i.e. sand tank models, analog models and mathematical models, including analytical methods and numerical models. The first two methods were primarily used prior to the advent of the modern high speed digital computers. Since the advent of computers, numerical models have been the favored type of model for studying ground water.

One widely used numerical model that was developed by the U.S. Geological Survey is MODFLOW[1]. An example of a previous study compared the results of several analytical methods to a two-dimensional ground water flow model and showed that simplifying assumptions needed for use of the analytical methods resulted in differences in stream flow depletion from the numerical model that ranged from 20 percent, due to neglect of partial penetration, to 45 percent, due to neglect of clogging layer resistance, after 58 days of pumping *Spalding and Khaleel* [1991][2]. This study was done not for the determination of regional stream depletion analysis with regional datasets, but was used to show the impacts of a single well on a stream with detailed, known parameters to perform a numerical analysis.

For those areas of the state where an existing MODFLOW model suitable for regional analysis is available, it is used to develop the 10/50 areas. However, much of the state is not covered by suitable numerical model(s). In order to properly use a numerical model the appropriate detail of data must be supplied as inputs to the numerical model. Due to lack of detailed data and the time constraints for this report a suitable numerical model

[1] McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.
[2] Spalding, C.P. and R. Khaleel. 1991. An evaluation of analytical solutions to estimate drawdown and stream depletions by wells. *Water Resour. Res. 27*(4). 597-609.

could not be developed for areas where a model does not already exist. In these areas an analytical method was used.

This study uses the analytical method described by Jenkins in 1968, which is commonly known as the Stream Depletion Factor (SDF)[3] . This method lends itself to the basin wide aspect of the task described by this report. A list of the assumptions for the Jenkins method is contained in the USGS publication referred to earlier. The method Jenkins described was built upon equations previously published by Glover and Balmer (1954)[4], Maasland and Bittinger (1963)[5] Gautuschi (1964)[6] and others. Jenkins specifically developed his tools for ease of use for water administrators. This was one major reason for selecting this tool for this analysis as well as the fact that the detail of data necessary on a regional basis is available and this tool is currently used by other states for administrative purposes, including Colorado and Wyoming.

Modified versions of the Jenkins SDF method were also considered because the assumptions in the original Jenkins method do not always fit real world situations. Jenkins SDF can be modified to address situations such as boundary conditions[7] and streambed conductance[8]. These modifications require data on these parameters to perform the analysis. No modifications were made to Jenkins for this analysis because of the lack of published data necessary for the calculations. Generally these additional calculations are required only when near the stream or boundary condition. As you move away from the stream the percent impact of the parameters becomes a small fraction of the overall total analysis.

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[3] Jenkins, C.T. 1968. Techniques for computing rate and volume of stream depletion by wells. Techniques of Water Resources Investigations, U.S. Geological Survey, Chapter D1, Book 4.
[4] Glover, R.E. and C.G. Balmer, 1954. River depletion resulting from pumping a well near a river. Am. Geophys. Union Trans. V. 35. pt 3, pp. 468-470.
[5] Maasland, D.E. and M. W. Bittinger (eds.). 1963. Summaries of solved cases in rectangular coordinates, Appendix A. In Transient ground-water hydraulics symposium. Colorado State Univ. Proc., pub. CER63DEM-MWB70. 233 pp.
[6] Gautschi, Walter. 1964. Error function and Fresnel integrals. In Abromowitz, Milton and Irene A. Stegun (eds.). Handbook of mathematical functions with formulas, graphs, and mathematical tables. U.S. Dept. Commerce. Natl. Bur. Standards. Appl. Math. Ser. 55, pp. 295-329.
[7] Miller, C.D. and Durnford, D.S., 2005, Modified Use of the "SDF" Semi-Analytical Stream Depletion Model in Bounded Alluvial Aquifers, Hydrology Days, 146-159.
[8] Zlotnik, V.A., 2004, A concept of maximum stream depletion rate for leaky aquifers in alluvial valleys, Water Resources Reseach, Vol. 40, W06507.

Hydrologically Connected Area

In areas covered by numerical models the steps taken to define the 10/50 line and associated hydrologically connected area are documented in the respective model documentation in Appendix E. The upper portion of the Little Blue River, the eastern portion of the TriBasin NRD associated with the Platte River, and that portion of the Loup River associated with Platte River depletions were evaluated by combination of the Jenkins Stream Depletion Factor analysis, Cooperative Hydrology Study (COHYST) models and numeric groundwater models derived from the COHYST model to do the analysis and draw the 10/50 line.

In areas that are not covered by an acceptable numerical model and where sufficient data existed, the following steps were taken to define the 10/50 areas using the Jenkins Method.

Step 1 Data preparation.

- Develop transmissivity maps and associated datasets for all basins being studied.
- Develop specific yield maps and associated datasets for all basins being studied.
- Select appropriate maps of perennial stream reaches.
- Use Geographic Information System (GIS) software to develop raster grid points and associated SDF values.

Step 2 Evaluate available data to determine if the principal aquifer is present and if sufficient data exists to determine that a given stream reach is in hydraulic connection with the principal aquifer.

Step 3 Complete Jenkins SDF calculations using customized GIS software.

Step 4 Modify the point shapefile to create the 10/50 management area.

Data Preparation

The following data were necessary for determining the 10/50 area

- Aquifer transmissivity and specific yield
- Locations of perennial streams
- Grid of points within study area

The aquifer properties used in the study were found in the report "Mapping of Aquifer Properties – Transmissivity and Specific Yield – for Selected River Basins in Central and Eastern Nebraska" published by the Conservation and Survey Division[9] (CSD).

The location and extent of perennial streams were found from a CSD GIS shapefile[10]. The main stems of each river and its tributaries were included in the calculations for individual basins.

A grid of points was created in ArcView[11] GIS. These points were spaced at one-mile intervals within and beyond the study area. ArcView is a GIS program used to view, process, and query spatially referenced data.

Principal Aquifer and Hydraulic Connection

This information was primarily determined from maps generated by the Conservation and Survey Division[9]. Other supporting evidence from published reports was also used in some cases and is referenced in where used.

[9] Summerside, S., Olafsen-Lackey, S., Goeke, J., and Myers, W., 2005, Mapping of Aquifer Properties – Transmissivity and Specific Yield – for Selected River Basins in Central and Eastern Nebraska.
[10] http://csd.unl.edu/general/gis-datasets.asp#Streams_-_Simplified
[11] ArcView ESRI Corporation

Jenkins Calculations

There are two equations necessary to make the 10/50 determination at each point in the grid, the depletion percentage term and the SDF term.

Depletion percentage: v/Qt

Dimensionless term: $\frac{tT}{a^2 S}$

Where: v = volume of stream depletion during time t

Qt = net volume pumped during time t

t = time during the pumping period since pumping began

T = average transmissivity of the aquifer

a = perpendicular distance between the well and stream

S = average specific yield of the aquifer

A large number of calculations are necessary to make the 10/50 area determination. To facilitate the amount of calculation necessary, ArcView was customized to do much of the work. The goal of the process was to solve the above equations for the 'a' or distance term and compare that to the actual distance from the point to the perennial stream. The known values for the equations are:

- t is 50 years or 18262 days.
- T is the aquifer transmissivity – which is determined by computing the average transmissivity along the perpendicular line between the well and the perennial stream in ArcView.
- S is the aquifer specific yield – which is determined by computing the average specific yield along the perpendicular line between the well and the perennial stream in ArcView.
- v/Qt is equal to 0.1 or 10%. From the nomograph, the corresponding dimensionless term value is equal to 0.359.

Once the ‘a’ or distance value is solved for, the actual perpendicular distance from the point to the perennial stream is determined. If the actual distance is less than the computed distance, the point is included as part of the 10/50 area. These points were stored as a point shape file for further analysis.

Analysis for SDF was only completed for points that fell in areas where the principle aquifer exists and is in hydraulic connection with the stream. These areas were defined from information found in the CSD aquifer properties report.

Management Area Analysis

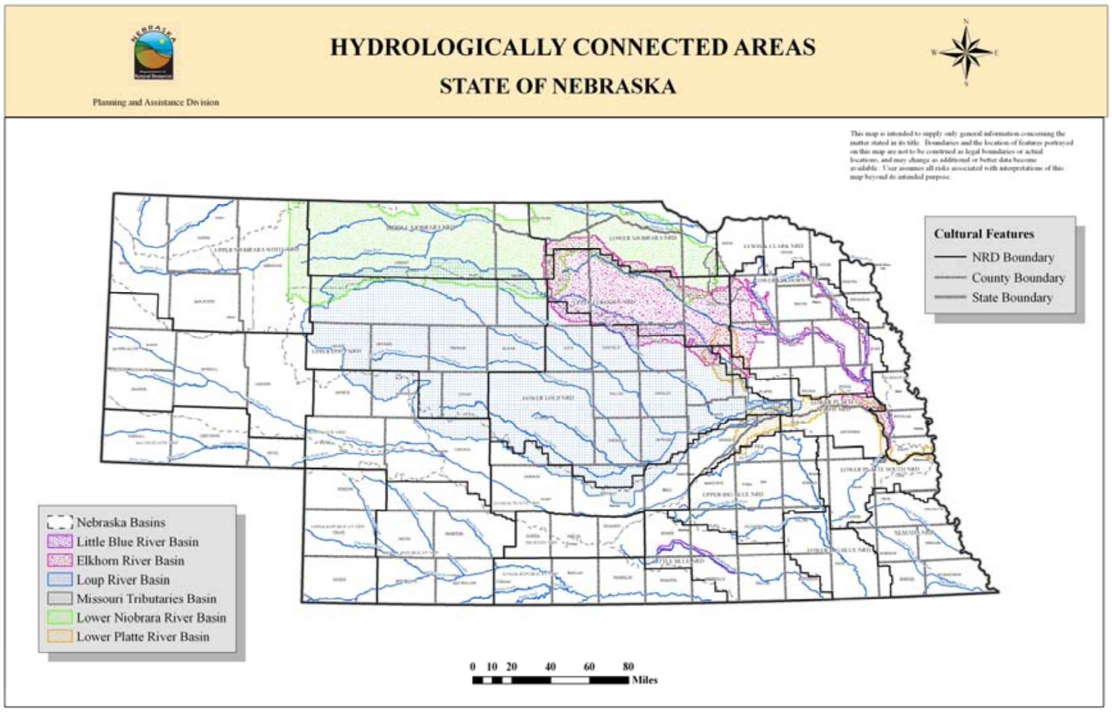
Many ArcView functions were used to convert the point shapefile into a polygon shapefile. The process included converting the point file into a series of one-mile polygon cells with the original point at the center of the cell. The polygon cells were then merged into a single polygon. The results polygon had its ‘jagged’ edges removed to produce a polygon with a ‘smoothed’ appearance. After smoothing some 10/50 areas extended into the areas previously defined by the CSD as consisting of no principle aquifer or having no hydraulic connection with the stream. The smoothed polygon was modified to remove such areas.

This final 10/50 polygon was then converted into the management area polygon by determining the portion of legal description sections that fell within the 10/50 polygon. If 50% or more of the section polygon fell within the 10/50 polygon, the section was included. The final edit to the management polygons was to clip out of the legal description sections the areas that fell outside of the perennial streams that formed the boundaries to the study areas.

Results

Figure D-1 shows the areas where ground water and surface water are hydrologically connected. The shaded areas on each map represent the results of the above process.

Figure D-1. Hydrologically Connected Areas.



<u>Reconstructing the Surface Water Administration Record</u>

The surface water administration record was reconstructed if administration records between 1985 and 2004 showed times when the senior surface water appropriation making a call on junior surface water appropriations had a priority date later than 1985. The purpose was to construct an administrative record as if the all surface water appropriations that exist as of 2004 existed in 1985.

The following steps were taken to reconstruct the surface water administration record:

- Compare the senior surface water appropriation to the historical daily streamflow values for 1985 to 2004.
- If the senior surface water appropriation was greater than the historical daily, assume that surface water administration would have occurred.
- Create tables showing the 20-year average number of days when surface water was available for diversion for the July 1 through August 31 and the May 1 through September 30 time periods.

<u>Future Impact of Current Ground Water Well Development and of Additional Ground Water Well Development</u>

According to Nebraska Revised Statutes § 46-713(Reissue 2004) the Department is to calculate the lag impacts of the current level of ground water well development on surface water supplies into the reasonably foreseeable future. The Department shall also determine the future impacts if development continues. According to Department rule Title 457 Chapter 24, twenty-five years shall be the time period for consideration of future impacts.

Similar to the analysis for the hydrologically connected area, this type of analysis can also be computed using Jenkins SDF equations and nomographs. Two separate analyses were performed: 1) determine the lag impacts of the current well development and 2) determine the lag impacts of current plus continued well development.

The following steps were taken to compute the lag impact:

1. Define the study area.
2. Determine which wells will be used to calculate the lag impact (depletive wells).
3. Project the locations of wells that will be part of the future development in the basin. These wells were only considered for the second analysis, continued well development.

4. Calculate the annual volume of depletion the stream will experience due to the existing wells and future wells for the next 25 years
5. Convert annual acre-feet values to average annual cubic feet per second values to estimate streamflow impact.

Study Area

The study area for each river basin is defined by ground water boundary conditions. Those conditions include perennial baseflow streams, non-hydrologically connected areas, and other conditions which cause static ground water levels or prevent the flow of ground water.

Depletive Wells

Not every well within in the Department well database was used to calculate lag impacts. Only high capacity (rate of flow greater than 50 gpm) active irrigation, industrial, public water supply, or unprotected public water supply wells were selected for this analysis, as these cause most of the lag impacts. Other depletive wells such as the abandoned or inactive high capacity wells, livestock watering wells and domestic wells were not included because of the relatively small amount of water they use and because the database is not complete for these types of wells.

Future Well Development

Future development was estimated by analyzing the trend of the current rate of well development over the last 20 years and location of existing well development in the study area.

Figure D-2 shows the cumulative well development within the Loup River study area. The blue line shows the cumulative number of registered depletive wells in the basin and the red line shows the linear trend for the last 20 years. The slope of the line shows 154 new wells per year. Therefore the future well development estimation for the Loup River study area was 154 wells per year for the next 25 years.

The future wells were located geographically within the study area by overlaying each future development well on a randomly selected existing well within the study area. This method for locating the wells was selected because the existing wells seem to be clustered together and future development will likely occur near areas where development has already occurred. Figure D-3 shows the location of existing depletive wells within the Loup River Basin.

Figure D-2. Cumulative Well Development in the Loup River Study Area.

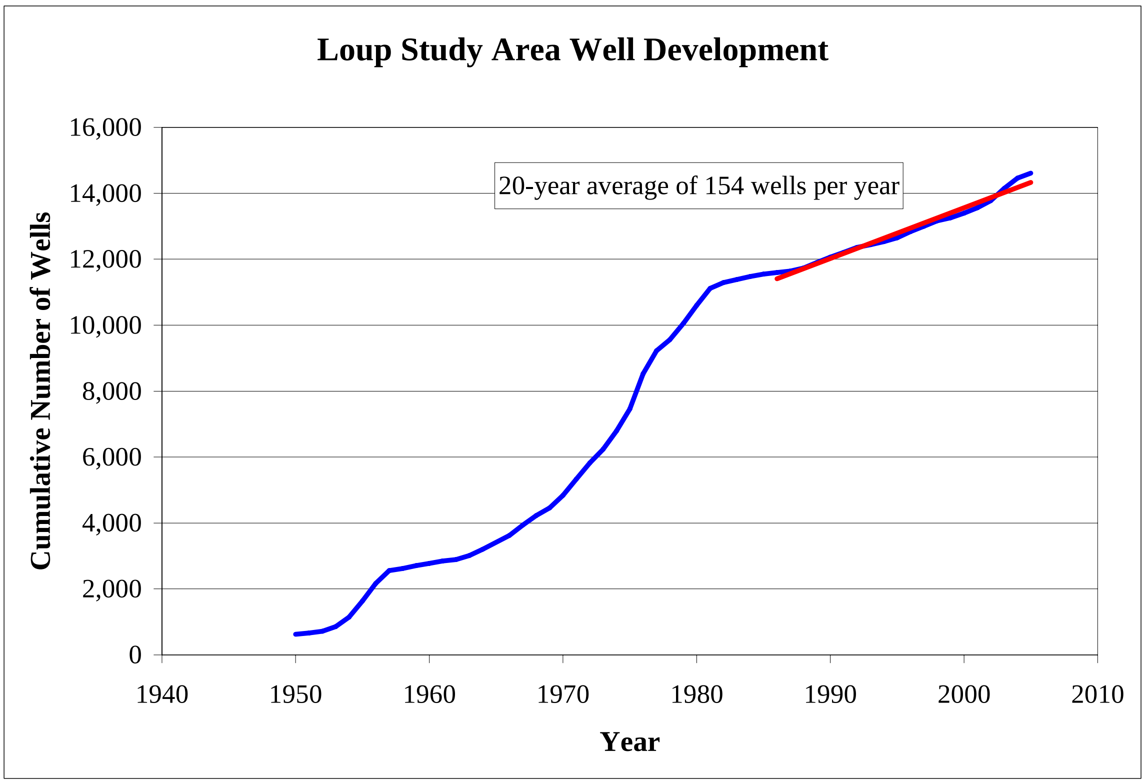
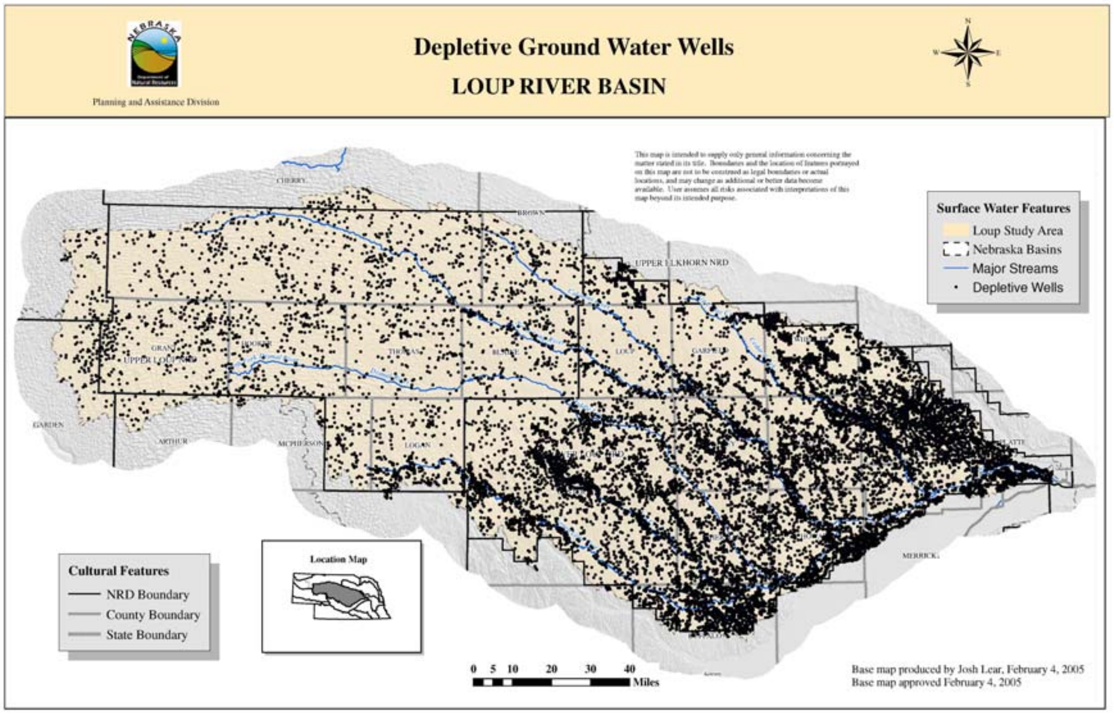


Figure D-3. Loup River Basin Depletive Wells.



Annual Depletions Calculations

In order to estimate the future stream depletions, the level of depletion for each year between 2005 and 2030 must be calculated. This depletion value can be calculated for each existing depletive well in the study area using Jenkins SDF method. The methodology equations used include the depletion percentage term and the dimensionless term.

Depletion percentage: v/Qt

Dimensionless term: $\frac{tT}{a^2S}$

The goal of the depletion analysis is to solve for the 'v' term, the cumulative value of stream depletion each year. The rest of the variables in the equation are known and are described in the section "Hydrologically Connected Area *Jenkins Calculations*" or below.

Q is the annual volume of water pumped for consumptive use over the well age in acre-feet. This is calculated by multiplying the net corn crop irrigation requirement[12] by an average field size in acres. The average field size was estimated to be 90 acres. The average field size was developed using the results described in section "Development of Ground Water Irrigated Acres per Well" found in this document. Industrial and public water supply wells are treated the same as irrigation wells for this analysis.

Each well in the basin has this type of analysis completed and recorded into the database. The depletion values in the database are modified if a well falls within multiple basin study areas. If the well falls into two basin study areas, the depletion is divided by 2, if it falls within three basin study areas; the depletion is divided by 3. This type of modification is done so that the total depletion is not overestimated in overlapping areas.

The final annual results for such an analysis can be seen in Table 1. Once the process has been repeated for each year from 2006 to 2030, the volume depleted in year 'X' can be calculated by subtracting the cumulative depletion for year 'X-1' from the cumulative depletion calculated for year 'X'.

[12] Dr. Derrel Martin, College of Engineering and Technology, Department of Biological Systems Engineering, University of Nebraska, Publication in process.

Table D-1. Sample Depletion Analysis Results.

Year	Cumulative Depletion (Acre-Feet)	Annual Depletion (Acre-Feet)
2005	3,814,368	157,412
2006	3,974,815	160,447
2007	4,138,043	163,228
2008	4,304,249	166,206
2009	4,473,398	169,149
2010	4,645,100	171,702
2011	4,819,213	174,113
2012	4,995,949	176,736
2013	5,175,176	179,227
2014	5,357,076	181,900
2015	5,541,308	184,232
2016	5,727,910	186,602
2017	5,916,848	188,938
2018	6,107,993	191,145
2019	6,301,696	193,703
2020	6,497,913	196,217
2021	6,696,558	198,645
2022	6,897,714	201,156
2023	7,101,208	203,494
2024	7,307,043	205,835
2025	7,515,023	207,980
2026	7,725,565	210,542
2027	7,938,715	213,150
2028	8,154,208	215,493
2029	8,371,876	217,668
2030	8,592,034	220,158

Estimated Stream Flow Impact

The results from the annual depletion analysis can then be converted from annual acre-feet of depletion to an average annual cubic feet per second of water by dividing the difference between the 2005 and the 2030 value by 724.46 (the conversion factor for acre-feet/year to cfs). For Table D-1 above, the results would be (220,158 – 157,412) / 724.46 or 87 cfs. These values can then be used for estimating the total change in stream flow over time.

Conversions for the above equations:

- 1 cubic foot per second = 31,557,600 cubic feet per year
- 1 acre-foot = 43,560 cubic feet
- 1 cubic foot per second = 724.46 acre-feet per year

The methodology section described above was independently peer reviewed by the Nebraska Water Science Center, U.S. Geological Survey in October of 2005. The conclusion was “The NWSC reviewers found the document technically sound.” A copy of the peer review transmittal letter is in Appendix G.

<u>Development of Ground Water Irrigated Acres per Well</u>

Estimation of the number of acres irrigated per ground water well was completed after three methodologies were evaluated:

Method 1: Average Method

All active irrigation wells in the Nebraska Department of Natural Resources Ground Water Well database were queried and distributed into the nine study basins. The average registered acres per well were computed for each basin. The ground water well database acres figure is based upon the number of acres provided by the applicant when the well was originally registered. An examination in the Republican River Basin showed that number was 25% to 33% higher than the actual measured irrigated acreage number. Therefore three alternate variations on Method 1 have been produced, decreasing the acres per well by 25, 30, and 35%.

Method 2: 1995 Study Ground Water Irrigated Acres

Based on the ground water irrigated acres by county in the U.S. Geological Survey / Nebraska Natural Resources Commission 1995 Water Use Study Report and the number of active irrigation wells for each county in 1995 from Nebraska Department of Natural Resources Ground Water Well database, the average number of acres per well for each county was computed. After attributing each irrigation well and its associated average acres into one of the nine study basins, the average irrigated acres per well for each basin was computed by dividing the basin total acres by basin total number of irrigation wells.

Method 3: Combination of 1995 Report Results and 2002 Agriculture Census Data

The total number of irrigated acres and ground water irrigated acres by county in the 1995 Water Use Study Report, total irrigated acres by county from the 2002 Agriculture Census, and the number of active irrigation wells in 2002 from Nebraska Department of Natural Resources Well Database were used to estimate the number of irrigated acres per well in 2002.

By assuming that ground water acres accounted for 95% of the increase in irrigated acres between 1995 and 2002, ground water irrigated acres per county in 2002 were estimated as the 1995 ground water irrigated acres plus 95% of the change in irrigated acres between 2002 and 1995. Then using the estimated ground water irrigated acres for each county in 2002 and the number of irrigation wells in 2002, an average number of acres per well for each county was computed.

All irrigation wells with their average acres per well by county were assigned to their corresponding basins using GIS analyses. Then the total numbers of acres and wells for each basin were totaled. An average number of acres per well by basin in 2002 was developed by dividing the total acres by the number of wells in each basin. The results obtained with the three methodologies are shown in Table D-2.

Table D-2. Number of Ground Water Irrigated Acres per Well.

Basin	Method 1				Method 2	Method 3
	Average	1A (75%)	1B (70%)	1C (65%)		
Big Blue	120	90	84	78	91.7	89.7
Elkhorn River	131	98.3	91.7	85.2	99.2	95.9
Little Blue	126	94.5	88.2	81.9	96.3	92.6
Loup River	126	94.5	88.2	81.9	85.6	80.7
Lower Platte	106	79.5	74.2	68.9	85.7	84.4
Missouri Tributaries					116.2	103.9
Nemaha	138	103.5	96.6	89.7	54.6	63.8
Niobrara	130	97.5	91	84.5	83.7	78.4
Tri-Basin					100.1	99.6

Examination of the results produced by the three methods indicates that there is not a lot of difference between them. Method 1 was eliminated because selection of the correct percentage reduction for each basin would be purely an educated guess until such time as actual data is collected to substantiate the numbers. Method 2 produces defensible numbers but is limited by its use of 1995 data. Method 3 is the procedure with the best available data.

Method 3 was selected as the preferred alternative. This process utilizes the information from a very detailed study done in 1995, and calibrates it to actual survey data collected in the 2002 Census of Agriculture. This procedure offers the additional advantage that it can be re-calibrated when the 2007 Census of Agriculture becomes available to see how the average number of acres per well in each basin have changed over time. Between census years, the number of acres irrigated can be estimated using the current number of registered wells in each basin times the number of acres per well.

There are a total of 89,695 irrigation wells in Nebraska as of October 2005. Registration information shows that 37,519 of these are not in the area included in the nine basins evaluated. A breakdown of the location of the remaining 52,176 irrigation wells is shown in Table D-3.

Table D-3. Number of Irrigation Wells by Basin.

Basin	Number of Irrigation Wells
Big Blue	14,169
Elkhorn River	8,350
Little Blue	6,720
Loup River	9,953
Lower Platte	5,375
Missouri Tributaries	1,642
Nemaha	411
Niobrara	4,030
Tri-Basin	1,526
Nine Basin Total	52,176

There are an additional 3,539 high capacity, non-irrigation wells registered in Nebraska. Of these, 1220 are not in the nine basins evaluated. The remaining 2319 wells are registered for a variety of uses: Aquaculture, Commercial/Industrial, Domestic, Livestock, Public Water Supplier, and Other. The distribution of these wells in the nine basins is shown in Table D-4.

Table D-4. Number of Non-Irrigation Wells by Use by Basin.

	Aquaculture	Commercial/ Industrial	Domestic	Livestock	Public Water Supply	Other	Total
Big Blue	4	58	19	12	244	12	349
Elkhorn River	2	88	18	79	230	31	448
Little Blue	1	21	15	9	114	10	170
Loup River	10	40	25	63	166	7	311
Lower Platte	3	108	51	8	292	29	491
Missouri Tributaries	5	72	18	20	137	14	266
Nemaha		16	2	1	135	4	158
Niobrara	3	3	5	17	72	4	104
Tri-Basin		11	2	1	8		22

The U.S. Environmental Protection Agency reports that consumptive use varies by water use category[13]. They estimated that the rate of consumption is highest for livestock at 67%, followed by irrigation at 56%. Domestic use consumes 23%, while industrial/ mining and commercial uses consume 16% and 11 % respectively. Thermoelectric use consumes only 3% while public uses and losses are not even quantified as consumptive use by them.

Because these 2,319 wells are such a small portion of the total number of high capacity wells in the state (2%), and no data exists in the registration database to indicate the annual pumpage of these wells, no additional efforts were made to identify the pumpage and calculate consumptive use at this time.

The well numbers were then supplied for use in lag impact calculations along with the irrigated acres per well.

<u>Quantifying Impacts of Stream Depletions on Senior Surface Water Appropriation Administration</u>

The impacts of the additional depletion on water administration can be quantified by:

- Determine the total future depletions at the measuring gages.
- Use the most recent daily streamflow records (1985-2004) as a base for the years 2011 through 2030.
- Subtracting the depletion from the historical daily flow values.
- Compare the depleted flows values to the senior surface water appropriation.
- If the senior surface water appropriation was greater than the historical daily, assume that surface water administration would have occurred.
- Create tables showing the 20-year average number of days when surface water was available for diversion for the July 1 through August 31 and the May 1 through September 30 time periods.

[13] http://www.epa.gov/watrhome/you/chap1.html

Converting Inches of Net Corn Crop Irrigation Requirement to Days Necessary to Divert

Assumptions include a downtime of 10%, due to mechanical failures and such, a diversion rate of 1 cfs per 70 acres, this is the most common rate that surface water appropriations are permitted for, and an irrigation efficiency of 80%. Steps include:

- Multiplying the Net Corn Crop Irrigation Requirement by 0.65 or 0.85 to find the 65% and 85% inches.
- Converting 1 cfs/70 acres to inches per day
  - 1 cfs = 1.983 acre-feet/day
  - 1 foot = 12 inches
  - (1 / 70) * 1.983 * 12 = 0.34 inches / day
- Calculate the Gross Irrigation Requirement by dividing the 65% and 85% values by 0.8 (the efficiency)
- Calculate the number of days by dividing the gross irrigation requirement by the 0.34 inches per days rate of diversion and by 0.9 (to account for the downtime)
  - Gross Requirement / 0.34 / 0.9

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