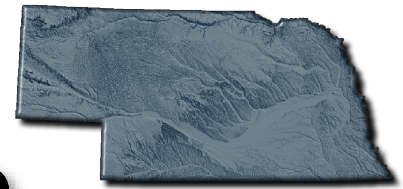
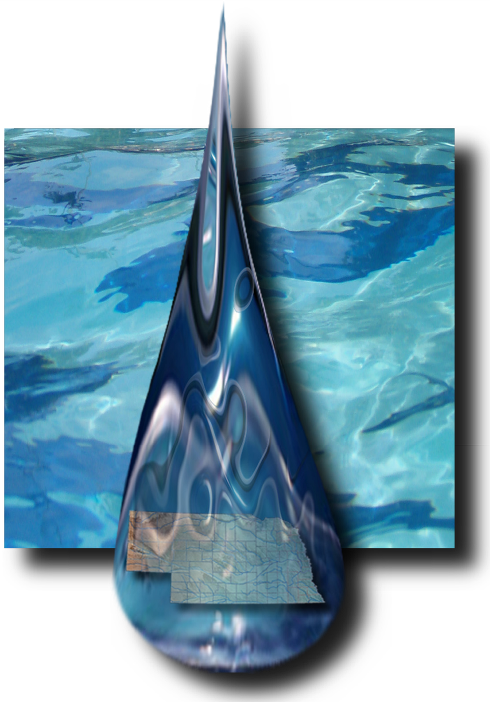
Nebraska Department of Natural Resources





2009 Annual Evaluation of Availability of Hydrologically Connected Water Supplies

Determination of Fully Appropriated

Published by the
Nebraska Department of Natural Resources
April 8, 2009

Nebraska Department of Natural Resources

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Report Organization

This report is divided into nine sections. Section One is the report summary. Section Two is the introduction to the report and contains the purpose, background, and organization. The pertinent statutory and regulatory language can be found in Section Three and in Appendix B. Detailed descriptions of the methodologies used in the analyses can be found in Section Four. Sections Five through Eight are the evaluations of the Big Blue River basins, Lower Niobrara River Basin, Lower Platte River Basin, and Missouri Tributary basins, respectively. Each basin evaluation includes a description of the nature and extent of present water uses, the geographic area considered to have hydrologically connected ground water and surface water (i.e., the “10/50 area”), conclusions about the adequacy of the long-term water supply, and whether the conclusions would change if no additional constraints were placed on water development in the basin. Section Nine is a summary of the basin subsections and the report conclusions. The appendices contain additional detailed information not found within the main body of the report.

1.0 SUMMARY

The Department of Natural Resources (Department) has evaluated the expected long-term availability of surface water supplies and hydrologically connected ground water supplies of the Blue River basins, the lower portion of the Niobrara River Basin, Lower Platte River Basin, and Missouri Tributary basins. The results of this evaluation show that the Blue River basins, Missouri Tributary basins, lower portion of the Niobrara River Basin, and the Lower Platte River Basin are not fully appropriated at the present time. Analysis of future water supplies in the Lower Platte River Basin indicates that, if no additional constraints are placed on ground water and surface water development and reasonable projections are made of the extent of future development, then the effects on the long-term water supply would cause the basin to become fully appropriated in the future.

2.0 INTRODUCTION

2.1 Purpose

The purpose of this report is to fulfill the requirements of section 46-713 of the Ground Water Management and Protection Act (Act) (Neb. Rev. Stat. §§ 46-701 through 46-753). The Act requires the Department to report annually its evaluation of the expected long-term availability of hydrologically connected water supplies. This annual evaluation is required for every river basin, subbasin, or reach that has not either initiated the development of an integrated management plan (IMP) or implemented an IMP. No reevaluations were made in this report for basins, subbasins, or reaches that have previously been determined to be fully or overappropriated.

The evaluation and conclusions of this report are grouped into four river basins: the Blue River basins, Lower Niobrara River Basin, Lower Platte River Basin, and Missouri Tributary basins. This format is intended to reduce repetition; each appropriate basin, subbasin, and reach, however, was analyzed separately.

As required by law, the report also describes the nature and extent of present water uses in the basin, shows the geographic area considered to have hydrologically connected surface water and ground water supplies, and predicts how the Department's conclusions might change if no new legal restrictions are placed on water development in the basin. The report does not address the sufficiency of ground water supplies that are not hydrologically connected to surface water streams. The report includes a description of the criteria and methodologies used to determine which basins, subbasins, or reaches are preliminarily considered to be fully appropriated and which water supplies are hydrologically connected. The report is required to include a summary of relevant data provided by any interested party concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water uses on resources that are dependent on streamflow or ground water levels but that are not protected by appropriations or regulations. Appendix A contains the notice of request for any relevant data from any interested party and all comments received.

2.2 Background

This report addresses requirements that were added to the Act by passage of LB 962 in 2004. That bill was influenced by actions taken as a result of prior legislative activity. In 2002, the Nebraska Unicameral passed LB 1003, mandating the creation of a Water Policy Task Force to address conjunctive use management issues, inequities between surface water and ground water users, and water transfers/water banking. The forty-nine Task Force members, appointed by the Governor from a statutorily specified mix of organizations and interests, were asked to discuss issues, identify options for resolution of issues, and make recommendations to the legislature and governor relating to any water policy changes deemed desirable.

In December 2003, the Task Force provided the Legislature with the *Report of the Nebraska Water Policy Task Force to the 2003 Nebraska Legislature*. That report provided draft legislation and suggested changes to statutes. The Legislature considered the Task Force recommendations in its 2004 session and subsequently passed LB 962, which incorporated most of the Task Force recommendations. Governor Mike Johanns signed the bill into law on April 15, 2004.

The provisions of LB 962 require a proactive approach in anticipating and preventing conflicts between surface water and ground water users. Where conflicts already exist, it establishes principles and timelines for resolving those conflicts. It also added more flexibility to statutes governing transfer of surface water rights to a different location of use and updates a number of individual water management statutes.

Some of the key provisions of LB 962 that are part of current statutes include the following:

- Certain river basins were declared to be fully appropriated or overappropriated. The law automatically placed into fully appropriated status any natural resources district undertaking any integrated management process under previous law for integrated management of hydrologically connected ground water and surface water.

- Portions of the Platte River Basin were declared overappropriated by the legislature because the level of water resources development is not sustainable over the long term.

- The Department must make an annual determination by January 1, 2006, and by January 1 of each subsequent year as to which basins, subbasins, or reaches not previously designated as fully appropriated or overappropriated have since become fully appropriated. The Department must also complete an annual evaluation of the expected long-term availability of hydrologically connected water supplies in the basins, subbasins, or reaches and issue a report describing the results of the evaluation.

- When a basin, subbasin, or reach is declared overappropriated or determined to be fully appropriated, stays on new uses of ground water and surface water are automatically to be imposed. The Department and the natural resources districts (NRDs) involved are required to develop and implement jointly an integrated management plan (IMP) within three to five years of that designation.

- A key goal of each IMP must be to manage all hydrologically connected ground water and surface water for the purpose of sustaining a balance between water uses and water supplies so that the economic viability, social and environmental health, safety, and welfare of the basin, subbasin, or reach can be achieved and maintained for both the near and long term. In the overappropriated portions of the state, the IMP must provide for a reduction in current levels of water use so that it is possible to achieve a balance between water uses and water supplies.

- IMPs may rely on a number of voluntary and regulatory controls, including incentives, allocation of ground water withdrawals, rotation of use, and reduction of irrigated acres, among others.

- If disputes between the Department and the NRDs over the development or implementation of an IMP cannot be resolved, the Governor will appoint a five-member Interrelated Water Review Board to resolve the issue.

Since the passage of LB 962, a number of basins, subbasins, or reaches have been designated as fully or overappropriated (figures 2-1 and 2-2). Previous statutorily required reports on the evaluation of hydrologically connected water supplies are available online (http://www.dnr.ne.gov/docs/studiesandresearch.html) or upon request from the Department. This volume is the fourth statutorily required annual report.

Figure 2-1 Areas designated as fully appropriated or overappropriated basins, subbasins, and reaches since the passage of LB 962.

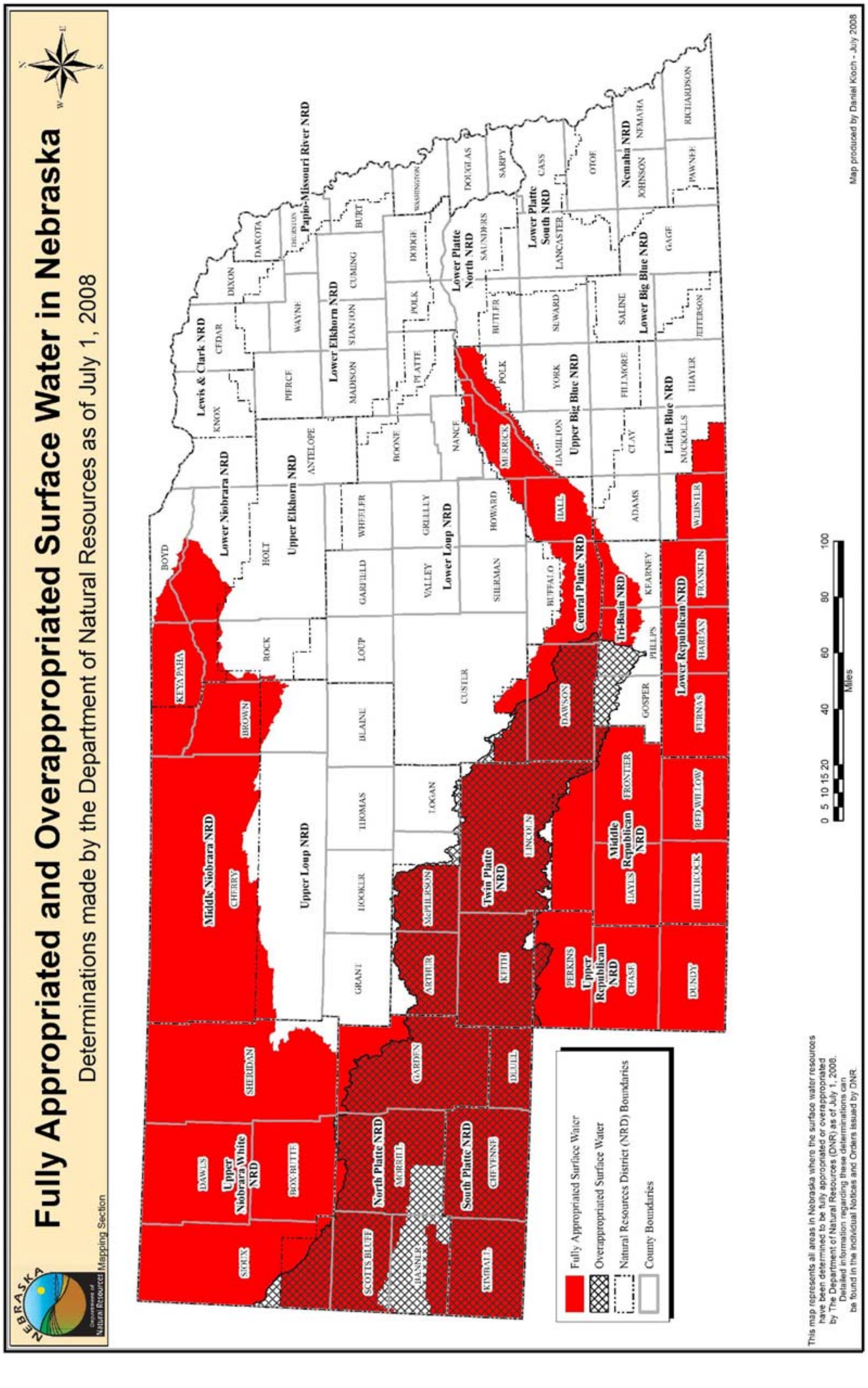
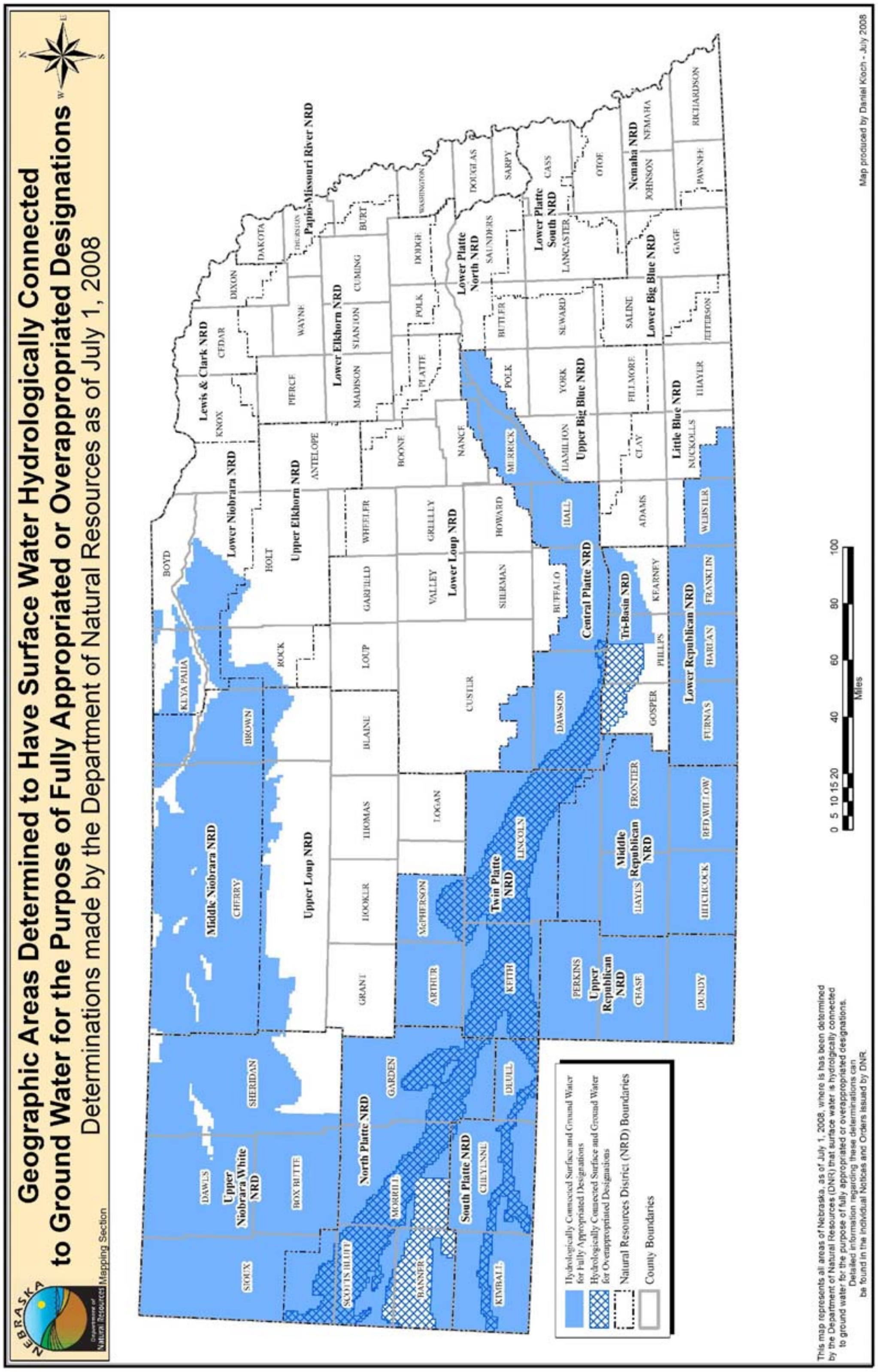


Figure 2-2 Areas designated as hydrologically connected to fully appropriated or overappropriated basins, subbasins, and reaches since the passage of LB 962.



3.0 LEGAL REQUIREMENTS

3.1 Section 46-713(1)(a) – Annual Evaluation and Report Required

A river basin's hydrologically connected water supplies include the surface water in the watershed or catchment that runs off to the stream and the ground water that is in hydrologic connection with the stream. For all evaluated basins, the geographic areas of hydrologically connected surface water and ground water, where present, are shown on a basin-wide map that is included in each basin subsection. On each of those maps, the surface watershed basin is shown by a solid line, and the hydrologically connected ground water portion of the basin is depicted by a shaded area.

Surface water supplies are considered to be hydrologically connected to a stream or stream reach if the surface water drains to that stream or reach. In accordance with Department rule 457 N.A.C. 24.001.02, the Department considers the area within which ground water is hydrologically connected to a stream to be that area in which "pumping of a well for 50 years will deplete a river or base flow tributary thereof by at least 10% of the amount pumped in that time" (i.e., the "10/50 area"). For the purposes of evaluation, a river basin may be divided into two or more subbasins or reaches. Only those basins that have not initiated development of or implemented an IMP are required to be evaluated.

In preparing its annual report, the Department is required by section 46-713(1)(d) to rely on the best scientific data, information, and methodologies readily available to ensure that the conclusions and results contained in the report are reliable. A list of the information the Department uses can be found in rule 457 N.A.C. 24.002 (Appendix B). The Department is also required to provide enough documentation in the report to allow others to replicate and assess the Department's data, information, methodologies, and conclusions independently. That documentation can be found throughout the report. The raw data used for these calculations and the spreadsheets with the calculations will be provided by the Department upon request.

3.2 Section 46-713(1)(b) – Conclusions Following Basin Evaluations

As a result of its annual evaluation, the Department is to arrive at a conclusion as to whether or not each river basin, subbasin, and reach evaluated is currently fully appropriated without the initiation of additional uses. The Department is also required to determine if and how its conclusions would change if no additional legal constraints were imposed on future development of hydrologically connected surface water and ground water. This determination is based on reasonable projections of the extent and location of future development in a basin.

3.3 Section 46-713(3)-Determination that a Basin is Fully Appropriated

The Department must make a final determination that a basin, subbasin, or reach is fully appropriated if the current uses of hydrologically connected surface and ground water in the basin, subbasin, or reach cause, or will in the reasonably foreseeable future cause, either (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural-flow or storage appropriations were granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved, or (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, other formal state contract or agreement, or applicable state or federal laws. Since these factors must be considered in making the final determination, they must also be part of the Department's considerations in reaching its conclusions.

The Department considered whether or not condition (c) would be met with regard to interstate compacts by reviewing the terms of any compacts in each basin and determining when noncompliance would occur if there were sufficient reductions in streamflow. There were no decrees, formal state contracts, or agreements in any of the basins evaluated this year; there is one interstate compact covering the Blue River basins.

With regard to noncompliance with state and federal law, it was determined that only the state and federal laws prohibiting the taking of threatened and endangered species could raise compliance issues that would trigger condition (c). The federal Endangered Species Act (ESA), 16 U.S.C. §§ 1530 *et seq.*, prohibits the taking of any federally listed threatened or endangered species of animal by the actual killing or harming of an individual member of the species (16 U.S.C. § 1532) and by degrading or destroying a species' habitat so much that the species cannot survive (50 CFR § 17.3). The state Nongame and Endangered Species Conservation Act (NNESCA), Neb. Rev. Stat. §§ 37-801 *et seq.*, also prohibits the actual killing or harming of an individual member of a listed species, but state law is not clear as to whether the degradation of a species' habitat is also considered a taking. It was concluded that any reductions in flow that may occur as a result of not determining a basin, subbasin, or reach to be fully appropriated will not cause noncompliance with either federal or state law at this time in any of the basins evaluated.

Prior to making its final determination, the Department must also hold a public hearing on its preliminary conclusions and consider any testimony and information given at the public hearing or hearings.

4.0 METHODOLOGY

Overview

This section provides an overview of the methodologies used in the Department's basin evaluations and is separated into four subsections. The first subsection will outline the legal requirements established in section 46-713 of the Ground Water Management and Protection Act and regulation 457 N.A.C. 24.001 (Appendix B) as they relate to the analysis. Subsection two will discuss the various methods available to assess stream depletions in hydrologically connected regimes and explain when specific methods were implemented by the Department. Subsection three will discuss the specific methods implemented by the Department to calculate the extent of the 10/50 area. The fourth subsection will proceed through the steps used in the evaluation of each basin.

4.1 Legal Obligation of the Department

4.1.1 The Legal Requirements of Section 46-713

The methodologies used for evaluation within this report were developed to meet the requirements of section 46-713 of the Act. The criteria set forth in section 46-713 require the Department to 1) describe the nature and extent of surface and ground water uses in each river basin, subbasin, or reach; 2) define the geographic area within which surface water and ground water are hydrologically connected; 3) define the extent to which current uses will affect available near-term and long-term water supplies; and 4) determine how conclusions, based on current development, would change if no additional legal constraints were imposed on reasonable projections of future development.

The description of the nature and extent of surface and ground water uses is developed based on information obtained through published reports from the University of Nebraska-Conservation and Survey Division (CSD), the U.S. Geological Survey (USGS), natural resources districts, Department databases, and other sources as noted in the text. The information represents the most current publications available. These data include information on transmissivity, specific yield, saturated thickness, depth to water, surficial geology, bedrock geology, water table elevation change, and test-hole information. These data are available on the UNL-Conservation and Survey Division and U.S. Geological Survey websites, http://snr.unl.edu/csd/ and http://waterdata.usgs.gov/ne/nwis/gw, respectively. All data utilized in this report are available from the Department upon request.

The Department is tasked with assessing the geographic area within which surface water and ground water are hydrologically connected. Regulation 457 N.A.C. 24.001.02 states that the geographic area within which the ground water and surface water are hydrologically connected is determined by calculating where, in each river basin, a well would deplete a river's flow by 10% of the amount of water the well could pump over a fifty-year period (i.e., "the 10/50 area").

The Department's evaluation of the extent to which current uses will affect available near-term and long-term water supplies considers current well development and the twenty-five-year lag impacts from that current development on surface water flows. For the purposes of this report, lag impacts are defined as the delayed effect that the consumptive use of water associated with well pumping will have on hydrologically connected streamflow and the associated impact on surface water appropriations.

The Department is also required to assess how its conclusions, based on current development, might change by predicting future development. The predictions of future development account for existing wells and wells that may be added in the next twenty-five years. In projecting the quantity of wells that may be added to the number of currently developed wells, the Department considers the following: 1) availability of lands suitable for irrigation; 2) well-construction moratoriums established by natural resources districts; and 3) trends in well development over the previous ten-year period.

4.1.2 Regulation 457 N.A.C. 24.001

Regulation 457 N.A.C. 24.001 generally states that a basin is fully appropriated if current uses of hydrologically connected surface water and ground water in a basin cause, or will cause in the reasonably foreseeable future, (a) the surface water to be insufficient to sustain over the long term the beneficial purposes for which the existing surface water appropriations were granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the basin's river or stream, or (c) reduction in streamflow sufficient to cause Nebraska to be in noncompliance with an interstate compact or decree, formal state contract, or state or federal laws.

In short, regulation 457 N.A.C. 24 states that the surface water supply is deemed to be insufficient if, at current levels of development, the most junior irrigation right in a basin, subbasin, or reach has been unable to divert sufficient surface water over the last twenty years to provide 85% of the amount of water a corn crop needs (the net corn crop irrigation requirement, or NCCIR) during the irrigation season (May 1 through September 30), or if the most junior irrigation right in a basin, subbasin, or reach is unable to divert 65% of the amount of water a corn crop needs during the key growing period of July 1 through August 31. For the purposes of this report, this is deemed the "65/85 rule".

If the requirements of the 65/85 rule are not satisfied, then the final step in a conclusion of whether a basin is fully appropriated is to apply what has been termed the "erosion rule" (457 N.A.C. 24.001.01C). This rule takes into account the fact that appropriations may be granted even though sufficient water is not available at the time they are granted to provide enough water for diversion to satisfy the requirements of the 65/85 rule. If an appropriation is unable to divert enough water to satisfy the requirements of the 65/85 rule, a second evaluation is completed to determine if the right has been “eroded.” According to regulation 457 N.A.C. 24.001.01B, in the event that the junior water right is not an irrigation right, the Department will utilize a standard of interference appropriate for the type of water use to determine whether flows are sufficient for that use, taking into account the purpose for which the appropriation was granted.

4.2 Methods Available for Assessing Stream Depletions

Several methods are available for estimating the extent and magnitude of stream depletions. Historically, three broad categories have been used to study ground water flow systems - sand tank models, analog models, and mathematical models, which include analytical models and numerical models. The first two methods were primarily used prior to the advent of modern, high-speed, digital computers. Since the advent of computers, analytical and numerical models have become the preferred methods for evaluating ground water flow. Limitations of each method must be considered by the user when examining the results of analyses and the appropriateness of each method for a given task.

4.2.1 Numerical Modeling Methods

With user-friendly interfaces and high-speed computers, numerical models have fast become the preferred method of evaluating regional ground water flow. One widely used numerical model developed by the U.S. Geological Survey is MODFLOW (McDonald and Harbaugh, 1988). For the purposes of this report, if an acceptable MODFLOW model suitable for regional analysis is available, then it will be utilized to assist in analysis. The areas for which an existing model was utilized in this year’s evaluation were the Blue basins, Loup Basin, and portions of the Elkhorn Basin.

The remaining basins discussed in this report are not currently represented in a suitable numerical model. Development of a numerical model requires a substantial amount of quality-assured data. Current data collection efforts may allow for suitable model development for these basins in the future. At present, however, analytical methods are the best available tool for the analysis of stream depletions within these basins.

4.2.2 Analytical Methods

Analytical methods for the analysis of streamflow depletions have been developed by Glover and Balmer (1954), Maasland and Bittinger (1963), Gautuschi (1964), and others to evaluate the impacts of wells on streams. The Jenkins (1968) method for calculation of stream depletion factors (SDF) (Appendix C) lends itself best to the basin-wide aspect of the task described by this report. This method is based on simplifying assumptions and was built upon previously published equations. The Jenkins method has been utilized by other states, including Colorado and Wyoming, for water administration purposes. For this report, the Jenkins method was used in the evaluation of the Lower Niobrara River Basin, portions of the Lower Platte River Basin, and Missouri Tributary basins.

Modified versions of the Jenkins method have been developed to address more complex situations, such as the presence of boundary conditions (Miller and Durnford, 2005) and a streambed (Zlotnik, 2004). These modified methods, however, require additional data that are generally not available for the basins in this evaluation. The dominant factors in determining the impact of a pumping well on a stream are the distance of the well from the stream and the length of time that the well is pumped. Thus, the impact of any other differences between actual hydrologic and geologic conditions and the idealized assumptions used in the Jenkins method decreases as the distance from the stream and any relevant boundary conditions and duration of pumping increase. Therefore, when looking at regional impacts, the simplifying assumptions of the Jenkins method are much less significant. For this reason, and because of a lack of published data necessary for the calculations, no modifications were made to the Jenkins method for the Department's analysis.

In some areas of the state, particularly in the glaciated eastern sections, information regarding hydrologic conditions is inadequate, and no method currently available can be used to determine the 10/50 area or the lag impact of ground water pumping from wells. These areas were not evaluated in the current report.

4.3 Development of the 10/50 Areas

The 10/50 area is defined as the geographic area within which ground water is hydrologically connected to surface water. A well constructed in the 10/50 area would deplete river flow by at least 10% of the water pumped over a fifty-year period. The 10/50 areas are not dependent on the quantity of water pumped, but rather on each basin's geologic characteristics and the distance between each well and the stream.

4.3.1 Use of Numerical Models

The Department reviewed available numerical models to assess their validity in defining the 10/50 area, predicting future lag impacts, and impacts from additional future development. Two models were identified as being qualified for use in this report. The Elkhorn-Loup model was developed through a joint partnership of various natural resources districts, the U.S. Geological Survey, and the Department. The Elkhorn-Loup model was used to define the extent of the 10/50 area and predict future lag impacts from current well development and projected future development for the Loup Basin and portions of the Elkhorn Basin. The Upper Big Blue Natural Resources District developed a numerical MODFLOW ground water model using Cooperative Hydrology Study (COHYST) data to delineate the extent of the 10/50 area hydrologically connected to the Little Blue River. Documentation for both of these ground water models is available in Appendix E.

4.3.2 Use of Analytical Methods

In areas where an acceptable numerical model has not been developed but where sufficient geologic data exist, (portions of the Lower Platte Basin, Missouri Tributaries basins, and Lower Niobrara Basin) the Jenkins SDF methodology was used to define the 10/50 area. The following steps were taken to calculate the extent of the 10/50 area:

1. Collect and prepare data (data will be provided by the Department upon request).
2. Evaluate available data to determine if the principal aquifer is present and if sufficient data exist to determine that a given stream reach is in hydrologic connection with the principal aquifer.
3. Complete Jenkins SDF calculations to delineate the 10/50 boundary for these basins.
4. Develop the 10/50 area.

In all other areas, where sufficient data do not exist or where the principal aquifer is not present, the 10/50 area could not be determined.

Step 1: Data Preparation

The following data are necessary for determining the extent of the 10/50 area:

- Aquifer transmissivity
- Aquifer specific yield
- Locations of perennial streams
- Point grid of distances to streams

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 (CSD, 2005).

The location and extent of perennial streams were found in the permanent streams GIS coverage available from the U.S. Geological Survey National Hydrography Dataset. The main stems of each river and of its perennial tributaries were included in the calculations for individual basins.

A point grid with a spacing of one mile was developed to identify specific distances from the stream and to store those locations which were within the 10/50 area.

Step 2: Identify Principal Aquifers and Hydrologic Connection to Perennial Streams

The extent of hydrologic connection between aquifers and streams was primarily determined from maps generated by the Conservation and Survey Division (CSD, 2005). Other supporting evidence from published reports was also used in some cases to delineate the extent of hydrologic connection between aquifers and streams, and this information is referenced where used.

Step 3: Perform Jenkins SDF Calculations

The Jenkins SDF method utilizes the following two terms, for which solutions are derived graphically using the curve shown in Figure 4-1.

Depletion percentage term: v/Qt

Dimensionless term: $\frac{t}{sdf}$

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

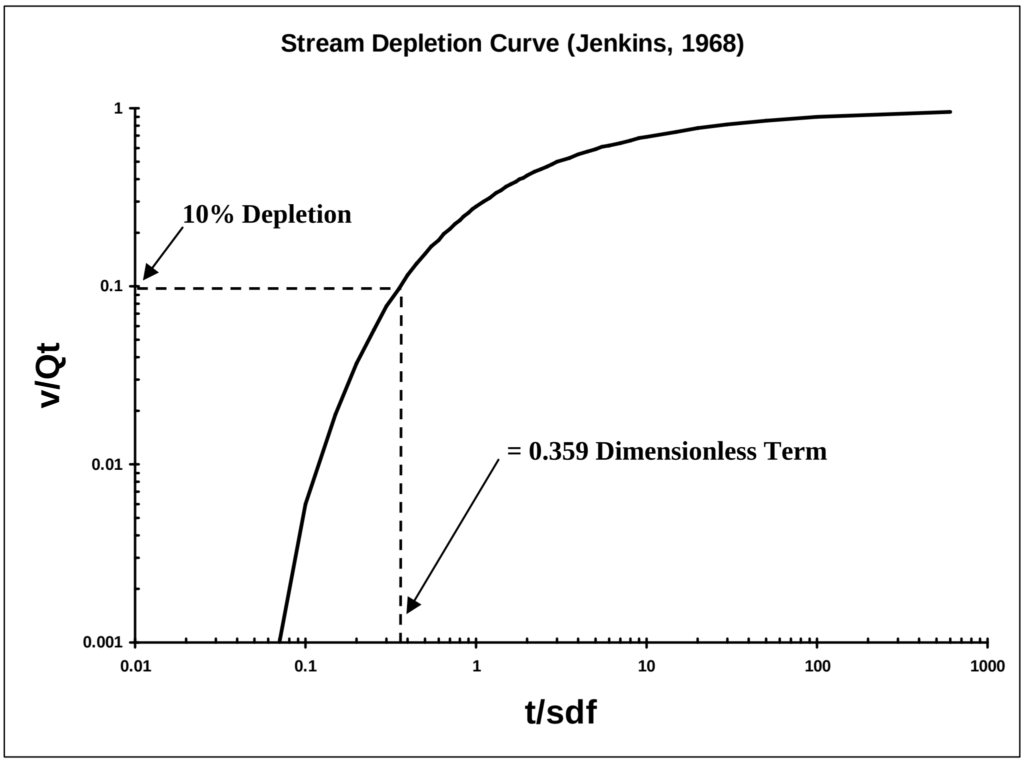
$$sdf = \frac{a^2 * S}{T}$$

where a = perpendicular distance between the well and stream

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

T = average transmissivity of the aquifer between the well and the stream

Figure 4-1 Stream depletion curve from Jenkins (1968).

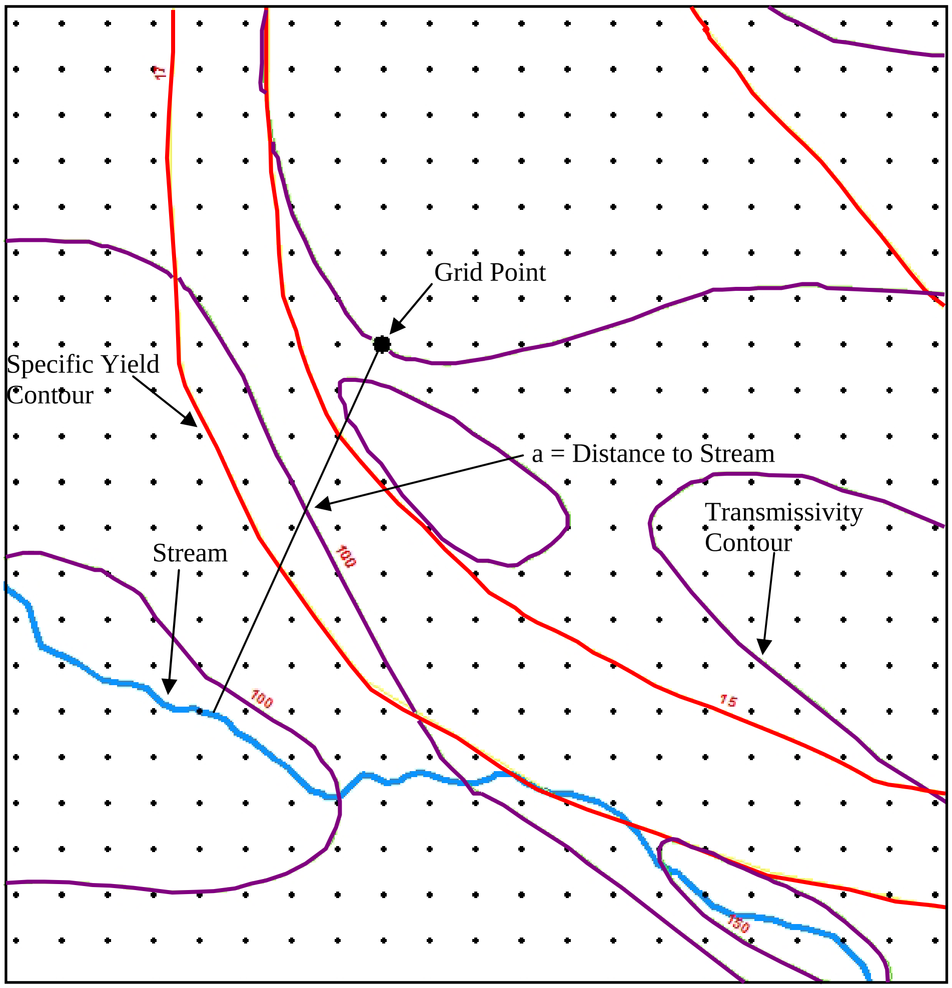


As illustrated in Figure 4-1, the dimensionless term will equal 0.359 when the depletion percentage is equal to 10%. The aquifer properties at each grid point and the distance of each grid point from the nearest perennial stream will be utilized to calculate the dimensionless term (Figure 4-2).

The known values for the 10/50 calculation are as follows:

- t is 50 years, or 18,262 days.
- T is the aquifer transmissivity.
- S is the aquifer specific yield.
- a is the perpendicular distance from the grid point to the nearest perennial stream.

Figure 4-2 An example of the data and method used in determination of the 10/50 area.



Step 4: Developing the 10/50 Area

Once the value for the dimensionless term is derived, those grid points with a dimensionless term value greater than 0.359 are included as part of the 10/50 area. All points that meet this requirement are merged to develop the complete 10/50 area for the basin.

4.4 Evaluating the Status of a Basin

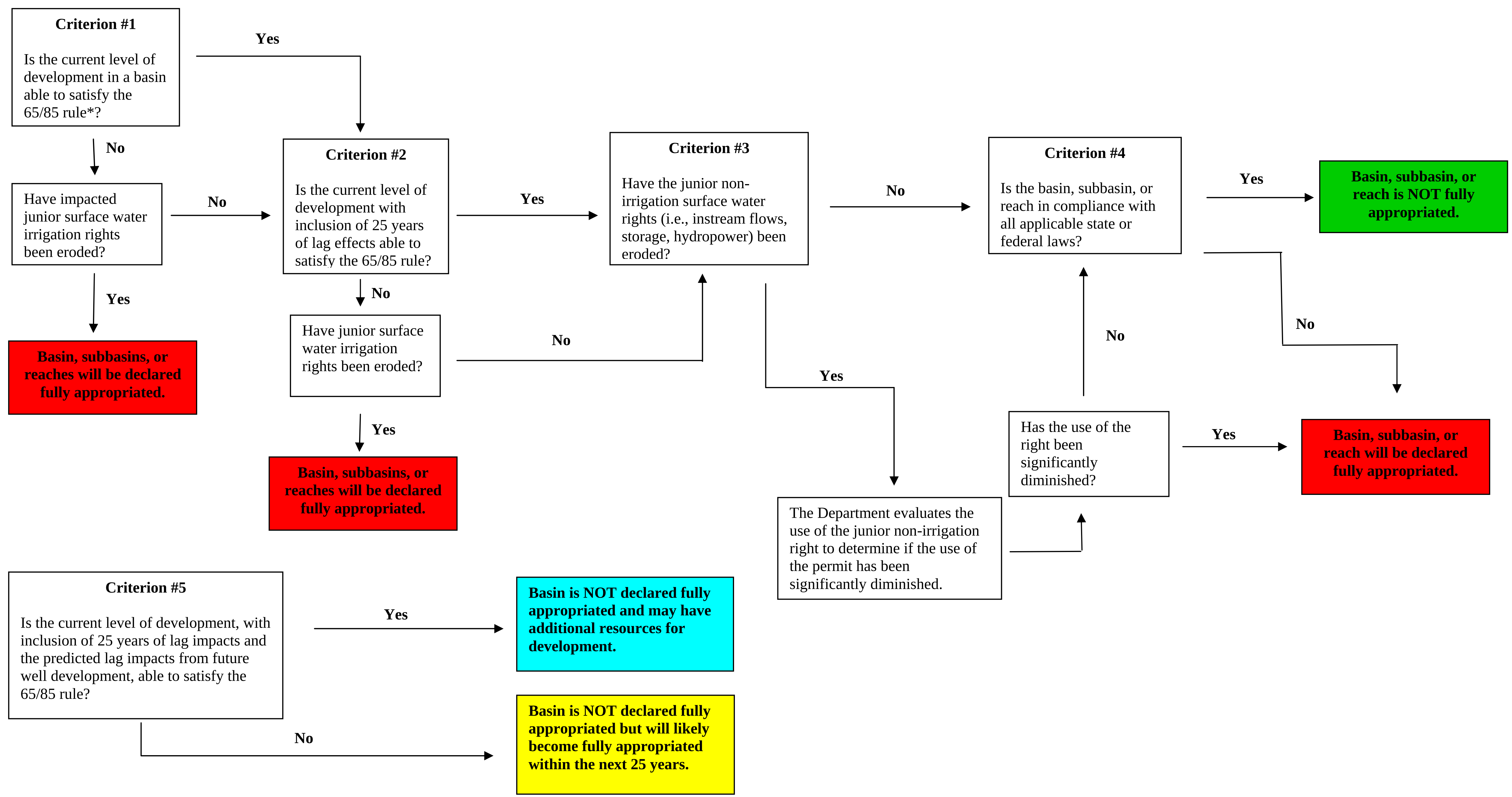
When determining the status of a basin, the Department evaluates five criteria: 1) that current levels of surface water and ground water development, without consideration of lag impacts from wells, are able to satisfy the 65/85 rule; 2) that current levels of surface water and ground water development, with consideration of twenty-five-year lag impacts, are able to satisfy the 65/85 rule; 3) that erosion of non-irrigation surface water rights, based on the standard of interference established by the Department, has not occurred; 4) that the basin, subbasin, or reach is in compliance with all applicable state and federal laws; and 5) that future development (including lag impacts) of ground water in the basin will not cause the basin to be unable to satisfy the 65/85 rule.

If criteria one and/or two are unable to be satisfied, then an additional test, the "erosion rule", is applied to junior irrigation rights. This is used to evaluate whether the ability to divert water by the most junior surface water appropriation has been eroded. Methods for implementation of the erosion rule are discussed in detail in Section 4.4.5. Figure 4-3 illustrates the evaluation process for determining whether a basin is fully appropriated.

Figure 4-3 Basin evaluation flow chart.

Evaluation of the Status of a Basin

Future Development



***In general terms, the 65/85 rule states that the surface water supply is deemed to be insufficient if, at current levels of development, the most junior irrigation right in a basin, subbasin, or reach has been unable to divert sufficient surface water over the last twenty years to provide 85% of the amount of water a corn crop needs (the net corn crop irrigation requirement) during the irrigation season (May 1 through September 30), or if the most junior irrigation right in a basin, subbasin, or reach is unable to divert 65% of the amount of water a corn crop needs during the key growing period of July 1 through August 31.**

Failure to satisfy criteria one, two, three, or four will cause a basin to be declared fully appropriated. Failure to satisfy criterion five alone will not cause a basin to be declared fully appropriated, but such failure would indicate that future development may cause the basin to become fully appropriated if current development trends continue.

4.4.1 The Role of Surface Water Administration Doctrine

The administration of surface water plays a key role in evaluating the sustainability of development within a basin, subbasin, or reach. Surface water appropriations in Nebraska are administered under the doctrine of prior appropriation. The basis for the doctrine is “first in time, first in right.” When surface water is in short supply in a basin, subbasin, or reach, the surface water appropriation with a senior priority date has the right to use any available water for beneficial use, up to its permitted limit, before any upstream junior surface water appropriation can use water. To exercise a senior right, the senior water appropriation will put a call on the stream; the Department will investigate the streamflows and, if necessary, issue closing orders to the upstream junior water appropriations, starting with the most junior right.

Although additional surface water development in a basin will deplete the overall surface water supplies during times when excess surface water is available, under the priority system a junior right cannot cause a senior surface water appropriation’s supply to be reduced. When the Department administers for a calling senior surface water appropriation, all upstream junior surface water appropriations, starting with the most junior appropriator, are shut off in order of priority, no matter how far upstream, until the calling senior surface water appropriation is satisfied. Therefore, in areas where surface water administration is already occurring, additional surface water development will not reduce the number of days surface water is available for diversion by a senior surface water appropriation. In areas that have not experienced surface water administration, it is not feasible to predict the point at which additional surface water development may cause surface water administration to occur.

The priority doctrine which governs surface water administration ensures that, if sufficient water is available for the most junior irrigation appropriation, then all irrigation appropriations will be satisfied. Therefore, the Department analyzed the water available to the most junior appropriator in each basin evaluation. When making the calculation of the number of days that surface water was available to the most junior irrigation surface water appropriator, the Department assumed that, if the junior appropriator was not closed, then he or she could have diverted at the full permitted diversion rate.

4.4.2 Evaluation of Current Water Supplies

The first criterion assessed to determine whether a basin is fully appropriated is to evaluate if the current water supply is sufficient to satisfy the 65/85 rule. The current water supply is estimated based on the most recent twenty-year period of streamflows (1988-2007). The following steps were taken to determine if current water supplies are sufficient to satisfy the 65/85 rule:

1. Determine the level of surface water administration that has occurred in each basin for the past 20 years.
2. Determine the crop irrigation requirement for junior irrigators subject to the administration.
3. Determine the number of days of diversion necessary to satisfy the 65/85 rule.
4. Compare the number of days available for diversion to the number of days necessary to satisfy the 65/85 rule.

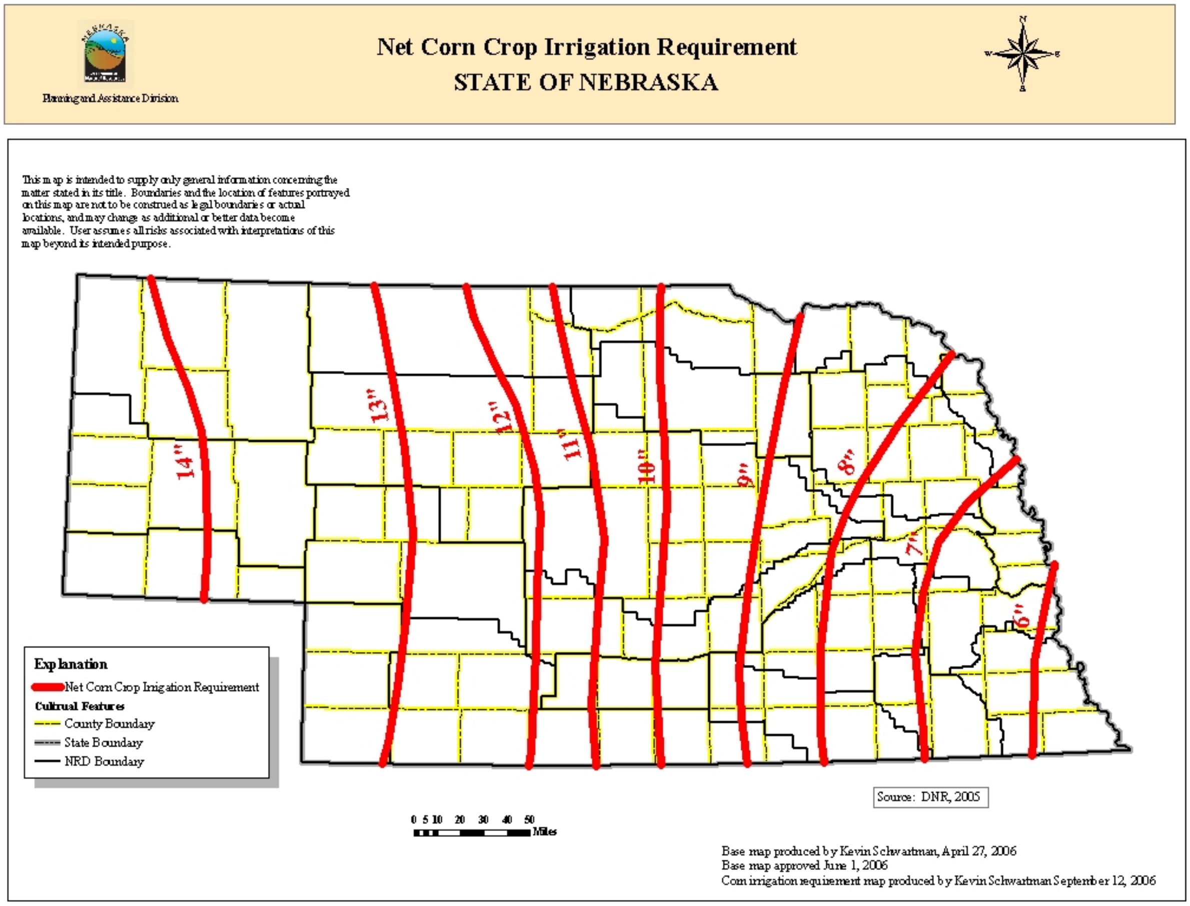
Step 1: Determine the Level of Surface Water Administration in the Past Twenty Years

The level of surface water administration is determined based on Department records for calls for administration for the previous twenty years (1988-2007). The calls for administration are used to develop a twenty-year average number of days for which administration was not occurring (days available for diversion). The days available for diversion are categorized based on the months in which they are available. Days that are available for diversion during July and August are categorized as available to meet the 65 portion of the 65/85 rule and days that are available for diversion during May, June, July, August, and September are categorized as available to meet the 85 portion of the 65/85 rule.

Step 2: Determine the Crop Irrigation Requirement

The net corn crop irrigation requirement (NCCIR) was developed to estimate the average minimum consumptive allocation of water necessary to yield a profitable corn crop to an individual operator. The NCCIR is used to determine the number of diversion days required for the most junior surface water appropriation to satisfy irrigation needs under the 65/85 rule (see Section 4.1.2). In developing the NCCIR, corn is used as the baseline crop because the most frequent beneficial use of water in all of the basins evaluated is for the irrigation of corn. The NCCIR accounts for the average evapotranspiration and average precipitation in an area and generally decreases from northwest to southeast across the state (Figure 4-4). The NCCIR distribution for each basin is set out in individual basin subsections. The method of developing the NCCIR is described in Appendix F.

Figure 4-4 Net corn crop irrigation requirement.



Step 3: Determine the Number of Days Necessary for Diversion

To determine a junior irrigator's diversion requirements, the NCCIR is converted to the number of days necessary for an operator to divert water to yield a profitable corn crop using these assumptions: 1) a downtime of 10%, due to mechanical failures and other causes; 2) a diversion rate of 1 cubic foot per second (cfs) per 70 acres (or 0.34 inches/day), as this is the most common rate approved by the Department for surface water appropriations; and 3) an irrigation efficiency of 80%. The steps to determine the number of days necessary for a specific operator to divert include the following:

1) Determine the geographic location of the operator.

2) Interpolate between the NCCIR contours to determine the specific need of the operator.

3) Multiply the NCCIR by 0.65 and 0.85 to find the 65% and 85% requirements.

4) Calculate the gross irrigation requirement by dividing the values from step 3 by 0.8 (the irrigation efficiency).

5) Divide the gross irrigation requirement by 0.34 inches per day (rate of diversion) and by 0.9 (to account for downtime) to determine the number of days of diversion necessary for an operator.

$$\text{Number of days necessary} = \frac{\text{gross requirement}}{(0.34)(0.9)}$$

Step 4: Compare the Number of Days Available for Diversion to the Number of Days Necessary for the Junior Irrigator to Satisfy the 65/85 Rule

The results of the calculation in Step 3 are compared against the results of Step 1 (the average number of days over the previous twenty-year period (1988-2007) that surface water was available for diversion) to evaluate whether a basin is fully appropriated. If the average number of days available for diversion is less than the number of days necessary to meet either the 65% or 85% criteria, then the basin, subbasin, or reach may be declared fully appropriated.

This test is the first criterion in the five-tiered test described at the beginning of Section 4.4. If the basin satisfies this test, then the second criterion is evaluated: the addition of lag impacts from current development.

4.4.3 Evaluation of Long Term Water Supplies

The second criterion assessed to determine whether a basin is fully appropriated is to evaluate if the long term water supply is sufficient to satisfy the 65/85 rule. The long term water supply is estimated based on the most recent twenty-year period of streamflows (1988-2007) and the lag impacts from current levels of well development. In those basins for which the appropriate geologic and hydrologic data were available and no numerical models exist; the following steps were taken to compute the lag impact from current development:

1. Define the ground water boundary for the study area.
2. Extract all high capacity wells from the Department’s database with a completion date prior to December 31, 2007.
3. Account for current year’s development.
4. Estimate the volume of water pumped from each well.
5. Calculate the twenty-five-year lag impacts.
6. Create lag-adjusted flow record.
7. Determine number of diversion days available.

In those basins for which an appropriate numerical model exists (e.g., the Loup River Basin and portions of the Elkhorn River Basin), the lag impacts were calculated using the numerical model. In those basins for which the appropriate geologic and hydrologic data were not available, the lag impacts were not calculated, due to uncertainty of the degree of hydrologic connection. In many of those cases, the number of days in which surface water is available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement, and the final conclusion would likely not change even with the addition of lag impacts.

Step 1: Define the Study Area Boundaries

The study area surface water boundary for each river basin is defined by the watershed boundary. The study area ground water boundary is defined by certain features that include the location of perennial baseflow streams, location of non-hydrologically connected areas, and ground water table highs that prevent flow to the stream of interest.

An individual well may fall into multiple basin study areas. If a well falls within multiple basin study areas, its total stream depletion is divided by the number of basin study areas that it intersects. For example, if a well falls into two basin study areas, the depletion is divided by 2. This prevents overestimation of depletions in overlapping areas. A sufficient number of wells in an overlapping area will likely, on average, be halfway between the two basins. Because SDF methodology is distance-based, splitting the depletion in half and assigning half of the total depletion to each basin is justified.

Step 2: Identify High Capacity Wells within the Study Area

In calculating lag impacts, the Department evaluates only high capacity wells, considered to be those wells with a pumping rate of greater than fifty gallons per minute (gpm). High capacity wells include active irrigation, industrial, public water supply, and unprotected public water supply wells (public water supply wells without statutory spacing protection). Other wells, such as decommissioned or inactive high capacity wells, livestock watering wells, and domestic wells were not included, because the Department's water well registration database is not complete for those well types. This omission is not considered significant, because these wells use relatively small amounts of water. All active high capacity wells with a completion date prior to December 31, 2007, were used in the analysis.

Step 3: Account for Current Year (2008) Development

Wells are not registered simultaneously with their completion date, so it was necessary to estimate the number of high capacity wells that will be registered as constructed between January 1, 2008, and

December 31, 2008. The first step in estimating the number of high capacity wells for 2008 is to average the well development rates within a basin over the previous three-year period (2005-2007), taking into account known limitations, such as moratoriums, on well development. Based on the rates, additional wells are randomly located geographically within the study area on soils that have been defined by the U.S. Department of Agriculture as irrigable. To ensure that land was available for development, a 1,400-foot-radius circle (slightly larger than the radius of an average center pivot) was drawn around each active high capacity well existing in the Department's water well registration database. All lands within the circles were removed from the inventory of irrigable land available for development. In addition, all irrigable land areas of less than forty acres in size that were available for new development were excluded. The wells extracted from the Department's water well registration database with a completion date prior to December 31, 2007, and those estimated to be developed in each basin for 2008 were then combined to serve as the basis for current well development.

Step 4: Estimate the Volume Pumped by Each Well

The volume pumped from a well for consumptive use (Qt) is determined by multiplying the NCCIR (see Section 4.4.2) by the number of acres irrigated by the well. The number of acres irrigated by each well was estimated to be ninety acres, for reasons documented in Appendix G (DNR, 2005). Industrial and public water supply wells are treated the same as irrigation wells for this analysis.

Example:

If Location of well: Custer County, Nebraska

NCCIR requirement (from Figure 4-4): 11 inches/year

Number of acres served: 90 acres

Then Qt: 11 inches/year * 90 acres = 990 acre-inches/year or 82.5 acre-feet/year

Step 5: Calculate Twenty-Five-Year Lag Impacts

The Jenkins SDF methodology is utilized to estimate the twenty-five-year lag impacts to streamflows due to current well development. The Jenkins SDF methodology allows for calculation of the streamflow depletion percentage of each well in the basin. The terms used in this methodology include the depletion percentage term and the dimensionless term, both defined below:

Depletion percentage term: v/Qt

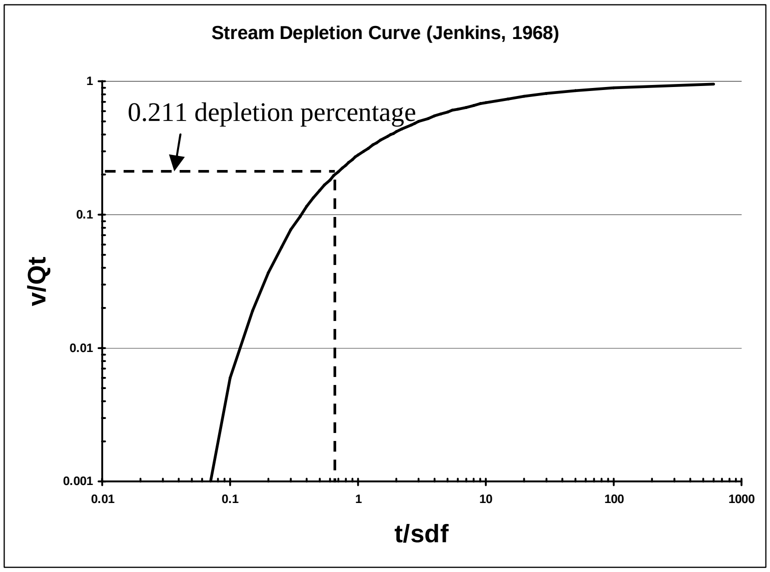
Dimensionless term: $\frac{tT}{a^2S}$ or $\frac{t}{sdf}$

The goal of this analysis is to solve for the 'v' term, or the volume of stream depletion (in acre-feet/year) over the twenty-five-year period. First, the dimensionless term is calculated using the following known variables:

- t is the time since the well was completed (2008-well completion year).
- T is the aquifer transmissivity.
- S is the aquifer specific yield.
- a is the perpendicular distance from the well to the nearest perennial stream.

Next, the dimensionless term is used to determine the percentage of depletion (v/Qt). For example, if the dimensionless term is equal to 0.7, then the depletion percentage is equal to 0.211, or 21.1% (see Figure 4-5).

Figure 4-5 Determining depletion percentage from the dimensionless term.



Finally, the stream depletion is calculated as follows:

v = Qt * percentage depletion

Where v = stream depletion in acre-feet/year

Qt = volume pumped in acre-feet/year

percentage depletion = value corresponding to the dimensionless term, from the graph in Figure 4-5

The depletion percentage is multiplied by the volume pumped, as calculated in Step Four, to determine total stream depletion. These results can be converted from annual acre-feet of depletion to cubic feet per second (cfs) by dividing by 724.46 (the conversion factor for acre-feet/year to cfs).

The next step is to calculate the twenty-five-year lag impacts. The twenty-five-year lag impacts for all current wells are calculated in a similar way, except that the time period for each well (t) is increased by twenty-five years (9,125 days). The depletion rate calculated in 2008 is subtracted from the depletion rate calculated in 2033 (twenty-five years into the future) to determine the lag impacts. An example of this process is illustrated below (Table 4-1).

Table 4-1 Example calculation of twenty-five-year lag impacts.

<table>
<tr><th>Year</th><th>Cumulative Depletion (cfs)</th><th>Additional Annual Depletion (cfs)</th><th>Lag (cfs)</th></tr>
<tr><td>2007</td><td>100</td><td rowspan="2">10</td><td rowspan="4">20</td></tr>
<tr><td>2008</td><td>110</td></tr>
<tr><td>2032</td><td>300</td><td rowspan="2">30</td></tr>
<tr><td>2033</td><td>330</td></tr>
</table>

Step 6: Create Lag-Adjusted Flow Record

The twenty-five-year lag impacts from all current wells within a basin are summed to generate a total stream depletion figure for the basin. A daily historic flow record is developed from stream gage data for the previous twenty-year period to represent variations in climate and precipitation in the basin. The sum of the lag impacts is subtracted from the daily historic record to develop a new flow record, here termed the “lag-adjusted flow record”.

Step 7: Determine the Number of Days Available for Diversion

The lag-adjusted flow record is used to calculate the average number of days available to the most junior appropriator within the basin for diversion. The new average number of days available for diversion is compared to the number of days necessary for the most junior surface water appropriator to divert in the basin. If the number of days necessary to meet either the 65% or 85% criterion is less than the average number of days available for diversion, then the basin, subbasin, or reach may be declared fully appropriated.

4.4.4 Peer Review of the Methodology

The methodology developed by the Department and described in Sections 4.4.2 and 4.4.3 was independently peer reviewed by the Nebraska Water Science Center of the U.S. Geological Survey in October 2005. The Center concluded, "The NWSC reviewers found the document technically sound." A copy of the peer review transmittal letter is in Appendix D.

4.4.5 Determining Erosion of Rights

If a basin has failed either the first or second criterion (described in Sections 4.4.2 and 4.4.3), then the next step in the Department's analysis is to apply what has been termed "the erosion rule" (457 N.A.C. 24.001.01C). This rule takes into account the fact that appropriations may be granted even though water supplies may be insufficient at the time the appropriation is granted to satisfy the requirements of the 65/85 rule. If an appropriation is unable to divert enough water to satisfy the requirements of the 65/85 rule, then the second evaluation is completed to determine if the right has been "eroded", i.e., if enough water was not available to satisfy the rule at the time the appropriation was granted.

In the event that the junior water right is not an irrigation right, regulation 457 N.A.C. 24.001.01B states that the Department will utilize a standard of interference appropriate for the type of use to determine whether flows are sufficient for the use, taking into account the purpose for which the appropriation was granted.

The erosion rule is applied through the use of historic streamflow data in a two-step process. The first step is to calculate the average number of days the most junior surface water appropriator would have been able to divert during the twenty-year period before the priority date of the appropriation. The second step is to calculate the average number of days the same junior surface water appropriator has been able to divert during the previous twenty years (i.e., 1988-2007). If the number of days available for diversion has decreased, then the right has been eroded. When making these calculations, the Department takes into account the lag effect of wells existing at the time of the priority date, as well as lag impacts from current well development.

The steps for determining whether a right has been eroded are as follows:

1. Gather the daily streamflow records from the twenty-year period prior to the appropriation being granted.
2. Gather the daily streamflow records for 1988-2007 to serve as the current twenty-year period.
3. Determine the twenty-five-year lagged ground water depletions from wells existing on the date the junior surface water appropriation was granted, and subtract them from the daily streamflow record for the twenty-year period prior to the granting of the appropriation.
4. Determine the twenty-five-year lagged ground water depletions from wells existing at the end of the current twenty-year period (using methodologies described in Section 4.4.4), and subtract them from the daily streamflow record for the current twenty-year period (1988-2007).
5. Assume that surface water administration would occur if the flow requirement of a senior surface water appropriation was greater than the depleted historical daily flow.
6. Conduct a month-by-month comparison of the average number of days available for the junior surface water appropriation to divert during the twenty-year period prior to the appropriation and the average number of days available to divert during the current twenty-year period.

If the average number of days available to the junior surface water appropriation for diversion during the current period (1988-2007) is less than the number of days available to the junior surface water appropriation for the twenty-year period prior to the appropriation, then the appropriation may be determined to be eroded.

4.4.6 Evaluation of Compliance with State and Federal Laws

To evaluate compliance with state and federal law, it was determined that, currently, only the state and federal laws prohibiting the taking of threatened and endangered species could raise compliance issues under section 46-713(3)(c). The federal Endangered Species Act, 16 U.S.C. §§ 1530 *et seq.*, prohibits the taking of any federally listed threatened or endangered species of animal by the actual killing or harming of an individual member of the species (16 U.S.C. § 1532) and by degrading or destroying a species' habitat so much that the species cannot survive (50 CFR § 17.3). The state Nongame and Endangered Species Conservation Act, Neb. Rev. Stat. §§ 37-801 *et seq.*, also prohibits the actual killing or harming of an individual member of a listed species, but it is not clear whether the degradation of a species' habitat is considered a taking under state law. For this year's report it was concluded that a reduction in streamflow will not cause noncompliance with either the federal or state endangered species laws in any of the basins evaluated at this time.

4.4.7 Evaluating Predicted Future Development in a Basin

The Department is required by section 46-713 to project the impact of reasonable future development within a basin on the potential for fully appropriated status. The results of this analysis alone cannot cause a basin to be declared fully appropriated. The analysis does, however, provide an estimate of the effects of current well development trends on the basin's future status.

The steps necessary to calculate the impacts of future development on streamflows parallel the steps outlined in Section 4.4.3. The specific steps necessary to conduct an analysis of the impacts of future well development on the status of a basin are as follows:

- Gather information on lag impacts of current wells (from calculations performed in Section 4.4.3).
- Project the rate of future well development.
- Incorporate projected future well development into the study area.
- Calculate the depletions of projected future well development.
- Subtract the depletions of projected future well development from the previous twenty-year lag-adjusted flow record (1988-2007), and recalculate the number of days available for diversion for the most junior surface water appropriation.

Step 1: Gather Information on Lag Impacts of Current Wells

The lag impacts from current well development are determined as outlined in Section 4.4.3 above, and the lag-adjusted flow record developed in Step 7 of Section 4.4.3 is that discussed in this section. In using the lag-adjusted flow record, the twenty-five-year lag impacts of current well development are accounted for, and the impacts from future wells can be removed directly from this new flow record.

Step 2: Project Future Well Development

When calculating impacts from future wells, the rate of future well development must be estimated. This estimation is completed by projecting the linear trend of current high capacity well development within a study area over the previous ten years (1998-2007). The yearly estimated well development for the study area is equivalent to the slope of the trend line and takes into account known limitations, such as moratoriums, on well development.

Step 3: Incorporate Future Wells into the Study Area

The number of future wells estimated in Step 2 above must be incorporated into the study area. The future wells are located geographically within the study area by randomly placing each future well on a site where the soils have been defined by the U.S. Department of Agriculture as irrigable. To ensure that land was available for development, a 1,400-foot-radius circle (slightly larger than the radius of an average center pivot) was drawn around every existing well, and all lands already irrigated within the circles were removed from the inventory of irrigable lands that are available for development. In addition, all irrigable land areas of less than forty acres in size that are available for new development were excluded.

Step 4: Calculate the Lag Impacts of Future Wells

Depletions from future wells are calculated following the same methodology outlined in Section 4.4.3. The depletions of future wells are calculated independently of current well development. The twenty-five-year depletions from future well development are removed from the lag-adjusted flow record created in Step 7 of Section 4.4.3 to develop the future lag-adjusted flow record.

Step 5: Create a Historic Flow Record with Lag Impacts from Current and Future Well Development

The historic record, with the twenty-five-year lag impacts from all current wells created at the end of Step 5 in Section 4.4.3 subtracted (i.e., the lag-adjusted flow record), is used as the starting point in developing the future lag-adjusted flow record. The depletions from future wells incorporated into the study area are calculated for each year through the twenty-five-year period and subtracted from the lag-adjusted flow record.

The sum of the future depletions is subtracted from the lag-adjusted daily flow record for the period 1988-2007 to create a future adjusted flow record to account for all current well lag impacts and potential future well depletions. The future lag-adjusted flow record is then used to calculate the average number of days available for diversion to the most junior appropriator within the basin. This new future lag-adjusted flow record is compared to the number of days necessary for the most junior surface water appropriator to divert in the basin.

In those basins for which the appropriate geologic and hydrologic data were not available, the impacts of future well development were not calculated, due to uncertainty of the degree of hydrologic connection. In many of those cases, the number of days in which surface water is available for diversion far exceeds the number of days necessary to meet the NCCIR, and the final conclusion would likely not change even with the addition of lag impacts.

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5.0 BLUE RIVER BASINS

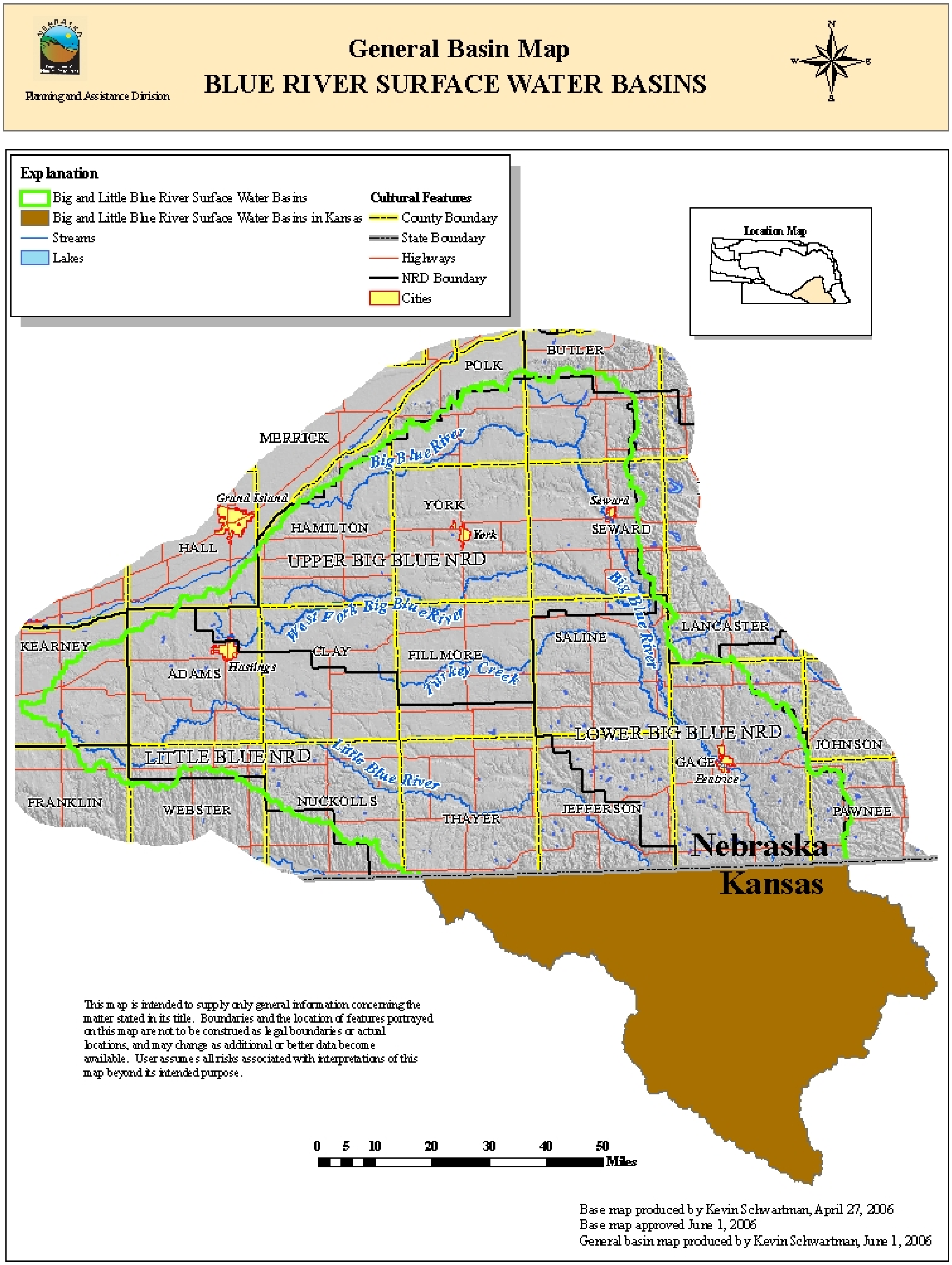
5.1 Summary

Based on the analysis of the sufficiency of the long-term surface water supply in the Blue River basins, the Department has reached a conclusion that the basins are not fully appropriated. Even though the effects of future ground water depletions on future water supplies were not estimated in the basins, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement. The best available data do not allow for analysis of whether this determination would change if no additional legal constraints are imposed on future development.

5.2 Basin Descriptions

The Blue River basins in Nebraska include all surface areas that drain into the Big Blue River and the Little Blue River and all aquifers that impact surface water flows of the basins (Figure 5-1). The total area of the Blue River surface water basins in Nebraska is approximately 7,100 square miles, of which 4,600 square miles are in the Big Blue River Basin and 2,500 square miles are in the Little Blue River Basin. Natural resources districts with significant area in the basins are the Little Blue Natural Resources District, the Lower Big Blue Natural Resources District, the Upper Big Blue Natural Resources District, and the Tri-Basin Natural Resources District. The basins are the subject of an interstate compact between Kansas and Nebraska that sets state-line target flows.

Figure 5-1 General basin map, Blue River basins.



5.3 Nature and Extent of Water Use

5.3.1 Ground Water

Ground water in the basins is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. A total of 25,316 ground water wells had been registered within the basins as of December 31, 2007 (Department registered ground water wells database) (Figure 5-2). The locations of all active ground water wells are shown in Figure 5-3.

Figure 5-2 Current well development by number of registered wells, Blue River basins.

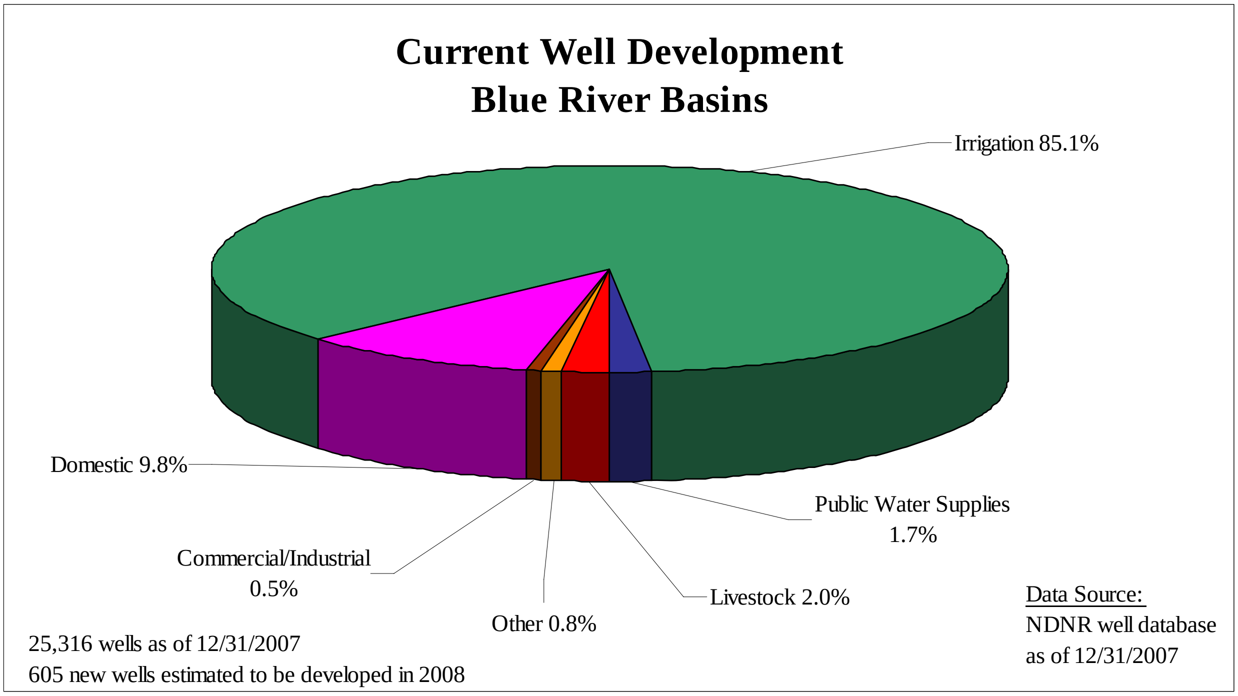
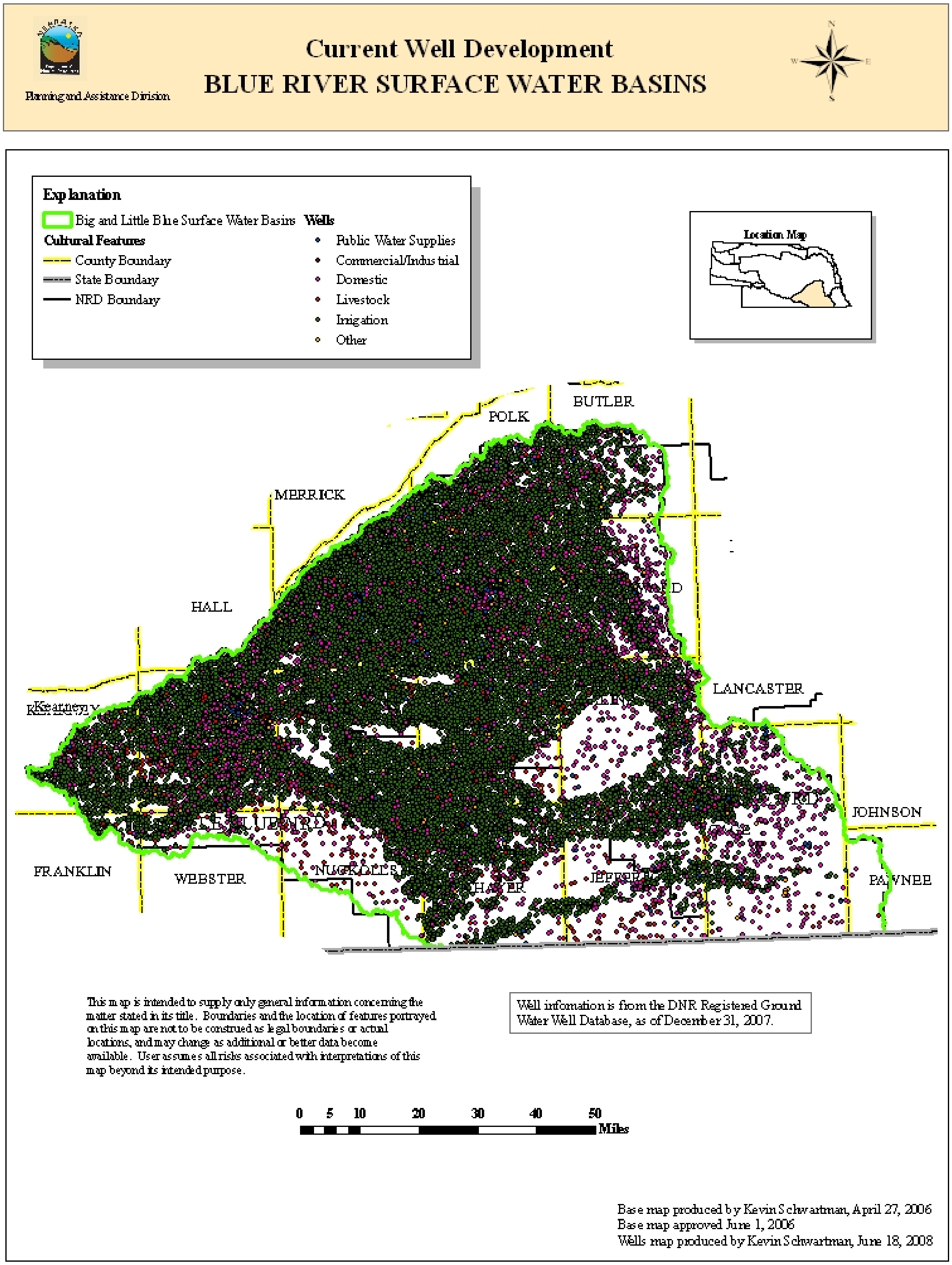


Figure 5-3 Current well locations, Blue River basins.



5.3.2 Surface Water

As of December 31, 2007, 2,576 surface water appropriations were held in the basins, issued for a variety of uses (Figure 5-4). Most of the surface water appropriations are for irrigation and storage use and tend to be located on the major streams. The first surface water appropriations in the basins were permitted in 1868, and development has continued through the present day. The approximate locations of the surface water diversion points are shown in Figure 5-5.

Figure 5-4 Surface water appropriations by number of diversion points, Blue River basins.

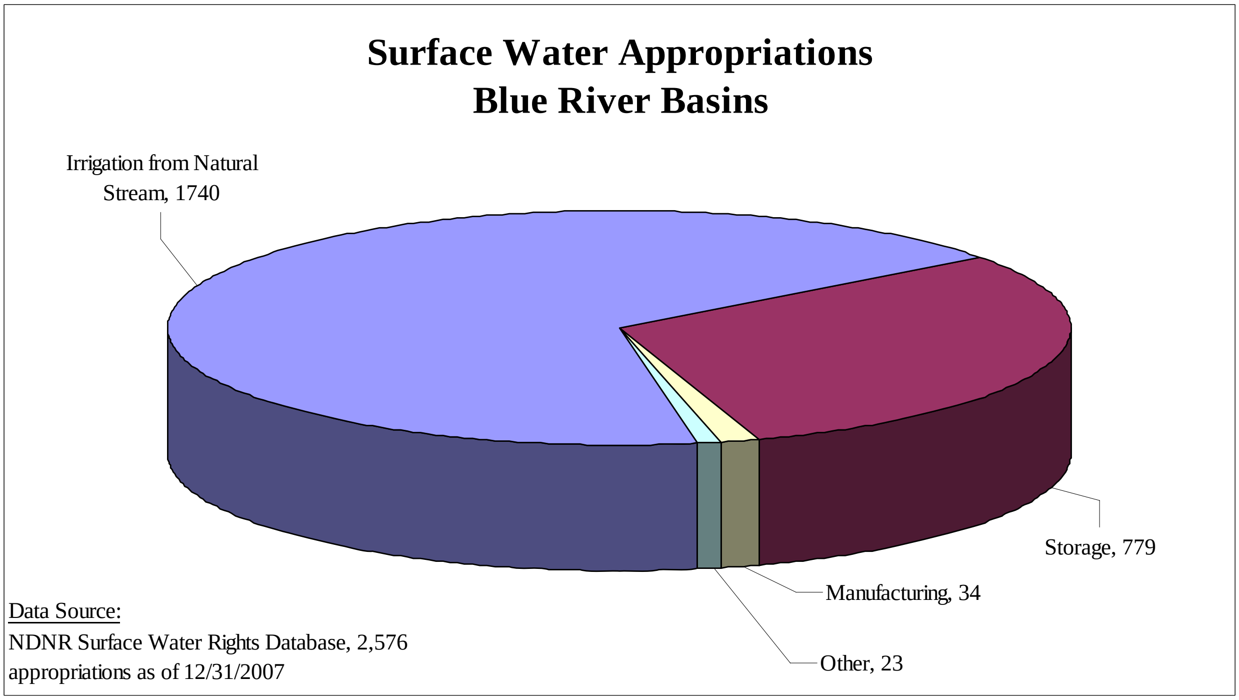
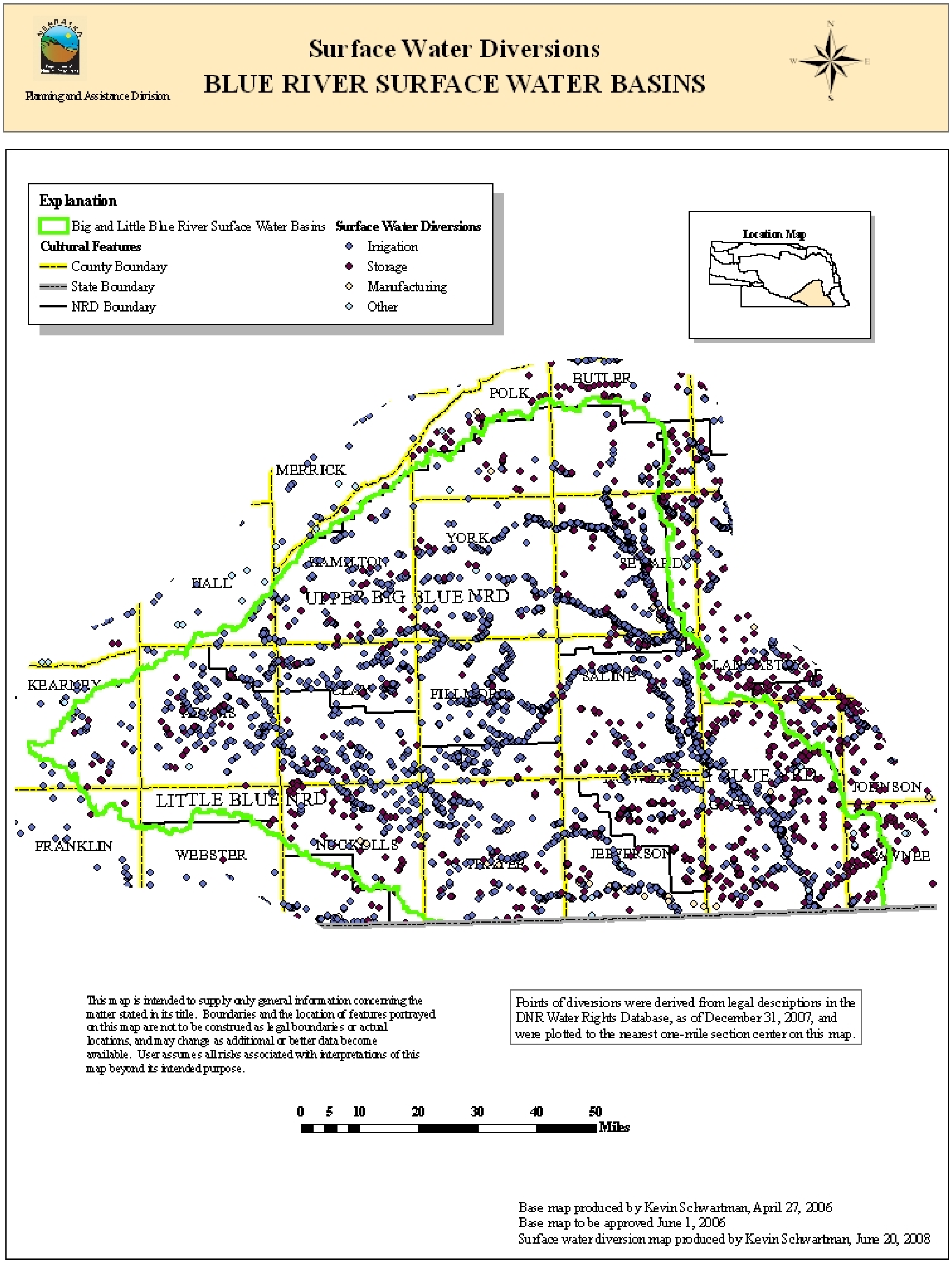


Figure 5-5 Surface water appropriation diversion locations, Blue River basins.

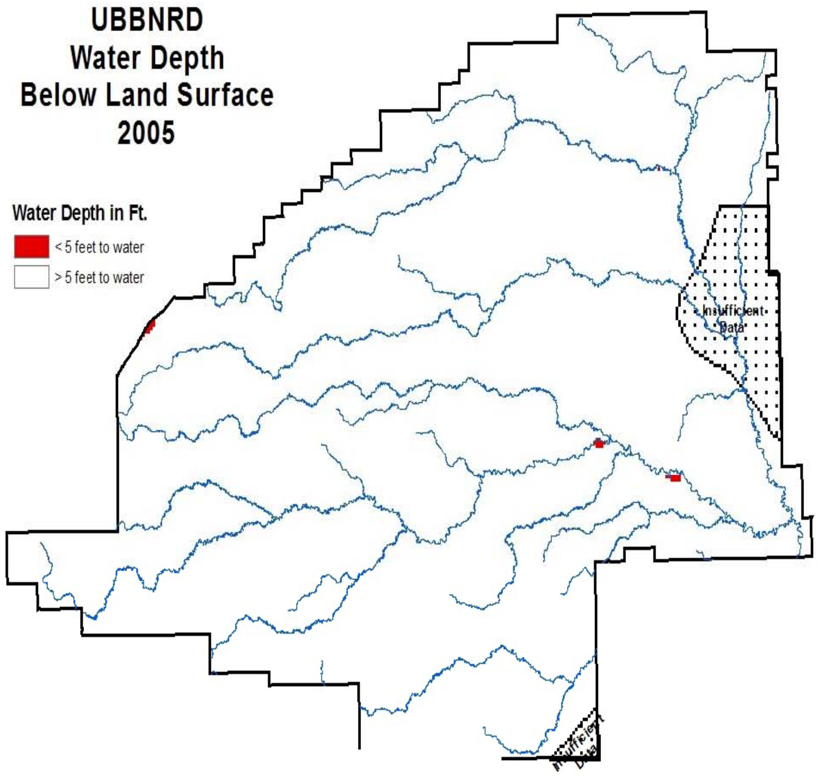


5.4 Hydrologically Connected Area

5.4.1 Big Blue River Basin

The Big Blue River Basin can be divided into two distinct areas based on the presence or absence of glacial deposits. At the present time, the Department cannot determine the 10/50 area for the Big Blue River and its tributaries in either of these areas. The stream depletion factor (SDF) methodology cannot be used to delineate the 10/50 area because of the restrictive and complex nature of the hydrogeology in the glaciated portions of the basin (CSD, 2005). The geology of the non-glaciated western area of the basin is less complex. In all but two small areas, however, the principal aquifer is not in hydrologic connection with the streams (Figure 5-6) (Bitner, 2005).

Figure 5-6 Areas of ground water and surface water connection, Upper Big Blue NRD (from Bitner, 2005).



GENERAL DEPTH OF GROUNDWATER BELOW LAND SURFACE

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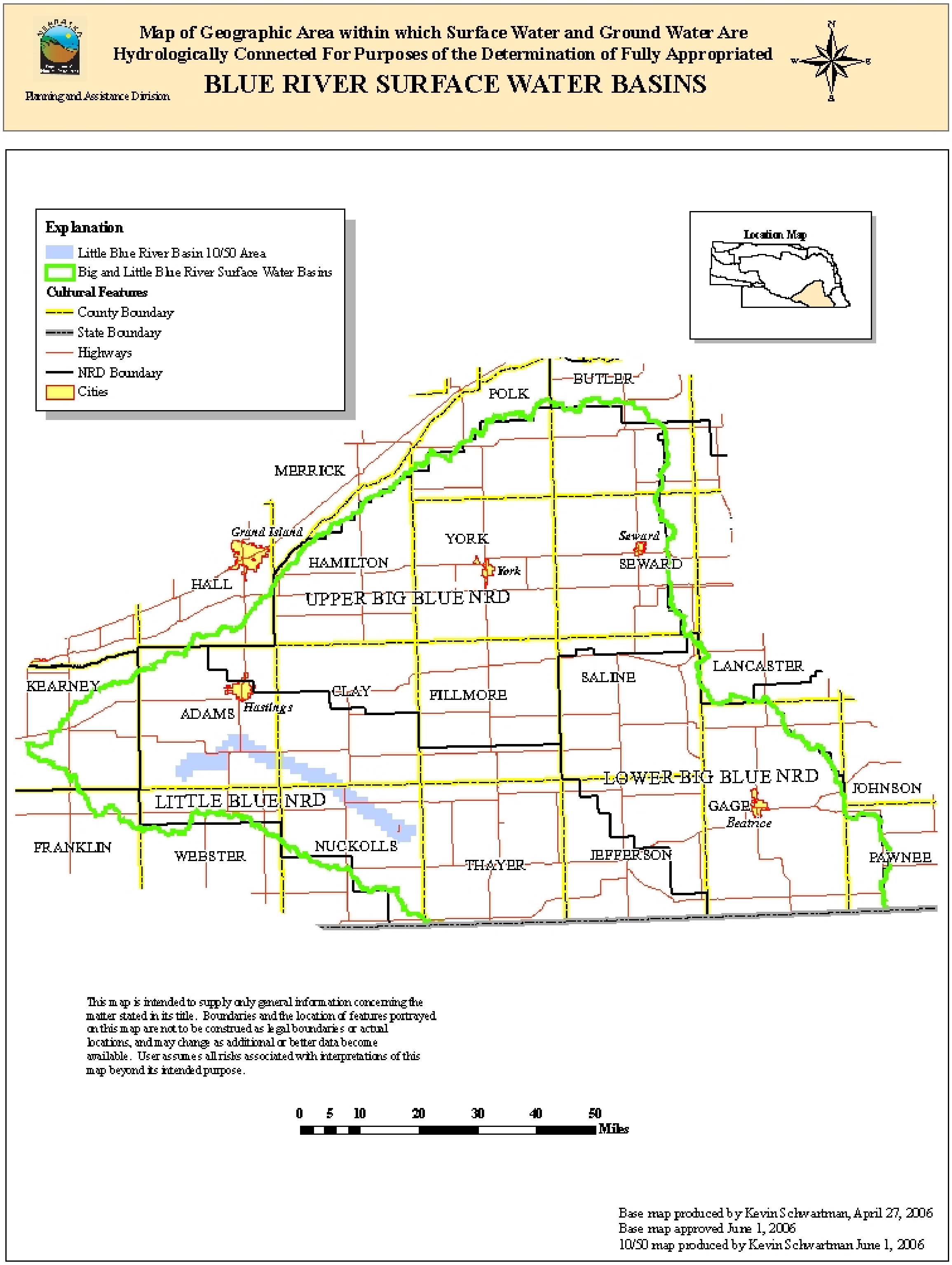
5.4.2 Little Blue River Basin

The Little Blue River Basin can also be divided into two distinct areas based on the presence or absence of glacial deposits. As with the Big Blue River Basin, the stream depletion factor (SDF) methodology cannot be used to delineate the 10/50 area because of the restrictive and complex nature of the hydrogeology in the glaciated portions of the basin (CSD, 2005). The 10/50 area for the other portions of the basin was determined from the results of the MODFLOW ground water model developed by the Upper Big Blue Natural Resources District (Bitner, 2005) (Figure 5-7).

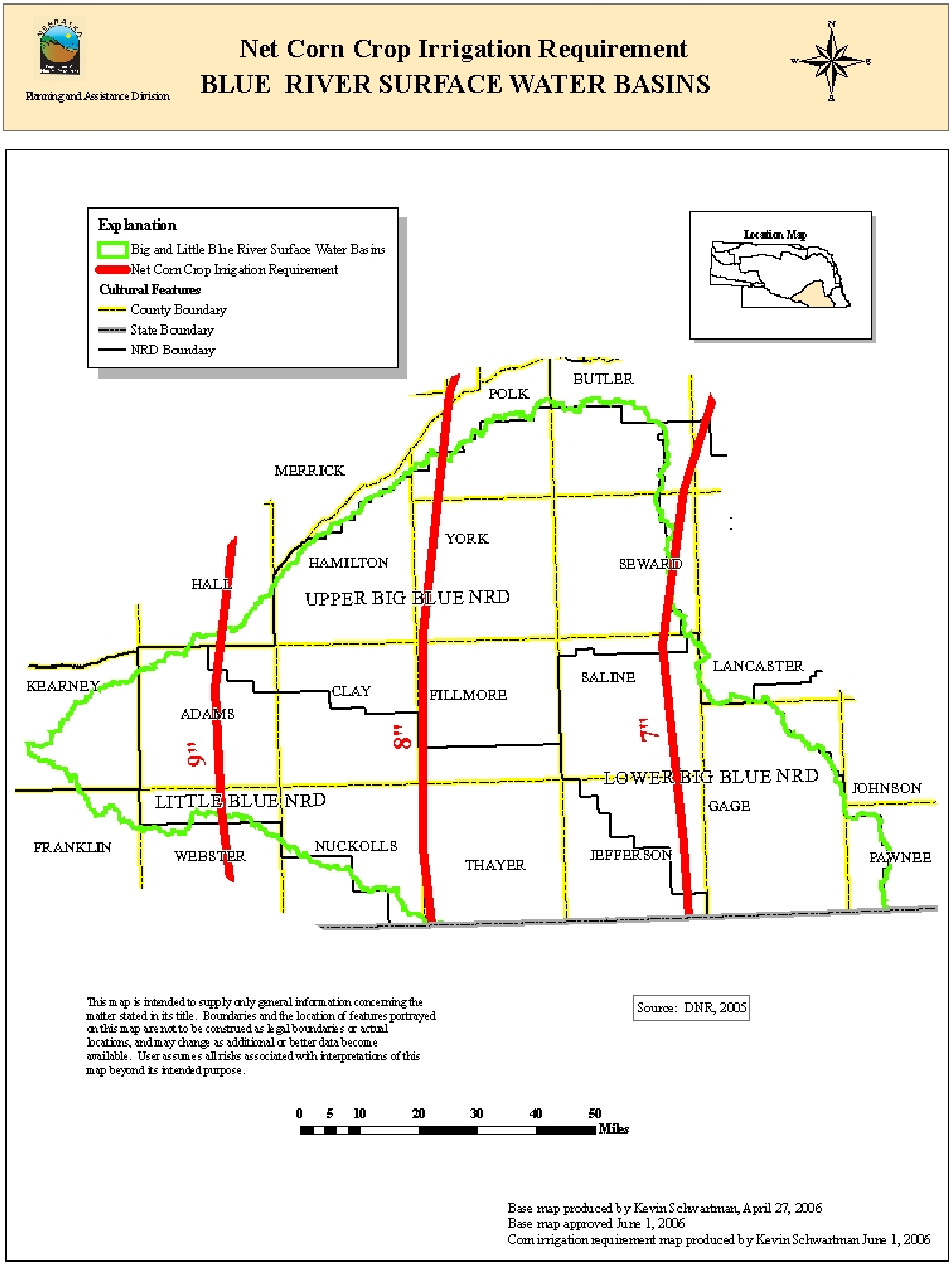
Figure 5-7 10/50 area, Little Blue River Basin (Bitner, 2005).



5.5 Net Corn Crop Irrigation Requirement

Figure 5-8 is a map of the net corn crop irrigation requirement for the Blue River basins (DNR, 2005). The greatest NCCIR of a junior surface water appropriation in the Big Blue River Basin is 9.0 inches, and the greatest NCCIR in the Little Blue River Basin is 9.7 inches. To assess the number of days required to be available for diversion, a surface water diversion rate equal to 1 cfs per 70 acres, a downtime of 10%, and an irrigation efficiency of 80% were assumed. Based on these assumptions, the junior surface water appropriation in the Big Blue River Basin would need 23.9 days annually to divert 65% of the NCCIR and 31.3 days to divert 85% of the NCCIR. The junior surface water appropriation in the Little Blue River Basin will need 25.8 days annually to divert 65% of the NCCIR and 33.7 days to divert 85% of the NCCIR.

Figure 5-8 Net corn crop irrigation requirement, Blue River basins.



5.6 Surface Water Closing Records

Tables 5-1 and 5-2 record all surface water administration that has occurred in the basins between 1988 and 2007.

Table 5-1 Surface water administration in the Big Blue River Basin, 1988-2007.

Year	Water Body	Days	Closing Date	Opening Date
2000	Turkey Creek	3	Jun 9	Jun 12
2000	Big Blue River above Lincoln Creek	2	Aug 15	Aug 17
2001	Big Blue River above Lincoln Creek	1	Aug 14	Aug 15
2002	Big Blue River above Lincoln Creek	11	Jul 11	Jul 22
2002	Big Blue River above Lincoln Creek	14	Jul 30	Aug 13
2002	Big Blue River Basin	8	Aug 5	Aug 13
2002	North Fork Big Blue River	1	Aug 14	Aug 15
2003	Big Blue River above Lincoln Creek	49	Jul 16	Sep 3
2003	Big Blue River Basin	11	Jul 17	Jul 28
2003	Big Blue River Basin	8	Aug 11	Aug 19
2004	Big Blue River above Lincoln Creek	16	Aug 3	Aug 19
2005	Big Blue River above Lincoln Creek	14	Jul 12	Jul 26
2005	Big Blue River Basin	13	Jul 13	Jul 26
2005	Big Blue River above West Fork	8	Jul 18	Jul 26
2005	Big Blue River above Lincoln Creek	11	Aug 4	Aug 15
2005	Big Blue River Basin	6	Aug 9	Aug 15
2005	Big Blue River above West Fork	5	Aug 10	Aug 15
2006	Big Blue River above West Fork	13	Jul 1	Jul 14
2006	Big Blue River above West Fork	22	Jul 17	Aug 8
2006	Big Blue River Basin	11	Jul 3	Jul 14
2006	Big Blue River Basin	5	Jul 19	Jul 24
2006	Big Blue River Basin	9	Jul 29	Aug 7

Table 5-2 Surface water administration in the Little Blue River Basin, 1988-2007.

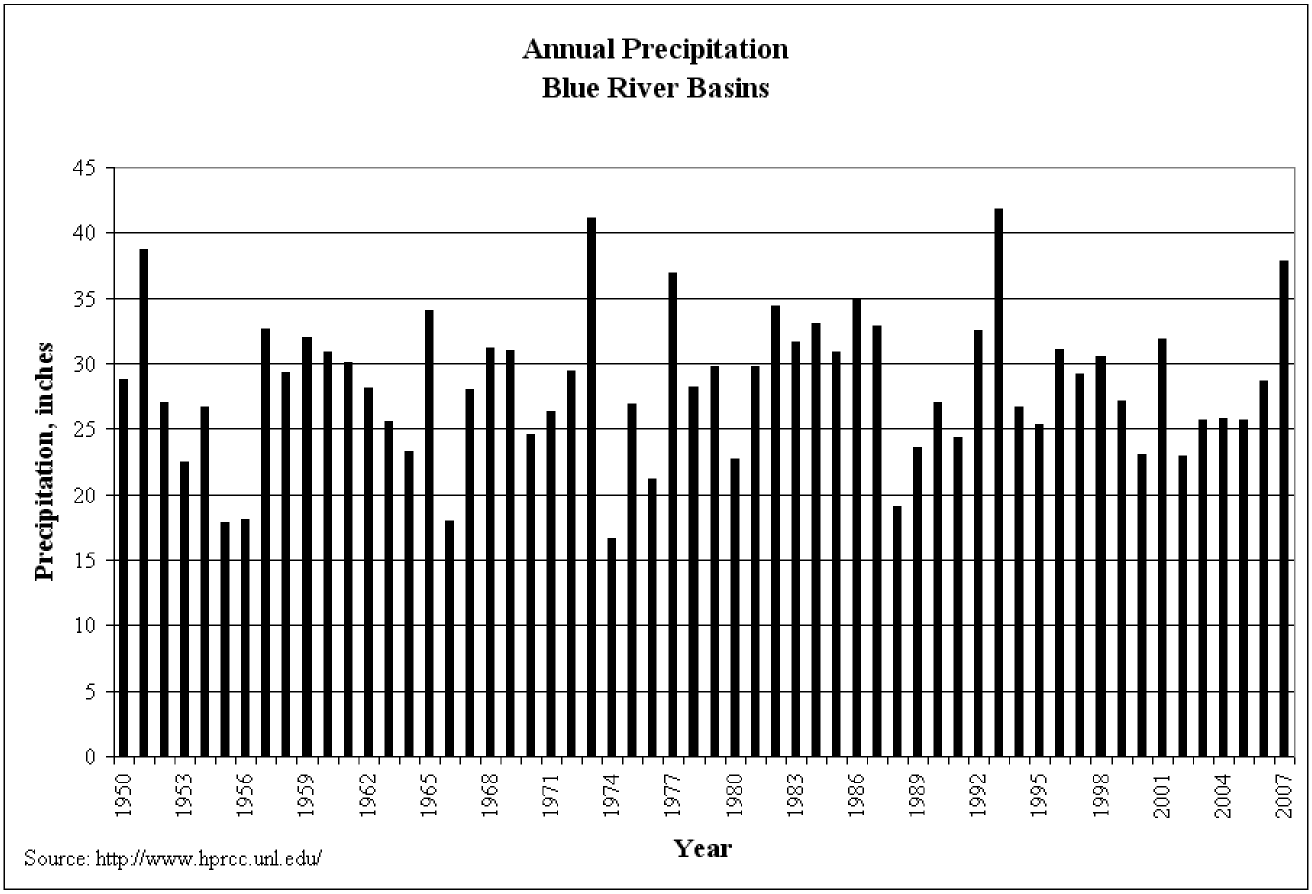
Year	Water Body	Days	Closing Date	Opening Date
1988	Little Blue River Basin	50	Aug 11	Sep 30
1989	Rose Creek	4		
1991	Little Blue River Basin	45	Aug 16	Sep 30
1991	Rose Creek	94	Jun 28	Sep 30
2002	Little Blue River Basin	11	Jul 18	Jul 29
2002	Little Blue River Basin	13	Aug 6	Aug 19
2002	Little Blue River Basin	7	Sep 9	Sep 16
2004	Little Blue River Basin	10	Sep 13	Sep 23
2005	Little Blue River Basin	15	Jul 11	Jul 26
2005	Little Blue River Basin	7	Aug 8	Aug 15
2006	Little Blue River Basin	9	Jul 5	Jul 14
2006	Little Blue River Basin	1	Jul 20	Jul 21
2006	Little Blue River Basin	7	Jul 31	Aug 7
2006	Little Blue River Basin	8	Aug 9	Aug 17

5.7 Evaluation of Current Development

5.7.1 Water Supply

In order to complete the long-term evaluation of surface water supplies, a future twenty-year water supply for the basins must be estimated. The basins' water sources are precipitation, which runs off as direct streamflow and infiltrates into the ground to discharge as baseflow, and ground water movement into the basins, which discharges as baseflow. Using methodology published in the *Journal of Hydrology* (Wen and Chen, 2005), a nonparametric Mann-Kendall trend test of the weighted average precipitation in the basins was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past fifty years (Figure 5-9). Data do not exist to test whether trends in ground water movement into the basin have changed. Therefore, using the previous twenty years of streamflow data as the best estimate of the future surface water supply is reasonable.

Figure 5-9 Annual precipitation, Blue River basins.



5.7.2 Depletions Analysis

The future depletions due to current well development that could be expected to affect streamflow in the Big Blue River Basin and the glaciated portion of the Little Blue River Basin were not estimated for the same reasons as those described in Section 5.4. The Upper Big Blue Natural Resources District has developed a MODFLOW ground water model for the other portions of the Little Blue River Basin, but that model is not sufficient to estimate future depletions at the current time.

5.7.3 Evaluation of Current Levels of Development against Future Water Supplies

The comparison of the near-term water supply days available for diversion to the number of days surface water is required to be available to divert 65% and 85% of the NCCIR is detailed in Tables 5-3 and 5-4. No estimate was developed for the long-term number of days available for diversion in the basins, due to limited understanding of the extent of hydrologic connection and the inadequacy of current data and models in predicting future stream depletions. Even though future impacts on current water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Table 5-3 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion in the Big Blue River Basin.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1988-2007)**
July 1 – August 31 (65% Requirement)	23.9	54.5 (30.6 days above the requirement)
May 1 – September 30 (85% Requirement)	31.3	145.3 (114.0 days above the requirement)

Table 5-4 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion in the Little Blue River Basin.

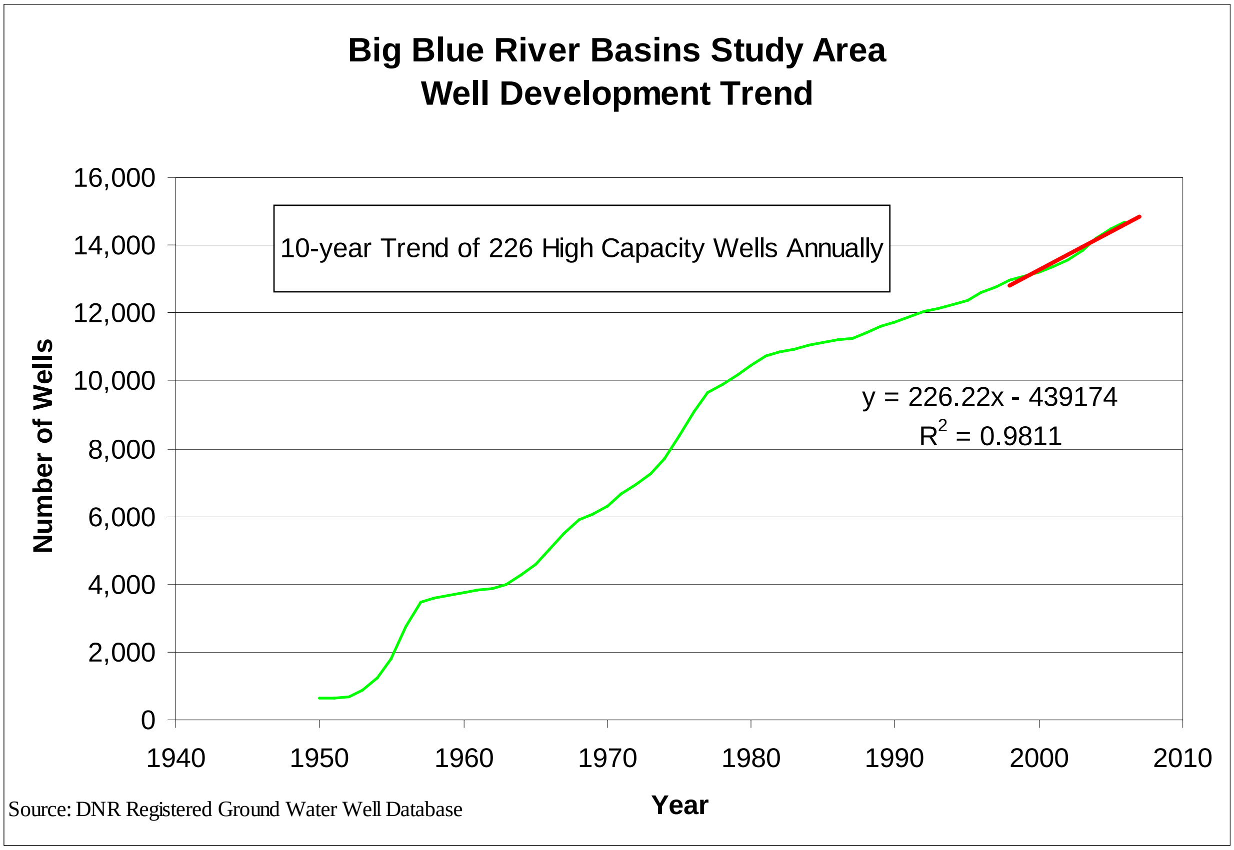
	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1988-2007)**
July 1 – August 31 (65% Requirement)	25.7	54.4 (28.7 days above the requirement)
May 1 – September 30 (85% Requirement)	33.6	141.2 (107.6 days above the requirement)

5.8 Evaluation of Predicted Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gpm) that would be completed over the next twenty-five years, if no new legal constraints on the construction of such wells were imposed, were calculated based on extrapolating the present-day rate of increase in well development into the future (Figure 5-10). The present-day rate of development is based on the linear trend of the previous ten years of development. Based on the analysis of the past ten years of development, the rate of increase in high capacity wells was calculated to be 226 wells per year in the basins.

For the same reasons as those stated above in Section 5.7.2, no estimates of depletions due to current and future ground water development were computed. Even though the effects on future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the NCCIR.

Figure 5-10 High capacity well development, Blue River basins.



5.9 Sufficiency to Avoid Noncompliance

The State of Nebraska is a signatory member of the Kansas – Nebraska Big Blue River Compact (Compact). The purposes of the Compact are to promote interstate comity, to achieve an equitable apportionment of the waters of the Big Blue River Basin, to encourage continuation of the active pollution-abatement programs in each of the two states, and to seek further reduction in pollution of the waters of the Big Blue River Basin.

The Compact sets state-line flow targets from May 1 through September 30. The state-line targets, measured in cubic feet of water per second, are shown in Table 5-5. If the flow targets are not met, then the State of Nebraska is required to take the following actions:

1. Limit surface water diversions by natural flow appropriators to their decreed appropriations;
2. Close natural flow appropriators with priority dates junior to November 1, 1968, in accordance with the doctrine of priority;
3. Ensure that no illegal surface water diversions are taking place; and
4. Regulate wells installed after November 1, 1968, within the alluvium and valley side terrace deposits downstream of Turkey Creek in the Big Blue River Basin and downstream of Walnut Creek in the Little Blue River Basin, unless the Compact Administration determines that such regulation would not yield any measurable increase in flows at the state line gage.

For the present time, the Compact Administration has found that the regulation of those wells will not yield measurable increases in flow at the state line.

Table 5-5 State-line flow targets for the Big Blue River.

Month	Big Blue River Target Flow	Little Blue River Target Flow
May	45 cfs	45 cfs
June	45 cfs	45 cfs
July	80 cfs	75 cfs
August	90 cfs	80 cfs
September	65 cfs	60 cfs

As long as Nebraska administers surface and ground water in compliance with the Compact, decreased streamflow, in and of itself, will not cause Nebraska to be in noncompliance; therefore, any depletion would not cause Nebraska to be in noncompliance. Decreased streamflows could, however, increase the number of times the state would have to administer water to remain in compliance, thereby reducing the number of days available for junior irrigators to divert.

5.10 Ground Water Recharge Sufficiency

The streamflow is sufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the stream, as explained in Appendix H.

5.11 Current Studies being Conducted to Assist with Future Analysis

The geologic complexity of the basins requires more sophisticated efforts in investigating the extent of hydrologic connection between ground water and surface water supplies. Development of a ground water model for the Big Blue and Little Blue River basins is currently being reviewed by the Department. If deemed suitable by the Department, the results will be used to determine the extent of the 10/50 area for the Big Blue and Little Blue basins. Future efforts may be made to refine this model to estimate lag impacts from wells within the 10/50 area.

5.12 Relevant Data Provided by Interested Parties

The Department published a request for relevant data from interested parties for this year's evaluation on May 12, 2008 (see Appendix A for Affidavit). The Department did not receive any such information.

5.13 Conclusions

Based on the evaluation of available information, the Department has reached a conclusion that the surface water and ground water supplies in hydrologic connection in the Blue River basins are not fully appropriated. The best available data do not allow for analysis of whether this determination would change if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water. Even though the future effects of current and estimated future development were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Bibliography of Hydrogeologic References for Big and Little Blue River Basins

Bitner, R.J. 2005. *A groundwater model to determine the area within the Upper Big Blue Natural Resources District where groundwater pumping has the potential to increase flow from the Platte River to the underlying aquifer by at least 10 percent of the volume pumped over a 50-year period.* Upper Big Blue Natural Resources District. York.

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln.

Wen, F. J. and X. H. Chen, 2006. Evaluation of the impact of groundwater irrigation on streamflow depletion in Nebraska*. Journal of Hydrology* 327: 603-617.

6.0 LOWER NIOBRARA RIVER BASIN

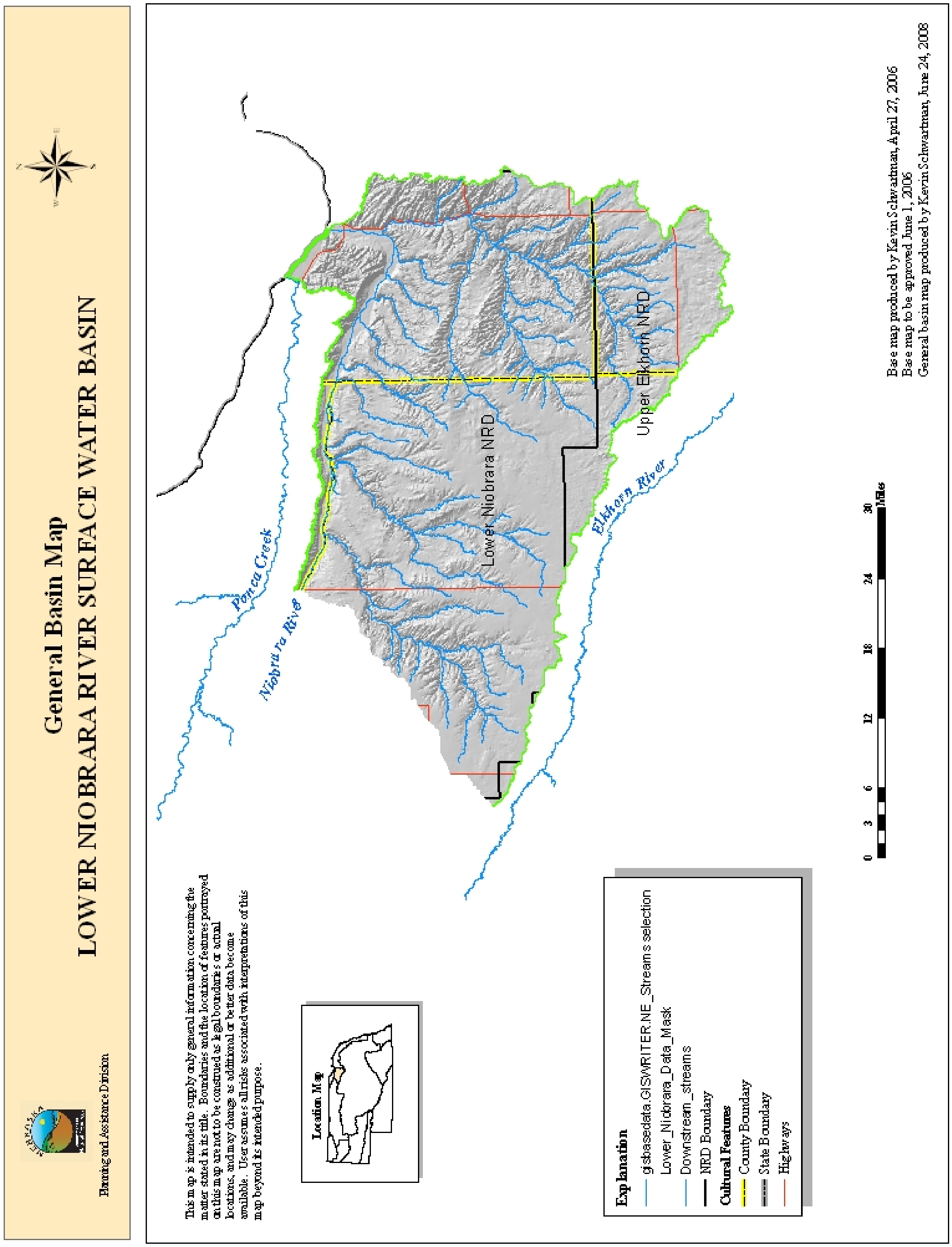
6.1 Summary

Based on the analysis of the sufficiency of the long-term surface water supply in the Lower Niobrara River Basin, the Department has reached a conclusion that the basin is not fully appropriated. The analysis of lag effects of current development for the Lower Niobrara Basin indicates a reduction in streamflows by 21 cfs in twenty-five years. The analysis of the impacts of future development on the Lower Niobrara Basin based on current development trends indicates a reduction in streamflows of 95 cfs in twenty-five years. The future number of days available to junior irrigators was not estimated, because only minimal surface water administration has occurred on the Niobrara River in the past twenty years. Even though the future number of days available to junior irrigators was not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

6.2 Basin Description

The Lower Niobrara River Basin in Nebraska is defined in this report as the surface areas in Nebraska that drain into the Niobrara River Basin and that have not previously been determined to be fully appropriated. This general basin area extends from the Spencer Hydropower facility in the west downstream to the confluence of the Niobrara River and the Missouri River and includes all aquifers that impact surface water flows in the basin (Figure 6-1). The total area of the Lower Niobrara River Basin evaluated in this year's report is approximately 1,200 square miles. The Lower Niobrara Natural Resources District and the Upper Elkhorn Natural Resources District are the only natural resources districts with significant area in the Lower Niobrara River Basin.

Figure 6-1 General basin map, Lower Niobrara River Basin.



6.3 Nature and Extent of Water Use

6.3.1 Ground Water

Ground water in the basin is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. A total of 2,333 ground water wells had been registered within the basin as of December 31, 2007 (Department registered ground water wells database) (Figure 6-2). The locations of all active ground water wells can be seen in Figure 6-3.

Figure 6-2 Current well development by number of registered wells, Lower Niobrara River Basin.

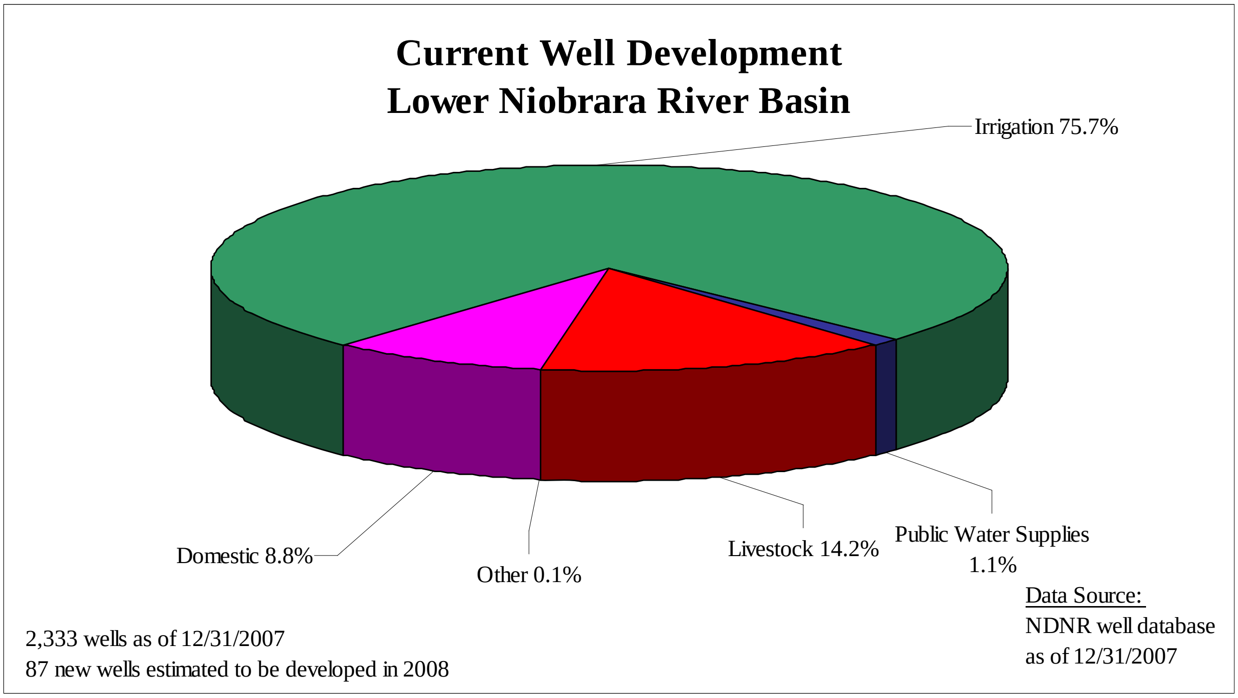
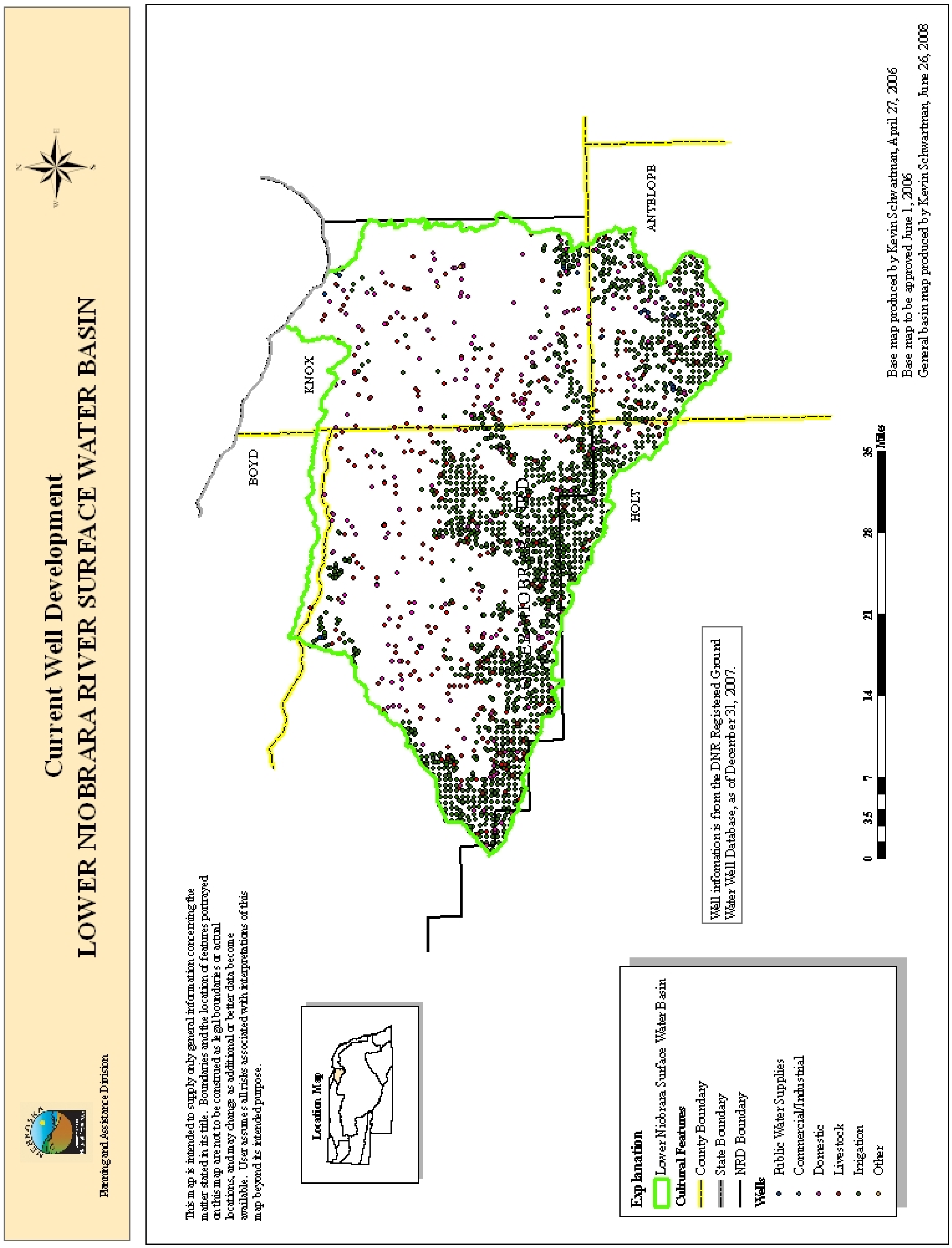


Figure 6-3 Current well locations, Lower Niobrara River Basin.



6.3.2 Surface Water

As of December 31, 2007, 286 surface water appropriations were held in the basin, issued for a variety of uses (Figure 6-4). Most of the surface water appropriations are for irrigation use and storage and tend to be located on the major streams. The first surface water appropriations in the basin were permitted in 1894, and development has continued through the present day. The approximate locations of the surface water diversion points are shown in Figure 6-5.

Figure 6-4 Surface water appropriations by number of diversion points, Lower Niobrara River Basin.

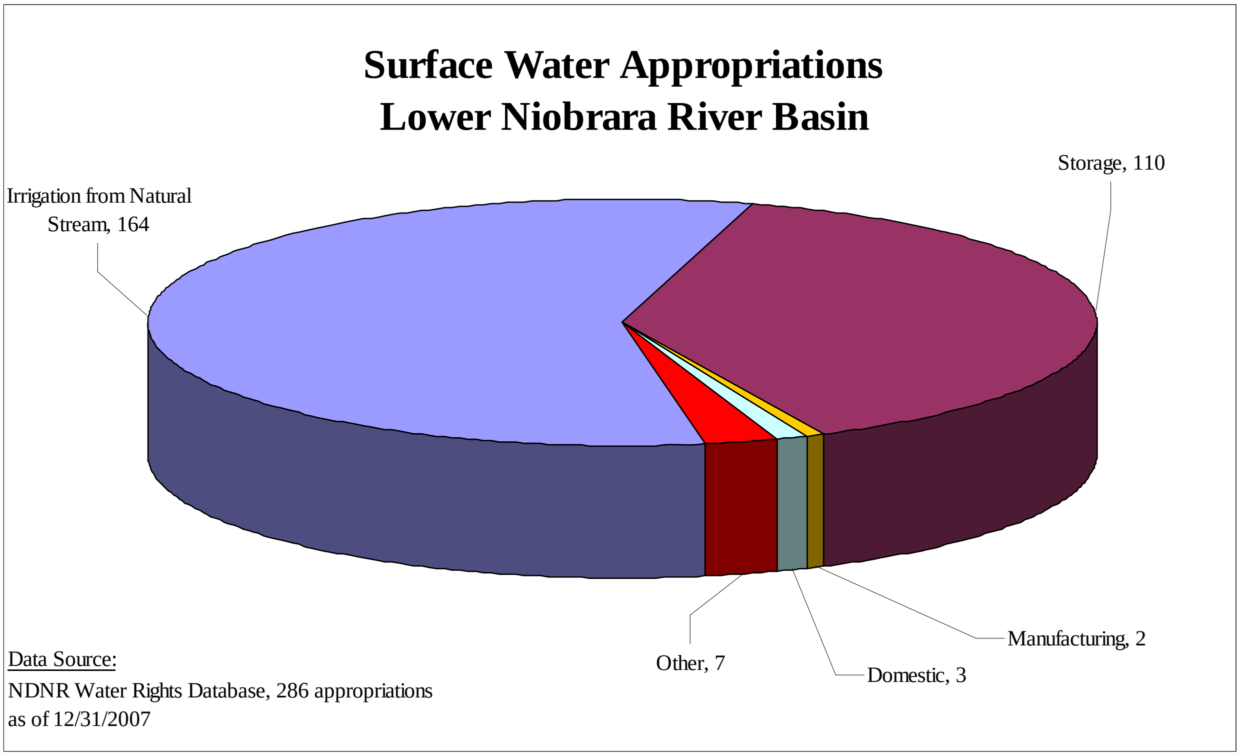
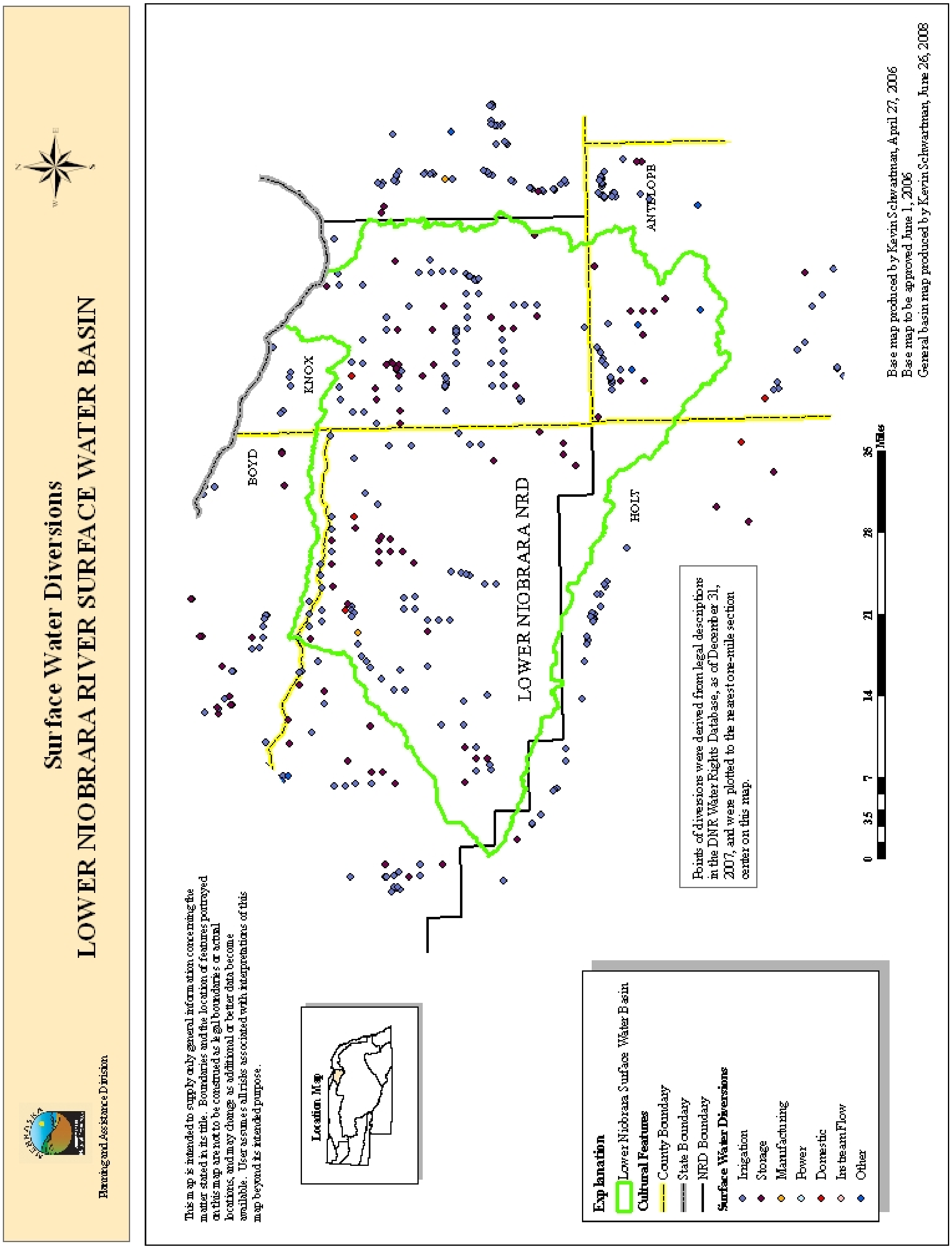


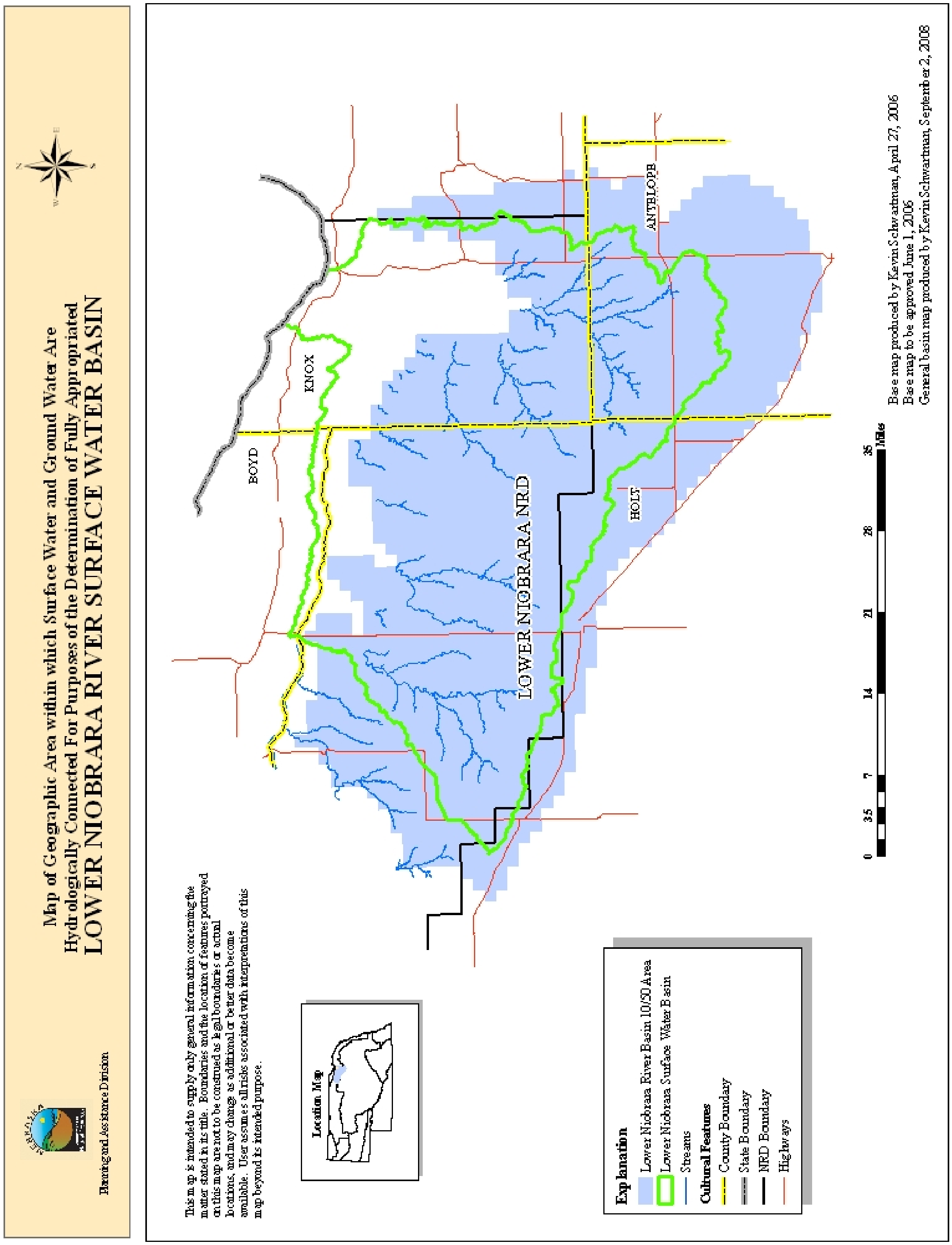
Figure 6-5 Surface water appropriation diversion locations, Lower Niobrara River Basin.



6.4 Hydrologically Connected Area

No sufficient numeric ground water model is available in the Lower Niobrara River Basin to determine the 10/50 area. Therefore, the 10/50 area was determined using stream depletion factor (SDF) methodology. Figure 6-6 specifies the extent of the 10/50 area. A description of the SDF methodology used appears in the “Methodology” section of this report.

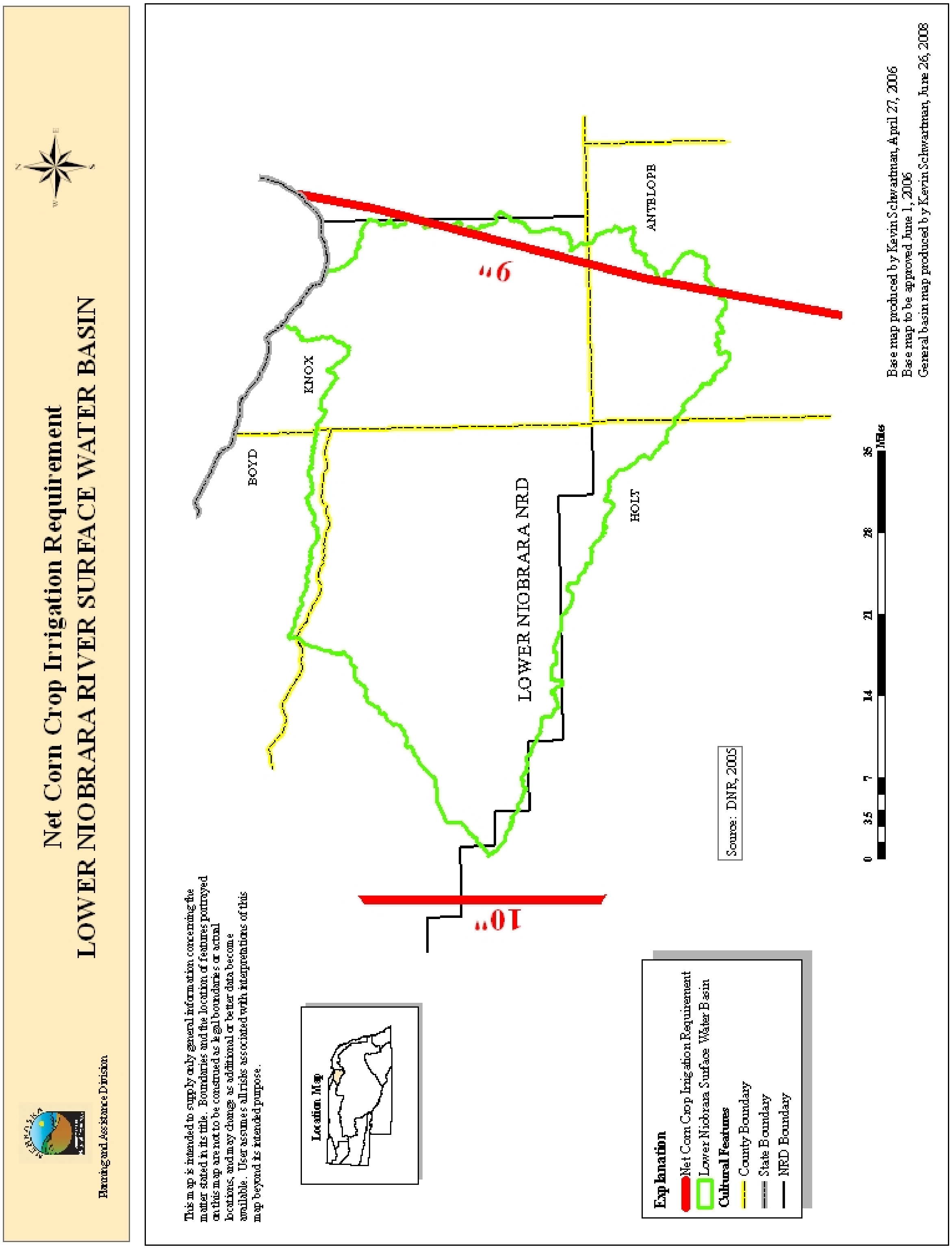
Figure 6-6 10/50 area, Lower Niobrara River Basin.



6.5 Net Corn Crop Irrigation Requirement

Figure 6-7 is a map of the net corn crop irrigation requirement for the basin (DNR, 2005). The NCCIR in the basin ranges from 8.9 to 9.6 inches. To assess the number of days required to be available for diversion, a surface water diversion rate equal to 1 cfs per 70 acres, a downtime of 10%, and an irrigation efficiency of 80% were assumed. Based on these assumptions, a junior surface water appropriation in the Lower Niobrara River Basin will require between 23.6 and 25.5 days annually to divert 65% of the NCCIR and between 30.9 and 33.3 days to divert 85% of the NCCIR.

Figure 6-7 Net corn crop irrigation requirement, Lower Niobrara River Basin.



6.6 Surface Water Closing Records

Table 6-1 records all surface water administration that has occurred in the basin between 1988 and 2007.

Table 6-1 Surface water administration in the Lower Niobrara River Basin, 1988-2007.

Year	Water Body	Days	Closing Date	Opening Date
1991	North Branch Verdigre Creek	3	Jul 26	Jul 29

6.7 Evaluation of Current Development

6.7.1 Current Water Supply

The current water supply is estimated by using the previous twenty years (1988-2007) of flows available for junior irrigation rights. The results of the analysis conducted for the Lower Niobrara River Basin are shown in Tables 6-2 and 6-3. The results indicate that the current surface water supply in the Lower Niobrara River Basin provides an average of 61.9 days available for diversion between July 1 and August 31 and 152.9 days available for diversion between May 1 and September 30.

Table 6-2 Estimate of the current number of days surface water is available for diversion in the Lower Niobrara River Basin.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
1988	62	153
1989	62	153
1990	62	153
1991	59	150
1992	62	153
1993	62	153
1994	62	153
1995	62	153
1996	62	153
1997	62	153
1998	62	153
1999	62	153
2000	62	153
2001	62	153
2002	62	153
2003	62	153
2004	62	153
2005	62	153
2006	62	153
2007	62	153
Average	61.9	152.9

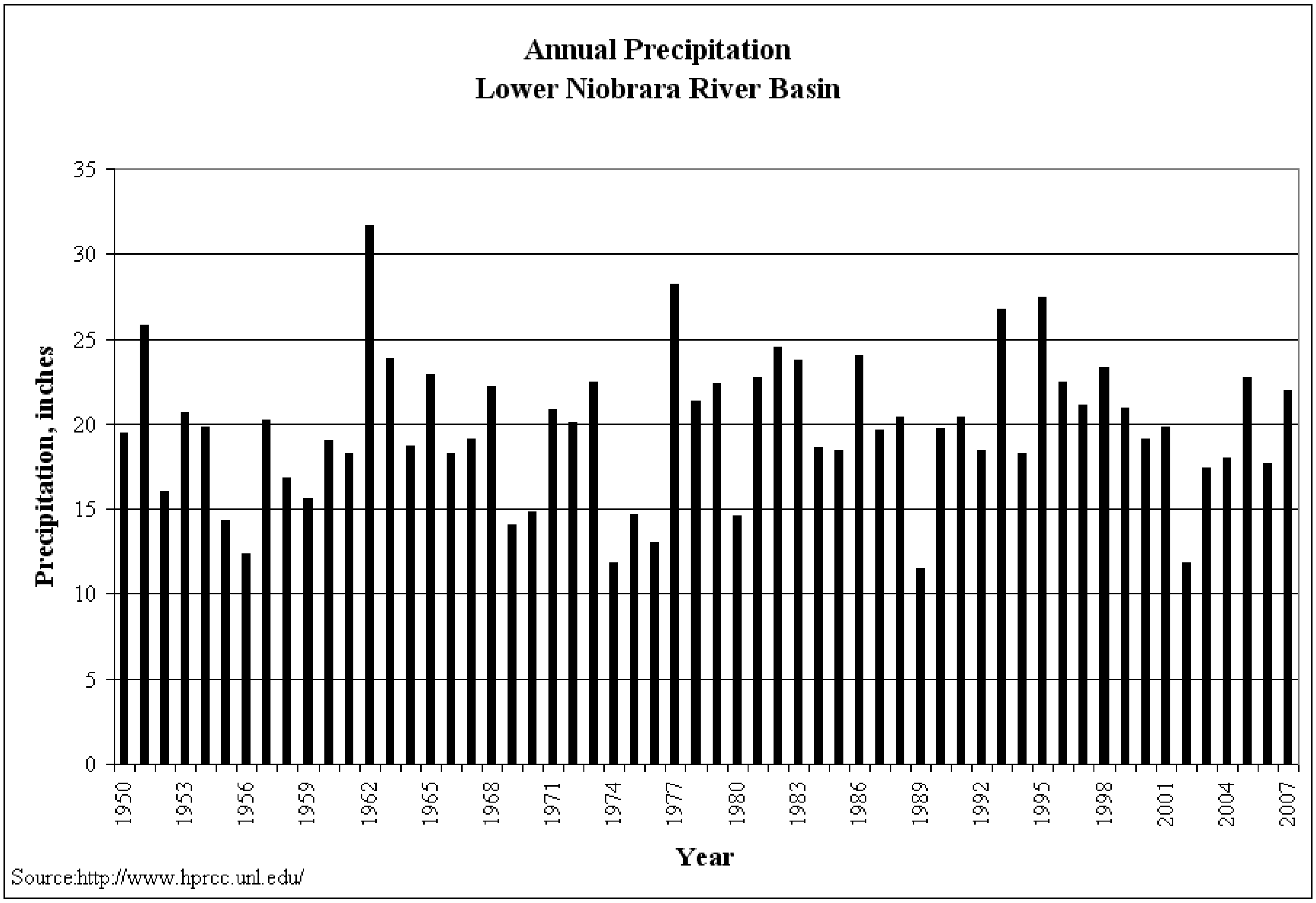
Table 6-3 Comparison between the number of days required to meet the net corn crop irrigation requirement and the current number of days surface water is available for diversion in the Lower Niobrara River Basin.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Current Development**
July 1 – August 31 (65% Requirement)	23.6 to 25.5	61.9 (at least 36.4 days above the requirement)
May 1 – September 30 (85% Requirement)	30.9 to 33.4	152.9 (at least 119.5 days above the requirement)

6.7.2 Water Supply

In order to complete the long-term evaluation of surface water supplies, a future twenty-year water supply for the basin must be estimated. The basin's major water sources are precipitation, which runs off as direct streamflow and infiltrates into the ground to discharge as baseflow; ground water movement into the basin, which discharges as baseflow; and streamflow from the middle Niobrara River. Using methodology published in the *Journal of Hydrology* (Wen and Chen, 2005), a nonparametric Mann-Kendall trend test of the weighted average precipitation in the basin was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past fifty years (Figure 6-8). Therefore, using the previous twenty years of precipitation and streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure 6-8 Annual precipitation, Lower Niobrara River Basin.



6.7.3 Depletions Analysis

The future depletions due to current well development that could be expected to affect streamflow in the basin were estimated using SDF methodology. The results estimate the future streamflows in the Lower Niobrara River Basin to be depleted by 21 cfs in twenty-five years.

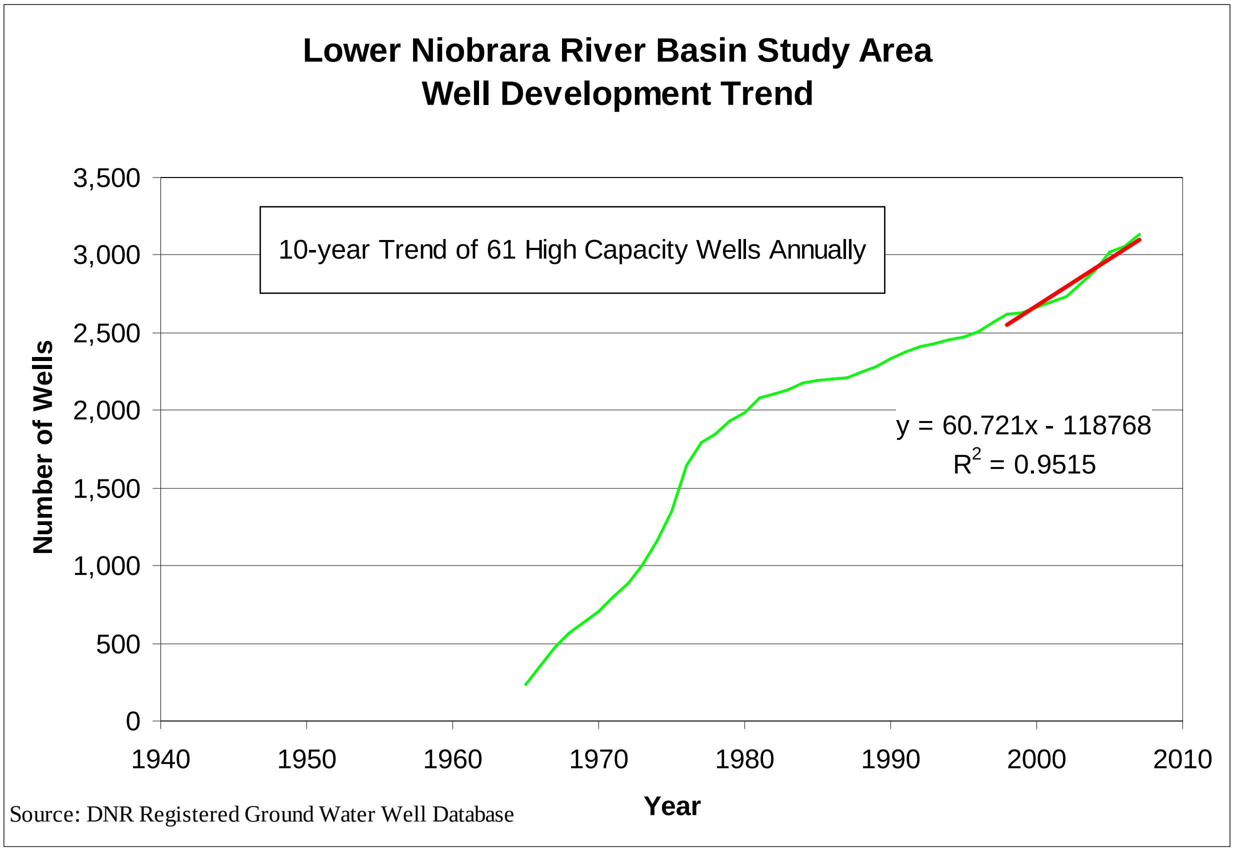
6.7.4 Evaluation of Current Levels of Development against Future Water Supplies

The estimates of the twenty-year average number of days available for diversion were not estimated for the Lower Niobrara Basin because only minimal surface water administration has previously occurred in the basin, and the threshold flows necessary to satisfy senior appropriations could not be estimated. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

6.8 Evaluation of Predicted Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gpm) that would be completed over the next twenty-five years, if no new legal constraints on the construction of such wells were imposed, were calculated based on extrapolating the present-day rate of increase in well development into the future (Figure 6-10). The present-day rate of development is based on the linear trend of the previous ten years of development. Based on the analysis of the past ten years of development, the rate of increase in high capacity wells is estimated to be 61 wells per year in the basin.

Figure 6-9 High capacity well development, Lower Niobrara River Basin.



The future depletions due to current and future well development that could be expected to affect streamflow in the basin were estimated using SDF methodology. The results estimate the future streamflow to be depleted by 47 cfs in ten years, 61 cfs in fifteen years, 78 cfs in twenty years, and 95 cfs in twenty-five years.

The estimate of the twenty-year average number of days surface water is available for diversion was not calculated because minimal surface water administration has previously occurred and the threshold flows necessary to satisfy senior appropriations could not be estimated. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

6.9 Sufficiency to Avoid Noncompliance

There are no compacts on any portions of the Lower Niobrara River Basin in Nebraska.

6.10 Ground Water Recharge Sufficiency

The streamflow is sufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the stream, as explained in Appendix H.

6.11 Current Studies being Conducted to Assist with Future Analysis

A substantial portion of the Niobrara River Basin on the south side of the river is included in the Elkhorn-Loup ground water model (ELM), which is currently being developed to evaluate the ground water-surface water relationship and the water supply of the Elkhorn and Loup River Basins. Although not developed specifically to evaluate the water supply in the Niobrara River Basin, this model may eventually be adapted to analyze water resources in the basin.

6.12 Relevant Data Provided by Interested Parties

The Department published a request for relevant data for this year's evaluation from interested parties on May 12, 2008 (see Appendix A for Affidavit). The Department did not receive any such information.

6.13 Conclusions

Based on the evaluation of available information, the Department has reached a conclusion that the surface water and ground water supplies in hydrologic connection in the Lower Niobrara River Basin are not fully appropriated. The analysis indicated that future water supplies will potentially be impacted by 21 cfs in twenty-five years, due to lag impacts from current levels of development, and by 95 cfs in twenty-five years if current development trends continue. Estimates of future water supplies for junior irrigators could not be estimated because only minimal surface water administration has occurred on the Niobrara River during the past twenty years. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

Bibliography of Hydrogeologic References for Lower Niobrara River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln.

Wen, F. J. and X. H. Chen, 2006. Evaluation of the impact of groundwater irrigation on streamflow depletion in Nebraska. *Journal of Hydrology* 327: 603-617.

7.0 LOWER PLATTE RIVER BASIN

7.1 Summary

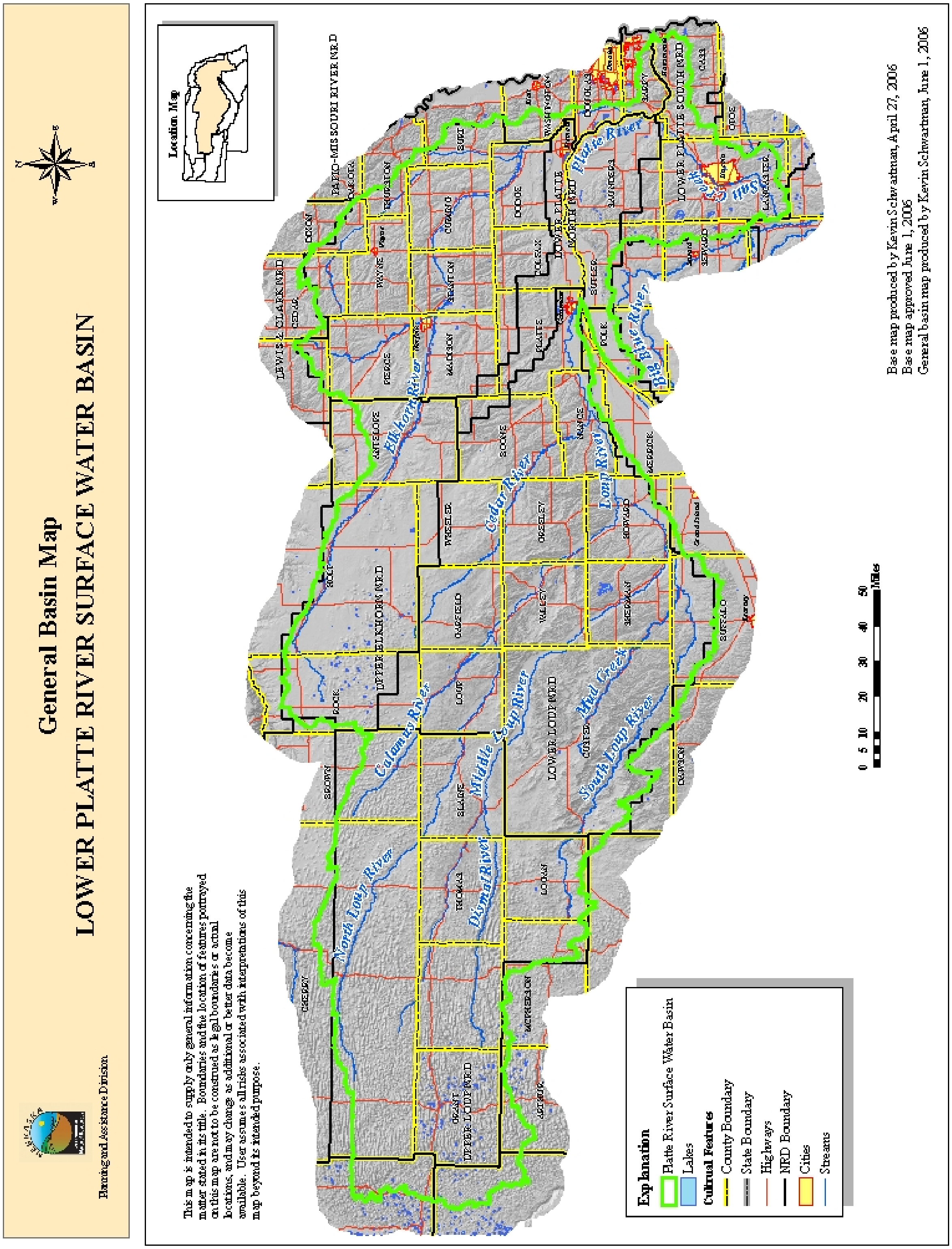
Based on the analysis of the sufficiency of the long-term surface water supply in the Lower Platte River Basin, the Department has reached a conclusion that the basin is not fully appropriated. The analysis of the lag effects from current development on the Lower Platte Basin indicates a reduction in streamflows of 616 cfs upstream of Louisville, approximately 202 cfs occurs due to lag impacts upstream of North Bend. The analysis of the impacts of future development (including the lag depletions from current levels of development) on the Lower Platte River Basin based on current development trends indicates a reduction in streamflows of 737 cfs in twenty-five years upstream of Louisville, approximately 255 cfs of which occurs due to development upstream of North Bend. The analysis of future water supplies in the Lower Platte River Basin indicates that, if no additional constraints are placed on ground water and surface water development and reasonable projections are made of the extent of future development, then the effects on the long-term water supply would cause the basin to become fully appropriated in the future.

7.2 Basin Description

The Lower Platte River is defined as the reach of the Platte River from its confluence with the Loup River to its confluence with the Missouri River. The Lower Platte River Basin is defined as all surface areas that drain into the Lower Platte River, including those areas that drain into the Loup River and the Elkhorn River, and all aquifers that impact surface water flows of the basin (Figure 7-1). The total area of the Lower Platte River surface water basin is approximately 25,400 square miles, of which approximately 15,200 square miles are in the Loup River subbasin and approximately 7,000 square miles are in the Elkhorn River subbasin. Natural resources districts with significant area in the basin are the Lower Platte South Natural Resources District; the Lower Platte North Natural Resources District; the Upper Elkhorn

Natural Resources District; the Lower Elkhorn Natural Resources District; the Upper Loup Natural Resources District; the Lower Loup Natural Resources District; and the Papio-Missouri River Natural Resources District.

Figure 7-1 General basin map, Lower Platte River Basin.



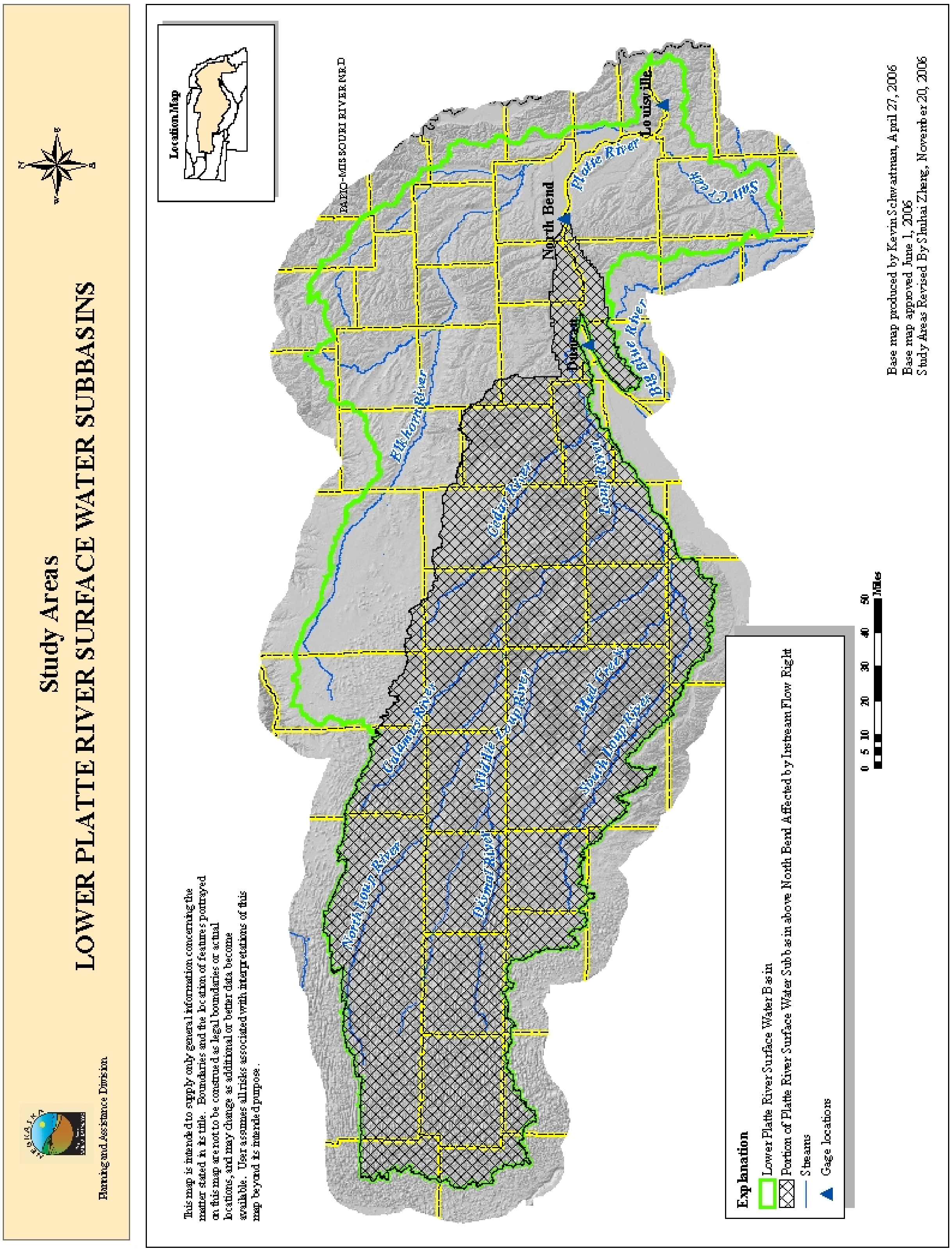
7.2.1 Subbasin Relationships

When considering the Lower Platte River Basin, it is important to understand the relationship between the senior surface water appropriations and the junior surface water appropriations in the Loup and Elkhorn River subbasins with regard to appropriations in the downstream portion of the Lower Platte River Basin. In general, when a senior water right calls for water, all water rights upstream of the senior right will be shut off to get water to the senior appropriator. Starting with the most junior appropriators, the Department will shut off as many junior appropriators as necessary to provide water to the senior appropriator. For senior appropriations along the Lower Platte River, this includes junior appropriators in the Loup and Elkhorn subbasins, because those subbasins provide flows to the reaches of the Lower Platte River that require administration for senior appropriators.

The senior appropriations calling for water in the Lower Platte River Basin are the instream flow rights. The instream flow rights have a priority date of November 30, 1993, and, when these appropriations are not being fulfilled, all surface water appropriations junior to that priority date will be closed. The instream flow appropriations are measured at the North Bend gage and the Louisville gage, although the appropriations extend to the confluence with the Missouri River. When instream flow appropriations are not met at the North Bend gage, all junior surface water appropriations above that gage, including those in the Loup River Basin, are closed to diversion (Figure 7-2). When instream flow appropriations are not met at both the North Bend and the Louisville gages, all junior surface water appropriations above both gages, including those in both the Loup and Elkhorn River subbasins, are closed to diversion. In circumstances where the instream flow appropriation is being met at the North Bend gage but not at the Louisville gage, all junior appropriations above the Louisville gage, including those in both the Loup and Elkhorn River subbasins, are closed to diversion.

Administration for the instream flow rights did not begin until 1997 when the permits were actually issued. Therefore, to evaluate a twenty-year record, the Department had to determine the number of days in which administration would have occurred if the instream flow rights had been in existence for the entire period of evaluation (1988-2007). Between 1988 and 2007, the junior surface water appropriations above North Bend, including those in the Loup River subbasin, would have been closed due to the instream flow appropriations not being met during July and August (the 65% time period from the 65/85 rule) for a total of 590 days. The junior surface water appropriations downstream of North Bend but upstream of Louisville would have been closed due to the instream flow appropriation not being met during July and August for a total of 549 days.

Figure 7-2 Map of the Platte River Basin highlighting the subbasin above the North Bend gage.



7.3 Nature and Extent of Water Use

7.3.1 Ground Water

Ground water in the basin is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. A total of 43,506 ground water wells had been registered within the basin as of December 31, 2007 (Department registered ground water wells database) (Figure 7-3). The locations of all active ground water wells can be seen in Figure 7-4.

Figure 7-3 Current well development by number of registered wells, Lower Platte River Basin.

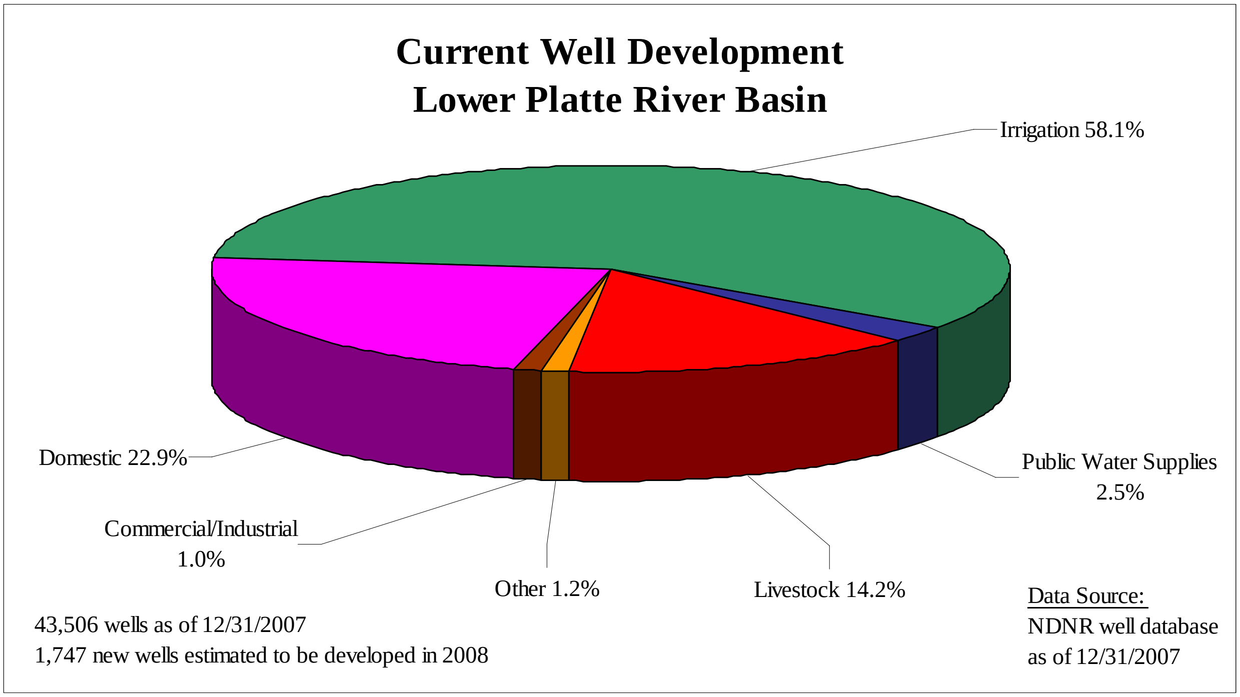
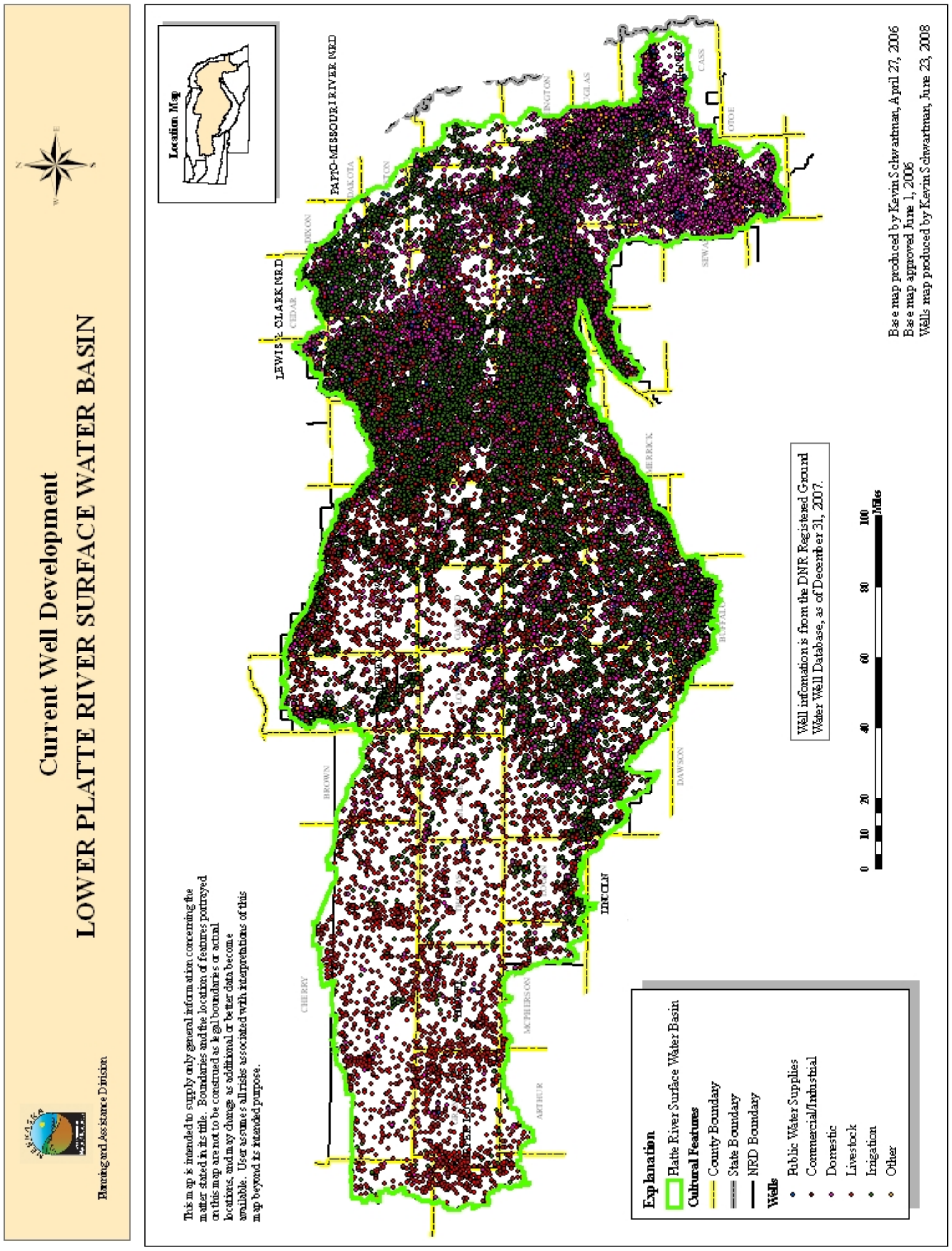


Figure 7-4 Current well locations, Lower Platte River Basin.



7.3.2 Surface Water

As of December 31, 2007, 2,935 surface water appropriations were held in the basin, issued for a variety of uses (Figure 7-5). Most of the surface water appropriations are for irrigation use and tend to be located on the major streams. In addition, two instream flow appropriations and two hydropower appropriations are held in the basin. The instream flow appropriations are located on the Platte River and are measured at North Bend and Louisville. The hydropower appropriations are located on the Loup River and the Cedar River. The first surface water appropriations in the basin were permitted in 1890, and development has continued through the present day. The approximate locations of the surface water diversion points are shown in Figure 7-6.

Figure 7-5 Surface water appropriations by number of diversion points, Lower Platte River Basin.

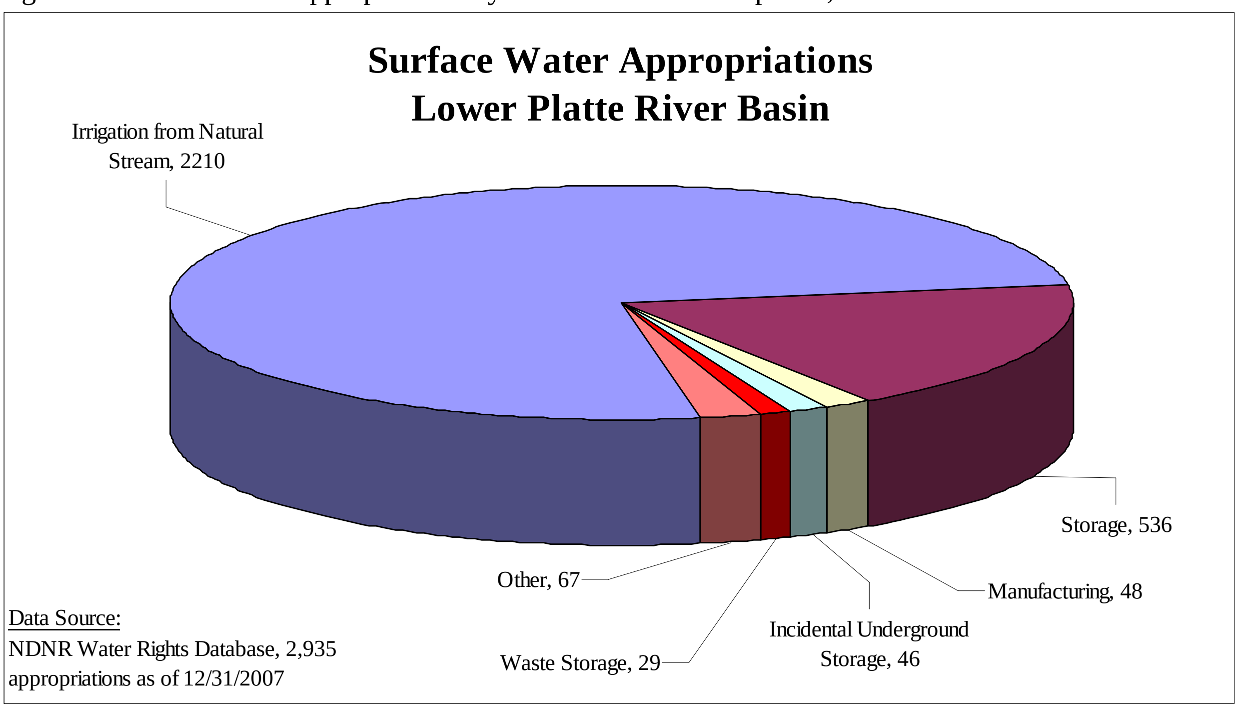
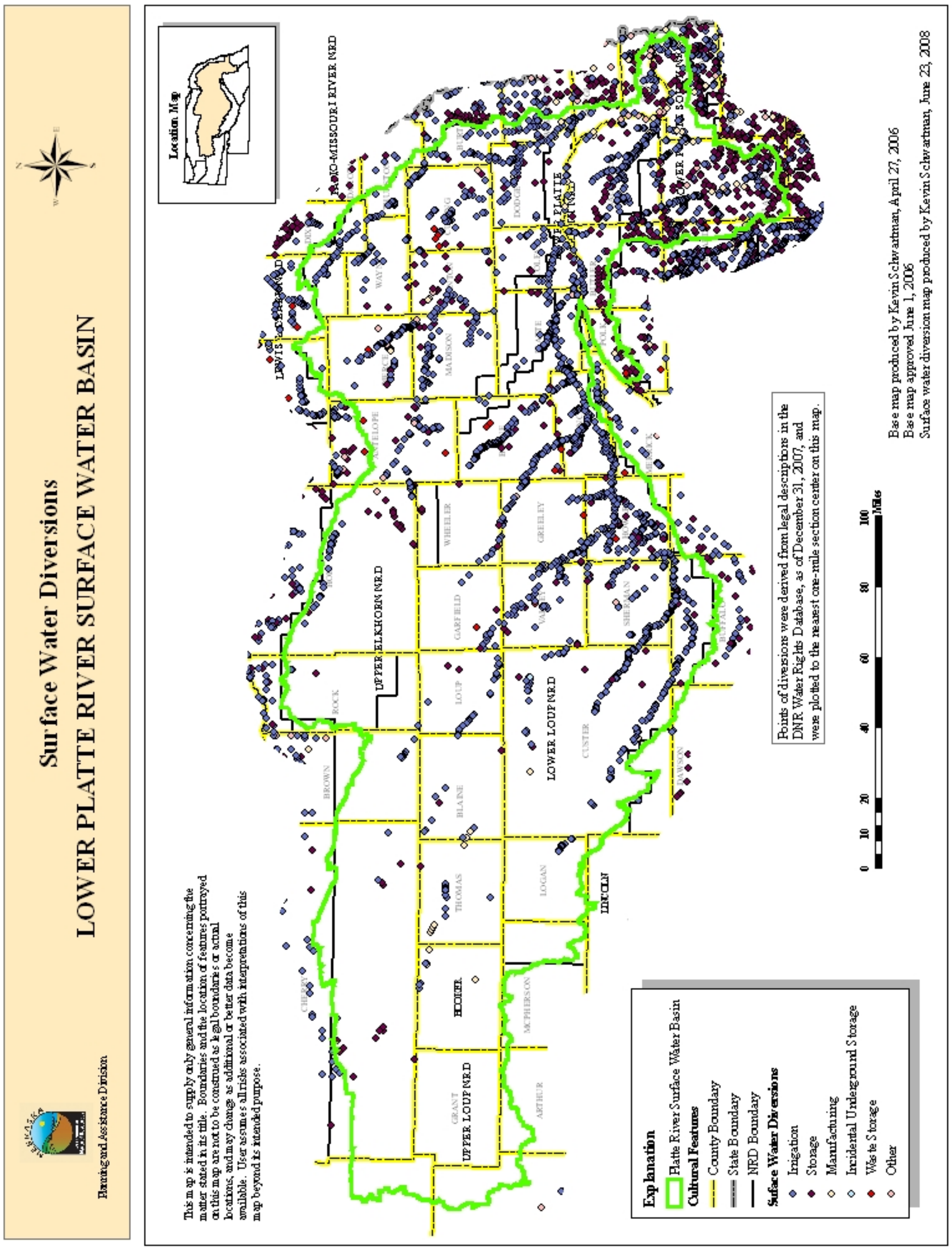


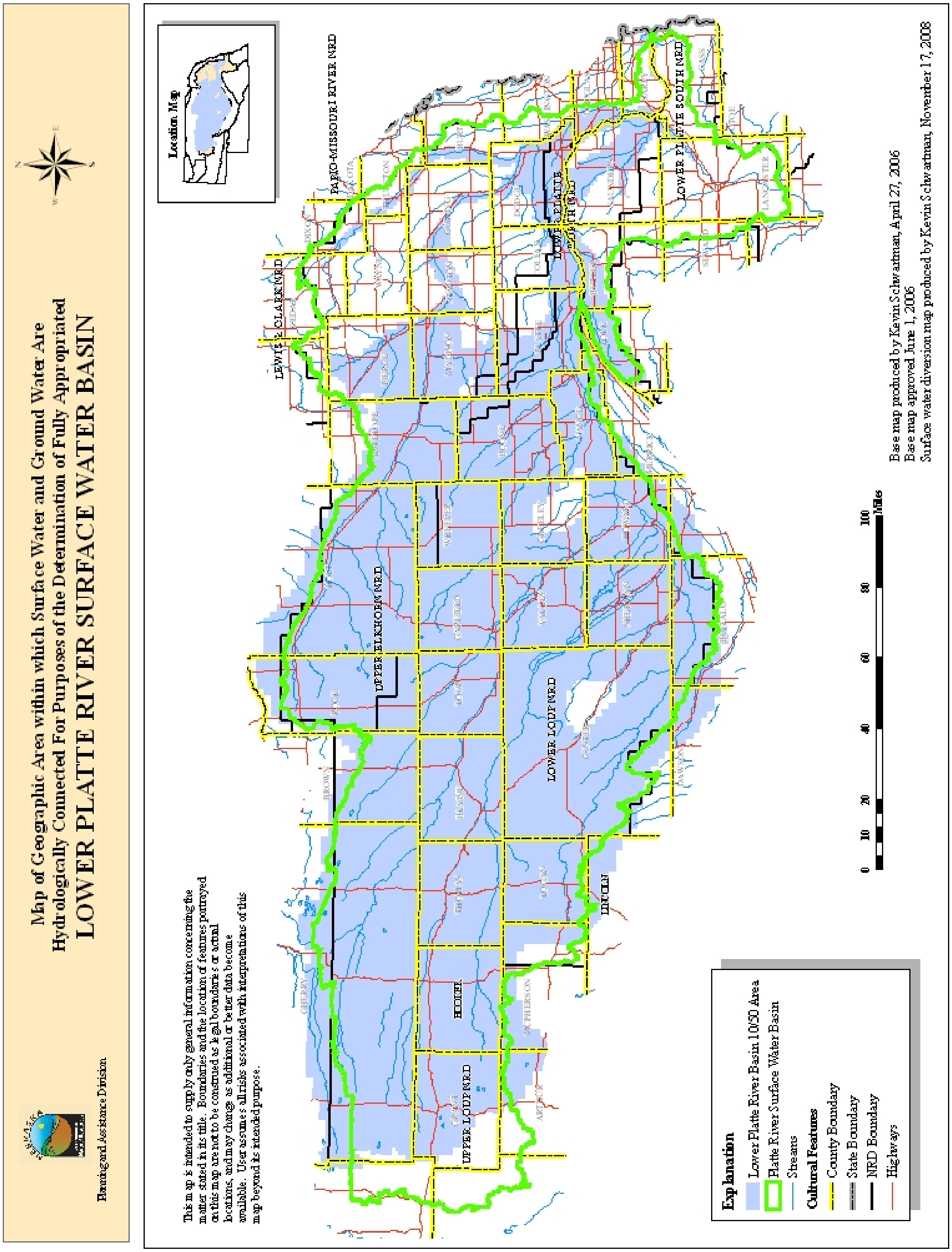
Figure 7-6 Surface water appropriation diversion locations, Lower Platte River Basin.



7.4 Hydrologically Connected Area

The Elkhorn-Loup model (ELM) was used to determine the extent of the 10/50 area for the Loup Basin and portions of the Elkhorn Basin. In areas that were not covered by the ELM but were considered to be hydrologically connected, the 10/50 area was determined using stream depletion factor (SDF) methodology. Figure 7-7 specifies the extent of the 10/50 area. A description of the SDF methodology used appears in the "Methodology" section of this report.

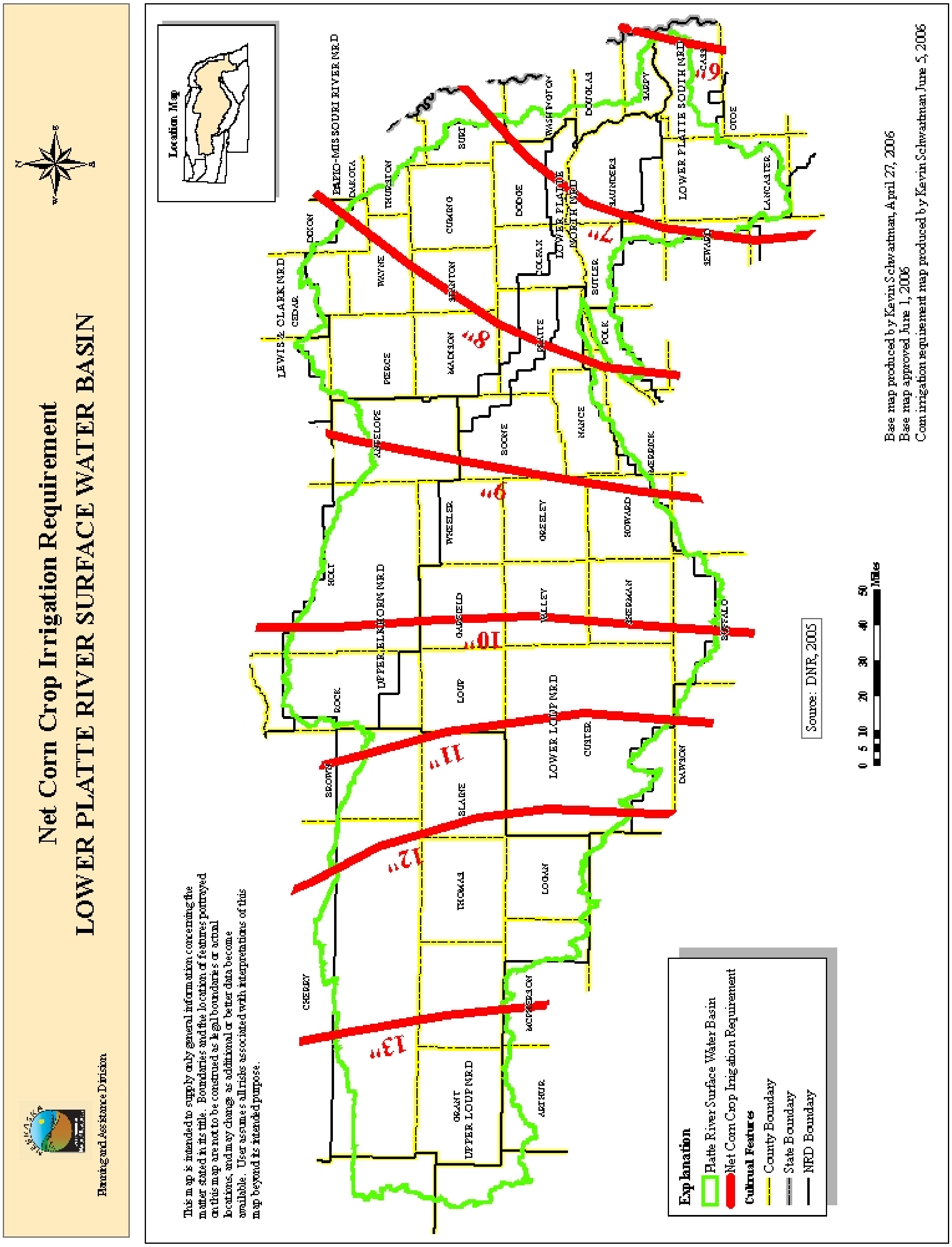
Figure 7-7 10/50 area, Lower Platte River Basin.



7.5 Net Corn Crop Irrigation Requirement

Figure 7-8 is a map of the net corn crop irrigation requirement for the Lower Platte River Basin (DNR, 2005). The NCCIR for a junior surface water appropriation above the North Bend gage is 10.52 inches. To assess the number of days required to be available for diversion, a surface water diversion rate equal to 1 cfs per 70 acres, a downtime of 10%, and an irrigation efficiency of 80% were assumed. Based on these assumptions, the most junior surface water appropriations would need 27.9 days annually to divert 65% of the NCCIR and 36.5 days to divert 85% of the NCCIR.

Figure 7-8 Net corn crop irrigation requirement, Lower Platte River Basin.



7.6 Surface Water Closing Records

Tables 7-1 and 7-2 record all surface water administration that has occurred in the basin upstream of the North Bend and Louisville gages, respectively, between 1988 and 2007. Additionally, the Department received a request from Loup Public Power District (LPPD) on May 2, 2008, to administer for their water rights in the Loup River Basin. At the time of this report the Department can not determine when the most junior surface water appropriations would have been closed and therefore unable to divert during the previous twenty-year period as required in 457 N.A.C. 001.01A. The Department is continuing to review this matter and may address it in future reports.

Table 7-1 Surface water administration in the Lower Platte River Basin upstream of the North Bend gage, 1988-2007.

Year	Water Body	Days	Closing Date	Opening Date
2000	Lower Platte River Basin above North Bend	53	Aug 8	Sep 30
2001	Lower Platte River Basin above North Bend	11	Aug 7	Aug 18
2002	Lower Platte River Basin above North Bend	6	Jun 6	Jun 12
2002	Lower Platte River Basin above North Bend	67	Jun 25	Aug 31
2002	Lower Platte River Basin above North Bend	24	Sep 6	Sep 30
2003	Lower Platte River Basin above North Bend	81	Jul 11	Sep 30
2004	Lower Platte River Basin above North Bend	13	May 6	May 19
2004	Lower Platte River Basin above North Bend	7	Jun 29	Jul 6
2004	Lower Platte River Basin above North Bend	58	Jul 27	Sep 23
2005	Lower Platte River Basin above North Bend	48	Jul 12	Aug 29
2005	Lower Platte River Basin above North Bend	28	Sep 2	Sep 30
2006	Lower Platte River Basin above North Bend	35	May 15	Jun 20
2006	Lower Platte River Basin above North Bend	45	Jun 26	Aug 10
2006	Lower Platte River Basin above North Bend	28	Aug 14	Sep 11
2006	Lower Platte River Basin above North Bend	22	Oct 5	Oct 27
2006	Lower Platte River Basin above North Bend	20	Oct 31	Nov 20
2007	Lower Platte River Basin above North Bend	5	July 9	July 14

Table 7-2 Surface water administration in the Lower Platte River Basin downstream of the North Bend gage and upstream of the Louisville gage 1988-2007.

Year	Water Body	Days	Closing Date	Opening Date
1990	Willow Creek	14	Aug 17	Aug 31
1991	Taylor Creek	4	Jul 30	Aug 3
1991	Taylor Creek	3	Aug 23	Aug 26
1991	Taylor Creek	7	Aug 28	Sep 4
1991	Union Creek	7	Aug 28	Sep 4
2000	Lower Platte River Basin above Louisville	53	Aug 8	Sep 30
2001	Lower Platte River Basin above Louisville	11	Aug 7	Aug 18
2002	Lower Platte River Basin above Louisville	6	Jun 6	Jun 12
2002	Lower Platte River Basin above Louisville	59	Jun 25	Aug 23
2002	Lower Platte River Basin above Louisville	4	Aug 27	Aug 31
2002	Lower Platte River Basin above Louisville	24	Sep 6	Sep 30
2003	Lower Platte River Basin above Louisville	66	Jul 14	Sep 18
2004	Lower Platte River Basin above Louisville	13	May 6	May 19
2004	Lower Platte River Basin above Louisville	7	Jun 29	Jul 6
2004	Lower Platte River Basin above Louisville	58	Jul 27	Sep 23
2005	Lower Platte River Basin above Louisville	14	Jul 12	Jul 26
2005	Lower Platte River Basin above Louisville	31	Jul 29	Aug 29
2005	Lower Platte River Basin above Louisville	28	Sep 2	Sep 30
2006	Lower Platte River Basin above Louisville	35	May 16	Jun 20
2006	Lower Platte River Basin above Louisville	45	Jun 26	Aug 10
2006	Lower Platte River Basin above Louisville	28	Aug 14	Sep 11
2006	Lower Platte River Basin above Louisville	22	Oct 5	Oct 27
2006	Lower Platte River Basin above Louisville	20	Oct 31	Nov 20
2007	Lower Platte River Basin above Louisville	5	July 9	July 14

7.7 Evaluation of Current Development

7.7.1 Current Water Supply

The current water supply is estimated by using the previous twenty years (1988-2007) of flows and comparing them to the flows necessary to satisfy the senior surface water appropriation (i.e., the instream flow appropriations). The results of the analyses conducted for the Lower Platte River Basin upstream of North Bend and downstream of North Bend and upstream of Louisville, respectively, are shown in Tables 7-3 and 7-4. The results indicate that the current surface water supply in the Lower Platte River Basin upstream of North Bend provides an average of 32.5 days available for diversion between July 1 and August 31 and 103.9 days available for diversion between May 1 and September 30 (Table 7-5). The results for the Lower Platte River Basin downstream of North Bend and upstream of Louisville indicate an average of 34.6 days available for diversion between July 1 and August 31 and 106.8 days available for diversion between May 1 and September 30 (Table 7-6).

Table 7-3 Estimate of the current number of days surface water is available for diversion upstream of North Bend.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
1988	10	69
1989	14	47
1990	16	77
1991	6	66
1992	62	153
1993	62	153
1994	56	143
1995	52	134
1996	62	153
1997	40	131
1998	62	153
1999	61	152
2000	32	94
2001	28	111
2002	2	48
2003	6	72
2004	20	75
2005	10	71
2006	0	6
2007	49	140
Average	32.5	103.9

Table 7-4 Estimate of the current number of days surface water is available for diversion downstream of North Bend and upstream of Louisville.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
1988	10	69
1989	15	49
1990	18	79
1991	10	71
1992	62	153
1993	62	153
1994	59	149
1995	53	144
1996	62	153
1997	43	134
1998	62	153
1999	62	153
2000	35	97
2001	34	118
2002	5	51
2003	11	77
2004	22	78
2005	12	73
2006	3	40
2007	51	142
Average	34.6	106.8

Table 7-5 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion upstream of North Bend.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Current Development**
July 1 – August 31 (65% Requirement)	27.9	32.5 (4.6 days above the requirement)
May 1 – September 30 (85% Requirement)	36.5	103.9 (67.4 days above the requirement)

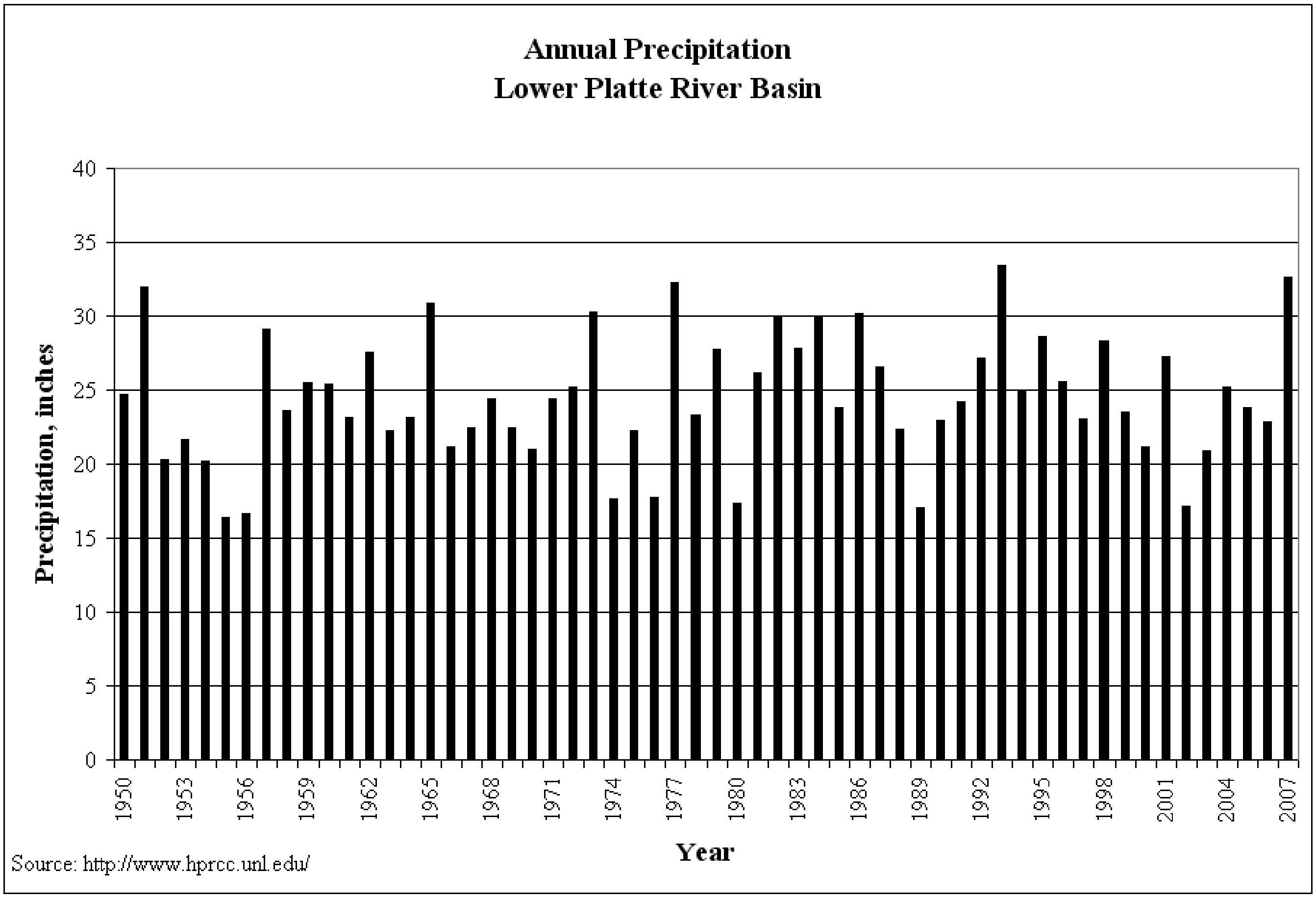
Table 7-6 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion downstream of North Bend and upstream of Louisville.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Current Development**
July 1 – August 31 (65% Requirement)	27.9	34.6 (6.7 days above the requirement)
May 1 – September 30 (85% Requirement)	36.5	106.8 (70.3 days above the requirement)

7.7.2 Water Supply

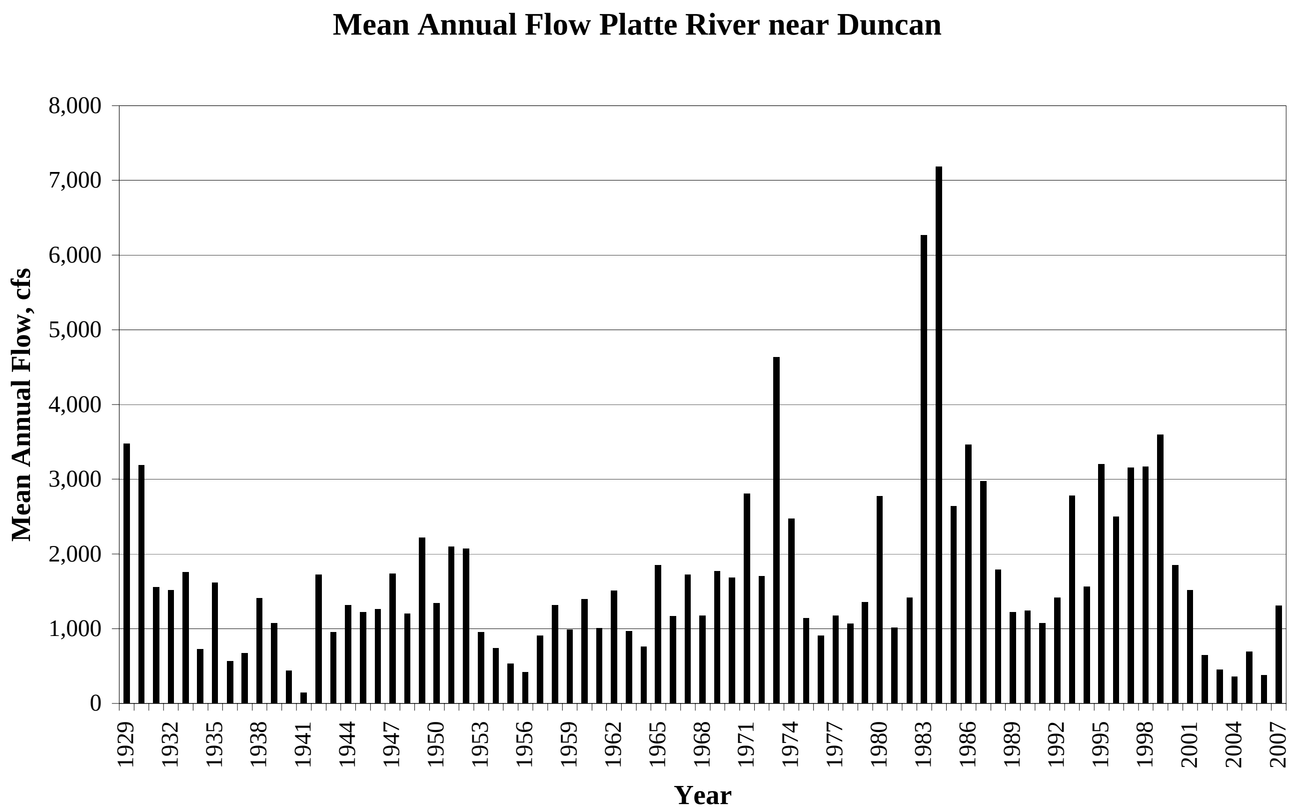
In order to complete the long-term evaluation of surface water supplies, a future twenty-year water supply for the basin must be estimated. The basin's major water sources are precipitation, which runs off as direct streamflow and infiltrates into the ground to discharge as baseflow; ground water movement into the basin, which discharges as baseflow; and streamflow from the middle Platte River. Using methodology published in the *Journal of Hydrology* (Wen and Chen, 2005), a nonparametric Mann-Kendall trend test of the weighted average precipitation in the basin was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past fifty years (Figure 7-9). The same type of statistical analysis of streamflow from the middle Platte River (using the Platte River at Duncan gage as inflow to the Lower Platte Basin), also showed no statistically significant trend ($P > 0.95$) (Figure 7-10). Therefore, using the previous twenty years of precipitation and streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure 7-9 Annual precipitation, Lower Platte River Basin[1]



[1] The results include precipitation stations covering the Loup, Elkhorn, and Platte River Basins.

Figure 7-10 Mean annual flow, Platte River near Duncan



Source: http://www.usgs.gov/

7.7.3 Depletions Analysis

The future depletions due to current well development that could be expected to affect streamflow in the basin were estimated using the ELM for the Loup Basin and portions of the Elkhorn Basin, whereas the SDF methodology was used in all other areas where data exist. The results estimate the future streamflow at North Bend to be depleted by 202 cfs in twenty-five years. The results estimate the future streamflow at Louisville to be depleted by 616 cfs in twenty-five years. The 616 cfs depletion at Louisville includes the 202 cfs at North Bend, 108 cfs calculated using the results of the ELM for the Elkhorn River upstream of Norfolk, 25 cfs calculated using the Jenkins method for areas downstream of North Bend and downstream of Norfolk but upstream of the Louisville gage, 160 cfs[1] from the Metropolitan Utilities District's Platte

West wellfield, located on the Platte River upstream of the confluence of the Platte and Elkhorn Rivers, and 121 cfs[2] from the Lincoln Water Systems's wellfield, located on the Platte River near Ashland.

7.7.4 Evaluation of Current Levels of Development against Future Water Supplies

The estimates of the twenty-year average number of days available for diversion are calculated by comparing the lag-adjusted future water supply with the flows necessary to satisfy the senior calling surface water appropriations (in this case, the instream flow rights) that have caused administration of junior appropriations in the basin. The results of the analyses are shown in Tables 7-7 and 7-8. The results of the analyses as compared to the numbers of days surface water is required to be available to divert 65% and 85% of the NCCIR are detailed in Tables 7-9 and 7-10. The long-term surface water supply estimates, given current levels of development, are sufficient to meet the needs of the most junior surface water appropriations for the Lower Platte River Basin upstream of North Bend.

[1]This is the maximum amount of water that is permitted to be pumped from the stream by the wellfield, not the entire amount of streamflow for which the induced recharge permit was granted.
[2]This is the difference between the maximum amount of water permitted to be pumped from the stream by the wellfield and the best estimate of average July-August water currently being pumped from the stream by the wellfield.

Table 7-7 Estimate of days surface water is available for diversion upstream of North Bend with current development and twenty-five-year lag impacts.

Year	**July 1 though August 31 Number of Days Surface Water is Available for Diversion**	**May 1 through September 30 Number of Days Surface Water is Available for Diversion**
1	**4**	**55**
2	**13**	**40**
3	**10**	**71**
4	**3**	**63**
5	**58**	**140**
6	**62**	**153**
7	**48**	**127**
8	**49**	**128**
9	**60**	**151**
10	**38**	**129**
11	**61**	**145**
12	**61**	**152**
13	**20**	**81**
14	**16**	**87**
15	**1**	**41**
16	**4**	**69**
17	**16**	**61**
18	**5**	**66**
19	**0**	**29**
20	**39**	**130**
Average	28.4	95.9

Table 7-8 Estimate of days surface water is available for diversion downstream of North Bend and upstream of Louisville with current development and twenty-five-year lag impacts.

Year	**July 1 though August 31 Number of Days Surface Water is Available for Diversion**	**May 1 through September 30 Number of Days Surface Water is Available for Diversion**
1	**4**	**55**
2	**13**	**41**
3	**12**	**73**
4	**6**	**66**
5	**58**	**140**
6	**62**	**153**
7	**50**	**136**
8	**50**	**132**
9	**60**	**151**
10	**42**	**133**
11	**62**	**146**
12	**62**	**153**
13	**26**	**87**
14	**21**	**93**
15	**4**	**44**
16	**6**	**71**
17	**17**	**62**
18	**7**	**68**
19	**2**	**33**
20	**39**	**130**
Average	30.2	98.4

Table 7-9 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion upstream of North Bend with current development and lag impacts.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development with Twenty-Five Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	27.9	28.4 (0.5 days above the requirement)
May 1 – September 30 (85% Requirement)	36.5	95.9 (59.4 days above the requirement)

Table 7-10 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion downstream of North Bend and upstream of Louisville with current development and lag impacts.

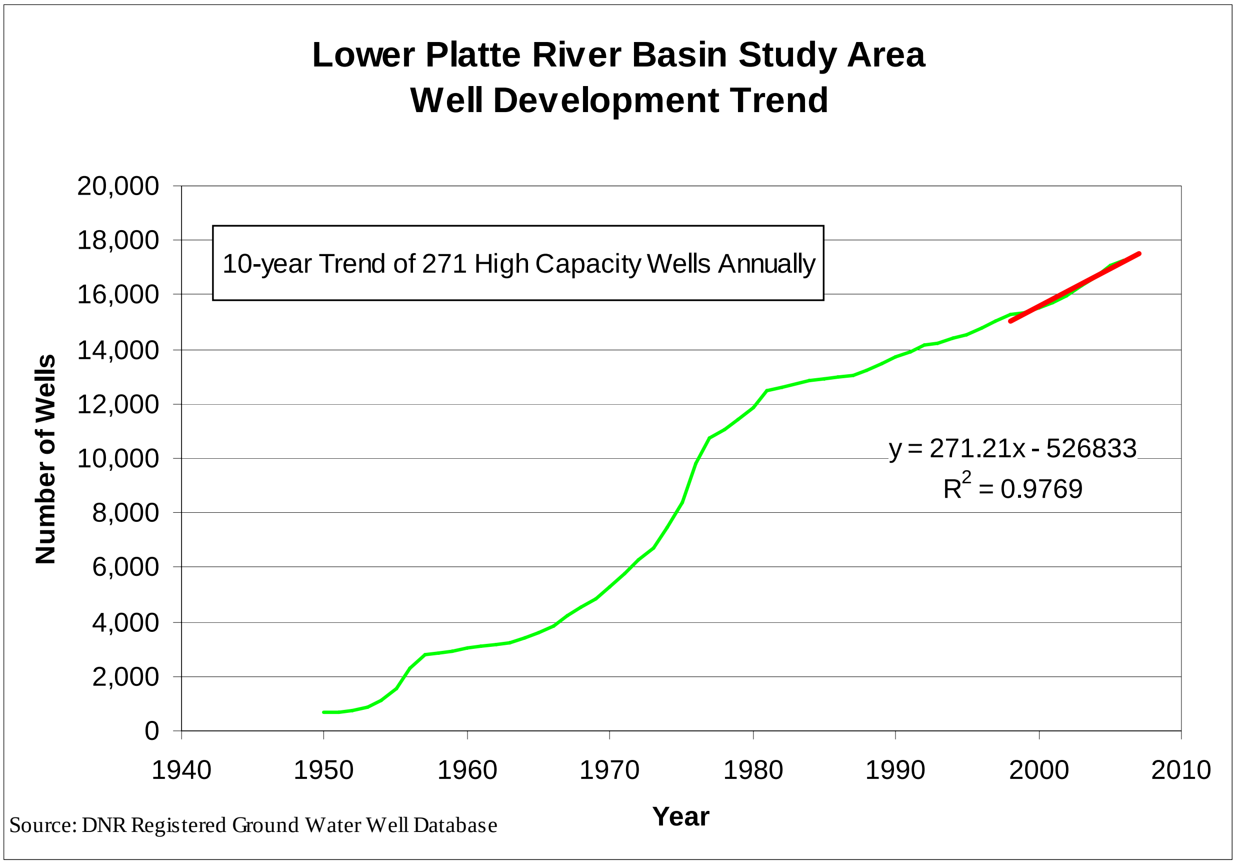
	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development with Twenty-Five Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	27.9	30.2 (2.3 days above the requirement)
May 1 – September 30 (85% Requirement)	36.5	98.4 (61.9 days above the requirement)

7.8 Evaluation of Predicted Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gpm) that would be completed over the next twenty-five years, if no new legal constraints on the construction of such wells were imposed, were calculated based on extrapolating the present-day rate of increase in well development into the future (Figure 7-11). The present-day rate of development is based on the linear trend of the previous ten years of development. Based on the analysis of the past ten years of development, the rate of increase in high capacity wells is estimated to be 271 wells per year in the basin.

At the present time, the Lower Loup Natural Resources District and portions of the Lower Platte North Natural Resources District have moratoriums on well development. Therefore, the yearly development figures for the Lower Loup Natural Resources District, and the affected portions of the Lower Platte North Natural Resources District, were not included in the estimate of future development.

Figure 7-11 High capacity well development, Lower Platte River Basin



The future depletions due to current and future well development that could be expected to affect streamflow in the basin were estimated using the Elkhorn Loup Model and the SDF methodology. The results estimate the future streamflow at North Bend to be depleted by 255 cfs in twenty-five years. This estimate includes the 202 cfs of lag from current levels of development and 53 cfs of depletion due to projected future irrigation development. The results estimate the future streamflow at Louisville to be depleted by 737 cfs in twenty-five years. This estimate includes the 616 cfs of lag depletion from current levels of development, 53 cfs of depletion due to projected future irrigation development upstream of North Bend and 68 cfs of depletion due to projected future irrigation development downstream of North Bend.

The estimate of the twenty-year average number of days surface water is available for diversion with additional future development is calculated by comparing the future lag-adjusted flow with the flows necessary to satisfy the senior surface water appropriation. The results of the analyses are shown in Tables 7-11 and 7-12. The results of the analyses as compared to the numbers of days surface water is required to be available to divert 65% and 85% of the NCCIR are detailed in Tables 7-13 and 7-14. The results indicate that, if no additional constraints are placed on ground water and surface water development and reasonable projections are made of the extent of future development, then the effects on the long-term water supply would cause the basin to become fully appropriated in the future.

Table 7-11 Estimated number of days surface water is available for diversion upstream of North Bend with current and predicted future development

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
1	**4**	**54**
2	**13**	**37**
3	**9**	**70**
4	**2**	**62**
5	**57**	**133**
6	**62**	**153**
7	**46**	**124**
8	**47**	**126**
9	**58**	**149**
10	**38**	**129**
11	**61**	**144**
12	**61**	**152**
13	**17**	**77**
14	**14**	**84**
15	**0**	**38**
16	**4**	**68**
17	**16**	**59**
18	**5**	**66**
19	**0**	**27**
20	**37**	**128**
Average	27.6	94.0

Table 7-12 Estimated number of days surface water is available for diversion downstream of North Bend and upstream of Louisville with current and predicted future development

Year	**July 1 though August 31 Number of Days Surface Water is Available for Diversion**	**May 1 through September 30 Number of Days Surface Water is Available for Diversion**
1	**4**	**54**
2	**13**	**38**
3	**11**	**72**
4	**5**	**65**
5	**57**	**133**
6	**62**	**153**
7	**48**	**133**
8	**48**	**129**
9	**58**	**149**
10	**41**	**132**
11	**62**	**145**
12	**62**	**153**
13	**24**	**84**
14	**17**	**88**
15	**3**	**41**
16	**6**	**70**
17	**17**	**60**
18	**7**	**68**
19	**2**	**30**
20	**37**	**128**
Average	29.2	96.3

Table 7-13 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion upstream of North Bend with current and predicted future development

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Future Development and Twenty-Five Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	27.9	27.6 (0.3 days below the requirement)
May 1 – September 30 (85% Requirement)	36.5	94.0 (57.5 days above the requirement)

Table 7-14 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion downstream of North Bend and upstream of Louisville with current and predicted future development

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Future Development and Twenty-Five Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	27.9	29.2 (1.3 days above the requirement)
May 1 – September 30 (85% Requirement)	36.5	96.3 (59.8 days above the requirement)

7.9 Instream Flow Surface Water Appropriation Analysis

During the non-irrigation season, the junior water rights in the Lower Platte River system are the Nebraska Game and Parks Commission’s instream flow rights. The purpose of these rights is to maintain habitat for the fish community. Therefore, the Department determined that an appropriate standard of interference would be to determine whether the instream flow requirements that could be met at the time the water rights were granted can still be met today.

To calculate the average monthly flow that the instream flow permits could have expected at the time they were granted, the twenty-year period prior to the permits being granted (1974-1993) was used. In conducting this analysis, the lag impacts were calculated for development through 1993 and subtracted from the daily flows (see Section 4.4.5 for more detail). The average number of days that flows were available for each month at the time the appropriations were obtained was compared with the current average number of days that flows are available for each month. The results are shown in Table 7-15 and 7-16.

Results indicate that the North Bend instream flow appropriation would experience minor erosion after twenty-five years for the months of March (2.0 days) and April (0.1 days). The Louisville instream flow appropriation would experience minor erosion after twenty-five years for the months of March (1.9 days) and April (0.2 days). The long-term surface water supply estimate in the basin is sufficient for the instream flow appropriations in the basin, based on the current level of development and the calculated twenty-five year lag impacts.

Table 7-15 Number of days North Bend instream flow appropriation expected to be met

Month	Number of Days Flows Met at Time of Application [1]	Number of Days Flows Met With Current Development [2]	Difference in the Number of Days Instream Flow Appropriation is Currently Met
October	14.8	17.8	3.0
November	18.0	19.6	1.7
December	18.4	21.4	3.0
January	19.8	21.8	2.0
February	22.2	23.8	1.6
March	30.8	28.8	-2.0
April	27.7	27.6	-0.1
May	26.3	26.5	0.2
June	22.1	24.4	2.3
July	12.8	16.1	3.3
August	11.2	12.7	1.5
September	13.6	15.5	1.9

Table 7-16 Number of days Louisville instream flow appropriation expected to be met

Month	Number of Days Flows Met at Time of Application [1]	Number of Days Flows Met With Current Development [2]	Difference in the Number of Days Instream Flow Appropriation is Currently Met
October	14.8	17.8	3.0
November	18.1	19.9	1.8
December	18.6	21.8	3.2
January	20.1	23.0	2.9
February	22.3	23.9	1.6
March	30.8	28.9	-1.9
April	27.8	27.6	-0.2
May	26.3	26.6	0.3
June	22.3	24.7	2.4
July	13.5	17.6	4.1
August	11.5	13.0	1.5
September	13.7	15.7	2.0

[1] The number of days instream flows would be expected to be met at the time of application (1974-1993) with lag effects of well development at the time of the appropriation

[2] The number of days instream flows would be expected to be met at current time (1988-2007) with lag effects of current well development

7.10 Sufficiency to Avoid Noncompliance

There are no interstate compacts or decrees, or other formal state contracts or agreements in the Lower Platte Basin that could be affected by reduced stream flows. There are state and federally endangered and threatened species in the Lower Platte River Basin. The requirements of the Nebraska Nongame and Endangered Species Conservation Act and the federal Endangered Species Act prevent actions that could cause harmful stream flow reductions. At this time, there is sufficient water supply in the basin to comply with NNESCA and the ESA. Because future development will be limited so as to continue compliance with NNESCA, the long-term surface water supply in the basin is sufficient.

7.11 Current Studies being Conducted to Assist with Future Analysis

Three major studies are currently being conducted within the Lower Platte River Basin. The first is the Eastern Nebraska Water Resources Assessment (ENWRA). ENWRA is an effort between several agencies to categorize the aquifer characteristics and the water supply of the glaciated portion of eastern Nebraska, which includes large areas of the Lower Platte River Basin. This extensive body of work will provide critical data for use in future reports.

The second is the Elkhorn-Loup ground water model (ELM) study Phase II. The ELM study is working to further refine the Phase I ground water model which covers a substantial portion of the Lower Platte River Basin, to evaluate the ground water and surface water relationship and the water supply of much of the Elkhorn and all of the Loup River basins. Efforts will be made to incorporate results from this model into future reports.

The third study being conducted is an evaluation of streambed conductance for the Elkhorn River. This study is a joint effort of several agencies and will work to develop vertical hydraulic conductivity values for potential use in future depletions analysis of the Elkhorn River Basin.

7.12 Relevant Data Provided by Interested Parties

The Department published a request for relevant data from interested parties for this year's evaluation on May 12, 2008 (see Appendix A for Affidavit). The Department did not receive any such information prior to the issuance of the draft annual evaluation report in December 2008, which included a preliminary conclusion that the Lower Platte Basin was fully appropriated. Subsequently, the Department held four public hearings on the preliminary determination that the Lower Platte Basin was determined to be fully appropriated. Both oral and written testimony was presented to the Department at those hearings. Summaries of excerpts from that testimony as well as Department responses to those excerpts are provided in Appendix A.

7.13 Conclusions

Based on the analysis of the sufficiency of the long-term surface water supply in the Lower Platte River Basin, the Department has reached a conclusion that, the Lower Platte River Basin upstream of the confluence with the Missouri River is presently not fully appropriated. The Department has also determined that if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water and reasonable projections are made on the extent and location of future development, then this conclusion would change to a conclusion that the basin is fully appropriated, based on current information.

Bibliography of Hydrogeologic References for Lower Platte River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln.

Wen, F. J. and X. H. Chen, 2006. Evaluation of the impact of groundwater irrigation on streamflow depletion in Nebraska. *Journal of Hydrology* 327: 603-617.

8.0 MISSOURI TRIBUTARY BASINS

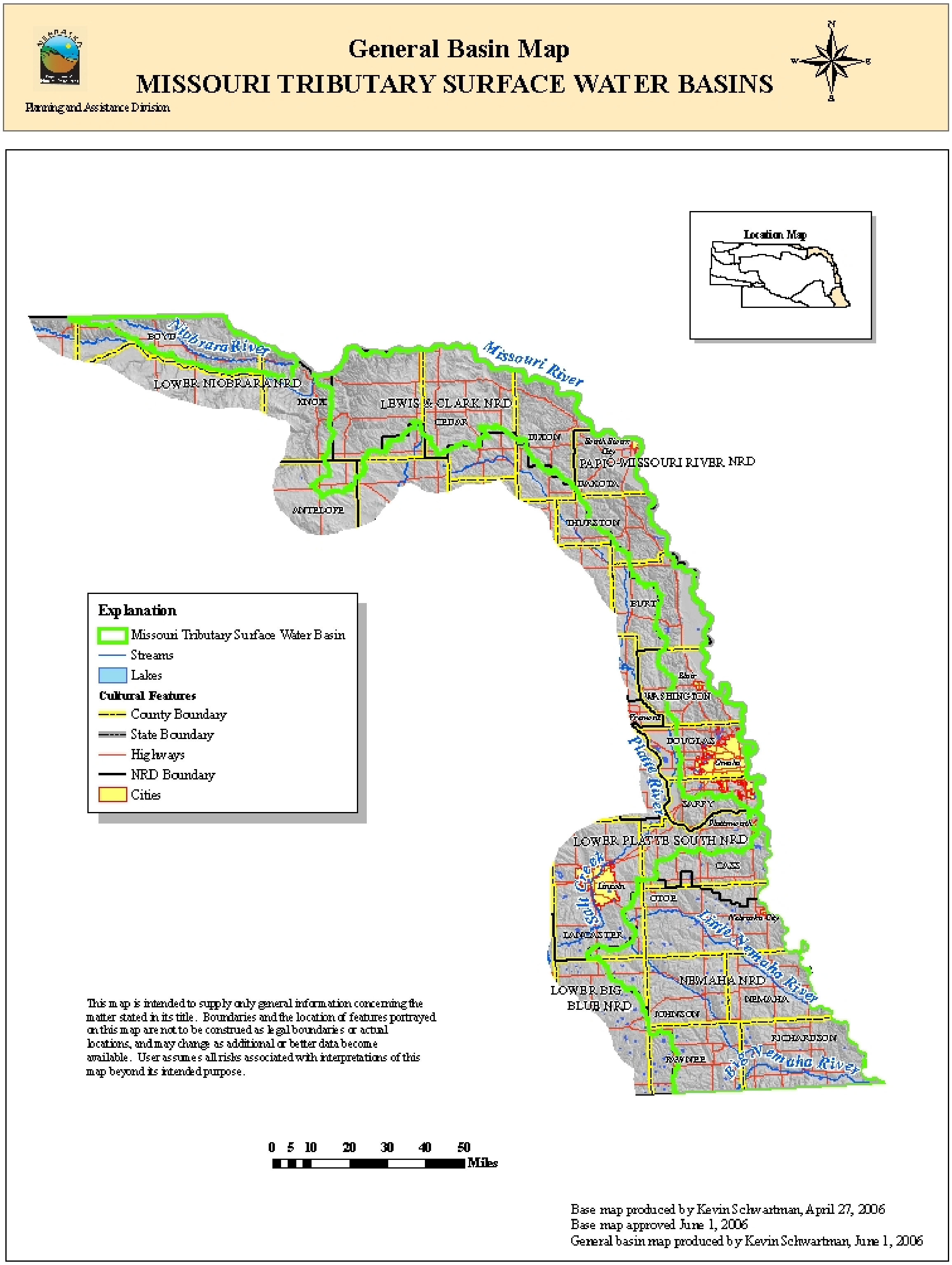
8.1 Summary

Based on the analysis of the sufficiency of the long-term surface water supply in the Missouri Tributary basins, the Department has reached a conclusion that the basins are not fully appropriated. Even though the effects of future ground water depletions on future water supplies were not estimated in the basins, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement. The best available data do not allow for analysis of whether this determination would change if no additional legal constraints are imposed on future development.

8.2 Basin Descriptions

The Missouri Tributary basins include all surface areas that drain directly into the Missouri River, with the exception of the Niobrara River and Platte River basins, and all aquifers that impact surface water flows in the basins (Figure 8-1). Major streams in these basins include Ponca Creek, Bazile Creek, Weeping Water Creek, the Little Nemaha River, and the Big Nemaha River. The total area of the Missouri Tributary surface water basins is approximately 6,200 square miles, of which approximately 450 square miles drain into the Missouri River above the Niobrara River confluence, approximately 3,000 square miles drain into the Missouri River between the Niobrara River confluence and the Platte River confluence, and 2,800 square miles drain into the Missouri River below the Platte River confluence. Natural resources districts with significant area in the basins are the Lower Niobrara Natural Resources District, the Lewis and Clark Natural Resources District, the Papio-Missouri River Natural Resources District, and the Nemaha Natural Resources District.

Figure 8-1 General basin map, Missouri Tributary basins.



8.3 Nature and Extent of Water Use

8.3.1 Ground Water

Ground water in the basins is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. A total of 6,082 ground water wells had been registered within the basins as of December 31, 2007 (Department registered ground water wells database) (Figure 8-2). The locations of all active ground water wells can be seen in Figure 8-3.

Figure 8-2 Current well development by number of registered wells, Missouri Tributary basins.

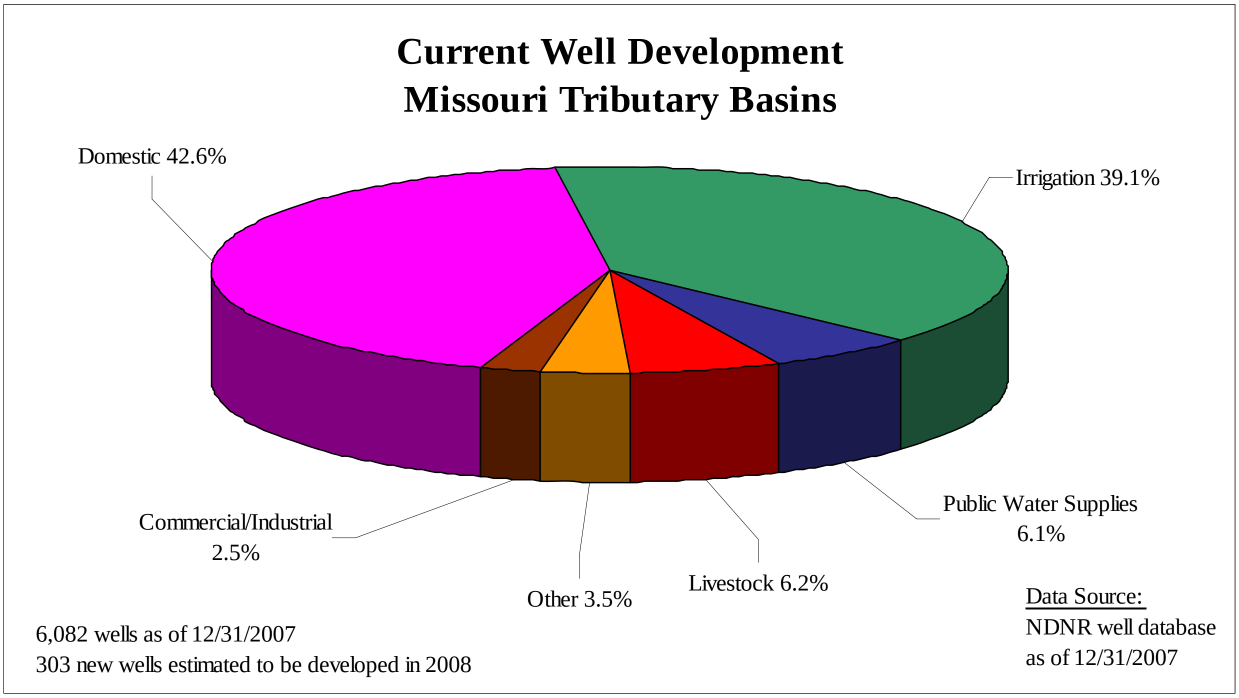
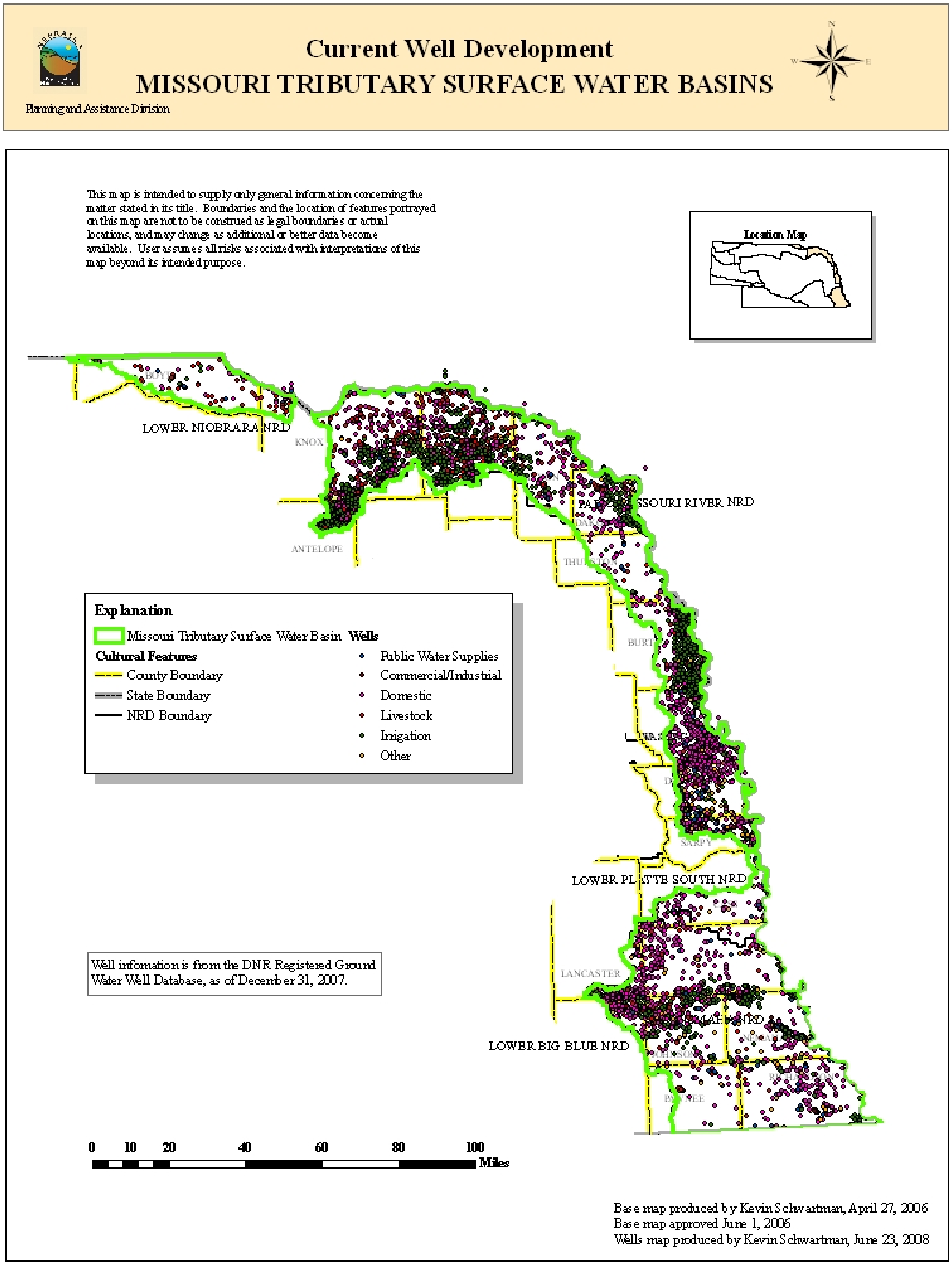


Figure 8-3 Current well locations, Missouri Tributary basins.



8.3.2 Surface Water

As of December 31, 2007, 1,413 surface water appropriations were held in the basins, issued for a variety of uses (Figure 8-4). Most of the surface water appropriations are for storage and irrigation use and tend to be located on the major streams. The first surface water appropriations in the basins were permitted in 1881, and development has continued through the present day. The approximate locations of the surface water diversion points are shown in Figure 8-5.

Figure 8-4 Surface water appropriations by number of diversion points, Missouri Tributary basins.

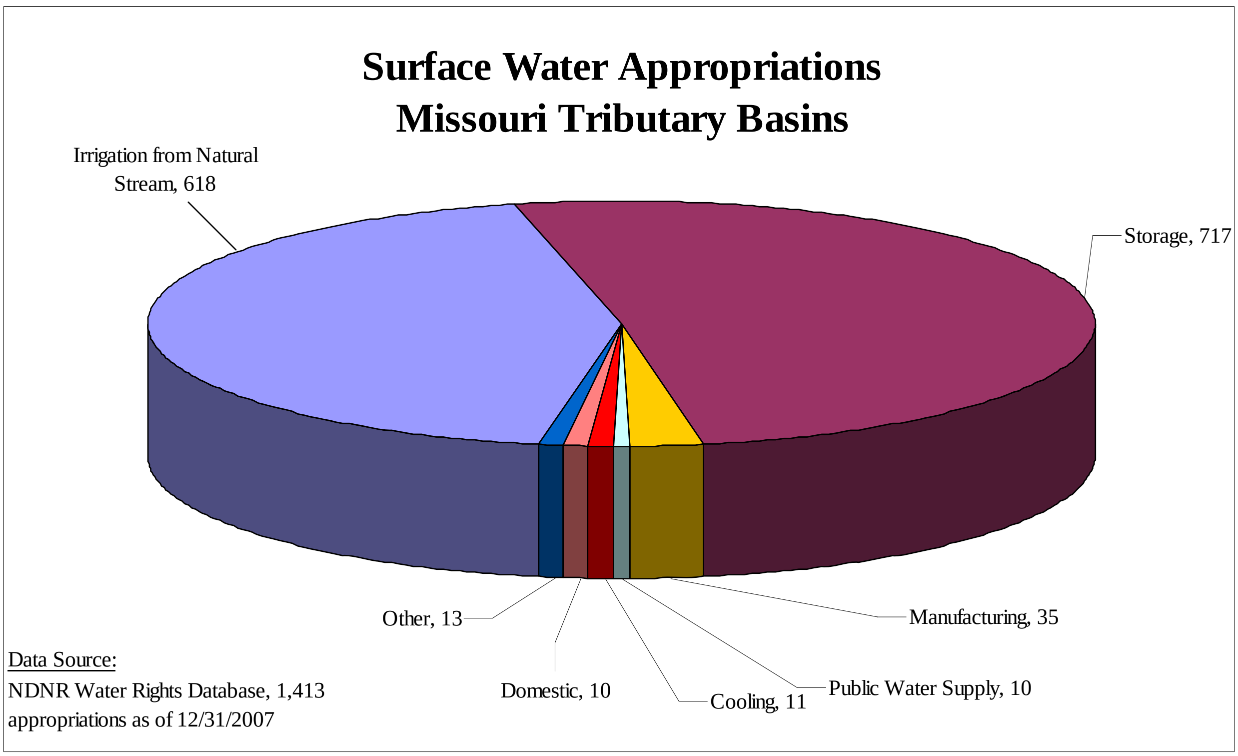
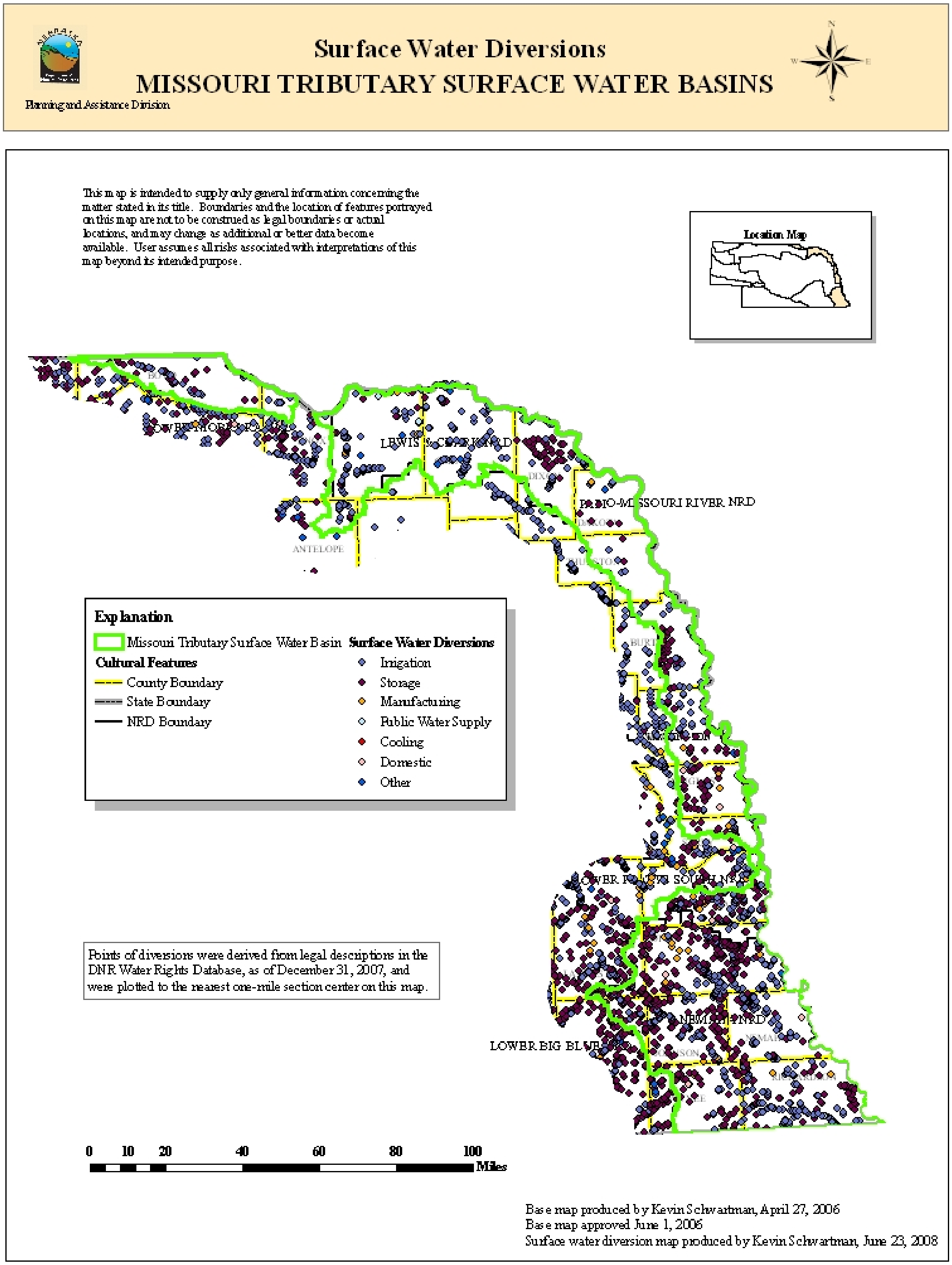


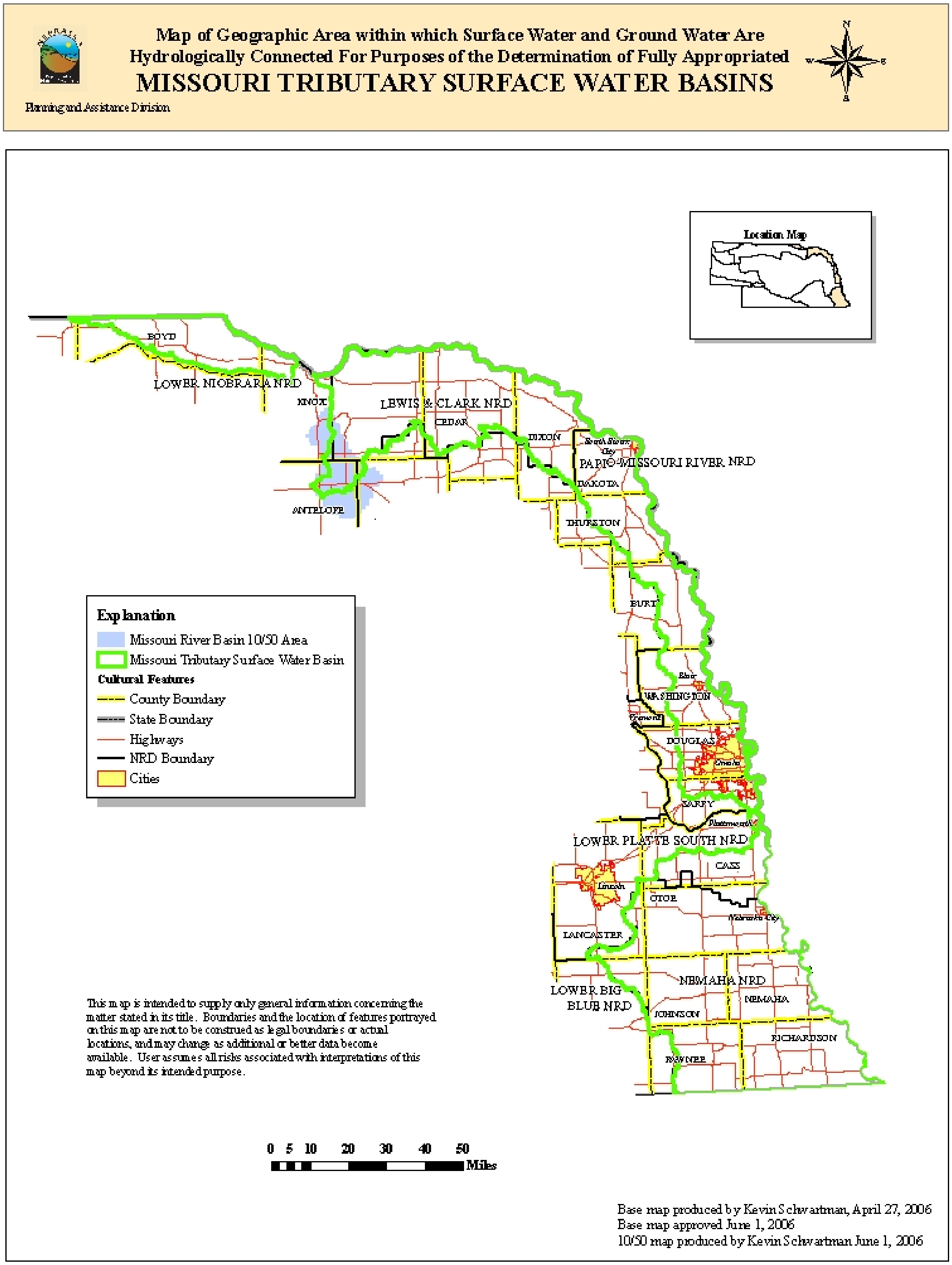
Figure 8-5 Surface water appropriation diversion locations, Missouri Tributary basins.



8.4 Hydrologically Connected Area

No sufficient numeric ground water model is available in the Missouri Tributary basins to determine the 10/50 area. The stream depletion factor (SDF) methodology can be applied only where sufficient data and appropriate hydrogeologic conditions exist. In most of the basins, the principal aquifer is absent or very thin due to the glaciated nature of the area (CSD, 2005). Additionally, where a principal aquifer is present, the complex hydrogeologic nature of the area makes the degree of connection between the ground water system and the surface water system either poor or uncertain (CSD, 2005). The area surrounding the headwaters of Bazile Creek is the only portion of the basins where the principal aquifer is both present and known to be in hydrologic connection with the streams. Consequently, this is the only portion of the study area in which the 10/50 area can be calculated (CSD, 2005) (Figure 8-6).

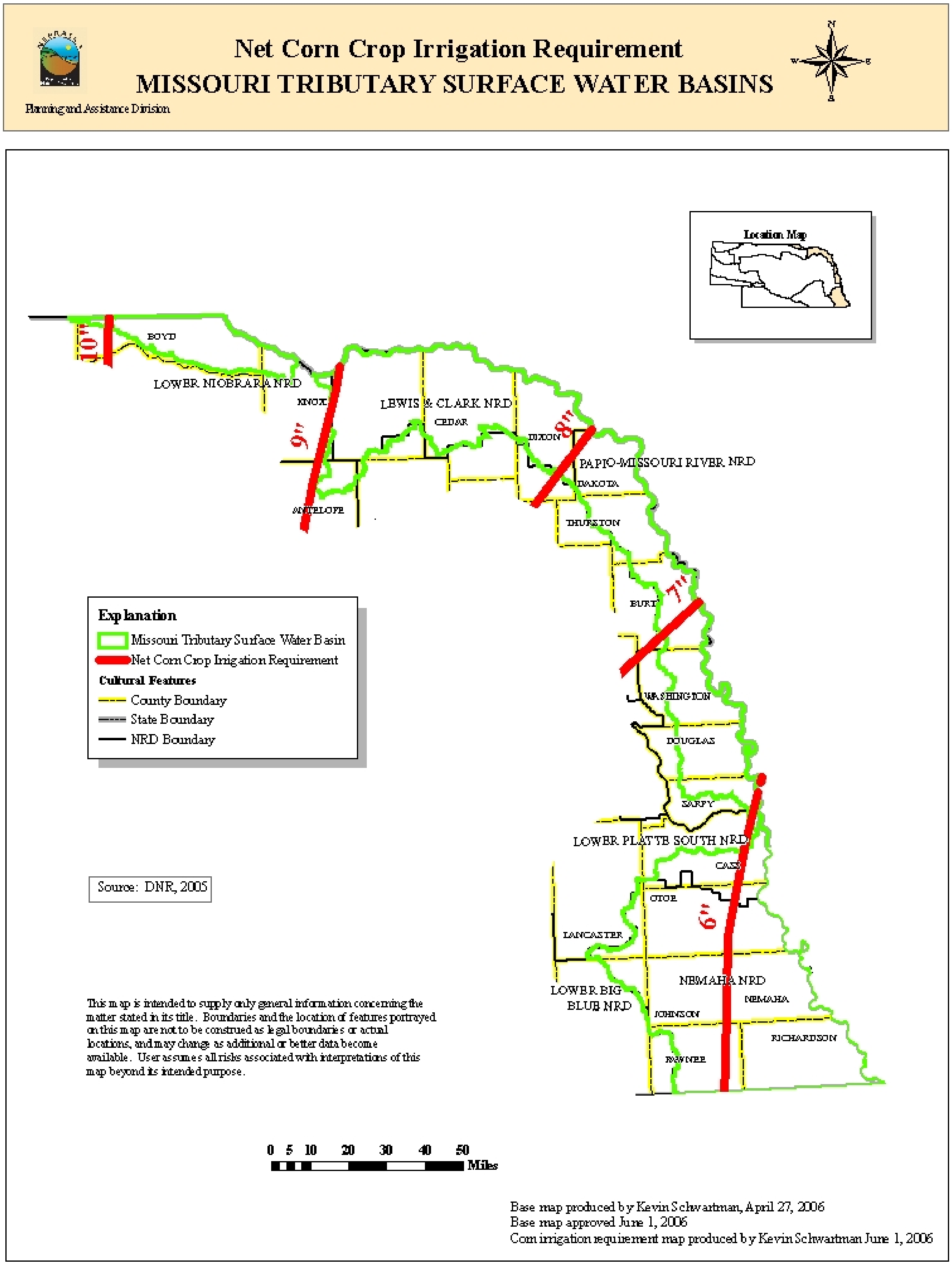
Figure 8-6 10/50 area, Missouri Tributary basins.



8.5 Net Corn Crop Irrigation Requirement

Figure 8-7 is a map of the net corn crop irrigation requirement for the basins (DNR, 2005). The NCCIR in the basins ranges from 5.3 to 10.0 inches. To assess the number of days required to be available for diversion, a surface water diversion rate equal to 1 cfs per 70 acres, a downtime of 10%, and an irrigation efficiency of 80% were assumed. Based on these assumptions, it will take a junior surface water appropriation between 14.1 and 26.6 days annually to divert 65% of the NCCIR and between 18.4 and 34.7 days to divert 85% of the NCCIR.

Figure 8-7 Net corn crop irrigation requirement, Missouri Tributary basins.



8.6 Surface Water Closing Records

Table 8-1 records all surface water administration that has occurred in the basins between 1988 and 2007.

Table 8-1 Surface water administration in the Missouri Tributary basins, 1988-2007.

Year	Water Body	Days	Closing Date	Opening Date
1988	Menominee Creek	???*	Jun 27	
1989	Little Nemaha River	25		
1989	North Fork Big Nemaha River	14		
1989	Long Branch	5		
1990	North Fork Little Nemaha River	14	July	July
1991	Little Nemaha River	7	Jul 2	Jul 9
1991	Little Nemaha River	19	Jul 18	Aug 6
1991	North Fork Little Nemaha River	1	Jul 8	Jul 9
2002	Weeping Water Creek	21	Jul 30	Aug 20
2004	Weeping Water Creek	3	Aug 23	Aug 26
2005	Weeping Water Creek	3	Jul 15	Jul 18

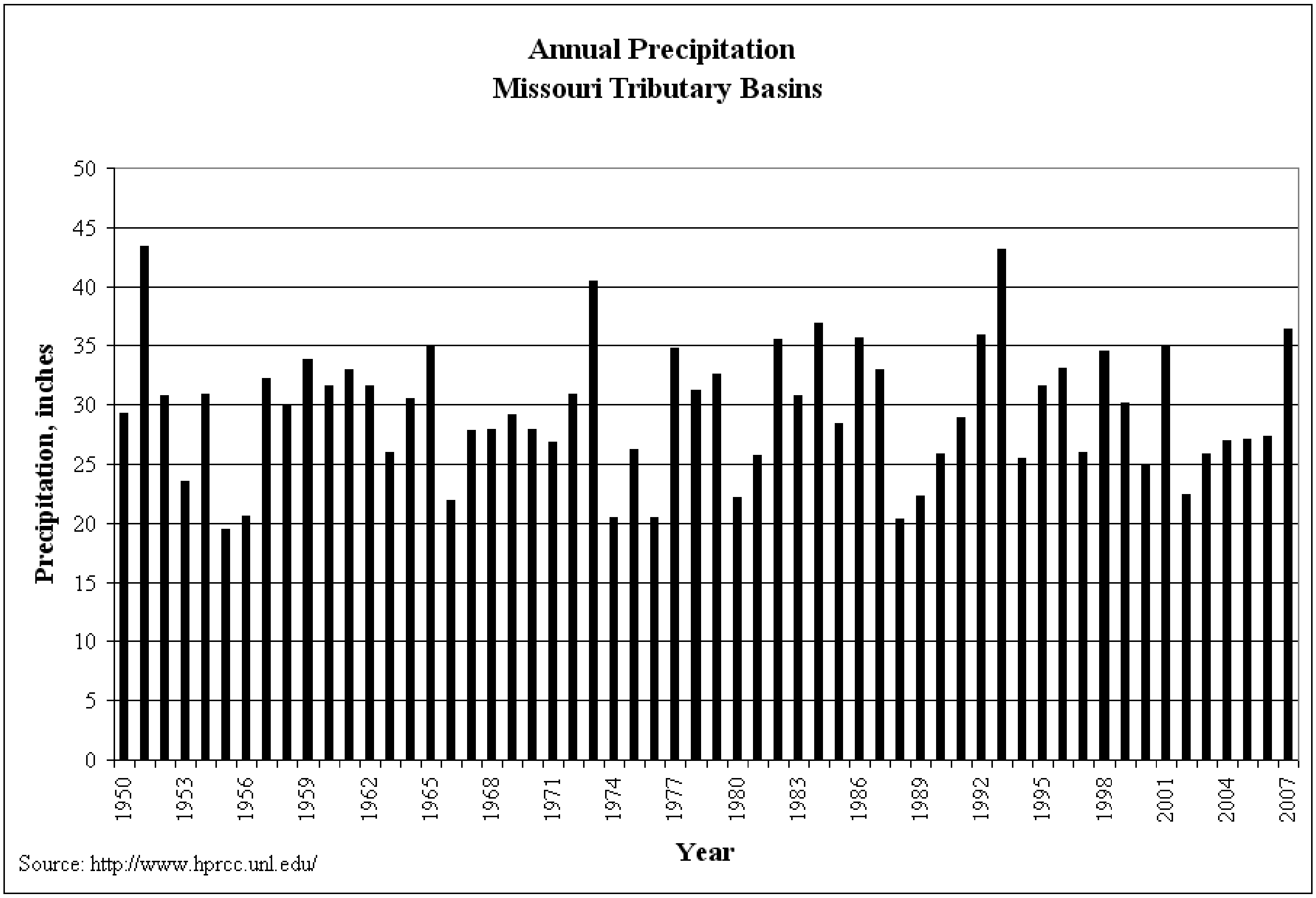
* Ending date could not be determined from administration records.

8.7 Evaluation of Current Development

8.7.1 Water Supply

In order to complete the long-term evaluation of surface water supplies, a future twenty-year water supply for the basins must be estimated. The basins' water sources are precipitation, which runs off as direct streamflow and infiltrates into the ground to discharge as baseflow, and ground water movement into the basins, which discharges as baseflow. Using methodology published in the *Journal of Hydrology* (Wen and Chen, 2005), a nonparametric Mann-Kendall trend test of the weighted average precipitation in the basins was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past fifty years (Figure 8-8). Data do not exist to test whether trends in ground water movement into the basin have changed. Therefore, using the previous twenty years of streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure 8-8 Annual precipitation, Missouri Tributary basins.



8.7.2 Depletions Analysis

The future depletions due to current well development that could be expected to affect streamflow in the basins were not estimated, for the same reasons as those described in Section 8.4.

8.7.3 Evaluation of Current Levels of Development against Future Water Supplies

The comparison of the near-term water supply days available for diversion to the number of days surface water is required to be available to divert 65% and 85% of the NCCIR is detailed in Table 8-2. No estimate of the twenty-year average days available for diversion in the basins has been made, given the inadequacy of current data and models in predicting future stream depletions. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

Table 8-2 Comparison between the number of days required to meet the net corn crop irrigation requirement and number of days surface water is available for diversion in the Missouri Tributary basins.

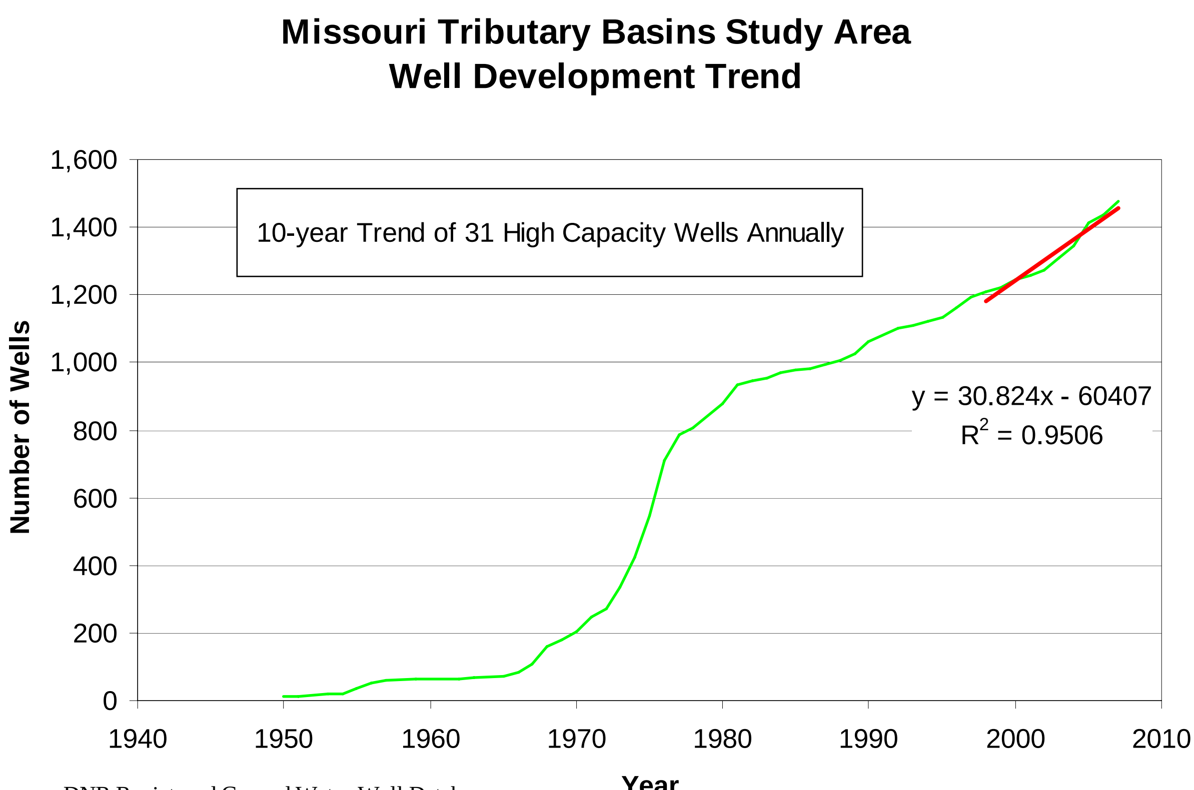
	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1988-2007)**
July 1 – August 31 (65% Requirement)	14.1 to 26.6	58.8 or greater (at least 32.2 days above the requirement)
May 1 – September 30 (85% Requirement)	18.4 to 34.7	149.8 or greater (at least 115.1 days above the requirement)

8.8 Evaluation of Predicted Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gpm) that would be completed over the next twenty-five years, if no new legal constraints on the construction of such wells were imposed, were calculated based on extrapolating the present-day rate of increase in well development into the future (Figure 8-9). The present-day rate of development is based on the linear trend of the previous ten years of development. Based on the analysis of the past ten years of development, the rate of increase in high capacity wells is calculated to be 31 wells per year in the basins.

For the same reasons as those stated above in Section 8.7.2, no estimates of depletions due to current and future ground water development were computed. Even though the effects on future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

Figure 8-9 High capacity well development, Missouri Tributary basins.



Source: DNR Registered Ground Water Well Database

8.9 Sufficiency to Avoid Noncompliance

There are no compacts on any portions of the Missouri Tributary basins in Nebraska.

8.10 Ground Water Recharge Sufficiency

The streamflow is sufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge form the stream (Appendix H).

8.11 Current Studies Being Conducted to Assist with Future Analysis

An effort to categorize the aquifer characteristics and the water supply of the glaciated portion of eastern Nebraska, which includes large areas of the Missouri Tributary basins, is underway. This extensive body of work will provide future reports with critical data on the hydrologically connected areas and impacts of future development.

8.12 Relevant Data Provided by Interested Parties

The Department published a request for relevant data for this year's evaluation from interested parties on May 12, 2008 (see Appendix A for Affidavit). The Department did not receive any such information.

8.13 Conclusions

Based on the evaluation of available information, the Department has reached a conclusion that the Missouri Tributary basins are not fully appropriated. The best available data do not allow for analysis of whether this determination would change if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

Bibliography of Hydrogeologic References for Missouri Tributaries River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln.

Wen, F. J. and X. H. Chen, 2006. Evaluation of the impact of groundwater irrigation on streamflow depletion in Nebraska. *Journal of Hydrology* 327: 603-617.

9.0 BASIN SUMMARIES AND RESULTS

9.1 Blue River Basins

The Blue River basins are located in south-central Nebraska and consist of all of the surface water areas that drain into the Big Blue River and the Little Blue River and all aquifers that impact surface water flows of the basins.

The basins can be divided into two distinct areas, based on whether or not they were glaciated. In areas that were glaciated, the restrictive and complex nature of the hydrogeology does not allow for the use of stream depletion factor (SDF) methodologies. Therefore, the Department was unable to delineate the 10/50 area for the glaciated portions of the basins. In the non-glaciated portions of the Little Blue River Basin, a numerical ground water model was used to delineate the 10/50 area.

The numerical ground water model was not able to provide data on the lag impacts from ground water development; thus, no lag effects were calculated. However, because the Department determined that the near-term availability of surface water for diversion for each basin far exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the applicable time periods, the Department was able to reach a conclusion that no portion of the basins is fully appropriated without the lag-effect calculation. Because of the inability to calculate the lag effects of existing and future ground water development, the long-term surface water availability was not determined. Although reductions in flows may require water administration more often in the future, low flows do not cause noncompliance with the terms of the Kansas-Nebraska Big Blue River Compact.

9.2 Lower Niobrara Basin

The Lower Niobrara River Basin is located in the north-east portion of Nebraska and consists of all of the surface water areas that drain into the Niobrara River that had not previously been determined to be fully appropriated, from the Spencer Hydropower facility downstream to the confluence of the Niobrara River and the Missouri River, and all aquifers that impact surface water flows of the basin.

No sufficient numerical ground water model is available in the Lower Niobrara River Basin. Therefore, the stream depletion factor (SDF) methodology was used to determine the 10/50 area and lag impacts due to current and projected future well development. The analysis of lag effects of current development for the Lower Niobrara Basin indicates a reduction in streamflows by 21 cfs in twenty-five years. The analysis of the impacts of future development on the Lower Niobrara Basin based on current development trends indicates a reduction in streamflows of 95 cfs in twenty-five years.

The Department has reached a conclusion that no portion of the basin is fully appropriated. Estimates of future water supplies for junior irrigators could not be estimated due to minimal surface water administration during the past twenty years. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

9.3 Lower Platte River Basin

The Lower Platte River Basin is located in the central and eastern portions of Nebraska and consists of all the surface water areas that drain into the Platte River from its confluence with the Loup River to its confluence with the Missouri River, including those areas that drain into the Loup River and the Elkhorn River, and all aquifers that impact surface water flows of the basin.

The Elkhorn-Loup Model was used to determine the 10/50 area and the future lag impacts of existing groundwater uses for the extent of the area modeled, whereas all other hydrologically connected areas were evaluated using the stream depletion factor (SDF) methodology.

The Department has reached a conclusion that no portion of the basin is fully appropriated at this time. The long term availability of surface water for diversion exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the rule's applicable time periods in the basin. In addition, the surface water supply available to the instream flow appropriations in the basin (the junior appropriation calling for administration in the non-irrigation season) has not been significantly eroded. Based on reasonable projections of the extent and location of future development in the basin, however, the analysis also shows that this conclusion would change to a determination of fully appropriated if no additional constraints were placed on future surface water and ground water development.

9.4 Missouri Tributary Basins

The Missouri Tributary basins are located in the north-central and eastern portions of Nebraska and consist of all of the surface water areas that drain directly into the Missouri River, with the exception of the Niobrara River and Platte River basins, and all aquifers that impact surface water flows of the basins.

No sufficient numerical ground water model is available in the Missouri Tributary basins to determine the 10/50 area. Much of the basins were glaciated, and, in those areas, the restrictive and complex nature of the hydrogeology does not allow for the use of existing methodologies. Therefore, the Department was unable to delineate the 10/50 area for the glaciated portions of the basins. The non-glaciated area surrounding the headwaters of Bazile Creek is the only portion of the basins where the principal aquifer is both present and in hydrologic connection with the streams; therefore, the 10/50 area was delineated using SDF methodology.

The Department has reached a conclusion that no portion of the basins is fully appropriated. The near-term availability of surface water for diversion far exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the applicable time periods. The long-term surface water availability was not determined, due to a lack of geologic and hydrologic data and the inability to calculate the lag effects of existing and future ground water development. Even though the long-term water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the 65/85 rule.

9.5 Results of Analyses

Tables 9-1 and 9-2 summarize the results of the analysis for sufficiency of water availability for irrigation in each basin. These results indicate that the water supply is sufficient to meet the requirements of the 65/85 rule in all basins evaluated. The Lower Platte River Basin is projected to have insufficient water supply to meet the 65 rule in the future if current levels of surface water and ground water development continue.

Table 9-1 Summary of comparison between the number of days required to meet 65% of the net corn crop irrigation requirement and number of days in which surface water is available for diversion, July 1 – August 31.

	Days Necessary to Meet 65% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development**	**Average Number of Days Available for Diversion at Current Development with Twenty-Five Years of Lag Impacts**	**Average Number of Days Available for Diversion with Future Development and Twenty-Five Years of Lag Impacts**
Big Blue River Basin	23.9	54.5	54.5[1]	Not Calculated[2]
Little Blue River Basin	25.7	54.4	54.4[1]	Not Calculated[2]
Lower Platte River Basin upstream of North Bend, including the Loup River Basin	27.9	32.5	28.4	27.6
Lower Platte River Basin downstream of North Bend and upstream of Louisville including the Elkhorn River Basin	27.9	34.6	30.2	29.2
Lower Niobrara River Basin downstream of Spencer Hydropower	23.6 – 25.5	61.9	Not Calculated[3]	Not Calculated[3]
Missouri Tributary Basins	14.1 – 26.6	58.8	58.8[1]	Not Calculated[2]

[1] This number is the near-term average number of days in which surface water is available for diversion (1988–2007) without inclusion of twenty-five year lag impacts, because of the lack of geologic and hydrologic data and the inability to estimate lag depletions.

[2] This number was not estimated, because of the lack of geologic and hydrologic data and the inability to estimate future depletions.

[3] This number was not estimated, because of the lack of surface water administration in this portion of the basin.

Table 9-2 Summary of comparison between the number of days required to meet 85% of the net corn crop irrigation requirement and number of days in which surface water is available for diversion, May 1 – September 30

	Days Necessary to Meet 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development**	**Average Number of Days Available for Diversion at Current Development with Twenty-Five Years of Lag Impacts**	**Average Number of Days Available for Diversion with Future Development and Twenty-Five Years of Lag Impacts**
Big Blue River Basin	31.3	145.3	145.3[1]	Not Calculated[2]
Little Blue River Basin	33.6	141.2	141.2[1]	Not Calculated[2]
Lower Platte River Basin upstream of North Bend, including the Loup River Basin	36.5	103.9	95.9	94.0
Lower Platte River Basin downstream of North Bend and upstream of Louisville Elkhorn River Basin	36.5	106.8	98.4	96.3
Lower Niobrara River Basin downstream of Spencer Hydropower	30.9 – 33.4	152.9	Not Calculated[3]	Not Calculated[3]
Missouri Tributary Basins	18.4 – 34.7	149.8	149.8[1]	Not Calculated[2]

[1] This number is the near-term average number of days in which surface water is available for diversion (1988–2007) without inclusion of twenty-five year lag impacts, because of the lack of geologic and hydrologic data and the inability to estimate lag depletions.

[2] This number was not estimated, because of the lack of geologic and hydrologic data and the inability to estimate future depletions.

[3] This number was not estimated, because of the lack of surface water administration in this portion of the basin.

Appendix A

NOTICE TO PUBLIC
RELATING TO ANNUAL REPORT
REQUIRED PURSUANT TO Neb. Rev. Stat. § 46-713

The Nebraska Department of Natural Resources ("Department") hereby provides notice that the Department, in accordance with Section 46-713(1)(c), shall include in the annual report required to be issued by January 1 of 2009, for informational purposes only, a summary of relevant data provided by any interested party concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water uses on resources that are dependent on streamflow or ground water levels but are not protected by appropriations or regulations. Anyone wishing to provide relevant data must submit such relevant data by July 1, 2008, to the Department. The address for the Department of Natural Resources is 301 Centennial Mall South, P.O. Box 94676, Lincoln, Nebraska, 68509-4676, Attention: Jesse Bradley. FAX: (402) 471-2900.

The Department must complete an evaluation of the expected long-term availability of hydrologically connected water supplies for both existing and new surface water uses and existing and new ground water uses in each of the state's river basins and shall issue a report that describes the results of the evaluation by January 1, 2009, pursuant to Neb. Rev. Stat. § 46-713 (Reissue 2004). Based on the information reviewed in the evaluation process, the Department shall arrive at a preliminary conclusion for each river basin, subbasin, and reach evaluated as to whether such river basin, subbasin, or reach presently is fully appropriated without the initiation of additional uses.

For further information regarding the Department, and its activities, please refer to the Department's web site, at http://www.dnr.state.ne.us.

NEBRASKA DEPARTMENT OF NATURAL RESOURCES

NOTICE TO PUBLIC

OPPORTUNITY TO PROVIDE INFORMATION RELATED TO ANNUAL REPORT ON FULLY APPROPRIATED STATUS OF RIVER BASINS, SUBBASINS, REACHES

The Nebraska Department of Natural Resources ("Department") hereby provides notice that the Department, in accordance with Neb. Rev. Stat. Section 46-713(1)(c), shall include in the annual report required to be issued by January 1 of 2009, for informational purposes only, a summary of relevant data provided by any interested party concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water uses on resources that are dependent on streamflow or ground water levels but are not protected by appropriations or regulations in the evaluated basins. Anyone wishing to provide relevant data must submit such relevant data by July 1, 2008, to the Department. The address for the Department of Natural Resources is 301 Centennial Mall South, P.O. Box 94676, Lincoln, Nebraska, 68509-4676, Attention: Jesse Bradley. FAX: (402) 471-2900.

The Department must complete an evaluation of the expected long-term availability of hydrologically connected water supplies for both existing and new surface water uses and existing and new ground water uses in each of the state's river basins that are not currently considered to be overappropriated or fully appropriated and shall issue a report that describes the results of the evaluation by January 1, 2009, pursuant to Neb. Rev. Stat. § 46-713. Based on the information reviewed in the evaluation process, the Department shall arrive at a preliminary conclusion for each river basin, subbasin, and reach evaluated as to whether such river basin, subbasin, or reach presently is fully appropriated without the initiation of additional uses.

For further information regarding the Department and its activities, please refer to the Department's website, at http://www.dnr.ne.gov.

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AFFIDAVIT

State of Nebraska, County of Douglas, ss:

Joyce Sawatzki being duly sworn, deposes and says that he/she is an employee of The Omaha World-Herald, a legal daily newspaper printed and published in the county of Douglas and State of Nebraska, and of general circulation in the Counties of Douglas, and Sarpy and State of Nebraska, and that the attached printed notice was published in the said newspaper on the 11 day of May 2008, and that said newspaper is a legal newspaper under the statutes of the State of Nebraska. The above facts are within my personal knowledge. The Omaha World-Herald has an average circulation of 182,437 Daily and 227,515 Sunday, in 2008.

(Signed) Joyce Sawatzki   Title: **Account Executive**

Subscribed in my presence and sworn to before me this 12 day of May, 2008.

MIRANDA KAY SMITH
General Notary
State of Nebraska
My Commission Expires Jan 18, 2012

Miranda Kay Smith
Notary Public

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Paid By ______________

No information was provided by interested parties regarding relevant data concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water uses on resources that are dependent on streamflow or ground water levels but are not protected by appropriations or regulations.

Excerpts from Testimony Received from the Four Public Hearings on the Preliminary Determination that the Lower Platte River Basin is Fully Appropriated

Many concerns were voiced on various aspects of the preliminary determination that the Lower Platte River Basin is fully appropriated during the four public hearings held on the matter. This section summarizes some of these concerns and provides clarification and further explanation on the Department's rules, methods, and overall approach used to determine if a basin is fully appropriated.

1. **Concern: The Department did not use the best available data, science, and methods to complete the annual evaluation.**

   The Department makes every attempt to use all relevant data and the best currently available tools to complete its annual evaluation. The Department annually requests any information from the public and the local natural resource districts that would be relevant to the methods employed in the annual evaluation.

   This year, the report incorporated a newly developed tool, the Elkhorn-Loup Model (ELM), to analyze the future effects of groundwater pumping in the Loup River Basin and Elkhorn River Basin upstream of approximately Norfolk. The ELM was developed through a joint effort with eight local natural resource districts and the United States Geological Survey (USGS). The USGS published the results of this study prior to the annual analysis by the Department of hydrologically connected water supplies, making ELM the best available tool for the annual determination. The Department relied upon the methods and simulations developed by the USGS for the analysis, presented as representative of average climatic conditions. The results of these simulations were used to calculate the increase in stream depletions due to current groundwater uses after 25-years.

   Testimony provided to the Department at a hearing, indicated that an erroneous method was used by the USGS to calculate groundwater pumping under average climatic conditions (the model simulation used by the Department to project future effects of current ground water uses 25-years into the future). The Department further investigated this concern and concurred with the testimony that the simulation was erroneous.

Additionally, efforts are being made by the Department and local natural resource districts to expand the data and tools available for use in the Departments annual evaluation. While these studies have not been completed, they are anticipated to provide additional information that will improve upon methods or data currently used in the Departments annual evaluation.

2. **Concern: The Department did not consider increasing ground water levels or streamflows in its annual evaluation.**

Ground water levels were considered in the annual evaluation. An extensive collection of groundwater level data from over 60 years of data collection covering the area of the ELM study were utilized by the USGS to calibrate the ELM. The purpose of calibrating a ground water model is to match the the model's output with the historical ground water levels and ground water discharge to streams. If the model matches these historical ground water level and ground water discharge measurements it is said to be calibrated and our confidence in the predictive ability of the model is increased. The ELM is calibrated to changes in groundwater levels between 1940 and 2005.

Additionally, relying on ground water levels to determine when stream flows will be affected by ground water pumping, must be done cautiously. Changes in ground water levels may take long periods of time to be realized at the stream depending on the characteristics of the aquifer and the distance the well is from the stream. When extensive ground water pumping has led to conditions of substantially reduced stream flows, recovering these streamflows can require dramatic pumping reductions or may not even be possible in shorter time frames (Frenchman Unit Draft Appraisal Report, 2007).

Streamflows are directly used by the Department to determine the available supply within a given basin. The Department's method of evaluation uses the previous 20-years of streamflow data to determine the current water supply available. If streamflow supplies increase the evaluation will take into account that increased water supply.

3. Concern: Only wells within the hydrologically connected area (10/50) should have been used for determining the lag impacts of current well development.

The Department used all wells within the entire hydrologically connected area (the area where aquifers are present and are connected to streamflows) to determine future lag impacts of current well development. This is consistent with all prior evaluations. Testimony presented to the Department indicated that a literal interpretation of 457 N.A.C. 001.02A would require that only the wells within the 10/50 area should be used to determine lag impacts. Such a literal interpretation would not be consistent with Nebraska Revised Statues 46-713(3), which simply specifies the Department to consider "*then-current uses* of hydrologically connected surface water and ground water in the river basin, sub-basin, or reach" (emphasis added). Therefore, all depletions to a stream reach due to any then-current groundwater uses must be considered.

The 10/50 area is intended as a management area. To understand the difference this approach would make to the results of the annual evaluation, the Department used the area covered by the Elkhorn-Loup Model to determine the significance of wells outside of the 10/50 area. The results of that analysis indicated that less than 1% of the future lag impacts, which are estimated to occur in 25-years, result from wells outside of the 10/50 area. Therefore, there would be very little gain in managing the uses outside of this 10/50 area.

Additionally, concerns were expressed regarding the calculated lag effects from approximately 120 wells located downstream of the Louisville gage. The Department evaluated the effects of this specific group of wells and determined that future lag impacts 25-years into the future caused by these wells totaled 0.2 cfs. This difference in lag impacts did not have an effect on the calculated number of days available to meet the 65/85 rule.

4. Concern: The most junior surface water appropriation was not used to determine the number of days necessary to meet the requirements of the 65/85 rule.

The Department recognizes that 457 N.A.C. 001.01A could be interpreted literally to mean the absolute most junior surface water irrigation right in the basin (determined by priority date), no matter where the point of diversion is located. However, the Department has never applied the regulation so literally. In fact, such a literal interpretation of this rule would not meet the requirements of Nebraska Revised Statutes 46-713(3) and 3(a) which states " A river basin, subbasin, or reach shall be deemed fully appropriated if the department determines… that the then current uses of hydrologically connected surface water and ground water in the river basin, subbasin, or reach cause or will in the reasonably foreseeable future cause (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural-flow or storage appropriations were granted…."

Instead, the Department interprets its regulation to mean the most junior surface water appropriations that are subject to administration i.e. closed by a call from a senior water right. In the Lower Platte River Basin several such junior surface water appropriations exist. To proceed through the evaluation more efficiently the Department evaluates the most junior surface water appropriation with the greatest water need (based on crop irrigation requirements for corn). The Department could evaluate each most junior surface water appropriation individually but if the most junior surface water appropriation with the greatest water need is able to satisfy the requirement then evaluating the rest of the most junior surface water appropriations would only be a redundant process.

5. Concern: The Department should not use not a 10% downtime and 80% irrigation efficiency in determining the number of days necessary to satisfy the 65/85 rule as it causes an overestimation of the number of days necessary to satisfy the 65/85 rule.

The Department uses the 65/85 rule as a measure of what water supplies are necessary to sustain over the long term the beneficial or useful purposes for which existing natural flow irrigation appropriations were granted. The Department's 65/85 rule sets an acceptable level of reduction in streamflow supply that can occur prior to implementation of a joint planning effort between the Department and the local natural resource districts. Application of the 65/85 rule requires a number of assumptions. These assumptions were determined prior to the first annual evaluation by the Department (2006). The 65/85 rule is intended to be triggered by a change in water supply through an increase of use, a decrease in streamflow through reduced precipitation, or both. It is important to consistently apply these assumptions to ensure that the number of days available to meet the 65/85 rule is not sensitive to the assumptions.

6. Concern: Municipal well fields are not properly considered during the annual evaluation

In the annual evaluation, the Department is required to determine if a basin is fully appropriated based on present water uses and on predicted future impacts of those water uses. The Department has always estimated future impacts from all high capacity well development in the same way, including municipal well fields, and that is based on the water use requirements of a fully irrigated corn crop at that location.

An exception to this methodology was used to assess the future impacts of the new MUD west well field and the Lincoln Water Supply well field. The reason for this exception is that the Department was provided information specific to the well fields and the level of streamflow depletion that is expected to occur in 25-years. The analysis provided to the Department projects that the MUD well field will incur a 160 cfs depletion when at full permitted capacity but the average annual depletion would be limited to 80 cfs. The Department utilized the 160cfs rate as it is more likely that the well field will be at or near full capacity during the July-August portion of the irrigation season when water supplies are most critical in the Lower Platte River Basin.

Additionally, the information reviewed by the Department for the Lincoln Water Supply well field indicates that the well field will incur a depletion of 212 cfs when at full permitted capacity. The Department evaluated the current depletion by determining the average daily use for July and August for the previous three years. The difference between the current July and August use and the depletion the well field will incur when at maximum capacity served as the future impact estimated by the Department and was incorporated into the evaluation. This type of site specific information is not available for other municipal well fields at this time.

7. Concern: A fully appropriated determination would cause substantial economic impacts and stifle future development in the basin

The Departments annual evaluation is only intended to analyze the water supply relative to "then-current" water uses within each basin. The purpose is to prevent economic impacts to those then-current users that might result from overdevelopment of the water supply. However, when a basin is determined to be fully appropriated the required planning process must include clear goals and objectives with the purpose of sustaining a balance between water uses and water supplies so that the *economic viability*, social and environmental health, safety, and welfare or the river basin can be achieved and maintained for both the near term and long term.

8. Concern: Certain areas within the Lower Platte River Basin were not included within the hydrologically connected area.

The Department received testimony requesting that certain geographic areas be reexamined to determine if they warranted inclusion into the hydrologically connected area. The Department reevaluated the scientific basis for the preliminary determination and determined that certain geographic areas should be included in the hydrologically connected area which were not included in the preliminary determination. These geographic areas were in the Papio-Missouri River Natural Resources District and the Lower Platte South Natural Resources District.

Appendix B

APPROVED

DEC 04 2006

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GOVERNOR

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ATTORNEY GENERAL
BY...........
Assistant Attorney General
DATE....10-30-06

Title 457 - DEPARTMENT OF NATURAL RESOURCES
RULES FOR SURFACE WATER

Chapter 24 - DETERMINATION OF FULLY APPROPRIATED BASINS, SUB-BASINS OR REACHES

001 FULLY APPROPRIATED. Pursuant to Neb. Rev. Stat. § 46-713(3) (Reissue 2004, as amended), a river basin, subbasin, or reach shall be deemed fully appropriated if the Department of Natural Resources determines that then-current uses of hydrologically connected surface water and ground water in the river basin, subbasin, or reach cause or will in the reasonably foreseeable future cause (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural flow or storage appropriations were granted and the beneficial or useful purposes for which, at the time of approval, any existing instream appropriation was granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved, or (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, other formal state contract or agreement, or applicable state or federal laws.

001.01A Except as provided in 001.01C below, for purposes of Section 46-713(3)(a), the surface water supply for a river basin, subbasin, or reach shall be deemed insufficient, if, after considering the impact of the lag effect from existing groundwater pumping in the hydrologically connected area that will deplete the water supply within the next 25 years, it is projected that during the period of May 1 through September 30, inclusive, the most junior irrigation right will be unable to divert sufficient surface water to meet on average eighty-five percent of the annual crop irrigation requirement, or, during the period of July 1 through August 31, inclusive, will be unable to divert sufficient surface water to meet at least sixty-five percent of the annual crop irrigation requirement.

For purposes of this rule, the "annual crop irrigation requirement" will be determined by the annual irrigation requirement for corn. This requirement is based on the average evapotranspiration of corn that is fully watered to achieve the maximum yield and the average amount of precipitation that is effective in meeting the crop water requirements for the area.

The inability to divert will be based on stream flow data and diversion records, if such records are available for the most junior surface water appropriator. If these records are not available, the inability to divert will be based on the average number of days within each time period (May 1 to September 30 and July 1 to August 31) that the most junior surface water appropriation for irrigation would have been closed by the Department and therefore could not have diverted during the previous 20 year period. In making this

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calculation, if sufficient stream flow data and diversion data are not available, it will be assumed that if the appropriator was not closed, the appropriator could have diverted at the full permitted diversion rate. In addition the historical record will be adjusted to include the impacts of all currently existing surface water appropriations and the projected future impacts from currently existing ground water wells. The projected future impacts from ground water wells to be included shall be the impacts from ground water wells located in the hydrologically connected area that will impact the water supply over the next 25 year period.

001.01B In the event that the junior water rights are not irrigation rights, the Department will utilize a standard of interference appropriate for the use, taking into account the purpose for which the appropriation was granted.

001.01C If, at the time of the priority date of the most junior appropriation, the surface water appropriation could not have diverted surface water a sufficient number of days on average for the previous 20 years to satisfy the requirements of 001.01A, the surface water supply for a river basin, subbasin, or reach in which that surface water appropriation is located shall be deemed insufficient only if the average number of days surface water could have been diverted over the previous 20 years is less than the average number of days surface water could have been diverted for the 20 years previous to the time of the priority date of the appropriation.

When making this comparison, the calculations will follow the same procedures as described in 001.01A. When calculating the number of days an appropriator could have diverted at the time of the priority date of the appropriation, the impacts of all appropriations existing on the priority date of the appropriation and the impacts of wells existing on the priority date of the appropriation shall be applied in the same manner as in 001.01A. As in 001.01A above, in making this calculation, if sufficient stream flow data and diversion data are not available, it will be assumed that if the appropriator was not closed, the appropriator could have diverted at the full permitted diversion rate.

Use of the method described in this rule is not intended to express or imply any mandate or requirement that the method used herein must be included in the goals and objectives of any integrated management plan adopted for a river basin, subbasin or reach determined to be fully appropriated under this rule. Further, nothing in this section is intended to express or imply a priority of use between surface water uses and ground water uses.

001.02 The geographic area within which the Department preliminarily considers surface water and ground water to be hydrologically connected for the purpose prescribed in Section 46-713(3) is 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.

002 INFORMATION CONSIDERED. For making preliminary determinations required by Neb. Rev. Stat. Section 46-713 (Reissue 2004, as amended) the Department will use the best

scientific data and information readily available to the Department at the time of the determination. Information to be considered will include:

Surface water administrative records
Department Hydrographic Reports
Department and United States Geological Survey stream gage records
Department's registered well data base
Water level records and maps from Natural Resources Districts, the Department, the University of Nebraska, the United States Geological Survey or other publications subject to peer review
Technical hydrogeological reports from the University of Nebraska, the United States Geological Survey or other publications subject to peer review
Ground water models
Current rules and regulations of the Natural Resources Districts

The Department shall review this list periodically, and will propose amendments to this rule as necessary to incorporate scientific data and information that qualifies for inclusion in this rule, but was not available at the time this rule was adopted.

APPROVED
DEC 04 2006
Dave Heineman
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ATTORNEY GENERAL
BY..........
Assistant Attorney General
DATE 10-30-06

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DEC - 4 2006
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Appendix C

Techniques of Water-Resources Investigations
of the United States Geological Survey

Chapter D1

COMPUTATION OF RATE AND VOLUME OF STREAM DEPLETION BY WELLS

By C. T. Jenkins

Book 4

HYDROLOGIC ANALYSIS AND INTERPRETATION

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

First printing 1968

Second printing 1969

Third printing 1977

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

**For sale by the Branch of Distribution, U.S. Geological Survey,
1200 South Eads Street, Arlington, VA 22202**

PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and further subdivided into sections and chapters; Section D of Book 4 is on interrelated phases of the hydrologic cycle.

The unit of publication, the chapter, is limited to a narrow-field of subject matter. This format permits flexibility in revision and publication as the need arises.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is sold by the U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202 (authorized agent of Superintendent of Documents, Government Printing Office).

This manual is an expanded version of a paper, "Techniques for computing rate and volume of stream depletion of wells" (Jenkins, 1968a), that was prepared in the Colorado District, Water Resources Division, in cooperation with the Colorado Water Conservation Board and the Southeastern Colorado Water Conservancy District and published in Ground Water, the journal of the Technical Division, National Water Well Association.

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COMPUTATION OF RATE AND VOLUME OF STREAM DEPLETION BY WELLS

By C. T. Jenkins

Abstract

When field conditions approach certain assumed conditions, the depletion in flow of a nearby stream caused by pumping a well can be calculated readily by using dimensionless curves and tables. Computations can be made of (1) the rate of stream depletion at any time during the pumping period or the following nonpumping period, (2) the volume of water induced from the stream during any period, pumping or nonpumping, and (3) the effects, both in rate and volume of stream depletion, of any selected pattern of intermittent pumping. Sample computations illustrate the use of the curves and tables. An example shows that intermittent pumping may have a pattern of stream depletion not greatly different from a pattern for steady pumping of an equal volume.

The residual effects of pumping, that is, effects after pumping stops, on streamflow may often be greater than the effects during the pumping period. Adequate advance planning that includes consideration of residual effects thus is essential to effective management of a stream-aquifer system.

Introduction

With increasing frequency, problems of water management require evaluation of effects of ground-water withdrawal on surface supplies. Both rate and volume effects have significance. Effects after the pumping stops (called residual effects in this paper) are important also but have not previously been examined in detail. In fact, residual effects can be much greater than those during pumping. Curves and tables shown in this paper, although applicable to a large range of interactions, are especially oriented to the solution of problems involving very small interactions and to the evaluation of residual effects. Where many wells are concentrated near a stream, the combined withdrawals can have a significant effect on the availability of water in the stream.

In some instances, especially in the evaluation of residual effects, the grid spacing on the charts shown may prove to be too coarse to provide the desired precision. However, this precision can be attained either by interpolating between the tabular values supplied or by using curves prepared by plotting the tabular values on commercially available chart paper that is more finely divided.

The relations between the pumping of a well and the resulting depletion of a nearby stream have been derived by several investigators (Theis, 1941; Conover, 1954; Glover and Balmer, 1954; Glover, 1960; Theis and Conover, 1963; Hantush, 1964, 1965). The relations generally are shown in the form of equations and charts; however, except for the charts shown by Glover (1960), which were in a publication that had limited distribution, the charts are useful as computational tools only in the range of comparatively large effects, and rather formidable equations must be solved to evaluate small effects. The average user retreats in dismay when faced by the mysticism of "line source integral," "complementary error function," or "the second repeated integral of the error function." The primary purpose of this report is to provide tools that will simplify the seemingly intricate computations and to give examples of their use.

Because this writer definitely is a member of the community of "average users," he has exercised what he believes to be his prerogative of reversing the usual order of presentation. In this paper, the working tools—curves, tables, and sample computations—are shown first, and the discussion of their mathematical bases is relegated to the end of the report. The usefulness of the tools will not be greatly enhanced by an understanding of the material at the end of the report; it is shown for the benefit of those who desire to examine the mathematical bases of the tools.

The techniques demonstrated in this paper are not new, but they seem to have been rather well concealed from most users in the past. Their value to water managers is apparent, especially in the estimation of total volume of depletion and of residual effects.

Virtually all the literature that discusses the effects of pumping on streamflow fails to mention that the effects of recharge are identical, except for direction of flow. (See Glover, 1964, p. 48.) Only pumping will be considered in this paper, but the reader should be aware that the terms "recharging" and "accretion" can be substituted for "pumping" and "depletion," respectively.

Definitions and Assumptions

To avoid confusion owing to the use of the same symbol for the dimension time as for transmissivity, symbols for the dimensions time and length are set in Roman type, are capitalized, and are enclosed in brackets. All other symbols, except that designating the mathematical term "second repeated integral," are set in italics.

Stream depletion means either direct depletion of the stream or reduction of ground-water flow to the stream.

The symbols used in the main body of the report are defined below (those that have to do only with the mathematical bases are defined at the end of the report in the section on this subject):

T= transmissivity, $[L^2/T]$;
S= the specific yield of the aquifer, dimensionless;
t= time, during the pumping period, since pumping began, [T];
t_p= total time of pumping, [T];
t_i= time after pumping stops, [T];
Q= the net steady pumping rate, $[L^3/T]$; the steady pumping rate less the rate at which pumped water returns to the aquifer;
q= the rate of depletion of the stream, $[L^3/T]$;
Qt= the net volume pumped during time t, $[L^3]$;
Qt_p= the net volume pumped, $[L^3]$;
v= the volume of stream depletion during time t, t_p, or t_p+t_i, $[L^3]$;
a= the perpendicular distance from the pumped well to the stream, [L];
sdf= the stream depletion factor, [T].

The term "stream depletion factor" was introduced by Jenkins (1968a). It is arbitrarily defined as the time coordinate of the point where v=28 percent of Qt on a curve relating v and t. If the system meets the assumptions listed in this section, $sdf=a^2S/T$; in a complex system it can be considered to be an effective value of a^2S/T. The value of the sdf at any location in the system depends upon the integrated effects of the following: Irregular impermeable boundaries, stream meanders, aquifer properties and their areal variation, distance from the stream, and imperfect hydraulic connection between the stream and the aquifer.

The curves and tables in this report are dimensionless and can be used with any units. The units in the system must be consistent, however. For example, if Q and q are in acre-feet per day (acre-ft/day), v must be in acre-feet (acre-ft). If a is in feet (ft) and T/S is in gallons per day per foot (gal/day-ft), the value of T/S must be converted to square feet per day (ft^2/day). A T/S value of 10^6gal/day-ft equals (10^6gal/day-ft)$\times$($1ft^3$/7.48 gal) equals 134,000 ft^2/day.

The assumptions made for this analysis are the same as other investigators have made and are as follows:

1. T does not change with time. Thus for a water-table aquifer, drawdown is considered to be negligible when compared to the saturated thickness.
2. The temperature of the stream is assumed to be constant and to be the same as the temperature of the water in the aquifer.
3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent.
4. The stream that forms a boundary is straight and fully penetrates the aquifer.
5. Water is released instantaneously from storage.
6. The well is open to the full saturated thickness of the aquifer.
7. The pumping rate is steady during any period of pumping.

Field conditions never meet fully the idealized conditions described by the above assumptions.

The usefulness of the tools presented in this report will depend to a large extent on the degree to which the user recognizes departures from ideal conditions, and on how well he understands the effects of these departures on stream depletion.

Departure from idealized conditions may cause actual stream depletions to be either greater or less than the values determined by methods presented in this report. Although the user usually cannot determine the magnitude of these discrepancies, he should, where possible, be aware of the direction the discrepancies take.

Jenkins (1968b) has described the use of a model to evalute the effects on stream depletion of certain departures from the ideal. If a model is not available, the user of this report can be guided in estimating the *sdf* by the effects calculated in that report for selected departures from the idealized system. Intuitive reasoning will be useful in estimating the effects of departures from the ideal that are difficult to incorporate in a model. For example, where drawdowns at the well site are a substantial proportion of the aquifer thickness, T will decrease significantly. A decrease in T results in a decrease in the amount of stream depletion relative to the amount of water pumped.

Variations in water temperatures will cause variations in stream depletion, especially by large-capacity wells near the stream. Warm water is less viscous than cold water; hence stream depletion will be somewhat greater in the summer than in the winter, given the same pattern of pumping. Stream stages affect water-table gradients, and hence stream depletion.

Lowering of the water table on a flood plain may result in the capture of substantial amounts of water that would otherwise be transpired. The effect is similar to intercepting another recharge boundary, and the proportion of stream depletion to pumpage is decreased. Interception of a valley wall or other negative boundary will have the opposite effect.

If large-capacity wells are placed close to a stream, and streambed permeability is low compared to aquifer permeability, the water table may be drawn down below the bottom of the streambed. (See Moore and Jenkins, 1966.) Under these conditions, stream depletion depends upon streambed permeability, area of the streambed, temperature of the water, and stage of the stream, and the methods presented in this report are not applicable.

Both during and after pumping, some part and at times all of stream depletion can consist of ground water intercepted before reaching the stream. Thus a stream can be depleted over a certain reach, yet still be a gaining stream over that reach. The flow at the lower end of the reach is less than it would have been had depletion not occurred, and less by the amount of depletion. In order to predict the amount of streamflow at the lower end of the reach, residual effects of previous pumping or recharge must be considered. They can be approximately accounted for by using past records of pumping and recharge to "prestress" the calculations. The depletion due to the pumping under consideration will then be superimposed on the residual depletion, and the resultant value will be the net direct depletion from the stream.

Description of Curves and Tables

Effects during pumping

Curves A and B in figure 1 apply during the period of steady pumping. Curve A shows the relation between the dimensionless term t/sdf and the rate of stream depletion, q, at time t, expressed as a ratio to the pumping rate Q. Curve B shows the relation between t/sdf and the volume of stream depletion, v, during time t, expressed as a ratio to the volume pumped, Qt. The two curves labeled $1-q/Q$ and $1-\frac{v}{Qt}$ are shown to facilitate determination of values of q/Q and $\frac{v}{Qt}$ when the ratios exceed 0.5. The coordinates of curves A and B are tabulated in table 1. The number of significant figures shown for the values in table 1 was determined by needs for some of the computations described in the next section. Precision to more than two significant figures in reporting results probably will never be warranted.

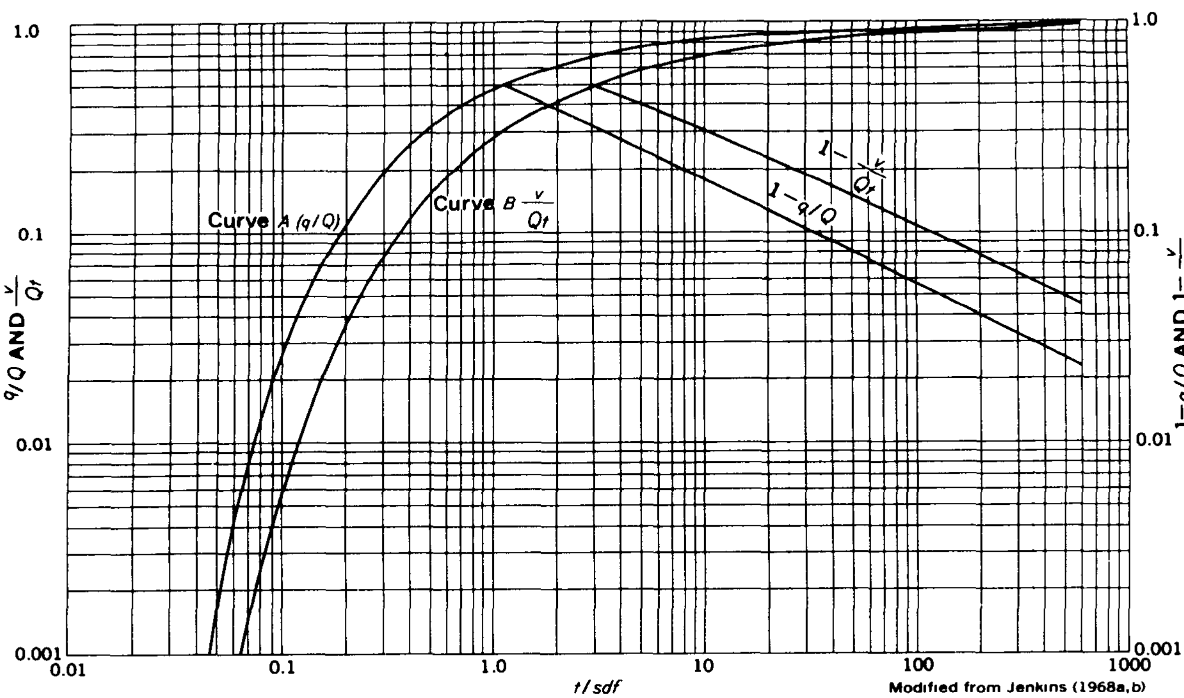


Figure 1.—Curves to determine rate and volume of stream depletion.

Residual effects

Stream depletion continues after pumping stops. As time approaches infinity, the volume of stream depletion approaches the volume pumped, if the assumption is made that the stream is the sole source of recharge. In any real case this is not true in the long term because precipitation and return flow from irrigation may represent the major portion of the recharge. To simplify the relation between well pumpage and stream depletion all other sources of water input are ignored in the following discussions. The rate and volume of depletion at any time after pumping ends can be computed by using the method of superposition, that is, by assuming that the pumping well continues to pump, and that an imaginary well at the same location is recharged continuously at the same rate the pumping well is discharging. The rate and volume of stream depletion at any time after pumping ends is equal to the differences between the rate and volume of depletion that would have occurred if pumping had continued, and the rate and volume of accretion resulting from recharge by the imaginary recharge well, starting from the time pumping ends.

Residual effects are shown in figures 2 and 3 for eight values of t_p/sdf. Problems concerned with values of t_p/sdf other than those for which curves are shown in figures 2 and 3 can be solved with an acceptable degree of accuracy by interpolation, but if the user desires a more accurate appraisal, separate computations can be made.

The computations shown in table 2, which are the basis for the curves labeled $t_p/sdf=0.35$ in figures 2 and 3 and for the curve in figure 4, will serve as an illustration of how additional curves can be constructed. As an aid to construction of curves such as those in figure 3, note that the curves are asymptotic to the ordinate $\frac{v}{Qsdf}$ $(=t_p/sdf)$.

Because Q is the same for both the pumping and recharging wells, residual q/Q can be computed directly from q/Q values in table 1. However, Qt is different for the two wells; so the ratios $\frac{v}{Qt}$ must be given a common denominator by multiplying by their respective values

Table 1.—Values of q/Q, $\frac{v}{Qt}$, and $\frac{v}{Qsdf}$ corresponding to selected values of t/sdf

$\frac{t}{sdf}$	q/Q	$\frac{v}{Qt}$	$\frac{v}{Qsdf}$
0	0	0	0
.07	.008	.001	.0001
.10	.025	.006	.0006
.15	.068	.019	.003
.20	.114	.037	.007
.25	.157	.057	.014
.30	.197	.077	.023
.35	.232	.097	.034
.40	.264	.115	.046
.45	.292	.134	.060
.50	.317	.151	.076
.55	.340	.167	.092
.60	.361	.182	.109
.65	.380	.197	.128
.70	.398	.211	.148
.75	.414	.224	.168
.80	.429	.236	.189
.85	.443	.248	.211
.90	.456	.259	.233
.95	.468	.270	.256
1.0	.480	.280	.280
1.1	.500	.299	.329
1.2	.519	.316	.379
1.3	.535	.333	.433
1.4	.550	.348	.487
1.5	.564	.362	.543
1.6	.576	.375	.600
1.7	.588	.387	.658
1.8	.598	.398	.716
1.9	.608	.409	.777
2.0	.617	.419	.838
2.2	.634	.438	.964
2.4	.648	.455	1.09
2.6	.661	.470	1.22
2.8	.673	.484	1.36
3.0	.683	.497	1.49
3.5	.705	.525	1.84
4.0	.724	.549	2.20
4.5	.739	.569	2.56
5.0	.752	.587	2.94
5.5	.763	.603	3.32
6.0	.773	.616	3.70
7	.789	.640	4.48
8	.803	.659	5.27
9	.814	.676	6.08
10	.823	.690	6.90
15	.855	.740	11.1
20	.874	.772	15.4
30	.897	.810	24.3
50	.920	.850	42.5
100	.944	.892	89.2
600	.977	.955	573

of t/sdf, to obtain the values given in table 1 for $\frac{v}{Qsdf}$. The "stepping" of the last six items in column 8, table 2, is the result of using linear interpolation in table 1. The errors are small and can be practically eliminated by drawing mean curves.

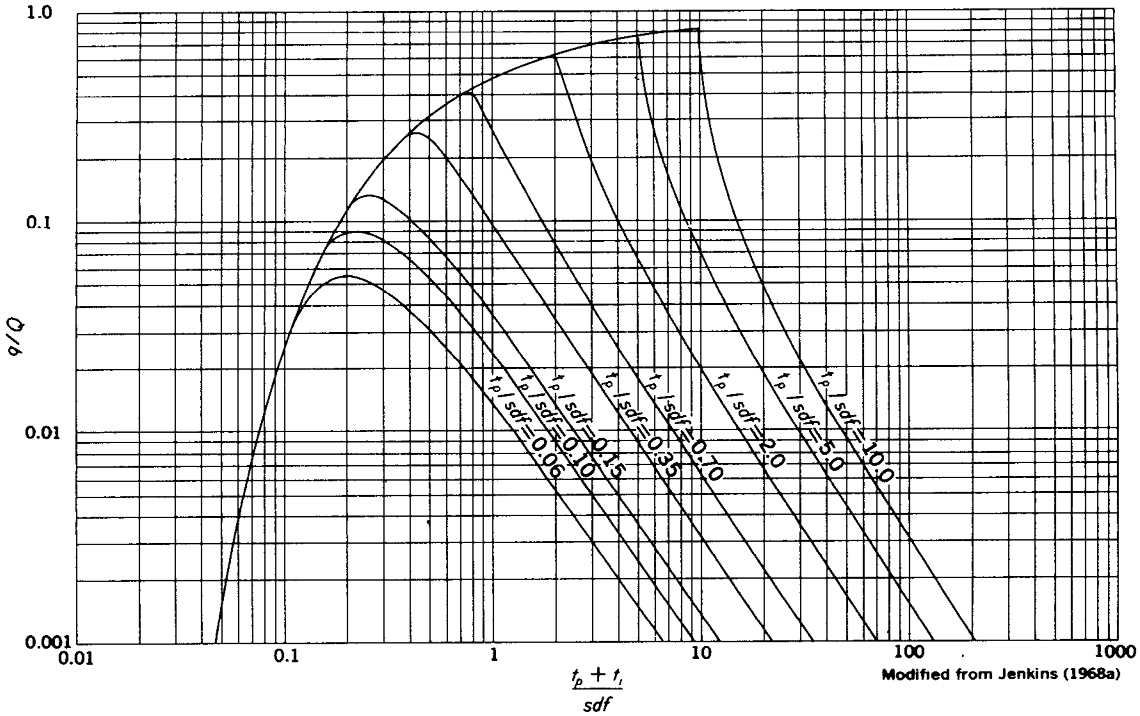
The magnitude, distribution, and extent of residual effects in a hypothetical field situation are shown in figure 4. The curve labeled q shows the relation between the rate of stream depletion, q, and time, t, resulting from pumping a well 3,660 feet from a stream at a rate of 10 acre-ft/day for 35 days. The ratio T/S is 134,000 ft ^{2}/day, which is not an unusual value for an alluvial aquifer. The *sdf* is 100 days. The pumping rate is 10 acre-ft/day; the maximum rate of stream depletion is 2.7 acre-ft/day. Pumping stops at the end of 35 days; the maximum rate of stream depletion occurs about 10 days later, and q still is about half the maximum rate 45 days after pumping stops.

The area in the rectangle under the line labeled Q represents total volume pumped; the area under the curve labeled q represents the volume of stream depletion. In terms of volume removed from the stream during the pumping period, the effect is small, only about 10 percent of the volume pumped. However, the effect continues, and as time approaches infinity, the volume of stream depletion approaches the volume pumped.

Consideration of such residual effects as are illustrated in figure 4 leads to the conclusion that the management of a system that uses both surface water and a connected ground-water reservoir requires a great deal of foresight. The immediate effects on streamflow of a change in pumping pattern may be very small; plans adequate for effective management of the resource generally require consideration of needs in the future—sometimes the distant future. The sample problems solved later in this report illustrate the value of long-range plans in water management.

Intermittent pumping

The curves in figure 5 illustrate the effect of one pattern of intermittent pumping. The computations are shown in table 3. Effects on the stream, both in volume removed and rate of removal are compared for two patterns of pumping of 63 acre-ft during a 42-day period. In both cases the aquifer has a ratio T/S of 134,000 ft²/day, and the well is 1,890 feet from the stream; thus the value for the $sdf=$ 26.7 days. During steady pumping, the well is pumped at a rate of 1.5 acre-ft/day for 42 days. In the intermittent pattern, the well is pumped at a rate of 5.25 acre-ft/day for



Modified from Jenkins (1968a)

Figure 2.—Curves to determine rate of stream depletion during and after pumping.

Table 2.—Computation of residual effects of pumping

[Pumping stopped when t/sdf=0.35]

Pumped well			Recharged well			Residual	Residual
t/sdf	q/Q	$\frac{v}{Qsdf}$	t/sdf	q/Q	$\frac{v}{Qsdf}$	q/Q	$\frac{v}{Qsdf}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0. 35	0. 232	0. 034	0	0	0	0. 232	0. 034
. 42	. 275	. 052	. 07	. 008	. 0001	. 267	. 052
. 45	. 292	. 060	. 10	. 025	. 0006	. 267	. 059
. 50	. 317	. 076	. 15	. 068	. 003	. 249	. 073
. 60	. 361	. 109	. 25	. 157	. 014	. 205	. 095
. 70	. 398	. 148	. 35	. 232	. 034	. 166	. 114
1. 00	. 480	. 280	. 65	. 380	. 128	. 099	. 152
1. 50	. 564	. 543	1. 15	. 510	. 354	. 053	. 189
2. 00	. 617	. 838	1. 65	. 581	. 629	. 035	. 209
3. 00	. 683	1. 49	2. 65	. 664	1. 255	. 019	. 235
5. 00	. 752	2. 94	4. 65	. 743	2. 67	. 009	. 27
7. 00	. 789	4. 48	6. 65	. 783	4. 21	. 006	. 27
10. 00	. 823	6. 90	9. 65	. 8198	6. 61	. 0032	. 29
15. 00	. 855	11. 1	14. 65	. 8528	10. 81	. 0022	. 29
20. 00	. 872	15. 3	19. 65	. 8718	15. 00	. 0012	. 30
30. 00	. 897	24. 3	29. 65	. 8961	23. 99	. 0009	. 31

1. $\frac{t_p+t_i}{sdf}=t/sdf$ for pumped well if pumping had continued.
2. q/Q for pumped well if pumping had continued. Values from table 1 for value of t/sdf indicated in column 1.
3. $\frac{v}{Qsdf}$ for pumped well if pumping had continued. Values from table 1 for value of t/sdf indicated in column 1.
4. t/sdf for recharged well, beginning at end of pumping.
5. q/Q for recharged well, beginning at end of pumping. Values from table 1 for value of t/sdf indicated in column 4.
6. $\frac{v}{Qsdf}$ for recharged well, beginning at end of pumping. Values from table 1 for value of t/sdf indicated in column 4.
7. Column 2 minus column 5; residual q/Q.
8. Column 3 minus column 6; residual $\frac{v}{Qsdf}$.

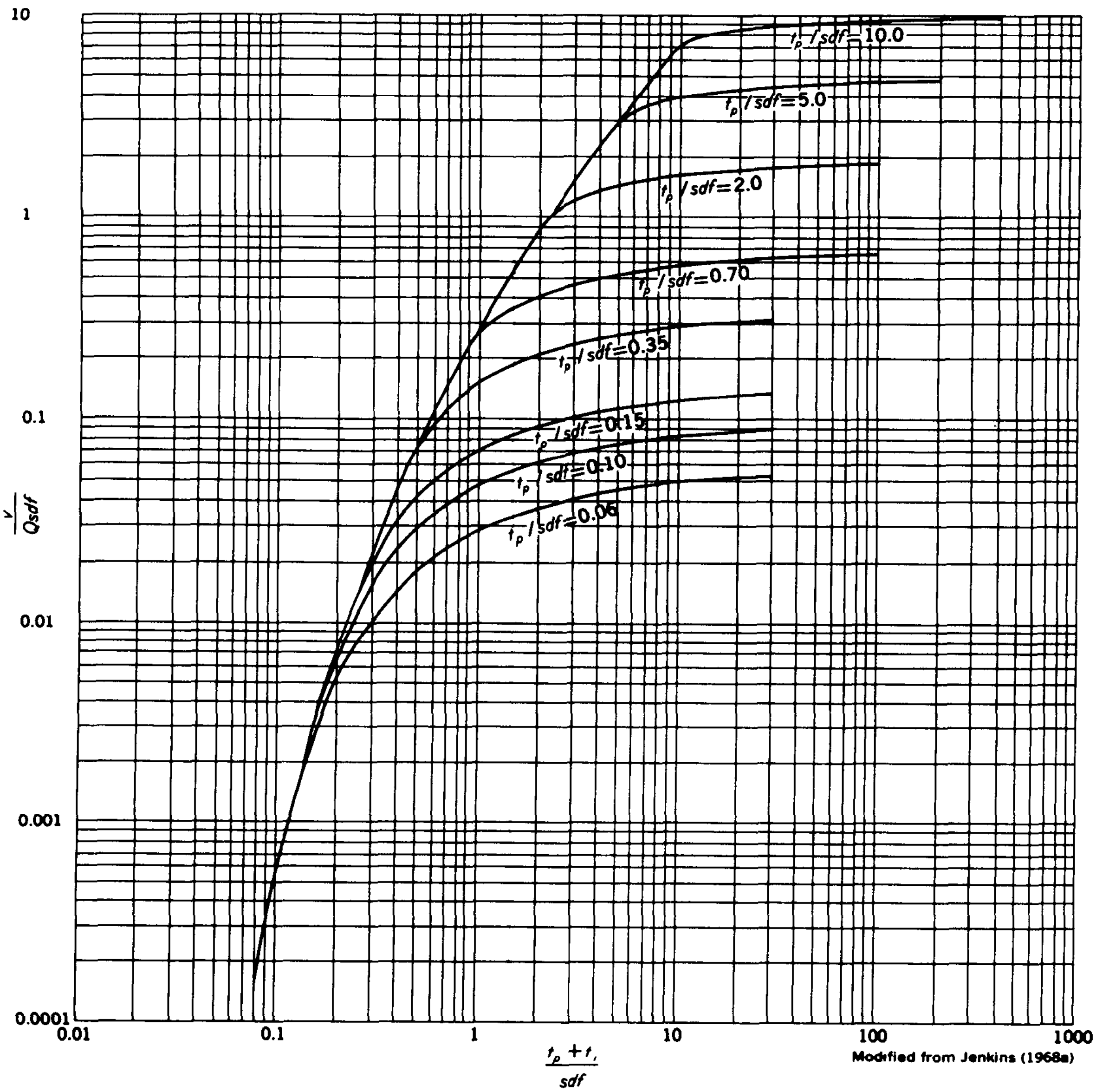


Figure 3.—Curves to determine volume of stream depletion during and after pumping.

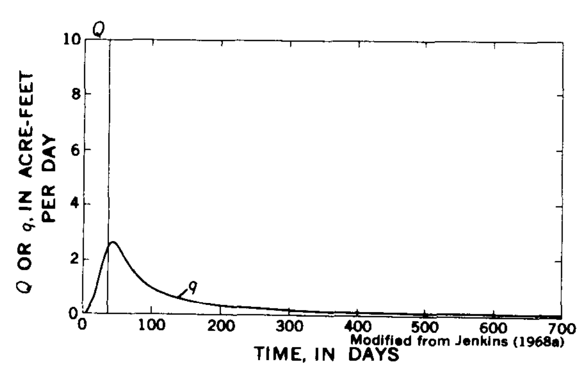


Figure 4.—Example of residual effects of well pumping 35 days.

4 days beginning 5 days after the beginning of the period, shut down 10 days, pumped 4 days, shut down 10 days, pumped 4 days, and shut down 5 days. The computed effects of the pattern of intermittent pumping are compared in figure 5 with those of the steady rate. The comparisons indicate that, within quite large ranges of intermittency, the effects of intermittent pumping are approximately the same as those of steady, continuous pumping of the same volume.

Table 3.—Computation of the effects of two selected

[a=1,890 ft, T/S=134,000 ft²/day, sdf=26.7 days. Intermittent pumping rate=5.25 acre-ft/day,

Time from beginning of period (days)	Steady pumping: Pumping period (1st–42d day inclusive) t/sdf	q/Q	$\frac{v}{Qsdf}$	q (acre-ft per day)	v (acre-ft)	Intermittent pumping: Pumping period (6th–9th day inclusive) Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$
0	0	0	0	0	0				
5	.187	.102	.006	.15	.2	0	0	0	0
9	.337	.223	.031	.33	1.2	4	.150	.068	.003
12	.449	.291	.060	.44	2.4	7	.262	.127	.015
19	.712	.402	.153	.60	6.1	14	.524	.080	.044
23	.861	.446	.216	.67	8.7	18	.674	.061	.054
26	.974	.471	.262	.71	10.5	21	.787	.050	.061
33	1.236	.525	.398	.79	15.9	28	1.049	.034	.071
37	1.386	.548	.479	.82	19.2	32	1.199	.029	.074
42	1.573	.573	.585	.86	23.4	37	1.386	.023	.081

Sample Computations

To illustrate the use of the curves and tables, solutions are shown of problems that might arise in the conjunctive management of ground water and surface water.

Problem I

Management criteria require that pumping cease when the rate of stream depletion by pumping reaches 0.14 acre-ft/day:

1. Under this restriction how long can a well 1.58 miles from the stream be pumped at the rate of 2 acre-ft/day if T/S is 10^6 gal/day-ft, and what is the volume of stream depletion during this time?
2. If pumping this well is stopped when q=0.14 acre-ft/day, what will the rate of stream depletion be 30 days later? What will be the volume of stream depletion at that time?
3. What will be the largest rate of stream depletion and when will it occur?

Given:

q=0.14 acre-ft/day
Q=2 acre-ft/day
a=1.58 miles
$T/S=10^6$ gal/day-ft
t_i=30 days

$$sdf=a^2S/T=\frac{a^2}{T/S}=\frac{(1.58\text{ mi})^2\,(5{,}280\text{ ft/mi})^2}{(10^6\text{ gal/day-ft})\,(1\text{ ft}^3/7.48\text{ gal})}$$
$$=520\text{ days.}$$

Find:

t_p
v at t_p
q at t_p+t_i
v at t_p+t_i
q max
t of q max.

Part 1

From information given, the ratio of the rate of stream depletion to the rate of pumping is

$$q/Q=\frac{(0.14\text{ acre-ft/day})}{(2\text{ acre-ft/day})}=0.07.$$

From curve A (fig. 1)

$$t/sdf=0.15.$$

Substitute the value under "Given" for sdf, and

$$t=(0.15)(520\text{ days})=78\text{ days.}$$

The total time the well can be pumped is 78 days.

When

$$t/sdf=0.15.$$

then from curve B (fig. 1),

$$\frac{v}{Qt}=0.02.$$

Substitute the values for Q and t, and the volume of stream depletion during this time is

$$v=(0.02)(2\text{ acre-ft/day})(78\text{ days})$$
$$=3.1\text{ acre-ft.}$$

patterns of pumping on a nearby stream

t_p/sdf=0.15 (see curves in figures 2 and 3). Steady pumping rate=1.5 acre-ft/day]

Intermittent pumping—Continued											
Pumping period (20th–23d day inclusive)				Pumping period (32d–35th day inclusive)				Totals			
Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$	Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$	q/Q	$\frac{v}{Qsdf}$	q (acre-ft per day)	v (acre-ft)
								0	0	0	0
								.068	.003	.36	.4
								.127	.015	.67	2.1
0	0	0	0					.080	.044	.42	6.2
4	.150	.068	.003					.129	.057	.68	8.0
7	.262	.127	.015					.177	.076	.93	10.7
14	.524	.080	.044	0	0	0	0	.114	.115	.60	16.1
18	.674	.061	.054	4	.150	.068	.003	.158	.131	.83	18.4
23	.861	.044	.063	9	.337	.223	.031	.188	.169	.99	23.7

During the 78-day pumping period, 3.1 acre-ft, out of a total of 156 acre-ft pumped, is stream depletion.

Part 2

If pumping is stopped at the end of 78 days, then $t_p/sdf=0.15$, and 30 days later,

$$\frac{t_p+t_i}{sdf}=\frac{108 \text{ days}}{520 \text{ days}}=0.21.$$

From figure 2: if

$$t_p/sdf=0.15$$

and

$$\frac{t_p+t_i}{sdf}=0.21,$$

$$q/Q=0.12.$$

Thus the rate of stream depletion is

$$q=(0.12)(2 \text{ acre-ft/day})$$
$$=0.24 \text{ acre-ft/day, 30 days after pumping stops.}$$

From figure 3

$$\frac{v}{Qsdf}=0.008.$$

Substitute the values for Q and sdf, and the total volume of the stream depletion at the end of 30 days is

$$v=(0.008)(2 \text{ acre-ft/day})(520 \text{ days})$$
$$=8.3 \text{ acre-ft of stream depletion during 108 days}$$

as a result of pumping 2 acre-ft/day during the first 78 days.

Part 3

If

$$t_p/sdf=0.15,$$

then from figure 2

$$\text{maximum } q/Q=0.13,$$

when

$$\frac{t_p+t_i}{sdf}=0.25.$$

Therefore

$$\text{maximum } q=(0.13)(2 \text{ acre-ft/day})$$
$$=0.26 \text{ acre-ft/day}$$

when

$$t_p+t_i=(0.25)(520 \text{ days})$$
$$=130 \text{ days, or 52 days after pumping stops.}$$

Problem II

An irrigator is restricted to a maximum withdrawal of 150 acre-ft during the 150-day growing season, provided his pumping depletes the stream less than 25 acre-ft during the season. His well is 1 mile from the stream, and $T/S=134{,}000$ ft^2/day. He will pump at the rate of 2.00 acre-ft/day, regulating his average pumping rate by shutting his pump off for the appropriate number of hours per day. Examine the effects of several possible pumping patterns: Given:

max=Qt 150 acre-ft
v max=25 acre-ft
t max=150 days
a=1 mile
T/S=134,000 ft^2/day

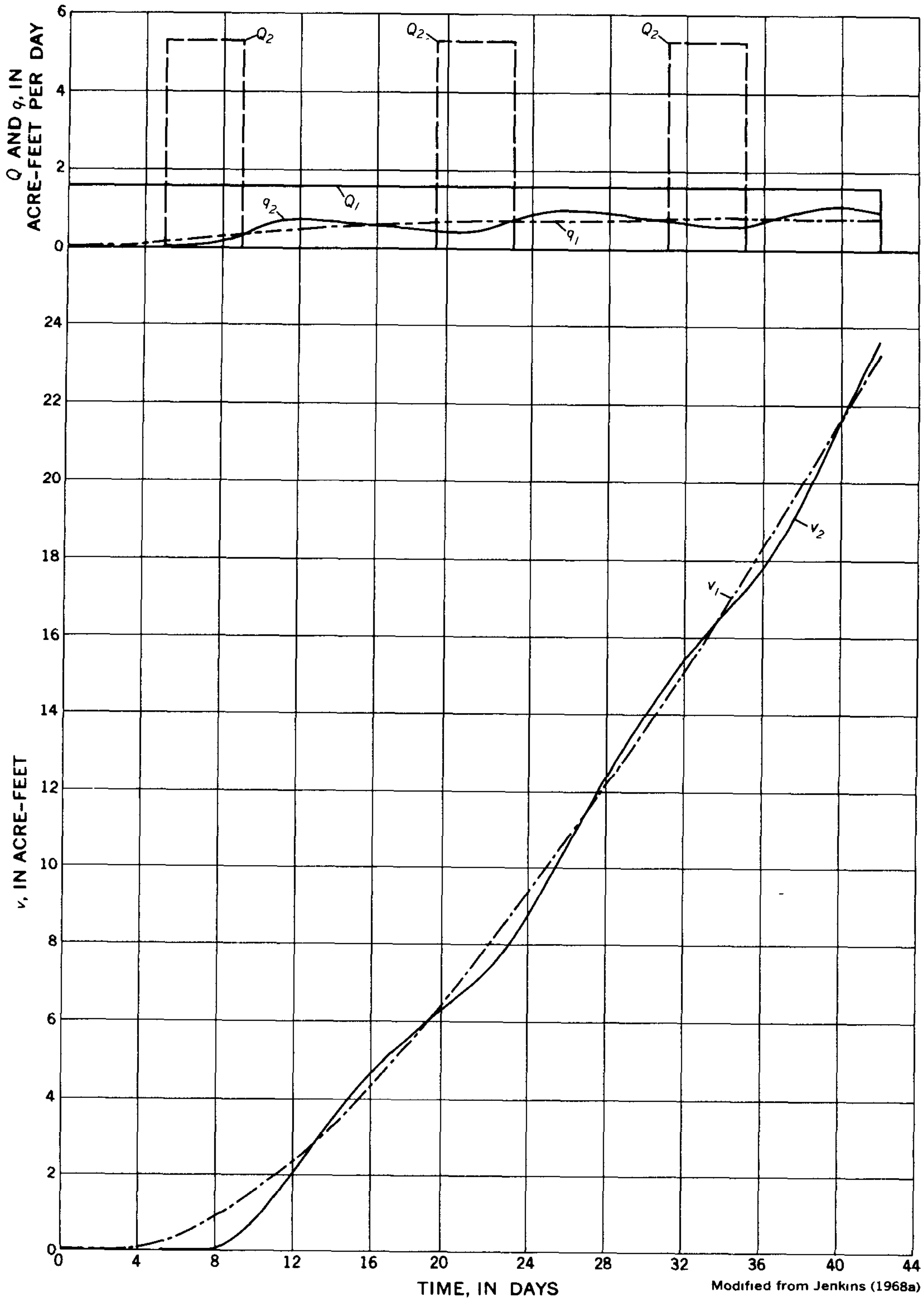


Figure 5.—Curves showing the effects of intermittent and steady pumping on a stream

$$sdf = a^2S/T = \frac{a^2}{T/S} = \frac{(5{,}280\ \text{ft})^2}{134{,}000\ \text{ft}^2/\text{day}} = 209\ \text{days}.$$

Find:

Various pumping patterns possible within the restrictions given.

Part 1

First, test to see if both restrictions apply to any combination of pumping time and rate within the 150-day period. Try ending pumping the last day of the season, beginning pumping at a time and rate such that pumping 150 acre-ft will result in a depletion of the stream of 25 acre-ft at the end of pumping.

$$Qt = 150\ \text{acre-ft},\ v = 25\ \text{acre-ft};\ \frac{v}{Qt} = 0.167.$$

From curve B (fig. 1)

$$t/sdf = 0.54.$$

Time will be

$$t = (0.54)\ (209\ \text{days})$$
$= 113$ days, or 37 days after beginning of season.

Pumping rate will be

$$Q = \frac{150\ \text{acre-ft}}{113\ \text{days}} = 1.33\ \text{acre-ft/day}.$$

He can pump 16 hours per day, beginning 113 days before the end of the season.

If pumping 150 acre-ft during the 113-day period at the end of the season results in 25 acre-ft of stream depletion, it follows that pumping 150 acre-ft—regardless of rate—in a shorter period at the end of the season will result in less than 25 acre-ft depletion, and the 150 acre-ft limit will apply. It also follows that pumping 150 acre-ft in the earlier periods will result in more than 25 acre-ft of stream depletion, hence the restriction on stream depletion will apply during the first part of the season.

Part 2

Begin pumping 60 days after the beginning of the season. Test reasoning that the restriction on volume pumped applies.

$$Qt = 150\ \text{acre-ft},$$
$$t = 90\ \text{days},$$

$$t/sdf = \frac{90\ \text{days}}{209\ \text{days}} = 0.43.$$

From curve B

$$\frac{v}{Qt} = 0.13.$$

The volume of stream depletion is

$$v = (0.13)\ (150\ \text{acre-ft}) = 19.5\ \text{acre-ft}.$$

The restriction on the volume of stream depletion has not been exceeded; therefore, the restriction on volume pumped does apply, and the allowable pumping rate would be

$$Q = \frac{150\ \text{acre-ft}}{90\ \text{days}} = 1.67\ \text{acre-ft/day}$$

which is the equivalent of pumping at the rate of 2.00 acre-ft/day for 20 hours per day.

Part 3

Begin pumping at the beginning of the season, pump for 73 days. Test reasoning that the restriction on stream depletion applies.

$$t_p/sdf = 73\ \text{days}/209\ \text{days} = 0.35.$$

From figure 3, for

$$t/sdf = 0.35$$

and

$$\frac{t_p + t_i}{sdf} = \frac{150\ \text{days}}{209\ \text{days}} = 0.72,$$

$$\frac{v}{Qsdf} = 0.12.$$

The steady pumping rate is

$$Q = \frac{25\ \text{acre-ft}}{(0.12)(209\ \text{days})} = 1.00\ \text{acre-ft/day},$$

and the net volume pumped is

$$Qt = (1.00\ \text{acre-ft/day})\ (73\ \text{days}) = 73\ \text{acre-ft}.$$

Therefore, the restriction on volume of stream depletion does apply. He can pump 12 hours per day at a rate of 2.00 acre-ft/day during a 73-day pumping period at the beginning of the season.

Part 4

The irrigator elects to pump 6 hours per day for the first 32 days of the season. What is the highest rate he can pump during the remaining 118 days?

Try assumption that restriction on volume of stream depletion will apply.

$$t_p/sdf=\frac{32 \text{ days}}{209 \text{ days}}=0.15$$

and

$$\frac{t_p+t_i}{sdf}=\frac{150 \text{ days}}{209 \text{ days}}=0.72.$$

From figure 3

$$\frac{v_1}{Qsdf}=0.057.$$

The volume of stream depletion during the 32 days is

$$v_1=(0.057)\ (0.5 \text{ acre-ft/day})\ (209 \text{ days}) =6.0 \text{ acre-ft}.$$

The net volume pumped during this time is

$$Q_1t_1=(0.5 \text{ acre-ft/day})\ (32 \text{ days})=16 \text{ acre-ft}.$$

Subtract v_1 from the allowable volume of stream depletion

$$25 \text{ acre-ft}-6 \text{ acre-ft}=19 \text{ acre-ft}=v_2.$$

If

$$t_2/sdf=\frac{118 \text{ days}}{209 \text{ days}}=0.56,$$

then from figure 1

$$\frac{v_2}{Q_2t_2}=0.17.$$

The volume pumped during the 118 days is

$$Q_2t_2=(19 \text{ acre-ft})/0.17=112 \text{ acre-ft}.$$

The values for the two periods total

$$(112+16) \text{ acre-ft}=128 \text{ acre-ft},$$

which is less than 150 acre-ft. Therefore the assumption that restriction on volume of stream depletion applies is correct.

$$Q_2=\frac{112 \text{ acre-ft}}{118 \text{ days}}=0.95 \text{ acre-ft/day}.$$

He can pump at the steady rate of 2.00 acre-ft/day for 11.4 hours per day during the last 118 days of the season.

The irrigator elects to pump continuously at the rate of 2.00 acre-ft/day. If he plans to pump until the end of the season, how soon can he start pumping? (See Part 5.) If he plans to start pumping at the beginning of the season, how long can he pump? (See Part 6.) If he plans to start pumping 50 days after the beginning of the season, how long can he pump? (See Part 7.)

Part 5

$$Qt=150 \text{ acre-ft},$$

$$t=\frac{150 \text{ acre-ft}}{2 \text{ acre-ft/day}}=75 \text{ days}$$

$$t/sdf=\frac{75 \text{ days}}{209 \text{ days}}=0.36.$$

From curve B (fig. 1)

$$\frac{v}{Qt}=0.10.$$

The volume of stream depletion is

$$v=15.0 \text{ acre-ft}.$$

Therefore the restriction on volume pumped applies, and he can pump continuously at the rate of 2 acre-ft/day, beginning 75 days before the end of the season.

Part 6

Assume that the restriction on stream depletion applies,

$$\frac{v}{Qsdf}=\frac{25 \text{ acre-ft}}{(2 \text{ acre-ft/day})\ (209 \text{ days})}=0.060$$

and

$$\frac{t_p+t_i}{sdf}=\frac{150 \text{ days}}{209 \text{ days}}=0.72.$$

From figure 3

$$t_p/sdf \approx 0.17$$

$$t_p \approx (0.17)\ (209 \text{ days}) \approx 35 \text{ days}.$$

Therefore the irrigator can begin pumping at the beginning of the season and pump continuously at a rate of 2.00 acre-ft/day for about 35 days.

Part 7

Restriction on volume pumped limits pumping time to

$$\frac{150 \text{ acre-ft}}{2 \text{ acre-ft/day}}=75 \text{ days.}$$

Test to see if depletion restriction would be exceeded by 75 days of pumping beginning 50 days after the beginning of the season.

$$t_p+t_i=(150-50) \text{ days}=100 \text{ days.}$$

If

$$\frac{t_p+t_i}{sdf}=\frac{100 \text{ days}}{209 \text{ days}}=0.48$$

and

$$t_p/sdf=75 \text{ days}/209 \text{ days}=0.36,$$

then from figure 3

$$\frac{v}{Qsdf}=0.72.$$

The volume of stream depletion is

$$v\approx(0.72)(2 \text{ acre-ft/day})\ (209 \text{ days})$$

$$\approx 30 \text{ acre-ft},$$

which exceeds the 25 acre-ft restriction.

Try stopping pumping after 69 days. Use values from table 1 instead of interpolation between curves in figure 3.

$$t_i=(100-69) \text{ days}=31 \text{ days.}$$

If

$$\frac{t_p+t_i}{sdf}=0.48, \text{ then } \frac{v_1}{Qsdf}=0.070,$$

and if

$$\frac{t_i}{sdf}=0.15, \text{ then } \frac{v_2}{Qsdf}=0.003.$$

The net is

$$\frac{v}{Qsdf}=0.067.$$

The volume of steam depletion is

$$v=28 \text{ acre-ft.}$$

Try $t_p=54$ days, $t_i=46$ days.

$$\frac{t_p+t_i}{sdf}=0.48, \quad \frac{v_1}{Qsdf}=0.070,$$

and

$$\frac{t_i}{sdf}=0.22, \quad \frac{v_2}{Qsdf}=0.010.$$

The net is

$$\frac{v}{Qsdf}=0.060.$$

The volume of stream depletion is

$$v=25 \text{ acre-ft.}$$

Therefore, the irrigator can pump continuously at a rate of 2 acre-ft/day during the 54-day period beginning 50 days after the season begins.

Problem III

A well 4,000 feet from the stream is shut down after pumping at a rate of 250 gal/min for 150 days; $T/S=67{,}000 \text{ ft}^2\text{/day}$.

1. What effect did pumping the well have on the stream during the pumping period?
2. What will be the effect during the next 216 days after pumping was stopped?
3. What would the effect have been if pumping had continued during the entire 366 days?

Given:

Q = 250 gal/min
t_p = 150 days, 366 days
t_i = 216 days
a = 4,000 feet
$T/S=67{,}000 \text{ ft}^2\text{/day}$

$$sdf=\frac{(4000 \text{ ft})^2}{67{,}000 \text{ ft}^2\text{/day}}=239 \text{ days.}$$

Find:

q and v for $t_p=150$ days
q and v for $t_p+t_i=366$ days
q and v for $t_p=366$ days

Part 1

$$t_p/sdf=150 \text{ days}/239 \text{ days}=0.63.$$

The rate of pumping in consistent units is

$$Q=\left(\frac{250 \text{ gal}}{\text{min}}\right)\left(1{,}440\frac{\text{min}}{\text{day}}\right)\left(\frac{1 \text{ ft}^3}{7.48 \text{ gal}}\right)\left(\frac{1 \text{ acre-ft}}{43{,}560 \text{ ft}^3}\right)$$

$$=1.1 \text{ acre-ft/day.}$$

When

$$t=t_p,$$

$$t/sdf=0.63.$$

From curve A

$$q/Q=0.37.$$

From curve *B*

$$\frac{v}{Qt}=0.19.$$

At the end of 150 days,

$q=(1.1 \text{ acre-ft/day})\ (0.37)$
$=0.41$ acre-ft/day,
$v=(1.1 \text{ acre-ft/day})\ (150 \text{ days})\ (0.19)$
$=31$ acre-ft.

Part 2

When $t_p+t_i=(150+216)$ days $=366$ days,

$$\frac{t_p+t_i}{sdf}=1.53.$$

From figure 2 by interpolation,

$$q/Q=0.11.$$

From figure 3 by interpolation,

$$\frac{v}{Qsdf}=0.33.$$

Thus, 216 days after pumping ceased,

$q=(0.11)\ (1.1 \text{ acre-ft/day})$
$=0.12$ acre-ft/day,
$v=(0.33)\ (1.1 \text{ acre-ft/day})\ (239 \text{ days})$
$=87$ acre-ft.

The additional volume of stream depletion during the 216-day period would be

$(87-31)$ acre-ft $=56$ acre-ft.

Part 3

If pumping had continued for the entire 366-day period,

$$\frac{t}{sdf}=1.53,$$

and from table 1, $q/Q=0.568$ and

$$\frac{v}{Qt}=0.366.$$

$q=(0.568)\ (1.1 \text{ acre-ft/day})$
$=0.62$ acre-ft/day,
$v=(0.366)\ (1.1 \text{ acre-ft/day})\ (366 \text{ days})$
$=147$ acre-ft.

During the last 216 days the stream depletion would have been

$v=(147-31)$ acre-ft $=116$ acre-ft.

Problem IV

A municipal well is to be drilled in an alluvial aquifer near a stream. Downstream water uses require that depletion of the stream be limited to no more than 5,000 cubic meters during the dry season, which commonly is about 200 days long. The well will be pumped continuously at the rate of 0.03 m^3/sec (cubic meters per second) during the dry season only. Wet season recharge is ample to replenish storage depleted by the pumping in the previous dry season, thus residual effects can be disregarded. $T=30$ cm^2/sec (square centimeters per second), $S=0.20$.

What is the minimum allowable distance between the well and the stream?

Given:
$v=5{,}000 \text{ m}^3$
$Q=0.03 \text{ m}^3/\text{sec}$
$t_p=200$ days
$T=30 \text{ cm}^2/\text{sec}$
$S=0.20$
$Qt=(0.03 \text{ m}^3/\text{sec})\ (200 \text{ days})$
$(86{,}400 \text{ sec/day})=5.184\times10^5 \text{m}^3$

$$\frac{v}{Qt}=5{,}000 \text{ m}^3/5.184\times10^5 \text{ m}^3=0.01.$$

Find: *a*

From curve *B*

$$t/sdf=0.12=\frac{tT}{a^2S},$$

$$0.12=\frac{(200 \text{ days})\ (86{,}400 \text{ sec/day})\ (30 \text{ cm}^2/\text{sec})}{a^2(0.20)},$$

$$a^2=\frac{(200)\ (86{,}400)\ (30)\ \text{cm}^2}{(0.12)\ (0.20)}=2.16\times10^{10} \text{ cm}^2,$$

$$a=1.47\times10^5 \text{ cm}=1{,}470 \text{ meters}.$$

Problem V

A water company wants to install a well near a stream and pump it 90 days during the summer to supplement reservoir supplies. Downstream residents have protested that the well might dry up the stream. Natural streamflow at the lower end of the reach that would be affected by pumping is not expected to go below 2.0 ft³/sec in most years, and the downstream users have agreed that the well can be installed if depletion of the stream is limited to a maximum of 1.5 ft³/sec. The well would be 500 feet from the the stream and would pump 1,000 gpm. $T=50{,}000$ gpd/ft, and $S=0.20$.

1. Will the rate of stream depletion exceed 1.5 ft³/sec during the first season or any following season?
2. If so, when will the rate of stream depletion exceed 1.5 ft³/sec?
3. At what rate could the well be pumped in order not to exceed 1.5 ft³/sec of stream depletion?

Given:

q max allowable $=1.5$ ft³/sec
$a=500$ feet
$T=50{,}000$ gal/day-ft
$S=0.20$
$Q=1{,}000$ gal/min

$$sdf=\frac{(500\text{ ft})^2(0.20)(7.48\text{ gal/ft}^3)}{50{,}000\text{ gal/day-ft}}=7.5\text{ days}$$

Find:

q max
t for $q=1.5$ ft³/sec
Q for $q=1.5$ ft³/sec

Part 1

$$t_p=90\text{ days.}$$

$$t_p/sdf=12.$$

From figure 1,

$$1-q/Q=0.155.$$

Therefore

$q/Q=0.845,$

$$q=\frac{(0.845)(1{,}000\text{ gal/min})(1{,}440\text{ min/day})}{7.48\text{ gal/ft}^3}$$

$$=1.63\times10^5\text{ ft}^3\text{/day}$$

$$=1.88\text{ ft}^3\text{/sec.}$$

Therefore by the end of the first pumping period, the rate of stream depletion would have exceeded the allowable depletion of 1.5 ft³/sec.

Part 2

$$q=1.5\text{ ft}^3\text{/sec}=(1.5\text{ ft}^3\text{/sec})\ (86{,}400\text{ sec/day})$$
$$=1.30\times10^5\text{ ft}^3\text{/day}$$

$Q=1{,}000$ gal/min

$$=\frac{(1{,}000\text{ gal/min})(1{,}440\text{ min day})}{7.48\text{ gal/ft}^3}$$
$$=1.93\times10^5\text{ ft}^3\text{/day}$$

$$q/Q=1.30\times10^5/1.93\times10^5=0.67$$

$$1-q/Q=1.00-0.67=0.33.$$

From figure 1, curve $1-q/Q$

$$t/sdf=2.7,$$

$$t=(2.7)\ (7.5)=20\text{ days.}$$

Therefore, the rate of stream depletion will exceed 1.5 ft³/sec after 20 days pumping at 1,000 gal/min.

Part 3

From "Part 1," $q/Q=0.845$.

$$Q=q/0.845$$
$$=(1.30\times10^5\text{ ft}^3\text{/day})/0.845$$
$$=1.54\times10^5\text{ ft}^3\text{/day}$$
$$=800\text{ gal/min.}$$

Therefore, if pumping were reduced to 800 gal/min, the rate of stream depletion would not exceed 1.5 ft³/sec during the first 90-day period of pumping.

However, the residual effects of this pumping would carry over through the next pumping period.

The residual effect of the first pumping period on rate of stream depletion at the end of the second period, assuming no pumping during the second period, is as follows:

$$t_p+t_i=90\text{ days}+365\text{ days}=455\text{ days.}$$

$$\frac{t_p+t_i}{sdf}=61,\ t_i/sdf=49.$$

From figure 1,

$$(1-q/Q)_{p+i}=0.073,$$

$$(1-q/Q)_i=0.081,$$

and

$$q/Q=0.008.$$

Thus the rate of depletion is

$$q=(0.008)\ (1.54\times10^5\ \text{ft}^3/\text{day})$$
$$=1{,}230\ \text{ft}^3/\text{day}$$
$$=0.014\ \text{ft}^3/\text{sec}.$$

The effects are very slight. Pumping 800 gal/min during the second pumping period would exceed the allowable stream depletion rate by only 0.014 ft^3/sec. Reduction of the pumping rate to about 750 gal/min would keep rate of stream depletion below 1.5 ft^3/sec during several successive pumping seasons.

Mathematical Bases for Curves and Tables

The literature concerning the effect of a pumping well on a nearby stream contains several equations and charts that, although superficially greatly different, yield identical results. The basic curves and table (Curves *A* and *B*, and table 1) of this report can be derived from any of the published expressions. A cursory review of some of the pertinent equations may be useful to those interested in the mathematics.

Definitions

The notation that has been used in the literature is even more diverse than the published equations; consequently, definitions of only selected terms are given below. Complete definitions of all terms used are in the indicated references.

erf x=the error function of x

$$=\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt=1-\text{erfc}\ x$$

erfc x=the complementary error function of x

$$=\frac{2}{\sqrt{\pi}}\int_x^\infty e^{-t^2}dt$$

i^2erfc x=the second repeated integral of the error function.

The line source integral (Maasland and Bittinger, 1963, p. 84)

$$=\sqrt{\pi}\int_{x/\sqrt{4h^2t}}^{\infty}\frac{e^{-u^2}du}{u^2}$$

In the notation used in the main body of this report,

$$x/\sqrt{4h^2t}=\sqrt{\frac{sdf}{4t}}$$

Definitions and tabular values of erf x ,erfc x, and i^2erfc x are shown by Gautschi (1964, p. 297, 310–311, 316–317). Tabular values of the line source integral are shown by Maasland and Bittinger (1963, p. 84) and by Glover (1964, p. 45–53).

Mathematical base for curve A

Curve *A* and its coordinates in table 1 can be computed from Theis (1941), Conover (1954), and Theis and Conover (1963)

$$P=\frac{2}{\pi}\int_0^{\pi/2}e^{-k\sec^2 u}du \tag{1}$$

from Glover and Balmer (1954)

$$q/Q=1-P(x_1/\sqrt{4\alpha t}) \tag{2}$$

from Glover (1960)

$$q_1/Q=1-\frac{2}{\sqrt{\pi}}\int_0^{x_1/\sqrt{4\alpha t}}e^{-u^2}du \tag{3}$$

and from Hantush (1964, 1965)

$$Q_r=Q\text{erfc}\ (U) \tag{4}$$

Theis transformed his basic integral into equation 1 because the basic integral is laborious to evaluate, but in the form of equation 1, is amenable to either numerical or graphical solution. Equations 2, 3, and 4 are identical, and in the notation used in this paper are

$$q/Q=\text{erfc}\left(\sqrt{\frac{sdf}{4t}}\right)=1-\text{erf}\left(\sqrt{\frac{sdf}{4t}}\right). \tag{5}$$

Mathematical base for curve B

Curve B and its coordinates in table 1 can be computed either by integration of curve A or of the equations that are the base of curve A. Analytical integration of equations 2 and 3 is shown by Glover (1960) as

$$\int_0^t \frac{q_r}{Q}\,dt = 1 - \frac{2}{\sqrt{\pi}}\int_0^{x_1/\sqrt{4\alpha t}} e^{-u^2}du - \frac{2}{\pi}\left(\frac{x_1^2}{4\alpha t}\right)\sqrt{\pi}\int_{x_1/\sqrt{4\alpha t}}^{\infty} \frac{e^{-u^2}}{u^2}\,du \quad (6)$$

and equation 4 is integrated by Hantush (1964, 1965)

$$v_r = \int_0^{t_0} Q_r\,dt = 4Qt_0 \mathrm{i}^2\,\mathrm{erfc}\,(U_0) \quad (7)$$

In the notation used in this paper, equation 6 is

$$\frac{v}{Qt} = 1 - \mathrm{erf}\left(\sqrt{\frac{sdf}{4t}}\right) - \frac{2}{\pi}\left(\frac{sdf}{4t}\right)\sqrt{\pi}\int_{\sqrt{\frac{sdf}{4t}}}^{\infty} \frac{e^{-u^2}}{u^2}\,du \quad (8)$$

and equation 7 is

$$\frac{v}{Qt} = 4\mathrm{i}^2\,\mathrm{erfc}\left(\sqrt{\frac{sdf}{4t}}\right). \quad (9)$$

Equations 8 and 9 both can be expressed in terms extensively tabulated in Gautschi (1964, p. 310–311) as

$$\frac{v}{Qt} = \left(\frac{sdf}{2t}+1\right)\mathrm{erfc}\left(\sqrt{\frac{sdf}{4t}}\right) - \left(\sqrt{\frac{sdf}{4t}}\right)\frac{2}{\sqrt{\pi}}\exp\left(-\frac{sdf}{4t}\right) \quad (10)$$

Before discovering equations 6 and 7, the writer integrated curve A both numerically and graphically. The results were identical, within the limitations of the methods, to those obtained from equation 10.

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☆ U.S. Government Printing Office: 1977—240-961/125

Appendix D

United States Department of the Interior

U.S. GEOLOGICAL SURVEY
Nebraska Water Science Center
5231 South 19 Street
Lincoln, NE 68512-1271

November 2, 2005

Ann S. Bleed, Acting Director
Nebraska Department of Natural Resources
P.O. Box 94676
Lincoln, NE 68509-4676

Dear Ann:

The U.S. Geological Survey Nebraska Water Science Center (NWSC) acknowledges the State of Nebraska Department of Natural Resources (NDNR) request for review of "Stream Depletion Line Calculations for Determination of Fully Appropriated Basins for the State of Nebraska". We were pleased to perform this task for NDNR. I assigned this review to Richard Luckey, Gregory Steele, and Steve Peterson, who are NWSC hydrologists experienced with the development of numerical models that describe ground water/surface water interactions.

The NWSC reviewers found the document to be technically sound, but have made suggestions to improve the final product. Copies of the reviewers notes and list of their recommendations are enclosed. Please feel free to contact me directly at (402) 328-4110 if we can be of further assistance.

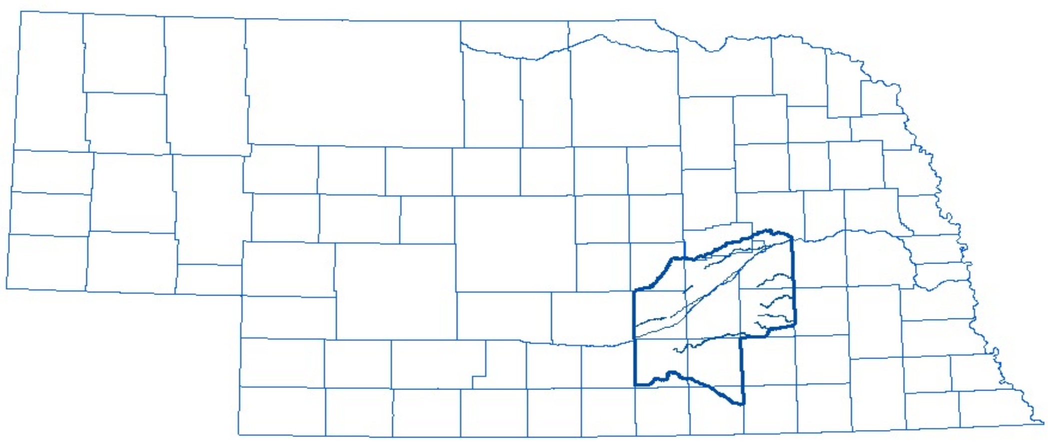
Sincerely,

Robert B. Swanson
Director

Enclosure

Appendix E

A GROUNDWATER MODEL TO DETERMINE THE AREA WITHIN THE UPPER BIG BLUE NATURAL RESOURCES DISTRICT WHERE GROUNDWATER PUMPING HAS THE POTENTIAL TO INCREASE FLOW FROM THE PLATTE RIVER TO THE UNDERLYING AQUIFER BY AT LEAST 10 PERCENT OF THE VOLUME PUMPED OVER A 50-YEAR PERIOD



Prepared By
R.J. Bitner, P.E.
Upper Big Blue Natural Resources District
September 2005

ACKNOWLEDGMENTS

The following persons provided assistance with inputs and reviews that were incorporated into the model and final report:

Courtney Hemenway, P.E., Hemenway Groundwater Engineering, Inc., provided a peer review of the model development, model inputs, model application, and report to ensure that these components are developed in accordance with acceptable standards.

Duane Woodward, Hydrologist, Central Platte Natural Resources District, reviewed the model and inputs for consistency with COHYST standards. Duane also assisted with evaluating recent river bed conductance data that was incorporated into the model.

Steve Peterson, Hydrologist, U.S. Geological Survey, assisted with implementation of the EMSI[1] GMS[2] modeling techniques.

Jim Cannia, Nebraska Department of Natural Resources, reviewed the model and model inputs regarding suitability for determining hydrologic connectivity of streams with the aquifer.

Marie Krausnick, Upper Big Blue Natural Resources District, provided assistance with GIS mapping.

Xun Hong Chen, Ph.D. and *Mark Burhach, Ph.D.*, University of Nebraska Conservation and Survey Division, provided Geoprobe electric logging, permeameter testing, and pump tests to estimate aquifer hydraulic conductivity and river bed conductance on the Platte River and Big Blue River.

Larry Cast, Geologist, reviewed test hole and irrigation well drilling logs to determine geologic and hydrologic properties of the layers used to define the aquifer.

Rich Kern, P.E., Hydrologist / Programmer, Nebraska Department of Natural Resources, provided computer programming of utilities to assist with database management, grouping geologic layer parameters, retrieving data from the DNR databases, and analysis of GMS - MODFLOW outputs.

COHYST Modelers[3], developed the COHYST Eastern Regional groundwater model from which this sub-regional model is derived.

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[1] EMSI is an acronym for “Environmental Modeling Systems, Inc.”

[2] GMS is an acronym for “Groundwater Modeling System”.

[3] COHYST is an acronym for “ Cooperative Hydrology Study”.

AUTHORIZATION

The groundwater model discussed in this report was commissioned by the Upper Big Blue Natural Resources District for the purpose of estimating the location of areas within the Natural Resources District that have the potential to be hydrologically connected to base-flow streams. The groundwater model and modeling results, shown in this report, have been presented to the Natural Resources District Board, and have been approved for submittal to the Nebraska Department of Natural Resources.

HGE
Hemenway Groundwater Engineering, Inc.

September 29, 2005

NE-0010-05

Mr. Jay Bitner
District Engineer
Upper Big Blue Natural Resources District
105 Lincoln Avenue
York, NE 68467

Dear Jay:

Subject: Groundwater Model Review for the Upper Big Blue Natural Resources District (UBBNRD)

As you requested, Hemenway Groundwater Engineering, Inc. (HGE) is pleased to submit this letter documenting the consulting services provided for the UBBNRD regarding your ongoing groundwater model development. HGE's Scope of Work (SOW) for consulting services was related to the review of the current groundwater computer model for the UBBNRD. The model is a sub-regional model of the area covered by the Eastern Model Unit (EMU) developed by the Nebraska Cooperative Hydrology Study (COHYST). The model utilizes the Groundwater Modeling System (GMS) pre- and post-processor modeling system and the United States Geological Survey (USGS) finite difference model MODFLOW 2000. The grids in the model are 1,320 feet by 1,320 feet or 40 acres per model grid, which is a refinement of the COHYST EMU model grid size of 2,640 feet by 2,640 feet. The focus of the UBBNRD model is to determine the depletion to the Platte River from wells, which represents 10 percent flow from the river after 50 years of well pumping. To determine the depletions, a baseline transient model was run without any wells pumping. Following the baseline run, the model was run numerous times with one well pumping at a new location at each model run. The depletions were calculated after each model run as a function of the distance of the well from the Platte River, and the 10 percent depletion line was mapped.

The services provided by HGE included reviewing the current UBBNRD groundwater model for "fatal flaws" and providing recommendations for improving and modifying the model to meet the intended purposes by the UBBNRD. HGE's recommendations were accepted and implemented by UBBNRD in the current groundwater model. The UBBNRD provided additional studies and information, model refinements, and improvements to the current COHYST EMU groundwater model. With these revisions and improvements, the current UBBNRD groundwater model meets the industry standards for groundwater modeling practices.

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Jay Bitner
Page 2
September 29, 2005

HGE looks forward to the opportunity to work with you and the UBBNRD in the future. If you have any questions regarding this letter or HGE's review of the UBBNRD groundwater model, please do not hesitate to contact me.

Sincerely,

Hemenway Groundwater Engineering, Inc.

Courtney Hemenway
President

HGE/UBBNRDGWMODELREVLET

TABLE OF CONTENTS

INTRODUCTION

This report discusses development and application of a groundwater model for a region that lies within the boundary of the Cooperative Hydrology Study (COHYST) eastern regional groundwater model[4] in Nebraska. The geographic area modeled is shown on Figure 1 and includes all, or portions of, Platte, Polk, York, Nance, Merrick, Hamilton, Clay, Nuckolls, Howard, Hall, and Adams Counties. The modeled area overlays portions of the Upper Big Blue, Central Platte, and Little Blue Natural Resources Districts. The total land surface within the model boundary is approximately 7,520 square miles (4.8 million acres).

PURPOSE

The purpose of this model is to provide a method for calculating the potential increase in the rate of flow from the Platte River to the underlying aquifer due to groundwater pumping near the Platte River within the Upper Big Blue Natural Resources District. The model is used to define a boundary encompassing the area within which a well pumping groundwater could increase flow from the Platte River to the underlying aquifer by an amount equal to, or greater than, 10 percent of the volume pumped over a period of 50 years. For purposes of determining whether or not a river basin is *fully appropriated* [5], the Nebraska Department of Natural Resources considers that wells within the 10 percent / 50-year boundary are hydrologically connected to the river.

CONCEPTUAL MODEL

The model boundaries are defined with a series of *fixed flow* arcs that specify flow into or out of the model, depending upon the direction and slope of the groundwater gradient at the boundary. The Platte River is defined with a series of *river* arcs which specify the river bed conductance, river bed thickness, and river stage. The model cells intersected by the river arcs are defined by the model as a series of point source river cells, each with its own conductance value. The model cells intersected by the fixed flow boundary arcs are defined by the model as a series of wells that are either source (injection) or sink (withdrawal), depending on whether the

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4 S. M. Peterson, *Groundwater Flow Model of the Eastern Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) Area*, 2005.

5 Nebraska Department of Natural Resources, Proposed Rule pursuant to Neb. Rev. Stat. §46-713.

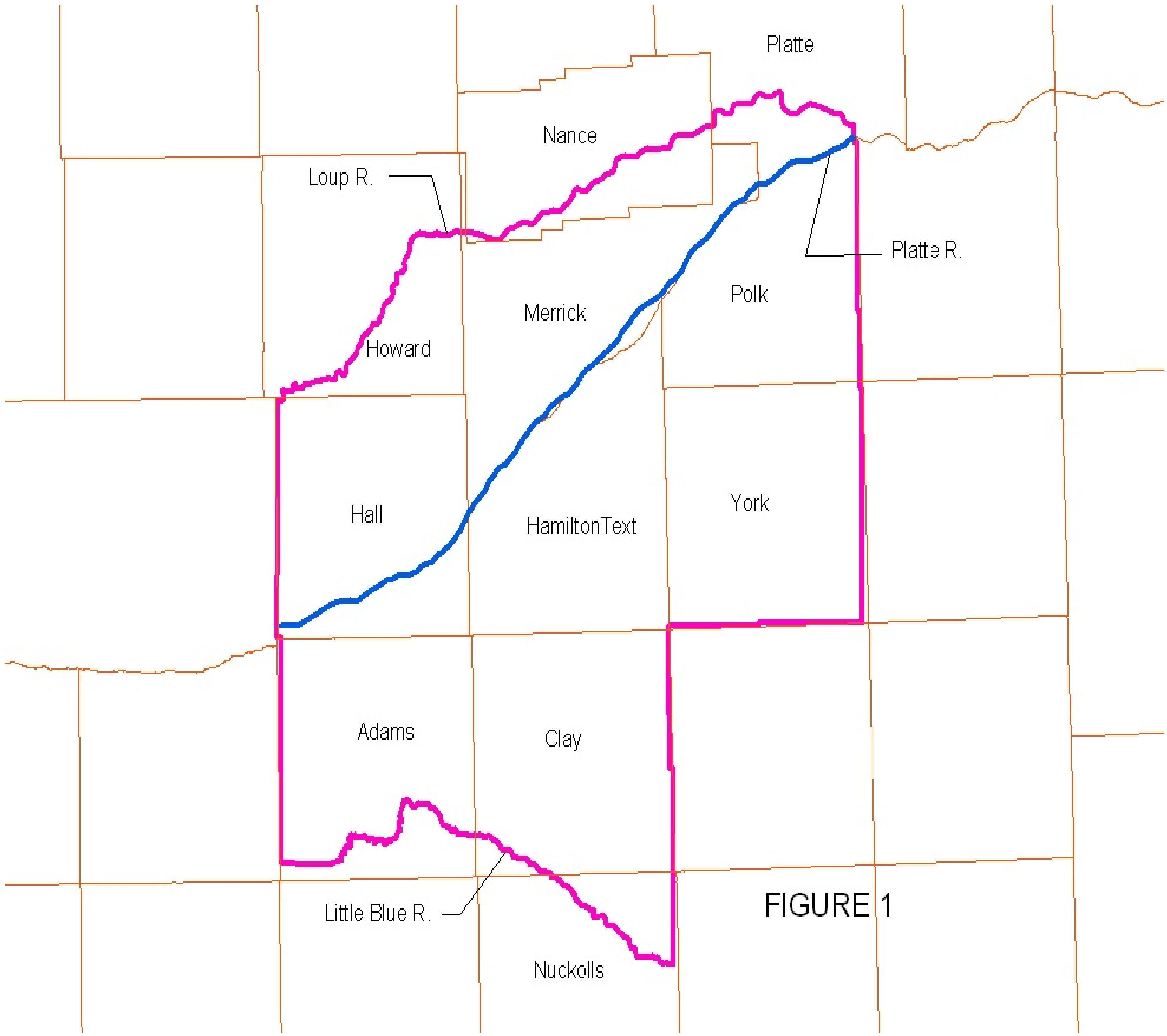
Platte
Nance
Loup R.
Platte R.
Polk
Merrick
Howard
Hall
HamiltonText
York
Adams
Clay
Little Blue R.
Nuckolls

FIGURE 1

boundary flow is into or out of the model at that point. The amount of river to aquifer flow induced by pumping is tested with a single well, which is moved from cell to cell parallel to the Platte River, at varying distances from the river. Other streams within the model boundary, such as the Big Blue River and its tributaries, including the West Fork Big Blue River, Lincoln Creek, and Beaver Creek, are not included in the model. The bed conductances of these rivers and streams are very low, approximately 0.0079 ft^2/day, and have minimal connectivity to the underlying aquifer[6] and the Platte River. Areal sources and sinks included in this model are recharge from precipitation, and evapotranspiration from rooted plants located in wet meadows near the Platte River. The model geology is represented by five unconfined layers. The numerical flow model is based on the following basic assumptions:

- At the scale in which this model is constructed, flow in the aquifer obeys Darcy's Law and mass and energy are conserved.
- Since the modeled fluid is groundwater, having a temperature in the range of 50 degrees Fahrenheit, the density and viscosity of water are constant over time and space.
- Parameters are uniform within each cell, and represent an estimate of their average value within the cell.
- The interchange of water between the aquifer and Platte River can be adequately simulated as one-dimensional flow through a discrete streambed layer. This conceptualization is appropriate over the scale at which this model is constructed.
- Hydraulic conductivity in the horizontal plane is isotropic; however, hydraulic conductivity in the vertical direction is not equal to hydraulic conductivity in the horizontal direction. The horizontal to vertical anisotropic ratio is assigned a value of 10 (i.e. horizontal hydraulic conductivity is ten times greater than vertical hydraulic conductivity), unless otherwise noted.

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[6] Xun Hong Chen, *River Bed Conductance Studies - West Fork Big Blue River and Platte River in Nebraska*, University of Nebraska Conservation and Survey Division, 2005.

GEOLOGIC AND HYDROSTRATIGRAPHIC UNITS

The model has five unconfined geologic layers. The layer definitions are consistent with those documented in the COHYST aquifer characterization report[7]. The model layers consist primarily of Quaternary deposits of Pleistocene alluvium, Pleistocene and Holocene loess, Holocene dune sand, and Holocene valley fill. Valley fill deposits are found along the Platte River and consist of gravel, sand, and silt. Alluvial deposits, which typically support high capacity wells, are found throughout the model area. In topographic bedrock highs these deposits are generally thinner, and produce lower yielding wells. Loess deposits are found throughout the model area, and the thickest deposits are located along the Platte River bluffs. The deposits become thinner as they approach the Platte River north of the loess bluffs. The Platte River bed contains a low permeability loess layer at about 10 to 20 feet below the current streambed surface[8]. The bedrock formation at the bottom of Layer 5 consists of shale, chalk, limestone, siltstone, and sandstone of Cretaceous age. These bedrock materials transmit very little water, and for modeling purposes are considered to be impermeable.

The model layers are numbered 1 through 5. Unit 1 is the top layer, and Unit 5 is the bottom layer. The layers used in this model are described as follows:

- Layer 1 — Top layer consisting of upper Quaternary age silt and clay with some sand and gravel
- Layer 2 — Middle Quaternary age sand and gravel
- Layer 3 — Lower Quaternary age silt and clay with some sand and gravel
- Layer 4 — Upper Tertiary age silt and clay with some sand and gravel
- Layer 5 — Middle Tertiary age sand and gravel underlain with bedrock materials consisting of shale, chalk, limestone, siltstone, and sandstone

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7 J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, November 2004.

8 See geoprobe electric logs shown in Appendix B

MODEL DESCRIPTION

The groundwater model is a three-dimensional finite difference computer model developed around the MODFLOW[9], Version 2000, groundwater modeling software enclosed within EMSI GMS[10], Version 5.1. The GMS software includes a pre-processor to read input data and place it in the model according to MODFLOW format requirements. GMS also does some post-processing of output in both graphical and numerical forms. The units of measure used in this model include feet for linear measure, days for time, feet per day for velocity, cubic feet for volume, and cubic feet per day for flow rate.

Model Grid

The model grid has 120,330 cells per layer. Each cell measures 1,320 feet per side, and covers an area of approximately 40 acres. Model feature locations are geo-referenced in the horizontal plane to the Nebraska State Plane Coordinate System, NAD 83 - feet. Top and bottom elevations of each layer are referenced to USGS mean sea level datum.

Modules

The MODFLOW software is modular in the sense that various modules (packages) can be activated for any particular modeling situation. The modules used in this model include river, well, recharge, and evapotranspiration.

River Module

The Platte River is simulated in this model as a series of arcs, connected at their upstream and downstream ends at nodes, with a combined length of 87.8 miles. Attributes associated with the arcs and nodes specify the river bed conductance, bottom of river bed elevation, and river stage. The hydrologic properties (K, S_y) of model cells identified as river cells (cells crossed by river arcs), and located in Layer 1, are adjusted to match the hydrologic properties of the underlying cell in Layer 2. In this way there is a direct connection of the Platte River bed to the aquifer, and the only limitation on inter-connectivity between the river bed and underlying

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9 M. G. McDonald and A.W. Harbaugh, *Modular Three-Dimensional Finite-Difference Groundwater Flow Model*, U.S. Geological Survey, 1984.

10 *Groundwater Modeling System (GMS)*, Environmental Modeling Systems, Inc. (EMSI), Park City, Utah.

aquifer is river bed conductance. River bed conductance is a function of river bed length, width, bed thickness, and hydraulic conductivity. MODFLOW uses the following equation[11] to calculate bed conductance:

EQ. 1 $$C = (k \times L \times W) / M$$

For each river arc "n":

C_n = streambed conductance ($ft^2/d/ft$)

k_{vn} = vertical hydraulic conductivity of the streambed (ft/d)

L_n = length of the streambed (ft)

W_n = width of streambed (ft)

M_n = thickness of streambed (ft)

For this model, the value of river bed conductance at each river arc is set at the same value as used in the COHYST Eastern Regional Model, except where detailed testing indicates the value should be different. The values established by testing were determined based on geoprobe and permeameter tests conducted by the University of Nebraska Conservation and Survey Division. Geoprobe electric logs, hydraulic conductivities, and bed conductance calculations are shown in Appendix B of this report. Platte River bed conductances used in this model are set at 11 $ft^2/d/ft$ in reaches where testing is completed. River bed conductances in the remaining reaches vary from 20 $ft^2/d/ft$ to 30 $ft^2/d/ft$.

Well Module

The potential increase in induced flow from the Platte River to the underlying aquifer, due to groundwater pumping near the Platte River, is tested with this model by placing a simulated pumping well at alternate cell locations, operating the model for a 50-year period at each location, and calculating the change in the water budget when compared with the baseline condition. The initial baseline condition is simulated with no pumping well.

For these simulations, pumping is assumed to be from Layer 2, the volume of water

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11 *Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite Difference, Groundwater Flow Model*, U.S. Geological Survey, Open-File Report 88-729, 1989.

pumped is set at 160 acre-feet per year, and the pumping rate is set to be continuous at 19,094.79 cubic feet per day. This volume of groundwater is approximately the average amount of water pumped in one year to irrigate a quarter section of crop. A gravity irrigated system would pump slightly more volume on average, and a pivot irrigated system would pump slightly less volume on average, based on the District's records of irrigation water use. Although irrigation systems typically operate at a higher pumping rate, are operated on an intermittent pumping schedule, and only operate for a few months per year, a continuous lower pumping rate is used to simplify the modeling process. The volume of water pumped per year would be the same with either continuous or transient pumping schedules. The continuous pumping schedule is not expected to give significantly different results than a transient pumping schedule would yield. Some comparisons of continuous and transient pumping were made to confirm this conclusion.

Recharge Module

Recharge is modeled as an areal source of inflow to the aquifer, and includes the amount of precipitation that percolates from the surface through Layer 1 into Layer 2. The recharge rate used in this model, in feet per day, is interpolated from the COHYST Eastern Model, pre-development period, scatter point data set. The scatter point file is derived from the COHYST EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is imported to the MODFLOW model recharge array. The recharge point of application option is set to the highest active layer at each grid cell. For this model, the minimum recharge rate is 0.000222 feet per day (0.97 inches per year), and the maximum rate is 0.000557 feet per day (2.44 inches per year). The mean rate is 0.000222 feet per day (0.972 inches per year). The recharge rate is held constant throughout the modeled time period, and does not vary from stress period to stress period.

Evapotranspiration Module

Evapotranspiration (ET) is modeled as the amount of groundwater extracted from the aquifer by rooted vegetation, and then evaporated from the plant canopy to the atmosphere external from the model. For this model ET is considered to be an areal sink; i.e., outflow from the model space. The ET rate data set used in this model is interpolated from the COHYST Eastern Model pre-development data set. A scatter point file is produced from the COHYST

EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is then imported to the MODFLOW model ET array. The point of ET withdrawal is the top of Layer 1, and the extinction depth is set at a specified depth (nominally 7 feet) below the top of Layer 1. For this sub-regional model, the minimum ET rate is 0.00 feet per day, and the maximum rate is 0.002993 feet per day (13.1 inches per year). The rate of evapotranspiration is held constant throughout the modeled time period, and does not vary from stress period to stress period.

Wetland areas, mostly located near the Platte River, are treated as groundwater sinks, where groundwater can be removed from the model space by plant evapotranspiration. The evapotranspiration rate, extinction depth, and active ET layer are interpolated to the model 2D grid from COHYST EMU scatter point data sets. Areas that have potential for significant evapotranspiration are selected using 1997 land use mapping data for wetlands (Dappen and Tooze, 2001), and also by defining areas where the depth to groundwater is on average 7 feet or less below land surface, according to USGS long-term depth to water data (U.S. Geological Survey National Water Information System, 1999).

Boundary Conditions

The model is bounded vertically by land surface at the top of Layer 1 and bedrock at the bottom of Layer 5. The model is bounded horizontally by fixed flow boundaries. A fixed flow boundary is a boundary where the flow is specified prior to the simulation and held constant throughout the simulation (McDonald and Harbaugh, 1988). At fixed flow boundaries the simulated water level can change, but flow across the boundary does not change. The northern model boundary is aligned with the Loup River and the southern boundary is aligned with the Little Blue River and southern boundary of Adams County. The eastern model boundary is aligned with the eastern boundaries of York and Polk Counties, and the western boundary is aligned with the western boundaries of Hall and Adams Counties, as shown on Figure 1. The rate of flow through each model boundary, in cubic feet per day, is calculated using the Darcy Equation.

EQ. 2 $$Q_n = k_n \times i_n \times A_n$$

For each boundary arc "n"

Q_n = fixed rate of flow through the boundary, ft^3/d

k_n = weighted horizontal hydraulic conductivity, ft/d

i_n = gradient of the 1950 groundwater surface perpendicular to the boundary flow plane, ft/ft

A_n = cross sectional area of the flow plane at the boundary, ft^2

Each layer's thickness determines the relative weight given to each layer's hydraulic conductivity for this calculation. The calculated boundary flow is distributed evenly over the saturated thickness between the groundwater level and the base of the aquifer at each boundary arc. Appendix A contains calculations and supporting documents used to compute boundary fixed flows. A boundary flow is not computed for Layer 1, since it is a silty clay layer generally representing the unsaturated zone which overlays the saturated zone.

Model Flow Simulation

The MODFLOW software has several packages (BCF, LPF, and HUF) available for calculating conductance coefficients and groundwater storage parameters to be used in the finite-difference equations that calculate flow between cells. The Layer Property Flow (LPF) package is selected as the internal flow calculation methodology for this model. The LPF package reads input data for hydraulic conductivity and global top and bottom elevation data for each cell (layer). Transmissivity is calculated for each cell at the beginning of each iteration of the flow equation matrix solution process. The LPF package calculates leakance between layers using the vertical hydraulic conductivity, based on estimated anisotropic ratio K_x/K_z, and distance between nodes obtained from global elevation data.

Flow Equation Solver

The MODFLOW software has several linear differential equation "solver" packages (SIP1, PCG2, SCR1, and GMG) available. For this model, the pre-conditioned conjugate-gradient[12] (PCG2) package is selected to solve the linear finite difference equation matrix. For a transient groundwater model, the solution matrix is expressed as shown in EQ. 3, where [A] is the coefficient matrix, [x] is a vector of hydraulic heads, and [b] is a vector of defined flows, associated with head-dependent boundary conditions and storage terms at each grid cell.

EQ. 3
$$[A] \bullet [\vec{x}] = [\vec{b}]$$

The matrix is solved iteratively until both head-change and residual convergence criteria are met. The convergence criteria are too large if the global groundwater flow budget discrepancy is unacceptably large. In general, a global budget discrepancy less than one percent is considered acceptable. Convergence criteria for this model, specified in the input options for the PCG2 module, are 0.5 foot for heads and 10.0 ft^3/d for flow residual. The iteration parameters are not specified, but rather are calculated internally.

Aquifer Characteristics

Aquifer properties are input for each layer, including horizontal hydraulic conductivity (K_x), vertical anisotropic ratio (K_x/K_z) or vertical hydraulic conductivity K_z, horizontal anisotropic ratio (K_x/K_y), Specific Storage (S_s), and specific yield (S_y). The procedures used to estimate parameter values for each layer are described in the COHYST hydrostratigraphic Units Characterization Report[13].

<u>Hydraulic Conductivity K_x</u>

Test well logs, interpreted by Reed and Piskin[14], are the basis for horizontal hydraulic conductivity values used in this groundwater model and the COHYST eastern regional model. The interpreted values for each layer are weighted according to layer thickness, and the weighted average value of K_x is then determined for each model layer at each test well location. The

12 P. Concus, G. H. Golub, and D. P. O'Leary, A Generalized Conjugate Gradient for the Numerical Solution of Elliptical Partial Differential Equations, Academic Press, 1976.

13 J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, *Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report*, November 2004.

14 E. C. Reed and R. Piskin, unpublished report, University of Nebraska Conservation and Survey Division.

process used to weight the values is written in a computer code called *Geoparm*[15]. A 2D data set is then created by interpolating the computed values. The 2D data set is then used to set the MODFLOW array of values for each layer.

Anisotropic Ratios

As described previously in this report, the vertical anisotropic ratio, K_x/K_z , is estimated to be 10.0 for all layers at each grid cell, unless pump testing indicates a different ratio, and the horizontal anisotropic ratio, K_x/K_y, is estimated to be 1.0.

Specific Yield S_y

Data compiled by USGS, and summarized by Reed and Piskin, is the basis for specific yield values used in this groundwater model and the COHYST eastern regional model. As discussed in the Hydrostratigraphic Units Report, specific yield values are interpreted for each layer material classification. The interpreted values are then weighted using the Geoparm program to establish specific yield for each model layer at each test well location. The computed values are then interpolated to the model's 2D grid for each model layer. The 2D data sets are then used to set the MODFLOW array values for each layer.

Specific Storage Ss

All layers in this model are considered to be unconfined; however, the LPF simulation options available in MODFLOW are either confined or convertible. The convertible option is selected for all layers, and the specific storage for all layers, except Layer 1, is set to $2.1e^{-3}$; this value is based on discussions with UNL Conservation and Survey[16] and takes into account low potential for changes in aquifer storage due to height of overburden or changes in hydraulic head. The specific storage for Layer 1 is set to 0.16, the estimated specific yield, since this layer is always unconfined, and cannot be converted to confined.

Specific storage is the volume of water per unit volume of *confined* saturated aquifer that is absorbed, or expelled, due to changes in pressure within the aquifer. Overburden tends to

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15 R. Kern, *Nebraska Cooperative Hydrology Study Computer Program Documentation GeoParam - Hydraulic Conductivity from Well Logs*, Nebraska Department of Natural Resources.

16 Personal communication with Xun Hong Chen, University of Nebraska, Conservation and Survey Division.

consolidate the aquifer (reduce storage volume), and hydraulic pressure head tends to offset consolidation (increase storage volume).

Storativity for a *confined* layer is equal to the product of specific storage and layer thickness. Storativity for an *unconfined* layer is equal to the specific yield plus the product of groundwater depth and specific storage.

PRE-DEVELOPMENT PERIOD

Geologic and hydrogeologic layer parameters used in this model are derived from calibrated COHYST eastern regional model (EMU) data. The EMU was calibrated for the pre-groundwater development period by varying and adjusting evapotranspiration, recharge, hydraulic conductivity, properties at horizontal flow boundaries, and streambed conductances. For this model the evapotranspiration, recharge and horizontal hydraulic conductivity are interpolated from EMU scatter point files. Streambed conductances and vertical hydraulic conductivities are adjusted at some locations based on recent testing conducted by the University of Nebraska Conservation and Survey. Fixed flows at boundaries are computed for each boundary arc as previously described. Observed water levels, measured between 1946 and 1955, are used to establish the starting head values.

Observed water levels used to establish starting heads are from a period of relatively stable conditions. Observation points were selected as being representative of pre-groundwater development, and only the most reliable data within 4-mile by 4-mile grid cells were selected (by COHYST modelers) for EMU calibration. This selection process prevents a cluster of closely spaced observation wells from dominating the calibration process. After screening values in all of the 4 by 4-mile cells, a few points that appeared to have large errors in location or land-surface elevation were excluded from the calibration data set. The starting heads file for this model is based on a sub-set of the EMU calibration data set that contains 209 of the observation points.

The ability of this model to represent a 50-year period of pre-groundwater development conditions is evaluated by comparing the percent discrepancy in global groundwater flow budget, as well as the mean difference, mean absolute difference, and root mean square of the differences between observed pre-development groundwater levels at the beginning and end of a 50-year computer run without well development.

Mean Difference

The mean difference (MD) of observed and simulated water levels is defined in EQ.4. The variable h_0 is the observed water level and h_s is the simulated water level at each of the n observation points. The mean difference is used here as a measure of overall bias in calibration, and as such should be close to zero at calibration.

EQ.4 $$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_0 - h_s\right)_i$$

Mean Absolute Difference

The mean absolute difference (MAD) of observed and simulated water levels is defined in EQ.5. The MAD is used here to evaluate the overall model calibration, since positive and negative differences do not cancel each other. All differences are given an equal weight, so a few measurements with large differences will not dominate the result.

EQ.5 $$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|h_0 - h_s\right|_i$$

MODFLOW calculates the water level changes as draw-downs, therefore positive changes are declines and negative changes are rises.

Root Mean Square Difference

The root mean square difference (RMSD), also referred to as the quadratic mean, is defined in EQ. 6. This statistic is the standard deviation of the differences between observed groundwater levels and groundwater levels produced by the model, for the pre-development period. Assuming that the differences between observed and modeled water levels are normally distributed about the mean difference, the standard deviation gives a measure for determining the range within which the differences can be expected to occur. Statistically, 68.27% of the differences are expected to occur within MD ± RMSD, and 95.45% of the differences are expected to occur within MD ± (2)(RMSD).

EQ. 6 $$RMSD = \left[\frac{1}{n}\sum_{1}^{n}\left(h_s - h_0\right)_i^2\right]^{0.5}$$

PRE-DEVELOPMENT MODEL - WITHOUT PUMPING

Starting heads for the pre-development model are obtained by interpolating the observed pre-development water levels to the model 2D grid, which is then imported to the MODFLOW model starting head data set. The observation data points are also imported to the model so that heads computed by the model can be compared to the starting heads for the purpose of evaluating groundwater level changes over the 50-year period. Figures 2 and 3 show the locations of water level observation points, water level contours, and statistical variation at each observation point for the starting heads and 50-year model run. Statistical variations are shown in 10 feet increments; green indicates variation from 0 to 10 feet, yellow indicates variation from 10 to 20 feet, and red indicates variation from 20 to 30 feet. If the indicator is above the line, the computed water level is higher than observed, and if the indicator is below the line the computed water level is lower than observed at that observation point. The mean difference between observed and interpolated water levels, for both starting heads and 50-year model run, is 0.240 feet, the mean absolute difference is 1.376 feet, and the root mean square difference is 2.235 feet. Statistically it can be expected that approximately 95% of the differences between observed and computed water levels will occur within ± 2.235 feet of the mean difference.

The global groundwater inflow and outflow budgets, without well development, are shown in Tables 1 and 2 for the 50-year model run.

TABLE 1

MODEL INFLOW VOLUMETRIC BUDGET

Inflow From	Inflow Volume (KAF)	Inflow Rate (KAF / Yr.)	Percent of Inflow (%)
Storage	19,088	382	52.1
Fixed Flow Boundary	2,324	46	6.4
Platte River	4,388	88	12.0
Recharge	10,781	216	29.5
Total Inflow	36,580	732	100

TABLE 2

MODEL OUTFLOW VOLUMETRIC BUDGET

Outflow From	Outflow Volume (KAF)	Outflow Rate (KAF / Yr.)	Percent of Outflow (%)
Storage	22,196	444	60.7
Fixed Flow Boundary	5,599	112	15.3
Platte River	106	2	0.3
Evapotranspiration	8,681	174	23.7
Total Outflow	36,582	732	100

For the 50-year no well development scenario, the model calculates flow from the Platte River to the underlying aquifer at an average rate of 86 acre-feet per year within the model boundaries. This river to aquifer flow, without pumping, is the baseline for computing induced river to aquifer flow due to groundwater pumping. The global groundwater flow budget discrepancy is less than 0.01 percent.

HYDROLOGICALLY CONNECTED AREA

The portion of the Upper Big Blue Natural Resources District that is considered to be "hydrologically connected" to the Platte River, is that area contained between the Platte River, the Upper Big Blue NRD boundary, and the 10% / 50 year line. Groundwater pumping wells contained within this area are determined by the model to have the potential for inducing additional flow from the Platte River to the underlying aquifer by an amount of at least 10 percent of the volume pumped over a 50-year period. The increase in flow from the river to the aquifer is presented in terms of the "global" model volumetric budget; i.e., the water pumped from the well causes an increase in the mass of water moving from the river to the aquifer, but does not address the transport issues, such as source path or age of water pumped.

A baseline model run, without a pumping well, establishes the volume of water moving from the river to the aquifer due to non-pumping gradients. Independent model runs are then made for each new location of the single pumping well. The well is placed at the center of a grid

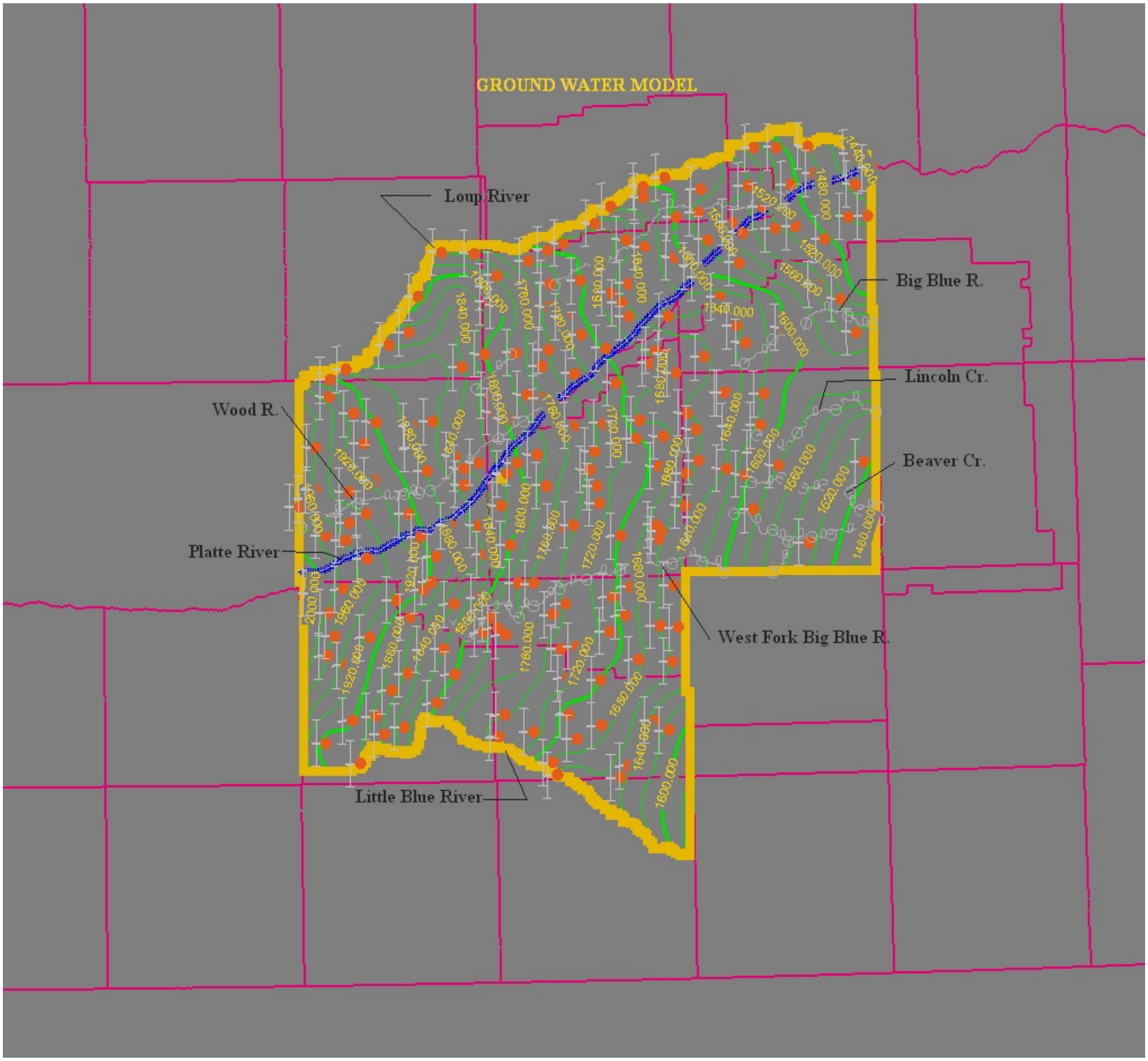


FIGURE 2

PRE-DEVELOPMENT G.W. LEVELS

STARTING HEADS

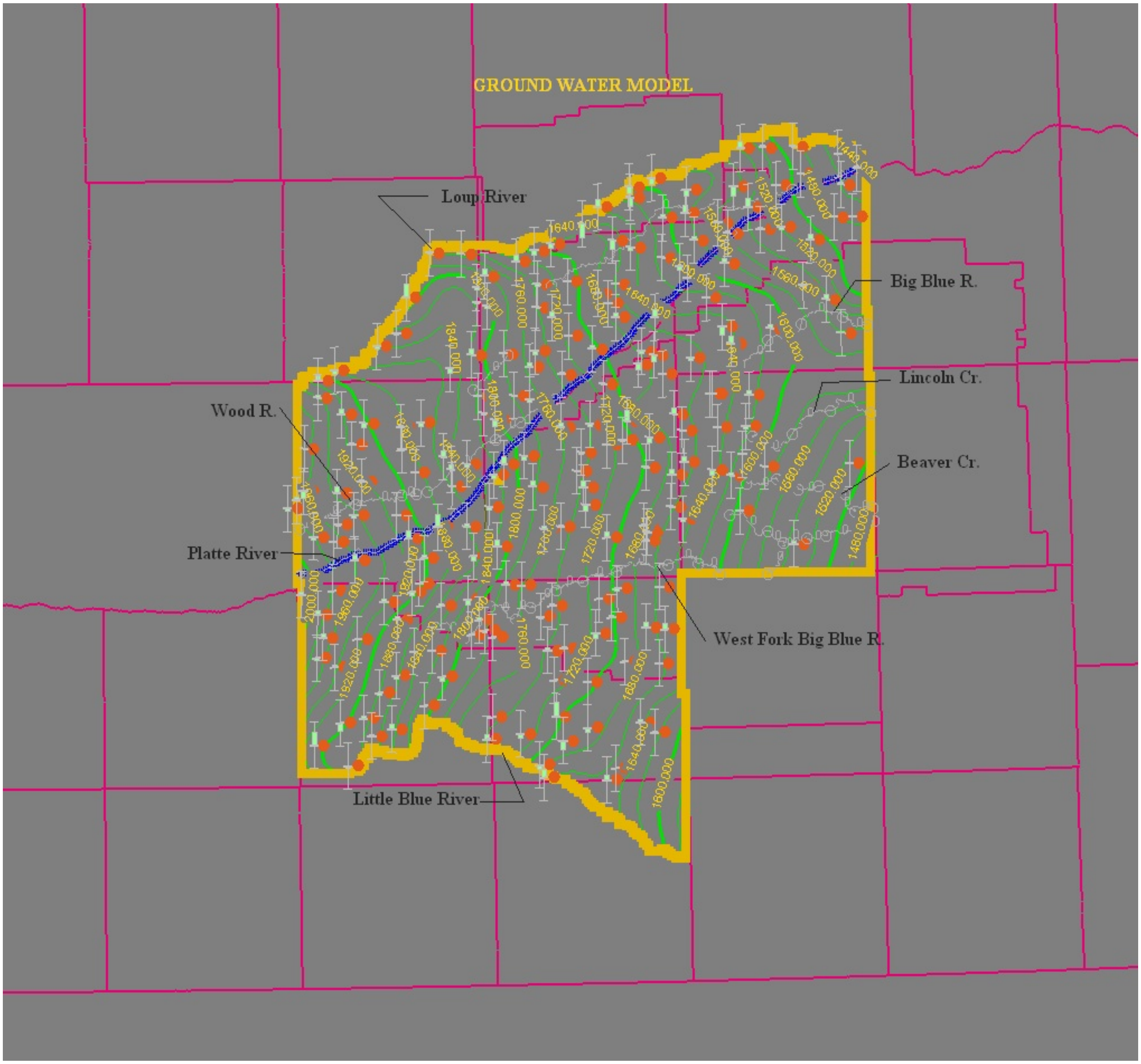


FIGURE 3

FIFTY YEAR MODEL G.W. LEVELS

CHANGES AT OBSERVATION WELLS

cell, and the well screen is assumed to be in Layer 2 for each run. The global volumetric budgets at the end of the 50th stress period are compared with and without pumping, and the difference in river flow into the model is used to determine the volume of water induced from the river to the aquifer due to pumping.

10% / 50-Year Boundary Determination

The 10% / 50-year boundary is determined by evaluating groundwater pumping along transects, spaced approximately 1 mile apart and perpendicular to the Platte River. Transect cells that lie on either side of the boundary line are interpolated linearly to determine the actual coordinates[17] of the boundary line on each transect. Table 3 is a summary of coordinates used to establish the 10 / 50 boundary line within the Upper Big Blue NRD. Figures 4 and 5 are graphical representations of the 10% / 50-year boundary line location.

TABLE 3

10% / 50-YEAR BOUNDARY WITHIN THE UPPER BIG BLUE NRD

STATE PLANE COORDINATES

Easting	Northing
2115914.5307	368243.7495
2119524.3678	373861.1446
2122067.5150	377912.3125
2124670.4467	383220.1545
2128158.4452	387639.9242
2132229.2680	391476.8695
2135624.8026	395989.1030
2139012.1417	400512.5376
2140957.5416	402519.5190
2145105.3989	406279.4298
2149493.4078	411118.6532
2153212.8089	415307.0203

[17] Coordinate system is North American Datum, 1983, Nebraska State Plane, Feet.

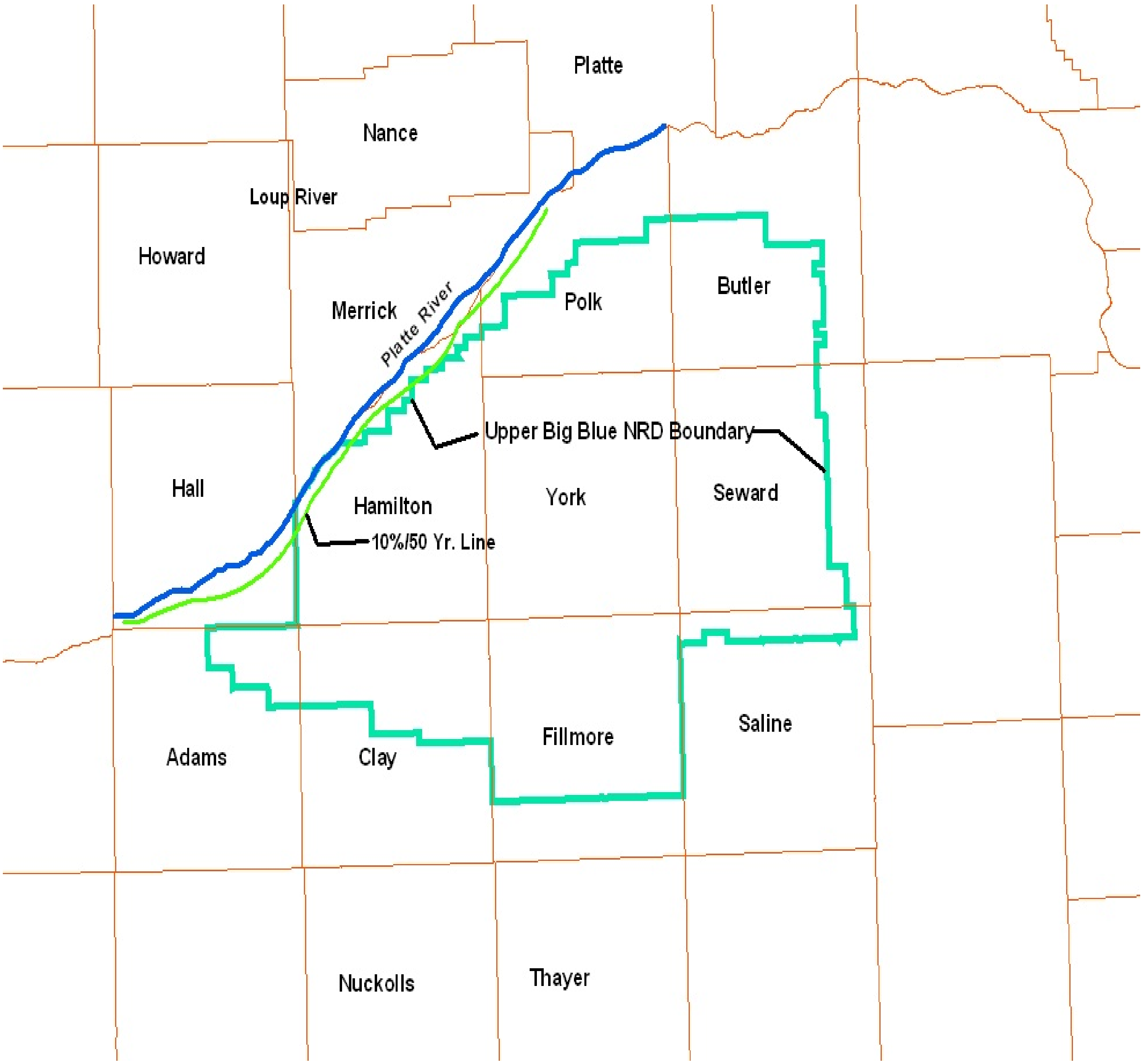


FIGURE 4

10% / 50-YEAR LINE PLATTE RIVER

HALL, HAMILTON AND POLK COUNTIES

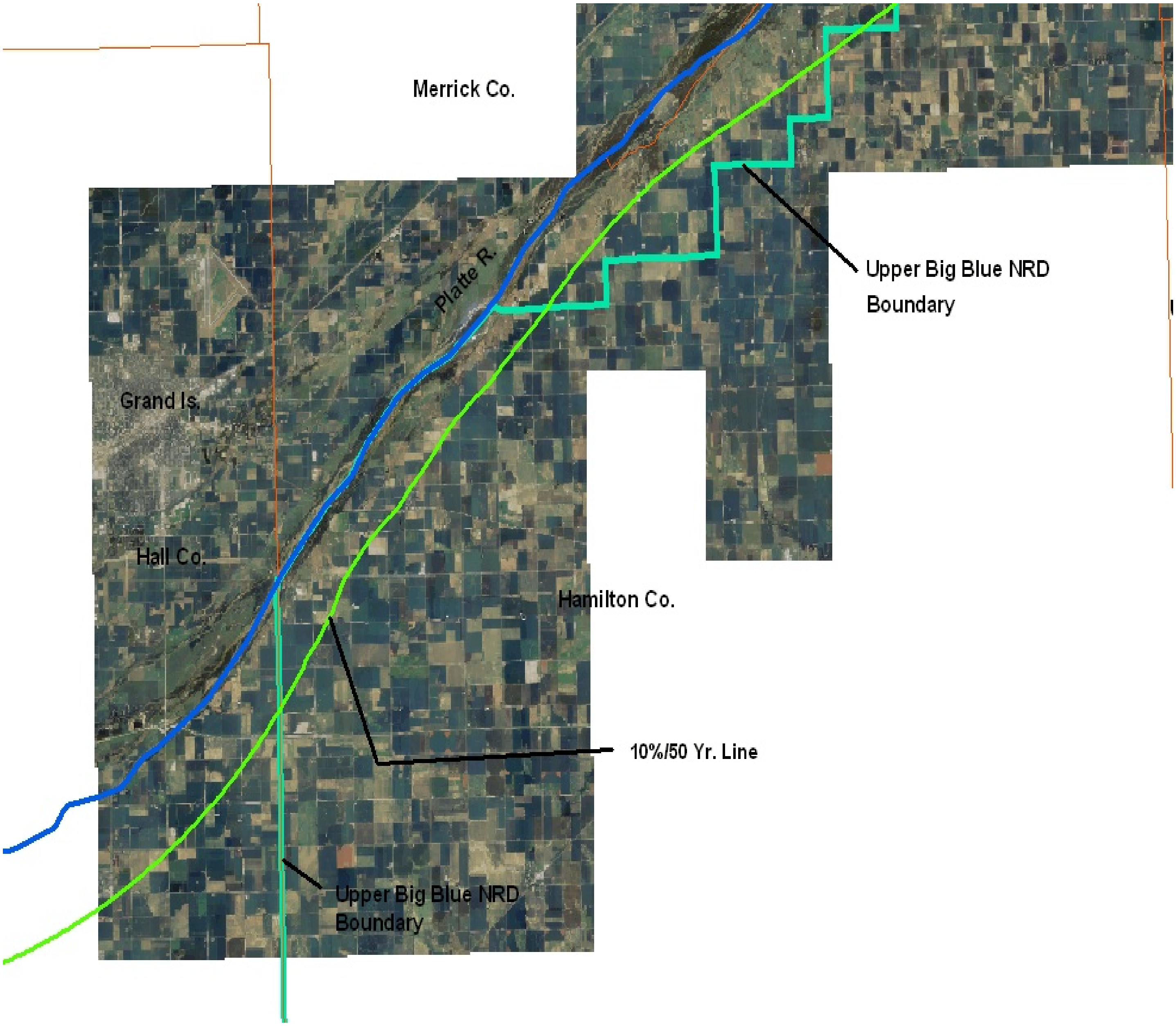


FIGURE 5

10% / 50-YEAR LINE PLATTE RIVER

WITHIN THE UPPER BIG BLUE NRD BOUNDARY

APPENDIX A

MODEL BOUNDARY

FIXED FLOW CALCULATIONS

Ground Water Model
Fixed Flow Boundary Estimates
Southern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
80	-0.000869	90	0.000000	44.3	0.000	1880.0	1660.4	219.6	46,017	10,105,333	0
38	-0.00208	90	0.000000	69.6	0.000	1833.0	1589.0	244.0	28,340	6,914,960	0
39	-0.00208	0	-0.002080	54.4	-0.113	1805.0	1557.6	247.4	27,847	6,889,348	-779,543
82	-0.00129	90	0.000000	59.8	0.000	1775.0	1551.3	223.7	41,096	9,193,175	0
23	-0.00089	90	0.000000	109.5	0.000	1740.0	1587.2	152.8	16,903	2,582,778	0
40	-0.000968	90	0.000000	84.0	0.000	1728.0	1600.4	127.6	30,987	3,953,941	0
41	-0.002924	72	-0.000904	144.8	-0.131	1680.0	1575.0	105.0	24,486	2,571,030	-336,384
1	-0.002000	35	-0.001638	192.1	-0.315	1650.0	1566.5	83.5	24,920	2,080,820	-654,872
42	0.001481	24	0.001353	93.3	0.126	1660.0	1562.9	97.1	35,838	3,479,870	439,268
43	0.002000	33	0.001677	82.0	0.138	1632.0	1467.0	165.0	35,201	5,808,165	798,866
36	0.002105	67	0.000822	94.2	0.077	1600.0	1410.6	189.4	31,263	5,921,212	458,766

Total Estimated 1950 Boundary Flow = -73,898

Ground Water Model
Fixed Flow Boundary Estimates
Northern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
79	-0.002609	54	-0.001534	34.9	-0.054	1910.0	1698.3	211.7	64,788	13,715,620	-734,063
66	-0.001696	49	-0.001113	178.6	-0.199	1735.0	1687.3	47.7	30,975	1,477,508	-293,616
67	-0.001885	70	-0.000645	54.3	-0.035	1790.0	1635.3	154.7	46,543	7,200,202	-252,062
78	-0.002924	0	0.000000	36.2	0.000	1775.0	1608.3	166.7	9,834	1,639,328	0
49	-0.002924	0	0.000000	19.3	0.000	1765.0	1611.0	154.0	10,939	1,684,606	0
50	-0.002924	26	-0.002628	11.1	-0.029	1750.0	1605.0	145.0	18,572	2,692,940	-78,557
75	-0.002924	26	-0.002628	18.7	-0.049	1730.0	1598.7	131.3	14,537	1,908,708	-93,803
68	-0.002924	26	-0.002628	35.5	-0.093	1715.0	1593.3	121.7	37,939	4,617,176	-430,767
69	-0.002827	29	-0.002473	69.4	-0.172	1670.0	1596.3	73.7	33,140	2,442,418	-419,107
70	-0.002827	29	-0.002473	121.3	-0.300	1630.0	1544.3	85.7	37,584	3,220,949	-966,028
71	-0.002827	29	-0.002473	175.5	-0.434	1595.0	1505.0	90.0	36,660	3,299,400	-1,431,717
77	-0.002310	63	-0.001049	121.7	-0.128	1585.0	1468.7	116.3	51,693	6,011,896	-767,292
72	-0.002310	63	-0.001049	53.8	-0.056	1505.0	1430.3	74.7	40,925	3,057,098	-172,485
37	-0.002310	63	-0.001049	17.7	-0.019	1480.0	1417.5	62.5	3,374	210,875	-3,914
74	-0.001571	51	-0.000989	21.5	-0.021	1475.0	1409.0	66.0	31,526	2,080,716	-44,228
73	-0.001571	51	-0.000989	18.9	-0.019	1445.0	1365.7	79.3	27,643	2,192,090	-40,961

Total Estimated 1950 Boundary Flow = -5,728,601

Ground Water Model
Fixed Flow Boundary Estimates
Eastern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
27	-0.001333	34	-0.001105	13.3	-0.015	1440.0	1323.2	116.8	11,533	1,347,054	-19,799
1	-0.001097	59	-0.000565	23.8	-0.013	1443.0	1318.4	124.6	9,800	1,220,753	-16,415
5	-0.001296	81	-0.000203	22.8	-0.005	1455.0	1304.0	151.0	15,820	2,388,820	-11,042
2	-0.001296	81	-0.000203	14.0	-0.003	1480.0	1298.4	181.6	23,550	4,276,680	-12,139
3	-0.002455	41	-0.001853	12.8	-0.024	1487.0	1302.1	184.9	26,940	4,981,206	-118,134
4	0.002261	0	0.000000	20.7	0.000	1555.0	1260.0	295.0	51,610	15,224,950	0
6	-0.002665	75	-0.000690	21.4	-0.015	1570.0	1207.1	362.9	33,086	12,006,909	-177,230
19	-0.001964	50	-0.001262	31.6	-0.040	1505.0	1206.0	299.0	26,280	7,857,720	-313,468
18	-0.001399	29	-0.001224	35.8	-0.044	1485.0	1210.9	274.1	34,070	9,338,587	-409,073
17	-0.001399	29	-0.001224	52.3	-0.064	1473.0	1191.8	281.2	8,860	2,491,432	-159,436
25	-0.001399	29	-0.001224	32.8	-0.040	1465.0	1267.9	197.1	24,300	4,789,530	-192,222
16	-0.001565	74	-0.000431	24.3	-0.010	1472.0	1318.6	153.4	18,560	2,847,104	-29,844
15	-0.001565	74	-0.000431	62.0	-0.027	1500.0	1318.3	181.7	19,950	3,624,915	-96,949
14	-0.001565	74	-0.000431	124.9	-0.054	1520.0	1310.1	209.9	13,430	2,818,957	-151,881
13	-0.001565	74	-0.000431	131.8	-0.057	1540.0	1308.8	231.2	12,850	2,970,920	-168,911
12	-0.001565	74	-0.000431	138.2	-0.060	1552.0	1328.8	223.2	10,080	2,249,856	-134,127
11	-0.001565	74	-0.000431	100.4	-0.043	1570.0	1371.8	198.2	13,820	2,739,124	-118,631
10	-0.001565	74	-0.000431	52.5	-0.023	1590.0	1409.6	180.4	8,470	1,527,988	-34,604
9	-0.001565	90	0.000000	45.2	0.000	1600.0	1425.0	175.0	5,450	953,750	0
8	-0.001565	90	0.000000	35.1	0.000	1615.0	1449.2	165.8	12,070	2,001,206	0
7	-0.001565	90	0.000000	22.4	0.000	1630.0	1489.1	140.9	9,460	1,332,914	0
26	-0.001399	90	-0.001399	23.4	-0.033	1638.0	1512.3	125.7	18,456	2,319,919	-75,946
20	-0.001399	90	-0.001399	72.3	-0.101	1640.0	1471.9	168.1	28,943	4,865,318	-492,116
21	-0.001399	90	-0.001399	30.0	-0.042	1647.0	1506.0	141	30,370	4,282,170	-179,723
22	-0.001794	41	-0.001354	77.2	-0.105	1595.0	1388.6	206.4	52,830	10,904,112	-1,139,751
23	-0.001696	22	-0.001573	117.6	-0.185	1577.0	1314.5	262.5	14,429	3,787,613	-700,430
24	-0.001555	7	-0.001543	109.1	-0.168	1575.0	1364.0	211	35,841	7,562,451	-1,273,411

Total Estimated 1950 Boundary Flow = -6,025,283

Ground Water Model
Fixed Flow Boundary Estimates
Western Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
1	0.000891	0	0.000891	29.5	0.026	1902.0	1745.3	156.7	10,227	1,602,571	42,123
2	0.001382	45	0.000977	56.5	0.055	1903.0	1782.5	120.5	12,141	1,462,991	80,776
4	0.003388	26.5	0.003032	50.5	0.153	1920.0	1812.4	107.6	9,090	978,084	149,762
12	0.002875	18.4	0.002728	45.0	0.123	1932.0	1811.7	120.3	12,930	1,555,479	190,952
3	0.002964	26.5	0.002653	48.5	0.129	1930.0	1784.8	145.2	13,060	1,896,312	243,961
13	0.002341	34.5	0.001929	54.1	0.104	1955.0	1720.3	234.7	26,130	6,132,711	640,096
5	0.002145	19.3	0.002024	51.6	0.104	1985.0	1694.7	290.3	25,910	7,521,673	785,727
6	0.001969	17.6	0.001877	50.0	0.094	2008.0	1768.2	239.8	40,530	9,719,094	912,056
7	0.001607	45	0.001136	40.7	0.046	2003.0	1818.3	184.7	35,491	6,555,188	303,166
14	0.001786	45	0.001263	31.9	0.040	1982.0	1797.9	184.1	11,750	2,163,175	87,146
8	0.001684	0	0.001684	17.6	0.030	1972.0	1759.4	212.6	34,700	7,377,220	218,649
9	0.001684	0	0.001684	10.0	0.017	1978.0	1731.2	246.8	14,990	3,699,532	62,300
10	0.001752	27.6	0.001553	9.2	0.014	1978.0	1722.8	255.2	10,340	2,638,768	37,693
11	0.001906	56.9	0.001041	19.2	0.020	1960.0	1713.6	246.4	19,299	4,755,274	95,033

Total Estimated 1950 Boundary Flow = 3,849,440

APPENDIX B

RIVER BED CONDUCTANCE

PLATTE RIVER

Platte River
Average Bed Conductance
Between Hwy. 34 And Chapman Bridges
Based On Permeameter Tests and Geoprobe Borings
UNL Conservation and Survey - August 2005

Transect	Site	K_{v1} (ft/d)	K_{v2} (ft/d)	Ecbase (mS/m)	M_1 (ft)	M_2 (ft)	K_v (ft/d)	L (ft)	W (ft)	M (ft)	C (ft^2/d/ft)
A1	NC	78.7	0.056	35	13.8	6.8	0.169	1	1	20.6	0.0082
A2	MC	78.7	0.056	35	15.9	6.9	0.185	1	1	22.8	0.0081
A3	SC	78.7	0.056	35	12.4	13.3	0.108	1	1	25.7	0.0042
B1	NC	109.7	0.056	35	21.6	1.7	0.763	1	1	23.3	0.0327
B2	MC	109.7	0.056	35	10.8	9.5	0.120	1	1	20.3	0.0059
B3	SC	109.7	0.056	35	8.5	8.1	0.115	1	1	16.6	0.0069

Average Unit C = 0.0110 ft^2/d per foot of river reach per foot of river width
Total Conductance C 11.0 ft^2/d per foot of river reach (using a river bed with of 1,000 ft.)

NOTES:
1. NC = North Channel
2. MC = Middle Channel
3. SC = South Channel
4. Site A is located in Sec 29, Twp 11N, Rng 8W, and is upstream from the BNSF railroad bridge over the Platte River near Grand Island
5. Site B is located in the NW^4 Sec 11, Twp 11N, Rng 8W, and is near the upstream from the Chapman Bridge near the intersection of 5th and B Streets
6. K_{v1} = vertical hydraulic conductivity of river bed material with EC log < 35 mS/m
7. K_{v2} = vertical hydraulic conductivity of river bed material with EC log >= 35 mS/m
8. K_v = wighted vertical hydraulic conductivity for total river bed thickness M
9. L = river reach length (use 1.0 ft. for this calculation)
10. W = river bed width (use 1.0 ft. to compute the unit condutance.
Apply total river bed width of 1,000 ft. to determine total bed conductance per linear foot of river reach between Hwy. 34 bridge and Chapman bridge
11. M1 = thickness of the river bed material with EC log < 35 mS/m)
(based on CSD geoprobe resistivity log)
12. M2 = thickness of the river bed material with EC log >= 35 mS/m)
(based on CSD geoprobe resistivity log)
13. M = total river bed thickness ($M_1 + M_2$)
14. Equation for computing river bed conductance

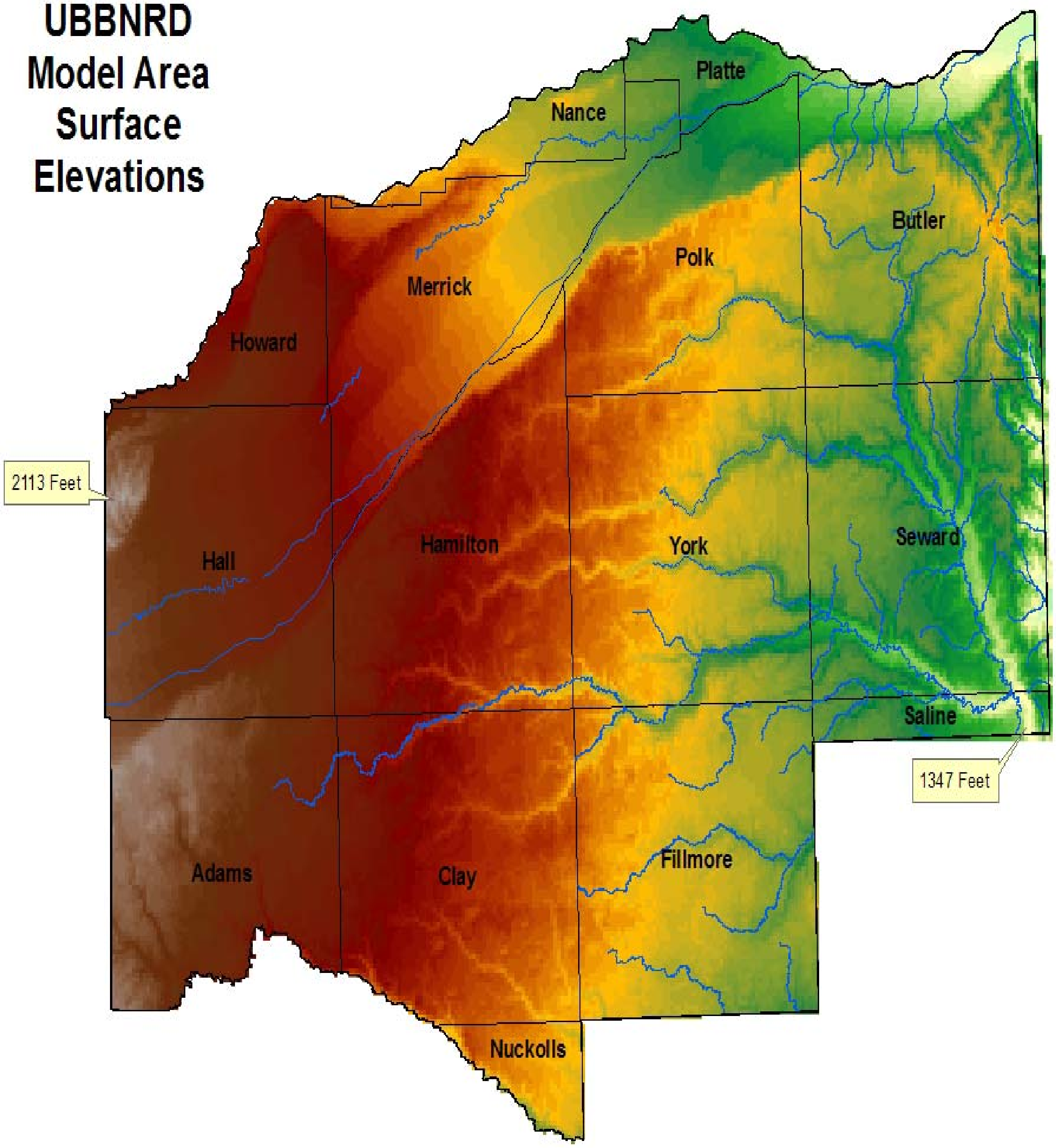
$$C = \frac{K_v \times L \times W}{M}$$

15. Equation for weighting vertical hydraulic conductivity:

$$Kv = \frac{M}{(M_1/K_{v1}) + (M_2/K_{v2})}$$

APPENDIX C
GROUNDWATER LEVEL MAPS
DEPTH TO GROUNDWATER

UBBNRD Model Area Surface Elevations



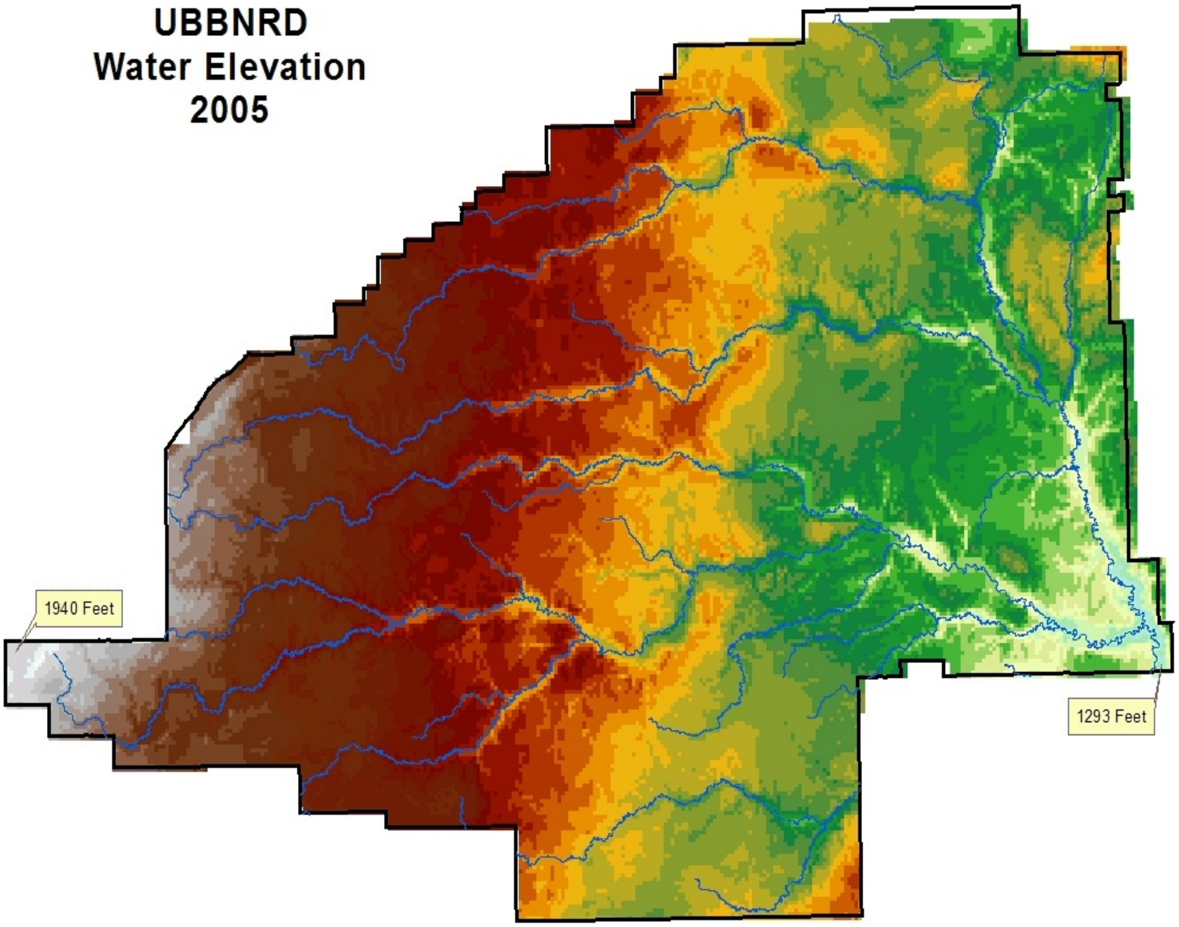


FIGURE 7

GENERAL GROUNDWATER ELEVATION MODEL

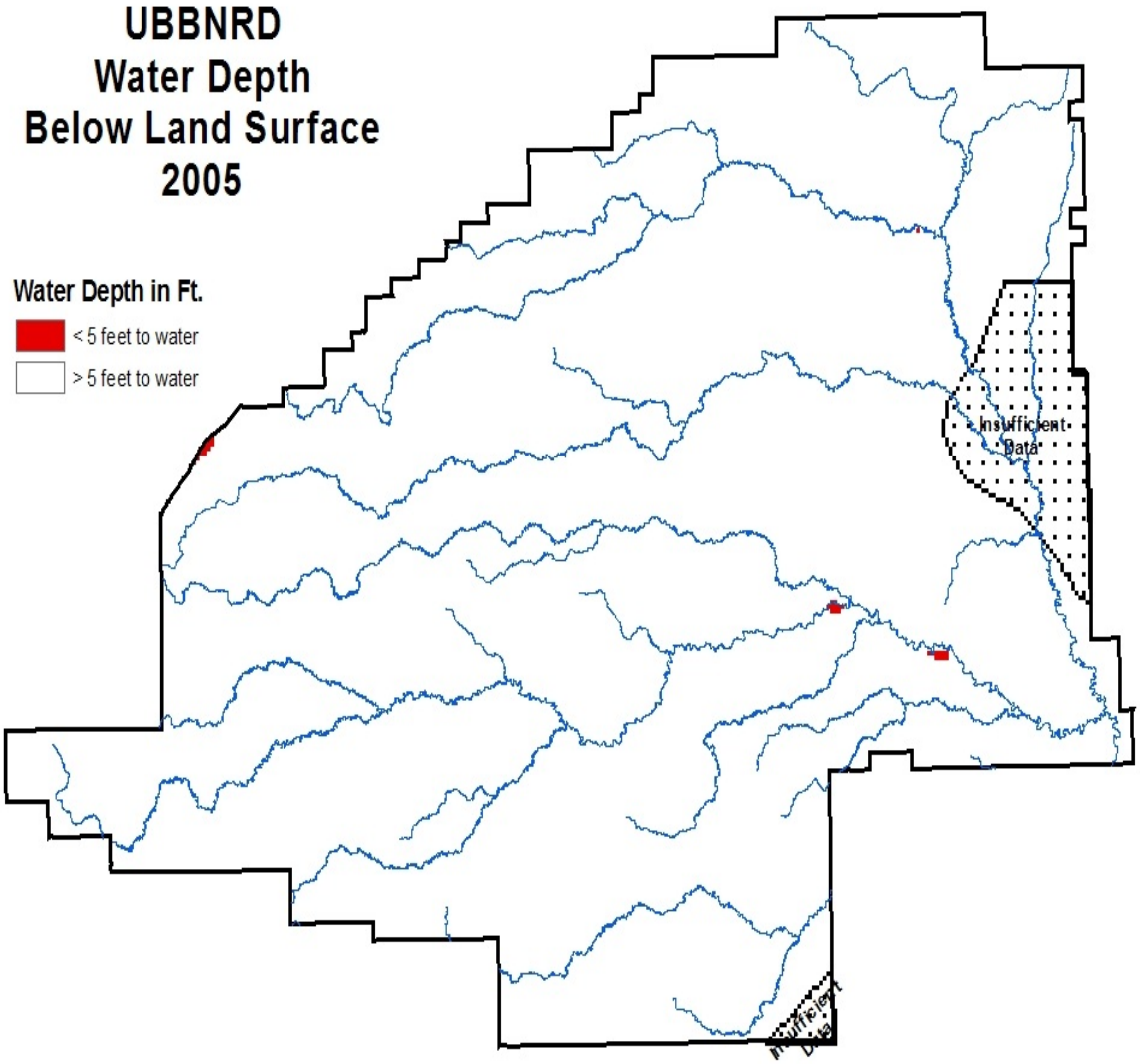


FIGURE 8

GENERAL DEPTH OF GROUNDWATER BELOW LAND SURFACE

science for a changing world

Prepared in cooperation with the Nebraska Department of Natural Resources, and the Upper Elkhorn, Lower Elkhorn, Upper Loup, Lower Loup, Middle Niobrara, Lower Niobrara, Lewis and Clark, and Lower Platte North Natural Resources Districts

Simulation of Ground-Water Flow and Effects of Ground-Water Irrigation on Base Flow in the Elkhorn and Loup River Basins, Nebraska

Scientific Investigations Report 2008–5143

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

Cover: Three-dimensional shaded relief of streams draining the Sand Hills area of Nebraska.

Simulation of Ground-Water Flow and Effects of Ground-Water Irrigation on Base Flow in the Elkhorn and Loup River Basins, Nebraska

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Prepared in cooperation with the Nebraska Department of Natural Resources, and the Upper Elkhorn, Lower Elkhorn, Upper Loup, Lower Loup, Middle Niobrara, Lower Niobrara, Lewis and Clark, and Lower Platte North Natural Resources Districts

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Suggested citation:
Peterson, S.M., Stanton, J.S., Saunders, A.T., and Bradley, J.R., 2008, Simulation of ground-water flow and effects of ground-water irrigation on base flow in the Elkhorn and Loup River Basins, Nebraska: U.S. Geological Survey Scientific Investigations Report 2008–5143, 65 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Crop water usage per unit area	
inches per year (in/yr)	25.4	millimeter (mm/yr)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Simulation of Ground-Water Flow and Effects of Ground-Water Irrigation on Base Flow in the Elkhorn and Loup River Basins, Nebraska

By Steven M. Peterson, Jennifer S. Stanton, Amanda T. Saunders, and Jesse R. Bradley[1]

Abstract

Irrigated agriculture is vital to the livelihood of communities in the Elkhorn and Loup River Basins in Nebraska, and ground water is used to irrigate most of the cropland. Concerns about the sustainability of ground-water and surface-water resources have prompted State and regional agencies to evaluate the cumulative effects of ground-water irrigation in this area. To facilitate understanding of the effects of ground-water irrigation, a numerical computer model was developed to simulate ground-water flow and assess the effects of ground-water irrigation (including ground-water withdrawals, hereinafter referred to as pumpage, and enhanced recharge) on stream base flow.

The study area covers approximately 30,800 square miles, and includes the Elkhorn River Basin upstream from Norfolk, Nebraska, and the Loup River Basin upstream from Columbus, Nebraska. The water-table aquifer consists of Quaternary-age sands and gravels and Tertiary-age silts, sands, and gravels. The simulation was constructed using one layer with 2-mile by 2-mile cell size.

Simulations were constructed to represent the ground-water system before 1940 and from 1940 through 2005, and to simulate hypothetical conditions from 2006 through 2045 or 2055. The first simulation represents steady-state conditions of the system before anthropogenic effects, and then simulates the effects of early surface-water development activities and recharge of water leaking from canals during 1895 to 1940. The first simulation ends at 1940 because before that time, very little pumpage for irrigation occurred, but after that time it became increasingly commonplace. The pre-1940 simulation was calibrated against measured water levels and estimated long-term base flow, and the 1940 through 2005 simulation was calibrated against measured water-level changes and estimated long-term base flow. The calibrated 1940 through 2005 simulation was used as the basis for analyzing hypothetical scenarios to evaluate the effects of ground-water irrigation on stream base flow for 1940 through 2005 and for 2006 through 2045. Simulated base flows were compared for scenarios that alternately did or did not include a representation of the effects of ground-water irrigation. The difference between simulated base flows for the two scenarios represents the predicted effects of ground-water irrigation on base flow.

Comparison of base flows between simulations with ground-water irrigation and no ground-water irrigation indicated that ground-water irrigation has cumulatively reduced streamflows from 1940 through 2005 by 888,000 acre-feet in the Elkhorn River Basin and by 2,273,000 acre-feet in the Loup River Basin. Generally, predicted cumulative effects of ground-water irrigation on base flow were 5 to 10 times larger from 2006 through 2045 than from 1940 through 2005, and were 7,678,000 acre-feet for the Elkhorn River Basin and 14,784,000 acre-feet for the Loup River Basin.

The calibrated simulation also was used to estimate base-flow depletion as a percentage of pumping volumes for a 50-year future time period, because base-flow depletion percentages are used to guide the placement of management boundaries in Nebraska. Mapped results of the base-flow depletion analysis conducted for most of the interior of the study area indicated that pumpage of one additional theoretical well simulated for a future 50-year period generally would result in more than 80 percent depletion when it was located close to the stream, except in areas where depletion was partly offset by reduced ground-water discharge to evapotranspiration in wetland areas. In many areas, depletion for the 50-year future period composed greater than 10 percent of the pumped water volume for theoretical wells placed less than 7 or 8 miles from the stream, though considerable variations existed because of the heterogeneity of the natural system represented in the simulation.

For a few streams, predicted future simulated base flows declined substantially. In two streams, the simulated results indicated that a gaining stream in 2005 would be a losing stream in 2055. For three streams simulated base flows in 2055 were absent. No further base-flow depletion occurred once simulated base flow was absent; therefore, base-flow

[1]Nebraska Department of Natural Resources

depletion as a percentage of the volume pumped more than 50 years declined from the time the stream went dry until the end of the analysis period. Additional depletion as a percentage of pumping would be expected if base flow was present through 2055.

Introduction

In central and eastern Nebraska, the Elkhorn and Loup Rivers provide surface-water flows for irrigation, recreation, hydropower production, and aquatic life. In addition, outflows of the Elkhorn and Loup Rivers merge with the Platte River near Waterloo, Nebraska, and Columbus, Nebraska (fig. 1), respectively, and support in-stream flow appropriations (such as Nebraska Game and Parks Commission In-Stream Appropriation A-17331 (Nebraska Department of Natural Resources, 2008). Outflows from the Elkhorn and Loup Rivers also recharge the aquifer used by large municipal water systems that pump ground water near the Platte River. Pumpage for irrigation, in turn, is vital to agricultural productivity, and hence the livelihood, of the communities in the Elkhorn-Loup Model study area (fig. 1). Recent drought (2000–06) has amplified concerns about the long-term sustainability of surface- and ground-water resources in the area, as well as concerns about the effect of ground-water irrigation on streamflow. Further, newly adopted state legislation requires a sustainable balance between long-term water supplies and uses of surface and ground water (Nebraska Department of Natural Resources, 2007). Thus, the U.S. Geological Survey (USGS), the Nebraska Department of Natural Resources (NDNR), and the Upper Elkhorn, Lower Elkhorn, Upper Loup, Lower Loup, Middle Niobrara, Lower Niobrara, Lewis and Clark, and Lower Platte North Natural Resources Districts (NRDs) (collectively referred to hereinafter as ELM NRDs) agreed to cooperatively study water resources in these basins. The Elkhorn-Loup Model (ELM) study area covers approximately 30,800 square miles (mi^2), and extends from the Niobrara River in the north to the Platte River in the south (fig. 1). The western boundary coincides roughly with the western boundary of the Upper Loup NRD, and the eastern boundary coincides roughly with the approximate location of the westernmost extent of glacial till in eastern Nebraska (Conservation and Survey Division, 2005d). The study will assist NDNR and the ELM NRDs in developing long-term strategies for management of hydrologically connected water supplies.

The goals of the study were to construct and calibrate a regional ground-water flow simulation of the study area, and to use the simulation as a tool to assess the past and future effects of ground-water irrigation on ground-water discharge to streams (hereinafter referred to as base flow). The study is anticipated to proceed in two phases. Phase one, documented in this report, focused mainly on using largely pre-existing data to develop a regional ground-water flow simulation. Phase two is planned to focus on refining the ground-water flow simulation using newly collected data and supporting analyses performed in 2007 and 2008. Both phases are intended to provide information that will assist state and regional agencies with water management efforts.

Purpose and Scope

The purpose of this report is to document the methodology and results of a simulation of ground-water flow and effects of ground-water irrigation on base flow in the ELM area at the completion of its first phase. The goal of the ELM project was to study surface- and ground-water resources in the Elkhorn River Basin upstream from Norfolk, Nebraska, and the Loup River Basin upstream from Columbus, Nebraska (fig. 1). The report describes the construction and calibration of the phase one regional ground-water flow simulation for the study area. Results from simulating hypothetical scenarios of past and future periods for conditions with and without ground-water irrigation are presented and compared. Differences in simulated base flows are interpreted as the effects of ground-water irrigation. Base-flow depletion for a 50-year period is calculated and presented as a percentage of well pumping volumes.

Study Area Description

About 60 percent of the Elkhorn-Loup Model area is overlain by the Nebraska Sand Hills (including Sand Hills lakes) (fig. 2), the largest sand-dune area in the Western Hemisphere (Keech and Bentall, 1971). The Sand Hills consist of various types of sand dunes, mostly stabilized with grasses, frequently with inter-dunal lakes. Soils in the Sand Hills are coarser-grained than in the rest of the ELM area, providing "a far greater rate of recharge than in any other upland area of comparable size in the High Plains region" (Keech and Bentall, 1971). Land in the Sand Hills is largely either undeveloped or used only for grazing livestock; row-crop agriculture is uncommon (Patti Dappen, Center for Advanced Land Management Information Technologies (CALMIT), University of Nebraska-Lincoln, written commun., 2006).

Other topographic regions present in the area are wet meadows and marsh plains, loess hills, river valleys, transitional sandy plains, dissected loess plains, plains, and river breaks (U.S. Environmental Protection Agency, 2003). Areas classified as river valleys or plains typically are flat or gently sloping, and mostly are used for row-crop agriculture.

Major streams in the area are the Elkhorn River and its tributaries upstream from Norfolk, Nebraska, and the Loup River and its tributaries upstream from Columbus, Nebraska (fig. 1). The part of the Elkhorn River Basin in the study area is approximately 2,700 mi^2 in size; the Elkhorn River flows from west-northwest to east-southeast, draining wet meadows, plains, and marshy plains east of the Sand Hills. The Loup River Basin within the study area is approximately 14,500 mi^2 in size and includes numerous large tributary streams (such as

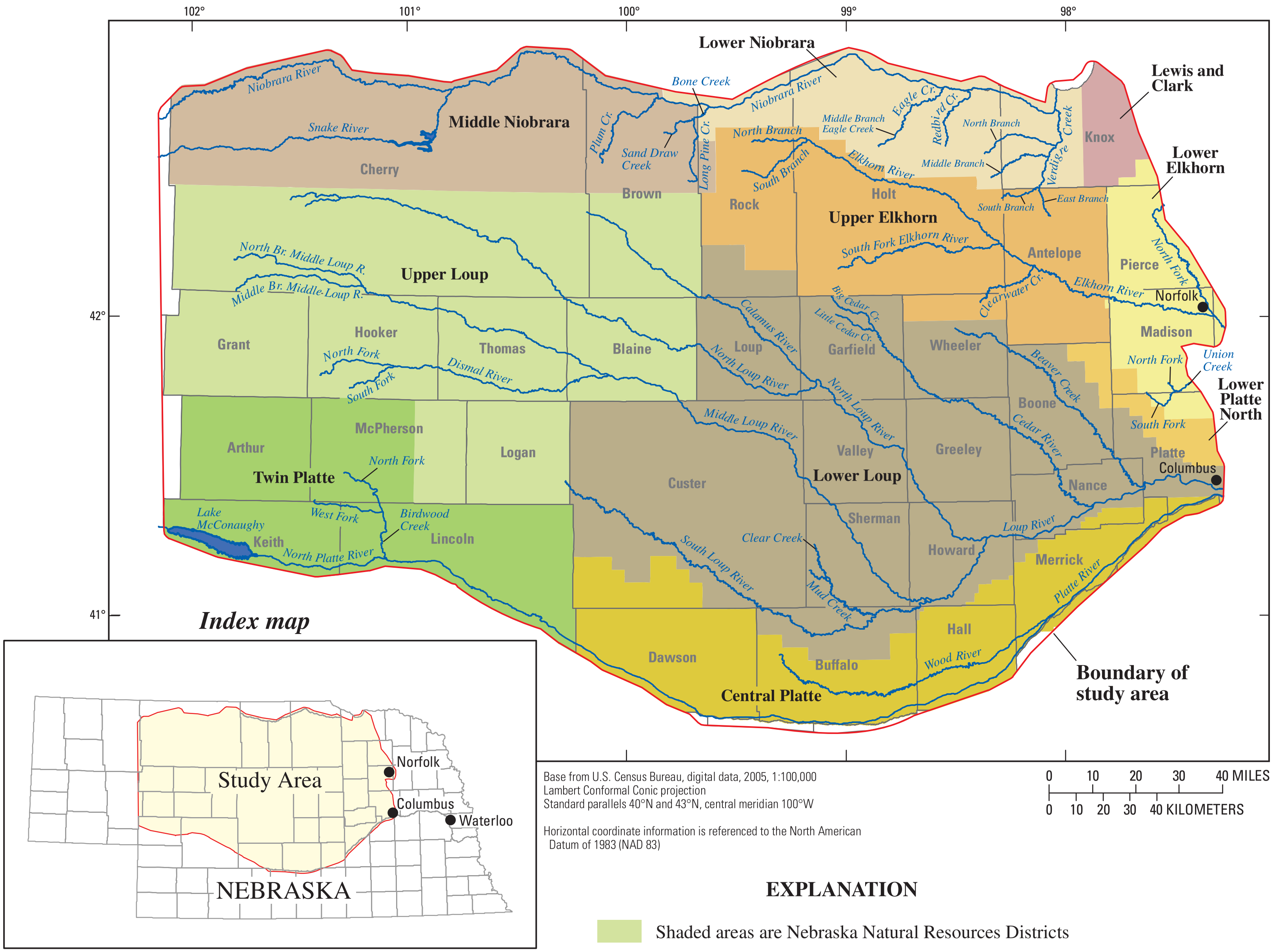


Figure 1. Location of the Elkhorn and Loup River Basins study area (Elkhorn-Loup Model area) in Nebraska, including major streams and Natural Resources Districts.

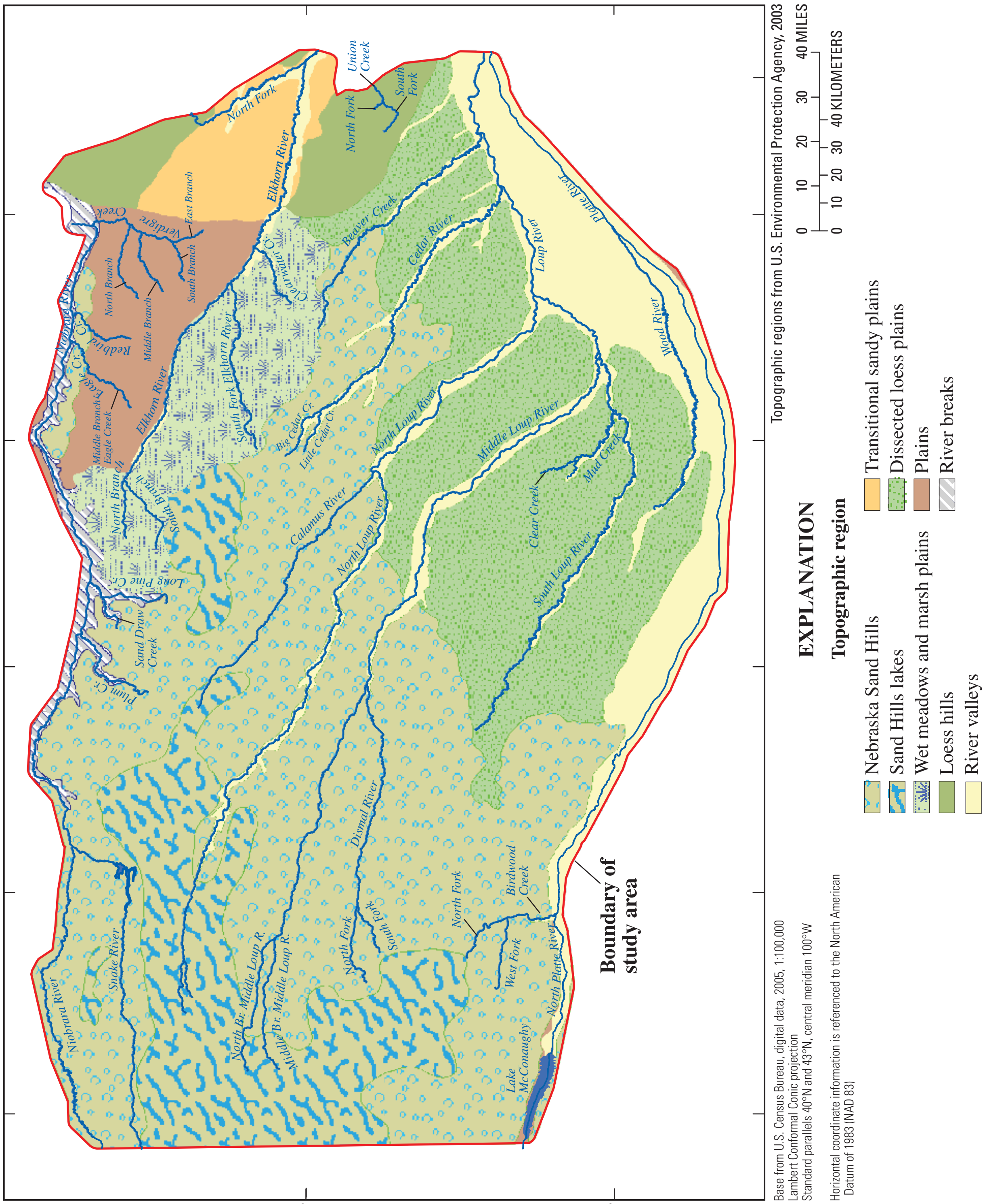


Figure 2. Topographic regions in the Elkhorn and Loup River Basins, Nebraska.

the North Loup River, Middle Loup River, and Cedar River) that originate in or at the boundary of the Sand Hills. Tributaries to the Loup River flow from northwest to southeast draining the Sand Hills and dissected loess plains. The Loup River flows either east or east-northeast through the large river valley region shared with the Platte River to the south.

Water Use and Management

Base flow is the primary component of streamflow in the Elkhorn and Loup River Basins. Based on ongoing surface-water modeling work for the ELM area (Kellan Strauch, U.S. Geological Survey, oral commun., 2007) approximately 66 percent of the annual flow in the Elkhorn River is derived from ground-water discharge, whereas about 87 percent of the Loup River total annual flow is derived from ground-water discharge. Szilagyi and others (2003) also reported that base flow composed a large part of total flow in this area, ranging from more than 90 percent of total flow in the central Sand Hills to at least 50 percent in the rest of the ELM area, though values were not reported for specific streams.

Agriculture is vital to the livelihood of the communities within the ELM area, and irrigation is common because of large rates of evaporation and small rates of precipitation (fig. 3). In 2005, there were more than 2.8 million acres of irrigated agriculture within the ELM area (Patti Dappen, CALMIT, University of Nebraska-Lincoln, written commun., 2006). Surface water was used to irrigate more than 488,000 acres (Rick Vollertsen, Nebraska Department of Natural Resources, written commun., 2005; Allan Schmidt, Middle Loup Public Power and Irrigation District, written commun., 2006; Mel Brozek, Sargent Irrigation District, written commun., 2006; Jack Wergen, Bureau of Reclamation, written commun., 2006; Darwin Lee, Farwell Irrigation District, written commun., 2006; William Peck, U.S. Bureau of Reclamation, written commun., 2006; Ron Wolfe, Twin Loups Irrigation District, written commun., 2006); ground water was used to irrigate the remaining 2.3 million acres. Most surface-water irrigation takes place in the Loup River Basin, whereas no large irrigation diversions occur in the Elkhorn River Basin.

According to the Nebraska Natural Resources Commission (1998), total annual ground-water use in 1995 was 634,000 acre-feet (acre-ft) and 830,000 acre-ft in the Elkhorn and Loup River Basins, respectively. Ground-water pumpage (hereinafter referred to as pumpage) for agricultural land irrigation was 86 percent of total pumpage in the Elkhorn River Basin and 94 percent of total pumpage in the Loup River Basin. Recent drought (2000–06; National Climatic Data Center, 2006) has amplified concerns about long-term water-use sustainability in the Elkhorn and Loup Rivers, sustainability of the ground-water resources, interaction of surface and ground water, and the effect of pumpage on base flow.

In Nebraska, the responsibility for administration of ground-water and surface-water quantity laws is assigned to two separate governmental entities. Ground water primarily is managed by 23 NRDs (Neb. Rev. Stat. 2-3213 and 2-3229, Reissue 1997). NRDs are regional government entities whose boundaries are based generally on major surface-water divides, though multiple NRDs exist within most major river basins. Surface water is managed by a state entity, the Nebraska Department of Natural Resources (NDNR). Doctrines governing ground-water and surface-water management differ as well. Ground water is governed by correlative rights, “share and share alike,” whereas surface water is governed by the prior appropriations doctrine, “first in time, first in right.”

In an effort to proactively resolve potential conflicts that may result between ground-water and surface-water users, state legislation was enacted in 2004 to ensure that long-term supplies of ground water and surface water are in balance with long-term demands. As part of this proactive approach, the NDNR is charged with conducting an annual evaluation of each river basin within the state, including the Elkhorn and Loup River Basins. This evaluation includes an assessment of the long-term effects of ground-water use on surface-water flows in areas where the aquifer is hydrologically connected to the stream. NDNR defines hydrologically connected areas as those areas within which pumping of a well for 50 years will deplete base flow by at least 10 percent of the pumped volume (Nebraska Department of Natural Resources, 2007).

If the results of the NDNR’s analysis indicate that long-term mean streamflows are insufficient to meet long-term demands in a basin based on current ground-water and surface-water use, that basin is declared fully appropriated. This designation results in a moratorium being placed on new wells, new surface-water appropriations, and expansion of irrigated acres. In addition, the NDNR and the NRDs within the hydrologically connected areas determined to be fully appropriated must jointly develop an integrated management plan (IMP; Nebraska Department of Natural Resources, 2007). The primary objective of an IMP is to achieve a sustainable balance of water demands and water supplies of the surface- and ground-water system in the short and long term. The results of phase one of the ELM project, documented herein, could be used to assist the NDNR in conducting its annual evaluation.

Hydrogeology

Quaternary-age wind-deposited loess and fine-grained sand, alluvial silt, sand, and gravel, and Tertiary-age silts, sands, and gravels of the Ogallala Group (Condra and Reed, 1943) constitute the important geologic deposits forming the water-table aquifer in the ELM area. The Ogallala Group overlies silts of the Tertiary-age Arikaree Group across the western one-half of the ELM area, and otherwise generally overlies poorly permeable Cretaceous-age shale and limestone (Conservation and Survey Division, 1998). The base of the aquifer slopes gently to the east at about 8 feet per mile (ft/mi), and contains fairly wide paleo-valleys that also predominantly drain eastward (fig. 4). The Quaternary- and Tertiary-age geologic units in the area generally are unconsolidated and are simulated as one hydrostratigraphic unit (and one simulation layer) because they function as one continuous, connected,

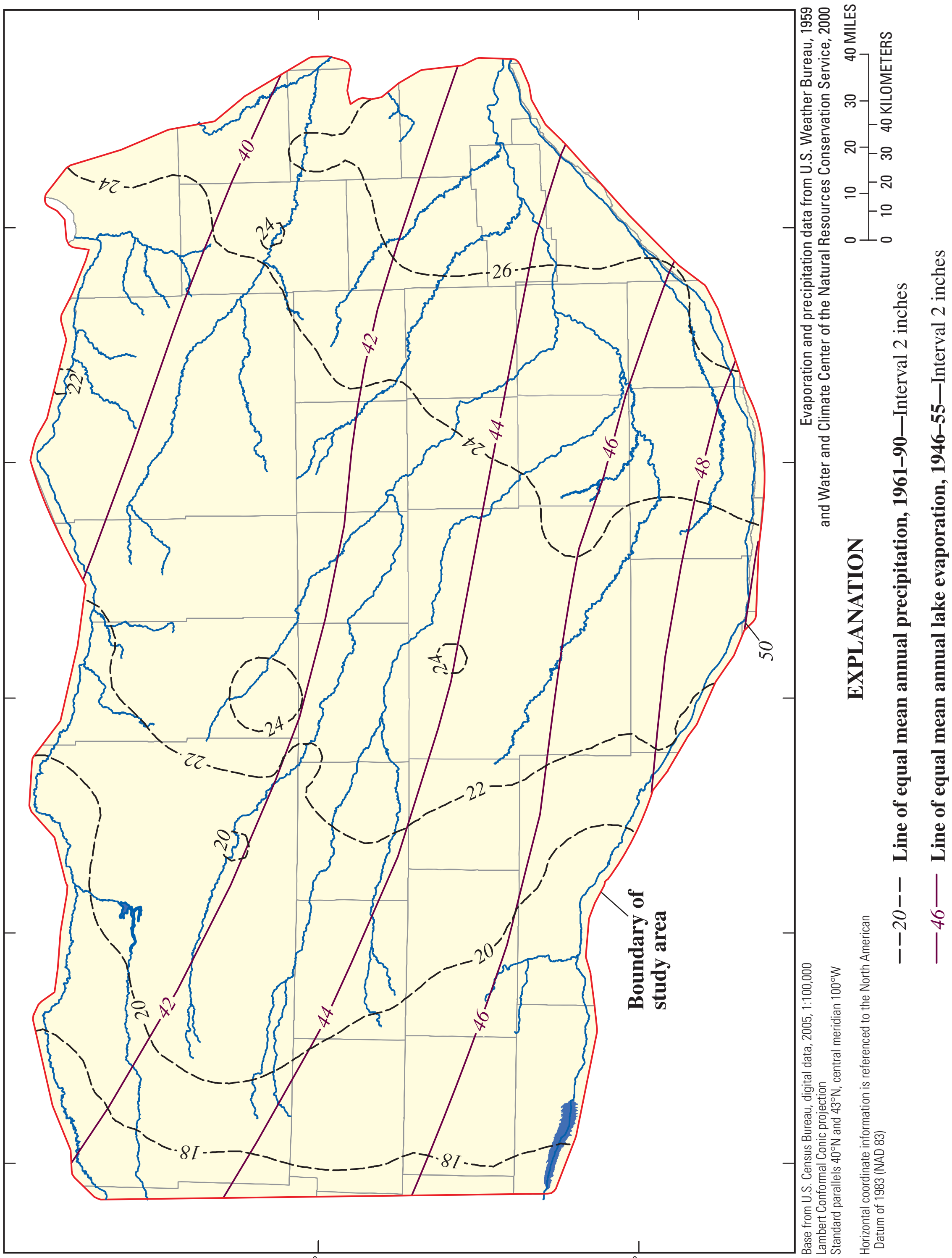
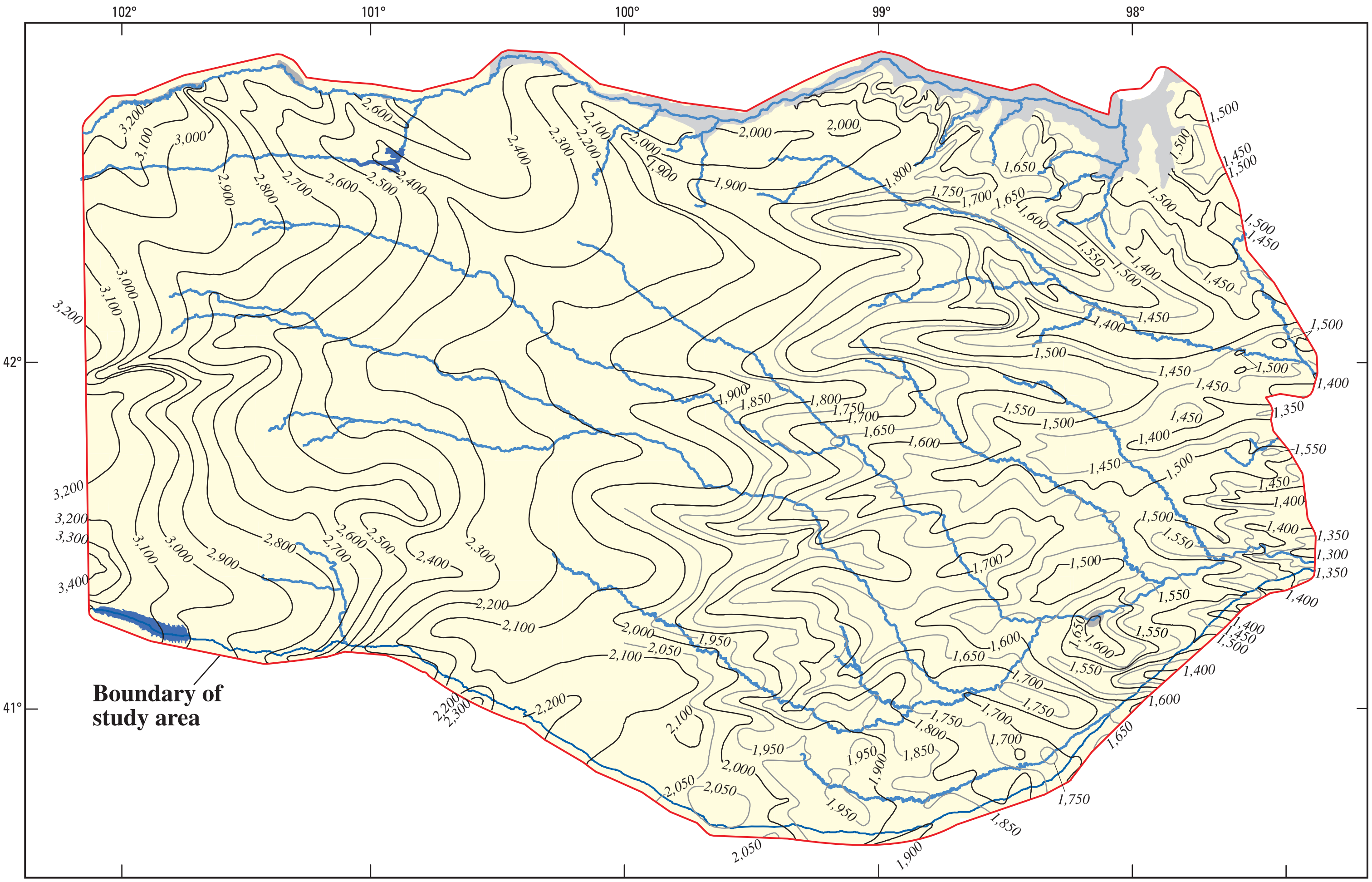


Figure 3. Mean annual 1961–90 precipitation and mean annual 1946–55 lake evaporation in the Elkhorn and Loup River Basins, Nebraska.



Base from U.S. Census Bureau, digital data, 2005, 1:100,000
Lambert Conformal Conic projection
Standard parallels 40°N and 43°N, central meridian 100°W

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

Base of aquifer elevations from Conservation and Survey Division, 2002

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

EXPLANATION

Area of little or no aquifer thickness

—1,900— **Base of aquifer elevation contour—**Interval 50 and 100 feet. Datum is National Geodetic Vertical Datum of 1929 (NGVD 29)

Figure 4. Elevation of the base of the water-table aquifer, Elkhorn and Loup River Basins, Nebraska.

water-table aquifer on the regional scale. However, they are distinct geologically, both in terms of their depositional characteristics and hydrogeologic properties, which control how water locally flows through them.

Quaternary-age deposits are composed of wind-deposited silts or fine-grained sands (usually referred to as loess), or alluvial silt, sand, and gravel. Wind-deposited sands of the Nebraska Sand Hills overlie about 60 percent of the study area but mostly are above the regional water table, as are Quaternary-age loess deposits. Quaternary-age deposits have sufficient saturated thickness to be developed as a source of ground water in most of the ELM area, and can be as much as 700 feet (ft) thick but more commonly are found to be 150 to 200 ft thick, with an average thickness of 144 ft (Conservation and Survey Division, 2006). The Quaternary-age deposits usually are the coarsest deposits found in the study area and can support sustained pumping rates in excess of 1,000 gallons per minute (gal/min) (Nebraska Department of Natural Resources, 2005a). The only part of the ELM area where the Quaternary-age deposits generally are absent is near the Niobrara River (fig. 5), where Cretaceous-age deposits outcrop near land surface.

Ogallala Group deposits are present in most of the study area and are composed of clays, silts, sands, gravels, and poorly consolidated sandstone and siltstone. Ogallala Group deposits are absent where they have been eroded away near the Niobrara River along the northern study area boundary, near the eastern boundary of the study area, and along the Platte River in the southeast part of the study area. Ogallala Group deposits tend to be finer-grained than the Quarternary-age deposits, but frequently have much larger saturated thicknesses (fig. 5) (Conservation and Survey Division, 2005b), so yields of ground water to wells generally are sufficient for agricultural irrigation. Maximum Ogallala Group thicknesses described in test holes in the ELM area were around 700 ft, with an average thickness of about 170 ft (Conservation and Survey Division, 2006); however, many of these test holes were not drilled all the way to the base of the Ogallala Group. Furthermore, the parts of the ELM area where the Ogallala Group deposits tend to be thickest actually contain the fewest number of test holes; therefore, the average thickness in test holes probably is not representative of the true average thickness in the study area.

Ground water in the ELM area generally flows from west to east with an average water-table slope of about 10 ft/mi (fig. 6) (Conservation and Survey Division, 2003). The water-table gradient tends to be larger in the Sand Hills, averaging 14 ft/mi, and is less in the rest of the area, averaging 8 to 9 ft/mi. Locally, such as near the Niobrara River, water-table gradients can be in excess of 10 ft/mi, and range from 20 to 80 ft/mi as ground water moves from an upper, gently eastward-sloping plateau toward deeply incised valleys of the Niobrara River and its tributaries.

Ground-Water Flow Simulation

Conceptual Flow Model

A conceptual flow model is a narrative and schematic description of a ground-water flow system, and construction of a conceptual flow model is an important step in the process of building a ground-water flow model. In simple terms, the conceptual flow model describes how the ground-water flow system of an area is believed to behave; therefore, a conceptual model will contain information believed to be important to the occurrence and movement of ground water. The two most important components of a conceptual flow model are the boundaries and the water budget. The boundaries represent different parts of the flow system and how they interact with the ground water, and the water budget describes how much of the total water in the flow system is accounted for by each of the boundaries. Components of a conceptual flow model will vary depending on the system in question and study objectives.

Boundaries are critical to proper model design (Anderson and Woessner, 1992). A boundary is a physical feature that has an effect on the simulated flow system that can be measured or estimated, and thus be represented in the simulation (Reilly, 2001). Boundaries are both internal and external; internal boundaries are features ‘inside’ the simulation domain, such as a representation of streams or evapotranspiration areas, and external boundaries are those at the lateral or vertical extent of the simulated domain. Time also is a boundary, because the conditions simulated may depend on the time period of interest; however, time is addressed in the “Numerical Model Construction” section of this report (see the Simulation Periods subsection) because it is a special kind of boundary.

For the ELM study, the lateral external boundaries of the simulation consisted of either a drain boundary or zero-flow boundary along the northern boundary, combined zero-flow boundaries or fixed water-level boundaries for the eastern and western boundaries, and a fixed water-level boundary for most of the southern boundary, except at the western end where for some simulation periods it is a general-head boundary (fig. 7). The bottom (vertical) boundary of the simulation is the base of the water-table aquifer, and the upper vertical boundary is the water table. Areas that had been previously categorized as having no aquifer present or having a very thin aquifer (Conservation and Survey Division, 2002) were not included in the simulation (fig. 7).

Because the boundaries and their function are a major part of the conceptual flow model, each type of boundary is described in greater detail in the following paragraphs, grouped by boundary type. The specific implementation of these boundaries into the ground-water flow simulation are described in the “Numerical Model Construction” section of this report.

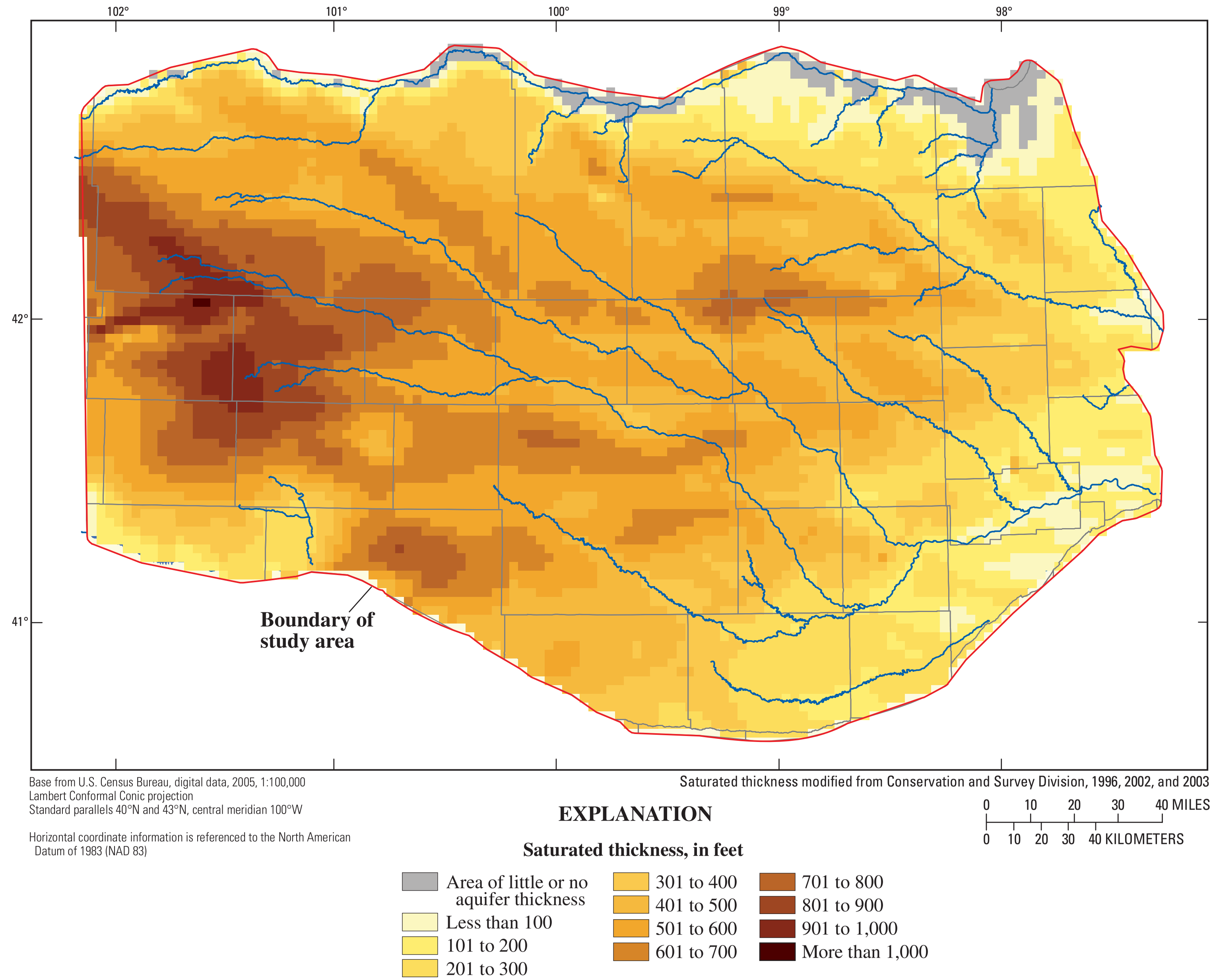


Figure 5. Maximum saturated thickness of the water-table aquifer, using 1979 and 1995 water-table contours, and areas with little or no aquifer thickness, Elkhorn and Loup River Basins, Nebraska.

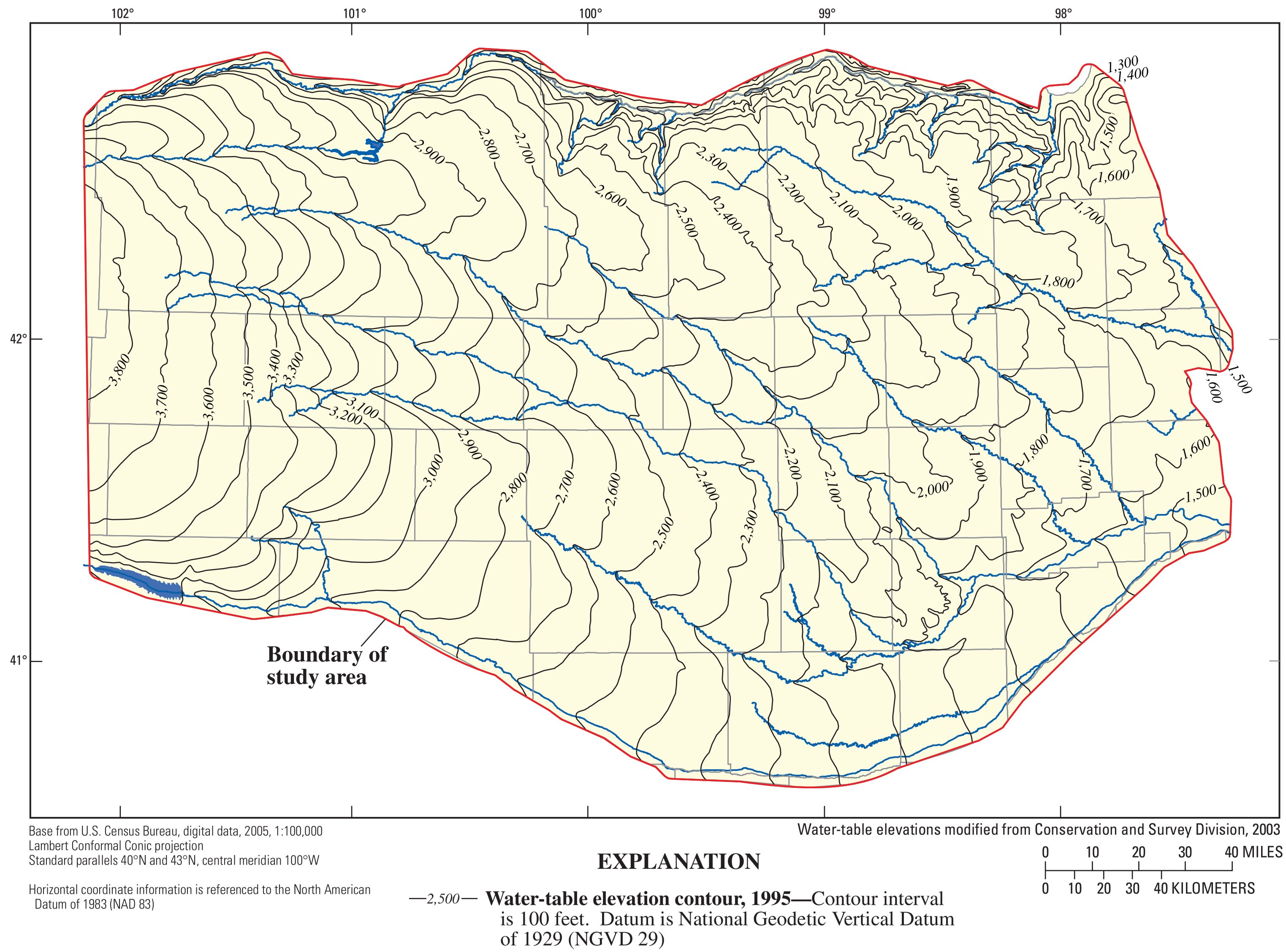


Figure 6. Configuration of water-table elevation contours in the Elkhorn and Loup River Basins, Nebraska, 1995.

A zero-flow boundary represents a hydrologic condition whereby no water flows across the boundary in any direction. A zero-flow boundary was used for several parts of the external boundary, as well as for the bottom boundary at the base of the aquifer. A zero-flow boundary was used for some reaches of the northern external boundary because the water-table aquifer thins from south to north and in some areas is absent near the Niobrara River valley (fig. 7). In some areas of the valley, the water-table aquifer is thin or absent, and the Niobrara River generally flows across poorly permeable Cretaceous-aged bedrock (Conservation and Survey Division, 1996a; 1996b). A zero-flow boundary also was used for parts of the eastern and western simulation boundaries where flow was dominantly parallel to the external boundary, thus no flow crosses the external boundary. Flow directions near these external boundaries were interpreted from a 1995 water-table contour map (Conservation and Survey Division, 2003). A zero-flow boundary also was used for the northern part of the eastern boundary, where the water-table aquifer is extremely thin and has a low hydraulic conductivity, indicating that flow is negligible for the regional system (Conservation and Survey Division, 2005b).

Fixed water-level boundaries were used for the central part of the eastern and western external simulation boundaries. In these areas, cross-boundary ground-water flow is likely to occur based on interpretations from 1995 water-table contours (Conservation and Survey Division, 2003). A fixed water-level boundary means that the initial water levels assigned to that boundary always are maintained. As water flows from a fixed water-level boundary downgradient, or as upgradient water flows to fixed water-level boundaries, water is either added to or removed from the simulated flow system to maintain the water level at the assigned elevation. Fixed water-level boundaries potentially could either add or remove large amounts of ground water from the simulated flow system because the assigned water level always is maintained. Therefore, it is common practice (Anderson and Woessner, 1992) to review the simulation outputs to verify that the amounts added or removed by a fixed-water level boundary are consistent with the gradient and transmissivity of the water-table aquifer in those areas. A fixed water-level boundary also was used for the southern external simulation boundary to represent ground-water discharge to the Platte River, or in some cases, water being lost by the Platte River to the ground-water system. In the long-term, water-levels in this area near the Platte River are stable; therefore, use of a fixed water-level boundary seemed appropriate and unlikely to affect simulation results in the interior of the simulation.

A drain boundary was used for some of the northern external simulation boundary and represents parts of the Niobrara River that may have sufficient saturated thickness in the river valley alluvium to allow interaction between the river and the ground-water system. A drain boundary removes water from a simulated ground-water flow system based on the difference between elevations assigned to the drain boundary and the simulated ground-water elevation, and based on physical properties describing the geometry and hydraulic conductivity of a hypothetical bed layer (McDonald and Harbaugh, 1988). This hypothetical bed layer may not always exist in nature, but if the actual streambed contained finer-grained sediments than those in the water-table aquifer, the conductance assigned to that drain boundary could be reduced to decrease the simulated flow from ground water to the drain boundary. Drain boundaries were used to simulate stream-aquifer interaction in the Niobrara River Basin (except the Snake River) because large gradients in simulated water levels in this area caused stability issues (the computer model could not iterate to a numerical solution) when stream boundaries were used to simulate stream-aquifer interaction. Niobrara River tributaries simulated with drain boundaries include Eagle Creek, Long Pine Creek, Plum Creek, Redbird Creek, Sand Draw Creek, and Verdigre Creek (fig. 7). These streams predominantly are gaining streams in nature, that is, most of their flow arises from ground-water discharge to the stream (base flow) (Kellan Strauch, U.S. Geological Survey, written commun., 2008); therefore, it is appropriate to simulate these streams using a drain boundary.

Stream boundaries were used to simulate most of the streams in the ELM area. Similar to drain boundaries, stream boundaries can remove water from the simulated ground-water flow system. The amount of water removed is controlled by the conductance of the hypothetical streambed layer and relative elevations of the stream stage and the simulated ground-water elevation (Prudic, 1989). However, stream boundaries also route the water removed from the water-table aquifer downstream based on Manning's equation (Prudic, 1989) and inputs describing the gradient and width of the channel, which is assumed to be rectangular. The simulated stream may contribute the routed water back to the water-table aquifer when the simulated ground-water elevation under the streambed is less than the simulated stream stage. The amount of loss is controlled by the difference in the elevations and conductance specified for the hypothetical streambed layer. Stream boundaries were used to simulate perennial reaches of Birdwood Creek, Cedar Creek, the Cedar River, the Calamus River, Clearwater Creek, the Dismal River, the Elkhorn River, the Loup River, the Middle Loup River, Mud Creek, the North Fork of the Elkhorn River, the North Loup River, the Snake River, the South Loup River, the South Fork of the Elkhorn River, Union Creek, and the Wood River (fig. 7). The Snake River was simulated using a stream boundary even though drain boundaries were used to simulate the rest of the streams in the Niobrara River Basin because water-level gradients in the Snake River area were smaller than they were in the rest of the Niobrara River Basin, and the water-table aquifer was thicker. Stream reaches not shown in figure 7 were not included in the simulation.

A general-head boundary was used to simulate Lake McConaughy (fig. 7) for 1940 through 2005. General-head boundaries are similar to fixed-water level boundaries, except that the interaction of the boundary with the simulated ground-water system is controlled by a conductance term, similar to

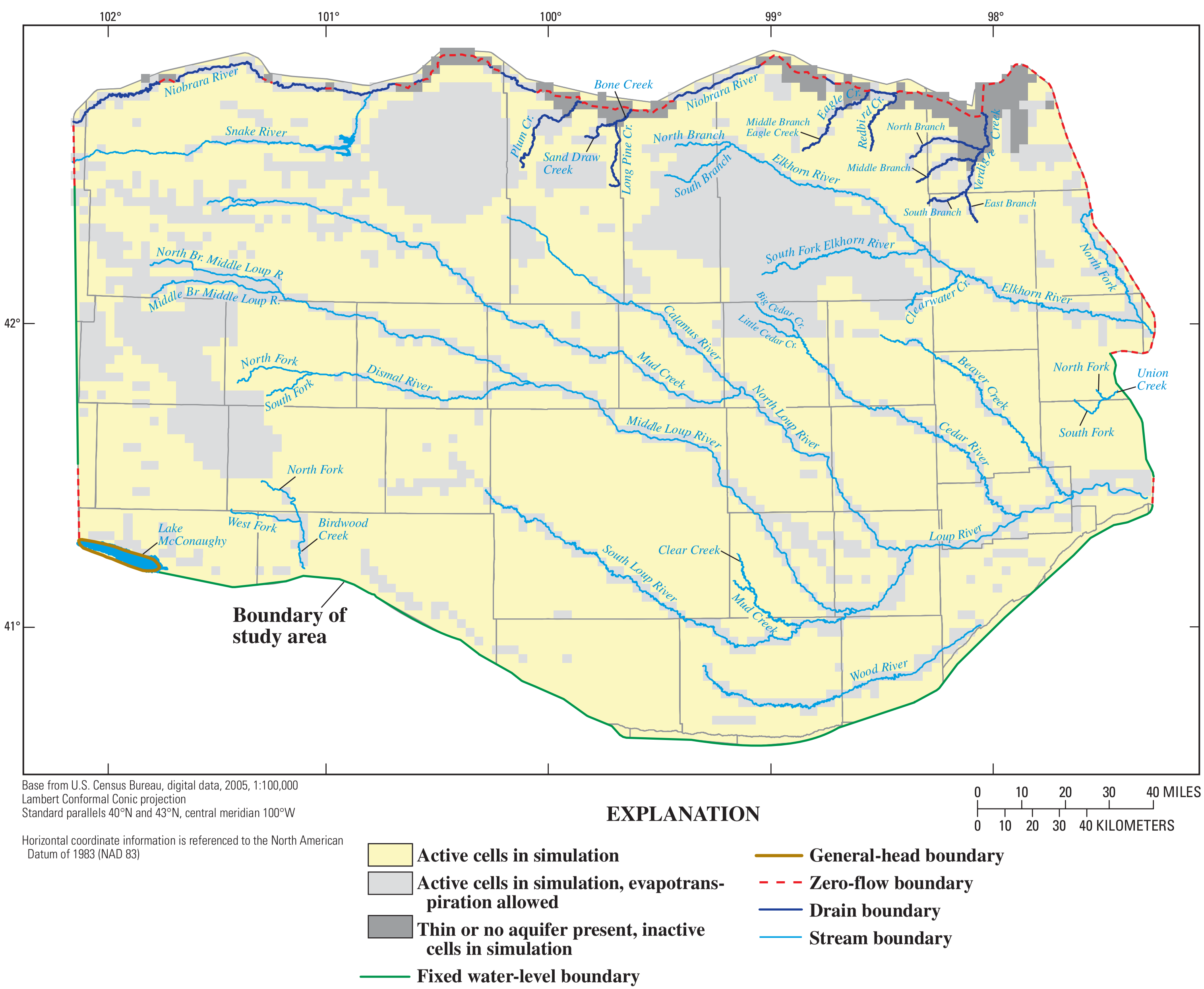


Figure 7. Conceptual flow model of the Elkhorn and Loup River Basins, Nebraska.

the term used for drain and stream boundaries (McDonald and Harbaugh, 1988). General-head boundaries commonly are used to simulate lakes, although, as with fixed-water level boundaries, care must be taken to ensure that the amount of water exchanged between the general-head boundary and the ground-water system is realistic, as must be done for all assigned boundaries (Reilly and Harbaugh, 2004).

Simulated evapotranspiration was used to represent the sum of transpiration of ground water by plants and evaporation of ground water near or at land surface. In some areas, evapotranspiration can remove large amounts of ground water at or near land surface; therefore, evapotranspiration was included in the ground-water flow simulation. The rate at which evapotranspiration can occur is controlled by the assigned maximum evapotranspiration rate, the relative elevation of the simulated ground-water levels and the assigned evapotranspiration elevation, and the input extinction depth, which is the depth below the evapotranspiration elevation at which evapotranspiration does not occur. Evapotranspiration was specified to occur near major streams and in areas mapped as wetlands or riparian areas (U.S. Fish and Wildlife Service, 2005), and the maximum evapotranspiration rate was set to zero in all other areas of the simulation. Simulated evapotranspiration for this report is specific to ground water and should not be confused with evapotranspiration of soil moisture or other sources of water not in connection with the regional water-table aquifer.

Recharge is the amount of water that infiltrates land surface and moves downward below the root zone and eventually crosses the regional water table; thus the term “recharge” is always used in this report to mean, more specifically, recharge to ground water. Recharge from precipitation was simulated as occurring nearly everywhere in the ELM, except on bluffs and escarpments, using the conceptual approach that recharge would be larger on coarser-grained soils than on finer-grained soils, and that it would be larger on level areas than on more steeply sloping areas. Recharge was not simulated on bluffs and escarpments because precipitation that falls on bluffs and escarpments likely becomes runoff instead of recharge.

The hydrologic budget consists of inflow and outflow components. The inflow budget components in the ELM were (1) ground water that had been released from storage (resulting in water-level declines), (2) ground-water flow into the study area from the west and from the Platte River, (3) seepage from Lake McConaughy, (4) recharge from canal and lateral seepage (alternately referred to as canal-seepage recharge), (5) additional recharge applied to irrigated cropland areas, (6) additional recharge applied to nonirrigated cropland areas, (7) additional recharge applied to Hall and Buffalo Counties, (8) recharge from precipitation, and (9) inflows of base flow from stream boundaries. The outflow budget components in the ELM were (1) ground-water outflow to storage (resulting in water-level rises), (2) ground-water flow out of the study area to the east and to the Platte River, (3) seepage to Lake McConaughy, (4) outflows to stream base flow, (5) outflows to stream base flow for streams represented by drain boundaries, (6) evapotranspiration, (7) pumpage for irrigation, and (8) pumpage for municipal use.

The relative magnitude of the conceptual flow model budget was estimated. The largest inflow component of the conceptual flow model budget was recharge from precipitation, and other inflow components were expected to be a small part of the overall budget. Stream base flow was expected to be the largest outflow, followed by evapotranspiration. Other budget components were expected to be a small part of the overall budget. Quantitative volumetric flow rates for each budget component were not available to compare to the conceptual flow model budget. However, our qualitative assessment of relative flow rates is our best representation of the budget given the data available and our current (2007) understanding of the ground-water flow system.

Numerical Model Construction

MODFLOW (McDonald and Harbaugh, 1988) and its revisions (Harbaugh and others, 2000; Harbaugh, 2005) are the most commonly used finite-difference ground-water flow model software. Simulations were built for this study using MODFLOW-2000, through the GMS 6.0 pre- and post-processor (Environmental Modeling Systems, Inc., 2007). The study area was simulated using a uniformly spaced grid consisting of 81 rows and 124 columns of 2 mi by 2 mi cells, and areas where the aquifer was thin or absent (Conservation and Survey Division, 2002) were not included in the simulation. The single vertical layer was simulated as an unconfined aquifer. Ground-water flow equations were solved using a geometric multigrid solver (GMG) (Wilson and Naff, 2004).

Assumptions

Whereas using MODFLOW and simulation of ground-water flow systems through finite-difference solution techniques implies many assumptions (McDonald and Harbaugh, 1988), some primary assumptions important for ELM study objectives are presented here.

1. *Regionally, flow predominantly is horizontal and the water-table aquifer is unconfined*. There is neither evidence for vertical ground-water flow or confining conditions in most of the simulation area nor regionally important confining units that might prevent full connection between deposits composing the water-table aquifer. Therefore, the system can be appropriately simulated with a single vertical simulation layer.

2. *Water flows through the water-table aquifer according to Darcian flow principles*. That is, the water in the water-table aquifer is incompressible, the water-table aquifer is homogeneous and isotropic, and behaves as if it is infinite in areal extent. Flow is laminar rather than turbulent.

3. *The water-table aquifer can be appropriately simulated using grid cells that are 2 mi by 2 mi in size, and water-table aquifer properties are uniform within the area of each grid cell.* It is recognized that some system properties change over distances less than 2 mi, but this assumption is appropriate for simulations meant to be used for regional management scenarios. In addition, using a relatively large cell size allowed simulations to run more quickly; shorter execution times improved efficiency of the simulation effort, to more effectively meet study objectives.

4. *Sources and sinks of water that have an important effect on the ground-water flow system, such as streams, pumpage, and recharge, can be appropriately simulated using grid cells that are 2 mi by 2 mi in size.* It is recognized that streams in the area actually occupy areas much less than 2 mi wide, but as with assumption 3, it is acceptable for simulations meant to be used for regional management scenarios. This assumption also means that this simulation cannot be used to analyze features that are within 1 mi of streams, because when aggregated to 2 mi cells, those features may be in the same grid cell as the stream. In some situations, the valleys of small streams may not be represented in the inputs to the much larger grid cells, and if the stream is controlled in nature entirely by processes that occur within the valley, the simulation may not correctly represent that stream. Lastly, land-use data in part control the pumpage and recharge used in the simulations, and land-use data were available at a finer resolution than the selected grid size, but any errors caused by aggregation of these data to 2 mi by 2 mi grid cells would be negligible in these simulation results. The selection of the grid cell size for building a simulation for this area was guided by the desire for simplicity, because simplicity enhances model transparency and helps keep model execution time short; short execution times facilitate completion of the numerous simulations needed to characterize and understand system behavior, and test models against data (Hill, 2006).

5. *The ground-water flow system before major anthropogenic effects was in long-term equilibrium, which can be approximated using a steady-state simulation*. As no anthropogenic effects would have been present in the system at that time, and ground-water levels would represent the integration of climate effects that occurred during the previous decades or centuries, this assumption is thought to be appropriate.

6. *Water that leaks from canals and eventually reaches the water table can be appropriately simulated as recharge*. Whereas this assumption may not be true for short periods, such as days or weeks, or for small areas, it is appropriate for a simulation spanning years and for regional ground-water flow systems.

Simulation Periods

As mentioned in the “Conceptual Flow Model” section of this report, time is a special simulation boundary that must be carefully considered when constructing a simulation. To represent time, ground-water systems can be simulated either under ‘steady-state’ or ‘transient’ conditions. A steady-state simulation represents an instantaneous snapshot of a ground-water system in equilibrium with all inflows and outflows. The simulated steady-state water level for a particular grid cell is independent of the assigned starting water level and does not change with time, rather it depends only on the properties assigned to the cell, the interaction with surrounding cells, and the sources and sinks affecting that cell, such as recharge or evapotranspiration.

In contrast, a transient simulation represents a specified period of elapsed time, such as a number of days, weeks, months, or years, broken up into “time steps” for each of which the solution is calculated. Generally, transient simulations are used to simulate some aspect of the system that is time-dependent, such as development of pumpage for irrigation that may begin and end in different places at different times; a transient simulation also might be used to simulate the effects of canal-seepage recharge as a new canal system begins operations or changes operations. Another difference from steady-state simulations is that a transient simulation calculates only the changes from the initial water levels because of the simulation stresses, so erroneous starting water levels can strongly affect simulation results (Reilly and Harbaugh, 2004). For some simulations, especially those of large regions, the amount of time for which non-equilibrium starting water levels could affect the simulation could be hundreds or even thousands of years.

For the ELM study, the primary goal was to simulate recent conditions, perhaps of the last few decades, accurately enough that the simulation could be used as a tool to evaluate system behavior during those last few decades, as well as to evaluate system response under assumed future conditions. The first surface-water diversions for irrigation began in the ELM area around 1895; pumpage for irrigation was becoming increasingly more common near the Platte River in the 1940s and expanded considerably during the 1950s, 1970s, and continued until current times (Nebraska Department of Natural Resources, 2005a). Water levels measured during these times were in a state of flux and not reliable to use as starting water levels. Therefore, a pre-1895 simulation was constructed to represent the system in long-term equilibrium before the onset of anthropogenic effects. Water levels from the pre-1895 simulation could then be used as reliable starting water levels for the pre-1940 transient simulation, and simulated 1940 water levels could be used as reliable starting water levels for the 1940 through 2005 simulation. Because major changes in land-use practices occurred from 1895 to 1940 and from 1940 through 2005, these were selected as critical periods for which to build separate transient simulations.

Following the pre-1895 steady-state simulation, transient simulations of 1895 to 1940 and 1940 through 2005 represented the effects of new activities that were changing the system. The simulation of 1895 to 1940 included the processes active during the long-term equilibrium of the steady-state simulation, but with added recharge of water that leaked from canals during this time. This simulation included two stress periods and 500 time steps, so each time step represented approximately 32.9 days. The simulation of 1940 through 2005 included pumpage for irrigation, canal-seepage recharge, additional recharge from precipitation on nonirrigated and irrigated cropland areas, and additional recharge applied to Hall and Buffalo Counties. The 1940 through 2005 period was simulated using annual (66) stress periods, each with 20 time steps of 18.3 days. Shorter time steps were used for 1940 through 2005 because it was expected that with the extra stresses applied to the system to simulate pumpage for irrigation, shorter time steps would improve the accuracy of the solution.

Pre-1940 Simulation

Simulation Inputs

This section describes simulation inputs that were not adjusted as part of the calibration process, including the water levels at fixed water-level boundaries, base of the water-table aquifer, specific yield, specific storage, canal-seepage recharge, stream and drain boundary inputs other than conductance, and evapotranspiration inputs other than the maximum evapotranspiration rate. Inputs that were adjusted for the subsequent transient simulation are described under "Simulation Inputs" in the "1940 through 2005 Simulation" section of this report.

Fixed water levels for the southern boundary were assigned based on simulated 1895 water levels from simulations built for the Platte River Basin (Clint Carney, Nebraska Public Power District, written commun., 2007). For the other fixed water-level boundaries, water levels were assigned based on the 1979 and 1995 water-table contour maps (Conservation and Survey Division, 1996c, 2003).

The base of water-table aquifer (lower boundary of the simulation) was derived from an elevation contour map created by the Conservation and Survey Division (2002) and additional test-hole drilling logs made available by the University of Nebraska (Conservation and Survey Division, 2006). Highest elevations (about 3,500 ft) are in the west and generally decrease to the east (to about 1,200 ft; fig. 4).

Specific yield values, representing water obtained by draining the aquifer pores (Fetter, 1994), were interpolated from points and contour lines obtained from the Conservation and Survey Division (2005c). Interpolated values ranged from 0.01 to 0.3 with a mean of 0.14. Smaller values were located in the northeast part of the study area in the Niobrara River valley. Areas of larger specific yield were located in the southwest (Arthur, Grant, Hooker, and McPherson Counties; fig. 1) and the southeast (primarily Boone, Merrick, and Platte Counties). Specific storage reflects the amount of water that is obtained as an aquifer undergoes decompression when water is removed (Fetter, 1994); though typically this is ignored for a regional unconfined flow system because it is much smaller than the amount of water yielded through aquifer drainage. For this simulation specific storage was set to a constant value of 0.00001 ft^{-1}.

Recharge from leakage of the Cozad, Dawson, Elm Creek, Gothenburg, and Kearney canal systems (fig. 8) was simulated during the pre-1940 period (table 1) with MODFLOW's recharge (RCH) package. Cozad, Dawson, Gothenburg, and Kearney canal systems began operation around 1895. The Elm Creek canal system began operation in 1929. Because neither measurements of canal seepage nor volumes of water delivered to fields were available for these canal systems, recharge from canal and lateral seepage was estimated to be 43 percent of the yearly water diverted from the Platte River, minus any water returned back to the Platte River, based on previous work (Duane Woodward, Central Platte NRD, oral commun., 2002). Canal-seepage recharge does not include enhanced recharge that may occur because of over-irrigation, that is, the application of surface water in excess of what the crops could use. Over-application could increase recharge or runoff from fields but was assumed to have minimal effect. Information describing over-application was not available. Recharge caused by leakage from each canal system was distributed evenly across the simulation grid cells within the extent of its delivery area.

Streambed elevations for streams simulated with MODFLOW's stream (STR) package were assigned from a digital elevation model (DEM) (Nebraska Department of Natural Resources, 1997) queried at regular intervals along each stream reach, and values were interpolated linearly between the assigned elevations in GMS 6.0 (Environmental Modeling Systems, Inc., 2007). Streambed width and elevation are used by the stream-routing package to compute streamflow volumes and stages (Prudic, 1989). Streambed width and elevation should not be confused with terms used related to conductance or stream leakage; readers desiring additional information regarding stream package terms are directed to Prudic (1989). The width of each stream reach was determined either from measurements made at stream-gaging stations or USGS 1:24,000-scale topographic maps. The stream bottom elevation partially controls the simulated interaction of the stream with the ground-water system; it was assigned to be 1 ft below the streambed elevation throughout the simulation domain. For streams simulated as drain boundaries using MODFLOW's drain (DRN) package, drain elevations were assigned by querying a DEM (Nebraska Department of Natural Resources, 1997) at regular intervals along each drain reach, and values were interpolated linearly between the manually assigned elevations in GMS 6.0.

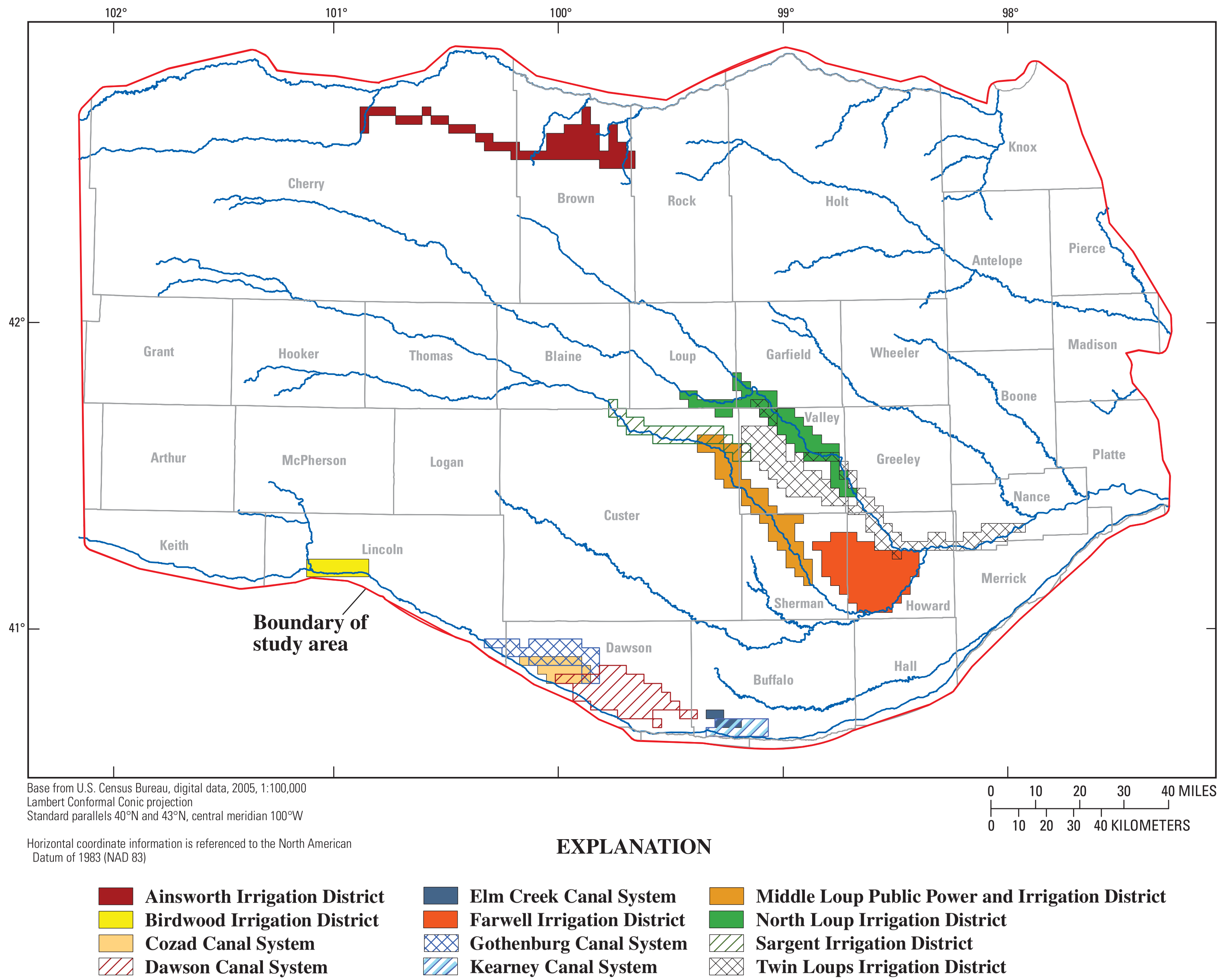


Figure 8. Canal systems and irrigation districts in the Elkhorn and Loup River Basins, Nebraska.

Table 1. Estimated recharge from canal and lateral seepage during the pre-1940 simulation, Elkhorn and Loup River Basins, Nebraska.

Canal system	First year of operation	Estimated annual seepage, in cubic feet	Estimated annual seepage, in acre-feet
Cozad	1895	506,777,047	11,634
Dawson	1895	1,093,051,096	25,093
Gothenburg	1895	1,508,221,462	34,624
Kearney	1895	214,968,603	4,935
Elm Creek	1929	134,382,602	3,085

Evapotranspiration was simulated using MODFLOW's evapotranspiration (ET) package. Evapotranspiration removes ground water at a specified maximum rate when the simulated water level is at or above a specified elevation, usually assigned as land-surface elevation. An extinction depth also is specified, and when the simulated water level is at or below this depth, evapotranspiration does not remove ground water from the simulation. Between the specified elevation and the extinction depth, the rate at which water is removed varies linearly between the maximum rate and zero (McDonald and Harbaugh, 1988). Extinction depth was set to a constant value of 5 ft. In nature, evapotranspiration may remove ground water more than 5 ft deep, but it is assumed that most ground-water discharge to evapotranspiration occurs within the top 5 ft and is minimal below that depth. The specified elevation for evapotranspiration was set to the 25th percentile of land-surface elevation in each grid cell as determined from a DEM having 30-m resolution (Nebraska Department of Natural Resources, 1997). The 25th percentile of land-surface elevations was used because evapotranspiration typically is confined to the lower elevations of a grid cell where ground water most likely is near the land surface.

Calibration Targets

Ground-water level measurements were obtained from the USGS National Water Information System (U.S. Geological Survey, 2005). Measurements generally were not widely made during the pre-1940 period. Therefore, observed ground-water levels used for calibrating this simulation were the earliest available measurements considered to have water levels unaffected by ground-water irrigation.

The first criteria applied to determine if a water-level measurement may have been affected by ground-water irrigation was whether or not the well was located on irrigated cropland. Initially, 934 wells within the study area were selected because they were not on parcels of land identified as irrigated in 2005. Subsequently, these 934 wells were filtered by removing all water levels that had been measured within 4 mi of an active irrigation well to reduce potential effects of pumping. This resulted in 546 water-level measurements being used for calibration of the pre-1940 simulation (fig. 9).

The 546 water-level measurements used for calibration were collected between 1928 and 2002, with a mean collection year of 1959. The distribution of water-level measurements was fairly consistent across the study area (fig. 9), though the measurements were more widely distributed in the south. Most water-level data that had been collected in later decades, such as from 1980 to 2002, were from Arthur and McPherson Counties, which were still mostly undeveloped for agriculture in 2005.

Estimated long-term base flow was determined using streamflow data recorded at 22 USGS streamflow-gaging stations (fig. 9) during the fall (October and November), using the entire period of record for each station. Fall discharge data were chosen because streamflows are less affected by diversions, riparian evapotranspiration, and runoff, and were therefore more likely to represent the base-flow component of streamflow. Methods used to estimate base-flow values have been described by Peterson and Carney (2002). A statistical or other detailed analysis of base-flow trends was beyond the scope of the study, but because the base-flow estimates were computed using the entire period of record, which in many cases includes several decades from about the 1930s to 2000s, the base-flow estimates are regarded as indicative of long-term base-flow conditions. Therefore, the approach to base-flow calibration was that if the 1940 simulated base flows were about the same as the "long-term" estimated base flows, the simulation was considered calibrated with respect to those base flows.

Calibration Process

In addition to the simulation inputs that were fixed during construction, some simulation inputs were adjusted through a trial-and-error approach to improve the match between the simulated and measured water levels, as well as the match between simulated and estimated long-term base flow. Model inputs that were adjusted during the calibration process included aquifer hydraulic conductivity, recharge from precipitation, stream-boundary conductance, drain-boundary conductance, and the maximum evapotranspiration rate.

Initial values of horizontal hydraulic conductivity (*HK*) were assigned based on a conceptual distribution. This conceptual distribution was based on expected regional trends of hydraulic conductivity represented by drawing polygons to assign one value of hydraulic conductivity for each polygon, interpreted to be contiguous areas of similar lithology. The initial *HK* values assigned to each polygon were from scientific literature (Fetter, 1994). The simplicity of this distribution enhanced convergence for the initial simulations. A second data set of *HK* was later derived from transmissivity contour maps and points provided by Conservation and Survey Division (Conservation and Survey Division, 2005b; Rick Vollertsen, Nebraska Department of Natural Resources, written commun., 2005) and aquifer saturated thickness in 1979 and

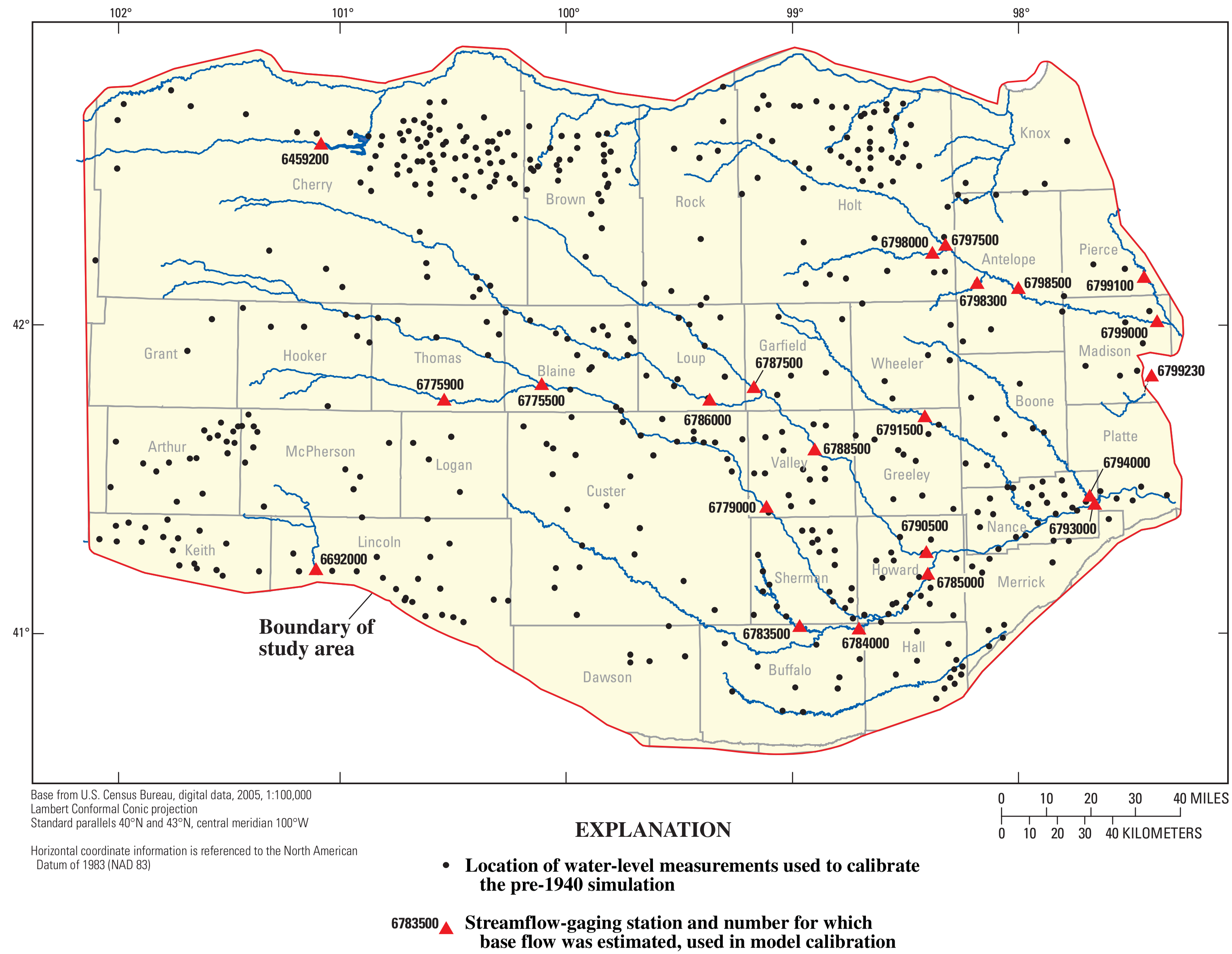


Figure 9. Distribution of water-level measurements used to calibrate the pre-1940 simulation, and distribution of streamflow-gaging stations with base-flow estimates used to calibrate the pre-1940 simulation and 1940 through 2005 simulation, Elkhorn and Loup River Basins, Nebraska.

1995 (Conservation and Survey Division, 1996c, 2003). The second *HK* data set was calculated by dividing transmissivity by saturated thickness. The saturated thickness was calculated by subtracting the interpolated aquifer base from the maximum water-table elevation from either 1979 or 1995. The maximum water-table elevation from 1979 or 1995 was used to avoid potentially small saturated thicknesses causing unreasonably large *HK* values. During the calibration process, the *HK* values represented by regional zones were refined locally using spatially varying values derived from the transmissivity maps and points, except in areas where the water-table aquifer is thin and in narrow buffer zones near most streams. In addition, one area in northeastern Custer, northern Valley, and northern Greeley Counties was assigned a uniform *HK* that improved simulated water levels and simulated base flow, though that assigned value did not agree with the spatially varying values derived from transmissivity maps (fig. 10). The *HK* value assigned to that area was 5 feet per day (ft/d), whereas interpolated *HK* values in that area were near 20 ft/d. In another area, reported to have high hydraulic conductivities surrounding a low-conductivity area caused by a bedrock high, a more detailed map of *HK* was used (Cannia and others, 2006) (Buffalo County, western edge of Hall County). The calibrated values of HK are shown in figure 10.

The distribution of recharge from precipitation primarily was based on topographic regions (Conservation and Survey Division, 1997). The largest values of recharge were assigned to areas with sandy soils and level terrain, and the smallest recharge from precipitation was assigned to areas with fine-grained soils and steep slopes. This resulted in a recharge potential for topographic regions being ranked as follows (descending from highest): Sand Hills, valleys, plains, dissected plains, rolling hills, and bluffs and escarpments. The regions shown in figure 2 are from a different source (U.S. Environmental Protection Agency, 2003), but are approximately equivalent to those in Conservation and Survey Division (1997), so an equivalent ranking using regions from figure 2 would be Sand Hills and Sand Hills lakes (Sand Hills), river valleys (valleys), plains and transitional sandy plains (plains), wet meadows and marsh plains (plains), dissected loess plains (dissected plains), loess hills (rolling hills), and river breaks (bluffs and escarpments).

Recharge from precipitation was calibrated by individual topographic regions while maintaining this ranking system, so recharge assigned to the Sand Hills region always was greater than that assigned to the valleys, which was greater than that assigned to the plains, and so forth. This step of the calibration was completed early in the overall calibration process and represented the primary part of the recharge calibration. Recharge assigned to topographic regions was later slightly modified according to average precipitation between 1895 and 2006 (National Climatic Data Center, 2006). Average precipitation for each of the seven climate divisions was used to modify recharge assigned to topographic regions so that areas with smaller or larger long-term average precipitation were assigned smaller or larger recharge values, while maintaining the ranking assigned based on topographic regions. Changes to recharge based on long-term average precipitation were much smaller than changes to recharge based on topographic regions and less important to overall calibration. The ranking of each climate division, from greatest 1895–2006 average annual precipitation to least, was division 6, division 3, division 8, division 5, division 2, division 7, and division 1. The largest calibrated recharge from precipitation was 3.1 inches per year (in/yr) in the Sand Hills, where recharge ranged from 2.4 to 3.1 in/yr, and ranged from 0.0 to 1.8 in/yr among the remaining regions (fig. 11).

In order to assign streambed and drain boundary conductance, streams were grouped into three classes according to estimated long-term base flow. The stream group with the largest estimated base flow was assigned the largest conductance value, the stream group with the lowest estimated base flow was assigned the lowest initial conductance, and the remainder of the streams were assigned a value of conductance between the other two values. The streambed conductance values were adjusted for each group individually based on the response of simulated water levels and base flow, while maintaining the ordinal relations among the groups. The conductance assigned to each group was adjusted iteratively, and the values that improved calibration the most were retained.

For the Dismal and Snake Rivers (fig. 12), conductance subsequently was individually calibrated because the simulated base flow initially was too high. For Birdwood Creek, the Elkhorn River, Mud Creek, Plum Creek, and the Snake River, calibration improved when conductance was adjusted to be lowest at the upstream end and increase downstream. As a result of the calibration process, conductance (per foot length in each grid cell) ranged from 0.20 to 31.50 ft/d (fig. 12). The units of feet per day listed for conductance are not the standard version used in MODFLOW; conductance takes into account the width, thickness, length, and hydraulic conductivity, and has units of square feet per day (ft^2/d). However, because GMS 6.0 calculates the length of the stream in each grid cell and applies that to a unit-length conductance assigned to the streambed (fig. 12), the reduced units become feet per day. Smaller streams generally had smaller values.

The maximum annual evapotranspiration rate initially was set uniformly to 14 in/yr, the value estimated at Odessa, Nebr., from measured evapotranspiration rates (Matt Landon, U.S. Geological Survey, oral commun., 2004). During the calibration process, several variations of maximum evapotranspiration rate were tested. Maximum evapotranspiration rates were expected to vary because of climatic conditions across the study area. Therefore, lake evaporation contours (fig. 3; U.S. Weather Bureau, 1959) were used in conjunction with the measured evapotranspiration rate at Odessa to create a spatially variable maximum evapotranspiration rate for input into the simulation. The lake evaporation contours indicate rates are largest in the south and decrease about 10 in/yr to the smallest rates in the northeast. The mapped variation was combined with the measured evapotranspiration rates at Odessa to generate the maximum evapotranspiration rates for

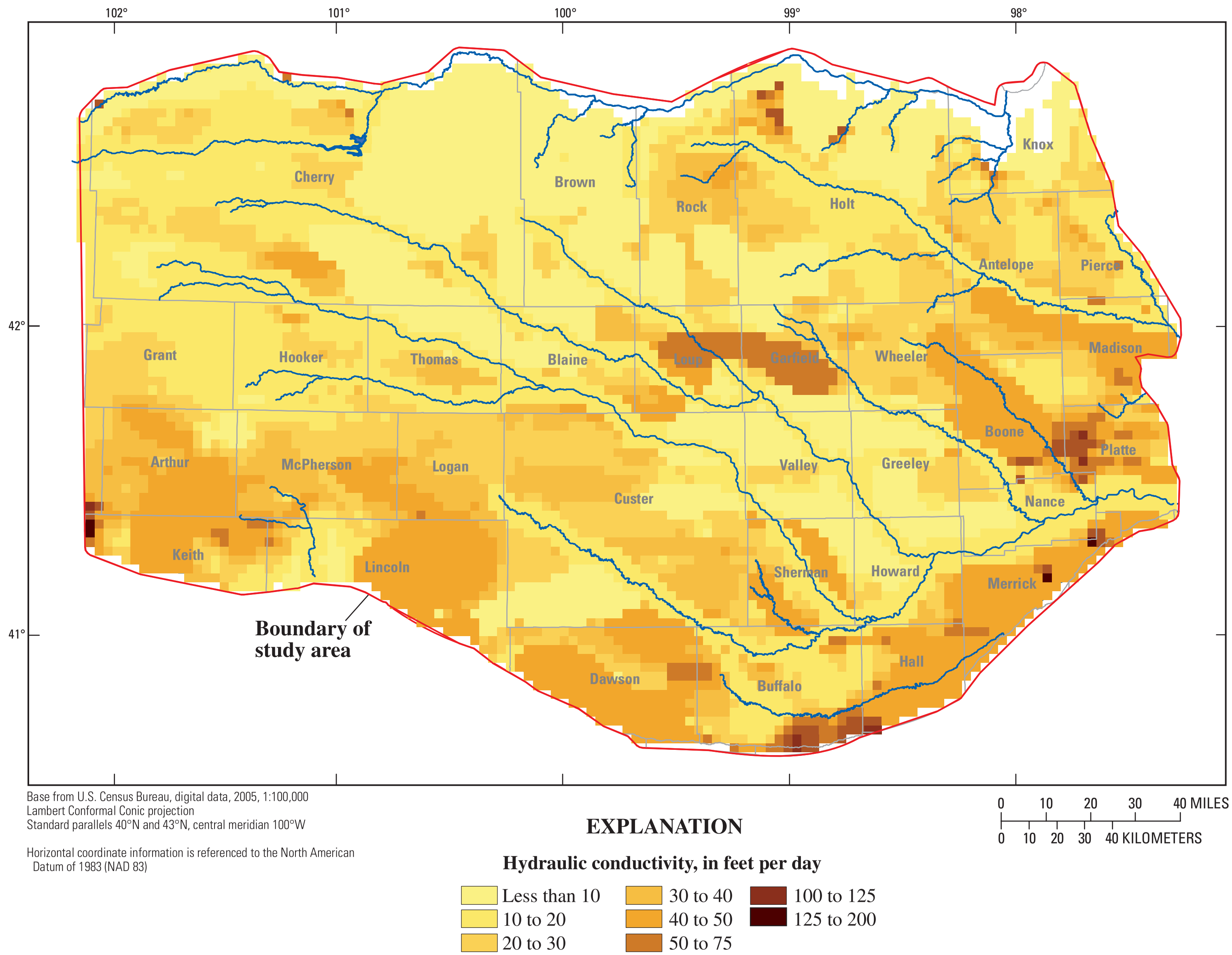


Figure 10. Calibrated hydraulic conductivity, Elkhorn and Loup River Basins, Nebraska.

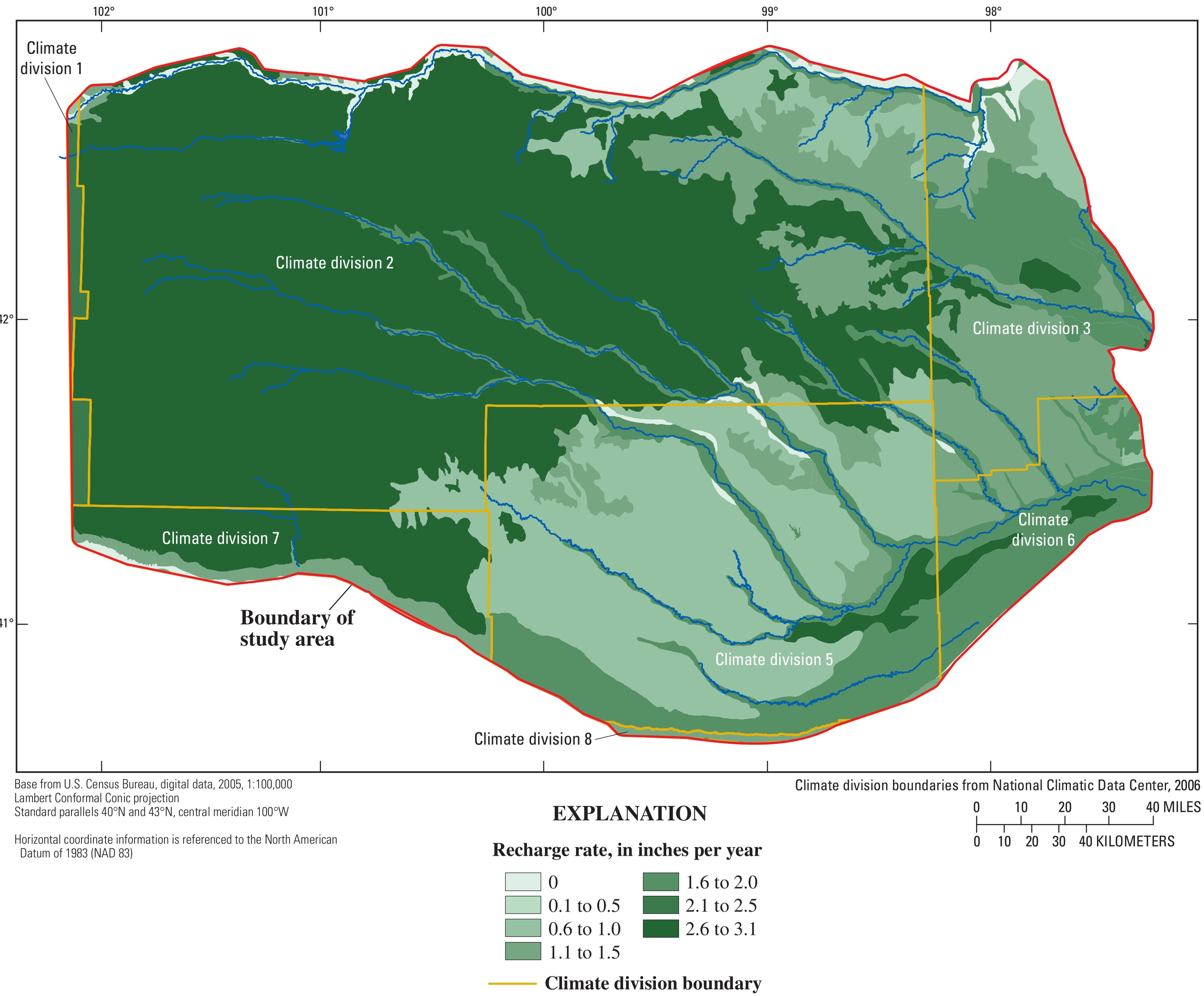


Figure 11. Calibrated pre-1940 recharge from precipitation, Elkhorn and Loup River Basins, Nebraska.

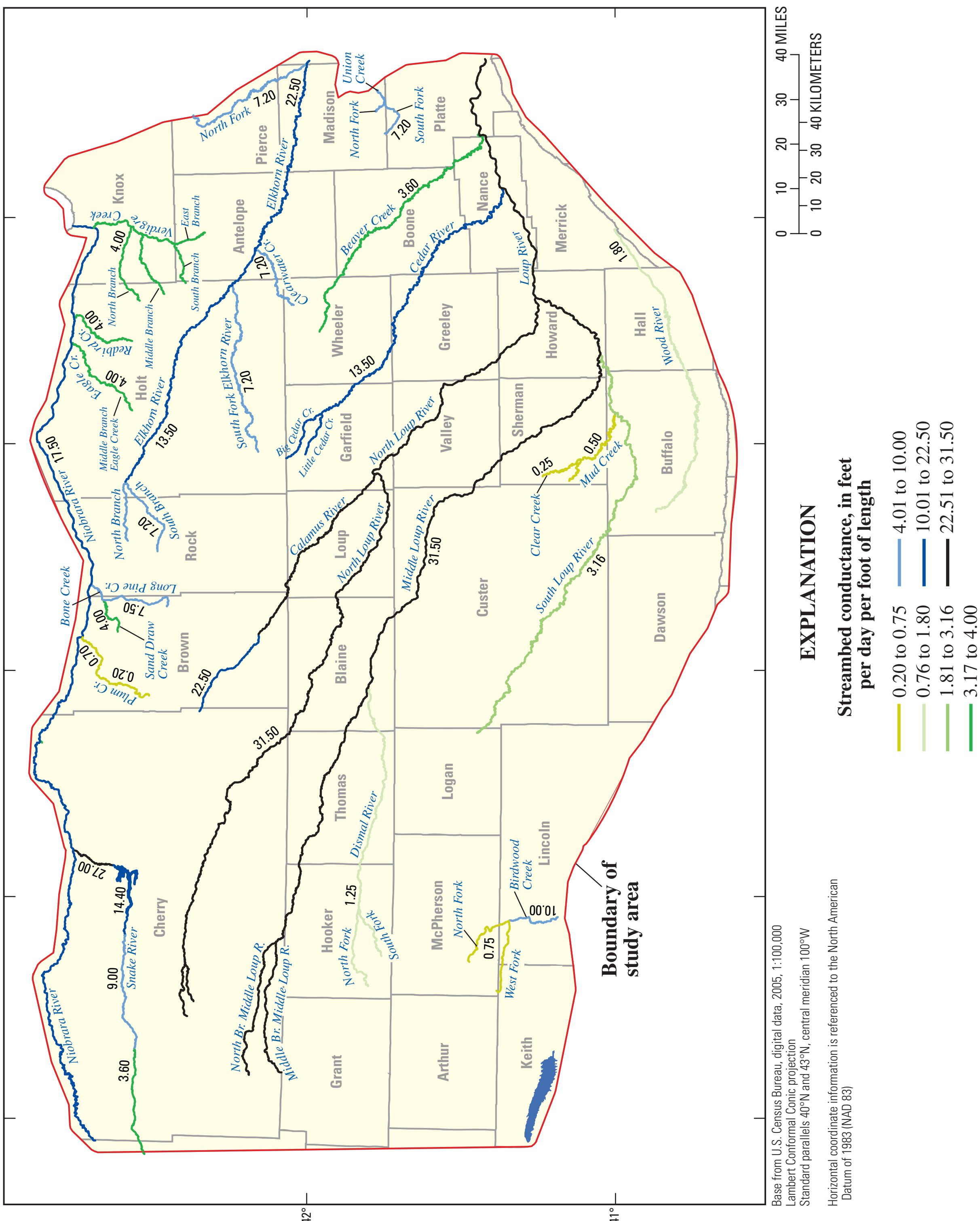


Figure 12. Calibrated streambed conductance, Elkhorn and Loup River Basins, Nebraska.

the simulation, which ranged from nearly 15 in/yr at Odessa to less than 4 in/yr in the northeast part of the ELM area (fig. 13). Using the mapped contours tied to the measured evapotranspiration rates at Odessa produced a better match between simulated and observed water levels and base flow than using a uniform maximum evapotranspiration rate for the entire area.

Simulation Results

Simulated steady-state results of the pre-1895 period were not compared to calibration targets because there was not sufficient calibration data against which to check the simulation results. However, 1895 simulated water levels were used as starting water levels for the 1895–1940 simulation, and 1940 simulation results were compared against measured water levels and estimated base flows. The 1940 simulation results were nearly the same as the 1895 results, except in areas affected by canal-seepage recharge included in the 1895 to 1940 simulation, which occurred in only Dawson and Buffalo Counties.

For 45 of the 546 water-level measurements, the observation location was either within a part of the model specified as inactive (fig. 7), or were too near the edge of the simulation for GMS to interpolate a comparison. Simulated 1940 water level was within 30 ft of measured water level for 384 of the remaining 501 points (77 percent) (fig. 14). Simulated 1940 water level was within 60 ft of measured water level at 471 points (94 percent). Differences between simulated and measured water level ranged from -385 to 243 ft. Many of the largest differences were near the northern boundary of the ELM area where steep hydraulic gradients exist that may be difficult to simulate accurately with 2-mi grid cells.

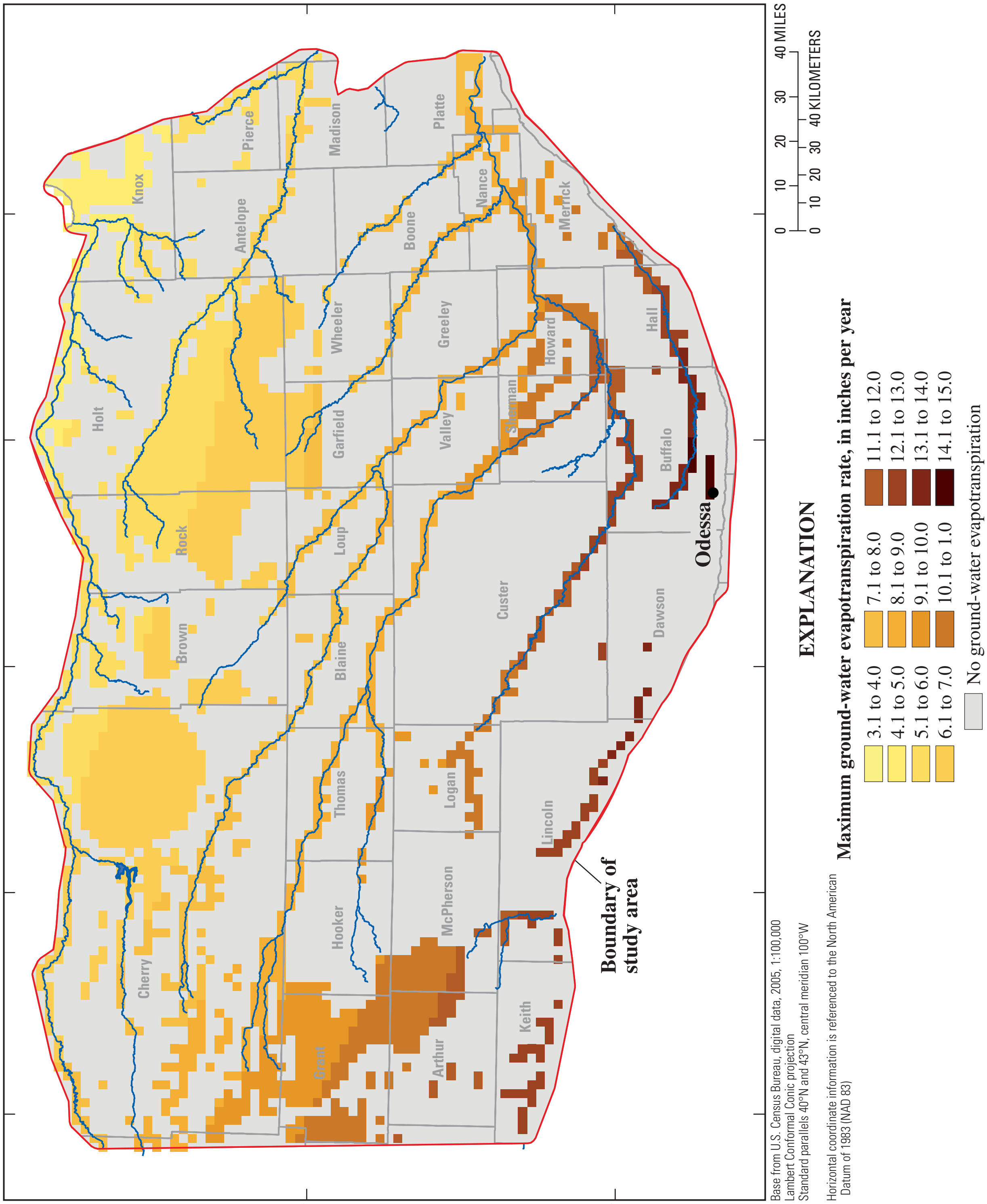
Three types of statistical summaries commonly are employed to measure differences between simulated and measured water levels—the mean difference, the mean absolute difference, and the root mean squared (RMS) difference. The mean difference is the mean of all differences between simulated and measured water levels. The mean absolute difference is the mean of the absolute value of the difference between simulated and measured water levels. The RMS difference commonly is referred to as the standard deviation, and is the square root of the mean squared differences between simulated and measured water levels.

The mean difference between the 1940 simulated water level and measured water level was -3.4 ft, indicating that measured water levels generally were higher than simulated water levels. The mean absolute difference was 22.1 ft, and the RMS difference was 37.9 ft. It generally is accepted that the RMS difference should be a small percentage of the total variation in simulated water levels for the problem domain (Anderson and Woessner, 1992). The RMS difference for this simulation, at 37.9 ft, is 1.5 percent of the total variation in simulated water levels, and 1.4 percent of the total relief of the water table in 1979 (about 2,650 ft) (Conservation and Survey Division, 1996c).

Simulated water-level contours for 1940 are shown alongside published interpolated water-level contours for 1979 (Conservation and Survey Division, 1996c) in figure 15. This comparison shows that simulated water levels generally match the published contours; however, the simulated water-level contours are more generalized and fail to represent localized relief in some areas, particularly along the northern boundary of the study area. In some areas, the failure of the simulated contours to match observed water-level contours can be at least partly explained because observed water levels had changed between 1940 and 1979, particularly near canal delivery areas. In addition, the published contours represent a hand-drawn interpretation of water-level data, which therefore also has associated subjectivity; the simulated 1940 contours conversely, were generated using GMS 6.0 and a modified inverse-distance weighted algorithm, and have similar subjectivity though the source of the subjectivity is different. Therefore, differences in the two sets of contours were expected.

Simulated 1940 base flow was compared to estimated long-term base flow for reaches ending at 22 USGS streamflow-gaging stations (table 2). ZONEBUDGET (Harbaugh, 1990) was used to retrieve simulated base flows from the simulation outputs for comparison, with the zones corresponding to the stream cells in between or upstream from streamflow-gaging stations (fig. 9) for which base-flow values were estimated (table 2). Surface-water features in the Niobrara River Basin were not considered as part of the analysis, except for the Snake River. The Snake River is the largest Niobrara River tributary included in the simulation, and was considered large enough to be comparable to the discretization of the regional model; therefore, base flow to the Snake River was considered during calibration. For some of the other Niobrara River tributaries, the regional aquifer may be absent under some parts of the streams, and the base flow of these smaller streams could be controlled by local hydrology not represented in the regional ground-water flow simulation, so these other streams were not considered during calibration.

For ten (45 percent) of the stream reaches considered during calibration, simulated 1940 base flow was within the estimated long-term base-flow range. At four (18 percent) of the reaches, simulated 1940 base flow was larger than the maximum estimated base flow. Simulated 1940 base flow was within 8 percent of the maximum estimate for three of those four reaches. However, the simulated 1940 base flow at Mud Creek near Sweetwater was 95 percent greater than the maximum estimated base flow. For eight (36 percent) of the reaches, simulated 1940 base flow was less than the minimum estimated base flow. Simulated 1940 base flow ranged from 2 to 53 percent less than the minimum estimated base flow. Streams with the smallest volume of estimated base flow had the largest underpredictions. Because these comparisons were calculated as a percentage, streams with smaller base flows mathematically are more likely to have larger errors. In addition, smaller streams are more likely to be simulated poorly with the 2 mi by 2 mi grid spacing used for these simulations.



Base from U.S. Census Bureau, digital data, 2005, 1:100,000
Lambert Conformal Conic projection
Standard parallels 40°N and 43°N, central meridian 100°W

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

Figure 13. Calibrated maximum annual evapotranspiration rates, Elkhorn and Loup River Basins, Nebraska.

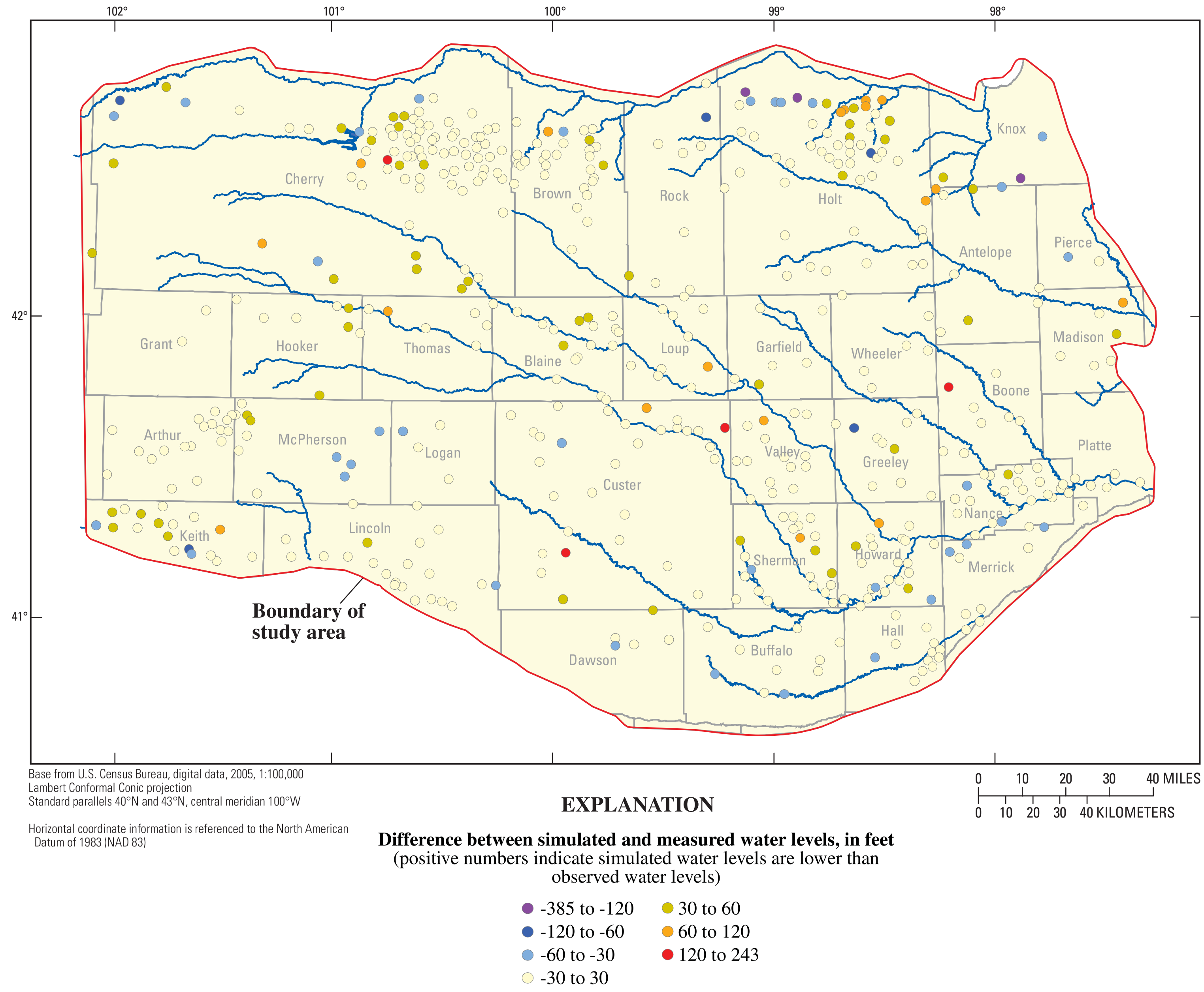


Figure 14. Differences between measured water level and simulated 1940 water level, Elkhorn and Loup River Basins, Nebraska.

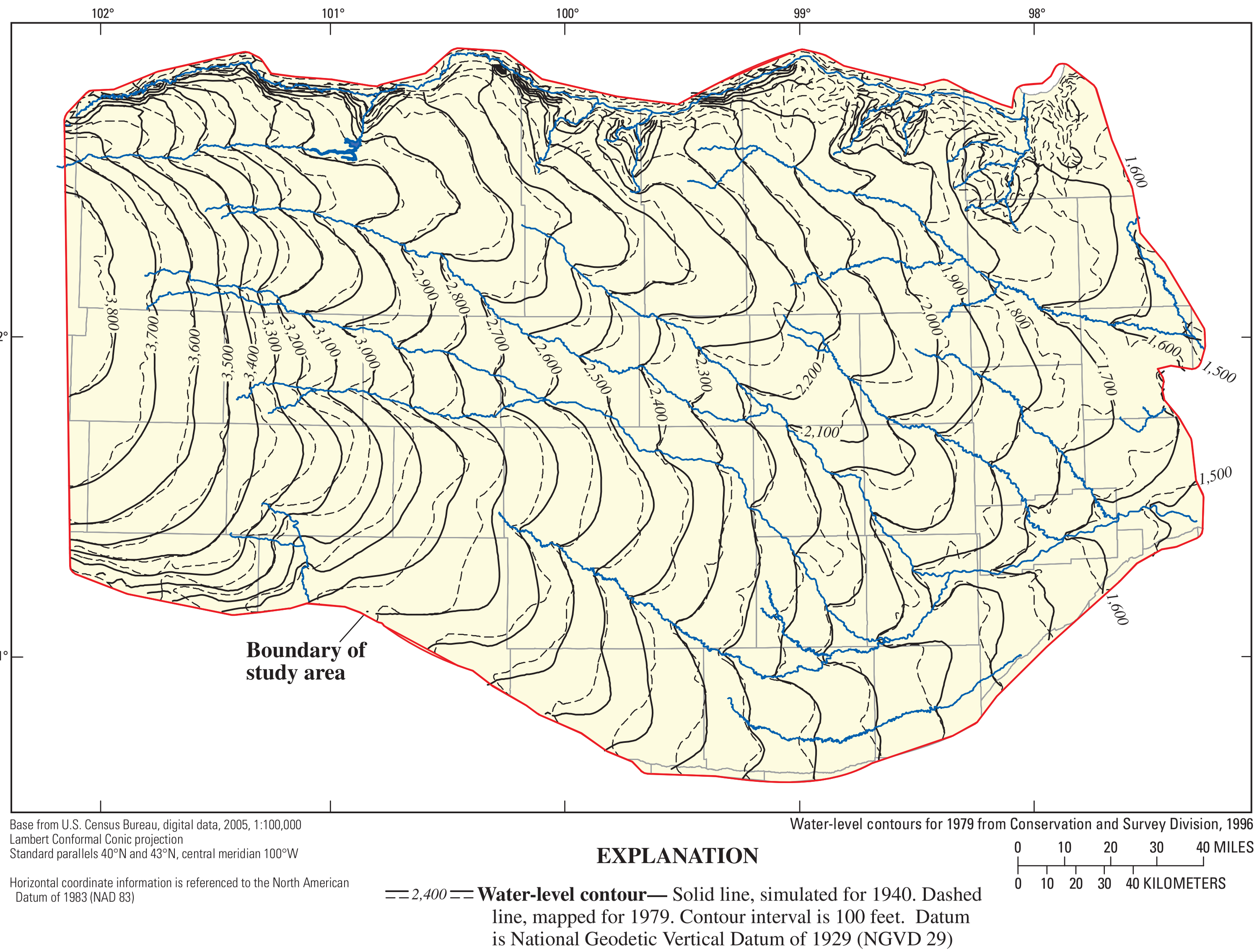


Figure 15. Simulated 1940 water-level elevation contours and published 1979 water-level elevation contours, Elkhorn and Loup River Basins, Nebraska.

Table 2. Estimated minimum and maximum base flow compared with simulated 1940 and 2005 base flow, Elkhorn and Loup River Basins, Nebraska.

[( ) number in parentheses indicates that stream had a net loss of water to the aquifer]

U.S. Geological Survey streamflow-gaging station and number	Estimated long-term base flow, in acre-feet per year		Period of record (start year, end year, number of years of data)	Simulated base flow, in acre-feet per year	
	Minimum	Maximum		To streams in 1940	To streams in 2005
Niobrara River Basin					
Snake River above Merritt Reservoir (06459200)	135,000	138,000	(1963, 1980, 18)	135,000	139,000
Elkhorn River Basin					
Elkhorn River at Ewing (06797500)	21,500	60,000	(1947, 2003, 56)	53,100	45,200
South Fork Elkhorn River at Ewing (06798000)	21,200	23,000	(1947, 1990, 32)	19,000	18,400
Clearwater Creek near Clearwater (06798300)	16,400	17,100	(1961, 1990, 17)	10,300	9,290
Elkhorn River at Neligh (06798500)	9,530	44,800	(1931, 1992, 60)	28,700	29,200
Elkhorn River at Norfolk (06799000)	59,000	94,000	(1896, 2003, 59)	57,100	60,300
North Fork Elkhorn River near Pierce (06799100)	22,300	23,800	(1960, 2003, 43)	16,700	18,100
Union Creek at Madison (06799230)	9,350	10,100	(1979, 1992, 14)	4,400	6,090
Loup River Basin					
Middle Loup River at Dunning (06775500)	276,000	283,000	(1946, 2003, 58)	279,000	280,000
Dismal River near Thedford (06775900)	138,000	140,000	(1967, 2003, 37)	140,000	141,000
Middle Loup River at Arcadia (06779000)	85,000	240,000	(1937, 1995, 57)	126,000	153,000
Mud Creek near Sweetwater (06783500)	7,750	7,900	(1946, 1994, 48)	15,400	14,600
South Loup River at St. Michael (06784000)	100,000	131,000	(1944, 2003, 60)	139,000	132,000
Middle Loup River at St. Paul (06785000)	(101,000)	182,000	(1928, 2003, 75)	42,900	78,700
North Loup River at Taylor (06786000)	303,000	321,000	(1937, 2003, 67)	305,000	312,000
Calamus River near Burwell (06787500)	179,000	192,000	(1941, 1995, 55)	175,000	179,000
North Loup River at Ord (06788500)	47,000	114,000	(1952, 1994, 42)	31,400	55,500
North Loup River near St. Paul (06790500)	18,500	64,000	(1928, 2004, 75)	53,700	78,000
Cedar River near Spalding (06791500)	92,400	96,000	(1945, 1994, 47)	86,400	87,100
Loup River near Genoa (06793000)	(80,000)	97,500	(1929, 2003, 63)	61,000	63,700
Beaver Creek at Genoa (06794000)	46,700	49,100	(1941, 2003, 63)	52,900	56,300
Platte River Basin					
Birdwood Creek near Hershey (06692000)	98,500	102,000	(1931, 1990, 59)	103,000	104,000

For the calibrated pre-1940 simulation, 83 percent of water entering the water-table aquifer (inflow) was from recharge from precipitation (table 3). Other sources of water were loss of stream base flow (13 percent), canal-seepage recharge (3 percent), and fixed water-level boundaries (1 percent). Ground-water discharge to stream base flow accounted for 61 percent of the water leaving the water-table aquifer (outflow). Water also was lost from the water-table aquifer by evapotranspiration (22 percent), fixed water-level boundaries (8 percent), base flow to drain boundaries (7 percent), and water entering storage (1 percent).

1940 through 2005 Simulation

The 1940 through 2005 transient simulation included inputs associated with ground-water irrigation, in addition to simulation inputs used to simulate the pre-1940 period. The 1940 through 2005 simulation also included additional recharge from precipitation applied to nonirrigated and irrigated cropland areas, additional recharge applied to Hall and Buffalo Counties, canal-seepage recharge from existing canals (as well as recharge resulting from canals that began operation after 1940), pumpage for irrigation, pumpage for municipal water supplies, and a general-head boundary simulating seepage to and from Lake McConaughy.

Table 3. Simulated ground-water budget for the pre-1940 simulation, Elkhorn and Loup River Basins, Nebraska.

[--, not applicable]

Budget component	Inflows		Outflows	
	Thousands of acre-feet per year	Percent of budget	Thousands of acre-feet per year	Percent of budget
Storage	0	0	47	1
Fixed-water level boundaries	42	1	343	8
All recharge	3,546	86	--	--
Canal-seepage recharge	115	3	--	--
Recharge from precipitation	3,431	83	--	--
Base flow to/from stream boundaries	528	13	2,529	61
Base flow to drain boundaries	--	--	298	7
Evapotranspiration	--	--	898	22
TOTAL	4,116	100	4,116	[1]99

[1]Does not total 100 percent because of rounding.

Estimation of Historical Land Use

Estimated pumpage for irrigation and a part of the recharge applied to the 1940 through 2005 simulation were dependent on the annual distribution of land-use classes. However, previously existing land-use data did not provide information about the distribution of crops irrigated with ground water or surface water or the distribution of nonirrigated crops, so these distributions had to be estimated.

Historical estimates of the distribution of these three land- and water-use categories were determined from a combination of data sources. Mapped locations of rangeland and cropland obtained from the National Agricultural Statistics Service (NASS) provided the basic distribution of land use within each grid cell in 2005 (U.S. Department of Agriculture, 2006). However, the NASS map did not classify irrigated and nonirrigated crops separately, as was necessary for the simulation. Therefore, the initial NASS data were evaluated by grid cell and compared to maps of surface-water irrigation districts, whereby some acres were classified as surface-water irrigated. Some acres were then assigned as irrigated with ground water using other data, and the remainder of the crop acres was classified as nonirrigated.

Maps of surface-water irrigated areas and tables of total acres irrigated by surface water were provided by Rick Vollertsen (Nebraska Department of Natural Resources, written commun., 2005), Allan Schmidt (Middle Loup Public Power and Irrigation District, written commun., 2006), Mel Brozek (Sargent Irrigation District, written commun., 2006), Jack Wergen (U.S. Bureau of Reclamation, written commun., 2006), Darwin Lee (Farwell Irrigation District, written commun., 2006), William Peck (U.S. Bureau of Reclamation, written commun., 2006), and Ron Wolfe (Twin Loups Irrigation District, written commun., 2006). The district boundaries (assigned to grid cells, fig. 8) and number of irrigated acres within each surface-water district are thought to be reasonably accurate, but the distribution of these acres within the boundaries of some of the districts is not well defined. For surface-water districts where the distribution of irrigated acres within the district was not well constrained, the acres were divided evenly among all grid cells within the district area.

To classify cropland acres as nonirrigated, surface-water irrigated, or ground-water irrigated, surface-water irrigated acres were first subtracted from each grid cell. The remaining cropland acres in the cell, which had the potential to be irrigated by ground water, were separated into nonirrigated and ground-water irrigated land by comparing the location of the cropland against the locations of active registered irrigation wells and the number of acres reported as irrigated in the well registration database (Nebraska Department of Natural Resources, 2005a). If the number of cropland acres in the cell was less than the acres attributed to registered irrigation wells in that grid cell, then all the remaining cropland acres were classified as ground-water irrigated; if the number of irrigated acres in the registered-well database was less than the remaining cropland in the cell, then the number of ground-water irrigated acres for that cell was set equal to the number of irrigated acres in the registered-well database, and the remainder was classified as nonirrigated. In addition, to limit potential errors that could have been caused by the assumptions implicit in using the irrigated acres associated with registered wells, the number of acres classified as ground-water irrigated in each county in 2005 was adjusted later to match the county totals from the 2005 land-use map (Center for Advanced Land Management Information Technologies, 2007), which was not available during the initial land-use estimation process.

Pre-2005 land-use data were estimated based on county-level crop statistics in the Census of Agriculture (U.S. Department of Agriculture, variously dated). The Census of Agriculture provided the number of nonirrigated and irrigated acres for each crop grown in each county every 5 years from 1950 to 2002. To produce the annual data required for the 1940 through 2005 simulation, yearly county-level values were interpolated between the data values provided every 5 years for 1950 to 2002. Crop acres from 1940 to 1949 were set to 1950 values. The mapped land use for 2005 was adjusted by a multiplier so that the total for each county for 2004 and preceding years matched the data interpolated from the Census of Agriculture data for each year. In the final data set used for the simulation, the number of acres assigned to each classification in each county matched the Census of Agriculture county-level statistics or the interpolation between the published years. If a county was only partially within the study area, the number of acres of each irrigated and nonirrigated crop was reduced by the proportion of the county that was outside the study area.

Simulation Inputs

This section describes simulation inputs that were not adjusted during calibration, including pumpage for irrigation, pumpage for municipal uses, canal-seepage recharge, and elevation assigned to a general head boundary representing Lake McConaughy. Unless described here or in the "Calibration Process" section, all other inputs remained the same as those used in the pre-1940 simulation.

The amount of pumpage for irrigation in the study area historically has not been measured. Therefore, annual pumpage for irrigation was estimated to be equal to the expected crop-water demand minus growing-season effective precipitation (the amount of precipitation available for crop consumption). The growing season is defined to be approximately May through September; effective precipitation is total precipitation minus the part that becomes runoff.

Crop-water requirements for each grid cell were based on the number of acres of each crop grown and the amount of water required to produce each of those crops (University of Nebraska, 1990 and 2002). Individual crop requirements were 25.5 in/yr for corn, 22 in/yr for soybeans, 20.5 in/yr for sorghum, 15.5 in/yr for dry beans, 33.5 in/yr for alfalfa, 23.2 in/yr for potatoes, and 17 in/yr for small grains and sunflowers. Individual crop water requirements were summed to yield a total water requirement for ground-water irrigated crops in each cell. All pumpage was calculated as net pumpage, which is the portion actually used by the crops and therefore lost to the system. Actual pumpage probably would be higher than net pumpage because of on-farm losses of pumped water before it could be applied to the crops. However, it was assumed that the major portion of the on-farm losses returns to the ground-water system as recharge, so on-farm losses were ignored for these calculations. The crops grown in each grid cell were estimated as described in the "Estimation of Historic Land Use" section of this report. Pumpage for irrigation was assigned only where the estimation indicated ground-water irrigated crops were present.

Estimated effective precipitation (precipitation that does not run off) was calculated for each year from 1940 through 2005 by adjusting growing season precipitation in each climate division (National Climatic Data Center, 2006) with Soil Conservation Service (SCS) rainfall-runoff curves for soil class A (U.S. Department of Agriculture, 1986; Woodward and others, 2002). Soil classes B, C, and D were assigned the same adjusted effective precipitation values as soil class A because soil class B data were not substantially different than soil class A data and because soil classes C and D did not compose large parts of the study area. The estimated effective precipitation for each growing season (defined in this report as May through September) was subtracted from the total water requirement of all crops to calculate the actual amount of water needed by crops that had been unmet by precipitation. Negative values indicated that the total water requirement for that cell would have been met by effective precipitation, in which case pumpage was set to zero.

Calculated pumpage for irrigation was then compared with available measured pumpage for 2005 (Russ Callan, Lower Loup Natural Resources District, written commun., 2007; Tylr Naprstek, Upper Elkhorn Natural Resources District, written commun., 2007) to determine whether or not the estimated pumpage rates should be adjusted. The average calculated volume of water pumped for corn in 2005 of 9.9 in/yr was compared to the average measured volume of water pumped for corn in 2005 minus an efficiency factor to account for on-farm losses, or about 6.5 in/yr. The original effective precipitation values were then modified by the difference between the calculated and measured pumping volumes for corn for 2005 (3.4 in/yr), for all years from 1940 through 2005. Finally, the modified effective precipitation values were subtracted from the combined water requirement for all crops to yield the final estimate of pumpage for irrigation for all years. Negative values indicated that the total water requirement for that cell would have been met by effective precipitation, in which case pumpage was set to zero. Total estimated yearly pumpage and the parts for corn and soybeans are shown in figure 16.

The amount of pumpage for municipal water supplies was obtained from the measured pumpage reported by municipalities in the study area (Shuhai Zheng, Nebraska Department of Natural Resources, written commun., 2007). Most of the reported pumpage data were from 2004; however, some values were from 2001 to 2003 or 2005. The reported pumpage rates were applied as a constant value to all years in the simulated 1940 through 2005 period.

In addition to the five canal systems in operation during the pre-1940 period, seven irrigation districts began operating new canal systems during the 1940 through 2005 period. The Birdwood Irrigation District started diverting water in 1946, Middle Loup Public Power and Irrigation District and North Loup Irrigation District started in 1947, Sargent Irrigation District started in 1957, Farwell Irrigation District started in 1963, Ainsworth Irrigation District started in 1965, and the Twin Loups Irrigation District started in 1987 (fig. 8). The only canal system that ceased operation during the 1940 through 2005 period was Elm Creek Canal (in 1962).

Calculated canal and lateral losses (canal seepage) based on water-mass balance were available for at least part of the

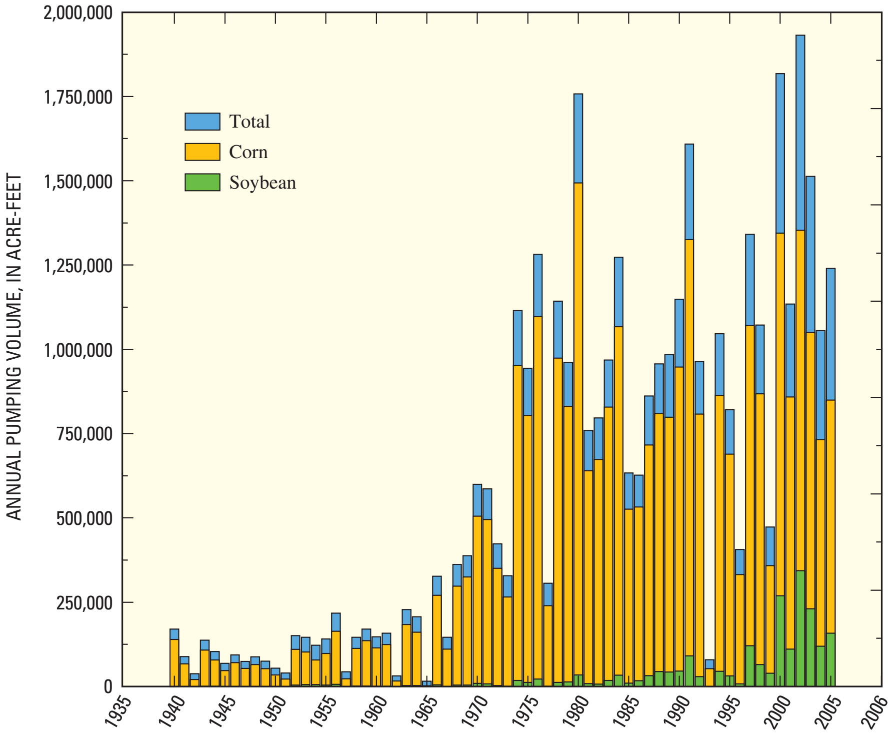


Figure 16. Yearly estimated pumpage for corn, soybeans, and total pumpage, Elkhorn and Loup River Basins, Nebraska, 1940 through 2005.

1940 through 2005 period for Middle Loup (Allan Schmidt, Middle Loup Public Power and Irrigation District, written commun., 2006), Sargent (Mel Brozek, Sargent Irrigation District, written commun., 2006), Farwell (Jack Wergen, Bureau of Reclamation, written commun., 2006, and Darwin Lee, Farwell Irrigation District, written commun., 2006), Ainsworth (William Peck, Bureau of Reclamation, written commun., 2006), and Twin Loups (Ron Wolfe, Twin Loups Irrigation District, written commun., 2006) Irrigation Districts. For all other irrigation districts and canal systems, canal seepage was estimated to be 43 percent of the total diverted water minus return flows, based on previous work (Duane Woodward, Central Platte NRD, oral commun., 2002) (fig. 17).

Lake McConaughy was represented in the simulation as a general-head boundary. This reservoir began storing water in 1940, reaching average storage capacity by about 1947. Water-level elevations from the end of the pre-1940 simulation were used as the starting water levels for the general-head boundary, as they were in the rest of the simulation domain. Though it was considered unlikely that changes in lake stage would have any major or far-reaching effects in the interior of the simulation area, analysis of readily available annual lake stage data (C. Steinke, Central Nebraska Public Power and Irrigation District, written commun., 2007) indicated variations in lake stage of tens of feet during 1940 through 2005. If any measured water-level changes that were to be used as observations had been near the lake, they could have been affected by these stage changes. Therefore, annual lake-stage elevations were assigned to the simulated 1940 through 2005 general-head boundary. For the parts of the model representing the lake, water-level elevations were set to the starting water-level elevations from the pre-1940 simulation if the lake-stage elevation was lower than the starting water-level elevation. Conductance for the general-head boundary was tested during simulation calibration and is discussed in the "Calibration Process" section of this report for the 1940 through 2005 simulation.

Calibration Targets

Though the starting water levels for the 1940 through 2005 simulation were the simulated 1940 water levels, uncertainty and misfit between the simulated 1940 water levels and the measured water levels probably would have biased a comparison of absolute water levels simulated from 1940 through 2005 against measured water levels. Therefore, simulated and measured water-level changes were used as the calibration targets because they provided a more clear indication of simulation calibration to conditions for the 1940 through 2005 period only (and various intermediate periods), rather than potentially being affected by errors that could have been present in the pre-1940 simulated water levels.

Ground-water level changes were calculated for the simulated and measured water levels in 10-year increments (1945–55, 1955–65, 1965–75, 1975–85, 1985–95, and 1995–2005) as well as for most of the simulation period (1945 to 2005). To obtain the largest number of calibration points, measured water levels (targets) were selected separately by decade from all available water-level measurements. For example, to calculate 1945–55 water-level change a well should have had measured water levels representing 1945 and 1955, but wells were not always measured in those specific

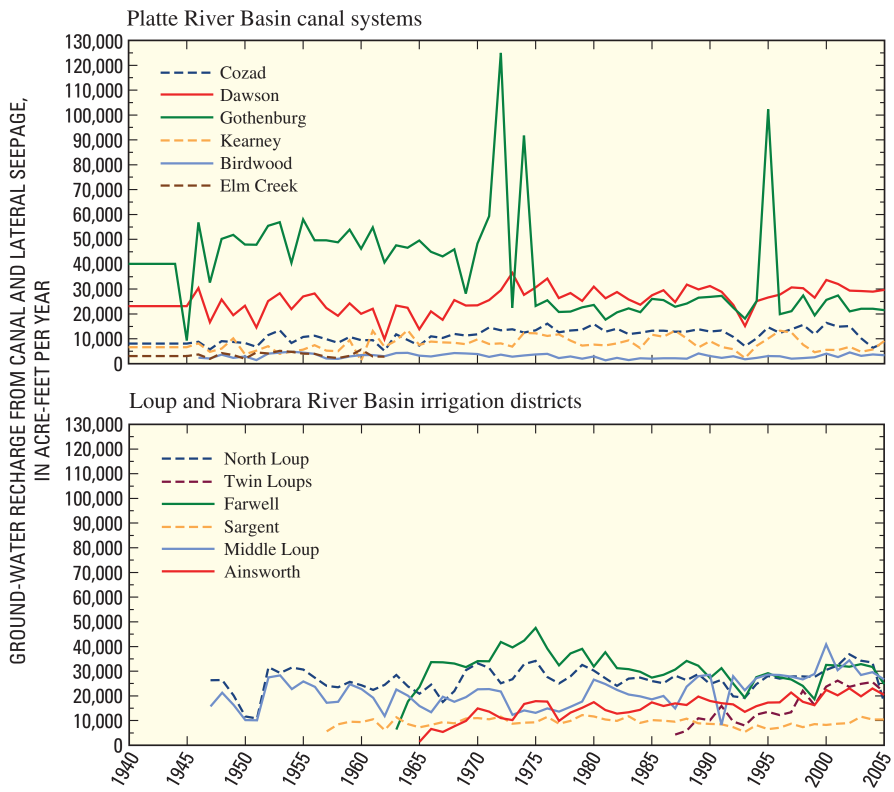


Figure 17. Estimated recharge from canal and lateral seepage, 1940 through 2005, Elkhorn and Loup River Basins, Nebraska.

years. Therefore, the measurement for 1945 would have been the measurement made between 1940 and 1949 closest to 1945, and the measurement for 1955 would have been the measurement made between 1950 and 1959 closest to 1955. In addition, some water levels randomly were removed from certain small areas of each set if many wells had been measured in that small area, because in many parts of the study area there were few measurements made or long distances between measured wells. This reduced the tendency for the areas with many measurements to obscure the calibration response of areas with fewer points.

The final set of measured water-level changes was not distributed evenly across the study area, nor was there an equal number for all time periods. Generally, there were more measured water levels in recent times than in early times; therefore, the 1995 through 2005 period had the most water-level changes.

Simulated 2005 base flow was compared with the same estimated long-term base flow used for the pre-1940 calibration. The same approach was used with respect to simulated 2005 base flow as was used for simulated 1940 base flow; if the simulated 2005 base flow was about the same as the estimated long-term base flow, the simulation was considered calibrated with respect to those base flows.

Calibration Process

As described previously in this report, estimated pumpage for irrigation was constrained using the best information available, so it was not adjusted during calibration of the 1940 through 2005 simulation. Recharge from precipitation occurring on unbroken (non-agricultural) lands was maintained at the same recharge from precipitation values used for the pre-1940 simulation. Canal-seepage recharge was estimated and also not adjusted during the calibration process. Pumpage for irrigation, when added to the 1940 through 2005 simulation, represents a substantial ground-water withdrawal; without an additional source of water, simulated water levels declined during the 1940 through 2005 period, though measured declines generally have not occurred in the study area. Therefore, the primary calibration strategy was to calibrate the simulation by increasing recharge applied to nonirrigated and irrigated cropland areas to balance the estimated (net) pumpage until simulated and measured water-level changes matched acceptably while ensuring that simulated 2005 base flows reasonably matched estimated base flows.

The conceptual model for enhanced recharge applied to agricultural cropland areas is that lands that have been plowed and that are used to grow crops allow precipitation to infiltrate more easily than those areas that remain unbroken (Scanlon and others, 2005). Similarly, the practice of irrigation causes soil moisture to be greater under irrigated agricultural lands; therefore, precipitation that occurs on irrigated lands also can infiltrate more easily and has a better chance of becoming recharge than precipitation that occurs on broken lands such as nonirrigated cropland (Luckey and Cannia, 2006). Therefore, areas with nonirrigated crops should allow more recharge from precipitation than unbroken lands, and areas with irrigated crops should allow more recharge than areas with nonirrigated crops. This concept of recharge is similar to that reported by Scanlon and others (2005), that recharge was greater under cultivated lands than under unbroken lands.

The rate of simulated recharge applied for these land classes to calibrate the simulation did not change with time during the 1940 through 2005 period, though the total amount of recharge did change with time as the amount of land classified as irrigated, nonirrigated, and rangeland changed. Recharge rate in the simulation was a calibration parameter and it is not known how the calibrated recharge compares to actually occurring recharge at a regional scale. However, if recharge rates applied to calibrate the simulation are similar to regionally occurring recharge rates, simulated recharge could be considered the long-term average recharge that occurred from that land classification type.

For recharge from precipitation occurring on nonirrigated and irrigated cropland areas, the iterative calibration process resulted in nonirrigated cropland areas allowing 0.5 in/yr more than recharge from precipitation applied to unbroken lands, and irrigated cropland areas allowing 3.5 in/yr more than recharge from precipitation applied to unbroken lands.

In addition, throughout the calibration process, simulated ground-water level declines consistently were larger than measured declines in an area of intense irrigation covering most of Hall County, southeast Buffalo County, and a small part of western Merrick County. Therefore, an additional 1 in/yr of recharge was added to the rate of recharge applied to irrigated lands in this area for 1970 through 2005, the period of most intense irrigation, to improve the calibration. This area may allow additional recharge because more fields are irrigated with gravity irrigation systems rather than the sprinkler irrigation systems more commonly used in other parts of the study area. Gravity irrigation systems typically lose more water to deep percolation than do sprinkler systems (Eisenhauer and others, 1996). In addition, it has been recognized that farmers in this area frequently dike the downgradient ends of fields (Duane Woodward, Central Platte Natural Resources District, oral commun., 2004). Diking field ends is not widely practiced throughout the rest of the study area but also would increase recharge by reducing runoff.

The conductance of the Lake McConaughy general-head boundary was adjusted during simulation calibration to test whether or not increasing or decreasing conductance from the initial estimate would improve the simulated water-level changes. Initial conductance values ranged from 0.08 to 2.50 ft^2/d per unit area. The range of conductance values tested was considered to be the range of reasonable values for lake-bed conductance by multiplying initial values by 0.4 and then by 20, but simulated water-level changes were not affected within this range; therefore, conductance of the Lake McConaughy general-head boundary was not changed.

Simulation Results

A statistical summary of the differences between the simulated and measured water-level changes for each 10-year time period and for 1945 through 2005 is shown in table 4. Spatial comparisons of simulated and measured water-level change for each time period are shown in figures 18–24. In many areas, neither simulated nor measured water levels changed more than 5 ft during a particular 10-year time period, and water-level changes were similar for simulated and measured values. However, several areas did not indicate agreement between simulated and measured water-level change. In the area of Cozad and Gothenburg Canal systems (fig. 8), the model simulated water-level rises from 1945 to 1955 that are not present in measured water-level changes, and the simulated changes from 1975 to 1985 were declines whereas measured water levels remained the same or rose. Simulated water-level rises for 1985 to 1995 were smaller than measured water-level rises in several parts of the study area, including the areas of the Twin Loups Irrigation District and Wheeler County. Simulated water-level declines for 1995 to 2005 were less than measured water-level declines between the South Loup/Loup River and the southern simulation boundary, and simulated water-level rises were less than measured water-level rises in the area of the Twin Loups Irrigation District.

Only 42 sites had a measured water level in both the 1940s and the 2000s and most were along the southern edge of the study area. Of those sites, 60 percent (25 of 42) had a simulated water-level change within 5 ft of measured water-level change. Unfortunately, measured water-level changes generally were not available in the same areas where simulated water-level rises and declines occurred. To better evaluate the match between simulated and measured water-level changes, simulated changes also were compared with predevelopment to spring 2005 water-level change maps published by the Conservation and Survey Division (2005a). Generally, simulated water-level changes were consistent with mapped water-level changes. However, several areas of simulated water-level changes do not correspond to mapped water-level changes. Simulated rises in Pierce and Knox Counties, near the Niobrara River in Brown County, and in southern Custer and northern Dawson Counties, are not present on the map. In addition, mapped rises in Hooker, Thomas, McPherson, and Logan Counties are not simulated. Mapped declines in Custer, Holt, Buffalo, and Hall Counties are for the most part replicated in the simulation. However, it is important to note that the mapped water-level changes were created using a variety of years defined as “predevelopment” in different areas, so disparities may be present in a strict comparison between simulated 1940 through 2005 water-level changes and mapped water-level changes from “predevelopment.”

The statistical differences between simulated and measured water-level changes for all of the time periods were averaged and weighted based on the number of calibration points selected in each time period. The weighting was done by multiplying the statistical difference for each period against the number of differences computed for that period, summing the weighted differences for all the periods, then dividing by the total number of differences for all periods. Therefore, periods with the most water-level changes more heavily affected

Table 4. Statistical summary of calibration for selected time periods of the 1940 through 2005 simulation, Elkhorn and Loup River Basins, Nebraska.

[Tabled values are differences between simulated and measured water-level change, in feet; negative values indicate simulated declines smaller than measured declines, or simulated rises larger than measured rises; --, not calculated]

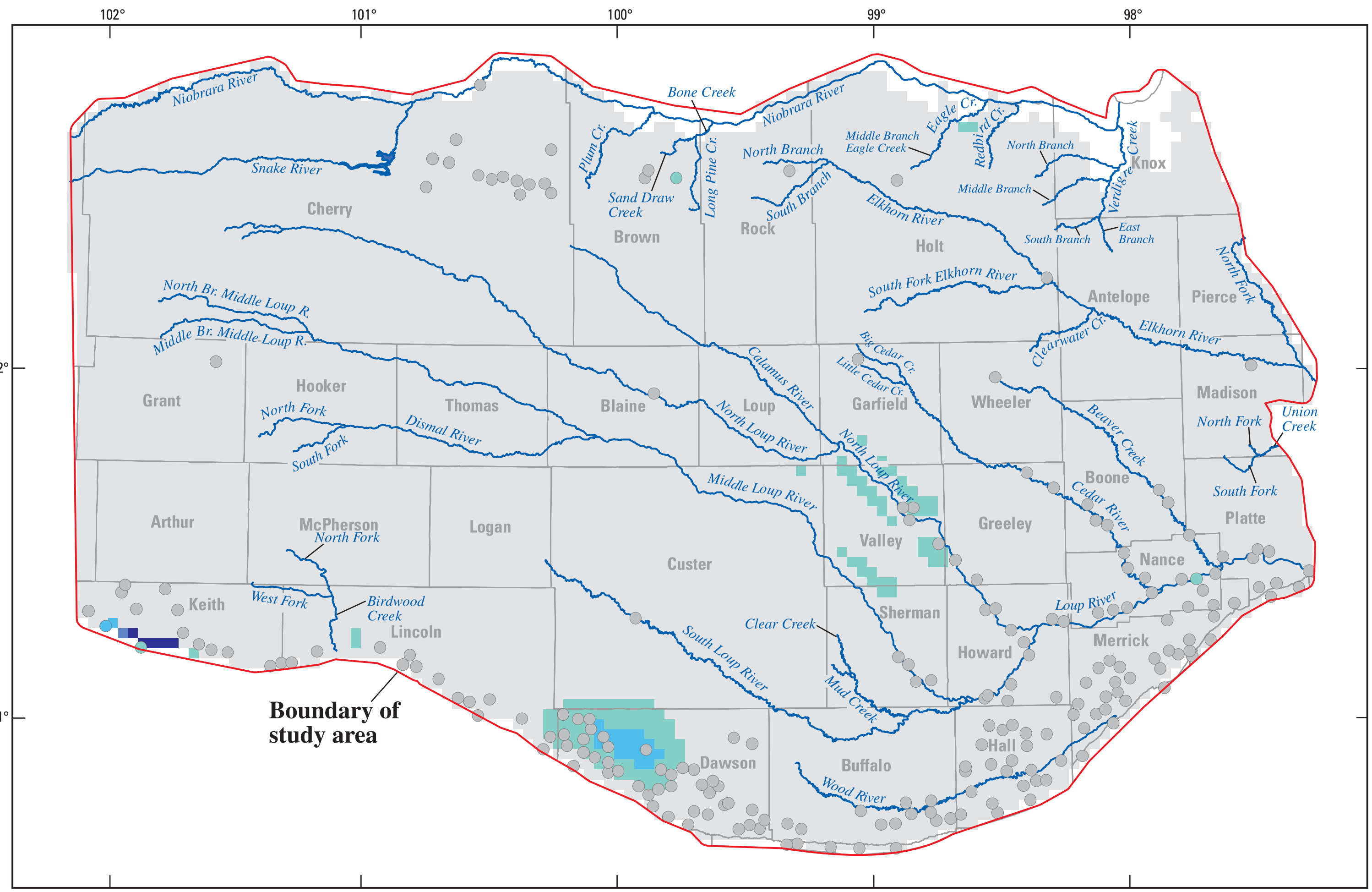
Time period	Number of measurements	Mean difference	Mean absolute difference	Root mean squared difference	Maximum difference	Percentage of sites with 5 feet of difference or less
1945–1955	207	-1.57	2.60	3.89	20.8	86
1955–1965	119	-1.55	2.35	3.08	8.4	87
1965–1975	158	-.15	3.22	5.28	29.3	84
1975–1985	411	-2.33	2.56	4.20	28.3	88
1985–1995	512	1.08	2.82	4.00	27.3	84
1995–2005	584	.02	3.03	4.60	36.5	83
1945–2005	42	1.19	5.04	6.39	17.7	60
Total measurements	**2,033**	**--**	**--**	**--**	**--**	**--**
Weighted average	**--**	**-.43**	**2.86**	**4.29**	**--**	**--**

model calibration because those periods more heavily affected the overall weighted-average statistics. The weighted-average mean difference was -0.43 ft, the weighted-average mean absolute difference was 2.86 ft, and the weighted-average RMS difference was 4.29 ft (table 4). Because the weighted-average mean difference is relatively close to zero, simulated water-level changes were not greatly biased as compared to measured water-level changes. Positive mean difference values indicate that either measured water-level declines were smaller than simulated water-level declines or that measured water-level rises were larger than simulated water-level rises. Positive mean difference values also can occur when measured water levels are rising and simulated water levels are declining. Conversely, negative mean difference values indicate that either measured water-level declines were larger than simulated water-level declines or that measured water-level rises were smaller than simulated water-level rises. Negative mean difference values also can occur when measured water levels are declining and simulated water levels are rising.

In addition to measured and mapped water-level changes, simulated water levels also were compared with time-series hydrographs for some wells for the 1940 through 2005 period (fig. 25). Site locations were chosen primarily based on availability of long-term water-level measurements, in addition to spatial distribution, distance from surface-water features, and proximity of the well screen to the water table, though this was not always possible in areas with fewer wells. Sites also were selected in areas of contrasting simulated water-level change—two sites were chosen in areas where simulated water levels declined at least 5 ft from 1940 through 2005 (wells 405226098390901, G; and 423641098580801, C), three sites were chosen in areas where simulated water levels rose at least 5 ft from 1940 through 2005 (wells 410306099402701, I; 413618099055801, E; and 415238097483700, D), and four sites were chosen in areas of little or no simulated water-level change from 1940 through 2005 (wells 404924098441801, H; 411333098144601, F; 420204101200501, A; and 422930100321801, B).

Because the primary goal of the transient simulation calibration was to match simulated water-level changes with measured water-level changes while maintaining simulated base flow about the same as estimated base flow, the criterion used to assess the hydrograph match was symmetry of water-level change patterns with time. Simulated and measured water-level elevations are not expected to match exactly, but the difference between simulated and measured water-level elevations should remain constant with time, and the magnitude of water-level rises and declines should be similar.

In areas of simulated water-level decline, simulated water-level change patterns were similar to measured change patterns, particularly at well 423641098580801 (C), though the simulated decline from about 1965 to 1975 was larger than the measured decline. At well 404924098441801 (H), the change patterns were comparable after about 1985, but the magnitudes of simulated rises and declines were less than those measured. However, the peaks and valleys exhibited by both hydrographs are in about the same place in time, which confirms that the simulation is demonstrating the correct trends at the correct times, even if the magnitudes are different. The same pattern was exhibited by hydrographs for well 405226098390901 (G), where the trends of sections of the simulated and measured hydrographs match after about 1980, as do the peaks and valleys, but the magnitude of the simulated changes are less than the measured changes. Because these three wells were located in areas where most of the land is used for ground-water irrigated crops, these results indicate that the simulation is generally simulating the effects of ground-water irrigation through time.



Base from U.S. Census Bureau, digital data, 2005, 1:100,000
Lambert Conformal Conic projection
Standard parallels 40°N and 43°N, central meridian 100°W

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

EXPLANATION

Water-level change 1945–55, in feet

	Simulated	Measured		
Greater than -25	Water-level rises		Greater than -25	
-25 to -15	Water-level rises		-25 to -15	
-15 to -10	Water-level rises		-15 to -10	
-10 to -5	Water-level rises		-10 to -5	
-5 to 5	Small rise or decline		-5 to 5	

	Simulated	Measured	
5 to 10	Water-level decline		5 to 10
10 to 15	Water-level decline		10 to 15
15 to 25	Water-level decline		15 to 25
Greater than 25	Water-level decline		Greater than 25

Figure 18. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1945–55.

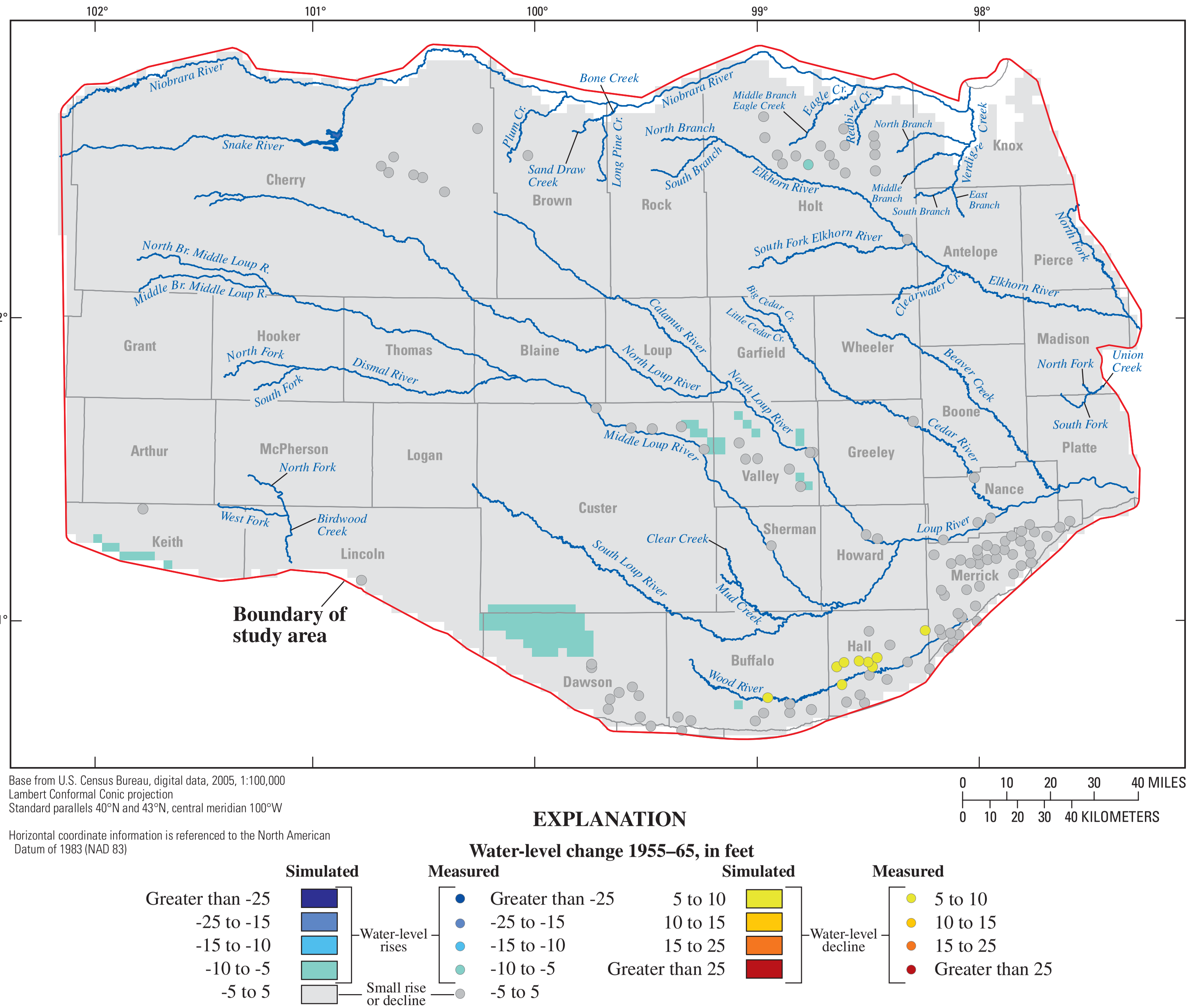


Figure 19. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1955–65.

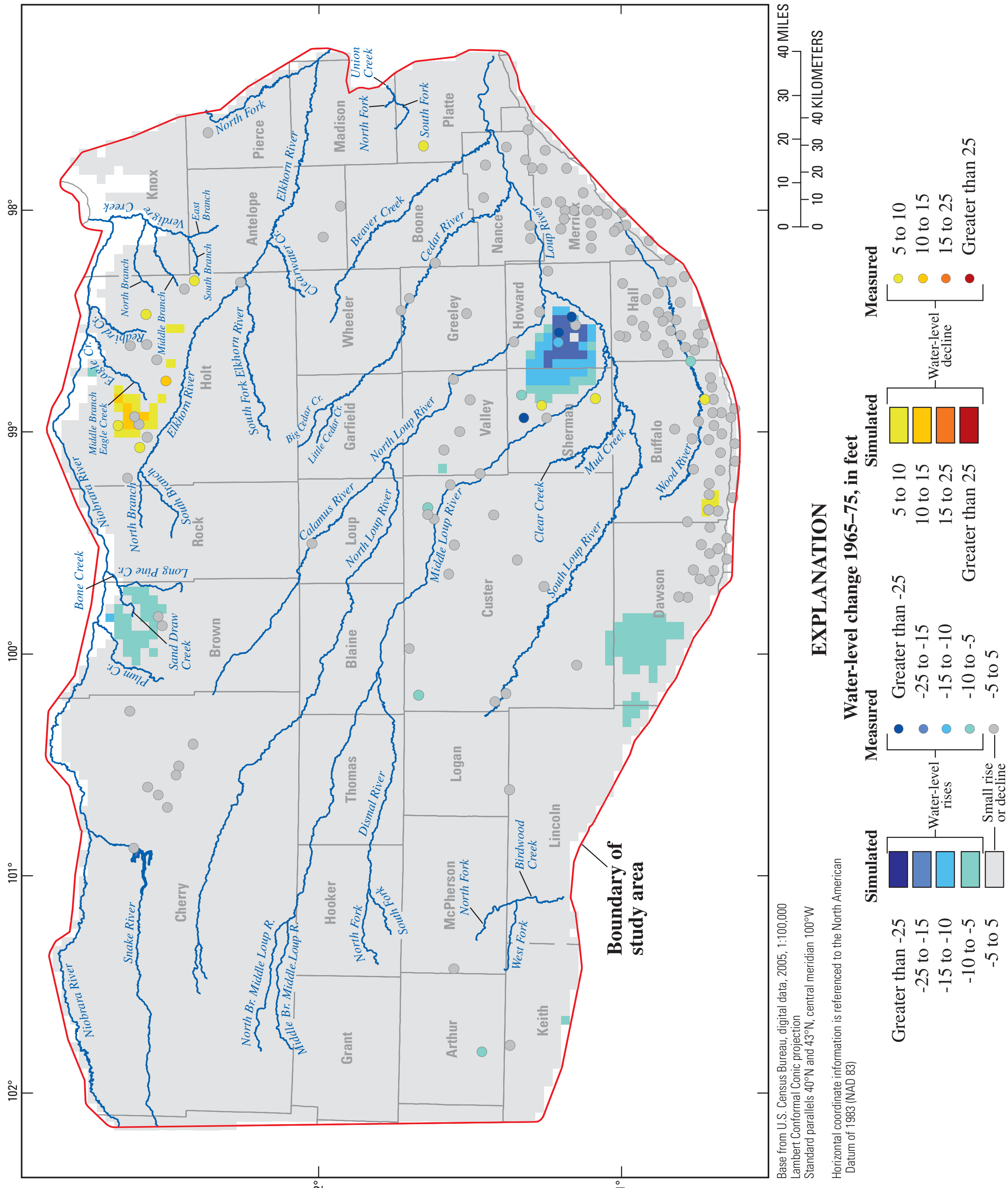


Figure 20. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1965–75.

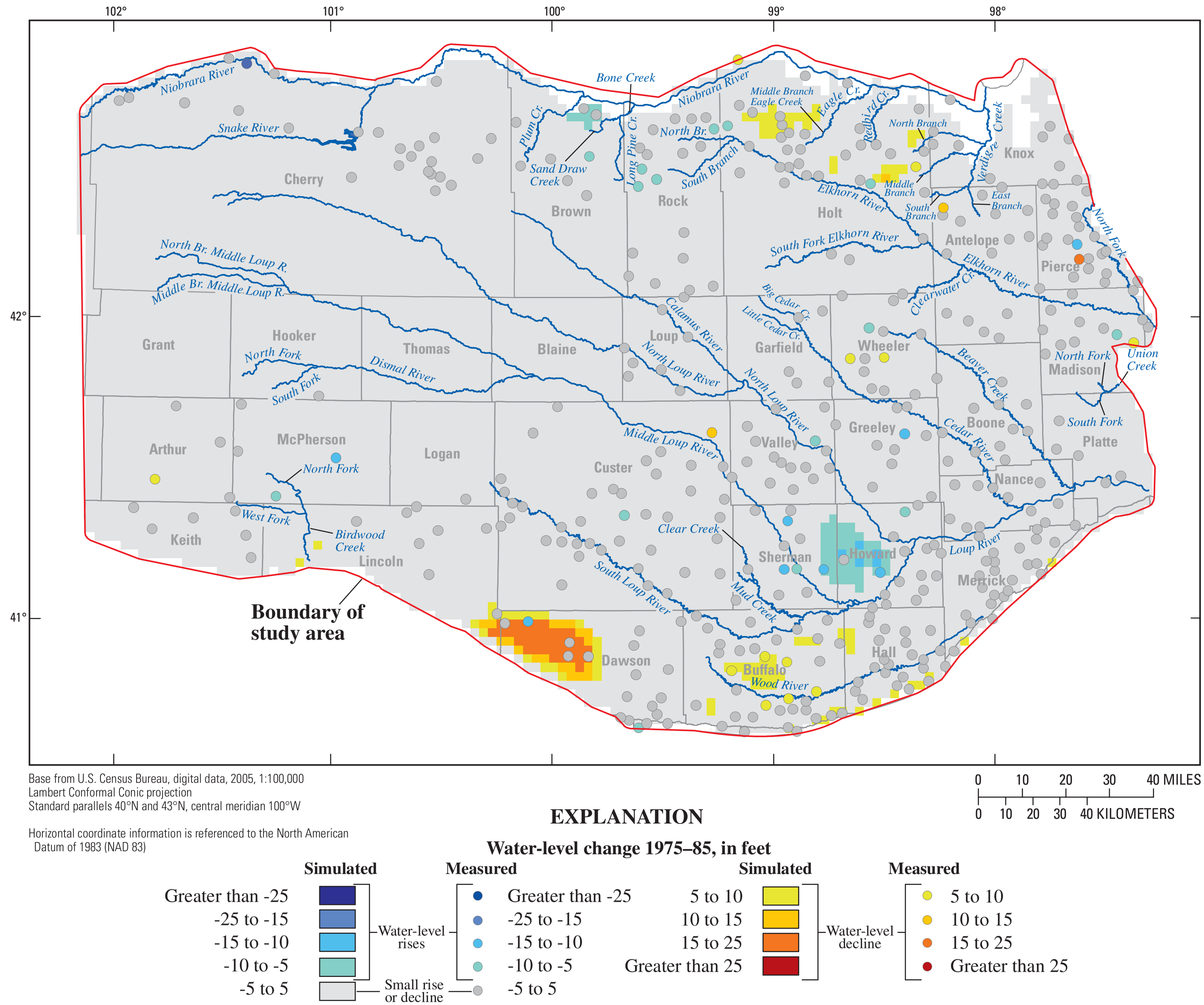


Figure 21. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1975–85.

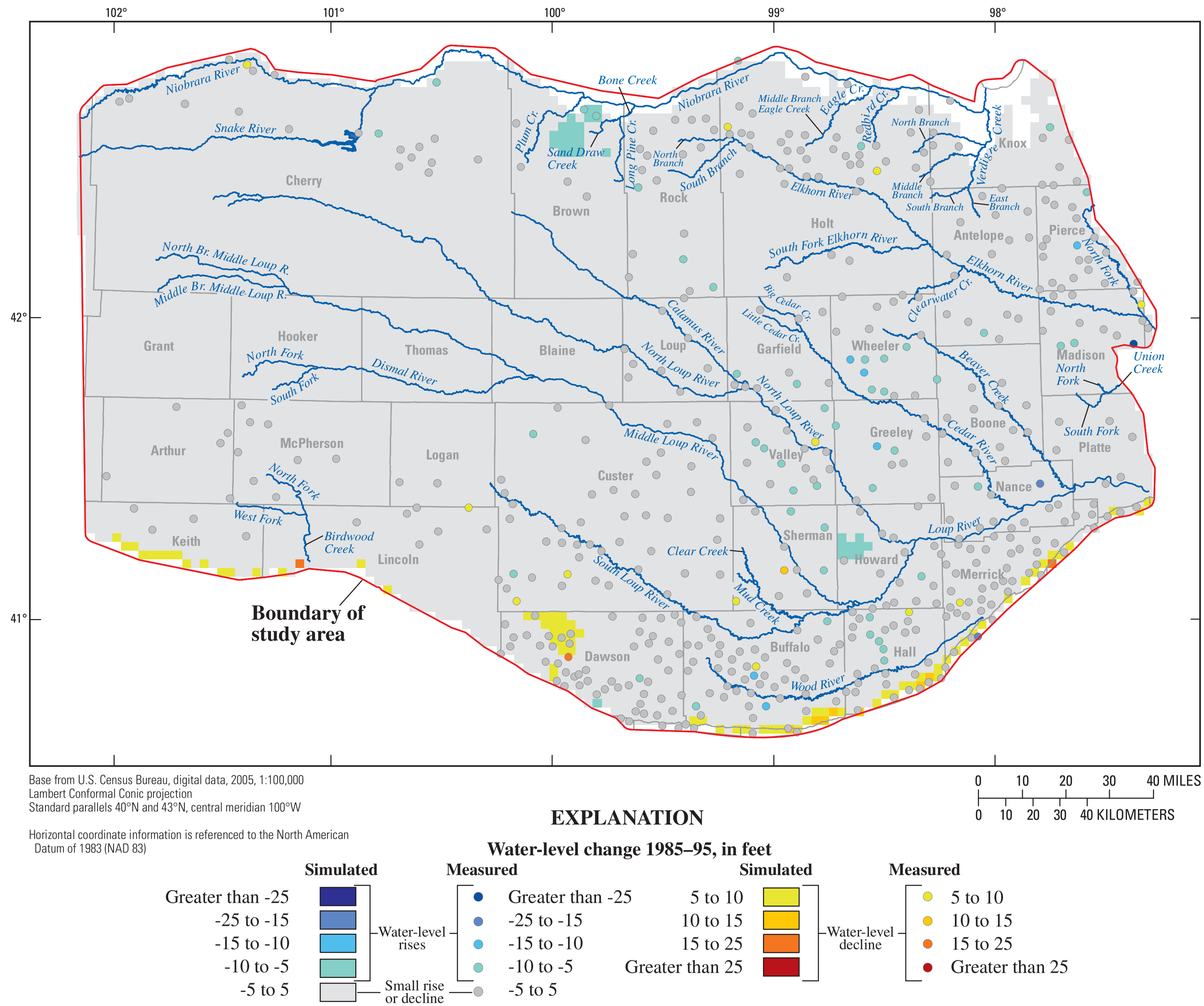


Figure 22. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1985–95.

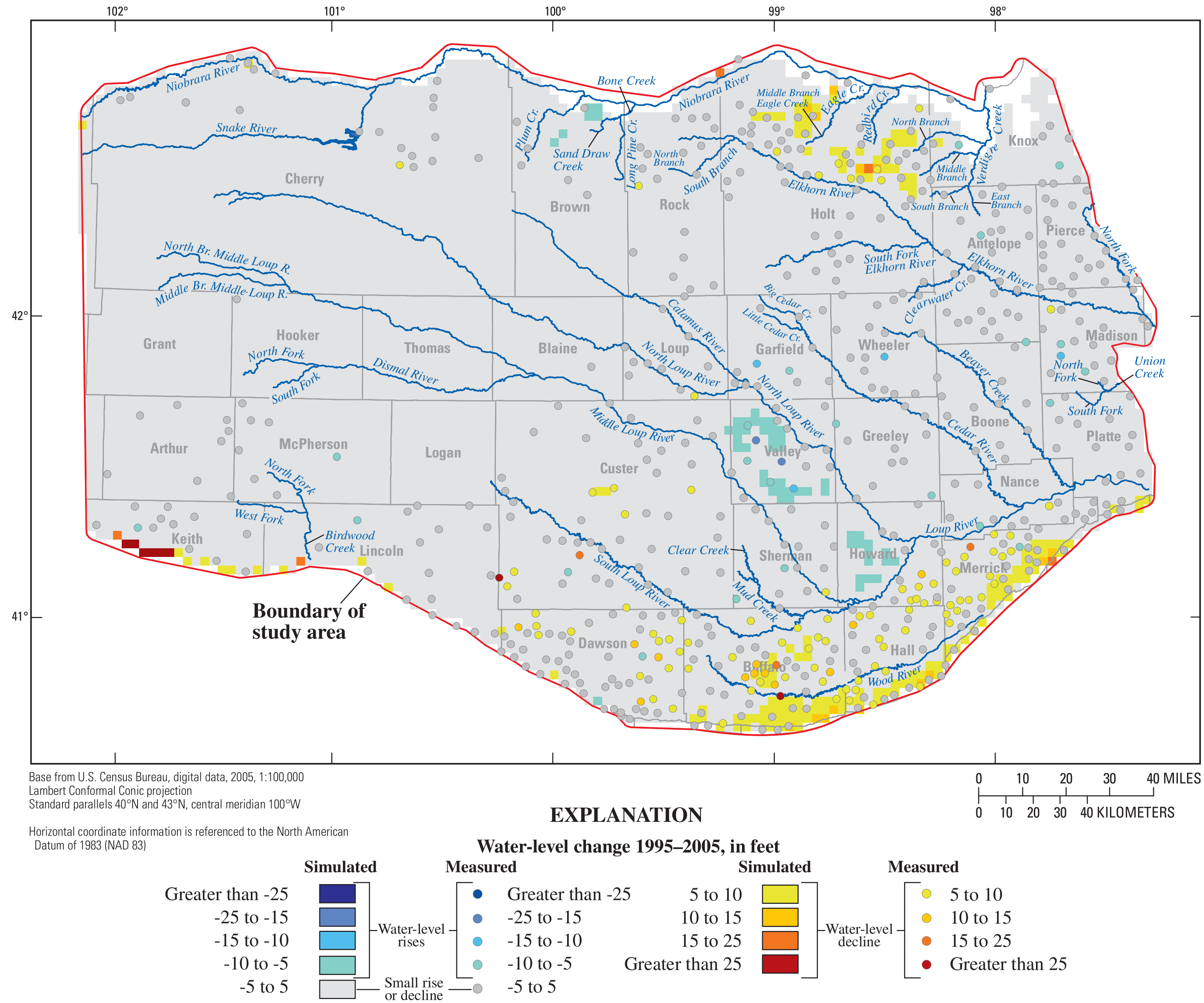
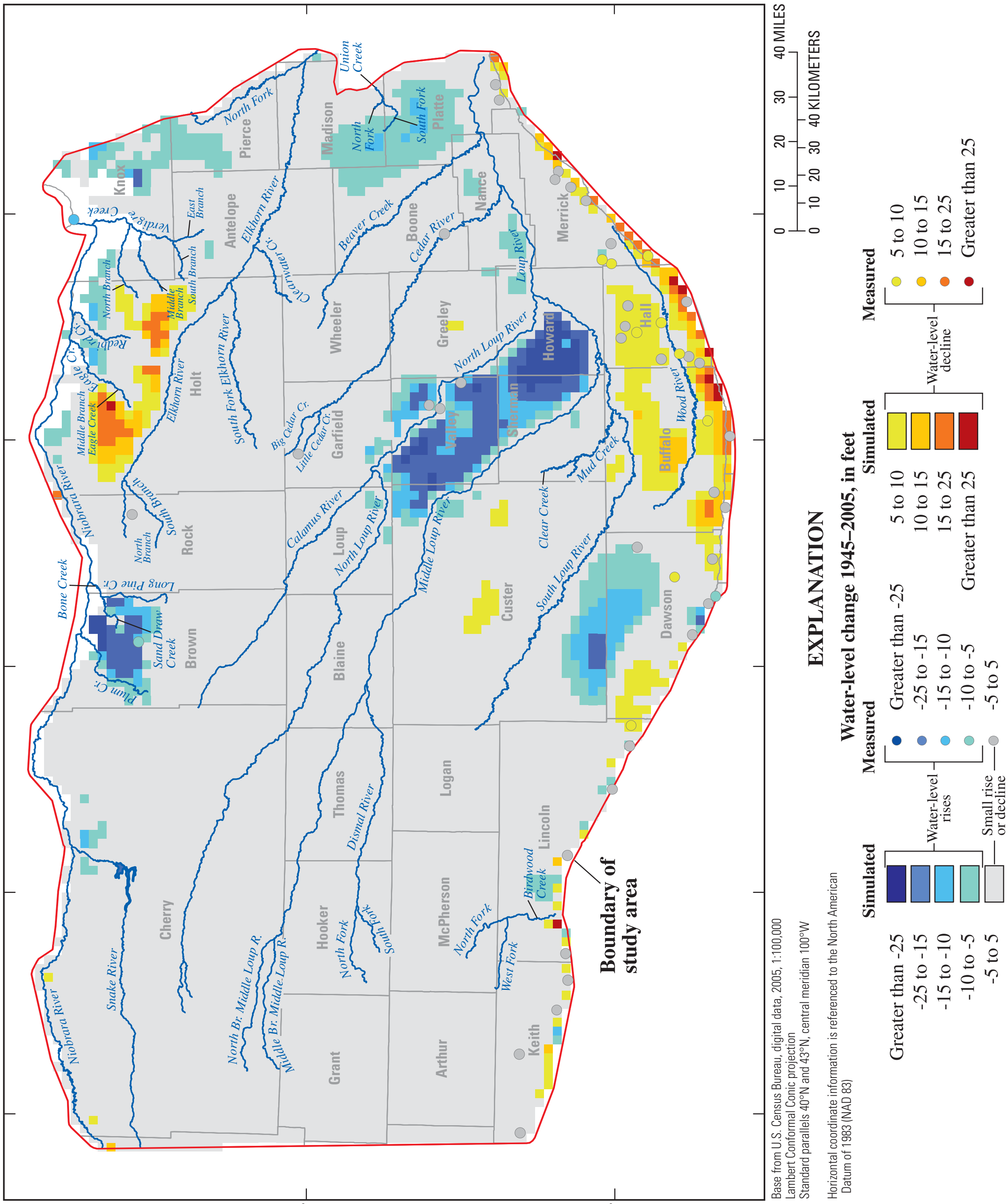


Figure 23. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1995–2005.



Base from U.S. Census Bureau, digital data, 2005, 1:100,000
Lambert Conformal Conic projection
Standard parallels 40°N and 43°N, central meridian 100°W

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

Figure 24. Differences between measured and simulated water-level changes, Elkhorn and Loup River Basins, Nebraska, 1945–2005.

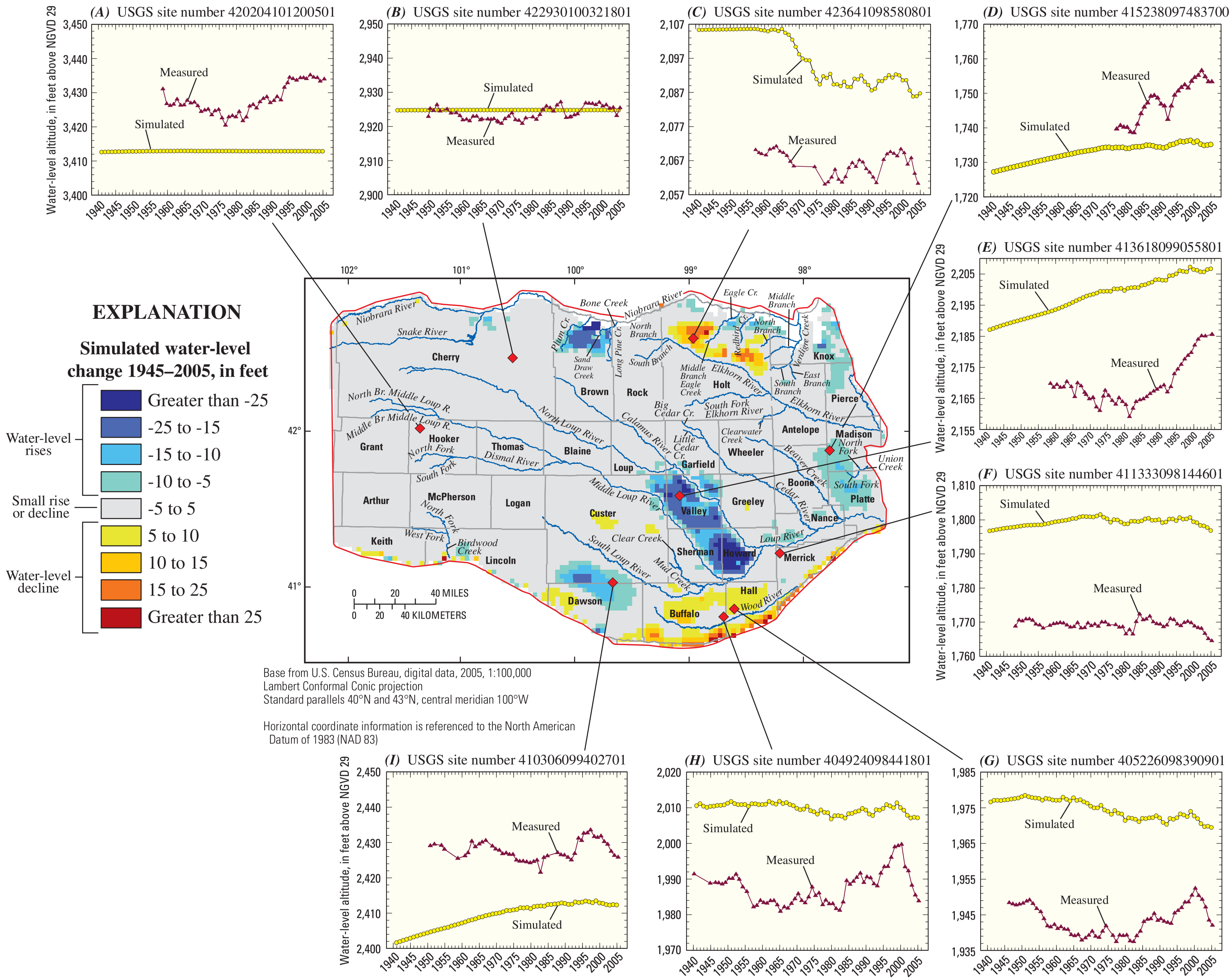


Figure 25. Calibration results for the 1940 through 2005 simulation, Elkhorn and Loup River Basins, Nebraska.

In areas of simulated water-level rise, the fit between simulated and measured change patterns was mixed. Simulated rises in southern Custer County were not present in the hydrograph for well 410306099402701 (I). Simulated water-level rises in Valley County generally were present in the hydrograph of well 413618099055801 (E) from the beginning to the end of record. From 1958 to 1982, however, measured water levels declined and simulated water levels rose, whereas after that time, the measured water levels increased by about the same amount as the simulated water levels increased during the 1940 through 2005 period. At well 415238097483700 (D), simulated and measured water levels rose, but simulated water levels had a smaller magnitude of rise and did not replicate two periods of measured declines.

In areas with small water-level changes, measured water-level fluctuations at two wells generally were replicated by the simulation (422930100321801, B; 411333098144601, F). However, the hydrograph for well 420204101200501 (A) shows that measured water levels fluctuated over a range of almost 15 ft, whereas simulated water levels did not change. The cause of this measured water-level rise is unclear; it does not occur in the hydrograph of well 422930100321801 (B), but based on only these few data, a conclusive determination cannot be made regarding regional water-level changes in undeveloped areas.

Simulated 2005 base flow was compared to estimated long-term base flow for 22 reaches based on streamflow-gaging stations (table 2, fig. 9). ZONEBUDGET (Harbaugh, 1990) was used to retrieve simulated base flows from the simulation outputs for comparison, with the zones corresponding to the stream cells in between or upstream from streamflow-gaging stations (fig. 9) for which base-flow values were estimated (table 2). A detailed analysis of base-flow trends was beyond the scope of this study, but because the base-flow estimates were computed using the period of record data, and in many cases the period of record is several decades from the 1930s to the 2000s, or at least a large part of that period, the base-flow estimates are regarded as indicative of long-term base flows. Therefore, the same approach to base-flow calibration was used for the simulated 2005 base flows as was used for the simulated 1940 base flows. If the simulated 2005 base flows were about the same as the “long-term” estimated base flows, the simulation was considered calibrated in respect to those base flows.

Simulated 2005 base flow at 45 percent (10 of the 22) of the USGS streamflow-gaging stations was within the range of estimated values (table 2). Simulated 2005 base flow at five stations was between 6 and 43 percent lower than the minimum estimated base flow. Simulated 2005 base flow was between 1 and 22 percent larger than the maximum estimated base flow at six stations, and about 85 percent larger than the maximum estimated base flow at one station (Mud Creek near Sweetwater). Streams with smaller 2005 base flow had the largest differences between the simulated and estimated base flow.

Averaged annually through the 1940 through 2005 simulation, approximately 68 percent of water entering the water-table aquifer was from recharge from precipitation (table 5). Other inflows of water were loss of stream base flow (10 percent), additional recharge applied to irrigated cropland areas (9 percent), canal-seepage recharge (5 percent), water leaving storage (3 percent), additional recharge applied to nonirrigated cropland areas (2 percent), and fixed water-level boundaries (1 percent). Ground-water discharge to stream base flow accounted for about one-half (53 percent) of the water leaving the water-table aquifer. Water also was lost from the water-table aquifer by evapotranspiration (19 percent), pumpage for irrigation (11 percent), fixed water-level boundaries (6 percent), base flow to drain boundaries (6 percent), water entering storage (4 percent), and pumpage for municipal use (<1 percent).

Sensitivity Analysis

Methods

Sensitivity of the calibrated simulation to changes in some of the simulation inputs was determined. The inputs tested primarily were calibration parameters or parameters for which uncertainty could have an important affect on the results. For example, most of the calibration of the pre-1940 simulation consisted of adjusting hydraulic conductivity and recharge, so these were included in sensitivity testing, as was recharge for the 1940 through 2005 simulation. Pumpage and specific yield were not calibration parameters for the 1940 through 2005 simulation, but pumpage affected how the inputs were adjusted to improve calibration, and uncertainty in specific yield might have affected the results, so these inputs also were tested for sensitivity.

The pre-1940 simulation and the 1940 through 2005 simulation were analyzed separately, and different inputs were investigated for different periods. The sensitivity analysis for each simulation consisted of uniformly increasing or decreasing a single simulation input and documenting how the input changes affected the comparison of simulated with measured water levels (pre-1940 simulation), simulated with measured water-level changes (1940 through 2005 simulation), and simulated 1940 and 2005 base flow with estimated long-term base flow. For the simulated 1940 water levels and simulated 1940 base flow, changes in streambed conductance, recharge from precipitation, hydraulic conductivity, and maximum evapotranspiration rate were investigated. For the simulated 1940 through 2005 water-level changes and simulated 2005 base flow, changes in specific yield, canal-seepage recharge, additional recharge applied to nonirrigated cropland areas, additional recharge applied to irrigated areas, and pumpage for irrigation were tested.

Table 5. Average annual simulated ground-water budget for the 1940 through 2005 simulation, Elkhorn and Loup River Basins, Nebraska.

[<, less than; --, not applicable]

Budget component	Inflows		Outflows	
	Thousands of acre-feet per year	Percentage of budget inflows	Thousands of acre-feet per year	Percentage of budget outflows
Storage	155	3	212	4
Fixed-water level boundaries	44	1	320	6
General-head boundary	12	<1	54	1
All recharge	4,302	[1]86	--	--
Canal-seepage recharge	262	5	--	--
Additional recharge applied to irrigated cropland areas	473	9	--	--
Additional recharge applied to nonirrigated cropland areas	118	2	--	--
Additional recharge applied to Hall and Buffalo Counties	16	<1	--	--
Recharge from precipitation	3,433	68	--	--
Base flow to/from stream boundaries	518	10	2,645	53
Base flow to drain boundaries	--	--	310	6
Evapotranspiration	--	--	933	19
Pumpage for irrigation	--	--	546	11
Pumpage for municipal use	--	--	10	<1
Total	**[1]5,032**	**100**	**[1]5,031**	**100**

[1]Sum of components does not equal total because of rounding.

Simulated 1940 Water Levels

The sensitivity of the simulated 1940 water levels to input changes was indicated by changes in the mean difference, mean absolute difference, and root mean square difference between measured and simulated 1940 water levels (table 6, fig. 26). The analysis indicated that simulated water levels were most sensitive to hydraulic conductivity and recharge from precipitation, and that decreases in hydraulic conductivity and increases in recharge would have brought the mean difference between simulated and measured water levels closer to zero. However, those changes would have degraded the mean absolute and root mean squared differences between simulated and measured water levels, so these changes would not have improved the overall simulation calibration. The simulation was relatively insensitive to changes in the maximum evapotranspiration rate and streambed conductance, and those changes did not cause universal improvement among the three comparative statistics.

Simulated 1940 Base Flow

The sensitivity of simulated 1940 base flow to streambed conductance, recharge from precipitation, hydraulic conductivity, and maximum evapotranspiration rate was investigated for four streams: Calamus River near Burwell, Middle Loup River at Arcadia, North Loup River near St. Paul, and Elkhorn River at Neligh (fig. 9). ZONEBUDGET (Harbaugh, 1990) was used to retrieve simulated base flows from the simulation outputs for comparison, with the zones corresponding to the stream cells in between or upstream from streamflow-gaging stations (fig. 9) for which base-flow values were estimated (table 2). These four streams were selected because they represent a variety of settings within the study area. The Calamus River, a Sand Hills stream, drains a gently sloping terrain in the east-central area of the Sand Hills and has steady flow, as indicated by the small range from the minimum to maximum estimated base flow (table 2). The Middle Loup River is a Sand Hills stream with more variable flow (both smaller and larger base flow than the Calamus River) that drains the west-central area of the Sand Hills, and it has been affected by surface-water irrigation districts. The reach of the North Loup River for which sensitivity results were recorded is a non-Sand Hills stream that has been affected by surface-water irrigation districts, whereas the Elkhorn River is a non-Sand Hills stream in the eastern part of the study area that has not been affected by surface-water irrigation.

At these four streams, adjustments to recharge from precipitation rates yielded the largest changes to simulated base-flow values (table 7, fig. 27). Simulated base flow also was sensitive to changes in hydraulic conductivity, but relatively insensitive to changes in maximum evapotranspiration rate and streambed conductance.

Table 6. Sensitivity of simulated 1940 water levels and 1940 through 2005 water-level changes to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.

[Tabled values are differences between simulated and measured water-level change, in feet; negative values indicate simulated declines smaller than measured declines, or simulated rises larger than measured rises. Values in bold under multiplier of '1.00' are the values from the calibrated simulation of that time period]

Type of statistic	Model input	Input multiplier, dimensionless								
		0.70	0.80	0.90	0.95	1.00	1.05	1.10	1.20	1.30
Pre-1940 simulation—comparison of measured water levels with simulated 1940 water levels										
Mean difference	Evapotranspiration	-1.38	-2.22	-2.85	-3.13	**-3.38**	-3.62	-3.84	-4.26	-4.63
	Hydraulic conductivity	6.16	2.37	-.72	-2.10	**-3.38**	-4.57	-5.69	-7.74	-9.64
	Recharge from precipitation	-14.30	-10.37	-6.74	-5.04	**-3.38**	-1.75	-.15	2.98	6.03
	Streambed conductance	-2.55	-2.88	-3.15	-3.27	**-3.38**	-3.49	-3.58	-3.76	-3.92
Mean absolute difference	Evapotranspiration	22.84	22.52	22.30	22.21	**22.14**	22.07	22.00	21.90	21.81
	Hydraulic conductivity	24.59	23.18	22.38	22.18	**22.14**	22.18	22.34	22.80	23.39
	Recharge from precipitation	24.70	23.11	22.33	22.14	**22.14**	22.27	22.58	23.50	24.58
	Streambed conductance	22.17	22.16	22.15	22.14	**22.14**	22.14	22.13	22.13	22.13
Root mean square difference	Evapotranspiration	38.92	38.50	38.15	37.99	**37.85**	37.72	37.59	37.38	37.17
	Hydraulic conductivity	40.73	38.91	38.09	37.91	**37.85**	37.88	38.00	38.39	38.92
	Recharge from precipitation	39.96	38.55	37.91	37.80	**37.85**	38.05	38.38	39.41	40.87
	Streambed conductance	37.82	37.83	37.83	37.84	**37.85**	37.85	37.86	37.88	37.89
1940 through 2005 simulation—comparison of measured water-level changes with simulated water-level changes										
Mean difference	Specific yield	-.31	-.36	-.40	-.41	**-.43**	-.44	-.45	-.47	-.49
	Canal-seepage recharge	-.30	-.34	-.39	-.41	**-.43**	-.45	-.47	-.52	-.56
	Dryland recharge	-.41	-.42	-.43	-.43	**-.43**	-.44	-.44	-.44	-.43
	Pumpage for irrigation	-1.09	-.87	-.65	-.54	**-.43**	-.32	-.20	.03	.27
	Additional recharge applied to irrigated cropland areas	.35	.08	-.18	-.30	**-.43**	-.55	-.68	-.92	-1.17
Mean absolute difference	Specific yield	2.98	2.93	2.89	2.87	**2.86**	2.84	2.83	2.81	2.79
	Canal-seepage recharge	2.77	2.80	2.83	2.84	**2.86**	2.87	2.89	2.92	2.96
	Dryland recharge	2.86	2.86	2.86	2.86	**2.86**	2.86	2.86	2.86	2.86
	Pumpage for irrigation	2.95	2.87	2.83	2.84	**2.86**	2.88	2.91	3.01	3.15
	Additional recharge applied to irrigated cropland areas	3.13	2.99	2.90	2.87	**2.86**	2.85	2.86	2.93	3.04
Root mean square difference	Specific yield	4.48	4.40	4.34	4.31	**4.29**	4.27	4.26	4.23	4.21
	Canal-seepage recharge	4.18	4.21	4.25	4.27	**4.29**	4.32	4.35	4.40	4.47
	Dryland recharge	4.29	4.29	4.29	4.29	**4.29**	4.29	4.29	4.29	4.29
	Pumpage for irrigation	4.38	4.31	4.28	4.28	**4.29**	4.32	4.36	4.48	4.65
	Additional recharge applied to irrigated cropland areas	4.60	4.44	4.34	4.31	**4.29**	4.29	4.31	4.37	4.49

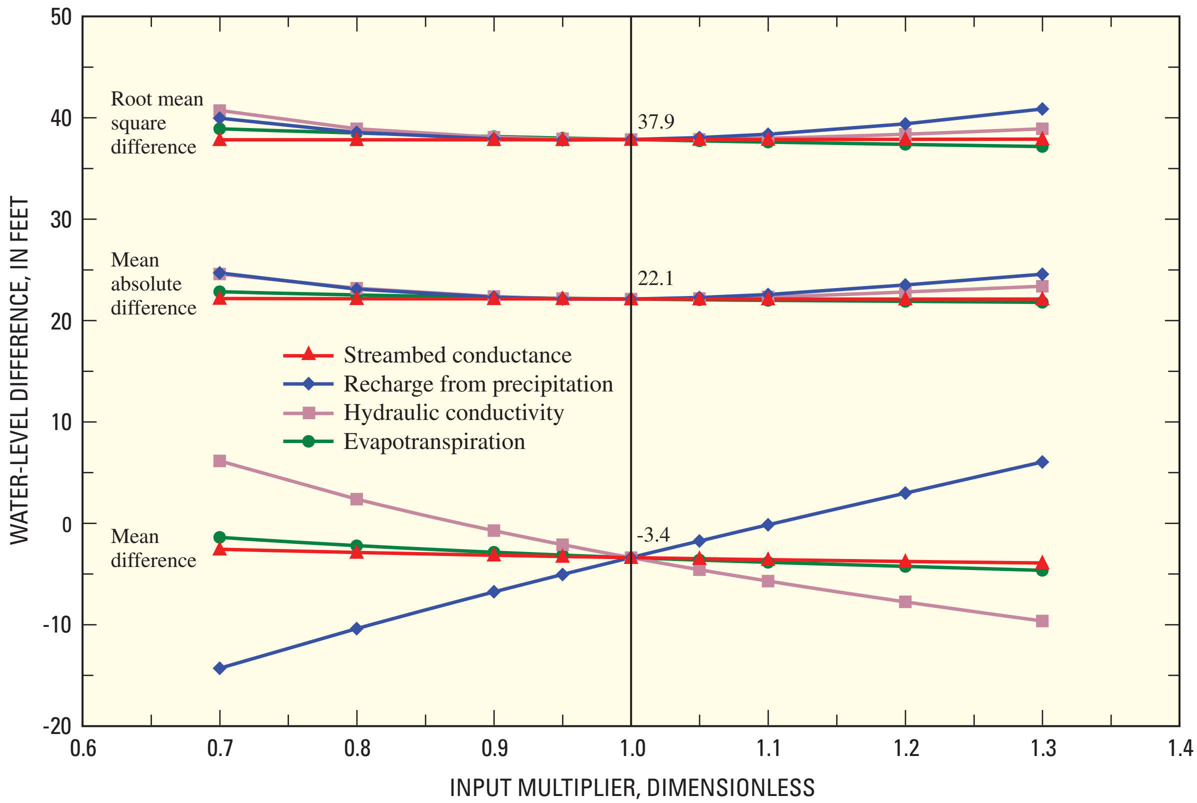


Figure 26. Sensitivity of simulated 1940 water levels to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.

Changes to simulation inputs during the sensitivity analysis for 1940 base flow did not indicate that input modifications would improve simulated 1940 base flow. Simulated 1940 base flow for the Elkhorn River at Neligh was within the range of estimated long-term base-flow values for all tests (table 7). For the Calamus River near Burwell, simulated 1940 base flow was less than the estimated minimum base flow for the calibrated simulation. Increases to recharge from precipitation and hydraulic conductivity caused simulated 1940 base flow for the Calamus River near Burwell to increase to within the estimated range; however, increases to these inputs degraded calibration results for simulated water levels and therefore would not have improved overall simulation calibration. Similar for the Elkhorn River at Neligh, simulated 1940 base flows at the North Loup River near St. Paul were within the estimated range for all tests except for an increase in recharge from precipitation by 30 percent. For the Middle Loup River at Arcadia, a decrease of recharge by 30 percent caused simulated 1940 base flow to be lower than the estimated minimum base flow, whereas changes to all other simulation inputs resulted in simulated 1940 base flow values within the estimated range.

Simulated 1940 through 2005 Water-Level Changes

A sensitivity analysis was conducted for the 1940 through 2005 simulation, using the weighted-average mean difference, mean absolute difference, and root mean squared difference between simulated and measured water-level changes, totaling 2,033 measurements for all time periods (method of weighting described in the “Simulation Results” section of this report for the 1940 through 2005 simulation). Simulated water-level changes were most sensitive to changes in pumpage for irrigation and additional recharge applied to irrigated cropland areas, least sensitive to changes in specific yield and canal-seepage recharge, and relatively insensitive to changes in additional recharge applied to nonirrigated cropland areas (table 6, fig. 28).

Results did not indicate that increases or decreases in specific yield, irrigated-land recharge, and pumpage for irrigation would improve simulation calibration. However, averaged mean difference, averaged mean absolute difference, and averaged root mean squared difference were all at a minimum when canal-seepage recharge was decreased 30 percent,

Table 7. Sensitivity of simulated 1940 and 2005 base flow to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.

[Units are acre-feet per year; ET, evapotranspiration; values in bold under multiplier of '1.00' are the values from the calibrated simulation of that time period]

U.S. Geological Survey streamflow-gaging station and number	Long-term estimated base flow		Model input	Adjusted base flow								
	Minimum flow	Maximum flow		Input multiplier								
				0.70	0.80	0.90	0.95	1.00	1.05	1.10	1.20	1.30
1940												
Calamus River near Burwell (06787500)	179,000	192,000	Maximum ET rate	178,000	176,000	175,000	175,000	**175,000**	174,000	174,000	174,000	173,000
			Streambed conductance	174,000	174,000	174,000	175,000	**175,000**	175,000	175,000	175,000	175,000
			Hydraulic conductivity	163,000	167,000	171,000	173,000	**175,000**	176,000	178,000	181,000	184,000
			Recharge from precipitation	131,000	146,000	160,000	167,000	**175,000**	182,000	189,000	204,000	219,000
Middle Loup River at Arcadia (06779000)	85,000	240,000	Maximum ET rate	131,000	129,000	127,000	126,000	**126,000**	125,000	124,000	122,000	121,000
			Streambed conductance	121,000	123,000	124,000	125,000	**126,000**	126,000	127,000	127,000	128,000
			Hydraulic conductivity	127,000	127,000	126,000	126,000	**126,000**	125,000	125,000	124,000	122,000
			Recharge from precipitation	83,800	97,700	112,000	119,000	**126,000**	132,000	139,000	152,000	165,000
North Loup River near St. Paul (06790500)	18,500	64,000	Maximum ET rate	53,900	53,800	53,800	53,800	**53,700**	53,700	53,700	53,600	53,600
			Streambed conductance	53,200	53,400	53,600	53,700	**53,700**	53,800	53,800	53,900	54,000
			Hydraulic conductivity	49,800	51,200	52,500	53,100	**53,700**	54,400	55,000	56,300	57,500
			Recharge from precipitation	41,900	45,800	49,800	51,700	**53,700**	55,700	57,600	61,500	65,300
Elkhorn River at Neligh (06798500)	9,530	44,800	Maximum ET rate	31,300	30,400	29,500	29,100	**28,700**	28,200	27,800	27,100	26,300
			Streambed conductance	27,900	28,200	28,400	28,500	**28,700**	28,800	28,900	29,100	29,200
			Hydraulic conductivity	24,900	26,100	27,400	28,100	**28,700**	29,200	29,800	31,000	32,100
			Recharge from precipitation	21,900	24,200	26,400	27,500	**28,700**	29,800	30,900	33,100	35,300

Table 7. Sensitivity of simulated 1940 and 2005 base flow to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.—Continued

[Units are acre-feet per year; ET, evapotranspiration; values in bold under multiplier of '1.00' are the values from the calibrated simulation of that time period]

U.S. Geological Survey streamflow-gaging station and number	Long-term estimated base flow		Model input	Adjusted base flow								
				Input multiplier								
	Minimum flow	Maximum flow		0.70	0.80	0.90	0.95	1.00	1.05	1.10	1.20	1.30
			2005									
Calamus River near Burwell (06787500)	179,000	192,000	Additional recharge from irrigated cropland areas	179,000	179,000	179,000	179,000	**179,000**	180,000	180,000	180,000	180,000
			Additional recharge from nonirrigated cropland areas	176,000	177,000	178,000	179,000	**179,000**	180,000	181,000	182,000	183,000
			Canal-seepage recharge	178,000	179,000	179,000	179,000	**179,000**	180,000	180,000	180,000	180,000
			Specific yield	179,000	179,000	179,000	179,000	**179,000**	179,000	179,000	179,000	179,000
			Pumpage for irrigation	180,000	180,000	180,000	179,000	**179,000**	179,000	179,000	179,000	179,000
Middle Loup River at Arcadia (06779000)	85,000	240,000	Additional recharge from irrigated cropland areas	148,000	150,000	151,000	152,000	**153,000**	154,000	155,000	157,000	158,000
			Additional recharge from nonirrigated cropland areas	151,000	151,000	152,000	153,000	**153,000**	153,000	154,000	155,000	156,000
			Canal-seepage recharge	144,000	147,000	150,000	152,000	**153,000**	155,000	156,000	159,000	162,000
			Specific yield	153,000	153,000	153,000	153,000	**153,000**	153,000	153,000	153,000	153,000
			Pumpage for irrigation	158,000	157,000	155,000	154,000	**153,000**	152,000	151,000	150,000	148,000
North Loup River near St. Paul (06790500)	18,500	64,000	Additional recharge from irrigated cropland areas	71,300	73,500	75,800	76,900	**78,000**	79,100	80,200	82,500	84,700
			Additional recharge from nonirrigated cropland areas	76,300	76,900	77,400	77,700	**78,000**	78,300	78,600	79,100	79,700
			Canal-seepage recharge	70,200	72,800	75,400	76,700	**78,000**	79,300	80,600	83,200	85,900
			Specific yield	80,000	79,300	78,600	78,300	**78,000**	77,700	77,500	76,900	76,500
			Pumpage for irrigation	83,900	82,000	80,000	79,000	**78,000**	77,000	76,000	74,100	72,100
Elkhorn River at Neligh (06798500)	9,530	44,800	Additional recharge from irrigated cropland areas	23,800	25,600	27,400	28,300	**29,200**	30,100	31,000	32,700	34,600
			Additional recharge from nonirrigated cropland areas	27,500	28,100	28,600	28,900	**29,200**	29,500	29,700	30,300	30,800
			Canal-seepage recharge	29,200	29,200	29,200	29,200	**29,200**	29,200	29,200	29,200	29,200
			Specific yield	29,100	29,100	29,200	29,200	**29,200**	29,200	29,200	29,200	29,200
			Pumpage for irrigation	33,100	31,800	30,500	29,800	**29,200**	28,500	27,900	26,600	25,300

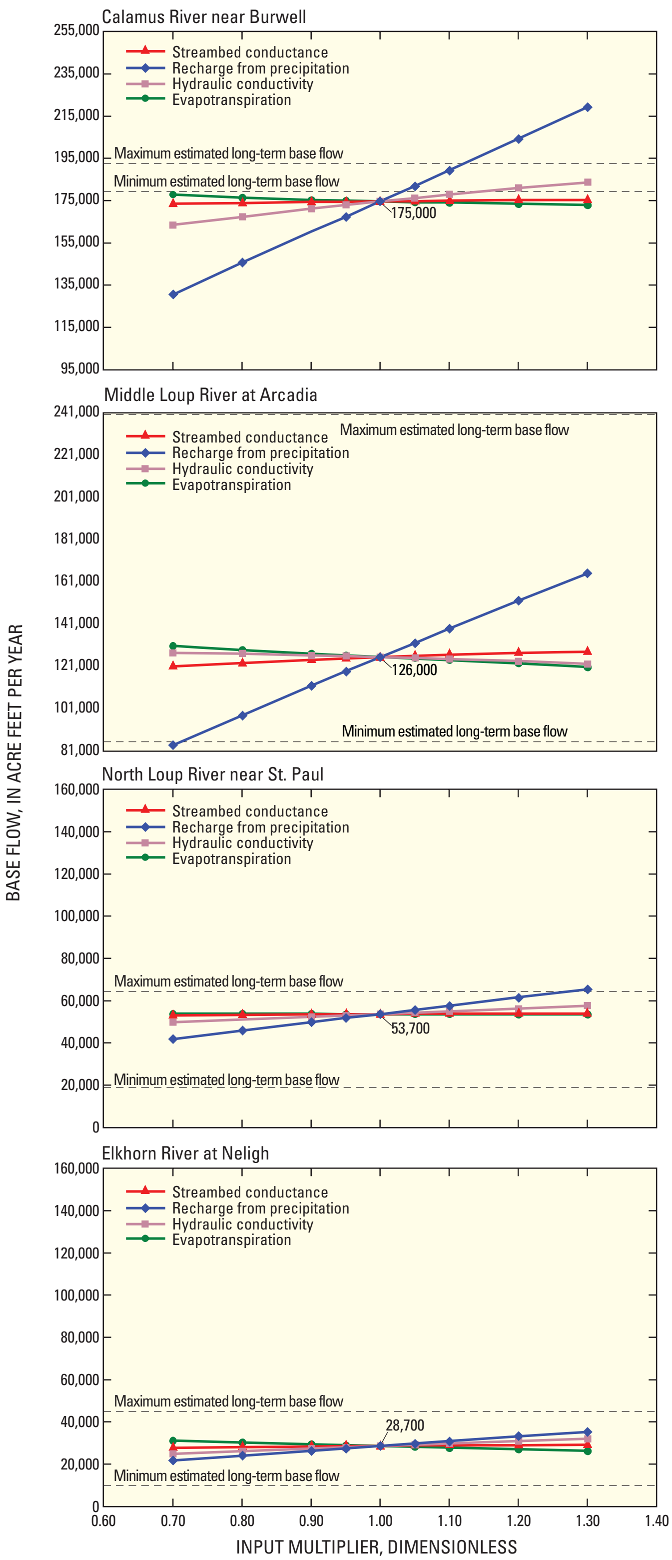


Figure 27. Sensitivity of the simulated 1940 base flow of selected streams to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.

indicating that a decrease in canal-seepage recharge would improve calibration. However, canal-seepage recharge was constrained with available data and was not adjusted during calibration; therefore it also was not adjusted after sensitivity analysis.

Simulated 2005 Base Flow

The sensitivity of simulated 2005 base flow to additional recharge applied to irrigated cropland areas, additional recharge applied to nonirrigated cropland areas, canal-seepage recharge, specific yield, and pumpage for irrigation was investigated for the same four streams that were used in the 1940 base-flow sensitivity analysis: Calamus River near Burwell, Middle Loup River at Arcadia, North Loup River near St. Paul, and Elkhorn River at Neligh (table 7, fig. 29). ZONEBUDGET (Harbaugh, 1990) was used to retrieve simulated base flows from the simulation outputs for comparison, with the zones corresponding to the reaches between or upstream from streamflow-gaging stations for which base-flow values were estimated (table 2). Simulated 2005 base flow was most sensitive to changes in additional recharge applied to irrigated cropland areas, canal-seepage recharge, and pumpage for irrigation.

For the Elkhorn and Middle Loup Rivers, simulated 2005 base flow was within the estimated base-flow range for the calibrated simulation and all changes to simulation inputs of up to 30 percent (fig. 29). Reductions greater than 5 percent to additional recharge applied to nonirrigated cropland areas and reductions greater than 20 percent to canal-seepage recharge caused simulated 2005 base flow for the Calamus River to be less than the minimum estimated base flow. Simulated 2005 base flow of the North Loup River was larger than the estimated range for the calibrated simulation and for all changes to inputs analyzed for sensitivity.

Reducing additional recharge applied to irrigated cropland areas caused North Loup River simulated 2005 base flow to improve but also degraded simulated water levels, which would not have improved overall simulation calibration. North Loup River simulated 2005 base flow decreased when pumpage for irrigation was increased, specific yield was increased, canal-seepage recharge was decreased, or additional recharge applied to irrigated cropland areas was decreased. However, increases to pumpage for irrigation degraded the mean absolute and root mean squared differences between simulated and measured water levels. Increases to specific yield caused only slight decreases in the North Loup River simulated 2005 base flow. Reductions in canal-seepage recharge caused North Loup River simulated 2005 base flow to decrease, but still not to less than the estimated maximum value. However, simulated canal-seepage recharge affecting this stream began after 1940 and increased greatly during the 1940 through 2005 period, and so could be considered to have increased by 100 percent; therefore, it was not surprising that a 30 percent reduction failed to reduce it to within the estimated range. In addition, canal-seepage recharge was relatively well

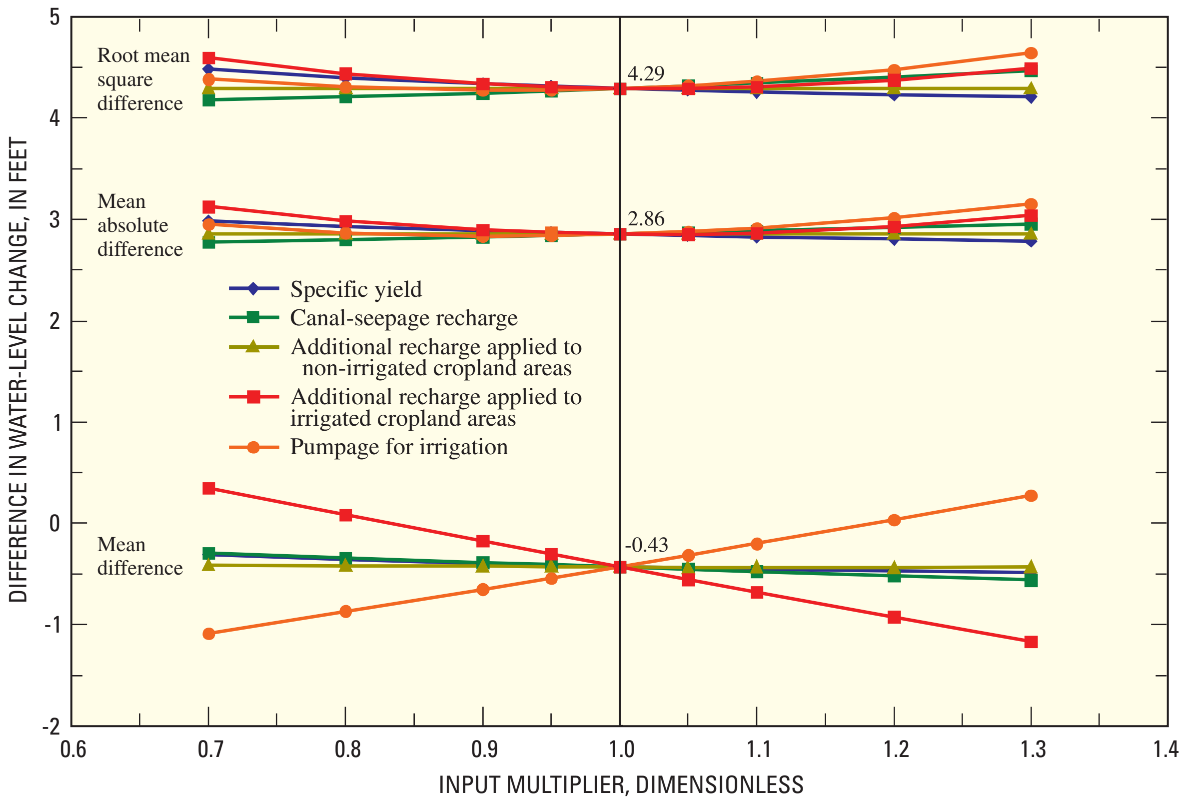


Figure 28. Sensitivity of the simulated 1940 through 2005 water-level changes to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska. (Results are a weighted average combining seven separate time periods.)

constrained for most surface-water irrigation districts, and thus was not a calibration parameter.

Effects of Ground-Water Irrigation on Base Flow

The calibrated simulation was used for two different types of analyses designed to provide information about the effects of ground-water irrigation on base flow, upon which long-term management decisions could be based. Both analyses used simulations of hypothetical future scenarios. The first analysis determined the effects of ground-water irrigation on simulated base flow for the calibrated 1940 through 2005 simulation and predicted future effects with a 2006 through 2045 simulation. Results of this analysis are described in the “Difference in Simulated Base Flow Caused by Ground-Water Irrigation” section of this report. The length of the future period in the hypothetical scenario used for this analysis was not tied to a specific rule or guideline; the desired result was to evaluate the effects of ground-water irrigation on simulated base flow for an extended period in the future. Therefore, 40 years was selected because it was thought to be an adequate period of time to analyze system responses demonstrated by comparing base flows for simulations with and without inputs related to ground-water irrigation.

The section entitled “Base-flow Depletion Percentage for a 50-year Period” describes a hypothetical scenario in which the simulation was used to create maps showing the simulated response of streams to pumping one additional theoretical well for 50 years. In other words, the map shows how much base-flow depletion would occur at each grid cell from various nearby streams, from pumping one new well from 2006 through 2055. This analysis was conducted because maps of percentage base-flow depletion for a specified period have been the basis for management boundaries in Nebraska (Nebraska Department of Natural Resources, 2005b, 2006).

Assumptions and Limitations

The analyses described in this report for determining the effects of ground-water irrigation on base flow are based on simulations that predict hypothetical future conditions, either 40 or 50 years beyond 2005. Future climate and land-use conditions in these simulations were estimated with the following assumptions. Future pumpage and additional recharge applied to irrigated cropland areas were estimated using 2005 land-use data, which assumes that in the future neither more nor less land would be used for growing crops. The average climatic

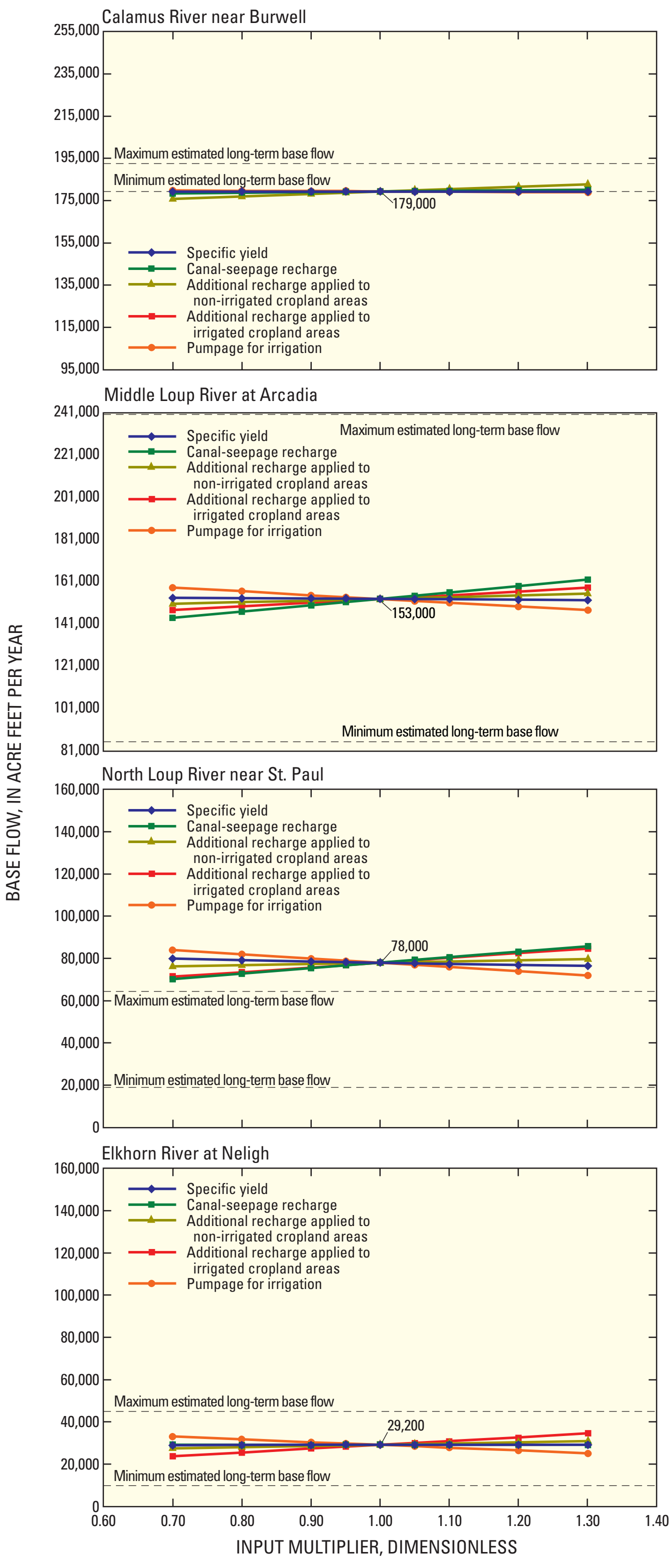


Figure 29. Sensitivity of the 2005 simulated base flow of selected streams to changes in simulation inputs, Elkhorn and Loup River Basins, Nebraska.

conditions for 1940 through 2005 also were used to estimate future pumpage for irrigation for the analysis simulations, and these average conditions were held constant throughout the analysis period. Although climate and land use are unlikely to remain the same for the next 40 or 50 years, future conditions are unknown. Therefore, either the 2005 conditions, in the case of cropland distribution, or average conditions, as in the case of climate, were used to represent future conditions.

The accuracy of the analyses described in this report is dependent on the assumption that the Elkhorn-Loup Model is a reasonably calibrated representation of the ground-water system and important processes affecting that system. This is thought to be true because the 1940 through 2005 simulation produced simulated water-level changes that were comparable to measured water-level changes while maintaining a reasonable match of simulated base flows to estimated long-term base flows. However, it was noted that the accuracy of the 1940 through 2005 simulation was dependent on simulated pumpage. Simulated pumpage, in turn, is dependent on other factors, as described in the description of simulation inputs for the 1940 through 2005 simulation, and in the “Simulation Limitations” section of this report. Though simulated pumpage is thought to be approximately correct, uncertainty in the simulated pumpage cannot be quantified; therefore, uncertainty in the analysis results also cannot be quantified. As with analyzing the system using analytical equations or any other method, the results of these analyses are tools to diagnose important system behavior, and should not be regarded as absolute or precise predictions of the future state of system components.

Difference in Simulated Base Flow Caused by Ground-Water Irrigation

State and regional water-resources managers have concerns about the long-term availability of the ground-water resources in the Elkhorn-Loup Model area, as well as the sustainability of base flow to streams as it constitutes a large part of flow of these streams. Stream systems constantly are changing in response to changes in climate, the ground-water system, and anthropogenic changes, so it can be difficult to assess what part of these base-flow changes were caused by ground-water irrigation as opposed to other factors.

Approach

The calibrated Elkhorn-Loup Model simulating 1940 and 2005 base flow suitably matched estimated long-term base flow, and the simulation included inputs specific to pumpage for irrigation and additional recharge applied to irrigated cropland areas. Therefore, the effects of ground-water irrigation on base flows were assessed by comparing base flows of the simulation representing current (2005) conditions with base flows of a simulation where pumpage for irrigation was removed and additional recharge applied to ground-water irrigated cropland areas was changed to the recharge rate applied to nonirrigated cropland areas. Future effects of ground-water irrigation on base flows were assessed by comparing a future simulation that included pumpage for irrigation and supplemental recharge to a future simulation that did not include pumpage for irrigation or the additional recharge above nonirrigated cropland area recharge rates.

To assess the effects of ground-water irrigation on simulated base flow, the calibrated 1940 through 2005 simulation (1940 through 2005 baseline simulation) was compared to the 1940 through 2005 simulation with no ground-water irrigation (NGWI simulation). The NGWI simulation included all of the same inputs as the 1940 through 2005 baseline simulation, but pumpage for irrigation was removed, and the additional recharge applied to ground-water irrigated cropland areas in the 1940 through 2005 baseline simulation (3.5 in/yr more than recharge from precipitation applied to unbroken lands) was reduced to the amount of additional recharge applied to nonirrigated cropland areas (0.5 in/yr more than recharge from precipitation applied to unbroken lands). Calibrated irrigated-land recharge was maintained for all surface-water irrigated crops. Simulated base flows from the 1940 through 2005 baseline simulation were compared against those from the 1940 through 2005 NGWI simulation. The difference in the two base-flow results represents the simulated effects of ground-water irrigation on 1940 through 2005 base flow.

This method was repeated for 2006 through 2045. The 2006 through 2045 baseline simulation was assigned the simulated baseline 2005 water levels as starting water levels, and other inputs were held constant for the remainder of the simulation period. Recharge was the same as that used in the baseline simulation for 2005, and pumpage for irrigation was based on 2005 land-use data and average 1940 through 2005 climatic conditions. Similarly, a second NGWI simulation was created, and was assigned the simulated NGWI 2005 water levels as starting water levels, and again, other inputs were held constant for the remainder of the simulation period. Recharge and pumpage (both for irrigation and municipal use) were the same as those used in the NGWI simulation for 2005. Simulated base flows from the 2006 through 2045 baseline simulation were compared with those from the 2006 through 2045 NGWI simulation. The difference in the two predictions represents the simulated effects of ground-water irrigation on simulated 2006 through 2045 base flow.

Results for 1940 through 2005

ZONEBUDGET (Harbaugh, 1990) was used to retrieve simulated base flows from the simulation outputs, by river reaches grouped into zones (fig. 30). The zones used were the upper Elkhorn River, from the upper perennial reach down to and including the South Fork of the Elkhorn River (zone 1); the lower Elkhorn River, from the end of zone 1 downstream to the eastern end of the ELM area, including the North Fork of the Elkhorn River (zone 2); the North Loup River, from the upper perennial reach down to the confluence with the Middle Loup River (zone 3); the Middle Loup River, from the upper perennial reach down to the confluence with the South Loup River (zone 4); the South Loup River from the upper perennial reach down to the confluence with the Middle Loup River (zone 5); and the downstream Loup River area, from the lower end of zones 3 and 4, downstream to the eastern end of the ELM area (zone 6) (fig. 30). The cumulative effects of ground-water irrigation on simulated 1940 through 2005 base flow are shown in figure 31.

The cumulative effects on simulated base flow followed a similar trend for all zones (fig. 31); effects were minimal before 1970, and increased steadily after 1970. This seems reasonable because before 1970, most ground-water irrigation was limited to areas near the Platte River, whereas ground-water irrigation became much more common throughout the interior of the study area after around 1970. The cumulative effect in 2005 was largest (about 695,000 acre-ft) for the Loup River downstream area (zone 6), though this is not surprising because streams in that zone probably are in close proximity to more ground-water irrigated acres than streams in other zones. The cumulative effect in 2005 was smallest for the Upper Elkhorn (zone 1), at about 438,000 acre-ft. Because inputs related to ground-water irrigation were removed from the entire ELM area at once, these analysis results do not indicate the location of the ground-water irrigation that affected each stream zone. The sum of the cumulative 1940 through 2005 effects for the Elkhorn River zones (1 and 2) was 888,000 acre-feet, whereas the sum of the cumulative 1940 through 2005 effects for the Loup River zones (3 through 6) was 2,273,000 acre-feet.

The annual rate of ground-water irrigation effects on simulated base flow for the various basins, reflecting in part the effects of climate variability from 1940 through 2005 on pumpage for irrigation, are shown in figure 32. As pumpage for irrigation increased or decreased each year (fig. 16) in response to the amount of growing season effective precipitation, the effects on simulated base flow also increased and decreased annually. For example, there were some years, such as 1978 and 1994, when the effects of ground-water irrigation on simulated base flow were zero or small for the North Loup River zone compared with the effects of ground-water irrigation in other years. This indicates that for those years when growing-season effective precipitation was large, causing pumpage for irrigation to be small, there was nearly no effect of ground-water irrigation on simulated base flow. In addition to the indirect effects of climate, the rates for each zone changed with time in response to land-use changes. As the amount of ground-water irrigated lands increased, so did pumpage for irrigation and associated enhanced recharge.

A few of the graphs show negative differences for one or a few short time periods (fig. 32), which indicate that the simulated base flow with irrigation exceeded simulated base flow without irrigation. These negative differences are an artifact caused by the different temporal representations used for pumpage for irrigation as opposed to recharge. Pumpage for irrigation varies annually in response to climate and land-use changes, but recharge was tied only to land-use changes, and did not change with climate. This means that recharge for

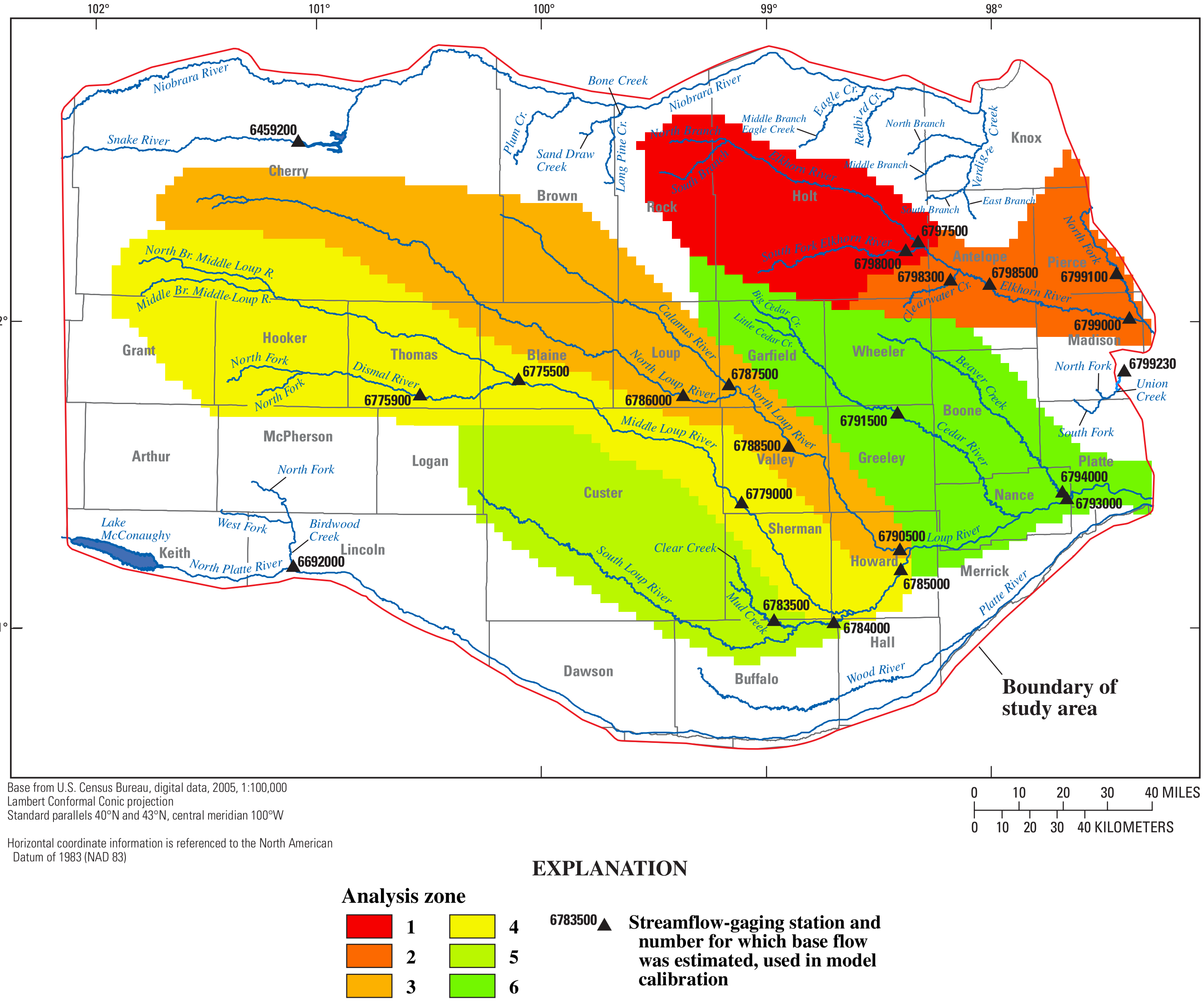


Figure 30. Zones used for analysis of the effects of ground-water irrigation on base flow, Elkhorn and Loup River Basins, Nebraska.

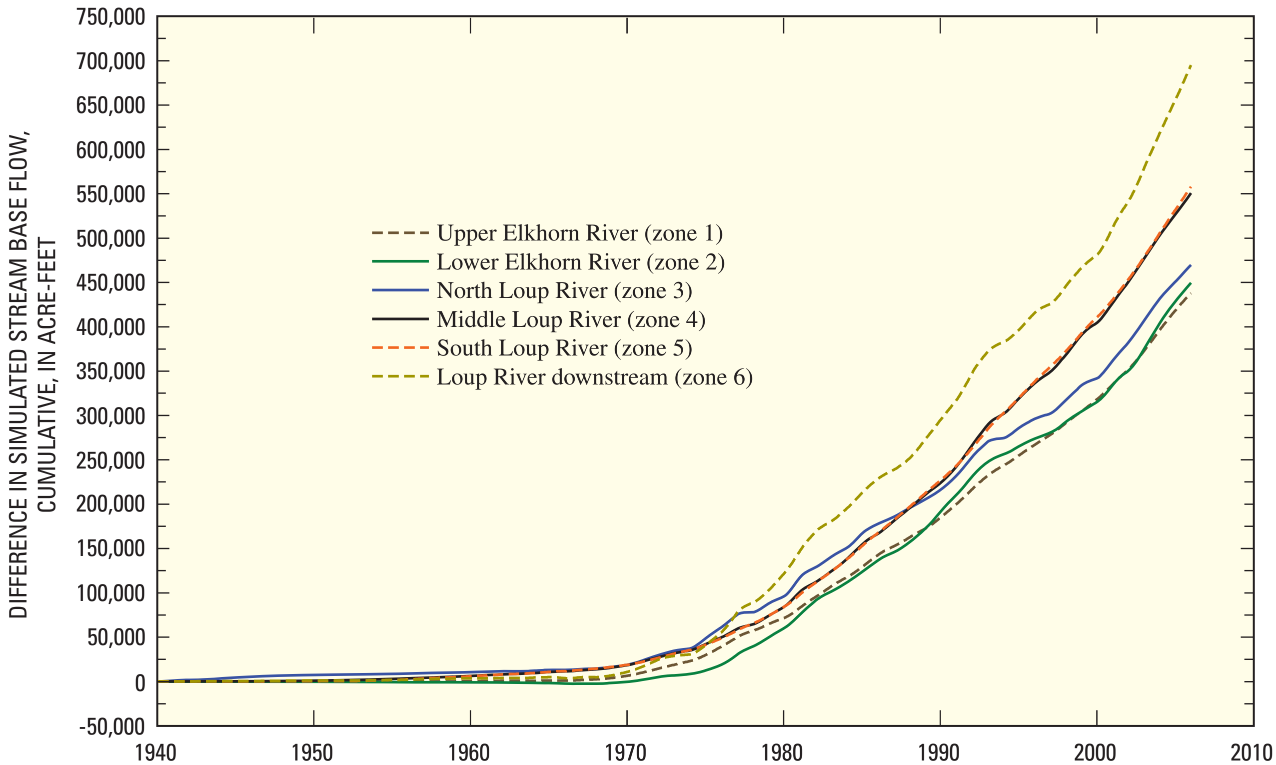


Figure 31. Cumulative effects of ground-water irrigation on simulated base flow, Elkhorn and Loup River Basins, Nebraska, 1940 through 2005. (Differences in simulated base flow for simulations with and without ground-water irrigation are graphed.)

a particular year potentially could increase for a simulation grid cell if more acres were classified as irrigated than for the previous year, while at the same time, if it were a year with increased precipitation during the growing season, pumpage for irrigation would be less than for the previous year. These artifacts are inconsequential for the longer period of the analysis, as they have a small magnitude and do not persist in the results, but rather were confined to a few specific periods, such as for the end of 1965, when the rate of effect was negative for 4 of the 6 zones.

The rates of simulated 2005 base flow by gaged reach and zone number for the baseline and NGWI simulations are listed in table 8. Simulated 2005 base flows for the NGWI simulation were at least as large as simulated 2005 base flows from the baseline simulation, though in most cases the increases were small compared to the overall magnitude of the simulated base flows. The simulated 2005 base flows in the table contrast with the cumulative volume of effects (fig. 31) and the annual rate of effects (fig. 32), as the tabled values are only a sample of the simulated 2005 base flows for the two simulations. The differences between the 2005 base flows for each simulation, summed by the zone numbers given in table 8, are equivalent to the rates presented in figure 32 for 2005.

However, because table 8 presents the information about the differences between the two simulations for specific reaches, effects to reaches within each zone can be evaluated. For instance, a casual inspection of the two reaches that zone 1 comprises, the Elkhorn River at Ewing plus the South Fork Elkhorn River at Ewing, show that simulated 2005 base flows for the former reach differ by about 16,500 acre-feet per year (acre-ft/yr) between the two simulations (45,200 acre-ft/yr for the baseline simulation, and 61,700 acre-ft/yr for the NGWI simulation). In contrast, for the South Fork Elkhorn River at Ewing, the difference in simulated 2005 base flows for the two simulations is only about 1,600 acre-ft/yr (18,400 acre-ft/yr for the baseline simulation and 20,000 acre-ft/yr for the NGWI simulation). Therefore, the effects of ground-water irrigation on simulated base flows of the Elkhorn River at Ewing accounted for more than 91 percent of the zone 1 total (18,100 acre-ft/yr) for 2005. Simulated 2045 and 2055 base flows (table 8) are discussed respectively in the sections entitled “Results for 2006 through 2045” and “Base-Flow Depletions for 2055,” later in this report.

Results for 2006 through 2045

As described in the “Approach” section for this analysis, two simulations were constructed for hypothetical conditions for 2006 through 2045. One simulation of future conditions used the simulated 2005 water levels from the baseline simulation as starting water levels and the other simulation used the

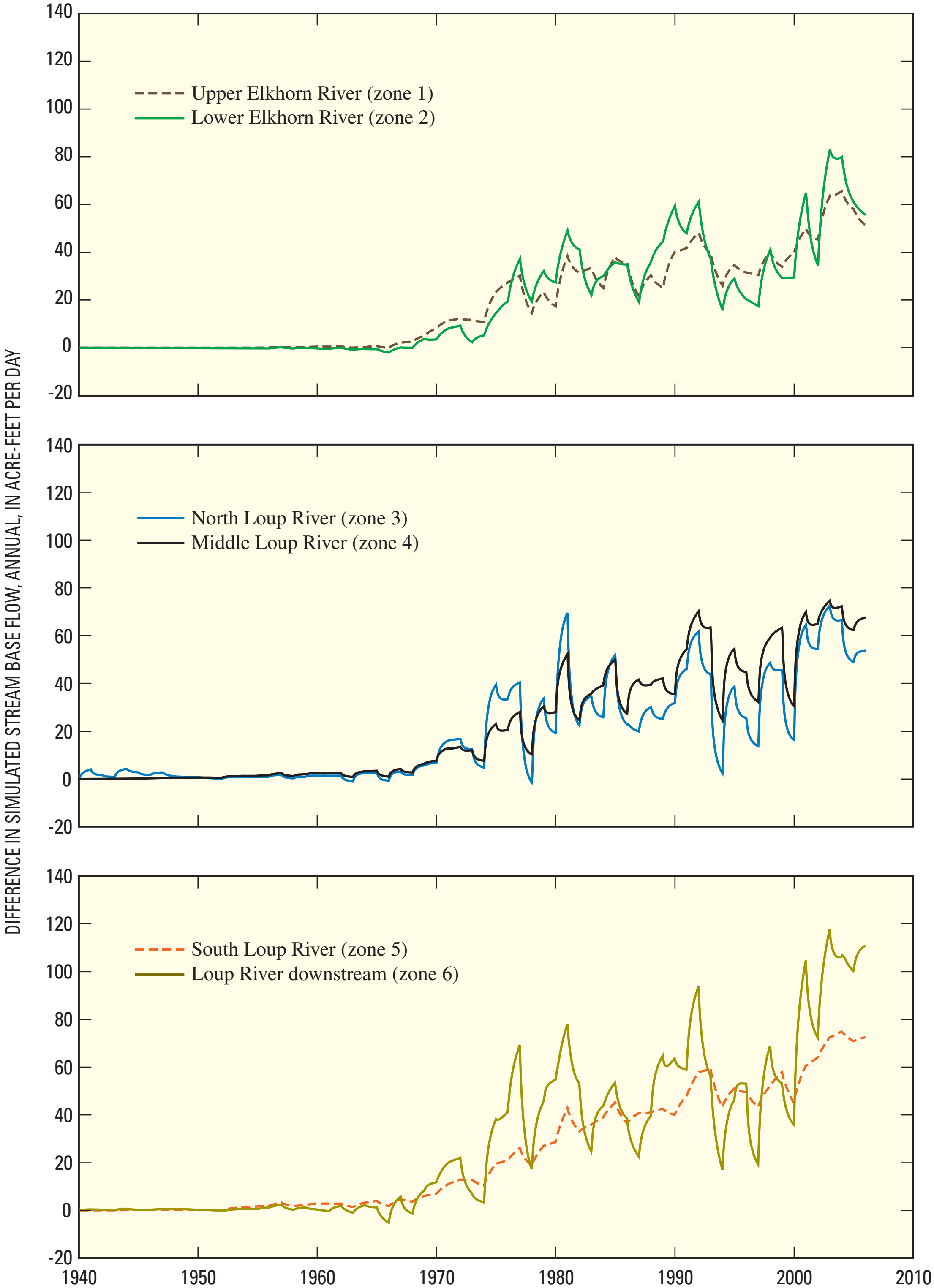


Figure 32. Annual rate of effects of ground-water irrigation on simulated base flow, Elkhorn and Loup River Basins, Nebraska, 1940 through 2005. (Differences in simulated base flow for simulations with and without ground-water irrigation are graphed.)

Table 8. Comparison of simulated base flow for simulations with and without ground-water irrigation, 2005, 2045, 2055, Elkhorn and Loup River Basins, Nebraska.

[number in parentheses indicate that stream has a net loss of water to the aquifer; no ground-water irrigation (NGWI)]

Analysis zone (fig. 30)	U.S. Geological Survey streamflow-gaging station and number	Ground-water discharge to streams (base flow), in acre-feet per year				
		Simulated conditions (baseline)			Simulated conditions (NGWI)	
		2005	2045	2055	2005	2045
	Niobrara River Basin					
NA	Snake River above Merritt Reservoir (06459200)	139,000	133,000	133,000	139,000	137,000
	Elkhorn River Basin					
1	Elkhorn River at Ewing (06797500)	45,200	6,140	4,810	61,700	62,200
1	South Fork Elkhorn River at Ewing (06798000)	18,400	10,400	9,900	20,000	190,700
	Sum	**63,600**	**16,500**	**14,700**	**81,700**	**81,900**
2	Clearwater Creek near Clearwater (06798300)	9,290	0	0	14,500	14,300
2	Elkhorn River at Neligh (06798500)	29,200	(12,900)	(14,700)	34,200	34,800
2	Elkhorn River at Norfolk (06799000)	60,300	(3,070)	[1]466	66,900	69,400
2	North Fork Elkhorn River near Pierce (06799100)	18,100	0	0	21,100	21,700
	Sum	**117,000**	**(16,000)**	**(14,200)**	**137,000**	**140,000**
NA	Union Creek at Madison (06799230)	6,090	[1]810	[1]630	8,130	8,570
	Loup River Basin					
3	North Loup River at Taylor (06786000)	312,000	302,000	301,000	315,000	311,000
3	Calamus River near Burwell (06787500)	179,000	175,000	174,000	180,000	179,000
3	North Loup River at Ord (06788500)	55,500	43,800	43,400	59,900	57,600
3	North Loup River near St. Paul (06790500)	78,000	50,700	47,100	89,000	93,000
	Sum	**625,000**	**572,000**	**566,000**	**644,000**	**641,000**
4	Middle Loup River at Dunning (06775500)	280,000	276,000	275,000	281,000	280,000
4	Dismal River near Thedford (06775900)	141,000	139,000	139,000	141,000	141,000
4	Middle Loup River at Arcadia (06779000)	153,000	130,000	127,000	163,000	167,000
4	Middle Loup River at St. Paul (06785000)	78,700	46,800	43,700	91,100	93,500
	Sum	**653,000**	**592,000**	**585,000**	**676,000**	**682,000**
5	Mud Creek near Sweetwater (06783500)	14,600	[1]1,880	[1]1,170	18,800	19,000
5	South Loup River at St. Michael (06784000)	132,000	74,500	67,000	154,000	155,000
	Sum	**147,000**	**76,400**	**68,200**	**173,000**	**174,000**
6	Cedar River near Spalding (06791500)	87,100	63,400	61,000	92,000	92,100
6	Loup River near Genoa (06793000)	63,700	(11,100)	(16,100)	80,400	82,900
6	Beaver Creek at Genoa (06794000)	56,300	[1]108	0	71,500	72,500
	Sum	**207,000**	**52,400**	**44,900**	**244,000**	**248,000**
	Platte River Basin					
NA	Birdwood Creek near Hershey (06692000)	104,000	98,000	98,000	104,000	105,000

[1]Values are reported to three significant digits, though simulation results have greater uncertainty than tabled values for streams with small base-flow values; values in these cases should be considered to be indicative only of relative magnitude.

simulated 2005 water levels from the NGWI simulation as starting water levels.

The cumulative effects of ground-water irrigation on simulated base flow for 2006 through 2045 for the same stream zones as analyzed for the 1940 through 2005 period are shown in figure 33. The plots of cumulative effects are nearly linear for 2006 through 2045 because the same pumpage and recharge were used for the entire simulation period. The largest cumulative effect for 2045 was for the downstream reaches of the Loup River (zone 6) at nearly 6,980,000 acre-ft. This is similar to the results for the 1940 through 2005 analysis, which showed the largest cumulative effect in zone 6, except that the magnitude of effect on simulated base flows for 2045 was about 10 times larger than it was for 2005. Large effects for the downstream reaches of the Loup River are expected as those reaches are in close proximity to more ground-water irrigated acres than streams in other zones. The smallest effect in 2045 was for the North Loup River (zone 3), at about 2,250,000 acre-ft, which is about five times the size of the smallest cumulative effect for 2005, which had been simulated for the upper Elkhorn River (zone 1).

The cumulative effects on simulated base flow were nearly identical for four of the zones until almost 2020, at which time the effects diverged, though they remained similar for the remainder of the analysis period (fig. 33). The only zones for which the cumulative effects clearly were larger are the lower Elkhorn River (zone 2) and the Loup River downstream (zone 6). The sum of cumulative 2006 through 2045 effects of ground-water irrigation on simulated base flow was 7,678,000 acre-feet for the Elkhorn River Basin (zones 1 and 2) and was 14,784,000 for the Loup River Basin (zones 3 through 6), more than 7 times larger than the effects predicted for 1940 through 2005.

A similar pattern of larger values for zones 2 and 6 resulted for the daily rates of effect on simulated base flow (fig. 34). Ground-water irrigation effects for zones 1, 3, 4, and 5 were similar throughout the simulation period, increasing in a relatively slow and uniform pattern from 2006 through 2045. Effects for zones 2 and 6 were different (and larger than for the other four zones). The rate of effect for zone 6 increased rapidly from 2006 to 2015, and then increased more slowly until 2045. The rate for zone 2 had a similar pattern to that for zone 6, until around 2036, when the rate of effect abruptly ceased increasing and declined slightly through the remainder of the simulation period.

Generally, rates of effects were four to eight times larger for 2045 than for 2005. Rates from 2006 through 2045 did not show the effects of climate variability because pumpage for irrigation was estimated assuming a constant value of growing-season effective precipitation representative of historically average climatic conditions.

There are a number of reasons why the rate of effects might change. In the simplest sense, curves of the rate of effect through time of a stress on a hydrologic system are expected to approach equilibrium if all other conditions remain constant (Lohman, 1972). As a system approaches equilibrium, the slope of a rate-of-effect curve will decrease with time, causing the curve to flatten and become nearly horizontal. The flattening of any of the curves shown in figure 34 with increasing time is considered an indication of an approach to equilibrium. Curve flattening is not present in figure 32, nor was it expected to appear, because the stresses in that simulation changed annually, whereas for the 2006 through 2045 simulation the stresses were constant through time.

Given that such curves are expected to follow a particular shape, it also means that whenever the shape of such a curve changes abruptly, some aspect of system hydrology has changed. For example, around 2015, as shown in figure 34, the curve for zone 6 (Loup River downstream) abruptly deviated from the smooth curve one might expect based on an informal extrapolation of the part of the curve from 2006 to 2015. In this case, the only definite conclusion that can be made based on the curve alone is that from 2006 to 2015, the effects of ground-water irrigation for zone 6 were being affected by one or more system responses that stopped affecting them after 2015. One system response that could have caused this particular change is evapotranspiration. As water levels in an area decline below the specified evapotranspiration elevation, the rate at which evapotranspiration removes ground water linearly decreases until the water level reaches the extinction depth, at which point evapotranspiration no longer removes ground water. In zone 6 streams during 2006 to 2015, the effects of ground-water irrigation on simulated base flow could have increased directly as the removal of ground water by evapotranspiration decreased. If the water levels declined below the evapotranspiration extinction depth around 2015, then the linear change in evapotranspiration rate would have stopped affecting the effects of ground-water irrigation on simulated base flow, and the response curve would then most likely have flattened out (again, if all other stresses and responses remain constant).

Reductions in ground-water discharge to evapotranspiration do not explain the absolute flattening or change to a slightly descending rate in the curve for zone 2 after about 2036. However, data in table 8 indicate that simulated 2045 base flows of the baseline simulation for some streams in this zone declined to zero (the North Fork Elkhorn River and Clearwater Creek near Clearwater). For the remaining two reaches, the Elkhorn River at Neligh and Elkhorn River at Norfolk, the simulated 2045 base flows represent a loss of nearly all the base flow gained by streams in zone 1, which is upstream. So, it appears that the curve for zone 2 flattens out because beyond 2036, the rate of effect is dependent only on the amount of simulated base flow routed into this area from upstream, and effects for zone 2 had reached the level where all simulated base flow leaves the stream and returns to the water-table aquifer. For the baseline simulation, the Elkhorn River at Ewing contributed more than 70 percent of the simulated 2005 base flow in zone 1, but it contributed only about 37 percent of the zone 1 simulated 2045 base flow, which had declined overall to only 26 percent of what it had been in 2005.

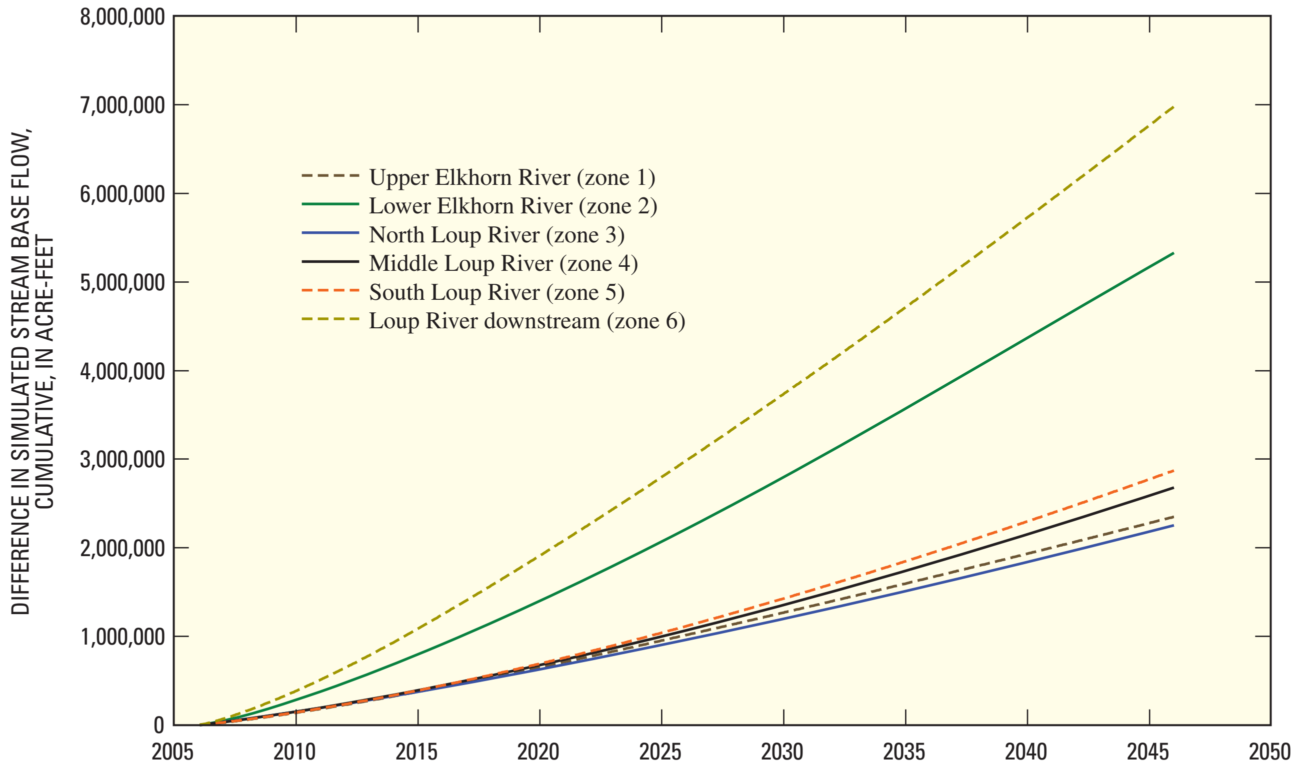


Figure 33. Cumulative effects of ground-water irrigation on simulated base flow, Elkhorn and Loup River Basins, Nebraska, 2006 through 2045.

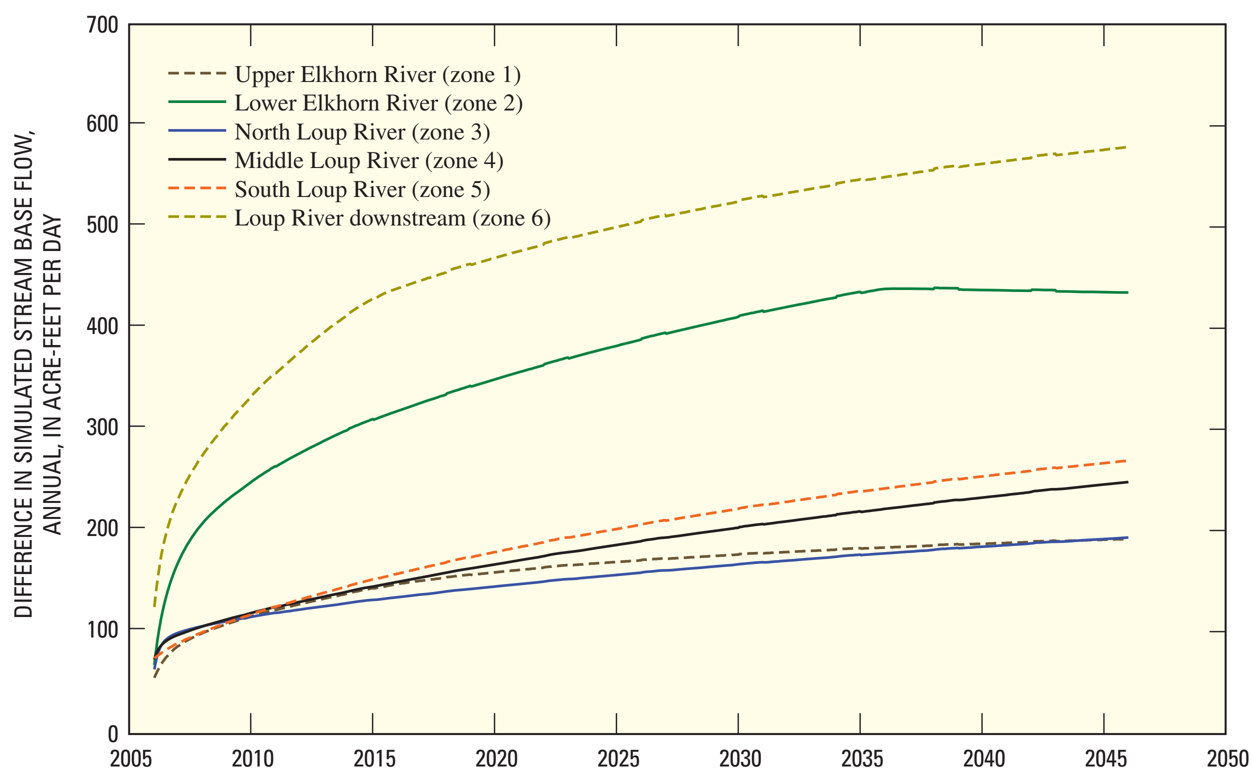


Figure 34. Annual rate of effects of ground-water irrigation on simulated base flow, Elkhorn and Loup River Basins, Nebraska, 2006 through 2045.

Similar to those in zones 1 and 2, simulated base flows in zones 5 and 6 in the baseline simulation declined from 2005 through 2045, and were 52 percent and 25 percent of simulated 2005 base flows, respectively. For Beaver Creek at Genoa there was no simulated base flow in 2045, and Loup River near Genoa had a net loss of water to the water-table aquifer in 2045.

Conversely, simulated 2045 base flows for zones 3 and 4, while having declined somewhat, were both still about 91 percent of the simulated 2005 base flows. For most stream reaches in zones 3 and 4 (table 8) the declines in simulated base flow from 2005 to 2045 were small in comparison to the overall magnitude of simulated base flows.

Simulated base flows for the NGWI simulation (table 8) generally were about the same in 2045 as they were in 2005. Many of the decreases and increases during the 2006 through 2045 simulation were small compared to the overall magnitude of simulated base flows. The cause of these minor declines was not further investigated.

The main objective of this analysis was to evaluate the effects of ground-water irrigation on base flow, by comparing base flow from simulations with and without simulation inputs representing ground-water irrigation. For a few streams, simulated 2045 base flow in the simulation with ground-water irrigation declined to zero; once stream base flow has declined to zero, the rate of effects to that stream cannot increase, though pumpage or other withdrawals of ground water could still affect storage, discharge to base flow of other streams, or other hydrologic components dependent on ground-water flow.

Base-Flow Depletion Percentage for a 50-Year Period

Streamflow depletion percentages for 40- or 50-year periods have been the basis for ground-water and surface-water management boundaries in Nebraska (Nebraska Department of Natural Resources, 2005b, 2006). However, existing streamflow depletion maps for the ELM area are based on analytical equations similar to those used by Jenkins (1968). Streamflow depletion as defined by Jenkins (1968) is the number of days a well is pumped until streamflow reductions caused by the well pumping become a predetermined percentage of the pumped volume. Jenkins' (1968) original analytical equation solved for 28 percent streamflow depletion during 40 years. The pumping effects (stream depletion) are composed of (1) additional water that leaks from the streambed to the water-table aquifer because of well pumping, usually referred to as induced seepage, or (2) the capture of ground water that would have discharged to the stream if it had not been captured by the pumping well, usually referred to as captured base flow. In gaining streams, such as many in Nebraska, the part of streamflow depletion caused by captured base flow usually is more than 90 percent of the total streamflow depletion, and induced seepage is only a small part. In contrast, induced seepage probably would constitute the largest part of streamflow depletions in losing streams.

Though the analytical equations presented by Jenkins (1968) are readily available and simple to implement, they do not account for all the factors that can affect streamflow depletion values. For example, recharge, evapotranspiration, the direction and magnitude of ground-water flow, changes in water-table elevation, and other factors all must be assumed to be negligible to derive the analytical equation. Not all these factors are operative in every location, but all have the potential to affect streamflow depletion caused by pumpage of one additional well. The calibrated Elkhorn-Loup Model, which accounts for many factors affecting streamflow depletion, was used to estimate the percentage of streamflow depletion caused by pumping during a 50-year period. These results are characterized as base-flow depletion, because that is the part of streamflow simulated by ELM simulations. Streamflow runoff is not represented in the simulations; therefore, depletions to runoff are not represented in the simulation results. This analysis is an appropriate use for the ELM because it concerns a large area and a long time period.

Approach

To determine the effect of pumpage on base-flow depletion, two simulations were constructed. Both simulations used the calibrated 1940 through 2005 simulation and started with the simulated 2005 water levels, but simulated the period from 2006 through 2055. The first simulation, called the baseline simulation, predicted the effect of maintaining the distribution of 2005 irrigated cropland areas through 2055. Recharge rates were constant during the simulation period and were equal to the recharge rates used in 2005 for the 1940 through 2005 simulation. Pumping rates also were held constant in the baseline simulation and were calculated by subtracting the average (modified) growing-season effective precipitation from 1940 through 2005 from the crop water demand in 2005. All other simulation inputs were the same as those used in the 1940 through 2005 simulation. This simulation essentially was the same as the one used for the baseline simulation for the 2005 through 2045 simulation described in the "Difference in Simulated Base Flow Caused by Ground-Water Irrigation" section of this report, except that for the base-flow depletion analysis, the baseline simulation was configured to run an additional 10 years, through 2055.

The second simulation, called the pumping-well simulation, also simulated the period from 2006 through 2055, and included the addition of one theoretical well pumped at a constant rate of 1 cubic foot per second (ft^3/s). Because the simulation response to the pumping rate of the additional well is nearly linear, the predicted depletion generally is not sensitive to the pumping rate selected for the additional well. Other than the additional well, all inputs were the same as those of the baseline simulation. The reduction in base flow caused by the addition of one pumping well was calculated as the reduction in base flow from the baseline simulation compared with the pumping-well simulation during the 50-year period. The volume of that reduction was divided by the volume pumped by the theoretical well to calculate the percentage base-flow depletion caused by that well.

To produce a map displaying the base-flow depletion caused by the addition of the theoretical well throughout the interior of the simulation area required the pumping-well simulation to be repeated for each grid cell for which a result was desired. To determine the base-flow depletion for each grid cell required assigning the theoretical pumping well to that cell, running the pumping-well simulation, and recording the results. The additional well was then moved sequentially to the next grid cell, and the process repeated, using a utility designed to manage these simulations and record the results in a database (CycleWellZB17, Rich Kern, Nebraska Department of Natural Resources, written commun., 2007). The simulated base flow for each of the pumping-well simulations was compared to the simulated base flow in the baseline simulation, and the difference was divided by the pumpage to calculate the percentage base-flow depletion for that grid cell. Changes in simulated base flow caused by the addition of the theoretical well were evaluated only for the Elkhorn and Loup River Basins; depletions caused to the Niobrara or Platte Rivers or their tributaries were not included. The base-flow depletion percentage caused by the additional pumping well in each grid cell was mapped to display the spatial distribution of simulated base-flow depletion (fig. 35).

Base-Flow Depletions for 2055

In many areas, base-flow depletion for the 50-year future period was greater than 10 percent for wells placed less than 7 or 8 mi from the stream, though considerable variations exist because of the heterogeneity of the natural system represented in the simulation (fig. 35). The distance from streams through which pumpage of one additional well caused depletions of 10 percent of pumpage mostly ranged from 5 to 12 mi, though in a few cases even pumpage in the same cell as the stream caused less than a 10 percent depletion.

Pumpage that occurred in the same grid cell as streams or that occurred in a cell next to streams often resulted in a large percentage of base-flow depletion, generally more than 80 percent of pumpage. This can be seen for much of the Loup River system, including the Loup River main stem, and its tributaries, including the Cedar River, North Loup River, and Middle Loup River (fig. 35). However, for the South Loup River and the Dismal River, the depletions were less than 80 percent in the grid cells containing those streams, ranging as low as 60 percent. For the Elkhorn River, depletions were even smaller, tending to be 40 to 60 percent along most of the river, except near the upper end of the Elkhorn River, where most projected depletions were less than 20 percent. For Beaver Creek, most of the depletions for the 2006 through 2055 simulation were less than 20 percent.

Many factors caused base-flow depletions for various streams to be different. Differences in depletions along every stream and across the area are caused by heterogeneity in simulation inputs and by differences in the simulated hydrology of the system. Further, because the simulation does not manufacture water to supply the theoretical well, the water pumped by that well must be balanced by some other change in the system. In some cases, such as for grid cells along parts of the South Loup River and for much of the upper Elkhorn River, the theoretical well reduced the amount of ground water removed by evapotranspiration (figs. 7, 13) instead of depleting base flow, so the base-flow depletion was less than in areas without evapotranspiration of ground water.

In some cases, such as near Beaver Creek and the lower Elkhorn River, and to a small extent near the Dismal River, pumpage of the additional well was at least partially balanced by water-level declines. For the Dismal River, this small decrease in water levels did not have a large effect on the amount of simulated base flow, but it seems that the area where depletions were larger than 10 percent extends further from the Dismal River than from some other streams. However, for Beaver Creek and the lower Elkhorn River, simulated base flows for 2055 either declined considerably from 2005 or base flows were absent.

In the case of Beaver Creek, the lack of simulated base flow in 2055 (table 8) precluded additional pumping wells near that stream from causing further depletions to those simulated base flows by 2055. Simulated base flows of Beaver Creek had declined to 108 acre-ft/yr by 2045, and probably were zero for some period before 2055 (table 8).

In the case of the lower Elkhorn River, simulated base flows indicated a total loss of the flow received from the upstream gaining sections at station 06798500 (table 8). The total loss for this reach occurred in the baseline simulation for 2055, though it was not clear when during 2005 through 2055 it occurred. There also was a total loss of simulated base flow for 2045 in the baseline simulation, but further downstream, at station 06799000 (table 8); the losses occurred mostly upstream from Neligh with additional losses between Neligh and Norfolk. In contrast, in 2055 the simulated base flow was lost upstream from Neligh and no base flow was simulated between Neligh and Norfolk, other than a small gain (466 acre-ft/yr). Regardless of when it occurred, the total loss of base flow in the lower Elkhorn River occurred both in the baseline and pumping-well simulations; therefore, it was not caused primarily by the addition of the theoretical well.

Even without additional work, it is reasonable to infer that if Beaver Creek or the lower sections of the Elkhorn River had more simulated base flow in 2055 (and before), and simulated base flow received from upstream reaches was not lost totally back to the water-table aquifer, that depletions of simulated base flow caused by the theoretical well pumpage in these areas would have been larger. The same would hold true for any stream that had little or no simulated base flow in the baseline simulation. No base-flow depletion can occur if simulated base flow is absent; therefore, base-flow depletion as a percentage of the volume pumped in 50 years declines from the time the stream goes dry until the end of the analysis

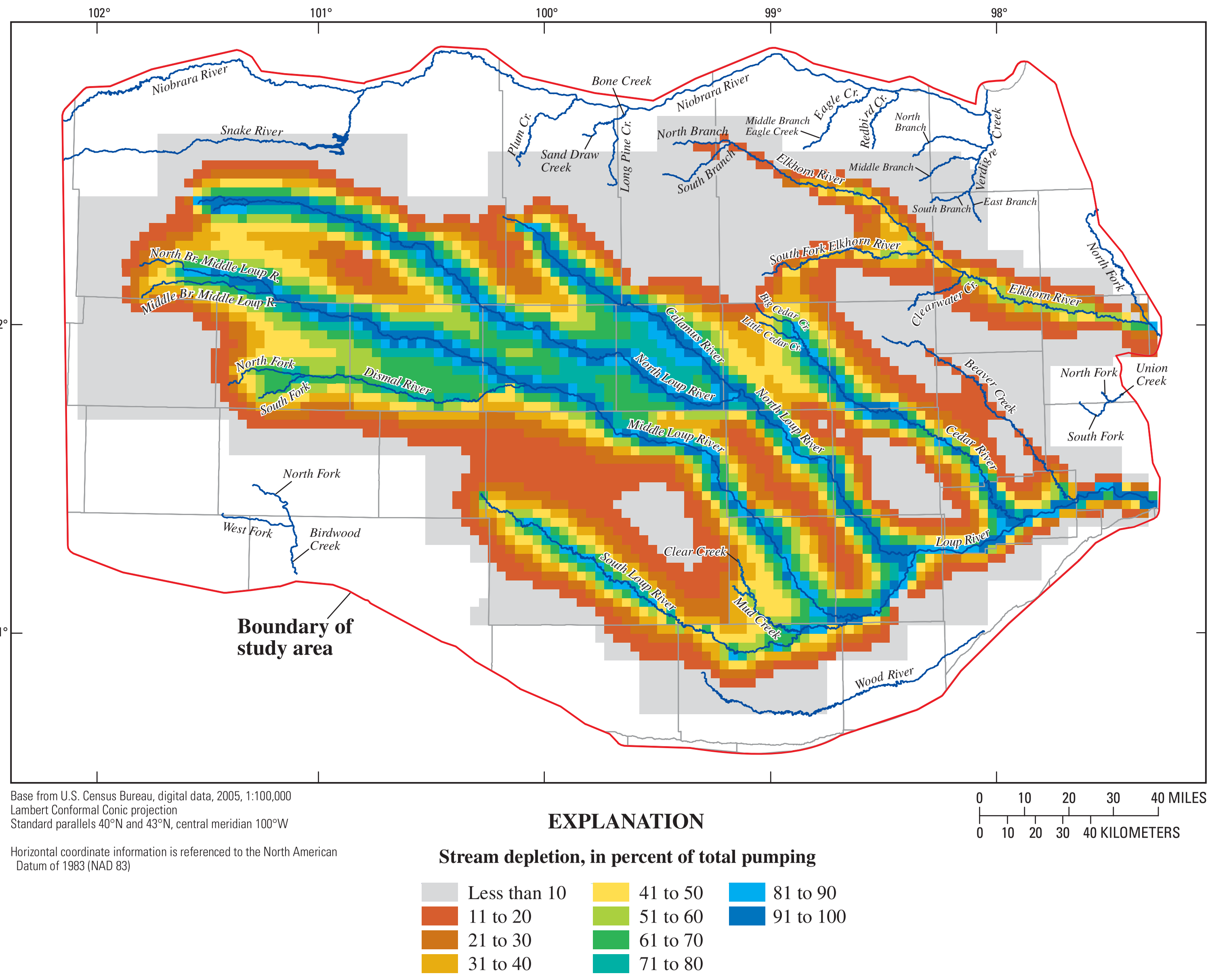


Figure 35. Base-flow depletion percentage for the Elkhorn and Loup River Basins, simulated for 2006 through 2055.

period. If runoff were considered for streams with no base flow, part of that runoff also could be lost to the water-table aquifer, increasing the total streamflow depletion above the base-flow depletion calculated in this analysis.

Simulation Limitations

Assumptions inherent to MODFLOW simulations are described in the "Numerical Model Construction" section of this report, but these are assumptions common to most studies of this type, and by themselves, those assumptions do not inherently limit the usefulness of the simulation as a tool. Most of the important limitations relate either to data used as simulation inputs or data used to estimate simulation inputs. The simulation of the 1940 through 2005 period predicted simulated water-level changes that were comparable to measured water-level changes, while maintaining an amount of simulated base flow that compared favorably to long-term base-flow estimates; therefore, the balance of the pumpage and recharge inputs was considered to be generally correct. Pumpage for irrigation was constrained using the best measured pumpage data available at the time of the calibration; however, the measured pumpage data correspond only to a short period of record at the end of the simulation period, and represented only a few parts of the study area instead of being uniformly distributed across the entire simulation area. In addition, in the calibrated 1940 through 2005 simulation, estimated pumpage for irrigation and recharge on agricultural lands was dependent on the land-use data. Land-use maps for 1940 through 2005 were based on the best, most reliable data available, but probably still contain errors. Errors in 1940 through 2005 land use would have caused errors in estimated pumpage for irrigation and in calibrated recharge applied to agricultural lands. Moreover, the relations of land use to pumping and land use to recharge also are uncertain.

A detailed analysis of base-flow trends through time was beyond the scope of this study, and no relevant reports of previous base flow-trend analyses by other authors were discovered. However, in the analysis related to Peterson and Carney (2002), no large trends were observed in base flow as defined for that analysis, which studied an area that partially overlaps the ELM area. Therefore, it was assumed at the beginning of the ELM study that no large trends of base-flow changes had occurred in the ELM area during the period of interest, and base-flow estimates were compiled using period of record data. Until an analysis of base-flow trends is completed, the uncertainty associated with this assumption cannot be investigated in a meaningful way and the effects of that uncertainty on the simulation results also is unknown.

Uncertainties in some simulation inputs are not quantifiable, and cause uncertainties in the results of the analyses that used these simulations that also are unquantifiable. As might be expected, the representativeness of the simulation also depends on how representative the past climate conditions and pumpage are of future climate conditions and pumpage. For example, if the 2006 through 2045 simulation is much drier or wetter than average, then the analysis results reported would either understate or overstate the effects of groundwater irrigation and projected base-flow depletions. However, as the amount by which future climate conditions might be drier or wetter than the average of past climate conditions is also unknown, it was considered acceptable to use the average of 1940-2005 climatic conditions to represent hypothetical future conditions.

Furthermore, the simulations documented in this report are considered acceptable, given the input data limitations, simulation assumptions, and resources available at the time of the simulation construction and calibration. However, given the large grid cell spacing (2 mi by 2 mi), these simulations are appropriate only for analyzing regional ground-water management scenarios over spatial scales of multiple counties and time scales of multiple years, and are not for analysis of small areas or short time periods.

Planned Work for Phase Two

Simulations and analyses reported herein are planned to be updated using components of the Phase Two Elkhorn-Loup Model study. These components include updating the elevation contour map of the base of the water-table aquifer, collecting synoptic streamflow measurements to map gains and losses along stream reaches, construction of a runoff-recharge model to estimate long-term patterns of recharge, geophysical mapping of resistivity patterns in canals, and collecting additional geologic data through test-hole drilling and surface and borehole geophysics. In addition to the new and refined data to be added to the simulations, parameter-estimation techniques (Hill, 1998; Doherty, 2004) will be investigated for phase two simulation calibration, and are expected to provide additional confidence in simulations and analysis, as well as providing quantitative information about calibration and related prediction uncertainty.

The simulated base flows for 1940 and 2005 were compared herein with estimated long-term base flows, but it is preferable to compare simulated and estimated base flows for shorter time periods as well. Accordingly, the simulation will be refined to include this new information, and calibration to base flows over shorter time periods will be evaluated. Analysis completed using the revised simulations will be based at least partially on optimization modeling to analyze water-resource management options.

Summary and Conclusions

In central and eastern Nebraska, the Elkhorn and Loup Rivers provide surface-water flows for irrigation, recreation, hydropower production, and aquatic life. Outflows from the

Elkhorn and Loup Rivers also recharge the aquifer used by large municipal water systems that pump ground water near the Platte River. Pumpage for irrigation is vital to agricultural productivity, and hence the livelihood, of the communities in the Elkhorn-Loup Model area. Recent drought (2000–06) has amplified concerns about the long-term sustainability of surface- and ground-water resources in the area, as well as concerns about the effect of ground-water irrigation on streamflow. Further, State legislation was enacted in 2004 to ensure that long-term supplies of ground water and surface water are in balance with long-term demands, and in some cases State and regional agencies must develop integrated management plans to describe how the goal of balancing water demands and supplies will be achieved. The purpose of this report is to document the methodology and results of a simulation of ground-water flow and effects of ground-water irrigation on base flow in the Elkhorn-Loup Model (ELM) area at the completion of its first phase. The goal of the ELM project was to study surface- and ground-water resources in the Elkhorn River Basin upstream from Norfolk, Nebraska, and the Loup River Basin upstream from Columbus, Nebraska and to provide information with which long-term management decisions can be made.

A ground-water flow simulation was constructed and calibrated for the area, using a 2-mi by 2-mi cell size and one layer, to represent the water-table aquifer, comprised of Quaternary-age alluvial deposits and Tertiary-age Ogallala Group deposits. The simulation domain included a 30,800-mi^2 area of north-central Nebraska, and simulated the pre-1940 and 1940 through 2005 periods. To calibrate the simulations, simulation outputs were compared with measured water levels, estimated long-term base flow, measured water-level changes for every decade from 1945 to 2005, and measured water-level changes from 1945 to 2005.

The calibrated simulation was used to analyze the annual and cumulative effects of ground-water irrigation on base flow for the 1940 through 2005 period and for the 2006 through 2045 period. For both time periods, streams most affected were those located in close proximity to more ground-water irrigated acres. Cumulative effects on base flows of six groups of streams in the ELM area through 2005 ranged from 438,000 acre-ft to 695,000 acre-ft. Generally, cumulative effects to stream groups were 5 to 10 times larger for the 2006 through 2045 simulation than for the 1940 through 2005 simulation, and ranged from about 2.3 million acre-ft up to nearly 7 million acre-ft. For a few streams, simulated 2045 base flow in the simulation with ground-water irrigation declined to zero; in these cases, if the simulated base flow of that stream in the simulation without ground-water irrigation did not change from 2006 to 2045, the effects of ground-water irrigation on base flow cannot further increase for that stream.

The calibrated simulation also was used as the basis for simulation of 2006 through 2055 to predict the base-flow depletion percentage caused by a well throughout most of the interior of the area, because base-flow depletion percentage provides the legal basis for water-management boundaries in Nebraska. For the Elkhorn and Loup River systems, pumpage of one additional theoretical well resulted in more than 10 percent base-flow depletion if within 7 to 8 mi of most streams, though common distances ranged from 5 to 12 mi among streams. In some locations, pumpage of an additional well in the same grid cell as a stream caused less than 10 percent base-flow depletion, but base-flow depletions usually were more than 80 percent of pumpage when the well was in the same grid cell as the stream. In some areas, depletions were smaller where mitigated by reductions in ground-water discharge to evapotranspiration, or where water-level declines changed the local interaction between surface and ground water. For a few streams, simulated base flow declined substantially from 2006 through 2055; in some of these cases the simulated 2055 base flow was absent. No base-flow depletion occurs if simulated base flow is absent; therefore, base-flow depletion as a percentage of the volume pumped in 50 years declines from the time the stream goes dry until the end of the analysis period. If runoff were considered for streams with no base flow, part of that runoff also could be depleted, increasing the total streamflow depletion above the depletion to base flow alone.

Simulations documented in this report have limitations, as do all tools used to analyze the function of natural systems. Uncertainties in some simulation inputs are not quantifiable, and cause uncertainties in the results of the analyses that used these simulations that also are unquantifiable. However, the simulations documented in this report are as accurate as could reasonably be expected given the input data limitations, simulation assumptions, and resources available at the time of the simulation construction and calibration. Given the large grid cell spacing (2 mi by 2 mi), these simulations are only appropriate for analyzing regional ground-water management scenarios over large areas and long time periods, and are not reliable for analysis of small areas or short time periods. Simulations of the Elkhorn-Loup Model area are planned to be refined through the addition of new data, interpretations, and innovative approaches to analysis during phase two of the study.

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Publishing support provided by:
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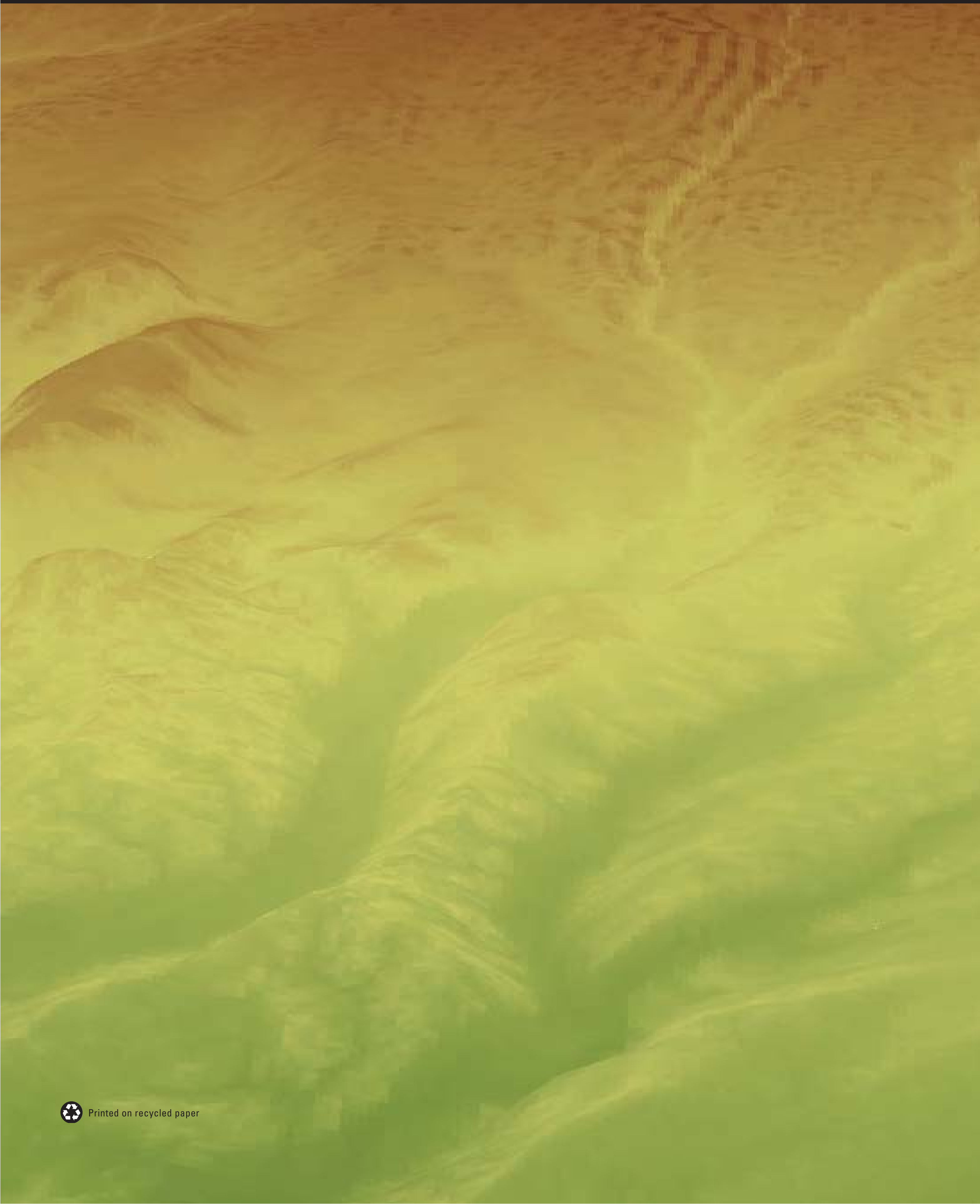

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Appendix F

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.

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[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

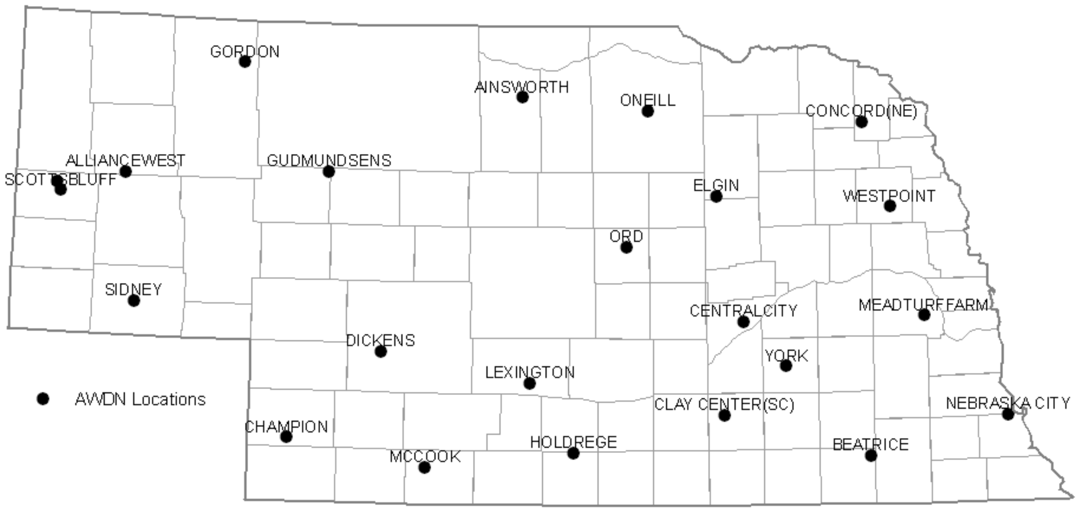

Figure 1. Location of automated weather stations used to calibrate the Hargreaves method.

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.

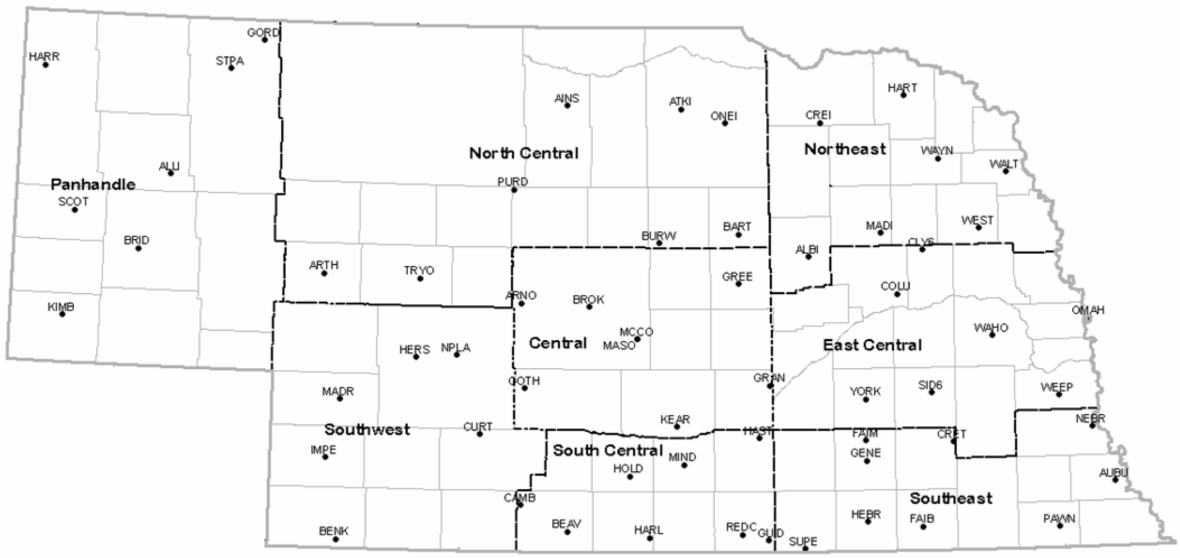

Figure 2. Location of National Weather Service stations used in simulations and Climatic Zones for Nebraska. Specific information for the NWS stations is included in Table 4.

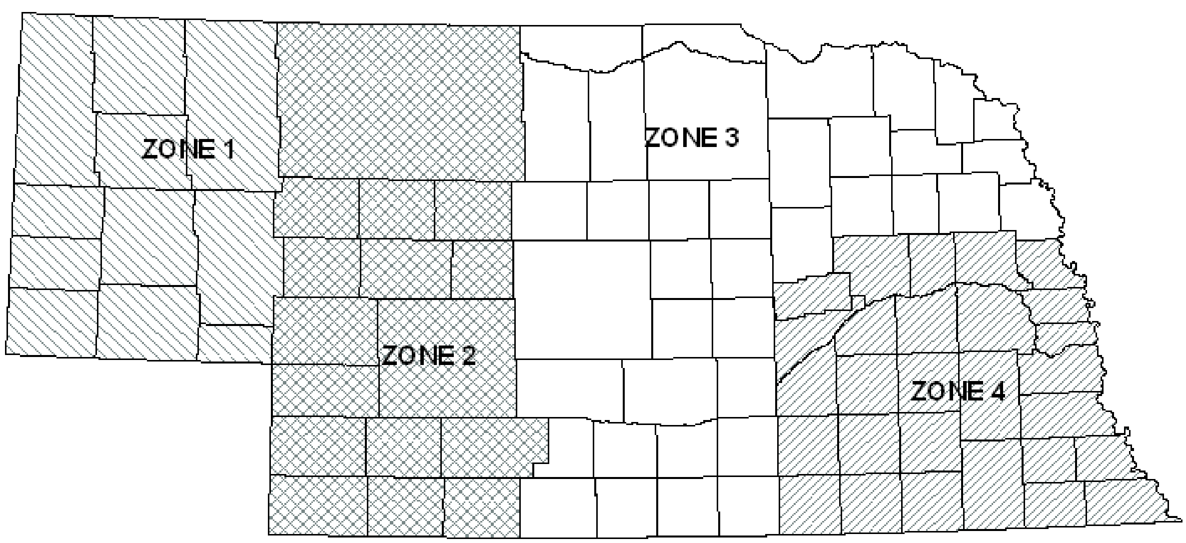

Figure 3. Location of management zones for the CROPSIM model.

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

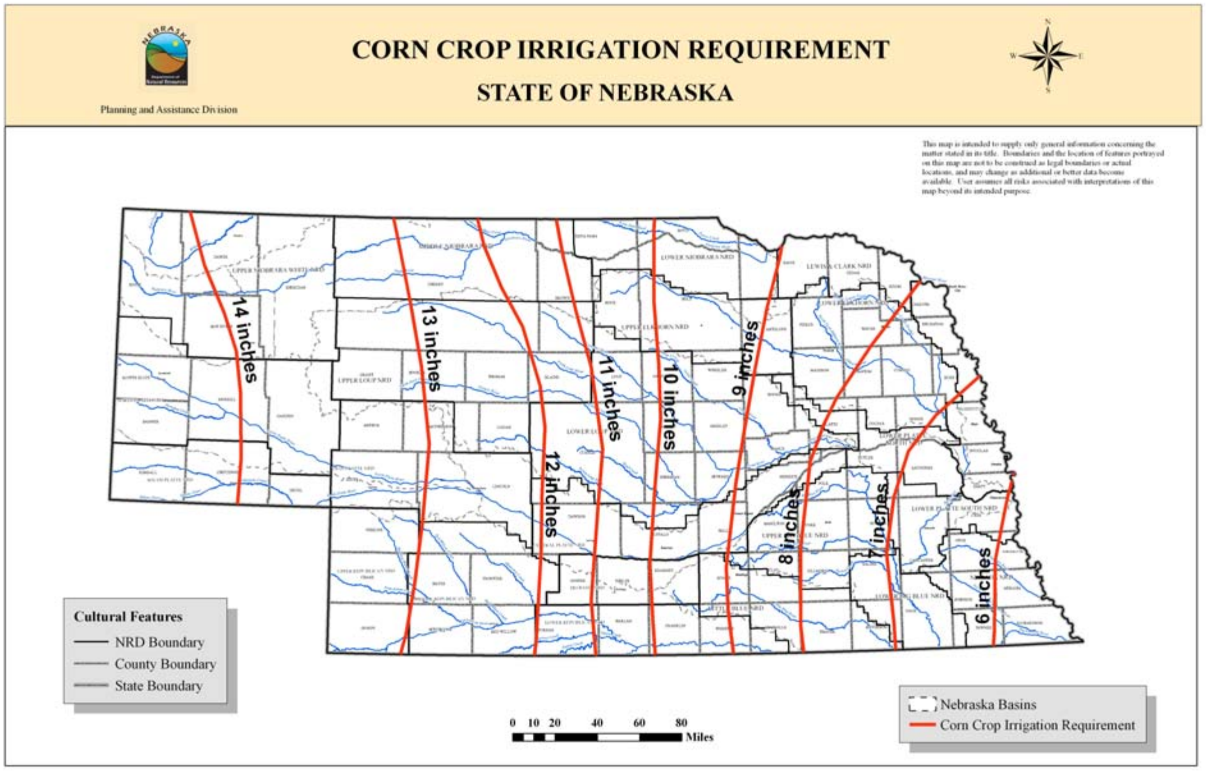

Figure 4. Map of net irrigation requirements (inches/year) for corn grown on fine sandy loam.

Appendix G

Appendix G

Development of Ground Water Irrigated Acres per Well

Estimation of the number of acres irrigated per ground water well was determined by evaluating three methodologies:

Method 1: Average Method

All active irrigation wells in the Nebraska Department of Natural Resources Ground Water Well database were queried and geographically located within the nine study basins. The average registered acres per well was computed for each basin. The ground water well database acreage value was obtained from the applicant when the well is originally registered. An examination in the Republican River Basin showed that number was, on average, 25% to 33% higher than the actual measured number of irrigated acres. Therefore, three alternate variations for 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 number of ground water irrigated acres for each 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 number of irrigated acres into one of the nine study basins, the average irrigated acres per well for each basin was computed by dividing the total irrigated acres in the basin by the total number of irrigation wells in the basin.

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 U.S. 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 from the DNR well database, 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 analysis. Then the total number 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 H-1.

Table H-1. 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 the estimated acres are fairly similar. 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 has 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 active 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 H-2.

Table H-2. 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, 1,220 are not in the nine basins evaluated. The remaining 2,319 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 H-3.

Table H-3. 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 of water varies by use category (EPA, 2005). They estimated that the rate of water 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 the EPA.

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.

Appendix H

Basic Assumptions Used in the Development of the Department of Natural Resources Proposed Method to Determine Whether a Stream and the Hydrologically Connected Ground Water Aquifers Are Fully Appropriated

Nebraska Revised Statutes § 46-713(3) states that a river basin subbasin or reach shall be deemed fully appropriated if the department determines that then-current uses of hydrologically connected surface water and ground water in the river basin, subbasin, or reach cause or will in the reasonably foreseeable future cause: (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural flow or storage appropriations and the beneficial or useful purposes for which, at the time of approval, any existing instream appropriation was granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved and (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, or other formal state contract or agreement, or applicable state off federal laws. This memo will address the assumptions relied upon to develop the method the Department proposes to use to address sections a and b of the statute.

In essence, if streamflow is sufficient enough to supply surface water appropriators, it is also sufficient to supply recharge for ground water wells dependent on the streamflow. This is true because any ground water aquifer that is hydrologically connected to a fully appropriated stream is also fully appropriated because the surface water and hydrologically connected ground water are both part of one interconnected system. A depletion in one component of this system depletes the other component. If there is an additional well and consumptive use of water in the ground water aquifers connected to the stream, the new well will either intercept and consume water that otherwise would have flowed to the stream or cause more water to flow from the stream to the aquifer. Eventually this additional consumption will cause not only additional depletions to the aquifer, but also additional depletions to the stream. In essence, the test of looking at the sufficiency of streamflow to satisfy a junior surface water right is like a canary in the coal mine; the junior water rights act as an alarm system signaling that the stream and the hydrologically connected ground water aquifers are both fully appropriated.

The nature of the connection between the stream and the aquifer determines how much and how fast water will flow between the stream and the aquifer. Water flows from a hydrologically connected aquifer to a stream, or vice versa, in response to the difference in the hydraulic head between the stream and the aquifer. Water flows down the hydraulic head gradient from areas of higher hydraulic head to areas of lower hydrologic head. Hydraulic head in ground water is a function of the combination of both the elevation and the pressure of the water. Water flows downhill in response to gravity and uphill in response to pressure from the weight of overlying aquifer materials and water.

In the case of a gaining stream, the water in the aquifer has a higher hydraulic head than the stream and water flows down gradient from the aquifer to the stream. In this situation, the addition of a pumping ground water well that removes water from the aquifer will lower the hydraulic head of the ground water in the aquifer and decrease the gradient between the higher hydraulic head in the aquifer and the lower hydraulic head in the stream. The decrease in the hydraulic gradient results in less water flowing from the aquifer to the stream.

In the case of a losing stream the water in the stream is at a higher hydraulic head than the ground water and water flows down gradient from the stream to the aquifer. As before, the addition of a pumping ground water well that removes water from the aquifer will lower the hydraulic head of the ground water in the aquifer. In this case the well will increase the hydraulic gradient between the higher head of the stream and the lower head in the aquifer and more water will flow from the stream to the aquifer, further depleting the stream. In either case, if the stream itself is already determined to be fully appropriated, than the whole integrated system must be fully appropriated.

One must also ask, is it possible for a stream itself to have sufficient water for all surface water rights but not have sufficient ground water to recharge wells dependent on streamflow? In this case, all the demands of the surface water rights would have to be satisfied, but the water in the ground water aquifer would be insufficient for the existing wells. Such a system could not happen on a gaining stream because if the ground water were insufficient to sustain the wells, there would be little or no water in the stream for the surface water users. According to Bentall and Shafer (1979) most streams in the State of Nebraska are gaining streams[1].

The remaining case would be a losing stream on which the major water supply to the stream and the hydrologically connected aquifers was from surface water runoff to the stream. Furthermore, this runoff would have to be sufficient to satisfy the junior surface water rights, or it would be determined to be fully appropriated under criteria (a) of the statute, but not sufficient enough to satisfy ground water wells for which the stream flow was a critical component of the supply. In areas on the White and Hat Creeks in western Nebraska, where isolated fractures in the Brule Formation are in close hydrologic connection to the stream but not to a surrounding ground water aquifer, there could be small stock and domestic wells that depend primarily on streamflow as their sole source of water. However, these streams have already been declared fully appropriated because the demands of the existing surface water rights are not met. There may also be such

[1] Availability and Use of Water in Nebraska 1975. 1979. Nebraska Water Survey Paper Number 48. Conservation and Survey Division Institute of Agriculture and Natural Resources, University of Nebraska Lincoln.

isolated physical systems in other parts of the state such as in the glacial till area of the eastern part of the state and along the Missouri River, but like the White River and Hat Creek, if the demands of the hydrologically wells are not being met, it is unlikely that the demands of any existing surface water rights would be met.