Stream Depletion Line Calculations for Determination of Fully Appropriated Basins for the State of Nebraska

Background

As part of the fully appropriated basin determination process pursuant to Nebraska Revised State Statute 46-713(3), the Department of Natural Resources has used the following methodology to determine the area where ground water and surface water are hydrologically connected. By rule[1], the geographic area in which groundwater and surface water is hydrologically connected for management purposes is defined as the "area within which pumping of a well for 50 years will deplete the river or a base flow tributary thereof by at least 10% of the amount pumped in that time" (10/50 area).

Methodology

All modeling efforts and methodologies have limitations which the user must take into consideration when determining the method to be used and whether results and analysis are appropriate for the task. Historically three broad categories of models have been used to study ground water flow systems, 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 high-speed computers numerical models have been the favored type of model for studying ground water. One widely used numerical model that was developed by the USGS is MODFLOW[2]. 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 <u>*Spalding and Khaleel* [1991]</u>[3].

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

This study uses the analytical method described by Jenkins in 1968, which is commonly known as the Stream Depletion Factor (SDF)[4]. This method lends itself to the basin wide

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[1] http://www.dnr.state.ne.us/LB962/Notice/FullyAppropriatedRuleFINAL.pdf

[2] MODFLOW USGS 1984?

[3] Spalding, C.P. and R. Khaleel. 1991. An evaluation of analytical solutions to estimate drawdowns and stream depletions by wells. *Water Resour. Res. 27*(4). 597-609.

[4] Jenkins, C.T. 1968. Techniques for computing rate and volume of stream depletion by wells. *Ground Water*, 6(2), 37-46.

aspect of the task described by this report. A list of the assumptions for the Jenkins method is contained in the USGS publication. The tools Jenkins described was built upon equations previously published by several authors including Glover and Balmer (1954)[5], Maasland and Bittinger (1963)[6] Gautuschi (1964)[7] 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 agencies for administrative purposes, including Colorado and Wyoming.

Modifications to 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[8] and streambed conductance[9]. 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.

10/50 Area Calculations

In areas covered by numerical models the steps were taken to define the 10/50 boundary areas are documented in the appropriate model documentation in the appendix. The areas being modeled numerically are the Upper portion of the Big Blue and Little Blue rivers, the eastern portion of the Tribasin NRD associated with the Platte River and the Portion of the Loup River associated with Platte River depletions.

In areas covered by the Jenkins method the following steps were taken to define the 10/50 boundary areas.

1. Data preparation.
    a. Transmissivity maps
    b. Specific yield maps
    c. Perennial Stream reaches

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[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] Zlotnik, V.A., 2004, A concept of maximum stream depletion rate for leaky aquifers in alluvial valleys, Water Resources Reseach, Vol. 40, W06507.

d. Grid point generation

2. Complete Jenkins SDF calculations.
3. Modify the point shapefile to create the 10/50 management area.

Data Preparation

The following data were necessary for determining the 10/50 depletion line

- 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[10] (CSD). The data from the report were converted to raster grids covering most of the study areas.

The location and extent of perennial streams were found from a CSD Geographic Information System shapefile[11]. 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[12] geographic information system. These points were spaced at one-mile intervals and within and beyond the study area. ArcView is a geographic information system program that allows the modeler to view, process, and query spatially referenced data.

Jenkins Calculations

There are two equations necessary to make the 10/50 calculation at each point in the grid, the depletion percentage term and the SDF term. They are not equally related to each other but rather related by the nomograph shown in Figure 1. For example (see lines on nomograph), a depletion percentage of 2% relates to a dimensionless term value of 0.17.

Depletion percentage: v/Qt

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

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 between the well and stream
a = perpendicular distance between the well and stream
S = average specific yield of the aquifer between the well and stream

Effective T&S for calculation is much more complex than T&S between well and stream, but this is probably a reasonable approximation.

Not necessarily true. Average over large area

[10] Summerside, S., Olafsen-Lackey, S., Goeke, J., and Myers, W., 2005, Mapping of Aquifer Properties – Tranmissivity and Specific Yield – for Selected River Basins in Central and Eastern Nebraska.

[11] http://csd.unl.edu/general/gis-datasets.asp#Streams_-_Simplified

[12] ArcView Reference?????

point out that this is a logarithmic plot

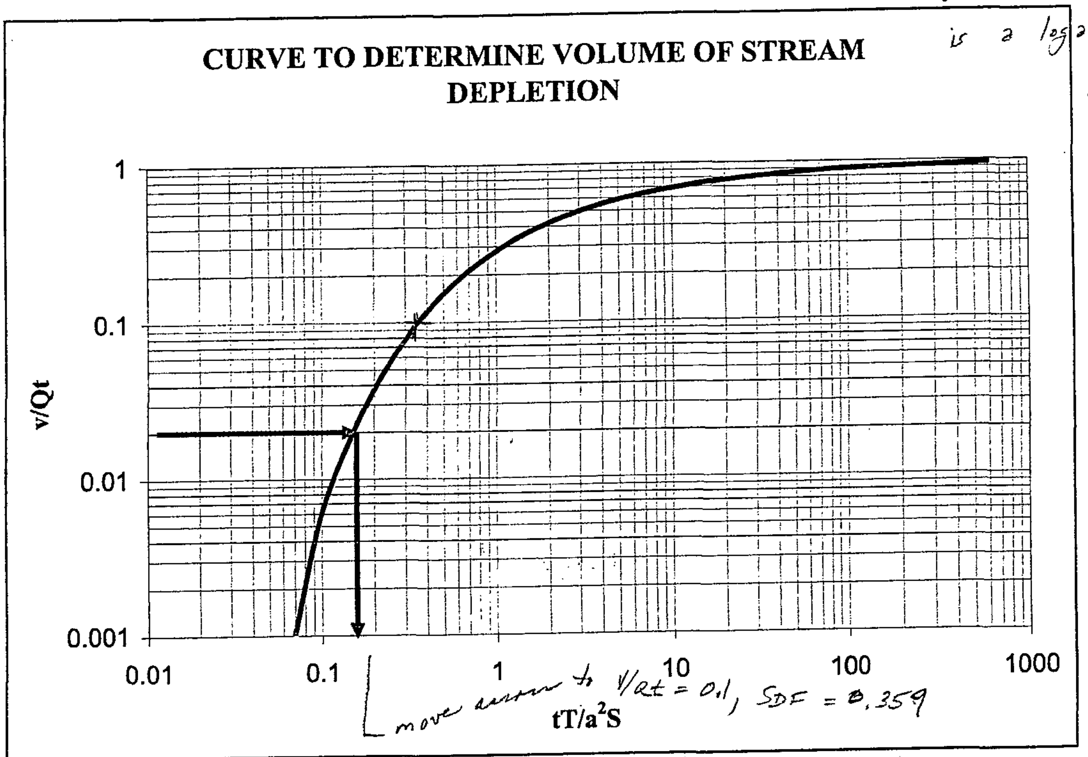

Figure 1. Relationship between the depletion term and SDF equation for Jenkins method.

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 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 18250 days. 18262 to account for leap years
- 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 0.358. 0.359 or 0.3589 check this

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 hydrologically connected to 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 which the original point was 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 hydrologic connection to the stream. The smoothed polygon was modified to remove such areas. Additional areas were removed from the area because of lack of data to put into the Jenkins method.

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 the legal description sections on the far side of perennial streams that formed the boundaries to the study areas.

Results

Figures 2 and 3 show the areas where ground water and surface water are hydrologically connected. The shaded areas on each map represent the results of the above process.

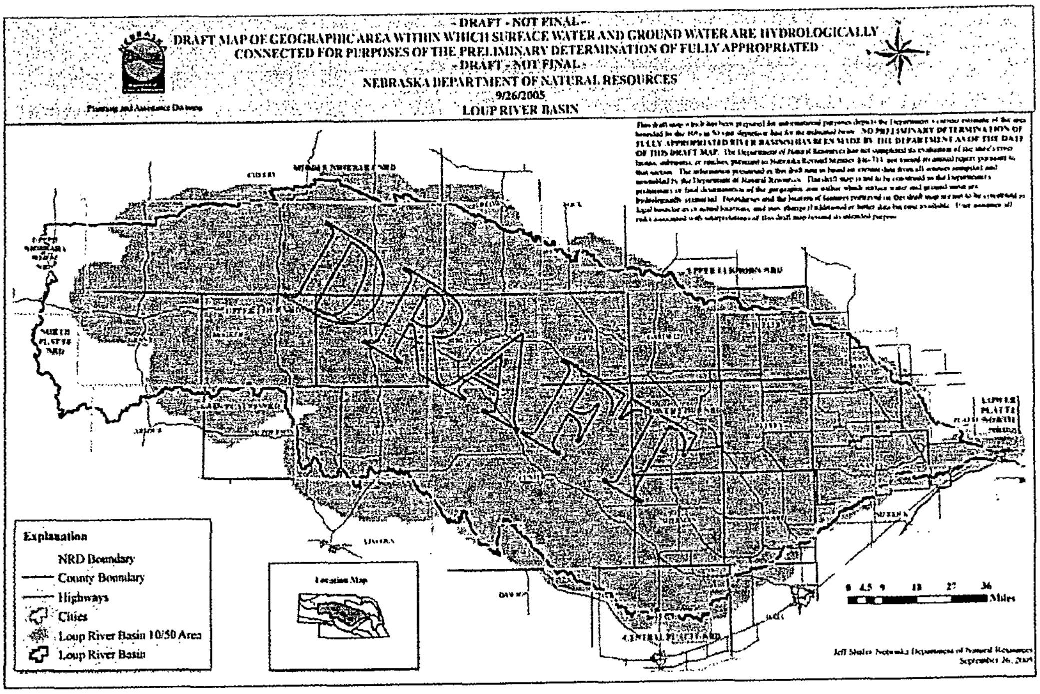

Figure 2. Loup River Basin 10/50 Area

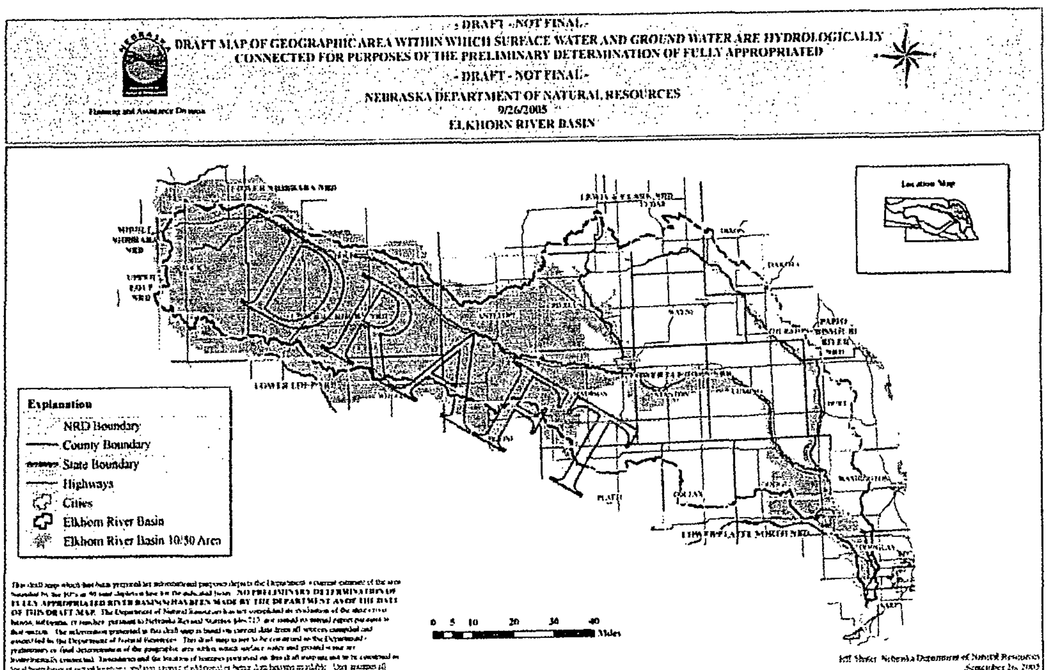

Figure 3. Elkhorn River Basin 10/50 Area

Lag Effect Calculations

According to Nebraska Revised State Statute 46-713(3)(to)The Department is to calculate the lag effects on streams from current well development and for future development. This type of analysis can also be computed using Jenkins SDF equations and nomographs. The time into the future which lag effects must be calculated is 25 years[13].

The following steps were taken to compute the lag effect:

1. Define the study area.
2. Determine which wells will be used to calculate the lag effect, depletive wells.
3. Project the locations of wells that will be part of the future development in the basin.
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 stream impact.

Study Area

The study area for each river basin is defined by ground water boundary conditions. Those conditions include perennial base flow streams, non-hydrologically connected areas, and other conditions which cause constant 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 effects. Only active wells that had a use defined as irrigation, industrial, public water supply, or unprotected public water supply were included. These were selected because they will create the most impact of the lag. Other depletive wells such as 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 looking at the current rate of well development and location of existing well development in the study area.

Figure 4 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.

[13] Statute Reference

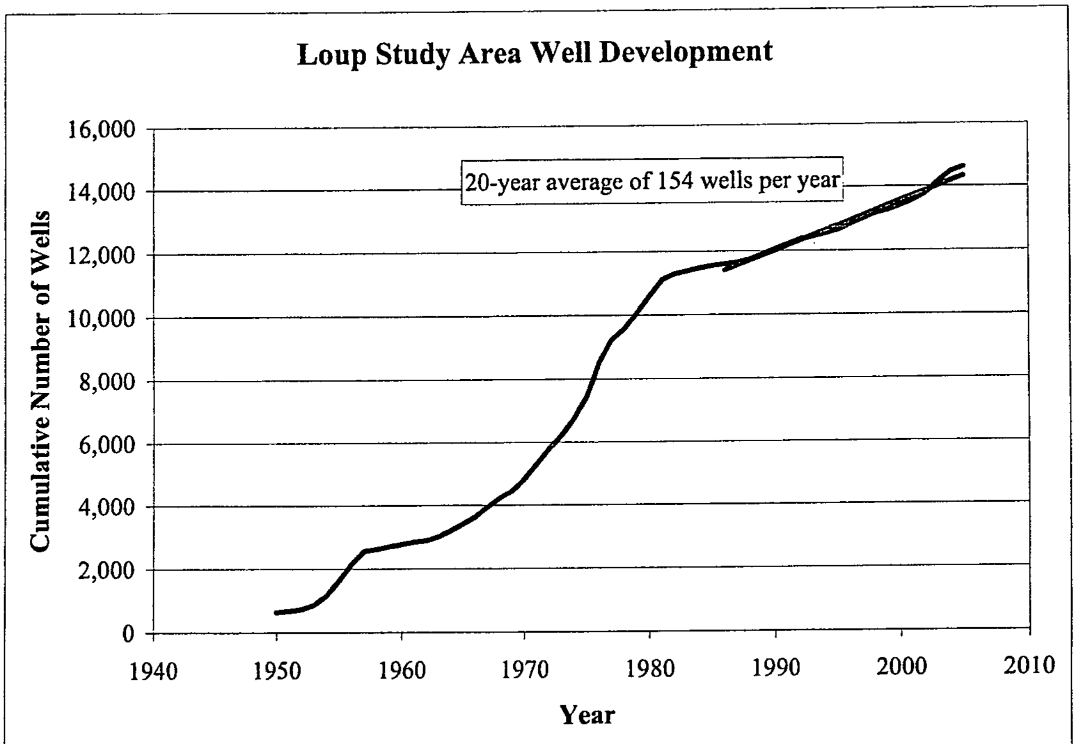

Figure 4. Cumulative Well Development in the Loup River Study Area.

The future wells were located geographically within the study area by overlaying each future 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 5 shows the location of existing depletive wells within the Loup River Basin.

Good method!

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. They are not equally related to each other but rather related by the nomograph shown in Figure 6. — Refer back to figure 1

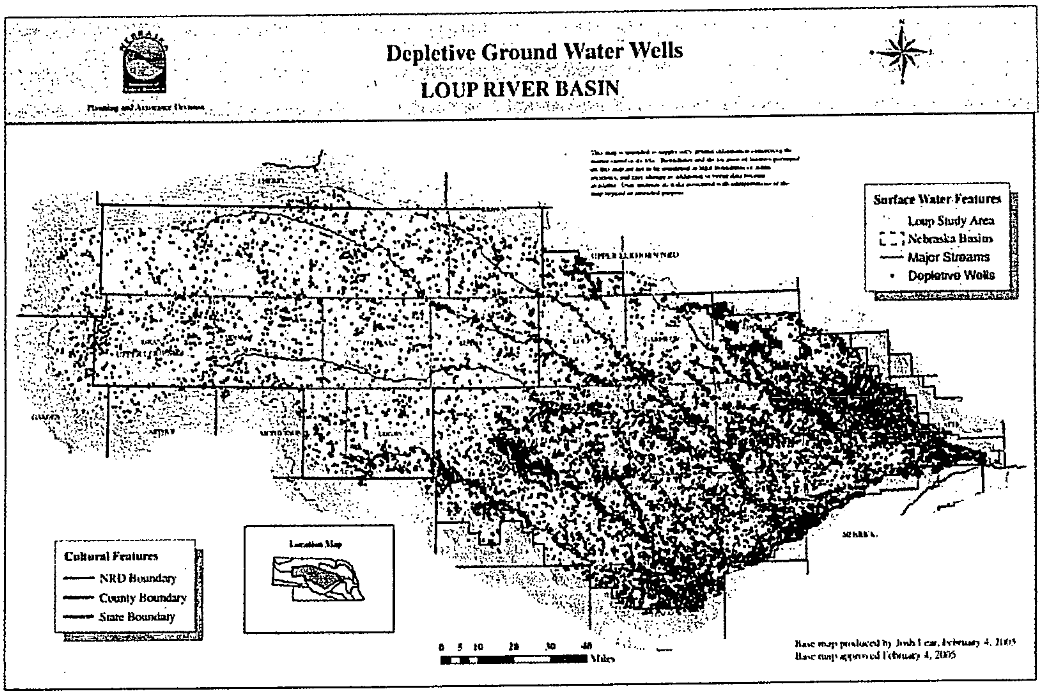

Figure 5. Loup River Basin Depletive Wells.

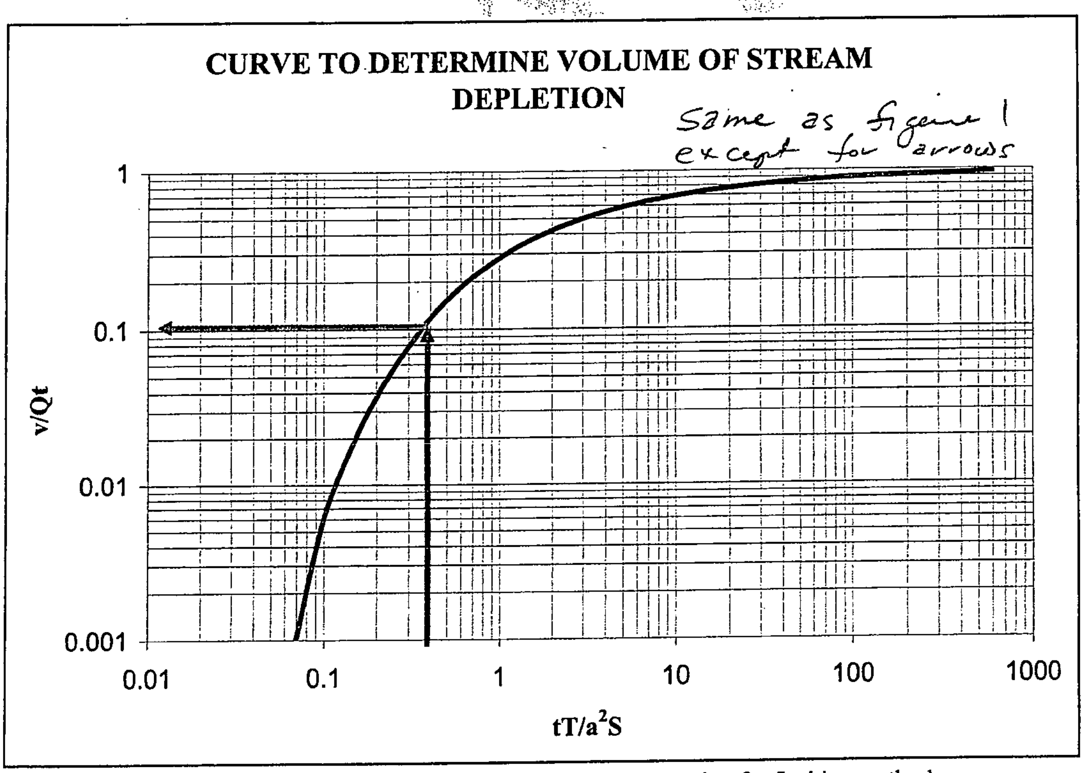

Figure 6. Relationship between the depletion term and SDF equation for Jenkins method.

Just refer back to p. 3. Doesn't fit here

Depletion percentage: v/Qt

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

Where:
v = cumulative volume of stream depletion during time t
Qt = cumulative volume pumped during time t
t = time during the pumping period since pumping began
T = average transmissivity of the aquifer between the well and stream
a = perpendicular distance between the well and stream
S = average specific yield of the aquifer between the well and stream

The goal of the depletion analysis is to solve for the 'v' ~~value of~~ (on p. 3) the ~~depletion~~ ~~term~~ cumulative volume of stream depletion for each year. The rest of the variables in the equation are known.

- t is the well age – which can be found in the well database by subtracting the installation year from the analysis year.
- 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. *see previous note.*
- a is the distance from the well to the perennial stream – which is a known based on an ArcView calculation.
- 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. *see previous note*
- Q is the annual volume of water pumped for consumptive use (over the well age) in acre-feet. This is calculated by multiplying the crop irrigation need[14] by an average field size in acres. The average field size is calculated by taking the average number of acres for each well in the database and then multiplying by 0.75. (use same notation) The multiplier is used because experience with the well database has shown that when large areas are considered, the well database over reports acres by approximately 33% (one third). (real = 75, reported = 100) Industrial and public water supply wells are treated the same as irrigation wells for this analysis. *Numbers are right, but example would help Joe Farmer.*

Each well in the basin has this type of analysis completed and recorded into the database. The values in the database for these wells are modified if the 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. *Good*

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'.

[14] UNL study reference??? *NebGuide*

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

Table 1. Example of Cumulative and Annual Depletion Table.

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 723.8 (the conversion factor for acre-feet/year to cfs). For the table above, the results would be (220,158 – 157,412) / 723.8 or 86.7 cfs. These values can then be used for estimating the total change in stream flow over time.

724.46

86.6

$1\ ft^3/s = 86{,}400\ ft^3/d = 31{,}557{,}600\ ft^3/yr\ (365.25\ d/yr) = 724.46\ AF/yr$