Prepared for:
BIG BEND GMD NO. 5
125 S. Main Street
Stafford, KS 57578-0007

HYDROLOGIC MODEL OF
BIG BEND GROUNDWATER MANAGEMENT DISTRICT NO. 5

JUNE 2010

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HYDROLOGIC MODEL OF

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HYDROLOGIC MODEL OF
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SUMMARY

The Big Bend Groundwater Management District No. 5 serves all or parts of eight counties in south-central Kansas as a subdivision of state government organized to promote local participation in water management and administrative standards through the Groundwater Management District Act (K.S.A. 82a-1020). The surface water of the Arkansas River and tributaries is interrelated to the aquifers managed under Big Bend Groundwater Management District No. 5 oversight. The District contains 4,866 irrigation wells and 55 surface diversions authorized to use 668,000 acre feet per year, of which about 500,000 acre feet per year is in recent exercise. Attention is currently focused on water-management alternatives that would improve the streamflow for habitat and water-right obligations, alongside better status of the overall water-management operation. This includes potential water-project developments in some areas.

The objective for a quantitative hydrogeological model of the surface and groundwater system is to clarify the relationship between alternative water-management actions and the resultant hydrologic conditions of the aquifer and streams. Capability is needed to address questions of watershed management, aquifer sustainability, efficiency of farm-water operations, accounting for sources of water and aquifer drawdown/buildup or stream depletion/accretion effects of proposed actions. The study area is Big Bend Groundwater Management District No. 5 and the upstream sub-basins that flow into the District.

The model was developed by consultants to Big Bend Groundwater Management District No. 5 with support from a technical advisory committee including state and federal agency staff and consultants, as well as information exchanged with the Rattlesnake Creek Partnership, a water user organization. The nature and function of a hydrogeologic model is outlined for use in simulating history and in projecting future conditions by means of integrating information on the system boundaries, heads, flows and governing equations into a formal code that accounts for the water balance. Also described, with an illustrative example, is how the model may be used in management planning.

The study area, from near Garden City in the west, to six miles east of the Big Bend Groundwater Management District No. 5 boundary, extends over 160 miles east to west and 90 miles north to south. Each quarter-section of a 12,182 square-mile area is characterized as to hydrogeologic properties using data-based estimates of water inflow, outflow, storage and use. The hydrologic system has been studied and gaged quantitatively since 1902, with parts of the area of interest covered by 17 mathematical models since 1980. Aquifer tests at dozens of sites have characterized the hydraulic properties of the groundwater resource. The past work provides a sound basis for a plausible range of recharge, aquifer properties, direct runoff, baseflow, return flow, evapotranspiration, managed water use and the trends of these parameters to be used as input for the model.

The geologic beds that constitute aquifers contributing to the water resource and water quality include recent alluvium, reworked Quaternary sediments of the "Great Bend Prairie" aquifer , the Pliocene Ogallala Formation, the Cretaceous Dakota Formation, and Permian Cedar Hills Sandstone with intervening bedrock shale and non-aquifer rocks. The geologic section of interest to the regional flow system ranges up to a half-mile below land surface. The Quaternary and recent unconsolidated sediments make up the primary well-production targets in Big Bend Groundwater

Management District No. 5. The underlying bedrock dips northwest at low angles but is in subcrop contact with the developed overburden aquifer. Permian beds in the east and Dakota aquifers in the central and southern parts of the study area carry deep regional water, some of it saline, to discharge into the lower layers of the unconsolidated primary aquifers.

Recharge styles are categorized as diffuse, focused, artificial, induced, and collateral. Data and available studies lead to a plausible range of recharge estimates, where diffuse natural recharge values are low at a few tenths of an inch per year, focused recharge rates are near one inch per year as an areal loading rate, artificial recharge from farm operations is up to seven inches per year, and induced or collateral recharge in interrupted reaches may be many feet per year as a loading rate to the aquifer from streambeds. The irrigation water use is nearly one million acre feet per year in the study area, with significant return flow. Trends indicate more efficient and lesser amounts of water use in recent decades. Evapotranspiration from the water table is treated as a climate-driven amount of about three feet per year in water-logged soil, ranging to near zero from a ten-foot depth below land surface. Evapotranspiration was the largest component of aquifer discharge and stream baseflow was the second largest component under pre-development conditions.

Water-level data for the study area has superior detail and coverage in state agency databases with 1,812 stations and 96,473 measurements. Big Bend Groundwater Management District No. 5 maintains the database on 138 water-table wells and 100 deeper aquifer wells. The characteristic transmissivity of the Quaternary aquifer is simulated to be 220 feet squared per day in shallow sands and 70 feet squared per day in deeper zones. Tested well efficiencies range from near 100 percent to 40 percent in terms of well performance relative to aquifer potential. Aquifer storage is simulated to be 0.20 for pore water and 2×10^{-6} per foot of thickness for elastic properties. Salt discharge in water from Permian beds is about 500 tonnes per day as chloride in the eastern areas at an estimated upward seepage rate of five cubic feet per second, plus or minus 50 percent.

The U.S. Geological Survey supports the well-established groundwater flow modeling program MODFLOW, which is applied here for quantitative numerical modeling. The program tracks the water balance in the study area modeled aquifer space on quarter-section detail. Water accounting is maintained in terms of recharge, stream leakage, drawdown of aquifer storage, and boundary inflow as positive additions to the aquifer-flow system, while well pumping, evapotranspiration, seepage to stream baseflow, buildup of water-table mounding, and boundary outflow are counted as negative flows out of the aquifer system. The plus and minus accounts balance over the simulation period of 1940-2007.

Data for program input was organized and formatted using MS Excel, ArcGIS 2009 and Visual Basic pre-processing tools. LANDSAT images are used to identify irrigated acres on places of use using ARCOBJECTS. The model grid has seven layers, 180 rows, and 335 columns, with columns in the north direction following Kansas South Zone Stateplane, NAD83 Coordinates. Each model cell is a half-mile on a side. Wells in some model runs are simulated with a pumping water level threshold ten feet above the bottom of the producing formation, which serves to reduce pumping rates where the aquifer becomes dewatered in the simulation. The service rate and lifetime of some wells is thereby constrained.

The model performance in accounting for aquifer flow, water level and streamflow is checked against historical conditions. Seepage rates from Permian beds into Quaternary sediments are comparable with earlier estimates by others. The model is considered to be suitable to address the management objectives of Big Bend Groundwater Management District No. 5. The model is useful to account for the sources of water that respond to the stresses on the hydrogeologic system. The stresses generally are net recharge and pumping. The sources of water to balance stresses are the response at streams, evapotranspiration and aquifer storage. The model has the capacity to quantify the response to total stress or to isolate single stresses such as pumping. We illustrate the results of both styles of model account with separate tabulations of the historical water budget. The simulated yield of the surface water and groundwater system in the model area varies around an average 1.58 million acre feet per year. System yield is sufficient to sustain long-term pumping in Big Bend Groundwater Management District No. 5 at water-use rates exercised in recent years.

The model is designed to address questions about the impact of management action on future hydrologic conditions. Two alternative baseline futures from years 2007 to 2074 are simulated to display a range of conditions that may prevail in the lack of new management action. The range of baseline futures is examined by copying forward the historical climate and by resampling climate (runoff, recharge and evapotranspiration) each month of the past 68 years, and projecting forward the recent pattern of average well operations. The two baselines are not a statement of future expectations; instead they illustrate a nominal range and pattern of climate and water use for evaluating altered conditions with management action. The baseline suggests that the aquifer and streams of Big Bend GMD No. 5 may be approaching effective balance for the 68-year future where drawdown and stream depletion trends are stable overall. Smaller areas of the overall system, however, display local or temporary drawdown and depletion inside the overall stability. The locations of balanced and transient trends are mapped in terms of impact on adjacent streams and aquifer storage.

A model calculation of an illustrative response to management action is presented to demonstrate how the model may be used in addressing questions on the effect of alternative actions. The illustrative case is simulated by constraining future exercise of permitted water use in the Rattlesnake Basin inside Big Bend Groundwater Management District No. 5 to those permits with a priority earlier than April 13, 1984.

That is the date at which subsequent permits were conditioned to protect regulatory minimum desirable streamflows. In that illustrative case, the effect on the hydrologic system is to reduce water use by an average of 11,290 acre feet per year below the baseline future, while increasing aquifer storage 5,125 acre feet per year and adding 2,741 acre feet per year to all interrelated streams. Wetland evapotranspiration removes the remainder of the curtailed pumping amount. The effect is displayed as a change relative to a smoothed average baseline. The effectiveness of the illustrative action is to produce 17 percent of the reduction in water use as a gain to Rattlesnake Creek flow and a lesser, two percent, impact in improving monthly MDS status. The smoothed baseline aids interpretation of the result, but the additional fluctuations in future conditions due to climate and use patterns should be recognized. This method of model analysis demonstrates the usual protocol for informing proposed management actions.

The model calculation is sensitive to parameter specifications, including net stresses, so that the uncertainty in input produces an acknowledged uncertainty in model results. The sensitivity is quantified for a variety of parameters. The results are relatively robust in the sense that the percent change in model results of greatest interest (flow and drawdown) vary proportionally less than the percent change in input might vary. The model results should be read with the understanding that specific local well, aquifer and climatic conditions may differ from the generalized character of the model. The computer files to run the model are publically available from the Big Bend Groundwater Management District No. 5 File Transfer Protocol site.

The model is designed to address Big Bend Groundwater Management District No. 5 management questions regarding impacts of alternative actions on future hydrologic conditions. During a period of transition which lasts decades, general impacts of a change in water use fall to a foreseeable degree on aquifer levels, streamflow and evapotranspiration. The model functions in a practical cause and effect style to inform a range of management alternatives. Within the appropriate scope, the model is suitable for use in guiding decisions on effective management and administrative practice.

INTRODUCTION

Big Bend Groundwater Management District No. 5

Big Bend Groundwater Management District No. 5 (Big Bend GMD No. 5) is a Kansas special district in a 3,947 square-mile area of all or parts of eight counties around the Great Bend Prairie of south-central Kansas (Figure 1). The District is authorized through the Groundwater Management District Act (K.S.A. 82a-1020) to promote local water users' participation in collecting and disseminating technical information, assistance in water management, administrative standards and policies, and in recommending water rules and regulations to the Chief Engineer. The Big Bend GMD No. 5 requires a tool to guide decisions on the connection between water-management action and hydrologic conditions in the District. The water resource being managed includes surface waters of reaches of the Arkansas River and tributaries such as Pawnee River and Rattlesnake Creek. The interrelated aquifers include river alluvium, the Ogallala and "Great Bend Prairie" areas of the High Plains aquifer system and locally underlying resources of the Dakota Sandstone aquifer. The current attention is on threshold targets for stream baseflow that have been set by state statute, on the potential for future development and on water-right obligations, alongside broader questions of the overall status of the hydrologic system.

Purpose

The purpose of developing a Big Bend GMD No. 5 hydrologic model is to clarify the physically-based relationships between water-management actions and the past hydrologic conditions, and to project future conditions in the aquifer and interrelated streams. Alternative water-management actions are to be examined as to their separate effects on conditions in the aquifer and streams. The model is intended to advance the understanding of the Big Bend GMD No. 5 hydrologic system by addressing watershed management, pumping water levels (PWL), sustainable aquifer lifetime, vertical-layering effect on the area of influence of wells, farm-water accounting of consumption and returns, moist-soil and wetland evapotranspiration (ET), among other factors. Model boundaries have been set several miles outside the area of interest to reduce their sensitivity to management issues. The model area focuses on Big Bend GMD No. 5 as the primary area of interest, but extends to related upstream sub-basins and the buffer zone of a peripheral township (Figure 2). The study area covers all or parts of 23 counties.

Model Function

The general nature of a groundwater model for use in simulation is introduced below. One can describe a groundwater model as a vehicle for the orderly calculation of the interactions of a large number of factors such as the shape, distribution and quantity of water in the aquifers, factors which are derived from the hydrologist's conceptual image of the groundwater system. Physically the model consists of a set of "FORTRAN" commands, which instruct a computer in making its calculations. The calculations arise from a mathematical (numerical) description of the physics of groundwater flow. The equations which govern groundwater flow contain terms specifying values for the aquifer's ability to store (specific storage and specific yield), and to redistribute water among localities with different water levels (hydraulic conductivity) and for accommodating pumpage and recharge rates. These terms, known as "parameters", define the characteristics of the flow system. The governing equations are, by themselves, an incomplete description of the system; other information is also required describing the shape of the aquifer and nature of the model boundaries with respect to connections between the aquifer and surface water or impermeable material (boundary conditions) and describing the water levels in the study area at some specified time (initial conditions). The governing equations, augmented by the specified boundary and initial water-level conditions, constitute a complete mathematical description of the groundwater system.

Boundary conditions consist of information specified *a priori* at the boundaries of the model. The boundaries include locations where the groundwater is in contact with adjacent bodies of surface water, the atmosphere, impermeable rock units, or in this case, simply where the extent of the study area is arbitrarily delimited because of a lack of effect of conditions at greater distances on the area of interest. In groundwater-flow simulation, boundary conditions can have two general forms: specified constant flow independent of head changes and head dependent flow that specifies the functional relationship between the hydraulic head and the flow. Both forms are used in the Big Bend GMD No. 5 model.

Initial conditions in the groundwater model consist of the specification of water levels everywhere within the model at some initial reference time. We use the year 1940 as an early date with sufficient data to bring to the Big Bend GMD No. 5 model, but before major well development.

The complete hydrologic model for the study of water quantities is comprised of the governing equation with its terms, boundary conditions and initial hydraulic-head specified. A valuable, but somewhat less-complete model, may be based on steady-state conditions. The steady water-level elevation and flow rates can be described and compared to observed data for steady conditions. Historical or future changes in the flow system are not considered in the steady state. The steady-state modeling procedure is useful in preliminary model interpretation.

In the Big Bend GMD No. 5 model, a steady-state solution is an appropriate initial condition for the more complete (non-steady or transient) simulation. The transient simulation then makes it possible to include information on aquifer storage properties and on the amount and schedule of flow changes (the stress or "excitation" being investigated), such as well pumpage, recharge and river diversions. The model finally runs to calculate the simulated water level and flow changes in response to the specified stress. An ultimate steady state can be examined for understanding long-term changes from initial conditions. To the degree that the mathematical model is a suitable realization of the physical system, it can be used to explain past conditions or to project the response of the groundwater system under future water-development programs.

Model Role in Management Planning

The sum of natural recharge processes and the natural direct flow at the mouth of a sub-basin can be viewed in water planning as the basin yield, expressed as water loading (inches per year) or as a water volume over the basin area. The natural basin yield will increase or decline with alterations in land use and development in the basin. Water planners recognize that sub-basin surface-water yield is related to the area that can be fully served to satisfy atmospheric demands for ET. Certain adjustments are necessary before planning the proper intensity of basin water use. For example, after adjusting for obligations to deliver water downstream to municipalities or others (such as senior water rights), and reserving or setting aside in the development plan an appropriate amount for ecological water or minimum desirable streamflows (MDS), then the remaining water can be allocated for in-basin development.

Groundwater development introduces a transient complication in the relatively simple surface-water yield. Groundwater development usually contributes to expanded basin yield for the period of allowable aquifer-storage depletion. Thereafter, aquifer and wellfield development serve best to operate the aquifer reservoir storage under the principle of sustainability. Sustainable yield is defined for Big Bend GMD No. 5 in KAR 5-25-1(l) as "*the long-term yield of the source of supply, including hydraulically connected surface water or groundwater, allowing for the reasonable raising and lowering of the water table*". In that case, the aquifer does not persistently add new water to the basin yield, but instead provides for leveling of fluctuations by operating the aquifer storage in conjunction with other basin sources. The sustained lower position of the water table also enhances the effectiveness of capturing the available supply by salvaging previously unmanaged riparian and moist-soil ET. That aspect serves to increase the accessible water sources for development. Aquifer management plans can create suitable conditions of aquifer water levels and associated ET for ecological and other purposes, while benefiting the overall basin yield for all purposes. Wellfields, however, commonly do not reach and intercept in full all surface components (ET, direct flow and baseflow) of basin yield, because the effectiveness of capturing surface sources of water is limited in accordance with well location and available drawdown. Surface diversions, along with wells, usually serve to access the remainder of the divertible basin yield.

At Big Bend GMD No. 5, well operations historically have varied by wet and dry periods. Some months, years and decades of high or low well use are followed by the alternate pattern. Thus, the stored aquifer resource has not been used on a uniformly decreasing curve to reach final sustainability. Instead, "reasonable raising and lowering of the water table" follows the sequential patterns of more or less demand. The long-term hydrologic condition continually fluctuates, rather than reaching a steady final condition. One role of the model is in estimating the degree to which Big Bend GMD No. 5 wellfield development operates to expand basin yield by relying on the stored aquifer resources, or operates sustainably by intercepting the allocated surface sources over time.

The available quantities of initial basin yield, the developed yield with associated storage depletion, and the sustainable yield alongside ET salvage are among the quantifiable objectives for use of the model in management planning.

Acknowledgements

Field conditions were inspected on July 25-27, 2008 in the company of Big Bend Groundwater Management District No. 5 Manager Sharon Falk and staff specialists

Juan Uribe and Orrin Feril. The model work began in November 2008. A serviceable model was produced by April 2009, with calibration and enhancement through the guidance of a technical review committee to October 2009. A draft version for review was released in December 2009. Scenarios were discussed in December 2009 for examination in 2010. Scenarios are to be documented in separate addenda to the body of the report. A complete set of model input files is distributed with this report. The model development was led by Balleau Groundwater, Inc. (BGW) with technical contributions and review by Kansas Department of Agriculture Division of Water Resources staff and consultant S.S. Papadopulos and Associates, Inc., alongside feedback from the Rattlesnake Creek Partnership consisting of Kansas Department of Agriculture Division of Water Resources, Big Bend GMD No. 5, Water Protection Association of Central Kansas and the U.S. Fish and Wildlife Service. Thanks are due to Andrew Lyon of the Division of Water Resources for helpful coordination of technical exchange. Big Bend GMD No. 5 staff and officials aided the model with local information on the actual practice of farm-water operations and with data on the observed performance of the stream and aquifer system.

The model version accompanying this report, nominated BBGMDMOD, makes provision for updates that may become necessary to integrate data from future climate or water operations, and to modify input to address site-specific questions. The computer files to run the model are available on the Big Bend GMD No. 5 File Transfer Protocol site at ftp.gmd5.org.

PREVIOUS MODEL WORK

The Arkansas River valley in west-central Kansas has been the object of quantitative water studies since the 1890s (Newell, 1896; Slichter, 1906; Transcript of Record Kansas vs. Colorado, 1906, testimony by Johnson, Darton, Newell, Slichter, Mead). Official stream gaging efforts began in 1895 with the first cooperative U.S. Geological Survey (USGS) program in the nation. Streamflow data are available from 1902, with water-table mapping published by Slichter from data in 1904 and depth-to-water observations from 1896 by Johnson at Garden City, "*The ground water plane sloped toward the river. The ground water was feeding into the river bed. The river bed served…as an evaporating pan for evaporating what was contributed from the slopes.*"

The study area benefits from earlier work in which the authors of 17 reports have expressed their concepts of the hydrogeologic system in formal quantitative models. Those studies are abstracted below. Table 1 summarizes the aquifer properties from 14 selected models.

An early numerical model by Sophocleous (1980) simulated the Pawnee Valley and recommended "*development of artificial recharge…to conserve water and to increase the efficiency of water use*". A model of the Great Bend aquifer was prepared in 1983 by Cobb and others.

Stullken and others (1985) developed steady-state models of western Kansas for pre-1950 conditions using the early Trescott and others (1976) two-dimensional program. One model covered the High Plains aquifer in Kansas south of Kearny, Finney, and Hodgeman Counties. They found the simulated groundwater flow near Bear Creek and Crooked Creek faults was complex due to slumping and sinkholes.

Recharge was treated separately as areal recharge (0.25 inch/year) and recharge from ephemeral stream sources (0.15 cubic feet per second (cfs)/mile).

Dunlap and others (1985) simulated the Arkansas River aquifers from the Colorado state line to east of Garden City using Trescott's (1975) three-dimensional program. The valley and upper aquifer (K_x=150 feet per day (ft/d)), a middle confining zone (K_x and K_z = 0.0075 ft/d) and a lower aquifer (K_x=115 ft/d) were simulated in separate layers. They ascribe reduced river flow to declining water levels and to decreased flow from Colorado.

Watts (1989) modeled the High Plains aquifer and four bedrock units in a five-layer MODFLOW grid to show the effects of Dakota aquifer development on the High Plains aquifer. He reviewed the field test data on bedrock hydraulics. Layer 1 represented the High Plains aquifer with K_x of 80 ft/d, and Arkansas River alluvium at 800 ft/d. Layer 2 was the Cretaceous confining bed with K_x of 0 and K_z of $1x10^{-5}$ ft/d. Layer 3 was Dakota aquifer at K_x of 7.0 ft/d and K_z at 0.1 ft/d. Layer 4 was Kiowa Shale at K_x of 0 and K_z of 1.3×10^{-6} ft/d. Layer 5 was Cheyenne aquifer at K_x of 9 ft/d and K_z of 0.01 ft/d. Watts concluded that development of the Dakota aquifer would not significantly affect the High Plains aquifer.

Layne GeoSciences, Inc. (1990), in Appendix E of Howard and others (1990), reports on a MODFLOW model of Walnut Creek Basin and the groundwater irrigation aspect of declining flow. The model excludes Cheyenne Bottoms itself. Alluvial horizontal hydraulic conductivity (K_x) was 225 to 275 ft/d. Seepage from Walnut Creek used a bed vertical hydraulic conductivity (K_z) of five ft/d. They concluded that up to 100,000 acre feet (AF) of alluvial storage had been depleted, which could be replenished by four years of non-pumping. They recommended watershed dams be used to supplement recharge.

Koelliker (1990) documented the POTYLD model (Koelliker and others, 1981) of drainage areas feeding Cheyenne Bottoms Wildlife Area (CBWA). He accounted for an Arkansas River diversion capacity at 80 cfs delivering up to 37,000 acre feet per year (AFY) and 79,000 AFY into the area from all sources. CBWA losses are about 74,000 AFY due to 60 inches of evaporation plus seepage from the full pond area. Koelliker tabulates 2,340 typical stock ponds in the watershed, each of 2.2 to 3.4 surface acres and 6.9 to 10.5 AF volume collecting runoff from 160 to 480 acres in four counties (Barton, Rush, Ness and Lane). Pond seepage is taken as 0.10 inch/day. Between 40 to 72 percent of cropland was terraced in those counties by year 2000. Koelliker finds that watershed dams are larger than typical stock ponds but behave like multiples of typical ponds, and are included in his tabulation. Water yield ranges from 0.22 to 1.58 inches/year accounting for watershed conditions he examined. Watershed dams detain runoff from 50 percent of the watershed areas and hold 8,000 AF (Koelliker, 1990). Koelliker reports the schedule of new watershed impoundments, for example in Barton County, ranged between five to ten per year peaking at over 20 per year in 1960s and 1970s, while farm terracing was constructed at a rate of 100 to 200 miles of terrace per year in those decades. In modeling the history of land use, we assume those were peak years of such activity throughout the model area. Koelliker recommends that watershed dams be required to release water downstream after detention for flood control.

Sophocleous and Birdie (1990) used Big Bend GMD No. 5's observation wells and Kansas Geological Survey (KGS) recharge assessment site data on Rattlesnake Creek in a model to constrain channel-sand transmissivity to 25,000 feet squared per day (ft^2/d), and the rest of the aquifer material to the transmissivity range 2,500 to 250 ft^2/d, with storativity of buried channel sand at 0.0001, and the rest of the aquifer material to the storativity range 0.01 to 0.001. K_v was 1.0 ft/d.

Whittemore and others (1993) examined the Dakota aquifer system in a vertical-slice MODFLOW model. They provide (their Table 4) a set of aquifer K_x and K_z for their model layers in the stratigraphic interval from the High Plains aquifer and associated alluvium to the Permian bedrock. We have adopted their values as initial estimates for bedrock in the Big Bend GMD No. 5 model.

Sophocleous and Perkins (1993) simulate the lower Rattlesnake Creek Basin and Quivira National Wildlife Refuge. They tabulate the water quality through the National Wildlife Refuge showing a three-fold increase in salinity with flow through the Refuge. They ran six management alternative scenarios with simulated effects on streamflow and on National Wildlife Refuge marshes. Protective stream corridors are recommended and the 1990 level of pumping is concluded to be unsustainable. The report states that the irrigators of the area had "*organized to protect their rights and contest any unfavorable results of this study*".

Sophocleous and others (1997) developed a Rattlesnake Basin model for evaluating long-term water management strategies, by integrating MODFLOW and SWAT (Arnold and others, 1994). The model was matched to data from 1955 through 1994, then ran a baseline future through year 2034. They recommended the model be used in a comparative, rather than predictive mode, and that certain improvements be made regarding soils, land use, aquifer and stream properties, and non-contributing runoff areas. Several scenarios of interest at the time were not run because of model-tool limitations. The scenarios not run were discussed in a following report (Sophocleous, 1998) where additional programming and enhanced tools were recommended to handle time-dependent stresses alongside recommended new climate and streamflow data collection. The 1997 model simulates climate, soil, streams and groundwater using a set of modeling tools developed for the purpose. The model was reviewed in 1998 with questions about the model performance (Keller-Bliesner Engineering, 1998). BGW examined the 1997 model in 2008 (electronic communication, May 12, 2008, BGW to Sharon Falk) and recommended that boundary conditions be expanded, that useful data be retained from the 1997 model and that the model be refreshed with the available new MODFLOW and GIS tools.

Ma and others (1997) used a flow and transport code (SWIFT-II, Sandia National Lab Report NUREG/CR-3328, 1986) to simulate salt water upconing on a conceptual scale, at the Siefkes site (T21S, R12W). They conclude clay layers control upconing, well screens should be placed above such clay layers, and that artificial recharge may alleviate a portion of the salt water problem. Their calibrated model parameters included aquifer horizontal hydraulic conductivity (K_{xy}) at 140 ft/d, K_z at 22.6 ft/d, porosity at 0.18, Permian bedrock K_{xy} at 0.14 ft/d, K_z at 0.023 ft/d, and bedrock porosity at 0.09, and alluvial clay K_{xy} at 0.011 ft/d, K_z at 0.001 ft/d, and porosity 0.30.

GEI/Burns & McDonnell (1998) report on a multi-layer MODFLOW model of the Quivira National Wildlife Refuge and a township upstream. Two layers were used for surface sand hills (K=12 ft/d) and for the "Great Bend Prairie" aquifer with (K=100 to 400 ft/d) with an intervening silty clay layer (K_z=0.00435 ft/d). They estimate pre-development aquifer discharge as upflow to Big Salt Marsh was 35,900 AFY which had been reduced by 1995 to 33,450 AFY due to regional wells (their Table VIII-1).

The USGS prepared a water routing and budget model of Quivira National Wildlife Refuge canal and pond operation (Jian, 1998). They found that pond storage was reduced by pond evaporation and by canal losses in year 1996, and that losses and remaining pond contents are sensitive to managing Little Salt Marsh target water levels. The USGS tabulates water feature data on drainage area, bottom elevation, surface area, capacity, seepage tests, water surface elevations and contents, lake evaporation, and water budget (Appendix A).

Luckey and Becker (1999) applied MODFLOW to the High Plains aquifer in three states including Kansas south of the Arkansas River and east to Ford County. They used 6,000-foot square cells in one layer. They found that natural recharge is "extremely variable," and that dry-land agriculture enhances recharge, as does irrigation. They simulated pre-development conditions and development from 1946 to 1998, and projected conditions to 2020. The area of salt dissolution between Bear Creek and Crooked Creek is simulated with reduced permeability. They note a rise of 20 feet in Ogallala water levels ascribed to enhanced recharge from dry-land cultivation. They calibrated streambed leakance and compared estimated to simulated discharge at 18 gaging locations. Recharge due to dry-land cultivation added 3.9 percent of precipitation or 0.64 inches/year to the aquifer. Baseflow discharge to streams was found to be sensitive to this term in the range of tens of cfs.

Dugan and Zelt (2000) provide a comprehensive soil moisture, consumptive use, runoff and recharge account for the Great Plains. Their soil-water approach has the strength of being independent of aquifer geohydrology. Their soil-water accounting findings pertinent to the Big Bend GMD No. 5 study area include:

a. Soil and vegetation characteristics considered together cause only a 50 percent variation in recharge compared to calculations from climate alone;
b. Mean potential ET ranges from 52 to 62 inches while mean precipitation ranges 18 to 30 inches. Minimum annual precipitation, however, is 8 to 12 inches;
c. Regional wet conditions are less common than regional dry conditions;
d. Capillary action from a high water table may sub-irrigate deep-rooted vegetation. "*This condition is common in the major stream valleys or flood plains…*";
e. Grassland has an annual water requirement comparable to alfalfa;
f. Runoff ranges from one to four inches, soil infiltration ranges 16 to 26 inches, and actual ET ranges 15 to 22 inches;

g. Potential deep percolation recharge from non-irrigated lands ranges from one to five inches/year (1951-1980);
h. Potential recharge tends to be larger for cropland than for natural vegetation;
i. Recharge in sandy soil frequently is more than ten percent of mean annual precipitation as compared to five percent for silty and clayey soils;
j. Potential deep-percolation recharge for irrigated conditions results from better moisture at the end of the irrigation season for winter carryover. Water applied in irrigation may substantially exceed consumptive irrigation requirement (CIR). A large part of excess pumpage returns to the aquifer. Without over-application of water, irrigated areas would recharge 1.5 to 7 inches/year. Overwatering causes even higher rates of return flow;
k. Net flux (pumping minus deep-percolation recharge) on irrigated land ranges from 6 to 17 inches/year as net aquifer depletion.

We consider the Dugan and Zelt (2000) results to be serviceable approximations, alongside Koelliker (1998) in Appendix B, for initial estimates of the soil-water operations in the Big Bend GMD No. 5 study area.

Whittemore and others (2006) developed a Mid-Ark MODFLOW model of the stream reach from above Kinsley to below Great Bend to simulate stream-aquifer interactions and the effect of pumping for use in planning and management. The model matches data for years 1944-2004 at one-quarter mile square cells. K_x ranges from 50 ft/d in bedrock to 80 ft/d in tributaries, 120 ft/d in the main aquifer and 160 ft/d in alluvium. Streambeds are assigned K_v of 1.31 ft/d. Precipitation adds an average 1.81 inches/year to the aquifer, but is variable year to year. Scenarios include an alternative history with more river inflow, and future years to 2054 with continued pumping, no pumping, and two cases of reduced pumping by 25,287 AFY or 5,000 AFY. Aquifer storage recovers after 20 years of no pumping.

The Mid-Ark model was reviewed by Larson (written communication, October 3, 2006, Steve Larson to Tina Alder) who concludes the model can be used to evaluate how future changes might impact conditions in the basin. Larson advised that adjustment in the time-varying constant-head boundary in the southeast may become necessary, which cannot be specifically determined without a model that includes the pumping from Rattlesnake Creek sub-basin.

BGW noted (BGW, 2008b) that two-thirds of the water turned off in each Mid-Ark model scenario remains in the aquifer without supporting the river flow. The model has time-varying specified-head boundaries in all but one scenario that makes ambiguous the isolated effect of pumping. The boundary effect can be removed by extending the model area. ET salvage accounts for less than one percent of the water balance in the riparian corridor, simulated as one model-cell each side of the river. A larger active ET area might involve a larger part of the water balance. BGW recommended the Mid-Ark scenarios of interest be re-examined in a model with extended boundaries and ET.

A concurrent modeling effort has been underway, led by KGS, for Southwest Kansas GMD No. 3 during the study period. The two models overlap in about a third of the Big Bend GMD No. 5 study area in parts of eight southwest counties (Figure 3). Technical concepts and approaches were shared between the two model teams, although the specifications for the overlap areas differ. The overlap provides an opportunity for future comparison of parallel results from two recent model realizations of hydrogeologic conditions in this area of Kansas.

The previous 30 years of quantitative work outlined above is useful in this study to indicate the range of parameter values and water routing thought to be reasonable. Previous model parameter specifications are summarized on Table 1. We gain from the earlier models the following information for use in this effort:

a) Recharge has several components, including natural diffuse and focused amounts. Recharge varies due to water and land-use operations. Precipitation is variably routed by several mechanisms to ET, runoff and recharge, while each component can vary downstream;

b) Hydraulic conductivities have been applied in the following ranges of ft/d;

Hydrological Unit	K (ft/d)
High Plains	Tens to hundreds
Alluvial sand	Several hundred
Alluvial clay	Hundredths
Shale bedrock	10^{-6} to 10^{-8}
Cretaceous aquifer	Units
Jurassic aquifer	Tenths
Permian aquifer	Tenths to units
Vertical properties	Tenths to hundredths of horizontal value
Streambed vertical	1-5
Pond seepage	0.1

c) Runoff and recharge vary from less than one to several inches per year, depending on land use, water operations, climate and watershed character. Recharge by return flow from overwatered farm operations can exceed seven inches per year;

d) Salinity increases eastward in the study area from bedrock sources and from ET concentration;

e) Aquifer conditions have been perturbed by land use since pioneer days;

f) A high water table loses water to moist soil evaporation and to vegetative root zone transpiration;

g) Well production is supported by multiple sources of water including depleted aquifer storage, captured streamflow, and salvaged ET.

The results from past work are applied in this model to indicate the plausible range of parameter values and water operations constraining the Big Bend GMD No. 5 model specifications. Slichter's 1904 map and Johnson's early observations of the flow and evaporative discharge near Garden City are used for headwater initial conditions of the Big Bend GMD No. 5 model (Transcript of Record, Kansas vs. Colorado, 1906).

Study Area

The model area includes Big Bend GMD No. 5 and upstream drainages of Pawnee and Walnut Creeks that feed into Big Bend GMD No. 5. The Arkansas River upstream to near Garden City is included, as is about a township peripheral to the primary area of interest extending into the Ninnescah River Basins to the east and other streams to the south. The upstream areas provide for examination of hydrologic effects on Big Bend GMD No. 5 from changes in hydrologic conditions upstream. The peripheral townships provide a zone to buffer the simulated impacts inside Big Bend GMD No. 5 from model boundary conditions. Figure 2 displays these areas.

Character of Hydrogeologic System

The stress (generally pumping and recharge) and response (drawdown or depletion) characteristics of a generalized hydrogeologic system, such as at Big Bend GMD No. 5, are related to the aquifer diffusivity and the distance to boundary sources of water. Diffusivity is an indicator of the rate of expansion of pressure responses in the aquifer. Higher transmissivity and smaller storativity mean a faster impact over a wider area in response to stresses from pumping. For example, where T is 10,000 ft^2/d and S is 0.2, typical of the Big Bend GMD No. 5's aquifer, the horizontal radius of influence from a well, as estimated from the non-equilibrium analytical relationship of Cooper and Jacob (1946), reaches about 0.3 miles from the well in a month, 1.2 miles in a year, 3.8 miles in ten years and ten miles in a 70-year time horizon. Water features such as rivers, wetlands or wells inside that radius can be expected to respond to the well stress. Aquifer tests show the vertical response from a well screen to the water table takes a matter of days. The deeper confined Dakota and Cedar Hills aquifers have elastic storage that makes their response even wider and faster than in the unconsolidated overburden.

Accordingly, the distance to a surface-water feature controls the timing of the transition from a well source that relies on aquifer storage towards a shift to recharge induced from the surface sources (surface water or ET salvage). The distance to such boundaries in Big Bend GMD No. 5 is such that many wells shift from aquifer storage to surface sources in a matter of months to years, and relatively few wells take decades to impact their ultimate sources. Some wells many miles from surface-water bodies or wells completed in deep confined aquifers are expected to deplete aquifer storage as a primary source for decades.

The overriding early source impacted by most wells is the ET boundary at the land surface. ET may be affected the first month if the well is constructed in a water-logged area. The ET boundary surrounds the streams and water bodies, so ET often is the source impacted by wells even before surface-water bodies respond to the well. The relative closeness of boundary sources and the relatively high diffusivity of the aquifer accounts for the exceptional performance of the Big Bend GMD No. 5 hydrologic system in arriving at an early equilibrium condition at many sites.

A new stress on the hydrologic system, such as a well, is propagated to the responsive flow-dependent boundaries at rates controlled by the aquifer properties as described above. The larger and most dominant stress in the Big Bend GMD No. 5 system, however, is not well pumping, but is the usual large variation in recharge and runoff amounts and the consequent direct-flow impact to streams. The trends of aquifer water level demonstrate greater response to recharge events and to extended dry or wet periods than to any monotonic downward trends that would be expected from well pumping in the absence of other sources of water. Thus, the focus of history-matching of observed trends in this model is the magnitude and schedule of recharge, which is thought to be dominant over other aquifer properties. For example, wells in the study area produce up to one million acre feet per year (MAFY) of stress on the system whereas recharge is estimated to range between 0.14 million MAFY to 3.7 MAFY and direct runoff to streams ranges 0.23 MAFY to 1.6 MAFY. Thus the theoretical relationships of the general hydrologic system suggest that the more sensitive factors for influencing system output are recharge and runoff; consequently, those factors receive the emphasis in model history-matching.

Geology

The geology of the model area is outlined below to describe the three-dimensional framework for use in delineating hydrogeologic parameters specified in the model. The geology is used as guidance for layout of permeability and storage of rock units while recognizing that a degree of hydraulic zonation may be found within and across the rock units.

The study area is centered on the physiographic region (KGS, 2005) of the Arkansas River lowlands, along with the adjacent High Plains and Smoky Hills regions and small areas of the Red Hills region to the south. The geology has been described in a regional geohydrology report (Gutentag and others, 1984) and in three-dimensional model documents for the area (Watts, 1989; Whittemore and others, 1993). The Big Bend GMD No. 5 study is intended to simulate flow in the shallow aquifers and in the interrelated deeper saline water zones. The outline below is abstracted from these reports on the geologic formations of interest to Big Bend GMD No. 5. Generalized surficial geology is shown on Figure 4 and bedrock geology in Figure 5.

The geologic section contains older marine sediments (generally the shales that constrain flow between rock layers) and continental or shore-line sediments (generally the sand or sandstones that carry the majority of flow within the bedrock layers). The oldest marine beds of interest are Permian Period units that consist of fine-grained red-beds and evaporites (salt). Upper Triassic and Jurassic continental sandstones locally overlie the Permian beds unconformably in the southwest of the study area, but are mostly absent from the model area. Cretaceous marine conditions laid down a major beach sand (Dakota Formation) followed by thick layers of impermeable marine clays with limestone layers. The subsequently eroded surface of the Cretaceous bedrock units received continental deposition from the Rocky Mountains laid down as the Ogallala Formation and High Plains aquifer system in Pliocene time (two to five million years ago). The Ogallala was partially cemented with secondary carbonates during its long period of saturation. The Arkansas River became an integrated drainage in an interglacial period over 100,000 years ago, eroding in the west and depositing the "Great Bend Prairie" sediment as a geomorphic lowland in the study area. The Pawnee Creek drainage is eroding westward into the Ogallala surface. The Arkansas River has migrated north by stream capture and avulsion across the Great Bend Prairie (Fent, 1950).

Pliocene and Quaternary sediments that make up the major High Plains aquifer lie on an earlier surface truncating Cretaceous to Permian beds that dip northwest. Cretaceous beds overly Permian beds in much of the model area where intervening beds are missing, due to Mesozoic erosion. The Cretaceous beds of Dakota Sandstone are developed for irrigation in Finney and Scott Counties. The Dakota Sandstone is 200- to 300-feet thick where it has not been subjected to erosion. It is thinner where it subcrops below Tertiary overburden south of the Arkansas River and in Pawnee Valley. Water can move between the High Plains aquifer and the bedrock, generally recharging by seepage downward in the west and discharging upward in the east of the study area.

In interglacial periods over the last 600,000 years windblown dune sands and loess covered the ancient soils producing a layered stratigraphy in the Great Bend Prairie. Recent surficial dune sands, absent integrated drainage networks, have become focused recharge areas. The recent alluvium filling up to 60 feet of modern river flood plains has been deposited in the Holocene interglacial of the last 13,000 years. The relatively younger High Plains sediments of the reworked "Great Bend Prairie" and undifferentiated recent river alluvium are the more productive water sources used by regional wells. The deeper Cretaceous and Permian flow systems contribute some interrelated water and salt load to the surficial aquifers. Collapse features due to shallow bedrock evaporite solution complicates some local flow relationships. Crooked Creek fault with up to 200 feet of displacement is considered to be of solution origin in the Big Bend GMD No. 5 model area. Bedrock dissolution has been implicated in structural explanations of the geomorphology of the Great Bend of the Arkansas River and of the low topography at Cheyenne Bottoms. The Hutchinson Salt Member of the Permian Wellington Formation lies below and is excluded from the flow system of interest.

The stratigraphy and lithology of these rocks are detailed in Zeller (1968). Zeller's Plate 1 is appended (Appendix C) for reference. Structure contours for the bedrock formations of interest are available from MacFarlane and others (1990). We have copied them in this report, Appendix D. The geologic formation subcrop areas are taken from the same authority and from Fader and Stullken (1978). The surface outcrop geology is applied as shown on the digital state map (KGS, 1992).

Hydrogeology

The land and water system of Big Bend GMD No. 5 involves about 2.53 million acres with two percent surface-water bodies and wetlands, less than one percent forest, shrub or barren areas, 32 percent grassland and 60 percent agricultural lands, dry and irrigated (KARS, 2008). About five percent of Big Bend GMD No. 5 land is developed for other purposes including urban. The water features of the Big Bend GMD No. 5 are illustrated on Figure 6. The Big Bend GMD No. 5 contains 4,866 irrigation wells and

55 surface diversions for irrigation on 680,000 acres. Big Bend GMD No. 5 water operations subject to management include about 470,000 AFY of well irrigation, 41,000 AFY of other well use, and less than 7,000 AFY of surface-water diversions. Supplemental irrigation and other water use in the Big Bend GMD No. 5 is near 500,000 AFY but near one MAFY in the extended study area of the model. The higher actual ET rates, in contrast to the pattern of potential ET rates, are concentrated inside Big Bend GMD No. 5, rather than in the dry western Ogallala outcrop areas with greater depth-to-water. Figure 7 displays the relative strength of ET loss areas based on a generalized surface energy balance from recent LANDSAT imagery (Waters Consulting, 2002). Much of the surficial moisture flux to the atmosphere (1,400 cfs) seen on Figure 7 is supplied from the aquifer to surface-water bodies and wetlands, or is pumped to irrigate crops since the 1970s. The quantity authorized for irrigation use inside Big Bend GMD No. 5 is 668,000 AFY. Stream baseflow east of Big Bend GMD No. 5 is about 300 cfs, or over 200,000 AFY, at Hutchinson and in the north and south forks of the Ninnescah River. The baseflow is generated as discharge from the aquifers. The stream baseflow plus the water-table return to the atmosphere from the root zone and from water-logged soil or water-table outcrop, plus actual ET from irrigation in recent decades represents the bulk of the flow system discharge from the aquifers of Big Bend GMD No. 5.

The following hydrology sections describe the patterns of water flux and storage in the groundwater and surface-water system that is relied upon by Big Bend GMD No. 5 water users.

<u>Recharge Processes</u>

Recharge consists of adding a flow of water across the water table. The processes involved are discussed below. Scanlon and others (2006), in a review of about 140 recharge-study areas, report that climate variability causes a three-fold variability in recharge, that changing natural grassland to cultivation may alter net discharge to become net recharge, and that changes in recharge from land use can be larger than from climatic causes. Variability is a dominant property of recharge.

Diffuse and Focused Recharge

Several processes contribute to the recharge total. The process of diffuse areal recharge derives from soil moisture during wet seasons or wet events that percolates below the root and redistribution zones to reach the water table. Focused recharge is another process derived from runoff into small-area geomorphologic detention features. Those focused areas may detain water in ponds or low-gradient watercourses where sufficient water loading accumulates to overcome ET and generate an excess of water that percolates more deeply to recharge. Focused recharge is analogous to the seepage component of transmission loss in the POTYLD model of Koelliker and others (1981). Playas and escarpment drainages may be intermittent or interrupted in terms of flow patterns, but they can provide focused recharge at the terminus of the live-flow reach. Figure 8 is a map of playas, ponds and watercourses with potential focused recharge in the study area.

Artificial Recharge

Artificial recharge is a separate process resulting from managed water operations at farms and other developed areas. Any excess of water load sufficient to outweigh actual ET can promote artificial recharge. Municipal water pipe leaks and landscape irrigation can cause recharge. Supplemental farm water can exceed plant-root zone requirements due to irrigation scheduling, rain events or other factors. A significant fraction of irrigation water application can become recharge. Alternatively, deficit irrigation might generate little or no artificial recharge, but with a reduced crop production.

Induced and Rejected Recharge

Streamflow is a further source of recharge where aquifer water levels are below the flowing stage of the streambed. Aquifer levels may be low either naturally or due to the effects of development. As shown on Figure 9, certain perennial stream reaches have dried up in history as documented by Kansas Department of Agriculture (2010). That phenomenon may be a consequence of induced recharge. Natural recharge from streams is distinguished from induced recharge, which is as an artificial condition.

Rejected recharge is that increment of excess water loading from soil moisture that is routed to surface-water runoff only because the water table is too high locally to receive the additional water load. Dewatering the aquifer allows that increment to be accepted as local recharge at the cost of local runoff amounts. With aquifer space made available, the rejected component of recharge differs from induced recharge slightly in that dewatering creates the opportunity for local diffuse and focused recharge, rather than water already in adjacent surface-water bodies, to add a greater load to the water table.

We note that the direct flow of a stream, in addition to baseflow, is subject to capture induced by lowering aquifer water levels. Where streams are interrupted or intermittent as in the Big Bend GMD No. 5 study area, direct flow also participates in natural and induced recharge. Direct flow of streams must be accounted for by the model to account for the full range of aquifer recharge processes.

Collateral Drawdown and Recharge

Drawdown and associated induced recharge is a common feature of interrupted streams. The effects translocated from depletion of live reaches into drawdown at interrupted reaches are discussed herein as "collateral" drawdown (or buildup) and consequent depletion or recharge, because the effects are associated with an indirect cause. Recharge of direct runoff at upstream reaches can contribute to baseflow in downstream reaches of a resurgent stream. This pattern proves to be an important part of the profile of interrupted gain and loss in the Arkansas River and tributaries. A reduction in upstream recharge may cause aquifer drawdown. However, that drawdown can be displaced many miles along the live-stream reach from an upstream cause of stream depletion. Figure 10 illustrates the nature of collateral drawdown when water is depleted from upstream areas that dry up an interrupted stream reach. In contrast to a perennial stream reach, any alluvial aquifer drawdown is amplified as a result of converting the river flow to interrupted (in space) and intermittent (in time) in the affected reaches. Collateral drawdown describes the effects that are translocated from the reach depleted by a causal well to the terminus of the live-stream reach. The new drawdown is in response to loss of the flow that formerly infiltrated at the terminus of the live reach. That process of impacting downstream flow and accentuating drawdown in distant areas is of interest to Big Bend GMD No. 5 and is a feature of the hydrologic system to be simulated with the model. MODFLOW has this function.

The various forms of recharge (diffuse, focused, rejected, artificial, natural stream and induced stream) are of interest to the Big Bend GMD No. 5 situation and are to be addressed in the model. The several components are simulated in the model sections below.

<u>Chloride-Ratio Recharge</u>

We apply chloride-ion concentration data to independently support a characteristic natural recharge rate. Chloride ratios of concentration in atmospheric deposition versus concentration in the water table are indicative of recharge rates. Atmospheric deposition (wet) is about 0.1 milligrams per liter (mg/l) chloride at the

Lake Scott State Park Station (National Trends Network, 2008). Areas of Quaternary (mainly dune sand) sediments in Big Bend GMD No. 5 and similar areas where Ogallala underlies dune sand sediments south of the Arkansas River display chloride in groundwater less than ten mg/l (Figure 11). The observed dilution ratio (0.1/10) indicates that approximately one percent of precipitation has reached the water table. Evaporative and plant transpiration processes concentrate the salt load brought into the root-zone soil by atmospheric deposition. A small fractional percent of runoff does not appreciably impact that ratio. Precipitation ranges from 18 to 24 inches west to east across the study area, implying 0.18 to 0.24 inches of recharge on the corresponding areas as a long-term average. Accounting for an uncertain increment of dry deposition of chloride would imply more (up to twice as much) recharge (Reedy and others, 2003). Local chloride values seen at less than ten mg/l also imply more local recharge. The one percent characteristic result represents any small amount of diffuse percolation on the interfluvial high ground, alongside focused local loading of water due to intermittent ponded areas and poorly-integrated watercourses that accumulate sufficient run-on water in small areas to overcome the prevailing moisture deficit and to produce net recharge.

Litke (2001) reports 3.2 mg/l as the freshest ten percent of chloride values for Kansas Quaternary deposits, and 12 mg/l for the Southern Ogallala formation suggesting that the characteristic dilution ratio may range from three percent to under one percent of precipitation in those outcrop areas. On a chloride-ratio basis, we consider a plausible range for direct and accumulated run-on recharge in permeable soils of Quaternary and Ogallala outcrop areas south of the Arkansas River between Finney and Stafford Counties is 0.2 to 0.5 inch/year. North of the river, chloride in the ground is commonly under 25 mg/l in the headwaters of Pawnee Basin, where recharge may be under 0.1 inch. The other recharge processes outlined above add to the natural recharge indicated by the regional chloride ratio.

Much of the remaining model-study area is in areas of Cretaceous and older bedrock outcrop or of discharging bedrock formations where the chloride ratios method would not apply due to extraneous sources of stored or transported salt. Bedrock areas are expected to have very small amounts of local recharge due to low permeability and typically steeper slopes promoting runoff. Net bedrock discharge, of course, implies no net recharge in those areas.

The observed chloride values represent water accumulated naturally under pre-development conditions. Ogallala and High Plains aquifer lateral seepage rates are under one mile per decade, so chloride sampled in the groundwater may represent recharge conditions originating some distance upgradient of the sample site.

Tracer Studies of Recharge

Overall recharge and discharge are the net of positive and negative processes at the water table. Actual ET and discharging seepage are the negative side. Recharge is net positive where it overcomes the negative side of the process. Available studies of natural tracers indicate the pattern.

McMahon and others (2003) report that an Ogallala rangeland (non-irrigated) site in Morton County averaged 5.1 millimeters per year (mm/year) or 0.20 inch/year water flux downward based on chloride in a 157-foot unsaturated zone. They estimated 0.3 mg/l in wet plus dry deposition, where groundwater was 13 mg/l. The average soil chloride concentration in 12 samples through the 157-foot interval was also 13 mg/l. They report the age of natural recharge was 1,600 years to reach the water table. However, a net upward flux does not appear to be ruled out at the rangeland site. The Ogallala rangeland interfluves are indeterminately either small positive or small negative recharge sites. The playa features tend to focus the identifiable recharge.

Irrigated sites in Finney County were reported by McMahon and others (2003) to have downward water-flux rates ten times faster than calculated for the rangeland site. Their irrigated sites recharge 53 mm/year or 2.1 inches/year, based on chloride displacement. Tritium in the water table implies even faster ratios of downward flow at two to three meters per year possibly related to preferential flow paths. Instead of hundreds of years or millennia for natural recharge, if any, from dry rangeland conditions, irrigation return flow appears to reach the water table at depths of 150 feet in decades. Shallower water table depths could be recharged by irrigation the same year.

Reedy and others (2003) report that National Atmospheric Deposition Program values for wet deposition may be multiplied by a factor of about two to approximate the sum of wet and dry deposition. They note that non-irrigated sites in the southern high plains suggest upward flow (negative recharge). The time lag for irrigation return flow ranges from less than one year at 15-foot depth or three years at 50-foot depth in sand, up to over 50 years for a 50-foot depth of sandy clay loam.

Such regional background information as discussed above is applied in the Big Bend GMD No. 5 model to constrain a plausible range of simulated values where natural diffuse recharge is very low, and focused recharge may be near one inch. Irrigation recharge is reasonably several inches as described in the sections below.

Irrigation Deep Percolation

Irrigation deep percolation becomes recharge in terms of the surplus of water applied to farms but not consumed by atmospheric demand. Irrigation water exported as runoff, if any, is considered negligible under good management. The hydrologic impact of irrigation water management, which is of primary interest to Big Bend GMD No. 5, is sensitive to deep percolation and associated return flow. Farm-water operations require a component of deep percolation of water, a leaching fraction, to maintain salt-balance in the crop root zone (Ayers and Westcot, 1985). The fraction depends on the salt concentration of applied water and tolerance of the crop, but may range typically from 15 to 30 percent additional applied water. Much of the necessary leaching is satisfied by operational inefficiencies from irrigation scheduling, excess rain, etc. Seldom is extra water applied solely for a leaching purpose. Soils accumulate salt in areas of shallow water and poor drainage. NRCS data (National Cooperative Soil Characterization Database, 2009) is mapped (Figure 12) to show where soil flushing by deep percolation is adequate or where it approaches or exceeds the recommended soil-moisture conductivity threshold of three mmho (Ayers and Westcot, 1985). High soil salinity appears to correlate with shallow water table areas.

The operational excess of applied farm water is evaluated in the Big Bend GMD No. 5 model by examining water-use reports of applied water plus effective rainfall, compared to potential ET of a reference crop on the corresponding irrigated acreage. A characteristic coefficient less than 1.0 is applied to reduce the potential ET requirement due to consideration of crop growth stage and coverage (crop coefficient) and other practicalities that make a 100 percent idealized water supply difficult to maintain. Reference ET by Hargreaves and Samani (1985) is a serviceable indicator of the largest amount of water the climate and any crop would use, from which the corresponding minimum return flow from applied water can be estimated. About 80 percent of reference ET is recognized as a practical actual depletion by planning full irrigation service (Hillel, 1998, p. 59). Thus the actual return flow amount is likely to be larger than the theoretical minimum return flow from a high level of reference ET.

State Rules and Regulations (KAR 5-3-24) callout "*reasonable quantities for irrigation use*" and a net irrigation requirement (NIR) for 50 and 80 percent rainfall probability for Stafford County. NIR is 1.03 feet and 1.21 feet for respective rainfall, and is 1.4 feet as a "*reasonable quantity for irrigation use*".

Water-use reports are available for each diversion and place of use (POU) in Big Bend GMD No. 5. The reports have been checked for quality by the Division of Water Resources (DWR) since 1990. Water-use reports plus effective rainfall compared to potential ET is used in the Big Bend GMD No. 5 model to indicate the prevailing water-use efficiency of each POU in the model. It is recognized that some farm operators practice shorting crop-water requirements and others provide more than a full water supply, as confirmed by the water-use data. Water consumption coefficients in the range of 0.8, suggested by Hillel (1998), represent a general expectation of operational effectiveness.

The Big Bend GMD No. 5 model applies the reported water use in terms of pumping. Any calculated residual excess from the farm operation is considered return flow to the water table at the POU. The accounting is by each farm. Accordingly, no assumed uniform efficiency is specified in the model. Instead, water use efficiency is derived in the Big Bend GMD No. 5 model from climate and from farm-specific water-use reports since 1990. This approach provides the model flexibility to display the hydrologic effect of any change in efficiency of farm water operations.

LANDSAT imagery has been compiled for representative August or September cloud-free dates each year from 1973 to 2007 covering all but the western-most model area. An example is presented on Figure 13. The full set of imagery is on file with Big Bend GMD No. 5. Vigorous vegetation on each POU is classified. The irrigated acreage is served by pumping under what is thought to have been less efficient operations in earlier years as estimated by USGS (Luckey and Becker, 1999). Climatic variation is accounted for throughout model history. Their estimated irrigation efficiency (consumed amount per applied amount) ranges from 45 percent in the 1950s to 85 percent in the 1990s as tabulated below.

Census Year(s)	Assumed Irrigation Efficiency
1949, 1954, 1959	45 Percent
1964, 1969	60 Percent
1974, 1978	70 Percent
1982	80 Percent
1987, 1992	85 Percent

LANDSAT acreage indexed to monthly climatic requirements is applied as historical pumping amounts on each POU. The model input for pumping and returns is detailed in a following section on "Well and Water-Management Operation".

Land Use and Recharge/Runoff Trends

The historical progress of land development in the study area has altered the patterns of runoff and recharge from prairie/rangeland through dry-land agriculture, with progressive soil and water conservation, to irrigation in increasingly efficient forms. The process is described in Koelliker (1998) "*Effects of Agriculture on Water Yield in Kansas*" (Appendix B) as an increase in runoff and baseflow due to clearing land in the decades from statehood to about WWII, followed by decreases due to retaining water on farm from expanded watershed management and irrigation development. The runoff and baseflow "*has been converted into more production on the land where it fell*". The deficit of rainfall to satisfy potential ET is given in Koelliker Figure 7.7 (1998, Chapter 7) for the model area. A 27-inch water deficit in Reno County can be contrasted with a 48-inch water deficit in Finney County. The strength of the climatic deficit affects the recharge opportunity in particular (Koelliker, Figure 7.10). Koelliker estimates that recharge remains under 0.1 inch/year for non-irrigated land uses wherever the water deficit exceeds 30 inches/year. As discussed above, we understand such low rates to be from accumulated "run-on" in local water features, rather than from areal recharge on topographic interfluves, where net recharge may be nil or negative.

The USGS (Luckey and Becker, 1999) has calibrated parts of Meade, Gray and Ford Counties, using recharge on dry land cultivation at 3.9 percent (or 0.8 inches of 20 inches) of rainfall (their p. 43) in order to match observed rising hydrographs since the 1930s (their Figure 21). Stream baseflow also is sensitive to that recharge in their model. Accounting for water-level trends and baseflow in areas outside irrigation development appears to require this land-use component of recharge.

Recharge is treated in the Big Bend GMD No. 5 model as a monthly variable around an historical trend due to land-use changes. The pre-development recharge was characteristically low, a few tenths of an inch. The historical change in recharge is based on a land-use trend as scheduled by Koelliker (1998, Figure 7.3) where initial baseflow from year 1860 nearly doubled due to land clearing into the 1960s, then declined after "*development of ground water resource*s". The decline of baseflow in recent decades results from net pumping (return flow minus pumping) being negative despite a large increase in recharge from agricultural returns. Total recharge currently may be many times more than the pre-development recharge rate. That process is accounted for to attribute historical change in baseflow to its cause. It is recognized that the 1930s to 1950s baseflow may have been artificially high at the time the wildlife refuges were established.

The historical phase of the Big Bend GMD No. 5 model is set up to run from years 1940 through 2007 as a period to match historical data available as a calibration target in those years. The earlier period of development from pioneer days to 1940 is planned to be treated in the model as a retrospective scenario (discussed below) to be examined for understanding of relationships, but with too little data for history checking. Prospective scenarios such as the illustrative one for post-1984 well operations (discussed below) are analogous model runs designed for understanding future conditions. Both styles of scenarios are useful because the model function has been checked for performance against data in the historical period. The history-matching that supports the scenarios is described in the sections to follow under "History Comparison and Trends".

Evapotranspiration

ET is a lumped term covering both evaporation (E) from soil moisture reaching the land surface and transpiration (T) which takes moisture from the plant root to the vegetation canopy system. Lubczynski (2009) reviews the recent literature on ET rates for trees. Following the Lubczynski discussion of these categories, T has more capacity than E has to reach deep layers of the soil profile. Water exposed to air at the land surface or the plant canopy is vaporized and lost to the local hydrological system. The process cools the vegetation and the exposed soil, as can be seen by remote sensing. T extracts more water than does E from fluctuating stored moisture in root zones above the water table or from root zones touching the top of the capillary zone. Both E and T intercept and remove moisture from rain or irrigation before it reaches the water table. T removed from the canopy usually is greater than the smaller contribution of water abstracted from the saturated capillary/water table at the bottom of the root zone. E also can be from both sources, but commonly has a large component from the saturated zone where the water table is within three to six feet in good agricultural soils.

The NRCS guidance (2007) gives root zone depths as five to nine feet for wheat, corn, and alfalfa. Annual weeds such as kochia roots can penetrate to ten feet and can recover more groundwater than cultivated crops. The capillary rise above the water table serves to feed those root zones. We adopt a ten-foot extinction depth for ET in the model, which is intended to cover water table extraction from underlying capillary feed to generalized root zones, and to cover losses at the land surface where bare ground may be present. The ten feet being simulated, represents a six-foot root depth plus a four-foot capillary rise, or a four-to-ten-foot capillary rise (depending on texture) in the lack of a vegetated cover. We have not separated riparian zone trees, which can reach deeper to 30 or more feet. The treatment of ET root zone and capillary zone extinction is diagrammed for illustration on Figure 14.

Butler and others (2004) quantify the ET loss in the 500-foot wide incised valley below the flood plain near Larned as losing three feet of water in year 2002, equivalent to a 600-gallons per minute irrigation operation every three miles along the river.

The Big Bend GMD No. 5 model treats ET in accordance with the above concepts. A technical memorandum reviewing the existing studies is attached in Appendix E. The findings of recent literature are summarized in Appendix E with the conclusions pertinent to the Big Bend GMD No. 5 model. Vegetation type appears not to be a sensitive factor for the strength of actual ET. Bare soil does not necessarily indicate low evaporation where the water table is shallow. Managing vegetation cover does not necessarily alter water-table depth, particularly where river stage and flood water overrides the other factors. We adopt the standard MODFLOW EVT package, which functions reasonably for the field conditions of interest.

Water Levels

Water-level data are required to set model boundary conditions and to provide a calibration target for the modeled aquifer flow system. These data are available from the water-level databases maintained by Kansas agencies.

We queried the KGS's Water Information Storage and Retrieval Database (WIZARD) (KGS, 2008a) using a polygon that enclosed the model area. This query returned 1,812 stations and 96,473 water-level records within the active model area. Most (80 percent) of the model area WIZARD data were collected after year 1971. The Big Bend GMD No. 5 measures water levels at hourly to yearly intervals at a network of 138 well sites with 238 screen completions, including 100 multi-completion piezometer nests. Big Bend GMD No. 5 contributes this data to the WIZARD system. Additional water-level data were obtained (KGS, 2008b) for the model area from the Water Well Completion Form Database (WWC5).

Data from the 1930s to the 1950s were transcribed and automated from the county geohydrology reports (Latta, B.F., 1944, Tables 22 and 23; McLaughlin, T.G., 1946, Tables 11, 12 and 13; McLaughlin, T.G., 1949, Table 15; McNellis, J.M., 1973, Table 13; Prescott, G.C., 1951, Table 8) and from Sophocleous and others (1990, Table 2). These early data provide a record of aquifer conditions in the 1940s and 1950s prior to the development of large-scale groundwater irrigation.

We merged the data from those multiple early-time data sources with perennial stream tie points to produce a pre-development water-level map. The merged database resulted in 2,025 early (1930s to 1950s) observations in the active model area with 764 observations in Big Bend GMD No. 5. The well data points, perennial stream tie points and pre-development water levels resulting from the merged dataset are shown on Figure 15. Flow paths are overlaid to show gain and loss to streams and wetlands.

The Figure 15 water-level map represents heads in the saturated surficial Pliocene and Quaternary sediments and in Cretaceous to Permian beds where they contain the water table outcrop. Macfarlane and others (1990, pgs. 24-29) examined fluid pressure versus depth profiles for Central Kansas. Bedrock units are known to discharge locally to support stream baseflow and salt loading to shallower aquifers. Vertical gradients have been reported at aquifer test sites and elsewhere within the Pliocene and Quaternary aquifers, as discussed below under "Aquifer Properties".

Figure 16 is a comparable map from observed data with superimposed groundwater flow paths in the decade of 2000s. The drawdown difference between the 1940s and 2000s is shown on Figure 17 to display the historically observed effects of development. These changes are used as a target for matching in the model performance.

Aquifer Properties

Aquifer hydraulic properties of permeability and transmissivity are required for calculating flow between model cells under prevailing hydraulic gradients. Data are available from a long history of field tests in the study area and from other authors' estimates. Stullken and others (1985) compiled test data for the Ogallala. Other areas and more recent tests are summarized in Table 2. Appendix F documents a reinterpretation of six multi-well tests conducted by Big Bend GMD No. 5 in the period 1995 through 1996. Figure 18 displays aquifer test locations for all available sources of data in the study area.

K_x and K_z values applied in previous models are listed in Table 1 for reference. The O'Rourke Bridge tests (Butler, 2004) and the Weller site test demonstrate that the alluvial head difference between the upper and lower sands is significant in the Mid-Ark reaches. Tested vertical permeability at those sites is a few tenths of a ft/d. The multiple silty-clay soil horizons accentuate anisotropy in flow of the Quaternary aquifers. A multi-layer model adds a physically-based distinction between these vertical zones. Constructed well screens in the deep sands cause drawdown that spreads out over a large area before leakage is induced from the overlying shallow sands and streambed. The practical difference in well impact is in the delayed timing of stream depletion, but larger radius of each well's area of influence. Being close to or far from the stream becomes less important where the stream has a degree of isolation from well screens by intervening clay or silt zones. The Big Bend GMD No. 5 model is designed to simulate such layered anisotropic features of the hydrologic system.

The data on multi-well response in vertical and radial patterns of aquifer properties is derived from interpretation of the six Big Bend GMD No. 5 data plots for farm-well tests in Appendix F alongside that of Butler and others (2004) at O'Rourke Bridge. Radial-flow storage-depletion analyses (Theis, 1935 and Cooper-Jacob, 1946) for transmissivity and storage are given in Appendix F alongside equivalent leaky-aquifer (Hantush and Jacob, 1955) results for vertical properties. The tabulated transmissivity is converted to hydraulic conductivity using a characteristic test-zone thickness based on the graphic logs and screen geometry. The tested hydraulic conductivity values lie in the range of 40 ft/d to 550 ft/d, characteristic of clean sand and gravel of river alluvium.

The initial storage coefficient for the Big Bend GMD No. 5 tests was in two groups, 0.0003 to 0.0005 at deep-screen sites and 0.025 to 0.005 at the shallower sites. The smaller values are interpreted to be an elastic response, such as caused by a small specific storage in a 100-foot thick system. The larger values at shallow sites are interpreted to reflect a component of pore-water drainage at the water table.

Vertical hydraulic conductivity (K_z) at the Big Bend GMD No. 5 sites is related to the cross-bed properties of the silt and clay layers. Leaky-bed thickness is assumed to be the clay or silt unit, commonly about 20 feet, between the screen interval and the full aquifer thickness (Appendix F). Some thin and silty zones may have K_z near 0.2 ft/d, which allows an observable leaky recharge to be induced over the four-day observation period. Other sites indicate tighter K_z, such that leakage effects are not observed during the test observation period.

The relationship of transmissivity to screen-zone depth suggests, with few exceptions, that the shallow sands have relatively high transmissivity and the deeper sands have less transmissivity. There is no apparent spatial correlation among the test locations. The variation in properties appears to be associated with depth and geology more than with location.

Based on the six Big Bend GMD No. 5 controlled tests, hydraulic conductivity values near 220 ft^2/d are characteristic of the shallow sands. Values near one-third to one-quarter of that characterize the deeper sands. Well-efficiency ranges from near 100 percent to near 40 percent and should be accounted for in projecting the yield and service lifetime of specific production wells. Storage properties during test periods of a few days reflect a mix of elastic and pore-water release, but pore-water storage is expected to dominate long-term properties. Induced recharge from adjacent streams was not apparent in the short-term test data trend, but is expected to be seen in longer-term performance of the hydrologic system. Anisotropy between horizontal and vertical hydraulic conductivity is significant and should be accounted for in characterizing the system. Anisotropy serves to delay stream interaction. Both recharging downward and discharging upward vertical gradients are seen among the several sites, depending on topography. The aquifer characteristics identified by Big Bend GMD No. 5 aquifer tests are suitable for use in quantitative model accounting of the source of water to wells and the interaction with surface-water features.

Lobmeyer and Weakly (1979) report aquifer test transmissivity of 2,000 and 7,100 ft^2/d for Dakota Sandstone. In western Kansas, water levels in the Dakota and deeper aquifers (based on drill stem tests) may be hundreds of feet below those in the High Plains aquifer across 600 to 1,000 feet of intervening shales (Whittemore and others, 1993). Heads between the geologic layers reverse to an upward gradient indicating discharge at the Dakota subcrop areas near Pawnee Valley and the Mid-Ark.

The values used to characterize the aquifer hydraulic properties as initial specifications in the model are compatible with the plausible range taken from quantitative results of other model authors on Table 1. Figure 19 is an indication of aquifer productivity taken from data on well yield in gallons per minute per unit of water column to the center of the screen, expressed as specific capacity and converted to units of transmissivity for convenient comparison. The pump-test results are used, alongside well productivity indications plotted on Figure 19 from well reports, to characterize the material properties. A plausible range of alluvial and unconsolidated-sediment permeability is between 40 and 500 ft/d. Initial elastic storage (S_s = 2 to 5 x 10^{-6} ft^{-1}) and 20 percent specific yield are supported at O'Rourke Bridge (Butler and others, 2004). The specifications for the Big Bend GMD No. 5 model respect that plausible range of values. The final values in the model are discussed in the section below on "Specification of Aquifer Properties".

Saline Flow System

Sophocleous and Perkins (1993, their Figure 20) document high salinity at depths below 66 to 90 feet at two monitor well sites near Quivira Marsh. Their saline aquifer zones confirm layered salinity profiles in the eastern areas of Big Bend GMD No. 5. Big Bend GMD No. 5 monitors 141 well sites and administers a program to control salt-water incursion. The underflow of salt load as described in Figure 28 of Quinodoz and Buddemeier (1997) is about 500 tonnes of chloride/day (± 50 percent) for the eastern area of the model from Permian beds containing about 40,000 mg/l chloride. About five cfs of Permian salt water discharge is implied for their study area. The model is designed to address the flow and the loading from bedrock sources, consistent with the earlier studies.

Surface Water

Data are available on the flow at 33 gaging stations plus ten Mid-Ark and 11 Rattlesnake Creek transect sites in the model area (Figure 20). Overlapping periods of record indicate baseflow gain or loss in selected reaches. Baseflow tracked by decade displays the progression of climatic and development impacts on baseflow. Small ponds and larger watershed structures have been identified (Koelliker, 1998 and 1990) as the overriding cause of reduced direct flow in the Wet Walnut and Pawnee Basins. Water stage and routing at Quivira National Wildlife Refuge is based on data in Jian (1998) or in GEI Consultants, Inc. and Burns & McDonnell (1998). Dundee diversion and CBWA lakes and wetlands, Pawnee Basin low-head dams, watershed structures and Horse-Thief Reservoir are included as features and displayed on Figure 21. The surface-water bodies and features are of interest for their aquifer interaction regarding gains and losses by seepage and water-table ET. Their operational details have been studied and reported by others (GEI, 1998; Howard and others, 1990; Jian, 1998) and are not the focus of this model.

Gaging data is the primary source of surface-water information. Direct flow is the overland runoff from rain or snowmelt events. Baseflow is seen in the fair-weather flow fed from decline of stored groundwater. Figure 20 shows gage locations. Baseflow can be used as a check on the Big Bend GMD No. 5 model performance in terms of aquifer discharge. Springs are identified from literature at 130 locations (Figure 22) with historical flow rates than can be checked against model performance.

Howard and others (1990), compiled information on CBWA history and operation, including dates of operation, target pool elevations by month, and area-content relationships. Tracy (1990) provides CBWA pool area, stage relationships and an estimate of ten years of monthly diversion at Dundee and from Wet Walnut to the CBWA. Tracy concludes that subdividing and deepening the main pool at CBWA can aid operational objectives. McClain and Hoffman (1987) compiled hydrologic environment information on CBWA. Cretaceous shale lies at 112-foot depth below the lakes with 70 feet of intervening blue silt, sand and clay below tan silt and clay, suggesting relatively low-permeability conditions. McClain and Hoffman (1987) present Walnut Basin rainfall-runoff relationships, the watershed delineation, schedule of terrace and impoundment growth, the expansion and contraction of water yield since year 1850, and conveyance losses from Dundee.

The surface-water data from stream gages and reports are used in the Big Bend GMD No. 5 model for history-matching and for specifying the stress due to past water management action.

Water Use

Historic water-use data are needed to specify model stress and to provide for management baselines and scenarios. Kansas agencies have collected water-use data since 1956. In 1987 reporting became mandatory in Big Bend GMD No. 5 and in 1990 DWR implemented a quality-control program for water-use data.

<u>Municipal, Industrial, Domestic, and Stock Use</u>

The population of the model area was about 146,000 persons in year 1940 (U.S. Census Bureau, 1995) and 163,000 in year 2000. There are 144 public supply water systems serving a population of about 130,000 people. In addition, well records (KGS 2008b) show there are about 12,000 self-supplied domestic wells in the model area. The self-supplied population is approximately 33,000 persons (163,000 population minus 130,000 persons with water service).

In recent years public water use has averaged 29,000 AFY. Domestic well water use is estimated to be about 3,000 AFY using a 79 gpd/capita use factor (Solley, 1993) for self-supply. Industrial and stock use has accounted for another 50,000 AFY in recent years. Public, non-domestic and non-irrigation well locations are displayed on Figure 23.

Irrigation Use

The principal water use in the model area is for irrigation, which is the primary water use of interest to Big Bend GMD No. 5. The places of use for irrigated farms are shown on Figure 24 (KGS, 2008c). The authorized amount for these farms is 1.79 MAFY model wide and 0.67 MAFY within Big Bend GMD No. 5.

The National Agricultural Statistics Service (NASS) data trend (NASS, 2010) of irrigated acres for the model area is about 450,000 acres per year harvested in the 1970s and 760,000 acres per year harvested in the 1980s. Irrigated acres from meter reports are also reported after year 1990. Irrigated acres reported to DWR have averaged 1.02 million acres per year model wide and 447,000 acres per year in Big Bend GMD No. 5 since year 1991.

"Reasonable quantities" (KAR 5-3-24) for irrigation in model area counties are 1.4 to 1.6 feet/year. In recent years 1.12 MAFY (1.1 feet/year) has been diverted for irrigation.

The concepts outlined above on geologic structure, recharge, discharge, aquifer properties, streamflow and water use are integrated in the numerical water-accounting scheme of the MODFLOW program (Harbaugh and others, 2000) as described below.

This section describes the specifications for the structure and parameters of the Big Bend GMD No. 5 model. Model input files are available at the GMD No. 5 FTP site: ftp.gmd5.org.

Numerical Program

MODFLOW-2000 (Harbaugh and others, 2000) provides an established method for calculating a full water balance for the overall surface and groundwater flow system. MODFLOW is a FORTRAN program coded to account for water flow and water levels in a gridded three-dimensional flow system with time steps. The numerical calculations follow recognized standards derived from specified initial conditions of head and flow, boundary conditions for head and flow being fixed or dependent, and the governing equations for flow and storage between or within the gridded cells. Our approach to specifying model parameters is based on using hydraulic conductivity and storativity values that are derived from the aquifer tests discussed above. Model calibration did not require adjustment of hydraulic conductivity or storativity; instead, recharge was adjusted within a plausible range of values to achieve a suitable calibration.

In the Big Bend GMD No. 5 model, the lateral model boundaries are set about a township outside of the area of interest. Conditions beyond that distance are thought to have no appreciable impact inside the area and the period of interest. Lateral boundaries are specified as constant flow or constant head, with corresponding heads matching the historic record of water level at the boundary location.

The boundary with the most flux in and out of the area of interest is the land surface/water table interface. Most of the action in terms of stream capture and ET salvage happens at this boundary. It is set by the elevation of streambeds and ET-surface specifications.

The bottom boundary is specified to be no flow underneath Permian bedrock layers that are thought to represent the limit of deep-zone interaction with the shallow flow system.

The programmed water balance keeps track of stream inflow, flow to the aquifer, overland flow, direct precipitation on the stream channel, stream ET and diversions. Farm-water operations track on-farm efficiency, delivery requirements, pumping, application efficiency, and net recharge in EXCEL sheets outside the MODFLOW program. These separate accounts exchange water to or from the aquifer space as necessary.

Model Input File Development

The model structure, input and calibration information was created using a number of primary, derived and ancillary datasets. The datasets were acquired then processed from digitally-published agency data, together with data from text references which were automated for this effort. The data were organized using Microsoft EXCEL, Geographic Information System (ArcGIS, 2009) techniques and programmed pre-processing tools. The category, dataset number (DN), name, purpose, processing steps and storage location for each of the 56 datasets are tabulated on Table 3.

Table 3 lists details regarding the datasets, data sources and data processing required to develop information for the model input files. The categories of data include climate; stream, recharge and water loading; pumping stress; geology; water levels and ancillary data.

A Visual Basic pre-processor ("RchETSFRcaltstV6.xlsb") is used to generate recharge, ET and streamflow routing package inputs. The Visual Basic file generators are coupled with calculations done with ARCGIS and EXCEL to produce the hydrogeologic flow package input ("HUFv2.xlsb") and well package inputs ("WellFileV5.xlsb"). LANDSAT image processing uses ARCOBJECTS, Visual Basic and EXCEL ("LANDSAT_PROCESSV2.xlsb").

Model Grid

A grid with seven layers, 180 rows and 335 columns represents the groundwater system spatially in an area of 90 miles north-south, and 167.5 miles east-west. The model grid is oriented with columns in the north direction following Kansas South Zone Stateplane, NAD83 Coordinates. In plan view, the model grid is constructed out of square cells 2,640 feet (a half mile) long on a side. Each grid cell is the size of a quarter section in the Public Land Survey. Grid layer thickness is variable as described below. The seven layers (Layer 1 on top) are MODFLOW HUF type "0" layers with specific yield in Layer 1, and elastic storage in deeper layers. The active grid covers an area of 12,182 square miles and ranges in thickness from 1,000 to 2,800 feet below ground. The grid is shown on Figure 25.

Simulated Time Period

The model-simulated historical time period runs from 1940 to the end of 2007. Initial steady-state (pre-development) conditions represent the hydrologic condition prior to 1940 on an average annual basis. The historical period, 1940 to the end of 2007, is represented with average months that are 30.4375 days long. Scenarios are set-up to extend the simulation period back to year 1870, forward to year 2074, and forward to an ultimate steady-state under developed water-use patterns.

Boundary Conditions

Boundary conditions are used to describe how water enters or leaves the groundwater system. Two types of boundary conditions are used in the model: specified flow and head-dependent flow. A specified flow boundary is a condition in which flow to or from the groundwater system is maintained independent of changes in groundwater head. A head-dependent flow boundary is a condition in which flow to or from the groundwater system is affected by groundwater head. The modeled boundary conditions are shown on Figure 26.

<u>Specified Flow</u>

Model specified-flow boundaries are used to represent much of the subsurface water that flows into and out from the regional groundwater system in a general direction from west to east. Specified flow is also used to represent groundwater recharge that occurs from mesa areas with playas and other land surfaces.

<u>Head-Dependent Flow</u>

Streams, ET and some subsurface flows are represented in the model with head-dependent flow boundaries. Streams interact with the groundwater system by either providing groundwater recharge when groundwater levels are lower than the simulated stream stage or by removing groundwater when the stream stage is lower than groundwater levels. ET discharges water from the groundwater system when simulated water levels are at shallow depths below the land surface, and the magnitude of subsurface flow can change in response to water-level changes in the flow domain.

Hydrogeologic Units

We compiled data from sources described above under "Geology" as outlined in Table 3 to provide a basis for the construction of a three-dimensional hydrogeologic unit solids model. The solids model provides a framework for specifying hydrologic parameter zones within the water-accounting model and provides a basis for using the Hydrogeologic Unit Flow (HUF) package (Anderman and Hill, 2003) that works with MODFLOW-2000. The HUF package is a tool that links to a database representing a three-dimensional solids model of hydrogeologic units that influence the movement of groundwater. The HUF package is used so that as future information results in improved hydrogeologic interpretations, they can readily be incorporated into the model. The data sources and the information each source provided for the solids model are summarized on Table 3. An exploded view of the HUF solids model is displayed on Figure 27, with cross-section views on Figure 28. The cross sections also show simulated horizontal-flow lines in the bedrock.

The model grid layers, which intersect with the HUF solids model, begin with a top layer containing the water table and the land surface with 40 feet more or less of saturated material. A clayey silty layer is commonly seen at that depth in the alluvium and Great Bend Prairie sediments. The second layer represents the remainder of the unconsolidated Quaternary sediments in Big Bend GMD No. 5. Anisotropy is represented between the two layers as a vertical hydraulic conductivity of a few tenths of a foot/day as seen in the aquifer tests (Table 2). The Dakota Formation, Cedar Hills Sandstone and underlying permeable beds are in the model as layers between less permeable confining beds. Fader and Stullken (1978) estimate Cedar Hills Sandstone is the major contributor of salinity at 5,000 to 10,000 AFY. The Crooked Creek Fault zone in Ford County offsets the Dakota beds.

Specification of Aquifer Properties

The framework for specifying hydrologic parameter zones is based on the three-dimensional hydrogeologic unit solids model developed herein (Figure 27). K multiplied by layer thickness produces the layer transmissivity. Specific storage (S_s) multiplied by layer thickness defines the layer storativity (S). A summary of specified hydrologic parameters is on Table 4. The accumulated transmissivity for the simulated Quaternary/Pliocene aquifer is in the range of about 4,000 to over 30,000 ft^2/d as shown on Figure 29.

The specification of parameters is generalized for zones in each hydrogeologic unit. Fifty-eight zones were created within Pliocene-Quaternary aquifers so they would be available if necessary for the purpose of model calibration. These zones were adapted from previous modeling efforts (Table 1) and from the pump tests on Table 2. The initial distribution of hydraulic conductivity, independent of the zones, is shown on Figure 30 in conjunction with Table 4.

During model calibration, we adjusted recharge within a plausible range of values, and found that it was not necessary to adjust the initial distribution of K. We maintained the zones, however, to allow flexibility in adjustment of model parameters to the extent that it may be necessary to better represent conditions that become apparent as the model is used in the future to simulate local or site-specific conditions.

Pore-water drainage (specific yield) is simulated at 0.20 in the uppermost active layer of the Pliocene-Quaternary aquifer. Specific yield is simulated at 0.03 where the uppermost aquifer is a bedrock unit. Specific storage is 2.0×10^{-6} per foot of drawdown model wide.

Values for K and S are compatible with the plausible range described above as taken from other models and field tests. The initial estimates were the values recommended in the aquifer test examination in Appendix F.

Specification of Model Stress

A summary of the modeled values that represent the hydrologic components of precipitation, diffuse recharge, focused recharge, runoff and potential ET is shown on Figure 31 for 193 hydrologic response units (HRU)[1] in the model area. The summary represents average values over the modeled historical period from years 1940 through 2007. Details of how each hydrologic component is input to the model are described below. Table 3 includes a summary of the process for deriving the model parameters described below.

Specified Recharge

Precipitation in the model area contributes to diffuse and focused recharge after accounting for soil ET and runoff. Diffuse recharge generally occurs over large areas where water percolates to the water table and focused recharge occurs along playas or drainages where runoff produces water loading in excess of ET. Specifying how that process is modeled involved developing a relationship between precipitation, recharge and runoff that could be translated into model input. The initial model specifications for recharge and runoff are derived from a relationship based on flow-duration curves. We use a flow-duration approach based on a cumulative observed-frequency curve describing the percentage of time that streamflow rates are equaled or exceeded during the period of record (Reiland, 1980, p. 2). The shape of the flow-duration curve is affected by basin topography, geology and patterns of precipitation. We use flow-

[1]A Hydrology Response Unit herein is defined as a watershed catchment delineated from a 10-m DEM. The values summarized on Figure 31 are dependent on soil type, topography and catchment area.

duration curves for gages along the Rattlesnake, Walnut and Pawnee Rivers and correlate the duration curves of observed monthly flow with same-month quantities of precipitation above each of the gages. Those relationships were extended throughout the model area. The correlation between precipitation and gaged flow provided a frequency-based set of curves that serve as a prototype to assist with specifying initial quantities of recharge and runoff in the model domain. The initial curves are refined during model calibration. Recharge is specified on individual model cells, independent of model-calculated variations in aquifer water levels. We specify diffuse recharge plus recharge focused on playas with the Recharge Package of MODFLOW-2000 (Harbaugh and others, 2000).

Table 3 summarizes the process of deriving model input for recharge, runoff and ET. Precipitation for each cell in 193 HRU is used to calculate a monthly value for diffuse "soak in" recharge, and focused transmission loss from watercourses. After calculating runoff from curves for each cell to watercourses by HRU, the runoff is adjusted in the pertinent cells and HRUs for watershed dams by reducing runoff and downstream transmission loss while increasing seepage and evaporation. At watershed dams, ET specified in adjacent watercourses responds to seepage mounds, while water is released downstream in months when runoff is greater than the storage contents. Recharge for each cell is the sum of soak in and transmission loss with pond adjustments. The relationship between monthly precipitation and specified recharge is shown on Figure 32. The recharge curves are categorized into zones representing variability based on soil type, as depicted on Figure 33. Figure 32 shows two sets of curves for Zones 7, 8 and 9, which are located in much of Big Bend GMD No. 5. The second set of curves represent post-1970 conditions that reflect the land-use change associated with water retained on farm areas. The post-1970 curves represent more recharge per inch per month of precipitation than in the earlier period prior to 1970. Irrigation return flow (deep percolation) adds soil moisture above the water table that enhances recharge from precipitation events. We found that the post-1970 curves improved the historical model calibration, compatible with that concept adapted from Koelliker in Appendix B.

Specified natural recharge into the model area from the land surface totals 693,000 AFY over 12,182 square miles in the 1940 initial condition, which translates to an average of 1.1 inches/year over the model area.

Head-Dependent Recharge

Recharge along intermittent streams is simulated with the Stream Flow Routing Package (SFR) of MODFLOW-2000 (Prudic and others, 2004). The recharge results from specifying monthly runoff from precipitation events in the model input. The model routes the water downstream and provides recharge along the streambed where head in the aquifer is below the streambed. Using the SFR package has the advantage of simulating the dynamic process of rejected recharge if the shallow water table rises to the elevation of the streambed during wetter than average years, or simulating induced recharge if the water table lowers from groundwater development or from drier than average conditions. The SFR package runs with a fixed river stage set at the minimum elevation derived from a 10-meter digital elevation model (DEM) (within a river grid cell). The relationship between precipitation and runoff specified in the SFR package is shown on Figure 34. The runoff quantities reflect total runoff model wide, of which only a portion becomes recharge depending on the associated head in the aquifer. The zones over which the precipitation-runoff curves are applied are shown on Figure 35. Runoff accumulates along river cells within an HRU.

The recharge patterns vary depending on whether a wetter-than-average month or a drier-than-average month is simulated. The recharge pattern in a wet month, June 1996, is shown on Figure 36; for contrast, the pattern in a dry month, June 1994, is shown on Figure 37. The difference in recharge patterns is shown on Figure 38.

Streams

Intermittent and perennial streams in the model area are simulated with the SFR package (Prudic and others, 2004). Streams chosen for simulation in the model were based the National Hydrography Dataset (NHD) (USGS, 2005); each named stream reach in the NHD is represented in the model. The SFR package requires input to represent the stream stage, the maximum leakage between the stream and the aquifer and the conductance from the stream to the aquifer. Modeled streams are simulated with a fixed river stage set at the minimum elevation derived from a ten-meter DEM and a maximum leakage as shown on Figure 39. The simulated conductance between a modeled streambed to the aquifer is one-half the maximum leakance shown on Figure 39. The maximum leakage of twice the conductance is in accordance with a two-foot stage above the base of the streambed that the SFR package accounts for in downstream routing of surface water. Flowing streams can become intermittent if diversions or drier than average conditions deplete enough streamflow. Likewise, intermittent streams can become perennial if hydrologic conditions for a period of time dictate that baseflow along stream segments expands. The full account of surface water and interaction with groundwater in the SFR package allows for analyzing collateral drawdown caused by upstream groundwater pumping that induces recharge along distant river segments, which is of interest to Big Bend GMD No. 5.

The Arkansas River stage has shifted downward from erosion as observed during the period of USGS flow gaging (Whittemore and others, 2006, p. 13) to a depth of about three to six feet. In the modeled historical period, we generalized Arkansas River erosion to six feet linearly applied from year 1960 to the end of 2007. Other watercourses are not incised in the model.

Evapotranspiration

Riparian ET is simulated with the ET Package of MODFLOW-2000 (Harbaugh and others, 2000). Model input to describe the interaction of ET with groundwater includes a maximum ET rate, a maximum ET surface, an extinction depth and a functional relationship that describes how the ET changes with variations in the simulated depth of the water table. We derived a reference crop ET_0 rate for the model area from the method of Hargreaves (Allen and others, 1998, Equation 52), which takes into account monthly variations in temperature at the scale of a four-kilometer square within the model area.[2] ET_0 is the amount of ET representing a well-watered grass and it expresses the evaporating power of the atmosphere. We intend for ET_0 to be the basis for the maximum ET rate that is used in the ET package. The maximum ET rate that can occur in the model varies monthly and is derived by subtracting monthly precipitation and runoff from ET_0. The locations where ET is simulated are based on localities where the depth-to-water mapped during pre-development conditions was ten feet or less, as shown on Figure 15. ET also is allowed to potentially occur along simulated streams where the depth-to-water is greater than ten feet, in the event that the water table may rise to a level within ten feet of the land surface. In those areas, the maximum ET rate is scaled to represent a corridor along the riverbed that is approximately 200-feet wide. The model-derived pre-development distribution of ET is shown on Figure 40. The simulation produces a total of 567,000 AFY of riparian and moist-soil actual ET during conditions of pre-development.

The Big Bend GMD No. 5 model will simulate ET throughout the wetland and riparian vegetation areas and will allow those areas to respond to pumping by expanding or contracting through the decades.

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[2] Monthly temperature data are available at the scale of a four kilometer grid from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) available from the PRISM Climate Group (www.prism.oregonstate.edu/about_us.phtml).

The maximum ET surface is elevation based and was initially derived by using the minimum elevation from three datasets: the average ten-meter DEM elevation merged with NRCS mapping of hydric soils, modeled river stream stages plus five feet, and a ten-foot elevation-based buffer around modeled streams. The intent of deriving the initial maximum ET surface as a combination of those datasets is to develop a surface that encompasses previously mapped soil data and the physical nature of the streams that incise the regional land surface. During model calibration, the maximum ET surface was adjusted regionally on the order of a few feet to improve observed baseflows at modeled streams.

Table 3 details the process of formulating a maximum ET rate each month for each cell with an active fraction of its area. The maximum ET rate is the potential ET_0 minus precipitation minus runoff for the active ET fraction of the cell area.

The modeled extinction depth is assumed to be ten feet below the maximum ET surface. Modeled ET varies linearly from the ET_0 potential rate at the land surface to zero at the ten-foot extinction depth.

Aquifer System Boundary Flow

Groundwater flows generally into the model area from the west and flows out of the model to the east and southeast. The method of specifying that underflow is based on an approach that integrates the flow with observed groundwater heads and specified aquifer properties.

The pre-development water-level map (Figure 15) was used to specify observed heads on the boundary of the model grid along the regional groundwater system. During a steady-state simulation, the specified heads produce a net inflow to the modeled aquifer primarily along the western boundary and a net outflow to the east and southeast. This flow is converted into a specified flow and the steady-state model is rerun. The result is a distribution of regional basin subsurface flow at a rate that integrates specified aquifer parameters with water levels observed in the field. In some areas where simulated streams flow out of the model boundary or where water-logged lands are mapped at the model boundary, specified heads were maintained to better account for changes that may occur along the model boundary (Figure 26). The resulting flow specified into the model is 134,000 AFY; outflow to the east and southeast is 148,000 AFY under conditions of pre-development.

Well and Water-Management Operations

Pumping water level (PWL) determines the service lifetime of wells under declining aquifer levels. The multi-node well package (MNW) (Halford and Hanson, 2002) provides PWL output. The well tests (Appendix F) show that well efficiency relative to formation drawdown ranges from near 100 percent to under 50 percent. Well efficiency is specified in MNW as neutral, but can be specified for particular wells of interest in scenarios. Alongside specific well performance from water-use reports, the generalized PWL pattern is simulated as a constraint on aquifer capacity to meet levels of demand. Declining yield due to PWL approaching the base of the aquifer is simulated in future baseline runs.

The relationship between farm pumping volume, CIR, and return flow from deep percolation is of interest. CIR is the USGS term for crop irrigation requirement needed after effective precipitation and root-zone uptake of shallow groundwater (Schmid and others, 2006). It is equivalent to the Kansas Supplement to the National Engineering Handbook term NIR after effective rainfall and carryover soil moisture. Handbook Section 652.0403 explicitly credits "*groundwater contribution*" as a deduction from NIR.

LANDSAT data to one-quarter acre resolution is used to check farm acreage in the 1980s before water-use reports became common, and to spot-check ET rates and distribution of ET intensity in vegetation types and land-use categories, including surface-water bodies.

Within the model area, the KGS maintains a Water Information Management and Analysis System (WIMAS) database that includes well and water-use information regarding meter records (M_{rec}), point of diversion (POD) locations, POU locations, reports of irrigated acres (RIA) and priority (PRI) dates. Information from that database is the basis for developing an approach to simulating groundwater pumping in the model area. Table 3 outlines how the WIMAS data was adapted into a format suitable for model input. A description of the process is below under "Irrigation Well Use".

DWR has quality checked the WIMAS database records since 1990, so meter records from 1991 through 2007 provide key information for simulated groundwater pumping over the historical period from 1940 through 2007. For example, in the modeled period from 1991 through 2007, simulated groundwater pumping for all wells matches the meter records; for the historical period prior to 1991, simulated pumping is related to the metered record from 1991 through 2007 using LANDSAT imagery. Below we describe how well use is represented in the modeled historical period for two general categories of well use: non-irrigation wells and irrigation wells.

Non-Irrigation Well Use

In the modeled period prior to 1991, non-irrigation wells are simulated to be pumping the average quantity observed from 1991 through 2007. The average pumping is turned on at the priority date recorded in WIMAS and held constant until the modeled historical period from 1991 through 2007, when pumping is simulated as reported in the metered record. The pumping stress from domestic wells (estimated at about 3,000 AFY for recent years) was not simulated due to the complexity of adding, scheduling and solving for the stress from 12,000 domestic wells. Return flow from non-irrigation well use is not accounted for in the model.

Irrigation Well Use

The modeled 1991-2007 period is simulated to match the meter reports and to apply water on the corresponding reported acres based on a calculation outside of MODFLOW. Outside of MODFLOW, PRISM precipitation is subtracted from Hargreaves reference crop ET_0 (Allen and others, 1998, Equation 52) to derive a well-watered crop reference irrigation requirement (IR_{ref}) under conditions of an optimally watered crop for the full growing season. We then apply an adjustment factor of 0.8 uniformly over the model area to derive average irrigation requirement (IR_{ave}) representing sub-optimal crop management and climatic watering constraints that typically affect crop growth. The 0.8 is intended to represent a factor to account for average crop and management conditions. Throughout the modeled history, a uniform three percent pre-infiltration water loss is accounted for to represent losses from spray, droplet or free water surfaces. Return flow to the water table is the remainder after the on-farm water account described above, which is specified as a gain to the water table in MODFLOW.

In the historical period from 1974-1990, the same accounting applies except we use a relationship of LANDSAT image acres to reported irrigated acres (Figure 41) and a trend in farm efficiency taken from the USGS (Luckey and Becker, 1999) to generate a pumping rate and return flow. The earliest years 1940-1973 have neither verified water-use reports nor images, so the water-right start date and the average 1991-2007 reported acres are used alongside the farm efficiency trend to generate a pumping rate and return flow for each farm. LANDSAT imagery was processed for the frame covering Big Bend GMD No. 5 and adjacent model areas, but the frame did not cover the western part of Big Bend GMD No. 3. Outside the LANDSAT frame, the average water use reported acreage was extended backward through the original water permit date. The resulting trend of irrigation pumping and return flow averaged over the entire model area is shown on Figure 42. Table 5 provides a summary of resulting irrigation return flow calculated model wide during the metered period from 1991 through 2007.

The District required meters to be installed by January 1993. Some areas outside of Big Bend GMD No. 5 did not have meters until later years. By applying only meter reports after 1991, the model might understate use in the early 1990s in some areas outside Big Bend GMD No. 5, whereas, the LANDSAT imagery captures such uses before 1990. Figure 42 suggests that climate is a more significant variable than are any shortcomings in water use reports.

Quivira and Cheyenne Bottoms Wildlife Areas

The Quivira and Cheyenne Bottoms lakes at the wildlife areas are simulated to represent their interaction with groundwater and to account for evaporation loss. Surface water is routed to the lake areas with the SFR of MODFLOW-2000 (Prudic and others, 2004). The lakes are simulated with routed water and a vertical hydraulic conductivity of 0.001 feet per day to represent sediment buildup at the lake bottoms with a lakebed thickness assumed to be one foot. Simulated lake areas are as depicted on Figure 21. Lake evaporation is simulated at a net rate of 34 inches per year as described in K.A.R. 5-6-7 (Pope, 2006).

The model input as described above was run and adjusted in a history-matching process described next.

MODEL COMPARISON WITH OBSERVED DATA

The comparison of model performance to field observations is described herein and is found to be suitable for the objectives of Big Bend GMD No. 5 management, as set out in the "Purpose" section of this report.

Calibration Procedure

The model calculates the simulated water level and flow at river and ET discharge areas as a response to the net stress specified as input. Stress is input in terms of each component of water added or removed by recharge or well operations. The net stress is produced by the combination of separate specific components of well production, return flow and all forms of recharge, such that calibration may produce a good match of historical data. The separate components of the specified stress are based on independent data and assumptions.

Calibration in matching historic performance adds to the model reliability. The model was compared with observed data to provide information for a calibration procedure of adjusting boundary conditions, recharge and runoff as the focus of calibration to reduce the difference between simulated and observed data. Aquifer parameters and well operations were not adjusted during the calibration. The calibration procedure involved an automated parameter estimation technique in conjunction with manual adjustment of model parameters. The parameter estimation technique aided with calibration of the recharge curves that represent post-1970 conditions as described in the "Specified Recharge" section of this report. The calibration procedure was followed until the difference between simulated and observed data was reasonable while model boundary flows and aquifer hydraulic properties represented a plausible range of values. The Technical Advisory Committee participated in that procedure. The adjustments of specifications were aided by an automated sensitivity profile of the model parameters.

History Comparison and Trends

Comparison of simulated to observed data is presented in terms of pre-development heads, transient well hydrographs, water-level contours and surface flow and base flow.

Pre-Development Heads

Calibration targets for the pre-development model simulation are from 2,025 early records of well water levels shown on Figure 43; the residual of observed and simulated heads at the wells is included. The statistics of a comparison between observed and simulated heads is shown on Figure 44 with a root mean square error of residuals equal to 15.1 feet in the model area and R-squared of 0.99. Out of the simulated well locations, 50 percent are within six feet of observed values.

Well Water-Level Changes

Calibration targets for the transient simulation that runs from 1940 to the end of 2007 are from the WIZARD groundwater level database. We compiled hydrograph data for 819 wells from the WIZARD database to compare observed water-level changes with simulated transient water-level responses caused by modeled climate and water use; the well locations are shown on Figure 45 with map identification (ID) numbers. Hydrographs for these locations are included in Appendix G. Simulated water-level hydrographs for three model layers (water table, lower Quaternary, and Dakota Sandstone) are included. Well screen depths for much of the well data are unknown. Figure 46 is a chart of winter water-level residual statistics by year for wells located in Big Bend GMD No. 5 and in the Pawnee Basin. "Residual" is the difference in feet between 819 well observations and simulations. Positive residuals indicate the model is simulating higher than observed; negative means lower than observed. The average and mean simulation trends are two or three feet higher than observed water levels; the cumulative change in residual accumulating the overall performance of the model through the years is near zero. One-fifth of wells are simulated about five-feet low and one-fifth are simulated about ten-feet high. A summary of observed and simulated water-level changes model wide during the historical period from 1940 through 2007 is shown on Figure 47.

Streamflow

The data available at 33 gaging stations (Figure 20) in the model area provide a means to compare model-simulated flow during the historical period from 1940 through 2007. Appendix G contains a series of simulated and observed flow duration curves that indicate the model is capable of simulating historical surface-water flow. The shape of flow-duration curves is affected by basin topography, geology and patterns of precipitation, so we present the model results in that context for comparison to observed historical flow. We interpret the observed flow that is exceeded 75 percent of the time on a duration curve to be indicative of baseflow, so the charts in Appendix G allow for a general comparison of baseflow and average monthly peak flow conditions.

The transect data available along the Rattlesnake Creek and at Mid-Ark sites provide additional data for inspection of model performance. Tables 6 and 7 show observed and simulated flows for available data in the historical period. The transect data are instantaneous flows (cfs) and the modeled are average monthly flows. Flow along the transects is highly variable and the comparison is between observed instantaneous flow and average monthly flow, so observed and simulated flows within the same order of magnitude are considered reasonable.

Figure 48 displays the flux areas of simulated discharge from saline Permian beds into Quaternary aquifers. The discharge of about 3.2 cfs from underlying saline sources is consistent with the estimates in Quinodoz and Buddemeier (1997).

WATER BUDGET

The calibrated model is used to quantify the sources of water in the study area in accordance with the accounting categories of the MODFLOW program. A series of time periods are represented as model "runs". The model water budget displays the magnitude of stresses (generally well pumping and recharge) and the responding sources of water (generally streams, ET, and aquifer storage) as simulated by a sequence of model runs. The model runs represent initial, transient (history and baseline future) and steady long-term hydrologic conditions. The budget terms in each model run are of interest for attributing the growing effects of development to various water features, and for indicating the overall yield of the hydrologic system at various times. The sequence of model runs and associated sources of water in water budget terms are outlined below. The historical run has been discussed above as part of calibration. The baseline future and long-term sustainability runs are further described in subsequent sections of the report.

Prior to simulating the historical period that represents the beginning of groundwater development, a steady condition representing year 1940 aquifer flow and water-level conditions is modeled. The purpose of the 1940 run is to provide initial conditions for the historical model run that was described in the section above. The historical phase (1940-2007) of modeling is followed by a baseline future of an equivalent 68-year period (2008-2075). Finally, a long-term sustainable model is run to indicate conditions that are to be expected after transient aquifer storage converts to steady conditions in the fully-developed aquifer system.

Table 8A displays for comparison the aquifer water-balance components and the differences from initial 1940 conditions for the average history, future baseline and long-term sustainable condition runs. The water balance and system yield results are summarized in Tables 8A and B for discussion of basin yield. Tables 8A and B are for the model-study area, not for the smaller area of Big Bend GMD No. 5. Stream leakage into the aquifer is seen to increase, while ET decreases progressively among the run periods. Well pumping eventually declines for the model study area in the long-term sustainable condition. The right-hand column of Table 8A lists the groundwater system yield for various periods. Aquifer storage serves to expand system yield in history and in the baseline future. The long-term sustainable yield does not rely on aquifer storage but is supported by renewable sources.

The global water balance summarized on Tables 8A and 8B also displays the differences in overall system yield among the model runs. System yield is the supply generated from surface and groundwater sources combined. Table 8B shows that 1.40 million AFY of system yield in the 1940s has increased to 1.58 million AFY in the long-term while recharge has increased, ET decreased and substantial amounts from stream baseflow and direct flow have been captured by well development. Garden City inflow is reduced significantly from the level of the 1940s. Under those conditions, the 779,000 AFY of long-term sustainable model-wide well production is supported by the net change in other components of the water balance, as seen in the "Net Long-Term Sustainable" rows of Table 8A. The loss of Garden City inflow (148,000 AFY) adds significantly to the stress of sustainable development on the basin yield. The developed steady-state model condition is projected to support about 779,000 AFY of model-wide well production from the resource base by capturing ET and streamflow. However, Big Bend GMD No. 5 well production remains sustainable at about 468,000 AFY as discussed below. Most of the future decline in well production lies in the western model area where surface-water interaction is small.

The 1940 groundwater balance in the model area involved 693,000 AFY of recharge which was removed by 567,000 AFY of ET and 110,000 AFY of net baseflow to streams, alongside minor outflow from lateral boundaries. These amounts assume steady conditions without storage change in 1940. The year 1940 was the end of a multi-year drought in the 1930s, thus recharge for initial conditions in the model is lower than in other periods. Ogallala aquifer storage might have been accreting in those years due to land use change. The 1940 surface water balance (Table 8B) in the STR model package includes the direct stream inflow, local runoff, and outflow components of hydrologic system yield. Inflow at Garden City and direct runoff from the model area (Table 8B) added about 709,000 AFY as surface water direct flow to the groundwater outflow. The sum of outflows in Tables 8A and B produced a total system yield in the model area of 1,400,000 AFY for the 1940s. The 1940 water balance adopted for initial model conditions, however, is not necessarily characteristic of previous or subsequent periods, due to climatic and land use changes causing variations in recharge and runoff. We calculate that system yield increased by 180,000 AFY to become 1,580,000 AFY in the historical and future periods.

The average historical condition of net water budget components is summarized in the second row of Table 8A. The main difference in history, in contrast to 1940s, is that wells and aquifer storage have been developed, while recharge has increased.

For more detail regarding the variability of hydrologic conditions, the annual water balance for the modeled history is illustrated in Tables 9 and 10. We have quantified the groundwater flow-budget change through history two ways, as an annual listing of net budget components and by isolating the budget components that account for source water to groundwater wells. One displays the condition of the annual water accounts, and the other displays the change in condition attributed to wells. The first account, in Table 9, involves reporting the modeled flow budget net components (stream interaction, ET, lateral boundaries, storage, recharge and well pumping) to show how combined stresses from well and recharge fluctuations serve to influence other components of the water balance. Positive values indicate flow into the aquifer and negative values indicate flow out of the aquifer in Table 9. The historical model from recent years 2000 through 2007 indicates that a recent average of 1.1 million AFY of total well use in the model area, combined with nearly equivalent 0.99 million AFY of recharge, is operating alongside 557,000 AFY of aquifer storage depletion, 375,000 AFY of continuing ET, and 55,000 AFY of on-going baseflow generation.

The second account, in Table 10, isolates historical groundwater pumping to investigate the source water that well stress alone derives from modeled flow budget components. In the second account (Table 10), we tabulate source water to wells independent of recharge changes. The well account is broken out by making two model runs for the historical period with and without wells operating, then tabulating the difference that well operation makes to model accounting. We find that from 2000 through 2007, the 1.1 million AFY of groundwater pumping derives its water as 556,000 AFY from aquifer storage (51 percent of pumping), 166,000 AFY from ET salvage (15 percent) and 370,000 AFY from streamflow capture (34 percent). The difference between the two accounts is in reporting the status of hydrologic conditions due to all stresses from climate and water operations combined (Table 9), or in reporting the isolated effect on other sources of water of a single operational stress from wells (Table 10). The two results indicate it is important, in reporting model results, to distinguish between the conditions produced by the net of all model stress and the difference in conditions produced by the isolated components of stress.

To further illustrate the model attribution of sources of water to wells, Figure 49A shows a monthly stacked bar chart of modeled flow components for the isolated well case. The solid line on Figure 49A represents the net simulated groundwater diversion each month of history. Figure 49B zooms in to the period from 1980 through 2007 to show additional detail. For comparison to values above for recent years since 2000, 54 percent of well diversions during the overall 68-year modeled historical period (1940 through 2007) has come from groundwater storage, 14 percent is salvaged ET and 32 percent is depleted from streams. The fractions are not appreciably different between the recent and the longer historical periods. Recharge induced from streams to fill aquifer storage during winter (Figure 49B) is a major component of the source water to wells.

The model also can be used to analyze depletion to specific stream reaches over specific time frames. Figure 50 depicts the locations of the simulated change in stream leakage from the 1960s to the 2000s.

The water budget components are not generally calibrated in the sense of history-matching. Well pumping after 1990 is taken from metered reports, and is not further adjusted.

2020-2030 Response Pattern

The hydrologic response to groundwater pumping has been mapped at certain times to inspect the spatial impact to hydrologic features. The spatial impact takes into account aquifer properties, aquifer structure and proximity to those features. Figure 51 illustrates the response at streams in central Big Bend GMD No. 5 from ten years of pumping a unit stress (for example 1 cfs) at any location in the area depicted; the analysis can serve as a screening method to provide an a priori idea of how the hydrologic system may respond to a proposed management scenario. The analysis applies average historical climate conditions to create a year 2020 starting condition, and then derives depletion to streams spatially from ten years of unit pumping to year 2030. Unit stresses are calculated at a density of each three square-mile area of the model. The model result on Figure 51 is plotted and contoured as color bands. For example, a well located in the 0.4 to 0.5 color band on Figure 51 can be approximated as impacting streams in the range of 40 to 50 percent of the pumping rate after ten years of pumping. The percentage terms of the figure mean that any pumping rate can be planned with a corresponding percentage impact on streams in ten years. Figure 51 can be used to identify areas of interest for most or least impact on adjacent streams in planning changes in water use. Figure 52 can be used in a complementary way to anticipate areas of most impact on aquifer drawdown where the rivers are least impacted. After using these two figures, the specific proposed action may be run in the model to examine the schedule, the amount and place of impact in greater detail.

Long-Term Response Pattern

The entire model space contains similar information. The model can be used to investigate the depletion to streams over a larger area and over a longer time-frame than ten years of projected pumping. An example is shown on Figure 53, which is derived in two steps. First, a steady-state projection from current levels of groundwater pumping model wide is simulated to develop a long-term future condition. The second step is to calculate how 70 years of pumping a unit stress affects that condition. Figure 53 displays the schedule and fraction of pumping at all locations in the model that are supported to some degree by stream depletion in the long-term sustained case. Recharge is at average historical climate conditions. The lowered water table (below the bed of active streams) means that some stream reaches are not responsive, whereas the reaches may have been interacting with groundwater in the 1940s. Under long-term sustainable conditions, the interaction of groundwater with surface streams is low in the west, but still effective in the east.

Accordingly, the model can be used to inspect details of the conditions in the long-term sustained case. The future condition of the aquifer for steady equilibrium conditions is of interest to see if Big Bend GMD No. 5 well production is sustainable at current levels. The model uses the MNW package to reduce well yield where PWL in wells reach ten feet above the formation bottom. Figure 54 displays the remaining saturated thickness in Big Bend GMD No. 5 for sustained equilibrium well production of 468,000 AFY, which is 99 percent of MNW irrigation well production in the recent decade. Thus, under average annual conditions, less than one percent of irrigation well production in Big Bend GMD No. 5, at locations indicated in Figure 54, is not projected to be sustainable in the long term.

Under long-term steady conditions, many sites in Big Bend GMD No. 5 would have reached equilibrium with adjacent streams in a matter of decades, whereas sites distant from streams would not interact appreciably. The time to equilibrium with well pumping varies by location in Big Bend GMD No. 5 from years to centuries.

Other conditions than those above can be examined with the model. The above cases are examples. In all such model runs the results depend upon the characteristic properties for the controlling parameter specifications, and the results should be read with the understanding that specific well, aquifer, and climate conditions may differ from the generalized character in the model.

BASELINE FUTURE

A baseline future model run simulates 68 future years, 2008-2076, a forward-looking period equivalent to that of the calibrated history. One purpose of examining such a future period is to anticipate the magnitude of climate-driven fluctuations on hydrologic conditions. Stress in the model from recharge and from pumping depends, to a large degree, on climate. The baseline future extends the groundwater uses from the 1991-2007 period, so the simulation includes up-to-date levels of use alongside climate conditions from past dry and wet sequences of months and years.

Two baselines are presented, one (Baseline A) is a simple copy forward of the historical climate series, but with recent pumping stress. A second baseline (B) is presented to illustrate a different reasonable range of fluctuating future conditions. Both cases have recharge similar to history assuming current land use. Current land use reflects the post-1970 set of recharge curves described in the "Specified Recharge" section of this report. The simulated aquifer and stream conditions show a range of fluctuation tending toward sustainability in Big Bend GMD No. 5. The two futures are displayed to illustrate that an allowance for fluctuation is necessary for management planning, but no particular order or sequence of wet and dry conditions is implied.

Table 11 presents the baseline net groundwater budget components for case B to be read alongside Table 9 for historical conditions. The impact of another 68 years of water use is to have model-wide stream leakage, ET and aquifer storage grow slowly as sources of water to the pumping wells. Local areas attain effective balance between wells and sources of water.

The Baseline B simulation is derived with the K-nearest neighbor (in this case "K" is the 20 nearest following months) bootstrap technique (Lall and Sharma, 1996) that rearranges the monthly climate from the 68-year history to produce an alternative 68-year climate sequence (2008-2076). Pumping, runoff, recharge and ET are calculated using recent land use associated with this climate time series. The climate sequence is selected to include decades of drought analogous to the 1950s and wet decades analogous to the 1990s. In Baseline B, hydrographs tend to show water levels and flow rates in a similar range of high and low fluctuations, but in a different pattern than in history-based Baseline A.

The baseline runs in both cases A and B for 68 years. Pumping is simulated with the MNW package for shallower (non-bedrock completion) wells model wide. Groundwater pumping for irrigation is calculated using average acres reported for the period from 1991 through 2007 and the climate time sequence for the respective baseline. The pumping in each baseline is then capped so that it generally does not exceed the average pumping that was metered for individual water-use reports from 1991 through 2007. The groundwater pumping is capped by checking whether the bootstrap-derived pumping the first year exceeds the metered average. If it does, then the pumping is reduced (capped) at the user's metered average. In the second year, we check whether the average of the first year and the second year of bootstrap derived pumping exceeds the metered average. If it does, then the second year of pumping is capped at the metered average. This procedure is followed for 68 future years in the Baseline B, where simulated net pumping averaged 949,301 AFY, and in Baseline A, where simulated net pumping averaged 984,280 AFY. The approach is compatible with managing future groundwater diversions to not exceed average metered use during the period from 1991 through 2007. This cumulative averaging procedure has the realistic advantage of allowing higher pumping rates during drought years. During years when groundwater pumping is capped as described above, irrigation return flow also is less, so it is reduced accordingly in the baselines, thus the overall quantity of water consumed for crop irrigation is relatively unaffected.

Horse Thief Reservoir (active in year 2009) operates during the baselines as a feature in the SFR package on Buckner Creek. Arkansas River inflow at Garden City mimics conditions during the period 1998-2007.

Figure 55 charts the history and extended Baselines A and B of annual pumping and recharge. The model runs monthly in all cases. The degree of variation to be anticipated is apparent from the chart.

The water-level change simulated at the end of the two 68-year futures is contoured on Figures 56 and 57. These changes are to be added to the historic water levels of year 2008. Baseline hydrographs of two example wells in Rattlesnake Basin (GMD 5 sites WQ-17 and BB1B) are given in Figures 58 and 59 with history and Baselines A and B charted for comparison of the amount and sequence of variation to be anticipated in planning.

Baseline hydrographs of two example gaging stations (Macksville and Zenith) are in Figures 60 and 61. Baselines A and B illustrate the variability to be expected at those locations. Figures 62 and 63 show the monthly flow-duration relationships at the same gaging stations for the two baseline conditions. There is little difference in the duration curves, although that range of monthly flows should be anticipated in baseline management planning.

ILLUSTRATIVE RESPONSE TO MANAGEMENT ACTION

The primary use of the model is in evaluating and comparing alternatives in consideration for management action. A screening analysis can be used to provide insight to scenario development. The model result on Figure 51, for example, shows which areas of water use are expected to be effective at streams on a ten-year schedule in Rattlesnake Basin. A model calculation of an illustrative response to management action is presented to demonstrate how the model may be used in addressing such questions. The purpose of the run is to display the type of information on proposed management action to be gained from the model.

A smoothed annual average version of the rearranged Baseline B, as presented in Appendix H, is intended to be used for examining proposed management activities. The smoothed-average baseline abstracts the effects of management from the "noise" of normal climatic variation. The climatic-caused variation in hydrologic conditions in the aquifer and streams is to be recognized and allowed for in planning, but the focus is on the effects of management action standing alone. Thus, the smoothed-average Baseline (B′) serves to display the management function, whereas the unsmoothed Baseline B brings out the necessary allowances for climate. The smoothed conditions for climate in Baseline B′ are derived by averaging the 68-year recharge (1,008,502 AFY) and runoff (540,000 AFY) in Baseline B. For groundwater pumping and calculated return flow, the smoothing is based on the average metered water use from the last ten years (1998 to 2008), averaging 1,049,056 AFY.

An illustrative case is simulated of constraining future exercise of permitted water use in Big Bend GMD No. 5 to those permits with a priority earlier than April 12, 1984, the date at which subsequent permits were conditioned to protect MDS. The location of post-April 1984 wells, and the magnitude of buildup to aquifer water levels at year 2075 are shown on Figure 64. The magnitude of curtailment and the benefited sources of water are charted on Figure 65. A set of figures and tables is given in Appendix H to show how model results may be understood. In that illustrative case, the effect on the hydrologic system is to reduce water use by 11,290 AFY below the baseline future, while increasing aquifer storage 5,125 AFY, raising ET losses by 3,423 AFY, and adding 2,741 AFY to streams. The effect is displayed as a change relative to the baseline.

To illustrate the trends of management effects alone, and the superimposed allowance to be recognized for climate variability, the effects of curtailment of post-1984 wells in two baselines B and B′ are charted on Figures 66 and 67. The Figures 68 through 71 show the gaging station effects as hydrographs and duration curves. Figure 71 illustrates that the median flow projected at Zenith gage is close to the same in both Baseline B and smoothed Baseline B′. However, the unmanaged climatic variability accounts for the large variability of projected flow (from dry to over 100 cfs) as monthly means in Baseline B. For this reason, we have adopted the procedure of calculating effects of management action using smoothed Baseline B′, then superimposing them on variable Baseline B, as in Appendix H.

One consideration is the effectiveness of a proposed action in terms of the magnitude of water operations relative to desired impacts. The benefit of the illustrative policy is to produce 17 percent of the change in managed water use as a gain to Rattlesnake Creek, but only two percent to improve the MDS status at Zenith gage (see Appendix H).

The result is found by making two runs of the model and examining the difference between them. The future baseline (run 1) is subtracted from an alternative future with post-1984 permitted use curtailed in the model (run 2). The difference in drawdown and in water balance at each feature of interest can be reported by examining the difference in the two runs. The difference due to curtailment is superimposed on the unsmoothed baseline B. This method of model analysis demonstrates the usual protocol for informing proposed management actions. It is emphasized that the specific action of curtailing post-1984 uses has not been proposed by Big Bend GMD No. 5, but is used here for illustration only. The formats of tables and figures in Appendix H are amenable to presentation of the results of a variety of such management scenarios.

SCENARIOS

This section describes model scenarios that may be appended to this report in the future.

Retrospective Runs

We adopt Koelliker's (1998) published (POTYLDR model) results for quantifying the early impact on runoff and deep percolation from tracts of land undergoing phases of development. Koelliker's relationships have been compiled for use in model examination of hydrologic effects of early land use from about 1870. Those quantities can be applied as scenarios in MODFLOW to see the associated effect on baseflow from the change in deep percolation, and the effect on downstream runoff (direct flow) from the change in runoff.

The Koelliker Table 7.1 quantifies the sensitivity of expected annual runoff and deep percolation from fields under a variety of farm conservation practices. His results in terms of an approximate average for Great Bend and Garden City reflect a historical retrospective scenario exploring how baseflow and stream routing of direct flow responded to representative land use in the period from 1860.

The retrospective scenario is:

		Inches of Water			
Year	Land Use	Runoff	Percolation	Change in Runoff	Change in Percolation
1860	Pasture/range	1.00	0.10	--	--
1870-1910	Growth in areas of row crops	2.25	0.12	+1.25	0.02
1920-1960	% level terrace	1.35	0.30	+0.35	+0.20
1970-2000	% conservation tillage + irrigation	2.70	1.00	+1.70	+0.90

The Big Bend GMD No. 5 model simulates a scheduled change in runoff and in deep percolation as a baseline for explaining past conditions. The growth of row crop development is taken as a percentage of each county reported in Department of Commerce, Bureau of the Census of Agriculture (1923). Improved land in farms grew by decade to become the following percentage of Kansas lands.

Year	Percent
1860	0.7
1870	3.7
1880	20.5
1890	42.6
1900	49.7
1910	57.1
1920	58.5

The retrospective scenario is set up and may be run as appropriate at Big Bend GMD No. 5 discretion.

Prospective Runs

The primary application of the model BBGMDMOD is to be in projecting the change in hydrologic conditions expected from proposed management action. The facility is provided for flexibility in addressing proposed actions. A format such as illustrated in Appendix H is planned for addenda to this report. Various scenarios are under discussion for model runs, including addressing upstream impacts, sustainability questions, aspects of the Rattlesnake Creek Management Plan including runs not made in the 1997 model because of input limitations, and aspects of the Mid-Ark 2006 model that was limited by boundary effects. Results of such model runs may be appended to this report as appropriate.

MODEL SENSITIVITY

The model calculation is sensitive to parameter specifications so that the uncertainty in input produces an acknowledged uncertainty in model results. The sensitivity is quantified for a variety of parameters in Table 12. Recharge and ET are confirmed to be more sensitive than the other model parameters. The model results are relatively robust in the sense that the model results vary less than the input might vary within a reasonable range.

The standard specifications for the model are examined for sensitivity of output for simulated storage (reflecting water levels), ET and river discharge under initial 1940 steady conditions and for the average of 68 years since 1940. The history is run after establishing a new steady-state for each parameter tested. Parameters tested are K_{xy}, K_z, specific yield, ET extinction depth, recharge package inflow, boundary flow, and inflow to the Arkansas River at Garden City. The range of tested values for each parameter is given on Table 12, expressed as a multiplier factor for the parameter value. The standard case is in the first row of Table 12. The resultant output value for comparison to the standard case is given for each test run, and the corresponding multiple is tabulated. The ratio of the multiplier factor for output relative to the multiplier factor for parameter input is also listed as a sensitivity coefficient for each component of output (Lin, 2010). The sensitivity coefficient indicates the relative importance of the tested parameter for impact on the model output. Sensitivity coefficients less than unity (1.0) are robust in that they have proportionally small impacts on the model. Sensitivity coefficients greater than 1.0 amplify their impact on model output. Among the parameter runs examined, permeability, specific yield, Arkansas River inflow and boundary flows are robust with attenuated impact of any plausible variations. The ET amount controlled by the extinction depth parameter has a strong impact on streamflow because changes in water participating in the ET process are traded off to changes (with opposite sign) in the streamflow process. We note that the lumped output parameter, ET plus net stream, remains relatively robust in steady-state and history. The sensitive parameters ET and streamflow are calibrated separately to match gaged records and shallow water table areas.

CONCLUSIONS

1. The Big Bend Groundwater Management District No. 5 requires a modeling tool to support management action leading to desirable hydrogeologic conditions in the District. Quantitative hydrogeologic information is sought on questions of upstream impacts, alternative controls on pumpage, minimum desirable streamflow targets, the priority-order of water rights, watershed management, sustainable lifetime of wells, aquifer layers and salinity, relationships to sources of water from moist-soil or wetland evapotranspiration versus stream and aquifer depletion, farm water-use accounting, and broader questions of the good status of the hydrologic system. Future water operations to be examined in the model are subject to Big Bend Groundwater Management District No. 5 management and Kansas Department of Agriculture Division of Water Resources administration.

2. The Big Bend Groundwater Management District No. 5 water operations subject to management include 470,000 acre feet per year of well irrigation, 41,000 acre feet per year of other well use, and less than 7,000 acre feet per year of surface-water diversions. The yield of the hydrologic system in the study area averages about 1.58 million acre feet per year. The primary effect of aquifer development for irrigation use in Big Bend Groundwater Management District No. 5 has been to satisfy the typical ten-inch irrigation water requirement on 680,000 acres by deriving water from the interrelated sources of stream capture, evapotranspiration salvage, and aquifer drawdown.

3. The Big Bend Groundwater Management District No. 5 prevailing sources of water are sufficient to maintain existing levels of development. Approximately one percent of existing use in Big Bend Groundwater Management District No. 5 may be limited in the long term by aquifer dewatering. Hydrologic conditions

are more sensitive to climate than to managed water use. Problematic conditions in Big Bend Groundwater Management District No. 5 tend to be local and temporary rather than systematic and persistent.

4. The Big Bend Groundwater Management District No. 5 model has integrated the information from earlier models and studies, together with the superior Kansas database on well and water uses, into a MODFLOW tool with the functional relationships needed to address questions in a practical cause and effect style. The model performance is suitable for use in guiding decisions on best management as indicated by the correspondence between the model and the observed historical conditions. Alternative baseline futures to year 2070 illustrate the range of hydrologic conditions that may prevail without further management or administrative intervention. A procedure is illustrated for examining the simulated hydrologic effects of proposed water management actions.

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TABLES

TABLE 1. MODEL-APPLIED K_x AND K_z IN PREVIOUSLY-RELEASED REPORTS

Model	Formation	K_x (ft/d)	K_z (ft/d)	Author
Trescott	Alluvium	150		Dunlap and others (1985)
	Silty Confining Zone	7.5×10^{-3}	7.5×10^{-3}	
	Lower Aquifer	115		
Trescott, Pinder, Larson	High Plains Aquifer	3 to 51		Stullken and others (1985)
	Streambed		1.34	
MODFLOW	High Plains	80 to 800		Watts (1989)
	Niobrara-Graneros	0	1×10^{-5}	
	Dakota	7	1×10^{-1}	
	Kiowa	0	1.3×10^{-6}	
	Cheyenne	9	1×10^{-2}	
MODFLOW	Alluvium	225 to 275		Layne GeoSciences (1990)
	Streambed		5	
POTYLD	Pond Bottom		8×10^{-3}	Koelliker (1990)
Trescott, Pinder, Larson	Channel Sand	490		Sophocleous and Birdie (1990)
	Aquifer	4.9 to 49	1.0	
MODFLOW	Great Bend Prairie	41 to 130		Sophocleous and Perkins (1993)
MODFLOW	High Plains Aquifer	80	8	Whittemore and others (1993)
	Alluvium	250	25	
	Upper Cretaceous Aquitard	9×10^{-7}	9×10^{-8}	
	Upper Dakota	4 to 10	3.1×10^{-3}	
	Kiowa Shale Aquitard	1.3×10^{-5}	1.3×10^{-6}	
	Lower Dakota	2.3 to 2.0	3.1×10^{-3}	
	Morrison-Dockum	0.15 to 0.5	0.015 to 0.05	
	Permian-Pennsylvanian Aquifer	2.7×10^{-3} to 2.7×10^{-5}	2.7×10^{-4} to 2.7×10^{-6}	
	Permian Sandstone Aquifer	1.6	0.16	
SWATMOD	Buried Channels	150 to 330		Sophocleous and others (1997)
	Other Great Bend Prairie	55 to 100		
	Riverbed per foot		1.1 to 0.42	
SWIFT-II	Great Bend Prairie	140	22.6	Ma and others (1997)
	Alluvial Clay	1.1×10^{-2}	1×10^{-3}	
	Permian Bedrock	1.4×10^{-1}	2.3×10^{-2}	
MODFLOW	Sand Hills	12		GEI Consultants and Burns & McDonnell (1998)
	Great Bend Prairie	100 to 400		
	Silty Clay Layer		4.35×10^{-3}	
MODFLOW	High Plains Aquifer	<25 to >100		Luckey and Becker (1999)
	Streambed Conductance		Calibrated	
SWASP	Soil Infiltration		50% to 90% of precip.	Dugan and Zelt (2000)
MODFLOW	Cretaceous	50		Whittemore and others (2006)
	Tributary Alluvium	80		
	Main Aquifer	120		
	Alluvium	160		
	Streambed		1.31	

TABLE 2. AQUIFER TEST RESULTS IN PREVIOUSLY-RELEASED REPORTS

Figure 18 Map ID	Test	Location[1]	Aquifer	T (ft^2/d)	S	K_x (ft/d)	K_z (ft/d)	Specific Capacity (gpm/ft)	References
13	Bliss Site (Reinterpret)	23S.13W.36.D	"Prairie" Aquifer	13,500	0.005	225	<0.01		Balleau (2008a)
15	Bookstore (Reinterpret)	24S.14W.29.C	"Prairie" Aquifer	9000	0.025	130	<0.3		Balleau (2008a)
12	Heyen (Reinterpret)	23S.13W.16	"Prairie" Aquifer	30,000	0.0005	550	<0.001		Balleau (2008a)
17	Ketterl Site (Reinterpret)	25S.17W.35.B	"Prairie" Aquifer	5000	0.0003	43	<0.003		Balleau (2008a)
23	Smith Site (Reinterpret)	27S.15W.5.C	"Prairie" Aquifer	20,000	0.0005	220	<0.2		Balleau (2008a)
	19 Test Holes	Near Hutchinson				130 to 400			Bayne (1956)
	Lab Tests	Western Reno County				1 to 586			Bayne (1956)
20	Slug	27S.12W.6.BAAB				88.1			Butler and others (1993)
21	Slug	27S.12W.6.BAAB				57.9			Butler and others (1993)
22	Slug	27S.12W.6.BAAB				10.8			Butler and others (1993)
31	O'Rourke Bridge	21S.15W	Arkansas Alluvium	3800	0.31	260			Butler and others (2004)
31	O'Rourke Bridge	21S.15W	High Plains Aquifer	5400	0.00017	290	0.007		Butler and others (2004)
6	Slug	21S.12W.31.CCCB				31.6			Butler and others (2004)
7	Slug	21S.12W.31.CCCB				56.8			Butler and others (2004)
16	Bookstore	24S.14W.29.C	"Prairie" Aquifer	10,000	0.025	72			Cobb (1979)
	5 Aquifer Tests	Great Bend Prairie		7000 to 16,000	0.004 to 0.17	56 to 128			Fader and Stullken (1978)
	Specific Capacity of 235 Irrigation Wells	Great Bend Prairie		2500 to 35,000 (Avg=11,000)		20 to 280 (Avg=88)			Fader and Stullken (1978)

TABLE 2. AQUIFER TEST RESULTS IN PREVIOUSLY-RELEASED REPORTS

Figure 18 Map ID	Test	Location[1]	Aquifer	T (ft^2/d)	S	K_x (ft/d)	K_z (ft/d)	Specific Capacity (gpm/ft)	References
4	Alexander	21S.21W.35.CC	Alluvium	18,600		390		57	Fishel (1952)
8	Brothers	22S.21W.3						65	Fishel (1952)
5	Bryant	22S.21W.4.AA						68	Fishel (1952)
11	Chilson	23S.22W.11.CC	Buckner Alluvium	5900		79		38	Fishel (1952)
9	Hirschler	22S.22W.23.BC	Buckner Alluvium	6800		83		45	Fishel (1952)
2	Lynam	21S.21W.21.BC	Pawnee Alluvium	61,500		1600		60	Fishel (1952)
3	Norris	21S.21W.35.BA	Pawnee Alluvium	12,700	0.017	207		65	Fishel (1952)
26	Pump	27S.13W.21.ACA1				155			Gillespie and Hargadine (1993)
27	Pump	28S.11W.10.A				200			Gillespie and Hargadine (1993)
30	Pump	28S.11W.32.A				200			Gillespie and Hargadine (1993)
29	Pump	28S.13W.26.DCB1				200			Gillespie and Hargadine (1993)
19 25 28	3 Aquifer Tests	26S.13W.19.A 27S.13W.21.B 28S.13W.26.D		14,700 to 24,000	0.1 to 0.15 (Projected)				Layton and Berry (1973)
		Ford and Hodgeman Counties	Dakota	7100				6 to 22	Lobmeyer and Weakly (1979)
		Ford and Hodgeman Counties	Dakota	2000					Lobmeyer and Weakly (1979)
	22 Sites	Central and SW Kansas	Dakota			3.6 to 88 (Mean=12.5)			Macfarlane and others (1998)
		Washington County	Dakota				0.0022		Macfarlane and others (1998)
31	O'Rourke Bridge	21S.15W	Arkansas Alluvium		0.19 to 0.21				McKay and others (2004)
			Pawnee Alluvium					6 to 66	Sophocleous (1980)

TABLE 2. AQUIFER TEST RESULTS IN PREVIOUSLY-RELEASED REPORTS

Figure 18 Map ID	Test	Location[1]	Aquifer	T (ft^2/d)	S	K_x (ft/d)	K_z (ft/d)	Specific Capacity (gpm/ft)	References
	Model Flood Wave	GMD #5 Transects	"Prairie" Aquifer	2500 to 25,000	0.0001 to 0.5	50 to 500	1 to 2		Sophocleous (1991)
1	Weller	19S.13W.36	Arkansas Alluvium	19,400	0.00056	223	1		Sophocleous and others (1988)
	68 Drillers' Logs	Various	"Prairie" Aquifer	6132	0.15	85			Sophocleous and others (1993)
14	Bliss Site	23S.13W.36.D	"Prairie" Aquifer	3257 to 20,937	0.0006 to 0.0041	35 to 226			Sophocleous and others (1997)
18	Ketterl Site	25S.17W.35.B	"Prairie" Aquifer	2481 to 4820	0.0002 to 0.0004	17 to 33			Sophocleous and others (1997)
24	Smith Site	27S.15W.5.C	"Prairie" Aquifer	2005 to 25,823		33 to 272			Sophocleous and others (1997)
10	Garden City Co.	23S.34W.15.ACBD	Dakota	1700	0.0002				Watts (1989)
	Regional Report	GMD #5 District	High Plains Aquifer			>25 to <200			Wilson and others (2002)

[1]Quarter sections are listed largest to smallest (A=NW, B=NE, C=SW, D=SE).

TABLE 3. DATA SET AND METHOD SUMMARY FOR BBGMDMOD INPUT SPECIFICATIONS*

Category	Data Set Number	Data Set Name	Use	Data Source and Processing Steps
Elevation and Drainages	1	National Elevation Data Set 1/3 Arc Second[1]	Elevation reference	Mosaic produced for model area
	2	Model Cell Elevation Data	1) Model land surface (mean cell elevation) 2) Stream bed elevation (minimum cell elevation) 3) ET surface	Land surface elevation statistics for each model cell
	3	National Hydrography Dataset[2]	1) Drainage reinforcement for catchment generation 2) Stream geometry and routing for Stream Flow Routing package	
	4	Model Area Catchments and Drainage Data (cell size ≈ 10 m)	Recharge and Runoff accounting	Process 1/3 arc-second DEM using ARC-Hydro Tools
	5	Model Area Catchments and Drainage Data (cell size = 2640 ft)	1) Used to define and index areas of water loading at playas and ephemeral streams 2) Used to compute topographic wetness index[3] (TWI)	Process Mean Model Cell Elevation with ARC-Hydro tools
	6	Administrative Watersheds and Subasins[4]	1) Administrative areas 2) Accounting areas	
Hydro Geologic Units	7	Generalized Surface Geology	Indicates generalized surface geologic units for model: Qa, HPA, Shales, Dakota aquifer or Permian rocks undivided	Adapted from the 1:500,000 digital geologic map of Kansas[5] by dissolving map units. Merged with the model grid by querying model cell centroid intersection with each geologic unit.
	8	Generalized Bedrock Subcrops	Indicates generalized subcropping geologic units for model: Shales, Dakota aquifer, Permian Cedar Hills and Permian rocks undivided	Adapted from the 1:500,000 digital geologic map of Kansas[5], digital Dakota aquifer mapping[6 and 7] and the year 1978 Fader and Stulken Great Bend Prairie subcrop map[8].
	9	Top of Bedrock Surface Beneath Quaternary and Pliocene Sedimentary Units	1) Used to assign thickness to Quaternary and Pliocene sedimentary units 2) Used to define the top of bedrock subcrop units	The following nine datasets were gridded with the ARC TOOL Box TOPOGRID tool using drainage enforcement to preserve paleo-drainages: 1) Boundary - Generalized Area of Pliocene and Quaternary sediments (DS5) 2) Point Elevation - Generalized bedrock outcrop elevations using (DS7) and (DS1) 3) Contour - Great Bend Prairie Pre-Cenozoic bedrock[9] 4) Point Elevation - Great Bend Prairie Pre-Cenozoic bedrock[9] 5) Contour - "Enhanced Bedrock Elevations Estimates for the Ogallala Aquifer"[10] 6) Point Elevation - "Enhanced Bedrock Elevations Estimates for the Ogallala Aquifer"[10] 7) Contour - Pawnee Valley alluvial base[11] 8) Contour - Walnut Valley alluvial base[12] 9) Contour - USGS base of High Plains Aquifer[13]
	10	Top of Dakota Aquifer Unit	1) Used to assign thickness to Cretaceous Shale using (DS9) 2) Used to define the top of the Dakota Sandstone	The following three datasets were gridded with the ARC TOOL Box TOPOGRID tool in two passes to preserve offsets at the Crooked Creek fault: 1) Boundary - Generalized Area of Dakota from (DS7) and (DS8) 2) Point Elevation - Generalized Dakota outcrop and subcrop elevations from (DS7) and (DS1), (DS8) and (DS9) 3) Contour - Dakota aquifer top contour[6 and 7]
	11	Base of Dakota Aquifer Unit	1) Used to assign thickness to the Upper Dakota Unit 2) Used to define the top and thickness of the middle Dakota unit (Kiowa shale)	The following three datasets were gridded with the ARC TOOL Box TOPOGRID tool in two passes to preserve offsets at the crooked creek fault: 1) Boundary - Generalized Area of Dakota from (DS10) and (DS11), 2) Point Elevation - Generalized Dakota outcrop and subcrop elevations from (DS7) and (DS1), (DS8) and (DS9) 3) Contour - Dakota aquifer base contour[6 and 7]
	12	Structure of the Stone Corral Dolomite	1) Used to define the top of the Permian Undivided unit	The following dataset was gridded with the ARC TOOL Box TOPOGRID tool: 1) Contour - Top of the Stone Coral Dolomite[14]
	13	Alluvial Aquifer Top and Thickness	1) MODFLOW HUF package input	Where the model surface geology (DS7) is alluvium: 1) The unit top is the mean model cell elevation (DS2) 2) The unit thickness is the unit top minus the bedrock surface (DS2 - DS9) This unit is further divided to account for portions occurring in model layer 1 and model layer 2.
	14	High Plains Aquifer Top and Thickness	1) MODFLOW HUF package input	Where the model surface geology (DS10) is HPA: 1) The unit top is the mean model cell elevation (DS4) 2) The unit thickness is the unit top minus the bedrock surface (DS10-DS4) This unit is further divided to account for portions occurring in model layer 1 and model layer 2.

TABLE 3. DATA SET AND METHOD SUMMARY FOR BBGMDMOD INPUT SPECIFICATIONS*

Category	Data Set Number	Data Set Name	Use	Data Source and Processing Steps
Hydro Geologic Units (Continued)	15	Cretaceous Shale Top and Thickness	1) MODFLOW HUF package input	Where the model surface geology (DS7) is Shale: 1) The unit top is the mean model cell elevation (DS2) 2) The unit thickness is the unit top minus the top of the Dakota (DS13) Where the Shales are in subcrop (DS11): 1) The unit top is the bedrock surface (DS12) 2) The unit thickness is the unit top minus the top of the Dakota (DS13)
	16	Upper Dakota Top and Thickness	1) MODFLOW HUF package input	From (DS10) and (DS11)
	17	Middle Dakota Units (Kiowa Shale) Top and Thickness	1) MODFLOW HUF package input	Where the thickness of the Dakota Sandstone aquifer is greater than 200 ft[15]: Where the Dakota outcrops (DS17): 1) The unit top is the mean model cell elevation (DS2) 2) The unit thickness is the Top of the Dakota (DS10) minus the Base of the Dakota (DS11) minus 200 ft Where the Dakota Sandstone is in subcrop (DS8): 1) The unit top is the bedrock surface (DS9) for alluvial/HPA subcrop 2) The unit top is the Dakota aquifer unit top (DS10) for shale subcrop 3) The unit thickness is the Top of the Dakota (DS10) minus the Base of the Dakota (DS11) minus 200 ft
	18	Cretaceous and Permian Aquifer (Cheyenne SS to Salt Plains SS) Top and Thickness	1) MODFLOW HUF package input	If in Cedar Hill sub crop (DS8), the unit thickness fills the space between the upper most unit and Permian undivided (DS19).
	19	Permian Aquifer Undivided (Below Salt Plains SS)	1) MODFLOW HUF package input	If the middle Dakota unit (DS17) is absent, the top of the unit is the top of bedrock (DS9) minus (DS18) else the top of the unit is bedrock subcrop elevation from (DS8) and (DS9) or the Stone Coral (DS12) plus 500 feet[8]
Climate	20	Monthly Precipitation (P) and Min-Max Temperature (T) Years 1895-2007	1) Used to calculate time trend of irrigation requirement 2) Used to calculate time trend of maximum monthly groundwater ET rate 3) Used to calculate time trend of monthly lake evaporation	1) Obtain PRSIM[16] precipitation ASCII grid files 2) Convert to ".img" format, clip to model area and reproject 3) Resample to model grid using nearest-neighbor technique
	21	Monthly Reference Crop Evapotranspiration Years 1895-2007 (ET_0)	1) Used to calculate time trend of irrigation requirement 2) Used to calculate time trend of maximum monthly groundwater ET rate 3) Used to calculate time trend of monthly lake evaporation	Calculate monthly (ET_0) for each model cell using PRISM MIN and Max monthly temperature (DS20) and mid-month solar radiation using the method of Hargreaves from FAO 56[17] (Equation 52)
Pumping Stress	22	Point of Diversion Locations (POD)	Provided the location and identification information for model pumping centers	The KGS WIMAS[18] data was spatially merged with the model grid to provide model coordinates.
	23	Place of Use Locations (POU)	1) Provided location information for application of modeled return flow 2) Provided tabulation areas for the LANDSAT acreage inventory	The KGS WIMAS[19] POU data was located by a GIS join operation with Public Land Survey quarter-quarter data. The POUs were then intersected with the model grid. The fractional overlap between each POU and its intersecting model grid cells was calculated and used to scale irrigation return flow.
	24	Priority Date (PRI)	Provides an "On" year: pumping is not formulated for a POD prior to the water-right priority date year.	From the KGS WIMAS[18] data
	25	Meter Record - AFY (Mrec)	1) Used to formulate all pumping stress after year 1990 2) The average meter record for the period 1991-2007 is used to formulate non-irrigation pumping stress prior to 1991 coming on at the priority date	The KGS WIMAS[18 and 20] data was cross-tabulated by year for each POD by Use and Water Right ID. Year 1991-2007 averages were calculated.
	26	Reported Irrigated Acres (RIA)	1) Used to formulate return flow after year 1990 2) Averaged for the period 1991-2007 to formulate pre-1991 pumping when a LANDSAT acreage estimate is not available 3) Used to calibrate LANDSAT irrigated acres estimate	The KGS WIMAS[18] data was cross-tabulated by year for each POD by Use and Water Right ID. Year 1991-2007 averages were calculated.
	27	Irrigated Acres Estimate Year 1974 to 1982 - Acres (Irr_{MSS})	Irrigated areas for years 1974-1982	1) Obtain LANDSAT MSS[21] scenes closest to August 1st with less than 10% cloud cover for Path/Row 31-33 and 31-34. 2) Calculate a histogram of Normalized Difference Vegetation Index (NDVI) strength for each POU for each image. 3) The POU area with NDVI greater than 0.3 is chosen as the image Irrigated area (by inspection, the >0.3 NDVI class generally corresponds to irrigated farms). 4) Irr_{MSS} is calculated using an image irrigated area to reported irrigated area relationship (see Figure 41).
	28	Irrigated Acres Estimate Year 1984 to 1990 - Acres (Irr_{TM})	Irrigated areas for years 1984-1990	1) Obtain LANDSAT TM5[22] scenes closest to August 1st with less than 10% cloud cover for Path/Row 29-33 and 29-34. 2) Calculate an area histogram of Enhanced Vegetation Index (EVI) strength for each POU for each image. 3) Calculate the average Enhanced Vegetation Index (EVI) strength for each CRP tract by township for each image. 4) The POU area with EVI greater than the average EVI in adjacent CRP tracts is the image irrigated area. 5) Irr_{TM} is calculated using image irrigated area to reported irrigated area relationship (see Figure 41).

TABLE 3. DATA SET AND METHOD SUMMARY FOR BBGMDMOD INPUT SPECIFICATIONS*

Category	Data Set Number	Data Set Name	Use	Data Source and Processing Steps
Pumping Stress (Continued)	29	Reference Irrigation Requirement - ft/yr (IR_{ref})	Provides a time-trend indication of irrigation requirement	IR_{ref} is then calculated as the sum of ET_0 for the irrigation months June-September (see Monthly Pumping and Return Flow Distribution below) minus the PRISM (DS20) precipitation for those months. In each case the PRISM data was sub-sampled into model cells using the nearest-neighbor technique.
	30	Average Irrigation Requirement - ft/yr (IR_{avg})	A calibrated/scaled Irrigation Requirement (IRref) used to calculate irrigation demand	Average Irrigation Requirement is the product of the reference irrigation requirement and a factor ($IR_{avg} = IR_{ref}$ x factor). The initial value is 0.8. The factor can be adjusted to account for average crop and farm management conditions.
	31	Irrigation Return Flow Trend	Used to formulate irrigation pumping when meter data are not available	The RF trend for the period 1940-1990 was adapted from modeling work done by the USGS[23].
	32	Yearly Pumping Trend - AFY (Q)	Used to formulate model pumping stress	1) For non-irrigation use after 1990 use Mrec, prior to 1990 use the 1991-2007 Mrec average. Pumping comes on at the priority date. 2) For the period prior to 1974 (no LANDSAT or meter data) irrigation pumping is calculated as the product of average 1991-2007 reported irrigated acres, the irrigation requirement and the inverse of the historical efficiency trend (RIAp x IR_{avg} x 1/Eff). 3) For the period 1974-1990 irrigation pumping is calculated as the product of the LANDSAT Irrigated acre estimate for each POU, the irrigation requirement and the inverse of the historical efficiency trend (Irr_{MSS} x IR_{avg} x 1/Eff or Irr_{TM} x IR_{avg} x 1/Eff). If a LANDSAT acreage estimate is not available then pumping is calculated as in (2) above. 4) For irrigation use after 1990 use Mrec.
	33	Yearly Irrigation Return Flow Trend - AFY (RF)	Used to formulate model pumping stress	1) If Irrigation pumping (Q) was calculated, then return flow is the product of Q and the return flow fraction (RF = (Q x RFfrac) - Pre-Infiltration Loss). For the period 1940-1990 pre-infiltration is equal to 3% of Q. 2) If Irrigation pumping (Q) was metered, then return flow is calculated using the reported irrigated acreage and the average irrigation requirement (RF = Mrec - (RIA x IR_{avg}) - Pre-Infiltration Loss). For the period 1991-2007 pre-infiltration is equal to 3% of Mrec.
	34	Monthly Pumping and Return Flow Distribution - AFM	Used to convert yearly RF and Q into a monthly pumping stress	Derived from NRCS handbook[24] values for monthly irrigation demand for a 50% precipitation year in south central Kansas.
Recharge, Runoff and ET	35	Time Series of Monthly Precipitation (DS20) for Active Model Cells (ft/d).	Main input for recharge runoff process	
	36	Time Series of Monthly Reference ET (DS21) for Active Model Cells (ft/d)	Main input for ET Process	
	37	Hru Number for Model Cells (Ordinal 1-193)	Hydrologic response unit number	
	38	The Model Cell Area with ET for Model Cells (ft^3)	Used to define to portion of each model cell where ET can potentially occur	
	39	Playa Water Loading for Each Model Cell in Hru (Fraction 0.0-1.0)	Provides a water loading index based on drainage area for playas and ephemeral streams	Developed from (DS5)
	40	Si Recharge Number for Cell (Ordinal 1-25)	Spatial distribution of applied recharge	Developed from a potential run off contributing area analysis and calculated using DS5 TWI and soil permeability data
	41	Ro Curve Number for Cell (Ordinal 1-25)	Spatial distribution of applied runoff	(DS37) merged to encompass major stream basins
	42	Model Cell Area (ft^2)	Model cell area for volumetric calculations	
	43	Time Series of Conductance by Month (L and W Fixed, K ft/d)	Hydraulic properties for SFR streams	Adapted from the MIDARK[25] model, refined during model calibration
	44	Time Series Stream/Lake Stages by Month (ft)		Developed during model calibration
	45	Time Series Inflow/Diversion by Month (cfs)	1) Provides inflow on the Arkansas at the model's western edge 2) Diversions to Cheyenne Bottoms at Dundee	1) Arkansas inflow was adapted from USGS gaging[26] at Garden City. 2) Dundee diversions were adapted from the MIDARK model input.
	46	Table of Monthly Precipitation to Monthly RO Curves (in/mo - in/mo)	Monthly precipitation to monthly runoff relationship	Developed during model calibration
	47	Table of Monthly Precipitation to Monthly Playa Recharge Curves (in/mo – in/mo)	Monthly precipitation to monthly playa recharge relationship	Developed during model calibration
	48	Table of Monthly Precipitation to Monthly SI Curves (in/mo - in/mo)	Monthly precipitation to monthly recharge relationship	Developed during model calibration
	49	Time Series of Lake Evaporation (ft/d)	Lake evaporation at Quiviara	Data from (DS20) and (DS21) indexed to match Kansas Lake evaporation map for Stafford county.
	50	Streambed Elevation (ft NAVD88)	SFR input	Minimum cell elevation data from (DS2)
	51	Streambed Incision Rate (ft/mo)	A factor to control the incision rate of streams	Adapted from the MIDARK[25] model, refined during model calibration
	52	Table of SFR Cells		1) GNIS named streams for the model area were queried from the NHD (DS3), these become the "Model streams." 2) Stream routing information was extracted from the NHD network data. 3) Model Streams were intersected with the model grid. 4) Streams "slivers" less than 100 ft within a model cell are eliminated and their length is distributed into adjacent cells. 5) Ponds, reservoirs and impoundments were located in the stream network and their area was defined using mapping and stage area curves. 6) Shape file and geodatabase tables were adapted into an EXCEL format compatible with SFR input.

TABLE 3. DATA SET AND METHOD SUMMARY FOR BBGMDMOD INPUT SPECIFICATIONS*

Category	Data Set Number	Data Set Name	Use	Data Source and Processing Steps
Recharge, Runoff and ET (Continued)	53	Watershed Dam Sites	Used to adjust runoff and recharge in HRU with watershed dam structures and other impoundments	Developed from the National dam inventory[27] and Pawnee watershed mapping
	54	Recharge Package Input		1) Apply SI (DS48) curve for cell to monthly precipitation (DS20) in cell. 2) Apply transmission loss curve (DS46) to precipitation in cell (DS20), tabulate for HRU (DS37). 3) Apply RO (DS37) curve to precipitation in cell, tabulate for HRU (DS37). 4) Adjust HRU (DS37) for watershed dams (DS53) (less RO, less TL, recharge at dam site, evaporation). Add recharge to cell with pond. 5) Sum recharge for each cell (SI + (TL x HRU loading (DS39)) + pond), write input.
	55	ET Package Input		Formulate a maximum ET rate that is equal to ET_0 for the cell minus precipitation minus runoff for fraction of cell area with ET, write input.
	56	SFR Package Input		1) Runoff = Runoff for HRU divided by number of SFR cells in HRU 2) Get streambed K from table 3) Get inflow from table 4) Get stream depth from table 5) Get lake evaporation for stress period from table 6) Write input

*(DS) in the table body refers to the data set number (column two) and is used to indicate derived data.

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[8]Fader, S.W. and Stullken, L.E., 1978, Geohydrology of the Great Bend Prairie, South-Central Kansas: Kansas Geological Survey Irrigation Series 4, 19 pp.

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MODEL

TABLE 4. SPECIFICATION FOR AQUIFER PROPERTIES

Zone Mapped on Figure 30	Geologic Unit[1]	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Specific Storage (ft^{-1})	Specific Yield	Locale
Bedrock Units						
	Kgg	0.01	0.01	2.0E-06	0.03	Deep
	Kdu	2	2	2.0E-06	0.03	Deep
	Kdl	0.01	0.01	2.0E-06	0.03	Deep
	KPu	0.25	0.25	2.0E-06	0.03	Deep
	Pu	0.1	0.1	2.0E-06	0.03	Deep
	Pu	0.1	0.1	2.0E-06	0.03	Shallow
Upper Quaternary-Pliocene Units						
QA1	Qa1	300	0.2	2.0E-06	0.2	Upper Ark
QA2	Qa1	250	0.1	2.0E-06	0.2	Pawnee
QA3	Qa1	250	0.2	2.0E-06	0.2	Walnut
QA4	Qa1	200	0.2	2.0E-06	0.2	C Bott.
QA5	Qa1	400	0.2	2.0E-06	0.2	R. Snake
QA6	Qa1	200	0.2	2.0E-06	0.2	South
QA7	Qa1	200	0.2	2.0E-06	0.2	East
QA8	Qa1	150	0.2	2.0E-06	0.2	Lower Ark
HPA1	HPA1	120	0.1	2.0E-06	0.2	NW
HPA2	HPA1	120	0.1	2.0E-06	0.2	GMD3 North
HPA3	HPA1	120	0.1	2.0E-06	0.2	GMD3 South
HPA4	HPA1	90	0.1	2.0E-06	0.2	MidArk NW
HPA5	HPA1	220	0.1	2.0E-06	0.2	MidArk Main
HPA6	HPA1	120	0.1	2.0E-06	0.2	MidArk NE
HPA7	HPA1	220	0.1	2.0E-06	0.2	RS West
HPA8	HPA1	220	0.1	2.0E-06	0.2	RS N1
HPA9	HPA1	220	0.1	2.0E-06	0.2	RS N2
HPA10	HPA1	220	0.1	2.0E-06	0.2	RS N3
HPA11	HPA1	220	0.1	2.0E-06	0.2	RS N4
HPA12	HPA1	220	0.1	2.0E-06	0.2	RS N5
HPA13	HPA1	220	0.1	2.0E-06	0.2	RS N6
HPA14	HPA1	220	0.1	2.0E-06	0.2	RS N7
HPA15	HPA1	220	0.1	2.0E-06	0.2	RS N8
HPA16	HPA1	220	0.1	2.0E-06	0.2	RS Main
HPA17	HPA1	220	0.1	2.0E-06	0.2	NE
HPA18	HPA1	70	0.7	2.0E-06	0.2	RS S1
HPA19	HPA1	70	0.7	2.0E-06	0.2	RS S2
HPA20	HPA1	220	0.1	2.0E-06	0.2	RS S3
HPA21	HPA1	220	0.1	2.0E-06	0.2	S SE

MODEL

TABLE 4. SPECIFICATION FOR AQUIFER PROPERTIES

Zone Mapped on Figure 30	Geologic Unit[1]	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Specific Storage (ft^{-1})	Specific Yield	Locale
Lower Quaternary-Pliocene Units						
QA1	Qa2	200	0.2	2.0E-06	0.2	Upper Ark
QA2	Qa2	250	0.2	2.0E-06	0.2	Pawnee
QA3	Qa2	250	0.2	2.0E-06	0.2	Walnut
QA4	Qa2	200	0.2	2.0E-06	0.2	C Bott.
QA5	Qa2	200	0.2	2.0E-06	0.2	R. Snake
QA6	Qa2	200	0.2	2.0E-06	0.2	South
QA7	Qa2	200	0.2	2.0E-06	0.2	East
QA8	Qa2	200	0.2	2.0E-06	0.2	Lower Ark
HPA1	HPA2	120	0.1	2.0E-06	0.2	NW
HPA2	HPA2	120	0.1	2.0E-06	0.2	GMD3 North
HPA3	HPA2	120	0.1	2.0E-06	0.2	GMD3 South
HPA4	HPA2	70	0.1	2.0E-06	0.2	MidArk NW
HPA5	HPA2	70	0.1	2.0E-06	0.2	MidArk Main
HPA6	HPA2	120	0.1	2.0E-06	0.2	MidArk NE
HPA7	HPA2	70	0.1	2.0E-06	0.2	RS West
HPA8	HPA2	70	0.1	2.0E-06	0.2	RS N1
HPA9	HPA2	70	0.1	2.0E-06	0.2	RS N2
HPA10	HPA2	70	0.1	2.0E-06	0.2	RS N3
HPA11	HPA2	70	0.1	2.0E-06	0.2	RS N4
HPA12	HPA2	70	0.1	2.0E-06	0.2	RS N5
HPA13	HPA2	70	0.1	2.0E-06	0.2	RS N6
HPA14	HPA2	70	0.1	2.0E-06	0.2	RS N7
HPA15	HPA2	70	0.1	2.0E-06	0.2	RS N8
HPA16	HPA2	70	0.1	2.0E-06	0.2	RS Main
HPA17	HPA2	70	0.1	2.0E-06	0.2	NE
HPA18	HPA2	70	0.7	2.0E-06	0.2	RS S1
HPA19	HPA2	70	0.7	2.0E-06	0.2	RS S2
HPA20	HPA2	70	0.1	2.0E-06	0.2	RS S3
HPA21	HPA2	70	0.1	2.0E-06	0.2	S SE

[1]Explanation for Geologic Unit:
HPA1 = High Plains Aquifer (Upper)
HPA2 = High Plains Aquifer (Lower)
Kdl = Cretaceous Dakota (Lower)
Kdu = Cretaceous Dakota (Upper)
Kgg = Cretaceous Shales
KPu = Cretaceous Permian Undivided
Pu = Permian Undivided
Qa1 = Quaternary-Pliocene Aquifer (Upper)
Qa2 = Quaternary-Pliocene Aquifer (Lower)

TABLE 5. CALCULATION OF IRRIGATION RETURN FLOW (AVERAGE MODEL WIDE)

Irrigation Budget Component	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Average
Calculated Crop Irrigation Requirement (CIR) (in/yr)	14.97	7.32	7.92	13.51	11.53	5.86	8.03	12.38	9.63	13.07	12.58	13.41	12.98	8.76	10.60	11.36	10.39	10.84
Metered Irrigation Water Applied (IWA) (in/yr)	17.98	11.80	11.13	15.93	13.75	11.73	11.17	13.79	12.13	14.43	14.42	15.58	15.09	11.93	12.41	13.98	11.52	13.46
Ratio of IWA to CIR	1.20	1.61	1.41	1.18	1.19	2.00	1.39	1.11	1.26	1.10	1.15	1.16	1.16	1.36	1.17	1.23	1.11	1.28
Pre-Infiltration Loss, 3% of IWA (in/yr)	0.54	0.35	0.33	0.48	0.41	0.35	0.34	0.41	0.36	0.43	0.43	0.47	0.45	0.36	0.37	0.42	0.35	0.40
Return Flow (in/yr)	2.47	4.13	2.88	1.95	1.80	5.52	2.81	0.99	2.14	0.93	1.41	1.71	1.66	2.80	1.44	2.20	0.78	2.21
Return Flow (% of IWA)	14%	35%	26%	12%	13%	47%	25%	7%	18%	6%	10%	11%	11%	24%	12%	16%	7%	17%

TABLE 6. OBSERVED AND SIMULATED RATTLESNAKE TRANSECT DATA (CFS)

Observation Date	DWR-1		GMD-T1		DWR-2		GMD-T2		GMD-T3		Macksville		GMD-T4		DWR-3		GMD-T5		DWR-4		DWR-5		DWR-6		Zenith	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
11/1/1959		14.4		26.2		27.8		33.7		40.7		40.0		44.5		48.7		60.6		71.3		78.7	58.9	77.8		79.8
4/1/1960		13.5		22.7		23.5		30.3		35.3		34.9		37.8		41.4		52.3		62.1		70.1	70.7	69.8		72.6
11/2/1960		12.3		21.0		21.9		26.9		31.7		31.2		33.7		37.4		48.0		55.9		61.6	46.2	58.7		59.5
4/1/1962		11.2		17.8		18.1		24.0		27.5		27.2		28.3		31.1		39.8		46.8		52.7	48.0	50.0		51.6
11/1/1962		14.8		28.9		31.4		39.0		45.3		44.8		48.1		52.0		63.2		72.2		78.6	44.8	76.8		79.1
3/1/1963		12.9		22.8		23.8		29.1		33.2		32.8		34.2		37.2		46.6		53.8		60.1	40.7	57.9		59.7
11/19/1963		13.7		25.7		27.4		32.9	26.0	37.8		37.3		39.1		42.1		51.2		59.2		64.1		60.4		60.9
7/21/1964		10.9		13.7		11.5		10.6		6.6		7.0		0.8		0.5		0.8		3.4		5.5	3.9	0.5		0.4
10/26/1964		11.0		18.3		18.4		21.3	12.0	22.4		22.3		20.0		21.5		26.7		31.4		34.1		28.3		27.3
11/10/1965		10.7		18.9		19.7		24.3	16.0	29.4		28.9		31.4		34.8		44.6		53.3		59.3		56.8		57.8
11/7/1966		8.9		13.3		12.9		15.1		16.5		16.3		15.1		17.1		23.7		29.1		32.8		27.8		27.3
10/18/1971		11.3		19.5		20.3		31.2		35.6		35.1		37.1		40.1		49.1		55.5		60.9		58.4		63.6
10/20/1971		11.3		19.5		20.3		31.2		35.6		35.1		37.1		40.1		49.1		55.5		60.9		58.4		63.6
4/6/1992		0.6		0.0		0.0		0.1	P	0.0		0.0		0.0		0.0	P	0.4	P	2.4		5.3	5.3	0.9		0.8
7/13/1992		4.5		9.5		8.0		17.7		19.3		19.6		12.7		13.0		17.2	5.1	20.8		26.4	12.0	25.5		30.2
10/1/1992		4.8		13.5		14.0		19.9		23.6		23.5		19.6		20.1		23.2	0.8	26.6		31.3	2.9	28.9		31.5
3/26/1993		4.2		12.0		13.1		22.3		28.2		27.8		30.1		33.4		43.7	LF	50.4		58.9	34.9	60.8		66.1
7/13/1993		12.7		31.8		36.9		67.1		85.1		83.8		100.7		108.9		137.5	LF	162.0		185.4	LF	209.4		258.9
10/1/1993		5.7		16.4		18.2		25.8		32.1		31.7		32.7		34.6		41.6	18.4	47.0		55.0	24.3	56.5		61.7
10/27/1993	Dry	5.7		16.4		18.2		25.8	16.2	32.1	17.0	31.7		32.7	17.3	34.6		41.6	21.6	47.0	28.0	55.0	29.4	56.5	32.0	61.7
11/17/1993	Dry	5.6		16.5		18.6		26.5	19.0	33.8	18.0	33.2		35.9	24.0	38.7	25.2	47.7	28.6	54.7	39.9	63.2	41.6	65.0	46.0	70.0
3/23/1994	Dry	4.5		10.9		11.3		15.6	17.0	18.9	18.0	18.7		18.1	19.9	19.8	22.2	26.8	26.4	32.2	32.4	40.1	34.2	40.4	34.0	43.5
5/18/1994	Dry	4.0		7.2		6.2		8.6	13.7	8.5	14.0	8.6		4.3	14.9	4.7	14.4	8.4	20.6	12.4	26.2	18.6	30.8	17.0	32.0	19.6
7/7/1994	Dry	3.6		4.2		1.7		6.6	1.1	4.1	1.0	4.5		0.0	0.0	0.0	0.1	2.5	1.2	5.8	6.4	11.2	6.5	9.1	6.1	15.5
9/21/1994	Dry	1.5		0.0		0.0		0.5		0.0	0.1	0.0		0.0	Dry	0.0	Dry	0.0	0.7	1.2	3.5	3.8	1.3	0.0	0.8	0.4
11/9/1994	Dry	2.3		4.5		2.1		4.9		4.6	1.3	4.8		0.0	Dry	0.9	0.0	6.0	1.4	10.0	6.2	15.0		12.2	6.1	13.8
3/21/1995	Dry	2.4		5.1		4.4		10.7	3.2	12.7	5.4	12.5		11.4	4.6	13.5	4.2	21.8	7.4	27.5	12.1	34.4	14.9	34.0	17.0	37.6
7/11/1995	Dry	4.6		13.0		12.5		18.7	23.8	20.5	19.0	20.4		17.1	31.0	16.8	28.5	19.3	32.3	22.5	39.2	29.1	37.5	28.8	45.0	33.4
9/26/1995	Dry	3.1		5.4		2.9		5.1	4.6	3.7	2.3	3.8		0.0	2.5	0.2	1.6	2.7	2.1	5.6	8.3	11.1	6.2	9.4	6.7	13.5
12/26/1995	Dry	3.2		7.5		7.0		10.7	8.0	13.5	5.0	13.3		11.6	9.3	13.1	4.4	20.1	7.3	25.0	13.0	31.3	12.8	30.0	26.0	32.4
3/18/1996	Dry	3.4		8.0		8.0		14.9	7.3	18.1	8.4	17.9		17.9	8.8	20.1	11.2	28.1	12.9	33.7	19.4	40.5	21.4	39.8	33.0	43.1
6/19/1996	Dry	3.7		11.3		12.2		21.0	6.5	22.6	6.8	22.6		19.7	8.9	20.3	10.3	25.3	13.1	29.5	19.9	35.9	21.3	35.0	24.0	39.2
5/12/1997	Dry	7.2		19.4		21.4		31.7	18.6	36.9	24.0	36.6		37.0	25.8	38.7	25.8	45.2	24.4	50.3	32.4	56.9	32.4	55.8	42.0	59.8
10/22/1997	Dry	13.5		33.7		37.8		52.1	23.2	62.7	25.0	61.8		67.3	26.5	70.8	27.7	81.5	29.8	89.1	36.6	98.1	34.2	100.3	39.0	106.7
9/10/1998	Dry	3.2		3.4		0.1		0.0	9.0	0.0	9.1	0.0		0.0	3.8	0.0	2.7	0.0	2.4	1.5	6.6	5.2	5.2	0.8	5.1	1.9
7/29/1999	Dry	3.9		9.6		8.8		14.8	10.9	16.2	9.2	16.1		14.0	7.2	14.7	7.6	20.1	9.6	24.3	16.4	31.2	17.9	30.8	24.0	36.9
9/6/2005	Dry	0.0		0.0		0.0		0.0		0.0	0.2	0.0		0.0	P	0.0		0.0		1.2	9.1	4.2	9.5	0.2	14.0	0.9
4/25/2006	Dry	0.0		0.0		0.0		1.1		0.0	0.7	0.0		0.0	P	0.1		2.6	P	5.6	10.4	10.0	11.9	7.2	9.9	9.4
9/28/2006	Dry	0.0		0.0		0.0		0.1		0.0	Dry	0.0		0.0	Dry	0.0		1.3	P	3.5	4.5	7.4	1.2	4.0	2.8	5.8
10/25/2007	Dry	15.5	Dry	0.0	P	0.0		0.9	6.5	0.0	10.0	0.0	5.9	0.0	6.6	0.7	6.1	3.5	9.3	6.8	14.4	12.0	15.8	10.1	19.0	13.0

LF = Large Flow
P = Ponded

TABLE 7. OBSERVED AND SIMULATED MID-ARKANSAS TRANSECT DATA (CFS)

Observation Date	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9		Site 10	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
3/4/1986		1.6		2.6		0.0		0.0		0.7	0.0	4.8	0.8	0.0		3.7	0.0	0.0	9.9	1.1
4/1/1986		4.9		9.1		8.3		0.0		3.0		12.7		1.7		23.9	0.0	18.9	12.9	36.0
5/6/1986		0.6		0.6		0.0		0.0		0.6	0.1	3.7	>1	0.0		1.3	0.0	0.0	13.7	4.0
3/6/1991		3.5		6.4		5.1		0.0		1.1		8.5	2.0	0.0		11.4	0.0	12.2		13.3
3/25/1992		1.5		3.4		0.0		0.0		0.5	0.0	5.5	0.0	0.0		0.0	0.0	0.0		10.7
6/1/1992		31.8		54.1		76.2		73.0		87.7		132.0		401.2		1527.2		1701.0		376.8
4/26/2000		6.1	161.7	9.8		10.6		9.7	146.9	14.9		26.9		0.5	157.5	45.5		45.7		12.9
5/31/2000	26.9	7.3	28.8	12.9	36.3	16.0	47.2	17.1	60.7	24.4	73.0	38.8	78.3	31.6	78.3	91.9	126.4	105.6	204.1	44.0
6/21/2000	8.0	5.1	12.9	9.2	16.9	10.9	21.9	9.8	30.2	14.8	40.6	28.2	50.6	14.4	46.2	67.0	50.8	72.0	102.4	49.1
7/11/2000	4.8	9.6	10.5	15.9	16.4	22.4	13.3	28.5	16.2	36.0	11.9	55.0	28.5	105.9	33.0	411.8		460.9		246.1
8/17/2000	6.3	0.7	10.4	0.1	12.8	0.4	12.2	0.0	18.5	0.6	20.5	4.8	25.7	0.0	23.7	3.6	6.3	0.0	33.0	0.0
9/20/2000	2.8	0.0	4.9	0.0	5.2	0.1	4.0	0.0	2.7	0.4	7.2	3.1	10.3	0.0	7.8	0.0	2.3	0.0	19.2	0.0
10/19/2000	3.2	7.4	4.3	11.2	4.9	11.1	2.5	6.6	2.2	4.9	3.5	17.8	7.5	0.7	4.4	39.0	1.1	26.2	15.1	32.6
11/21/2000	2.7	3.6	5.0	6.7	6.0	7.1	5.0	3.4	3.2	2.5	6.0	11.1	8.3	0.0	9.3	19.2	2.0	7.4	24.6	1.4
3/22/2001	22.3	4.2	24.1	8.1	26.3	8.6	0.0	6.2	27.5	9.2	26.0	18.1	29.4	0.0	27.0	28.9		20.6		5.4
4/26/2001	5.8	2.1	10.2	3.7	15.8	1.4	14.7	0.0	18.1	1.2	24.9	7.0	30.5	0.0	30.7	10.3	35.9	0.9		9.2
5/17/2001	5.6	17.3	8.6	28.6	10.4	38.8	9.5	47.5	13.0	68.0	18.8	97.3	29.7	148.5		697.5		769.6		269.8
6/28/2001	17.7	3.6	32.9	4.9	37.7	4.0	38.5	3.2	44.0	8.1	51.4	21.1	59.5	0.0	72.1	40.7	62.2	50.9	216.0	43.9
7/18/2001	3.4	3.0	6.5	3.0	7.5	1.6	6.5	0.0	7.4	2.8	14.5	14.8	19.2	3.5	22.7	32.7	10.7	33.4	45.7	44.0
8/20/2001	1.5	1.3	0.5	0.0	1.6	0.2	0.0	0.0	0.1	0.6	3.7	7.9	7.4	0.0	4.5	10.9	2.0	0.0	21.2	3.1
9/25/2001	1.4	5.8	0.7	10.0	0.9	11.2	0.0	5.7	0.1	5.9	5.2	23.4	23.7	23.9	39.3	91.8	143.1	104.4	268.3	113.8
10/25/2001	0.3	0.8	1.4	1.6	0.0	0.4	0.0	0.0	0.0	1.8	1.1	11.0	5.1	0.0	3.1	17.0	15.2	4.1	47.9	0.0
11/29/2001	0.4	1.8	1.3	3.8	0.1	2.3	0.0	0.0	0.0	2.1	0.2	10.4	3.9	0.0	1.1	14.2	5.4	0.8	26.1	0.0
1/8/2002	0.6	3.4	0.0	6.6	0.6	6.6	0.0	0.5	0.3	2.6	0.6	11.2	3.5	0.0	1.9	18.6	3.4	21.0	21.9	1.4
2/20/2002	0.3	2.5	1.3	5.2	1.3	4.4	0.0	0.0	0.3	2.1	0.5	9.7	3.4	0.0	1.5	14.8	3.6	14.7	22.0	0.0
3/28/2002	0.3	1.4	1.4	3.3	0.3	1.3	0.0	0.0	0.1	1.4	0.3	7.6	3.3	0.0	0.6	10.0	3.2	9.5	19.9	2.7
4/24/2002	0.3	2.1	1.7	4.2	1.3	2.2	0.0	0.0	0.2	1.3	0.3	7.8	2.5	0.0	0.4	10.9	2.3	11.8	15.9	12.2
5/23/2002	0.3	2.4	1.4	5.8	1.3	5.2	0.0	0.0	0.0	1.6	0.4	9.3	1.5	0.0	0.2	10.1	1.2	8.4	14.5	14.0
6/18/2002	0.1	2.1	0.9	4.4	0.6	2.7	0.0	0.0	0.0	1.6	0.1	9.3	1.1	0.0	0.1	18.1	0.5	22.3	16.0	28.6
8/28/2002	7.1	6.3	13.4	10.3	35.2	10.3	0.0	2.1	0.0	0.6	0.0	8.9	0.2	2.1	0.0	12.5	0.0	0.0	3.6	29.1
9/25/2002	0.2	0.1	1.4	0.3	1.4	0.1	0.0	0.0	0.0	0.4	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
11/6/2002	0.4	1.5	1.5	3.7	0.6	2.6	0.0	0.0	0.0	0.7	0.0	6.6	0.3	0.0	0.0	8.2	0.0	0.2	2.6	0.0
12/18/2002	0.2	2.1	1.4	5.0	0.2	4.6	0.0	0.0	0.0	1.0	0.0	7.3	1.1	0.0	0.0	8.7	0.0	1.2	1.8	0.0
5/7/2003	0.5	4.7	1.8	7.6	0.0	6.2	0.0	0.7	0.0	2.0	0.0	9.5	0.7	0.8	0.0	28.1	0.2	44.0	3.1	52.5
6/23/2003	0.5	5.2	0.9	7.4	0.0	5.3	0.0	0.0	0.0	0.8	0.0	6.3	0.8	0.0	0.0	10.1	0.0	9.1	3.2	39.3
7/16/2003	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.4	0.3	0.0	0.0	0.0	0.0	0.0	1.5	0.0
8/6/2003	0.0	3.0	0.0	4.0	0.0	1.0	0.0	0.0	0.0	0.4	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.7	23.1
9/16/2003	0.0	3.9	0.0	6.3	0.0	5.1	0.0	0.0	0.0	0.5	0.0	7.9	RO	0.0	RO	6.3	0.0	0.0	0.9	14.0
10/8/2003	0.0	0.0	0.7	1.3	0.0	0.0	0.0	0.0	0.0	0.5	0.0	5.0	1.1	0.0	0.0	1.2	0.0	0.0	0.2	2.6
11/6/2003	0.0	0.3	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.5	0.0	4.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
12/8/2003	0.0	1.7	0.0	4.3	0.0	1.3	0.0	0.0	0.0	0.6	0.0	5.1	0.0	0.0	0.0	4.3	0.0	0.0	0.0	0.2
1/23/2004	0.0	1.2	0.0	3.5	0.0	1.2	0.0	0.0	0.0	0.6	0.0	4.1	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0
2/20/2004	0.0	2.2	0.0	5.2	0.0	3.8	0.0	0.0	0.0	0.7	0.0	5.0	0.0	0.0	0.0	4.7	0.0	0.0	0.0	0.1
3/17/2004	0.0	4.2	0.0	8.9	0.0	9.3	0.0	0.0	0.0	1.8	0.0	9.4	0.0	0.0	0.0	15.4	0.0	1.6	0.0	27.2

TABLE 7. OBSERVED AND SIMULATED MID-ARKANSAS TRANSECT DATA (CFS)

Observation Date	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9		Site 10	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
4/16/2004	0.0	4.0	0.0	7.7	0.0	6.9	0.0	0.0	0.0	1.6	0.0	8.0	0.0	0.0	0.0	12.7	0.0	2.9	0.0	12.7
5/11/2004	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.5	0.0	2.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	11.6
6/5/2004	0.0	4.9	0.0	8.7	0.0	5.6	0.0	0.0	0.0	2.0	0.0	11.1	0.0	5.4	0.0	313.9	0.0	355.2	0.0	147.5
8/3/2004	0.0	3.7	0.0	4.9	0.0	5.1	0.0	2.7	0.0	4.3	0.0	15.3	0.0	0.0	0.0	23.0	0.0	22.3	0.0	23.6
9/3/2004	0.0	6.1	0.0	9.4	0.0	11.0	0.0	8.3	0.0	9.5	0.0	21.3	0.0	5.4	0.0	36.9	0.0	37.1	0.0	20.3
10/25/2004	0.0	3.5	0.0	7.1	0.0	8.0	0.0	4.8	0.0	7.8	0.0	18.4	0.0	2.7	0.0	33.2	0.0	34.4	0.0	14.0
11/23/2004	0.0	4.9	0.0	8.9	0.0	9.9	0.0	6.8	0.0	10.0	0.0	19.7	0.0	1.3	0.0	30.8	0.0	30.0	0.0	5.2
12/15/2004	0.0	1.9	0.0	4.5	0.0	3.5	0.0	0.0	0.0	2.7	0.0	9.7	0.0	0.0	0.0	15.4	0.0	10.7	0.0	0.0
2/4/2005	0.0	3.6	0.0	7.4	0.0	7.5	0.0	4.0	0.0	7.2	0.0	15.8	0.0	3.6	0.0	31.0	0.0	34.3	0.0	18.6
3/7/2005	0.0	2.0	0.0	4.3	0.0	2.4	0.0	0.0	0.0	2.3	0.0	8.5	0.0	0.0	0.0	12.3	0.0	9.5	0.0	5.2
4/19/2005	0.0	3.0	0.0	6.5	0.0	5.5	0.0	0.0	0.0	2.7	0.0	10.2	0.0	0.0	0.0	15.2	0.0	15.5	0.0	14.7
5/20/2005	0.0	2.8	0.0	5.4	0.0	3.2	0.0	0.0	0.0	1.5	0.0	7.4	0.0	0.0	0.0	9.3	0.0	4.6	0.0	9.7
6/20/2005	0.0	7.9	0.0	16.3	0.0	21.6	0.0	21.9	0.0	27.5	0.0	42.3	0.0	49.5	0.0	136.0	0.0	144.4	0.0	73.6
6/18/2005	0.0	7.9	0.0	16.3	0.0	21.6	0.0	21.9	0.0	27.5	0.0	42.3	0.0	49.5	0.0	136.0	0.0	144.4	0.0	73.6
8/12/2005	0.0	3.9	0.0	7.1	0.0	7.9	0.0	3.8	0.0	0.9	0.0	9.7	0.0	12.1	0.0	32.0	0.0	33.4	0.0	34.4

RO = Runoff Event

MODEL

TABLE 8A. GROUNDWATER BUDGET (AFY)

	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge[1]	Well Pumping	Sum of Outflow[2]
Model Run							
Net Steady State	-110,000	-567,000	-14,000	0	693,000	0	-691,000
Average History (1940-2007)	-93,000	-482,000	-18,000	256,000	924,000	-586,000	-1,180,000
Average Baseline B (2008-2075)	73,000	-407,000	-16,000	291,000	1,009,000	-949,000	-1,372,000
Net Long-Term Sustainable	190,000	-408,000	-15,000	0	1,008,000	-779,000	-1,202,000
Difference Between Runs							
Steady State and Average History	17,000	85,000	-4,000	256,000	231,000	-586,000	-488,000
Steady State and Average Baseline B	183,000	160,000	-2,000	291,000	316,000	-949,000	-681,000
Steady State and Long-Term Sustainable	300,000	159,000	-1,000	0	316,000	-779,000	-510,000

[1]Steady state represents initial conditions taken in 1940 at the end of a dry decade in the 1930s, thus recharge is lower at steady state than in subsequent periods.

[2]Sum of Outflow indicates the groundwater system yield, which includes transient sources from aquifer storage in history and baseline cases.

MODEL

TABLE 8B. SURFACE WATER BUDGET AND SYSTEM YIELD (AFY)

	Arkansas River at Garden City (STR Input)	Direct Runoff (STR Input)	Downstream Total Outflow (STR Output)	Downstream Direct Flow (w/o Baseflow Gain as Outflow)	System Yield (Sum of Groundwater and Direct Outflow)[1]
Model Run					
Net Steady State	217,000	493,000	820,000	709,000	1,400,000
Net Long-Term Sustainable	69,000	505,000	377,000	377,000	1,580,000
Difference Between Runs					
Steady State and Long-Term Sustainable	-148,000	12,000	-443,000	-332,000	180,000

[1]Sum of last column Table 8A (groundwater yield) plus downstream direct flow from STR package reduced for net baseflow gain (surface water yield).

MODEL

TABLE 9. HISTORICAL GROUNDWATER NET BUDGET COMPONENTS (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
Pre-Development	-110,174	-566,987	-14,270	-1,227	692,658	0
1940	-134,120	-530,752	-13,392	236,186	443,325	0
1941	-163,754	-451,516	-14,335	-627,610	1,257,566	0
1942	-240,219	-495,411	-17,945	-270,649	1,023,827	0
1943	-148,391	-683,365	-14,916	629,516	216,476	0
1944	-246,487	-414,648	-18,221	-988,744	1,669,444	0
1945	-265,151	-586,333	-19,093	312,281	558,911	-367
1946	-108,555	-636,311	-15,087	424,650	335,432	-1,166
1947	-161,207	-549,573	-15,942	227,258	505,679	-5,477
1948	-190,248	-509,125	-19,444	-747,015	1,472,523	-7,189
1949	-246,843	-550,232	-21,387	-232,406	1,058,565	-7,806
1950	-209,453	-594,756	-18,558	-504,925	1,332,476	-5,891
1951	-362,931	-427,069	-23,917	-1,017,450	1,838,040	-6,576
1952	-279,013	-767,284	-19,682	862,079	226,499	-22,628
1953	-133,632	-642,487	-14,831	625,906	198,340	-32,333
1954	-113,281	-676,618	-12,509	627,930	227,489	-53,814
1955	-87,579	-549,981	-12,610	125,456	619,956	-95,522
1956	-91,081	-650,834	-10,201	808,344	138,874	-194,085
1957	-108,568	-373,210	-17,770	-1,186,167	1,813,459	-126,066
1958	-230,229	-484,928	-20,226	-447,689	1,289,647	-106,427
1959	-180,403	-575,048	-18,546	307,130	625,918	-159,295
1960	-154,424	-527,935	-17,292	547,431	331,795	-178,640
1961	-125,367	-458,123	-16,568	59,244	666,838	-126,160
1962	-184,620	-519,301	-17,139	-238,397	1,072,267	-114,155
1963	-109,565	-638,590	-14,904	382,284	538,099	-158,355
1964	-69,572	-595,183	-13,304	543,411	380,307	-245,485
1965	-111,847	-483,971	-16,176	-353,264	1,114,421	-149,668
1966	-90,265	-645,166	-12,969	785,769	214,153	-251,684
1967	-58,190	-509,377	-14,316	-136,062	934,921	-217,482
1968	-38,537	-556,258	-13,870	451,170	541,400	-385,380
1969	-101,768	-424,612	-14,911	-34,350	881,315	-306,183
1970	-52,716	-581,081	-13,416	819,158	289,781	-463,172
1971	-5,492	-467,559	-12,316	351,493	625,088	-491,345
1972	-12,864	-473,805	-11,968	13,604	832,252	-348,803
1973	-179,771	-490,645	-20,623	-2,470,727	3,661,654	-500,420
1974	-277,010	-683,155	-21,472	1,171,283	480,042	-670,982
1975	-179,645	-563,513	-19,402	813,684	873,562	-923,741
1976	-128,844	-578,512	-17,835	791,010	1,076,104	-1,142,110
1977	-131,164	-406,552	-22,535	27,331	1,411,871	-878,333
1978	-117,058	-541,562	-20,839	1,203,987	885,887	-1,410,013

MODEL

TABLE 9. HISTORICAL GROUNDWATER NET BUDGET COMPONENTS (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
1979	-61,083	-439,793	-19,830	594,265	1,048,575	-1,122,245
1980	-33,852	-502,512	-18,709	1,723,284	327,417	-1,493,836
1981	-29,385	-383,745	-17,960	-407,596	1,610,279	-772,237
1982	-120,624	-452,894	-20,661	603,568	794,512	-802,815
1983	-41,047	-384,200	-18,422	1,338,696	528,737	-1,421,516
1984	80,036	-428,056	-16,988	1,180,373	668,738	-1,483,072
1985	93,796	-317,283	-18,539	307,712	886,467	-951,726
1986	86,302	-366,755	-19,297	118,120	971,507	-791,156
1987	45,911	-400,124	-21,851	-35,623	1,252,900	-840,196
1988	-35,763	-482,486	-17,146	1,591,684	196,301	-1,253,507
1989	-23,592	-365,023	-19,356	-808,006	1,788,559	-571,234
1990	-38,824	-402,414	-17,335	1,227,151	556,642	-1,323,228
1991	-34,195	-405,339	-12,788	1,585,626	259,683	-1,391,702
1992	33,193	-299,552	-15,442	-820,249	1,785,703	-682,174
1993	-148,179	-326,120	-22,082	-776,130	1,983,057	-709,863
1994	-101,038	-529,597	-17,567	1,558,693	312,720	-1,222,798
1995	14,326	-434,885	-21,112	-116,019	1,610,178	-1,052,111
1996	82,062	-371,527	-18,274	-701,372	1,581,079	-572,562
1997	-2,531	-353,115	-19,948	-290,572	1,431,904	-766,440
1998	73,120	-450,651	-20,239	649,553	912,459	-1,165,018
1999	83,684	-404,699	-22,623	564,702	714,079	-935,404
2000	-19,997	-431,252	-22,631	124,874	1,590,798	-1,241,511
2001	-35,457	-434,236	-20,500	985,255	704,148	-1,199,543
2002	-69,761	-389,399	-18,690	929,001	825,395	-1,276,616
2003	-75,275	-353,452	-20,070	1,230,841	433,718	-1,214,467
2004	-41,128	-303,572	-20,981	277,080	940,238	-851,067
2005	-77,539	-362,297	-21,844	684,282	765,354	-987,810
2006	4,895	-377,512	-18,114	721,602	727,884	-1,059,249
2007	-123,531	-346,612	-22,376	-494,974	1,927,744	-939,882
Average (1940 to 2007)	-93,314	-482,257	-17,821	256,441	923,544	-586,496
Average (2000 to 2007)	-54,724	-374,791	-20,651	557,245	989,410	-1,096,268

MODEL

TABLE 10. HISTORICAL GROUNDWATER BUDGET COMPONENTS
ISOLATING SOURCE WATER TO WELLS (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
Pre-Development	0	0	0	0	0	0
1940	0	0	0	0	0	0
1941	0	0	0	0	0	0
1942	0	0	0	0	0	0
1943	0	0	0	0	0	0
1944	0	0	0	0	0	0
1945	-113	-9	0	421	0	-367
1946	628	390	0	1,184	0	-1,166
1947	-344	425	0	4,665	0	-5,477
1948	329	627	0	6,243	0	-7,189
1949	1,193	855	0	5,581	0	-7,806
1950	1,282	1,067	0	3,678	0	-5,891
1951	1,566	981	0	4,149	0	-6,576
1952	1,334	2,561	-11	18,583	0	-22,628
1953	2,935	3,170	-2	25,586	0	-32,333
1954	4,967	5,871	12	42,276	0	-53,814
1955	14,795	8,038	76	72,328	0	-95,522
1956	10,017	21,305	212	163,221	0	-194,085
1957	50,433	14,342	106	62,102	0	-126,066
1958	39,613	13,558	30	53,629	0	-106,427
1959	41,109	18,030	84	99,328	0	-159,295
1960	45,503	21,439	72	111,572	0	-178,640
1961	50,315	17,514	71	58,151	0	-126,160
1962	42,627	19,923	67	51,213	0	-114,155
1963	47,126	24,818	179	87,125	0	-158,355
1964	43,846	30,269	232	169,868	0	-245,485
1965	67,013	21,923	211	60,610	0	-149,668
1966	57,867	32,304	417	161,113	0	-251,684
1967	71,726	25,934	324	119,171	0	-217,482
1968	81,144	32,786	366	270,792	0	-385,380
1969	97,065	24,540	381	184,962	0	-306,183
1970	93,239	43,837	441	325,667	0	-463,172
1971	120,911	39,146	800	329,437	0	-491,345
1972	130,594	38,057	860	178,624	0	-348,803
1973	147,795	40,007	855	311,511	0	-500,420
1974	118,819	62,652	828	488,670	0	-670,982
1975	145,494	74,232	928	703,776	0	-923,741
1976	171,118	106,629	1,114	864,726	0	-1,142,110
1977	212,069	95,890	1,189	569,412	0	-878,333
1978	214,708	129,294	1,537	1,065,024	0	-1,410,013

MODEL

TABLE 10. HISTORICAL GROUNDWATER BUDGET COMPONENTS
ISOLATING SOURCE WATER TO WELLS (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
1979	252,581	122,902	1,626	744,938	0	-1,122,245
1980	255,233	156,405	1,941	1,081,697	0	-1,493,836
1981	287,571	129,061	1,906	354,018	0	-772,237
1982	262,002	131,068	2,211	407,746	0	-802,815
1983	307,253	131,172	2,434	981,112	0	-1,421,516
1984	344,169	162,767	2,905	974,396	0	-1,483,072
1985	424,827	122,256	3,164	401,519	0	-951,726
1986	407,609	136,957	3,300	243,118	0	-791,156
1987	440,083	129,745	3,335	267,438	0	-840,196
1988	253,349	184,813	3,459	812,147	0	-1,253,507
1989	328,628	152,732	3,437	88,404	0	-571,234
1990	302,772	152,479	3,661	864,959	0	-1,323,228
1991	231,610	181,392	4,198	975,093	0	-1,391,702
1992	368,321	136,072	4,198	174,828	0	-682,174
1993	383,637	112,079	4,192	210,233	0	-709,863
1994	285,825	192,921	3,646	740,013	0	-1,222,798
1995	446,084	169,206	3,740	434,067	0	-1,052,111
1996	523,385	127,919	3,785	-82,292	0	-572,562
1997	516,274	131,412	3,928	114,890	0	-766,440
1998	555,385	170,253	4,167	435,362	0	-1,165,018
1999	560,422	153,531	4,450	217,695	0	-935,404
2000	449,966	173,287	4,566	612,952	0	-1,241,511
2001	417,778	183,625	4,493	594,246	0	-1,199,543
2002	320,512	185,105	4,543	767,480	0	-1,276,616
2003	323,829	172,010	4,627	716,287	0	-1,214,467
2004	362,862	141,023	4,764	342,765	0	-851,067
2005	339,805	156,718	4,825	486,499	0	-987,810
2006	339,201	165,623	4,592	550,715	0	-1,059,249
2007	402,685	154,100	4,748	378,563	0	-939,882
Average (1940 to 2007)	188,564	79,280	1,739	317,137	0	-586,496
Average (2000 to 2007)	369,580	166,436	4,645	556,189	0	-1,096,268

MODEL

TABLE 11. FUTURE BASELINE NET BUDGET COMPONENTS (BASELINE B) (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
2008	32,894	-468,123	-21,776	330,095	1,289,127	-1,158,965
2009	115,727	-411,969	-20,981	3,997	1,009,119	-694,512
2010	-9,629	-469,551	-17,457	1,122,441	484,241	-1,111,324
2011	41,333	-360,676	-14,879	1,294,601	308,127	-1,263,575
2012	157,619	-324,199	-17,206	620,013	640,415	-1,073,696
2013	85,631	-385,193	-15,205	987,657	383,083	-1,056,130
2014	108,031	-374,130	-12,032	991,927	182,992	-896,521
2015	135,602	-319,199	-13,439	-372,496	1,419,974	-848,249
2016	98,951	-348,402	-13,644	625,751	686,134	-1,046,859
2017	49,000	-404,563	-15,626	-325,369	1,627,102	-931,051
2018	93,489	-435,711	-13,479	700,061	842,884	-1,185,480
2019	8,171	-420,312	-9,568	1,524,053	106,268	-1,208,642
2020	202,948	-285,653	-10,513	309,855	876,840	-1,089,303
2021	162,082	-313,896	-14,045	-335,251	1,458,413	-958,458
2022	53,949	-379,564	-13,116	1,116,837	530,791	-1,304,479
2023	78,258	-354,680	-11,179	487,054	803,014	-1,000,092
2024	80,852	-366,482	-11,024	454,974	634,730	-792,914
2025	89,187	-372,174	-9,479	1,201,406	281,436	-1,189,705
2026	144,501	-285,608	-11,136	-488,302	1,397,524	-756,544
2027	147,612	-399,419	-11,425	814,309	565,159	-1,114,145
2028	197,774	-365,395	-10,855	427,832	699,972	-947,588
2029	147,982	-347,082	-10,110	-51,939	1,291,509	-1,029,760
2030	204,478	-371,579	-10,469	43,379	1,064,415	-929,193
2031	90,740	-421,632	-10,418	527,970	802,410	-990,066
2032	185,422	-341,972	-7,530	994,357	273,016	-1,096,946
2033	172,167	-333,452	-7,083	507,000	527,081	-866,221
2034	137,841	-247,071	-11,834	-736,142	1,671,840	-814,758
2035	79,161	-412,629	-12,378	1,135,279	183,743	-974,077
2036	176,412	-295,747	-9,432	226,606	889,537	-986,763
2037	166,060	-350,650	-11,571	-290,906	1,347,811	-860,809
2038	114,146	-385,235	-16,119	-288,989	1,654,526	-1,079,560
2039	26,709	-353,805	-22,636	-2,147,075	3,299,501	-801,619
2040	22,405	-561,795	-19,797	397,020	695,999	-534,889
2041	29,997	-450,047	-18,826	-397,106	1,293,931	-458,876
2042	-46,481	-463,076	-17,524	972,053	576,079	-1,021,895
2043	50,536	-348,950	-18,275	-664,220	1,441,984	-459,477
2044	-36,359	-489,974	-23,802	-409,649	1,785,306	-826,479
2045	20,557	-420,634	-23,107	557,076	724,143	-857,643
2046	60,601	-474,372	-19,951	1,322,082	355,287	-1,243,874
2047	-23,175	-460,293	-22,342	-424,694	1,937,673	-1,007,532

MODEL

TABLE 11. FUTURE BASELINE NET BUDGET COMPONENTS (BASELINE B) (AFY)

Year	Stream Leakage	ET	Model Boundary	Aquifer Storage	Recharge	Well Pumping
2048	98,999	-405,334	-21,450	243,948	1,153,206	-1,067,211
2049	98,233	-441,500	-19,542	214,397	918,736	-769,307
2050	33,653	-449,588	-18,216	611,080	755,142	-931,377
2051	25,938	-437,621	-17,761	12,972	1,092,651	-674,980
2052	116,906	-483,909	-19,750	-164,242	1,291,734	-743,373
2053	69,114	-450,981	-18,437	1,058,370	391,758	-1,049,058
2054	197,620	-355,218	-18,234	106,889	861,219	-791,148
2055	82,922	-343,054	-23,878	-2,187,601	3,016,877	-546,788
2056	-26,917	-527,212	-22,552	1,390,408	352,572	-1,165,212
2057	70,861	-480,192	-20,477	570,190	932,404	-1,073,571
2058	105,936	-430,860	-18,450	497,711	807,100	-960,393
2059	131,722	-307,604	-18,988	-185,805	1,252,710	-871,283
2060	60,126	-338,987	-23,185	-1,105,669	2,169,389	-763,028
2061	-49,910	-457,646	-24,386	-234,737	1,485,141	-720,313
2062	-61,033	-520,382	-22,370	1,044,984	617,321	-1,062,119
2063	18,454	-430,228	-20,428	500,051	944,147	-1,011,300
2064	-27,244	-458,119	-19,610	394,455	859,348	-750,292
2065	-58,456	-538,785	-22,740	-399,022	1,969,615	-949,495
2066	24,543	-475,202	-20,488	314,101	1,109,200	-950,818
2067	-17,124	-490,985	-16,980	1,345,817	366,558	-1,186,161
2068	-20,981	-472,439	-12,338	1,634,347	66,931	-1,195,305
2069	72,897	-334,396	-18,961	-1,864,783	2,958,276	-812,703
2070	-18,518	-519,393	-18,141	508,014	983,838	-937,871
2071	3,443	-522,649	-15,950	1,041,041	709,073	-1,216,534
2072	84,483	-386,442	-18,496	-866,917	1,740,926	-553,012
2073	16,809	-427,665	-17,696	1,190,699	312,419	-1,072,822
2074	90,165	-407,407	-16,155	876,452	545,392	-1,087,358
2075	164,860	-395,598	-12,604	544,130	871,311	-1,170,987
Average (2008 to 2075)	72,657	-406,828	-16,464	291,983	1,008,502	-949,301

TABLE 12. SENSITIVITY OF MODEL PARAMETERS

Sensitivity Case	Percentage Change of Input[1]	Steady State						Average 68-Year Historical Model Budget Component								
		Net Streams			ET			Net Storage			Net Streams			ET		
		AFY	Percentage Change of Output[1]	Sensitivity Coefficient[1]	AFY	Percentage Change of Output[1]	Sensitivity Coefficient[1]	AFY	Percentage Change of Output[1]	Sensitivity Coefficient[1]	AFY	Percentage Change of Output[1]	Sensitivity Coefficient[1]	AFY	Percentage Change of Output[1]	Sensitivity Coefficient[1]
Standard Main Aquifer K_{xy} = 220 ft/d (Upper) and 70 ft/d (Lower) Main Aquifer K_z = 0.1 ft/d Non-Bedrock Specific Yield = 0.2 ET Extinction Depth = 10 ft Recharge (Initial = 693,000 AFY, Avg Historical = 924,000 AFY) Inflow at Garden City as Gaged (29 to 726 cfs, Avg = 145 cfs) Flow at Boundaries as Calibrated (-19 cfs)		-110174	--	--	-566987	--	--	256441	--	--	-93314	--	--	-482257	--	--
Main GMD #5 Area Aquifer K_{xy}																
x 0.50	-50%	-71988	-34.7%	0.69	-613805	8.3%	-0.17	257870	0.6%	-0.01	-53520	-42.6%	0.85	-530888	10.1%	-0.20
x 0.75	-25%	-102439	-7.0%	0.28	-578389	2.0%	-0.08	258217	0.7%	-0.03	-85312	-8.6%	0.34	-493755	2.4%	-0.10
x 1.25	25%	-118617	7.7%	0.31	-556416	-1.9%	-0.07	253689	-1.1%	-0.04	-101956	9.3%	0.37	-466483	-3.3%	-0.13
x 1.50	50%	-123321	11.9%	0.24	-548997	-3.2%	-0.06	255861	-0.2%	0.00	-109034	16.8%	0.34	-458782	-4.9%	-0.10
Main GMD #5 Area Aquifer K_z																
x 10.0	900%	-112848	2.4%	0.00	-564841	-0.4%	0.00	259829	1.3%	0.00	-95570	2.4%	0.00	-482024	0.0%	0.00
x 0.1	-90%	-110466	0.3%	0.00	-567126	0.0%	0.00	251490	-1.9%	0.02	-87067	-6.7%	0.07	-482540	0.1%	0.00
Model-Wide Specific Yield																
x 0.75	-25%	-112142	1.8%	-0.07	-565532	-0.3%	0.01	252462	-1.6%	0.06	-94897	1.7%	-0.07	-475143	-1.5%	0.06
x 1.25	25%	-112140	1.8%	0.07	-565532	-0.3%	-0.01	264718	3.2%	0.13	-94607	1.4%	0.06	-487939	1.2%	0.05
ET Extinction Depth																
x 0.75	-25%	-357431	224.4%	-8.98	-317469	-44.0%	1.76	256319	0.0%	0.00	-300812	222.4%	-8.89	-270946	-43.8%	1.75
x 1.25	25%	25901	-123.5%	-4.94	-705743	24.5%	0.98	262694	2.4%	0.10	20033	-121.5%	-4.86	-602126	24.9%	0.99
Recharge (Recharge Package)																
x 0.75	-25%	3416	-103.1%	4.12	-513808	-9.4%	0.38	290504	13.3%	-0.53	33271	-135.7%	5.43	-417663	-13.4%	0.54
x 1.25	25%	-225268	104.5%	4.18	-619776	9.3%	0.37	233534	-8.9%	-0.36	-228222	144.6%	5.78	-547345	13.5%	0.54
Inflow at Garden City																
x 5.00	400%	NA[2]	--	--	NA	--	--	246025	-4.1%	-0.01	-73255	-21.5%	-0.05	-490306	1.7%	0.00
x 0.20	-80%	NA	--	--	NA	--	--	279572	9.0%	-0.11	-112361	20.4%	-0.26	-484776	0.5%	-0.01
Flow at Boundaries																
x 1.10	10%	NA	--	--	NA	--	--	255841	-0.2%	-0.02	-93816	0.5%	0.05	-483646	0.3%	0.03
x 0.90	-10%	NA	--	--	NA	--	--	262385	2.3%	-0.23	-94783	1.6%	-0.16	-481466	-0.2%	0.02

[1]Sensitivity Coefficient (dimensionless) is calculated as the ratio of percent change of the model output to percent change of the input parameter. The formula is [(testcase output - standardcase output) divided by the standardcase output] divided by [(test parameter value - standard parameter value) divided by the standard parameter value]. The coefficient indicates the relative importance of the tested parameter for impact on the model output. Values less than 1 are "robust" in the sense that the model change in response is proportionally smaller than the change in stress.

[2]NA means the case is not responsive for steady state conditions.

FIGURES

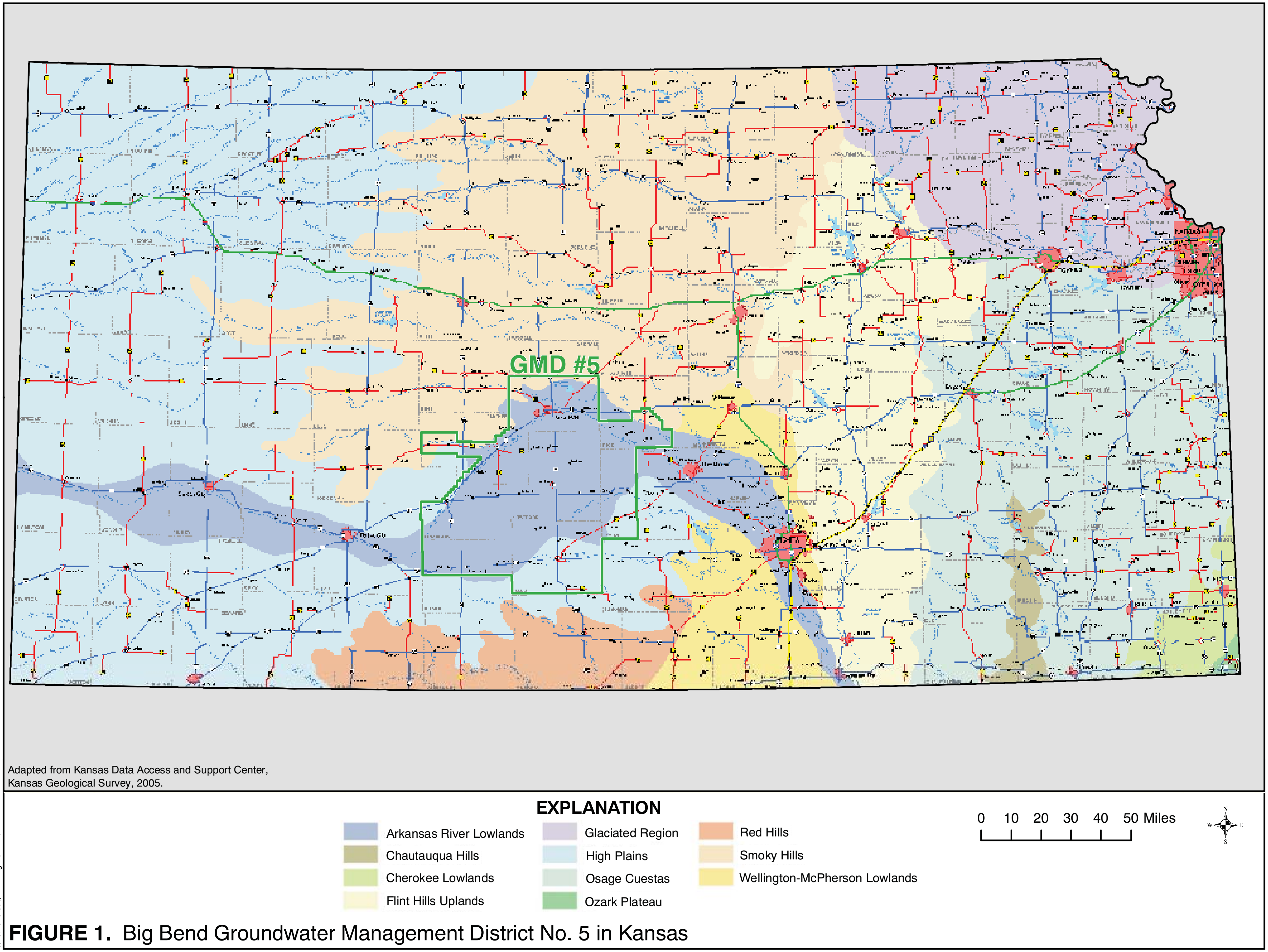
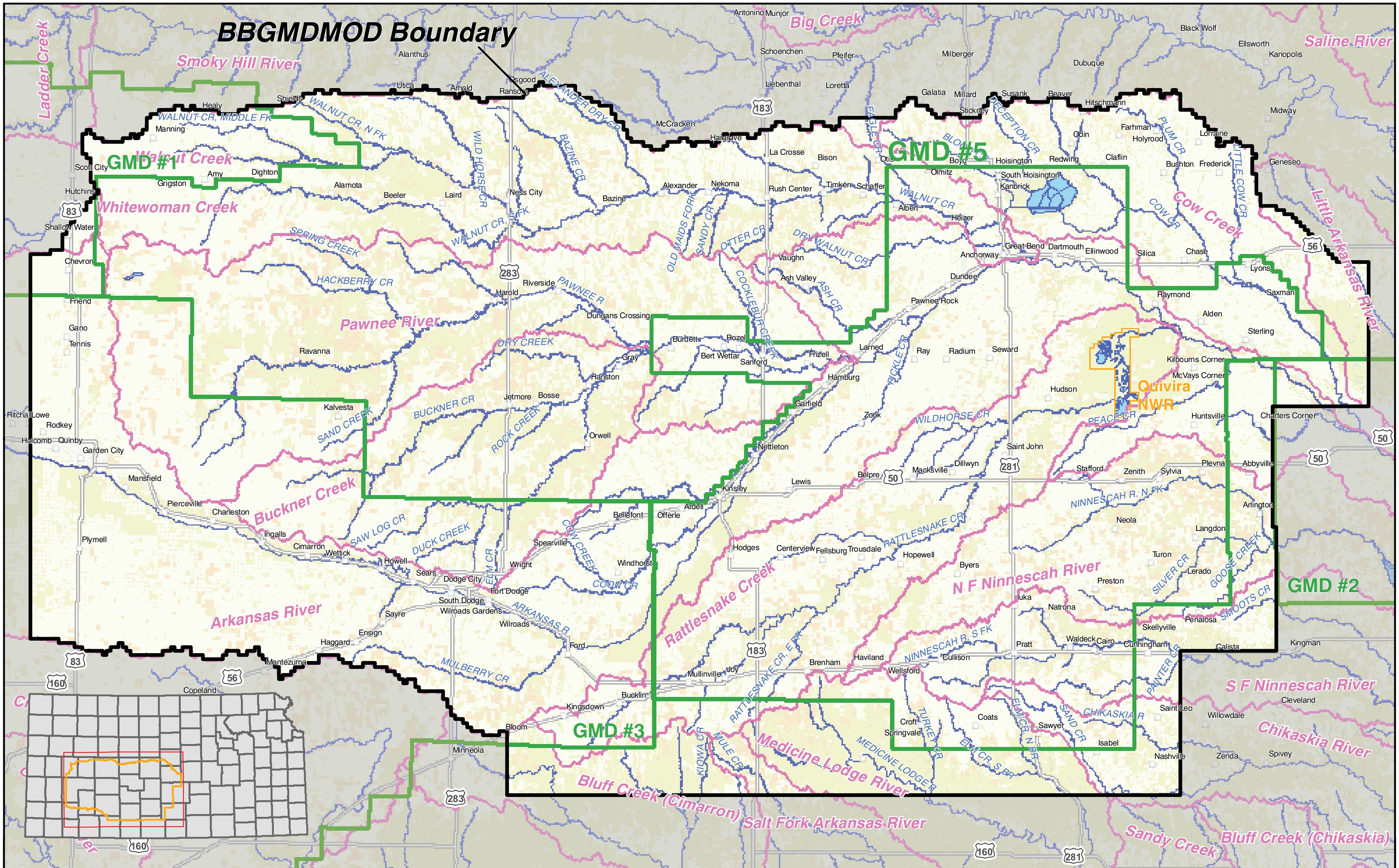
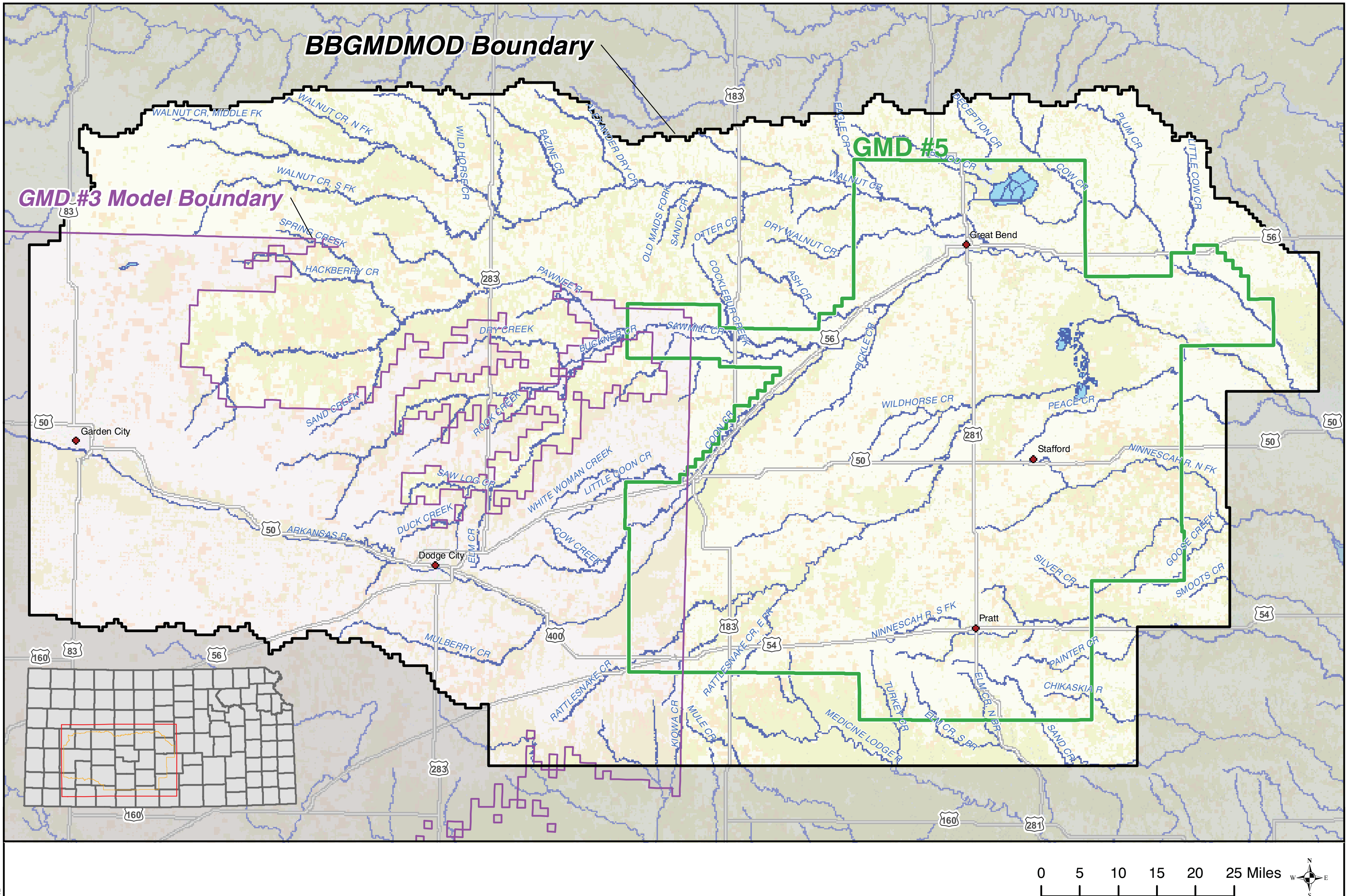


FIGURE 1. Big Bend Groundwater Management District No. 5 in Kansas



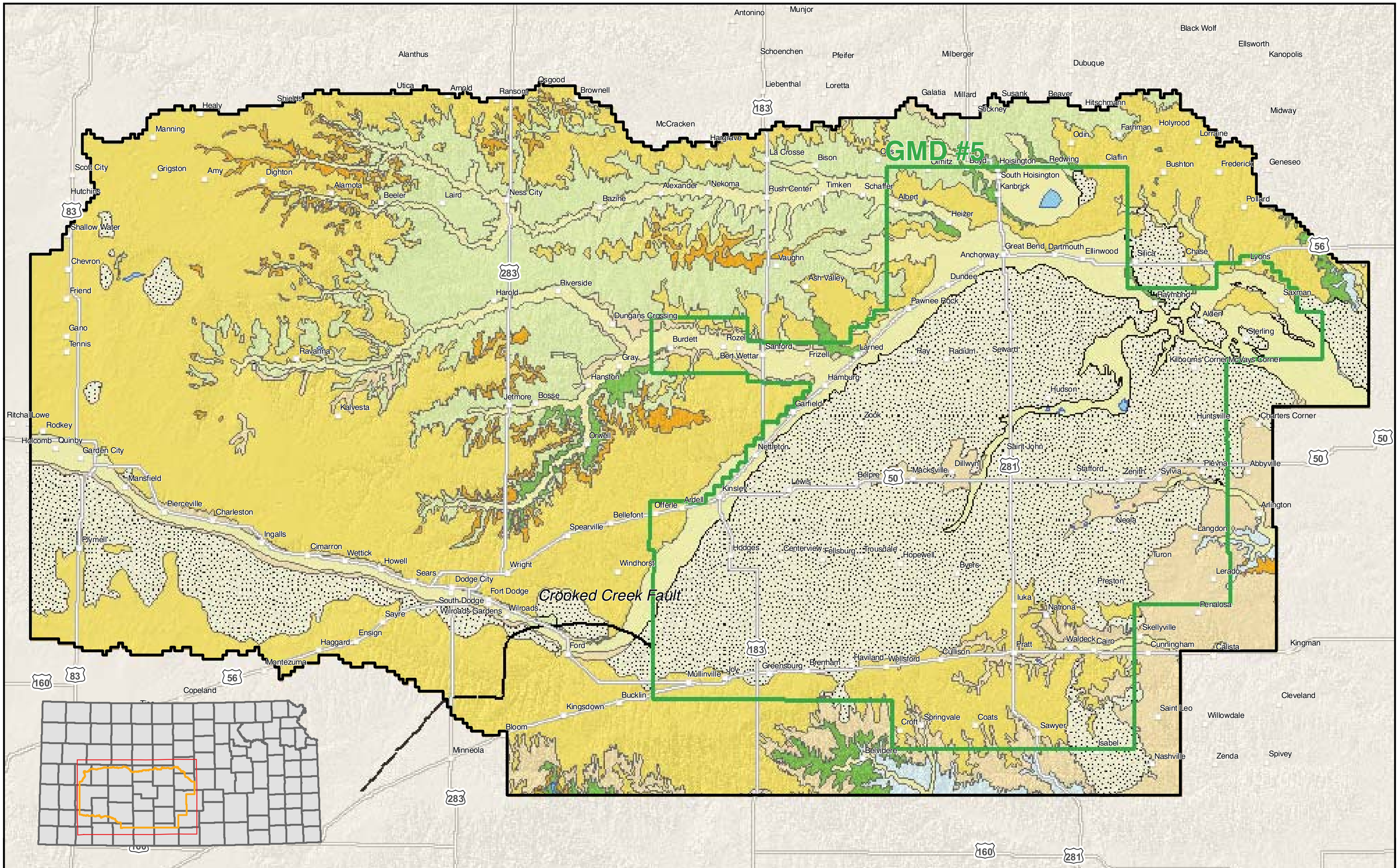
5/19/2010 ses/WPB Figure2.mxd

FIGURE 2. Locality Map



8/21/2008 ses/WPB proto2.MXD

FIGURE 3. Overlap of Concurrent Model Study Areas



EXPLANATION

- Quaternary Dune Sand
- Quaternary Loess
- Quaternary Alluvium (Post-Kansan Deposits)
- Quaternary Alluvium (Kansan and Older Deposits)
- Tertiary Ogallala
- Cretaceous Shales
- Cretaceous Dakota Group
- Permian

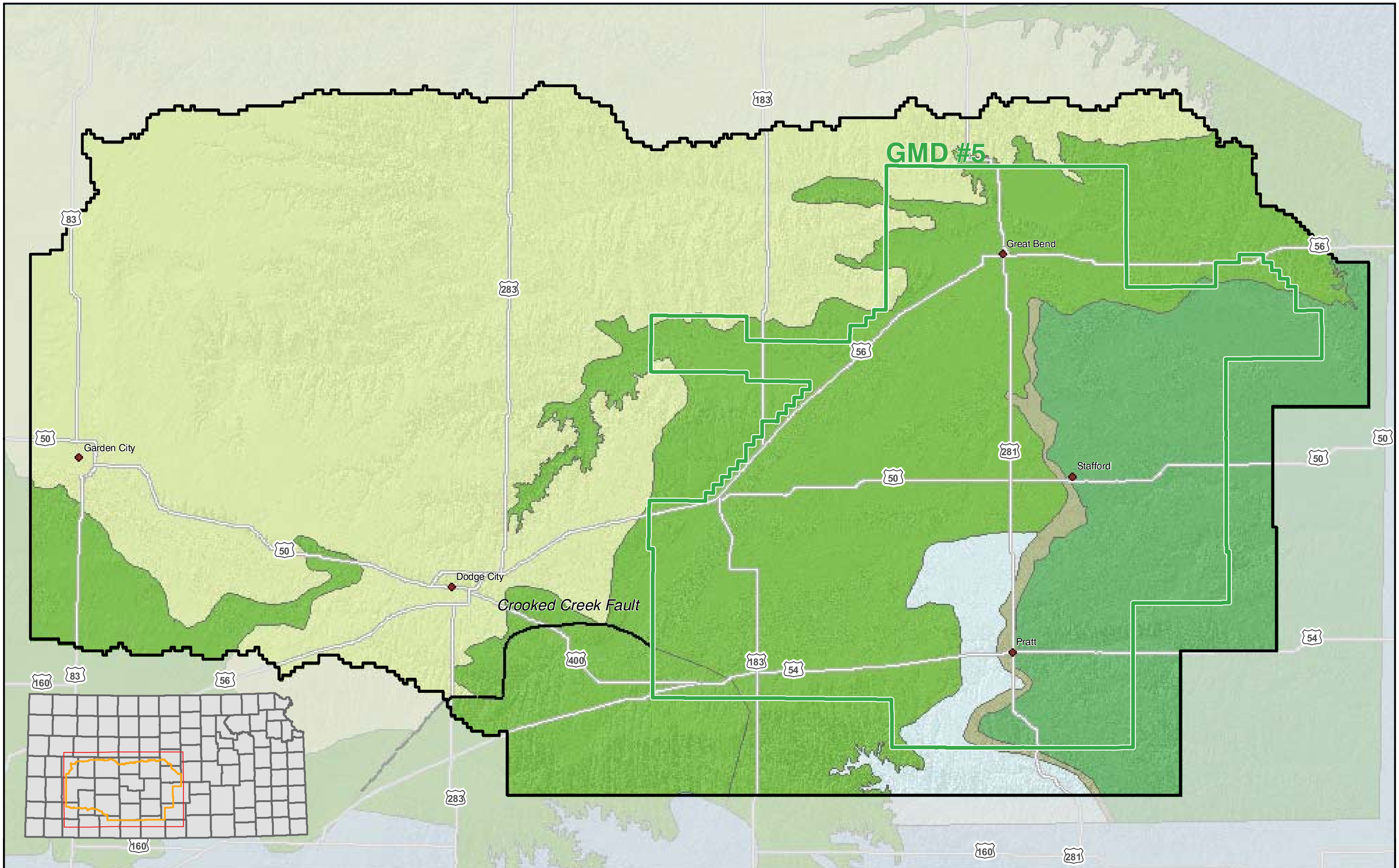
0 5 10 15 20 25 Miles

N W E S

5/19/2010 ses/WPB Figure4.mxd

FIGURE 4. Generalized Surficial Geology

Adapted from Kansas Geological Survey, 1992, Geology - Generalized Surficial, http://www.KansasGIS.org.



EXPLANATION

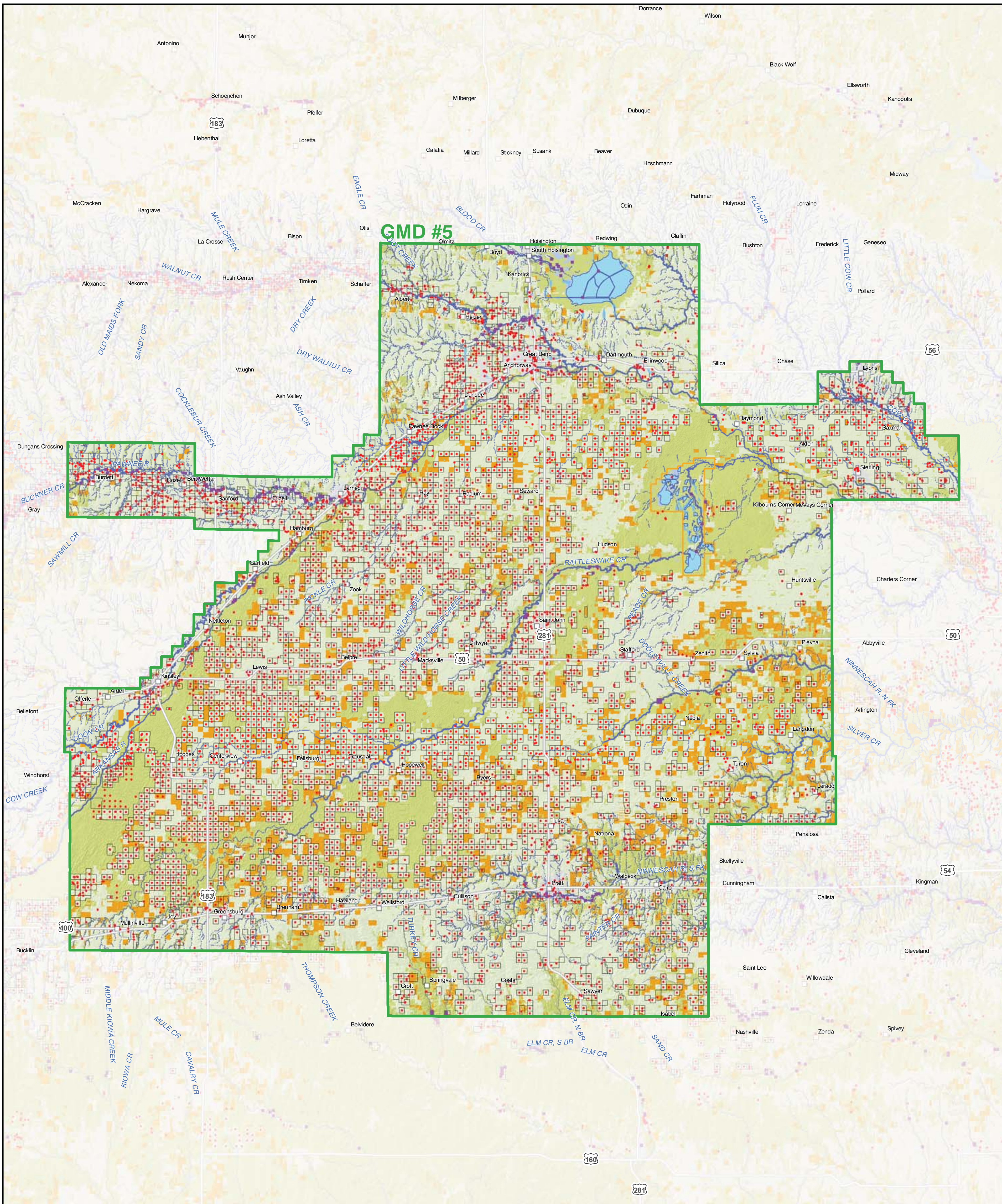
- Cretaceous Shales
- Cretaceous Dakota Group
- Permian Undivided
- Permian Cedar Hills
- Permian Harper-Salt Plain

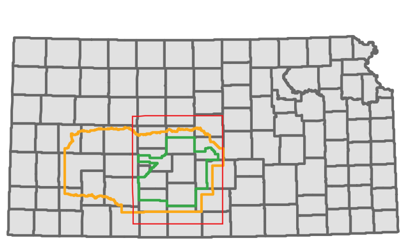
0 5 10 15 20 25 Miles

Adapted from: Fader and Stulken (1978) and Kansas Geological Survey Open-File Report 90-27

5/19/2010 ses/WPB Figure5.mxd

FIGURE 5. Generalized Bedrock Geology





EXPLANATION

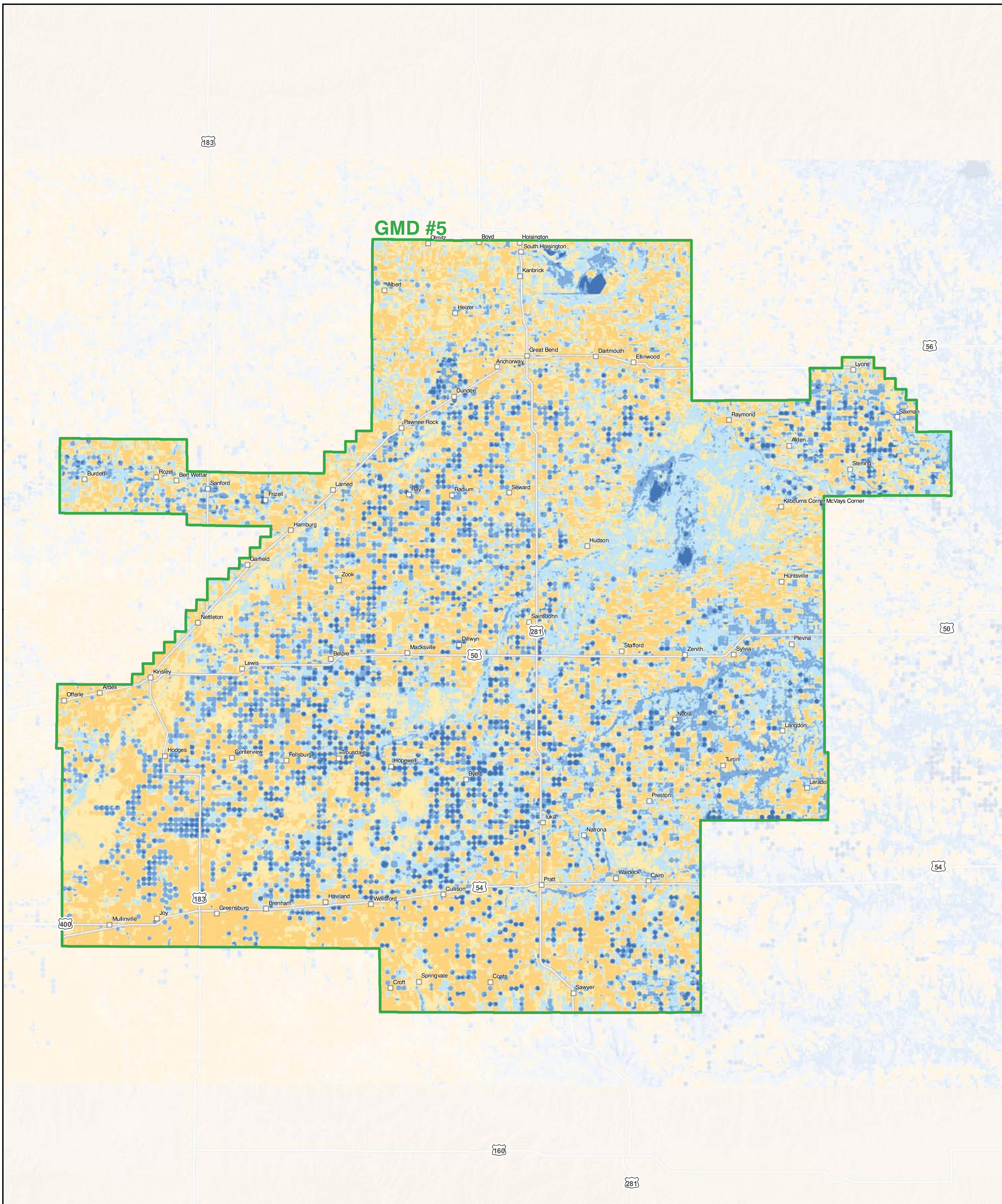
- Surface Water POD site and POU
- Groundwater POD sites and POU
- Canal
- Intermittent/Ephemeral Stream
- Perennial Stream
- Conservation Reserve Program Land
- Cropland (60%)
- Grassland (32%)
- Woodland (1%)
- Water (2%)
- Towns (5%)

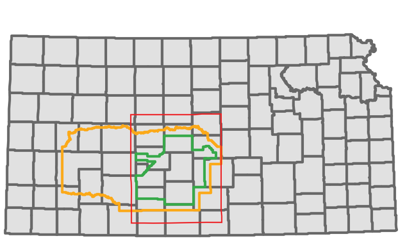
Note:
55 Surface Water POD Sites
4866 Groundwater POD Sites

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure6.mxd

FIGURE 6. Big Bend Groundwater Management District No. 5 Water Features





EXPLANATION

Percent of Reference Crop
Alfalfa Evaporative Loss
(LANDSAT 5 July 19, 2004)

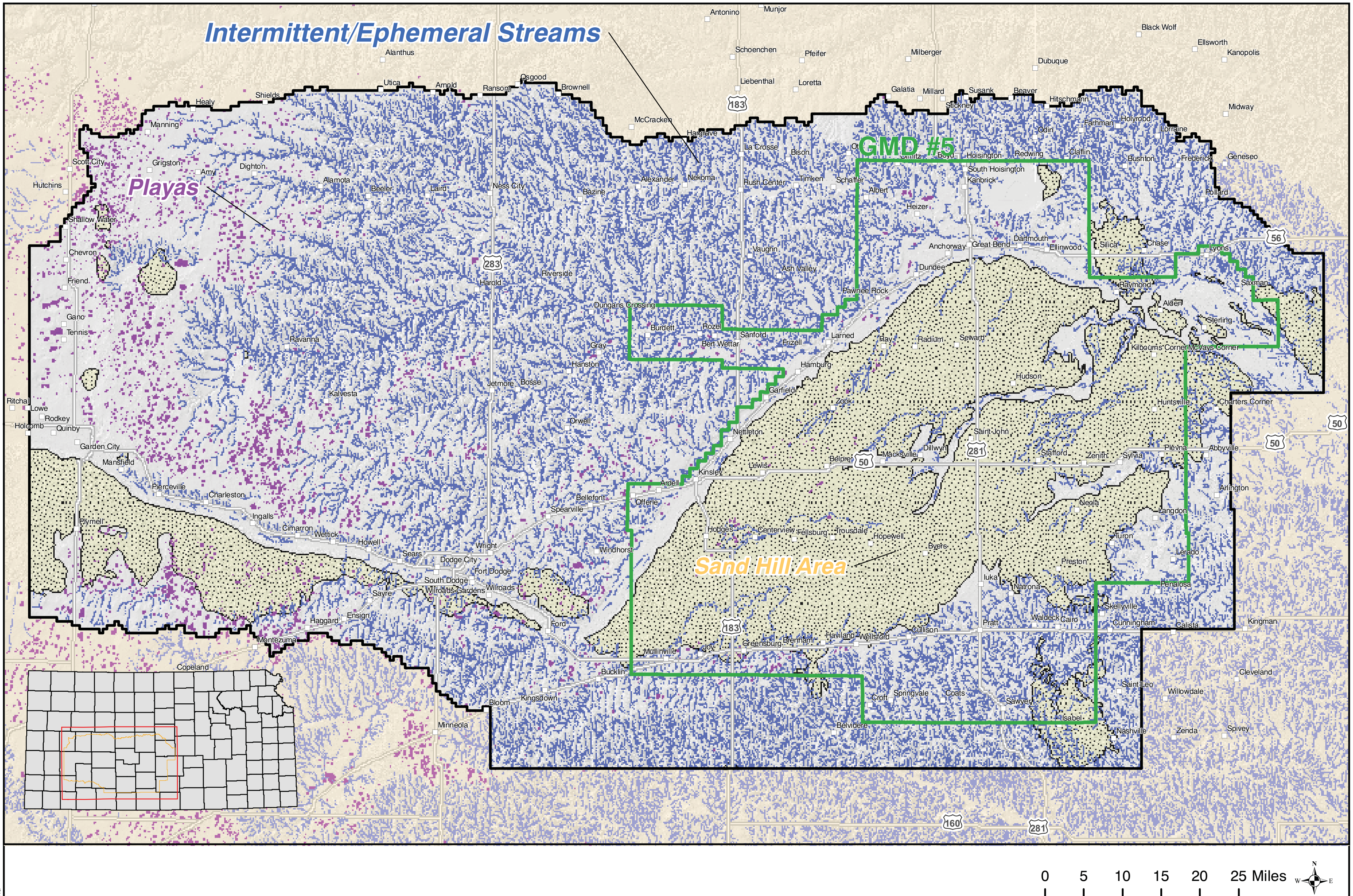
■	80 - 105
■	60 - 80
■	40 - 60
■	20 - 40
■	0 - 20

Total Approximately 1400 cfs
(at 9.6 mm/day reference rate)

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure7.mxd

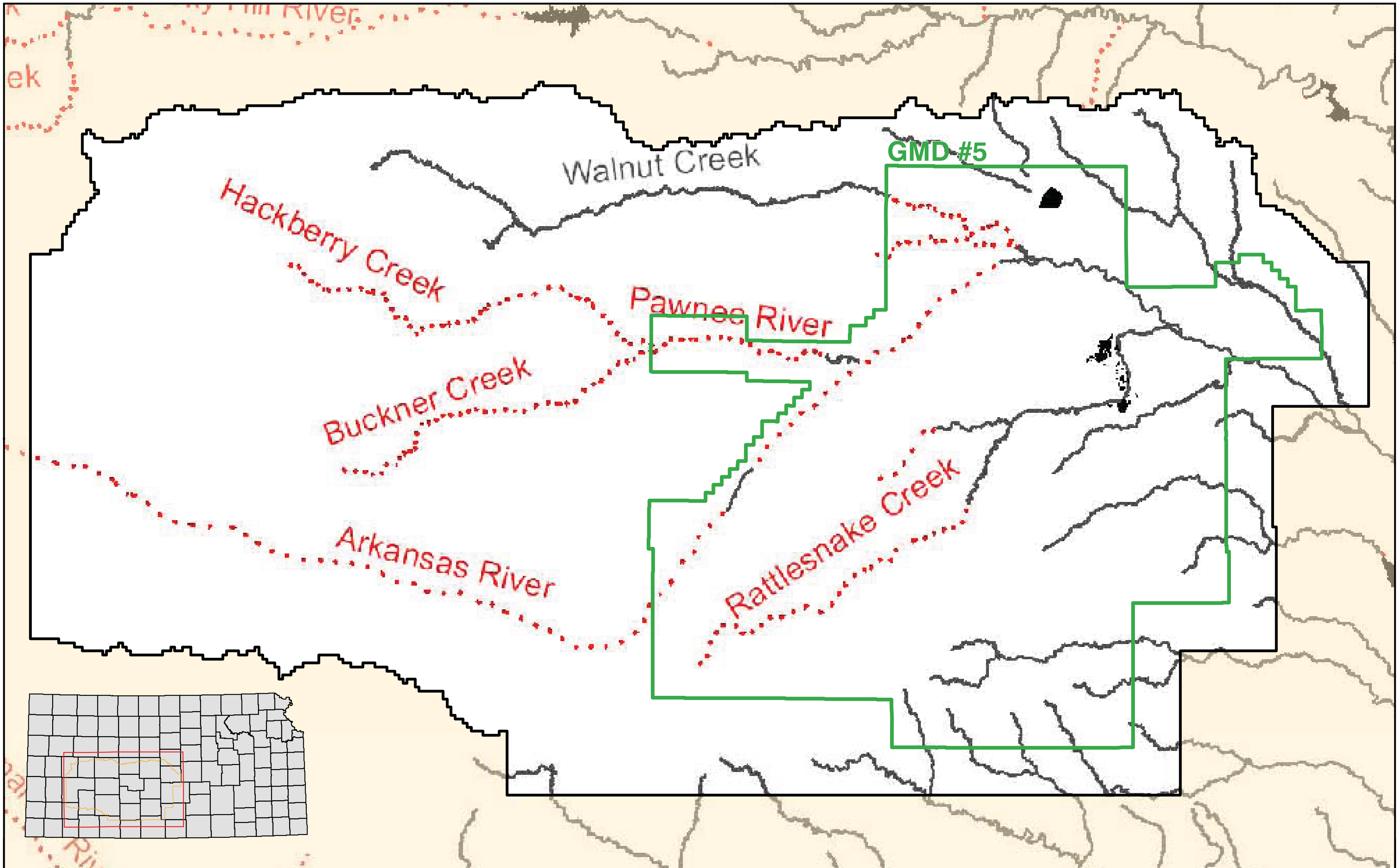
FIGURE 7. Strength of Evaporative Loss



5/19/2010 ses/WPB Figure8.mxd

FIGURE 8. Streams, Playas and Sand Hill Areas

Adapted from Kansas Geological Survey, 1992, Geology - Generalized Surficial, http://www.KansasGIS.org, Kansas Playa Wetlands from http://www.KansasGIS.org and the USGS National Hydrography Dataset



Adapted from Kansas Department of Agriculture Administrative Services, GIS.
Stream data provided by the Kansas Department of Health and Environment.
1961 coverage (USGS: special surveys)
2009 coverage (KDHE: long-term observations)

EXPLANATION

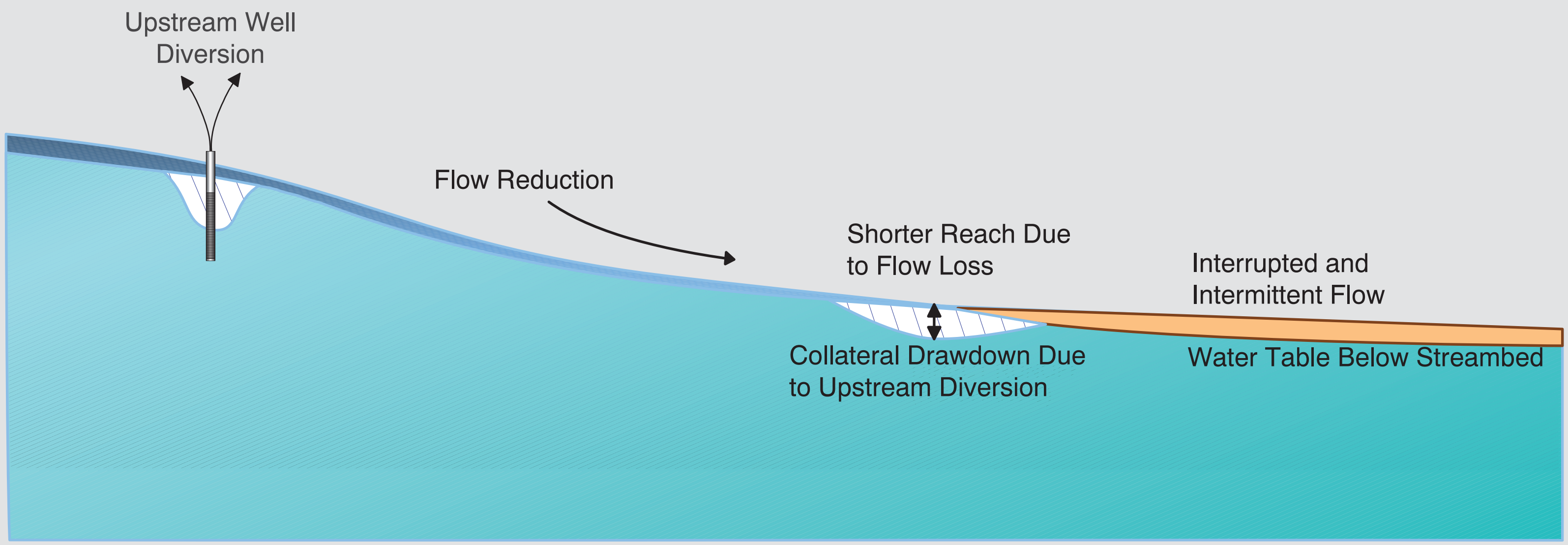
Streams Regarded as Perennial in 1961 but as Nonperennial in 2009

Streams Regarded as Perennial in Both 1961 and 2009

0 5 10 15 20 25 Miles

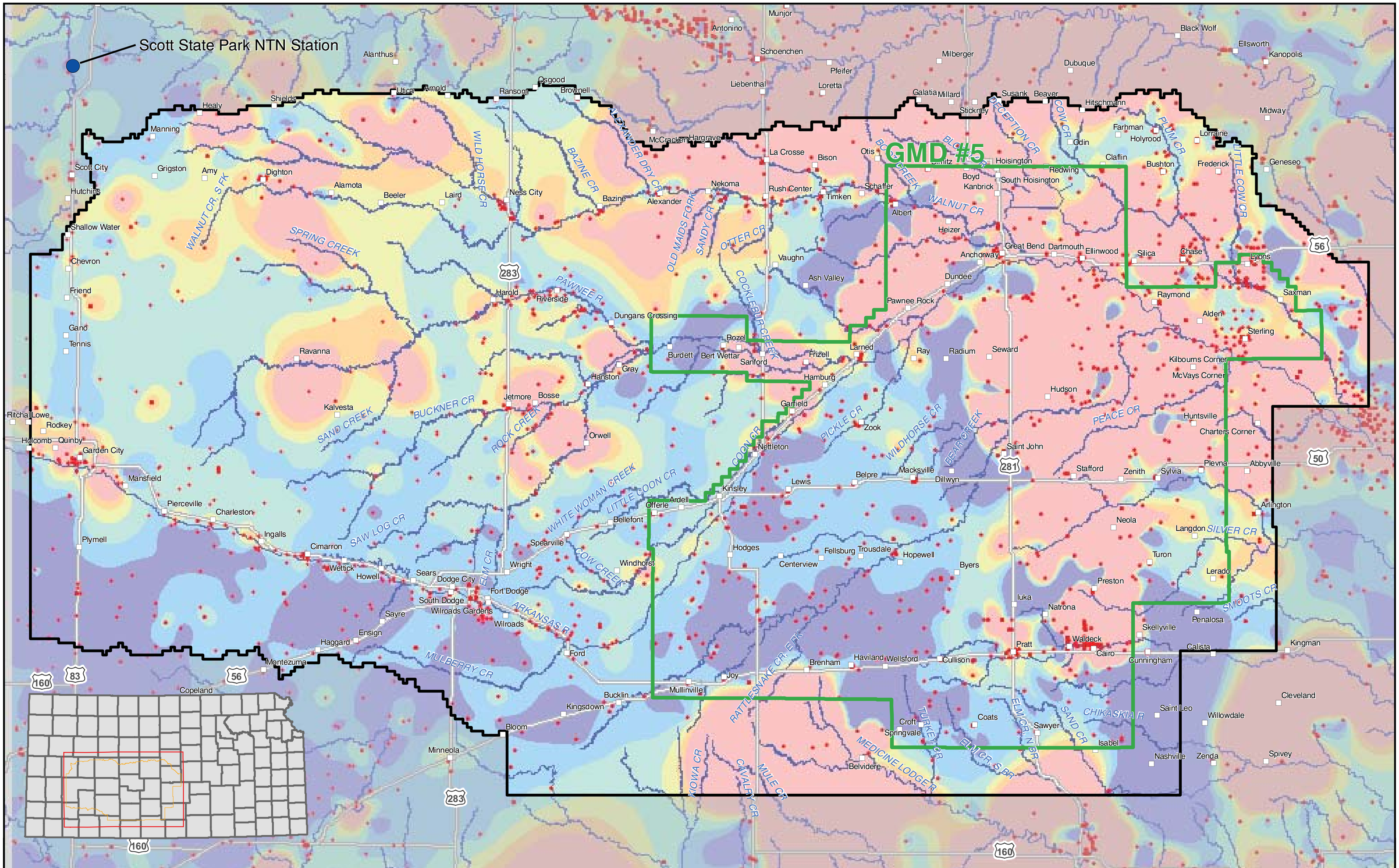
5/18/2010 ses/WPB Figure9.mxd

FIGURE 9. Extent of Perennial Reaches, Early and Late



5/19/2010 SES Figure10.dsf

FIGURE 10. Schematic of Collateral Drawdown



EXPLANATION

- Chloride Data Well Location (Adapted from USGS NWIS groundwater quality data)

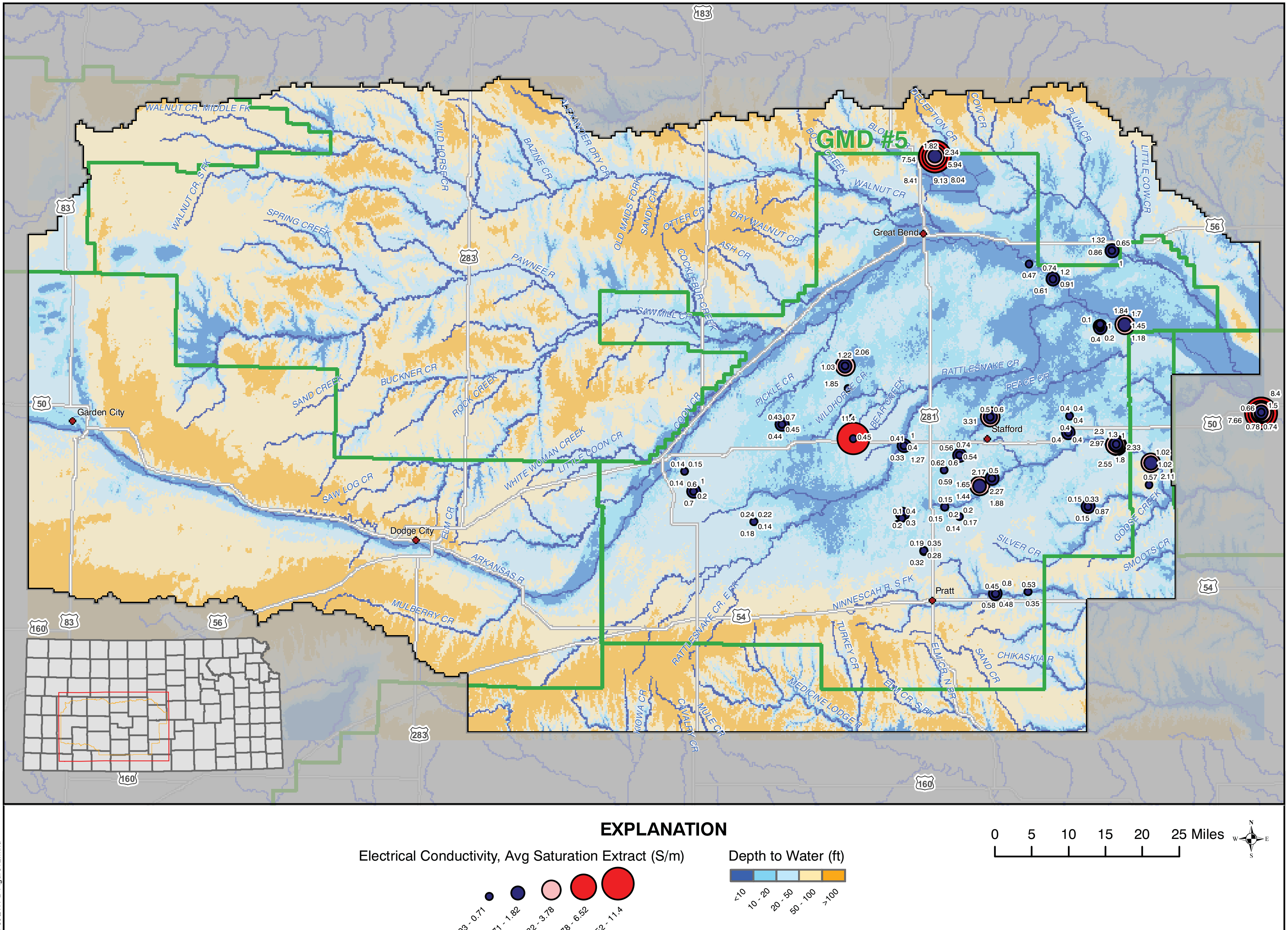
Contours of Chloride Concentration in Wells (mg/L)

< 10 | 10 - 25 | 25 - 50 | 50 - 100 | > 100

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure11.mxd

FIGURE 11. Chloride Concentration in Groundwater



5/19/2010 ses/WPB Figure12.mxd

FIGURE 12. Soil Profile Data

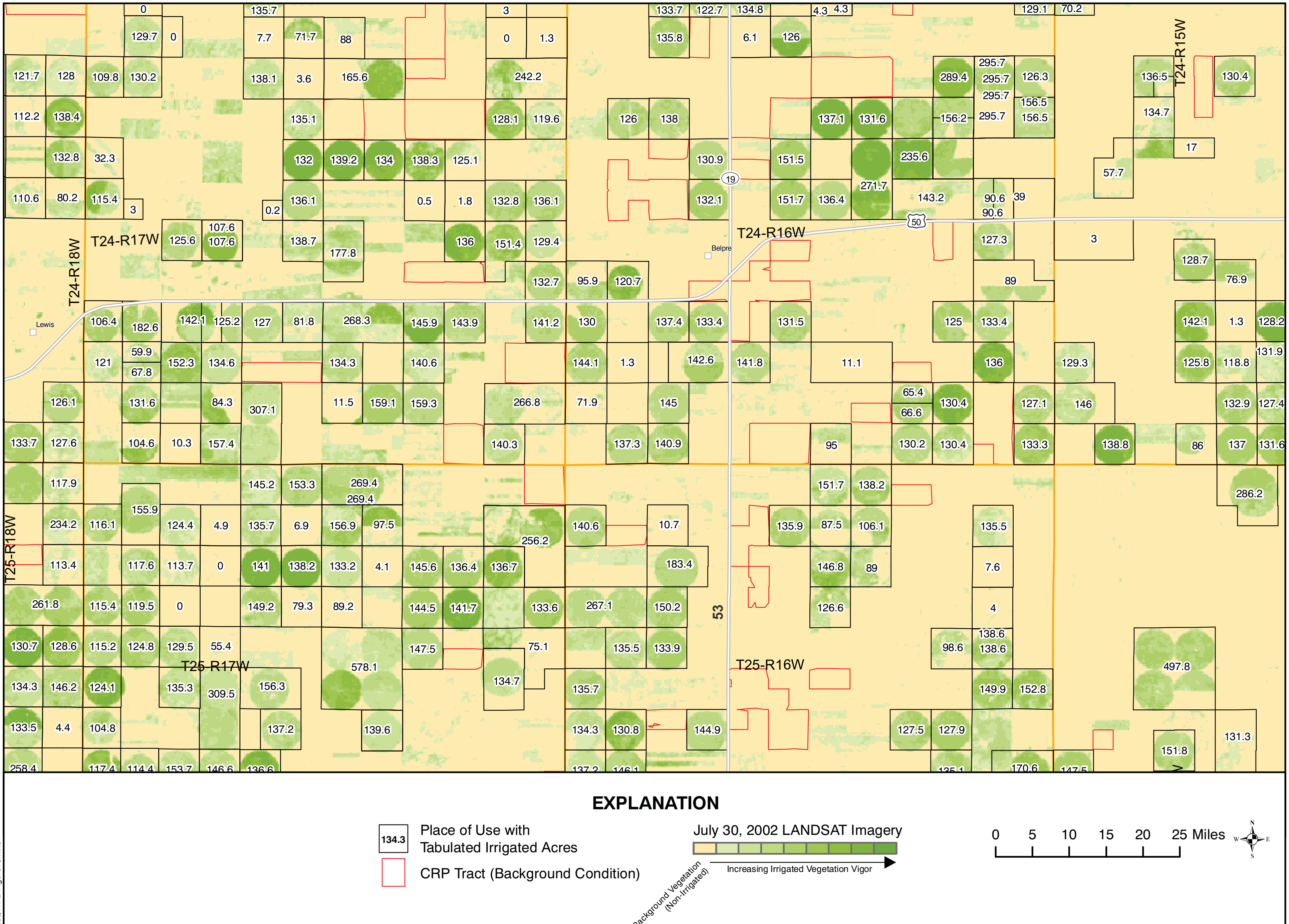
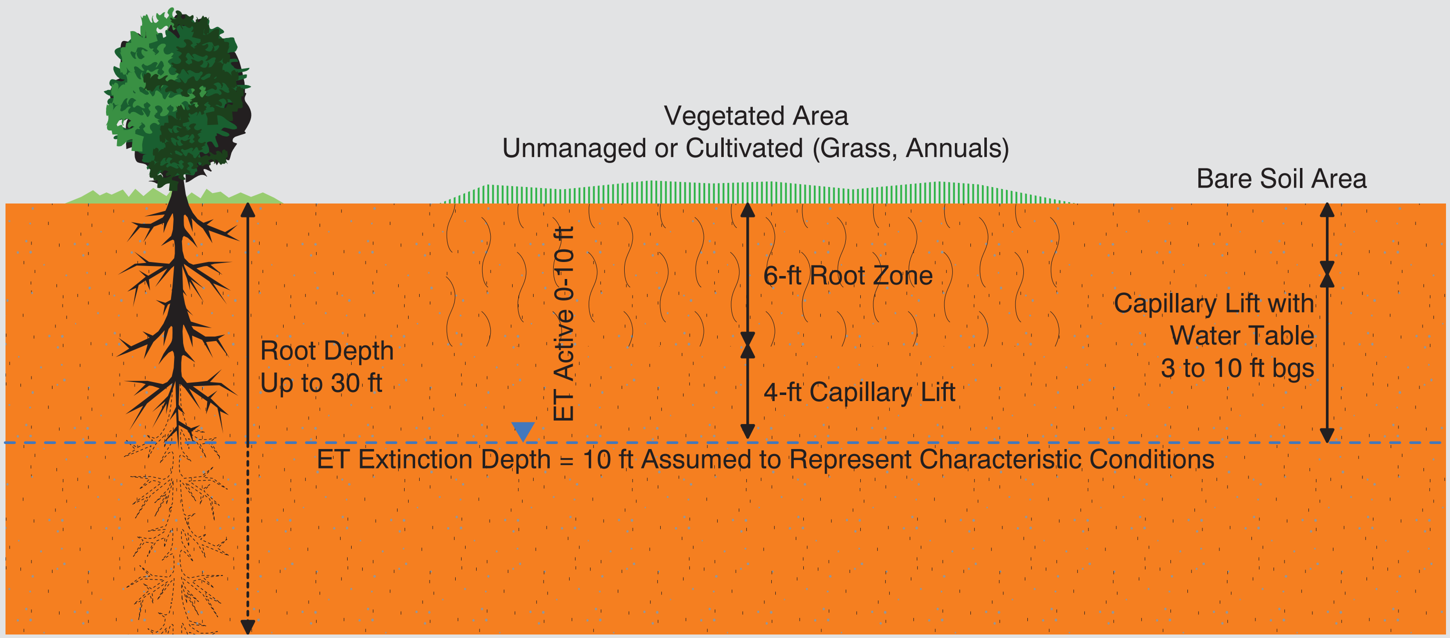


FIGURE 13. Example of LANDSAT Classified Imagery

5/19/2010 ses/WPB Figure13.mxd

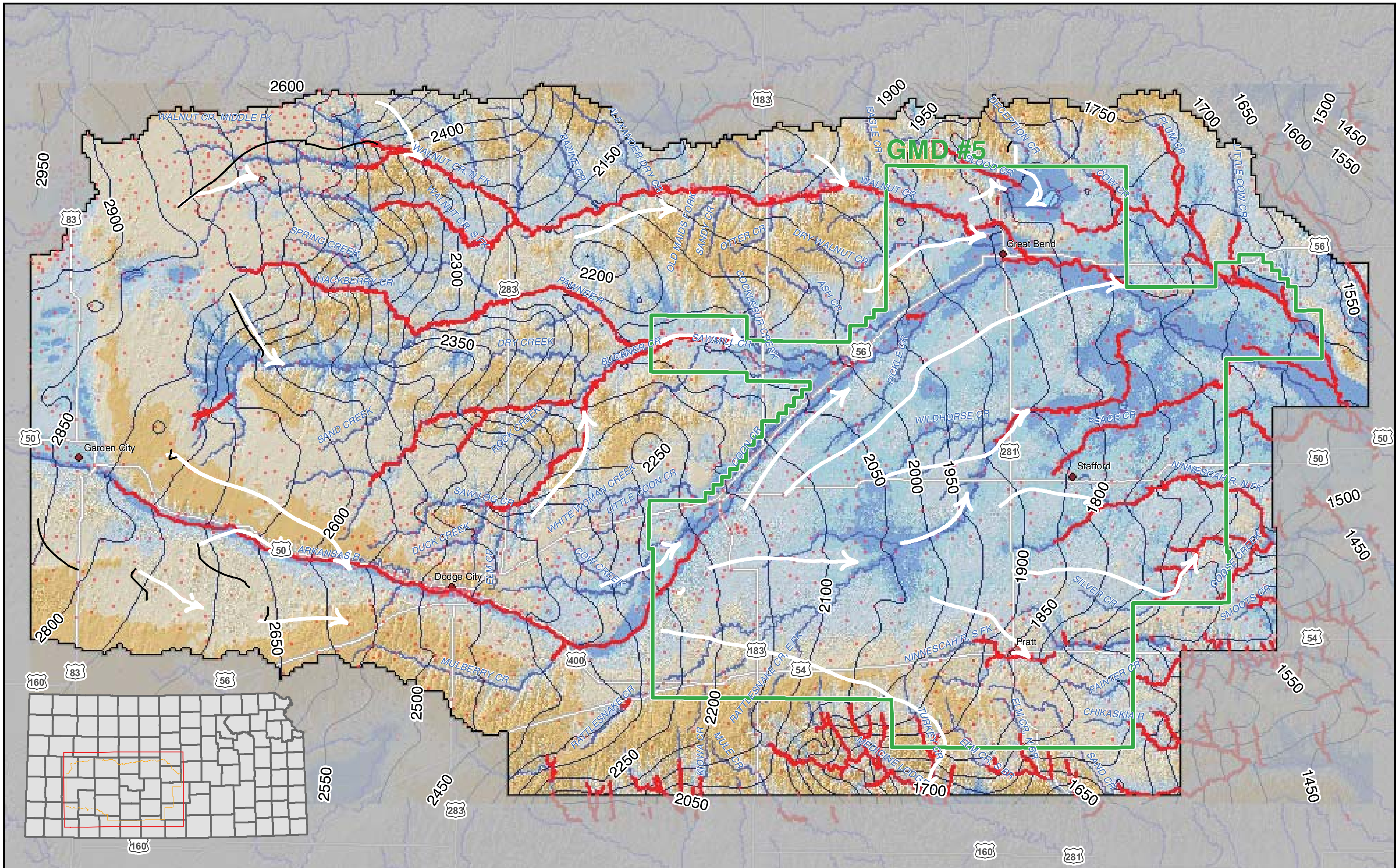


NOTES

- ET extinction depth = 10 ft with characteristic zero water table contribution to atmosphere.
- Bare soil area water table at 3 ft bgs would cause waterlogged soil to discharge to atmosphere.
- Maximum ET rate applies where surface is waterlogged.
- Riparian corridor water table at 30 ft bgs has zero contribution to atmosphere.

5/19/2010 SES Figure14.dsf

FIGURE 14. Evapotranspiration Diagram of Root Zone and Capillary Zone Extraction



EXPLANATION

Pre-Development Water-Table Contour (ft) and Generalized Flow Direction (Calculated Using 1930s through 1950s Water-Level Data)

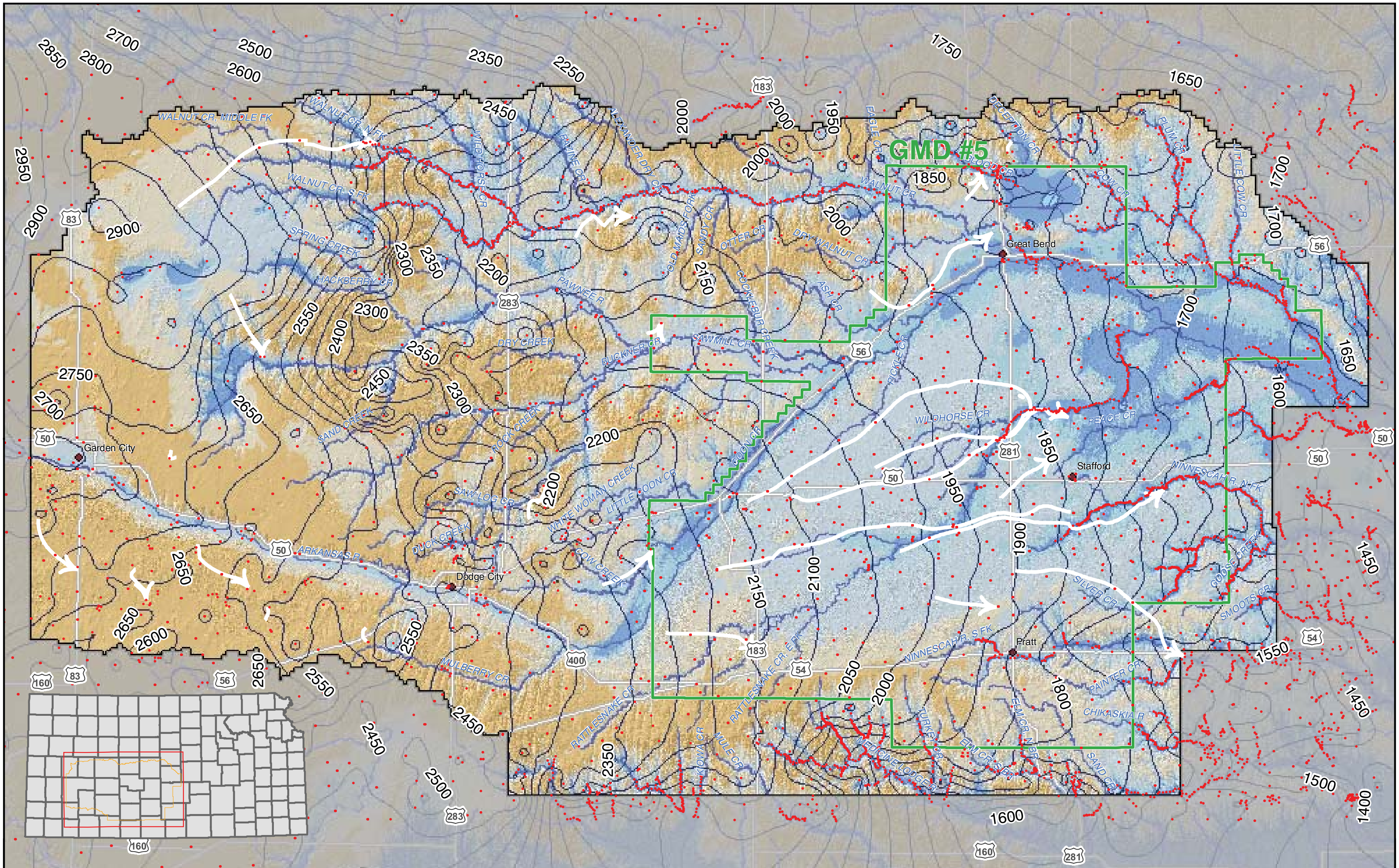
• Water Well Level and Stage Data Locations

Depth to Water (ft): <10; 10 - 20; 20 - 50; 50 - 100; >100

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure15.mxd

FIGURE 15. Pre-Development Water-Table Map and Flow Lines



EXPLANATION

1800 — 2000s Water-Table Contour (ft) and Generalized Flow Direction

• Water Well Level and Stage Data Locations

Depth to Water (ft): <10, 10 - 20, 20 - 50, 50 - 100, >100

0 5 10 15 20 25 Miles

N W E S

5/19/2010 ses/WPB Figure16.mxd

FIGURE 16. 2000s Water-Table Map and Flow Lines

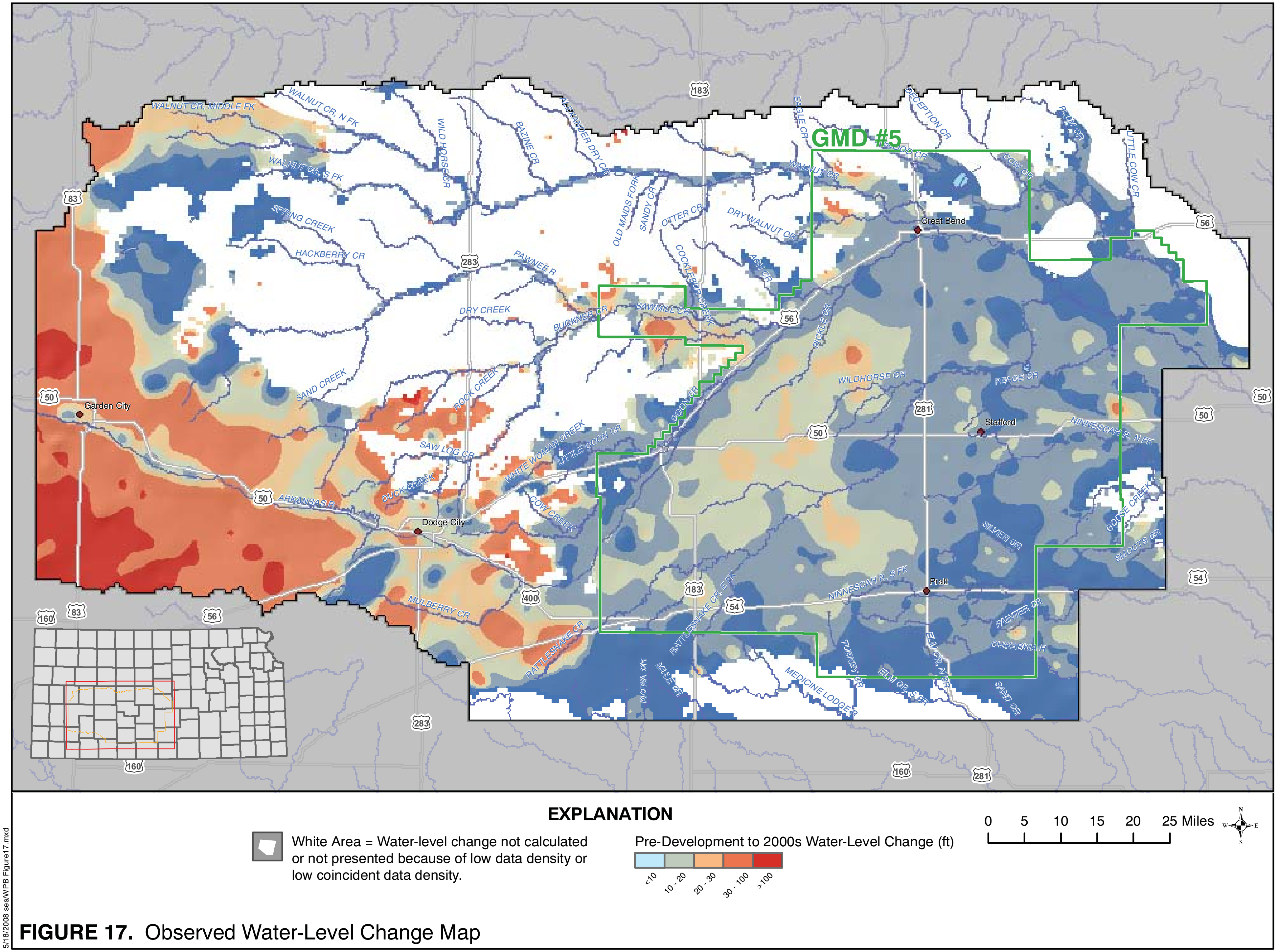
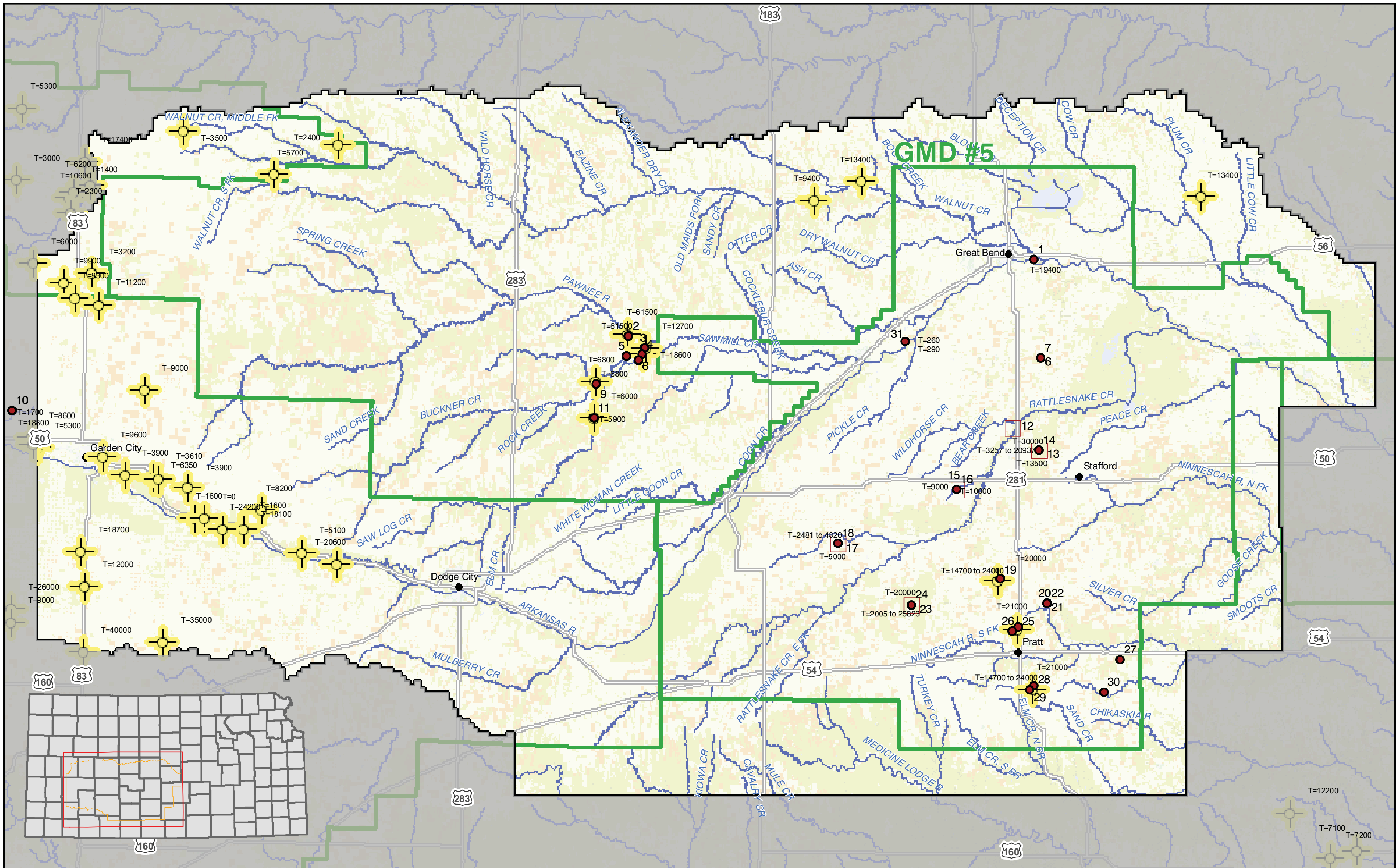


FIGURE 17. Observed Water-Level Change Map



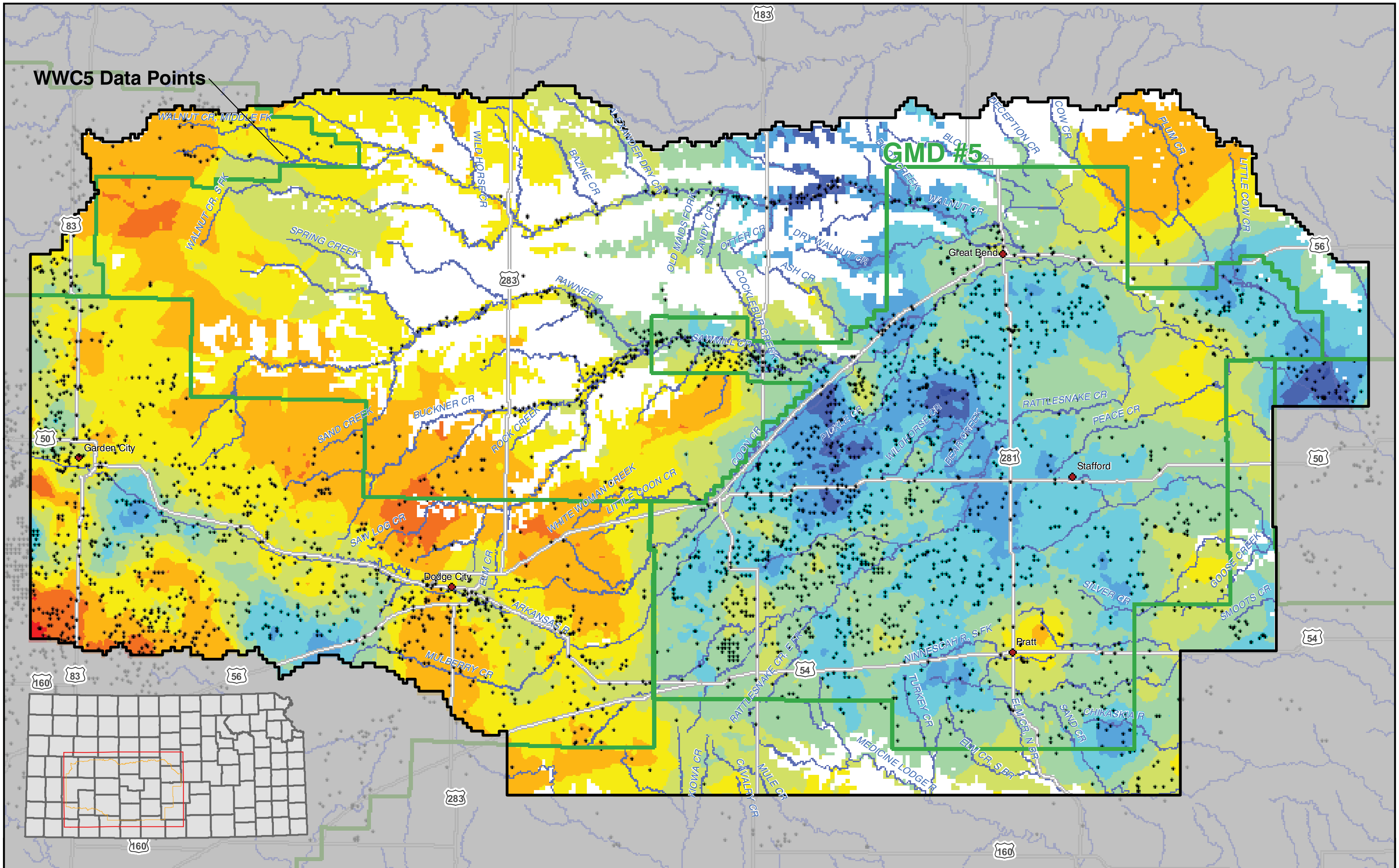
EXPLANATION

- Test site location from Stullken and others (1985), Table 9.
- 3 — Test site location with Map ID from Table 2 of this report.
- 12 — Test site location with Map ID from Table 2 of this report (analysis in Appendix F).
- T=5900 — Transmissivity (ft²/d)

0 5 10 15 20 25 Miles

FIGURE 18. Pump-Test Site Locations

5/19/2010 ses/WPB Figure18.mxd



EXPLANATION

Productivity Indicator (ft^2/d)

< 4,000; 4,000 - 6,000; 6,000 - 8,000; 8,000 - 10,000; 10,000 - 12,000; 12,000 - 14,000; 14,000 - 16,000; 16,000 - 18,000; 18,000 - 20,000; 20,000 - 22,000

Well screen and discharge information from WWC5 (http://www.kgs.ku.edu.magellan.waterwell/index.html)

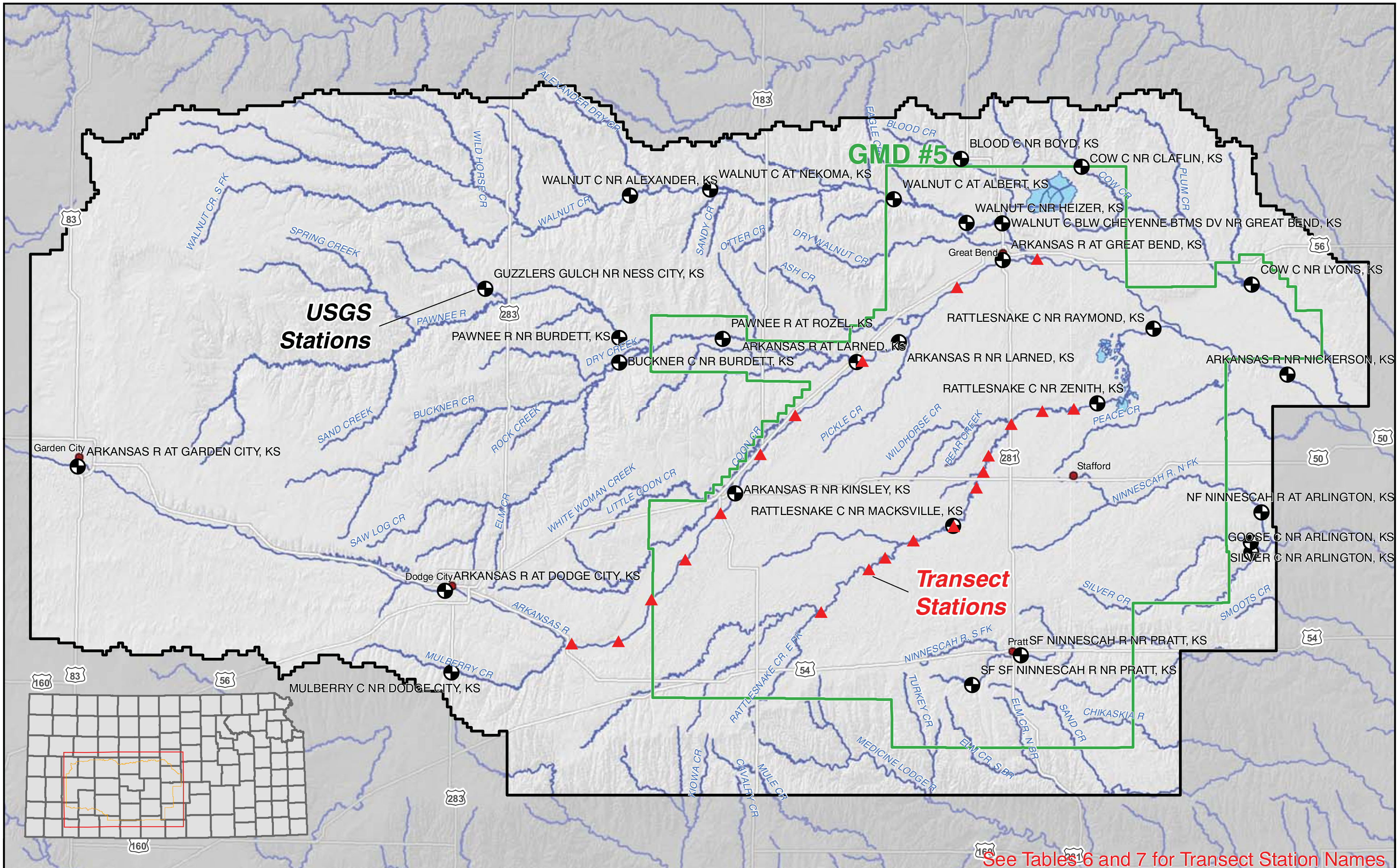
0 5 10 15 20 25 Miles

N W E S

Index of aquifer productivity = well yield in gpm per water column to center of screen depth expressed as specific capacity and converted to units of transmissivity.
Formula: (Q/s) x 270 = ft^2/d index

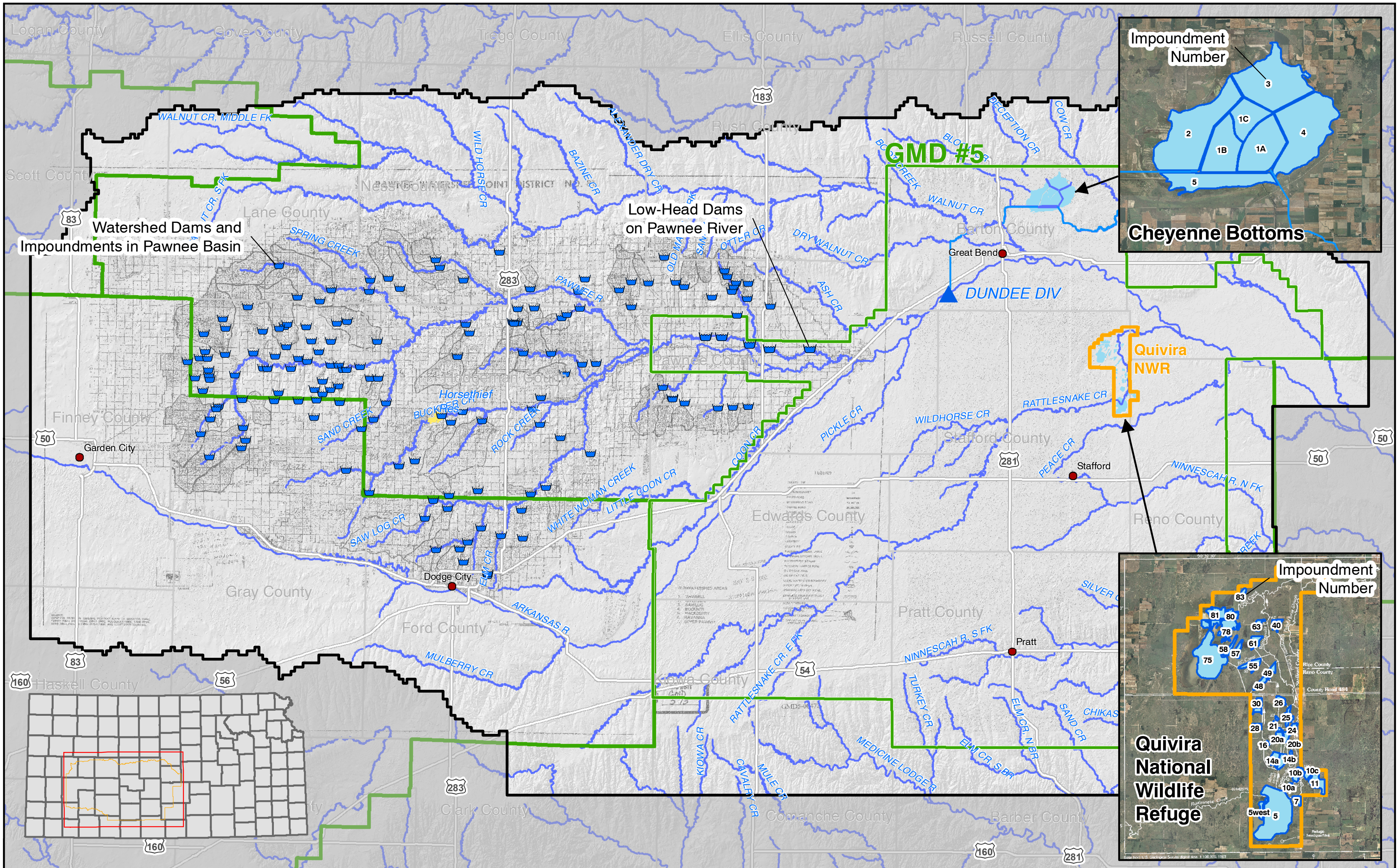
5/18/2010 ses/WPB Figure19.mxd

FIGURE 19. Aquifer Productivity



5/19/2010 ses/WPB Figure20.mxd

FIGURE 20. Stream Network and Gaging Stations

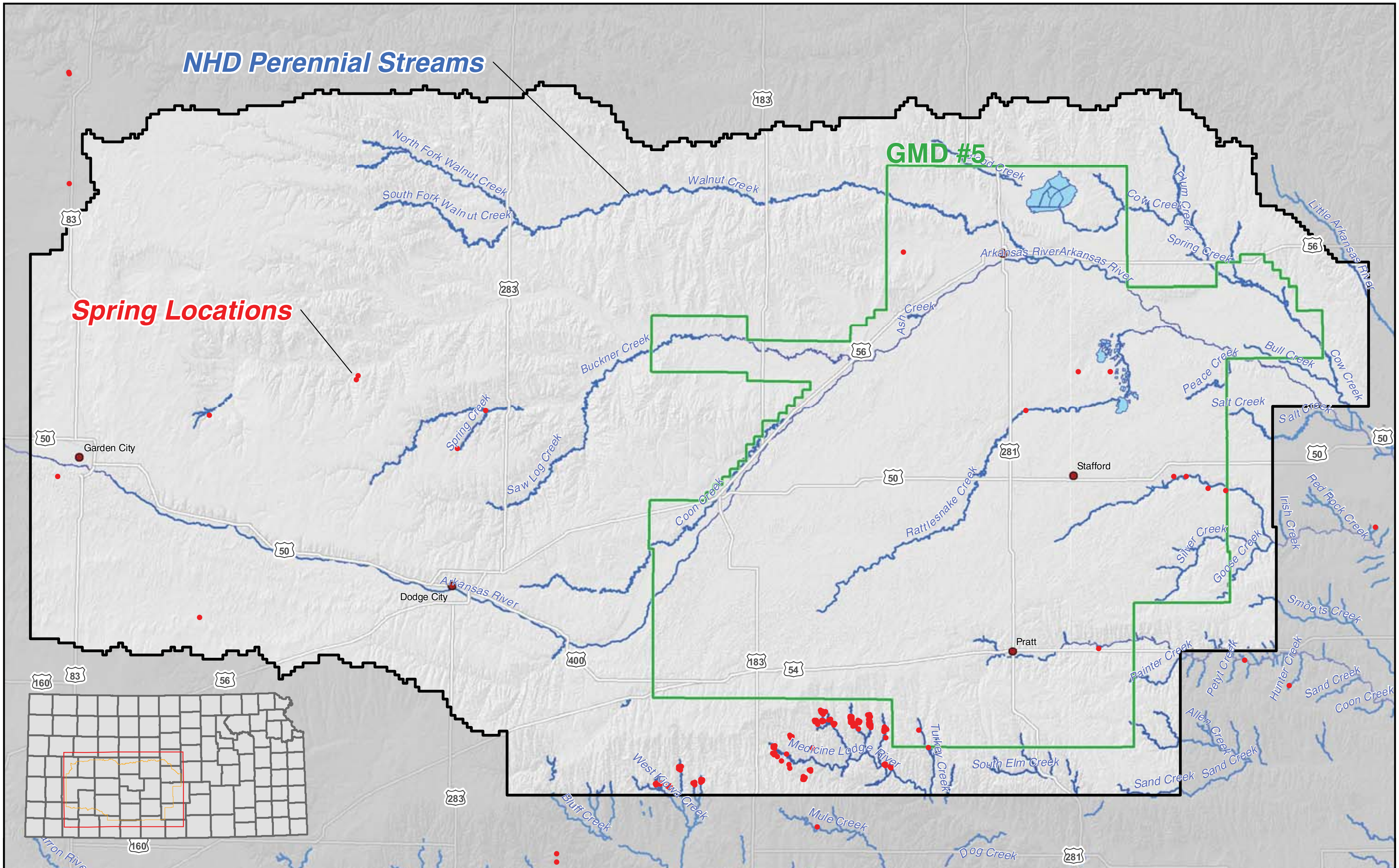


Watershed Dam Sources:
U.S. Army Corps of Engineers National Inventory of Dams https://nid.usace.army.mil.
Kansas Department of Agriculture Division of Water Resources.

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure21.mxd

FIGURE 21. Dams and Impoundments at Cheyenne Bottoms, Quivira National Wildlife Refuge, Low-Head Dams, Horsethief, and Watershed Dams



Sources:
U.S. Geological Survey, 2005, National Hydrography Dataset: http://nhd.usgs.gov, files "NHDH1108.mdb" and "NHDH1102.mdb", last process date 6/22/2005.
Kansas Department of Agriculture Division of Water Resources.

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure22.mxd

FIGURE 22. Perennial Streams and Spring Locations

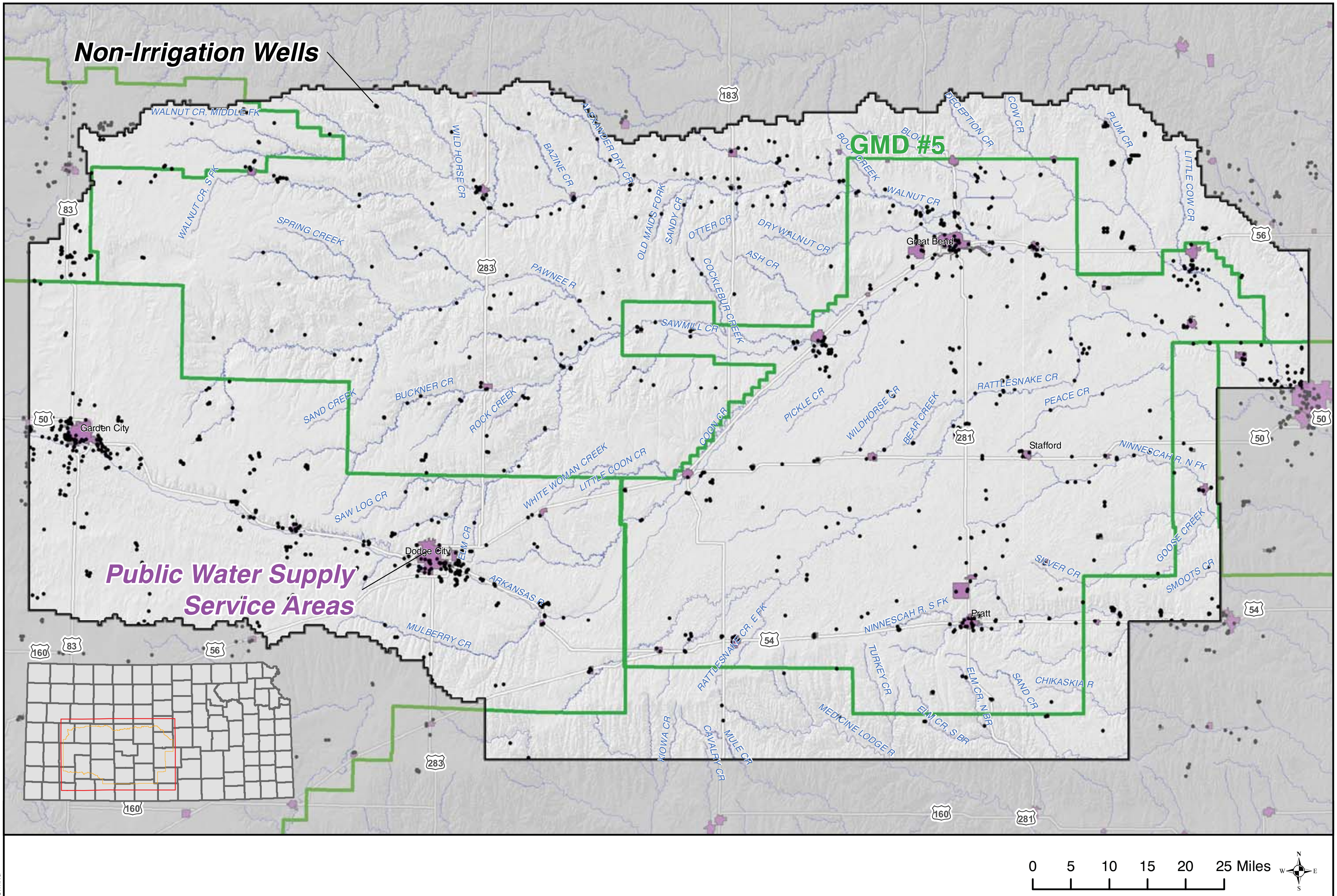
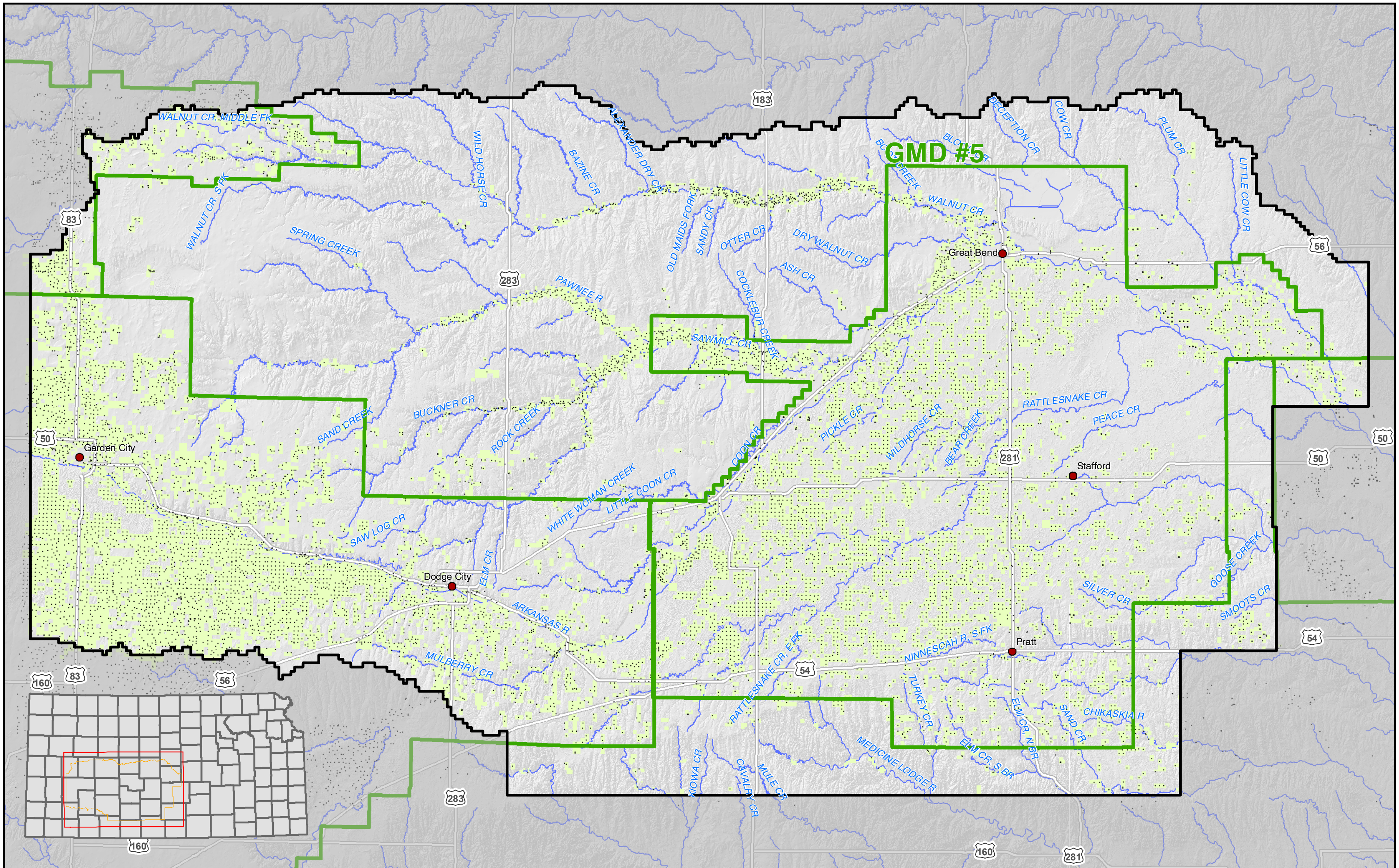


FIGURE 23. Public Water Supplies and Non-Irrigation Well Locations

5/19/2010 ses/WPB Figure23.mxd



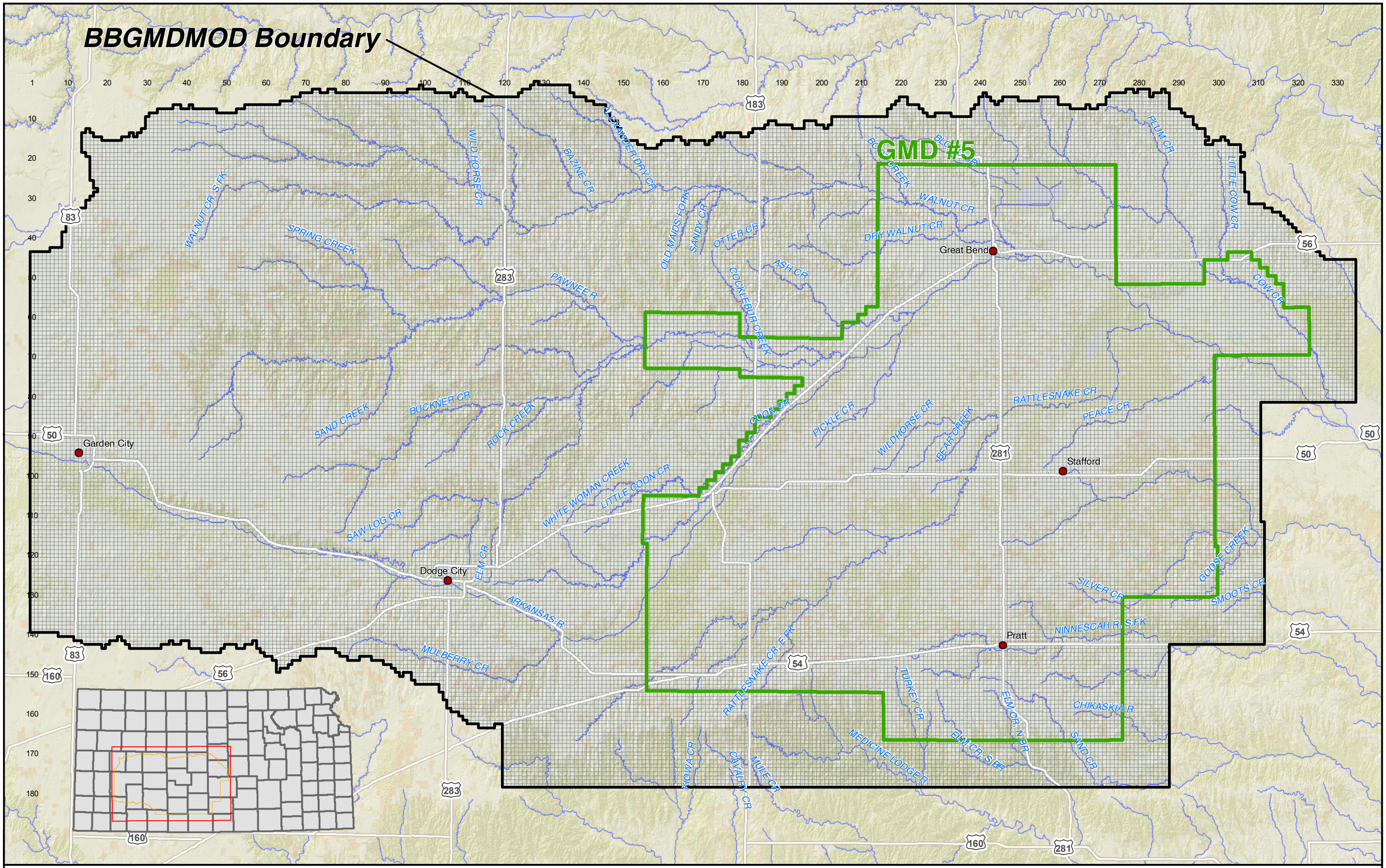
EXPLANATION

Irrigation PODs and Places of Use

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure24.mxd

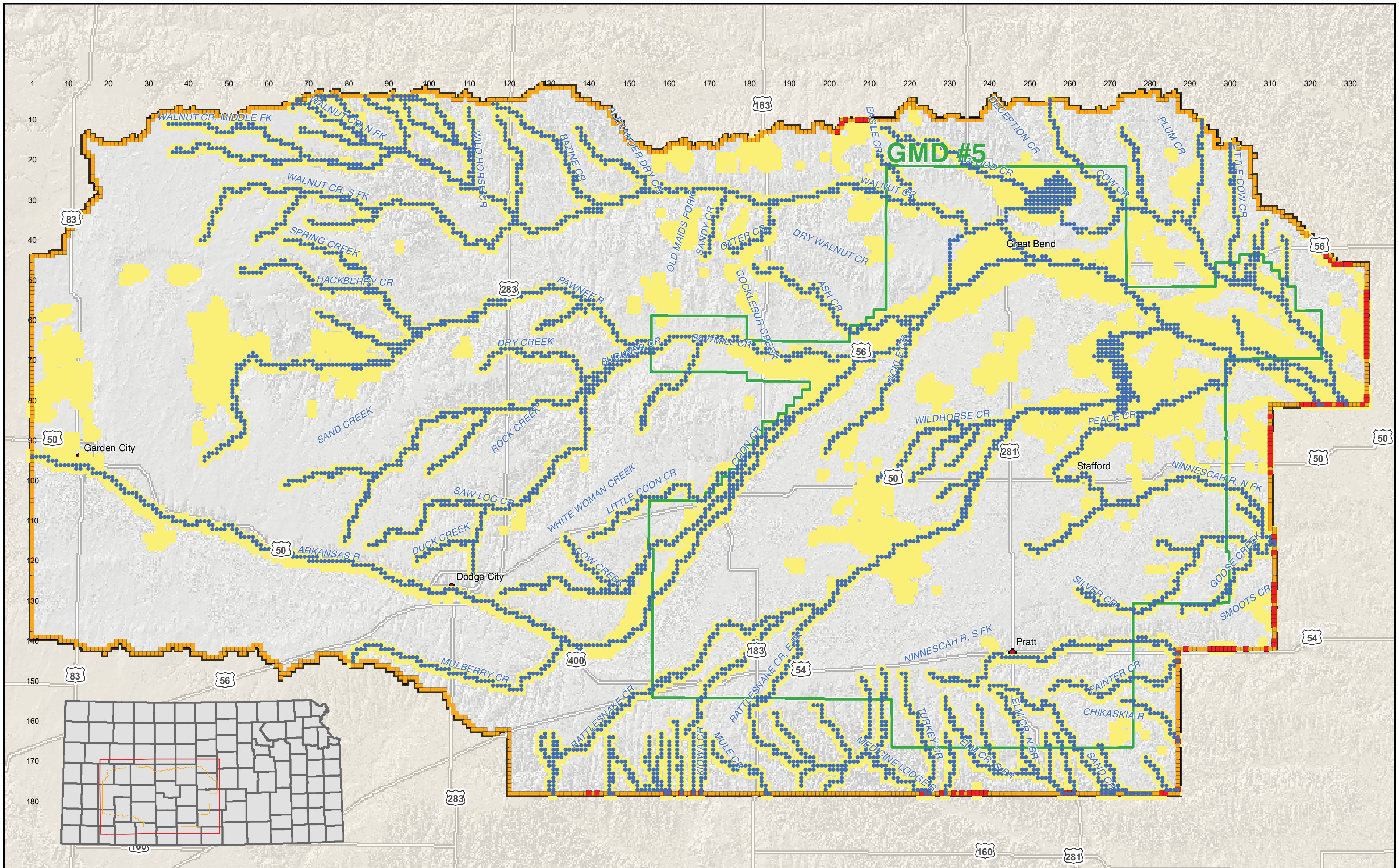
FIGURE 24. Irrigation Places of Use and Well Locations



MODEL GRID LAYOUT
180 Rows
335 Columns
48,727 Active Cells in Plan View
~341,089 Active Cells in 7 Layers

5/19/2010 ses/WPB Figure25.mxd

FIGURE 25. Model Grid



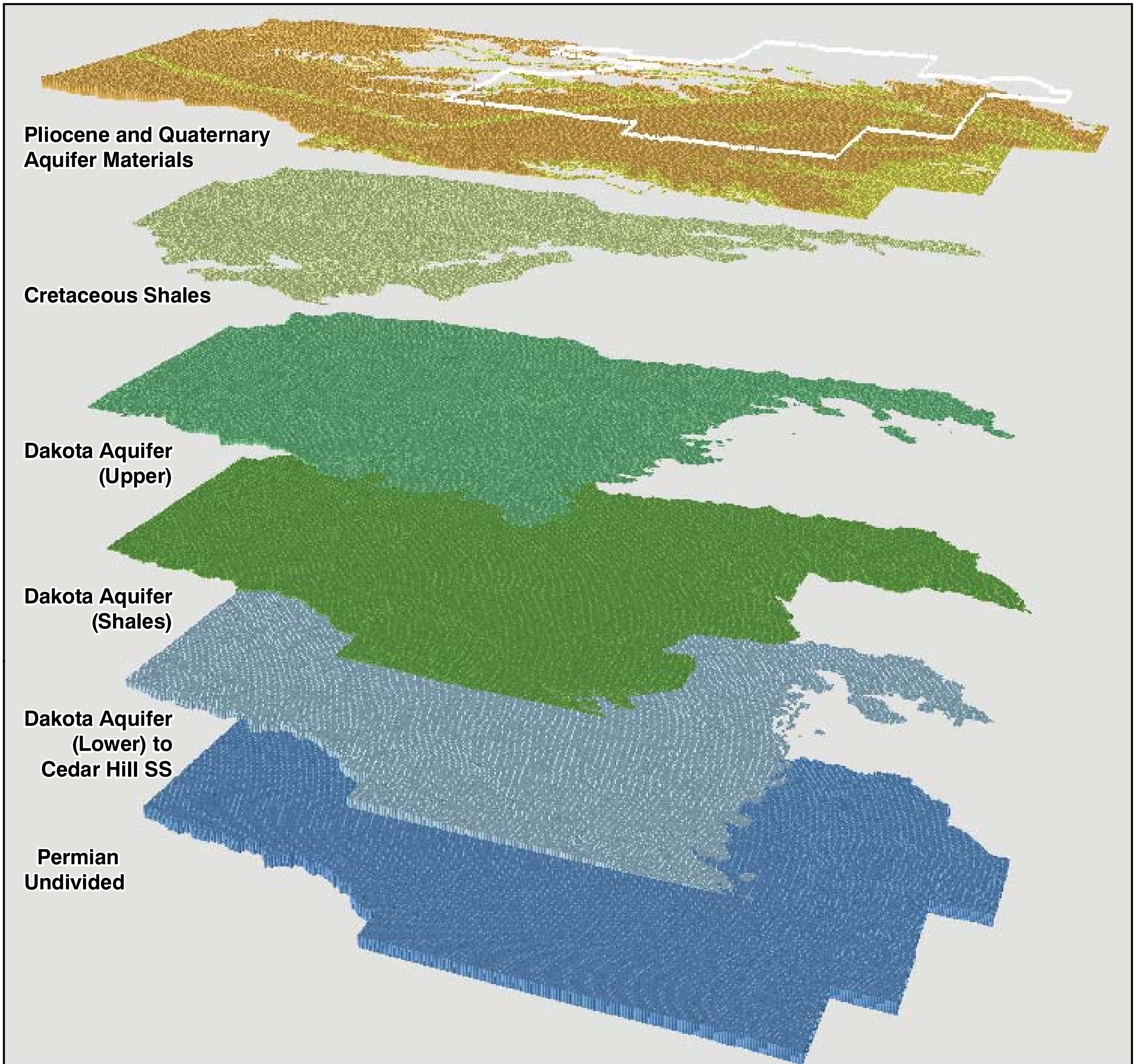
EXPLANATION

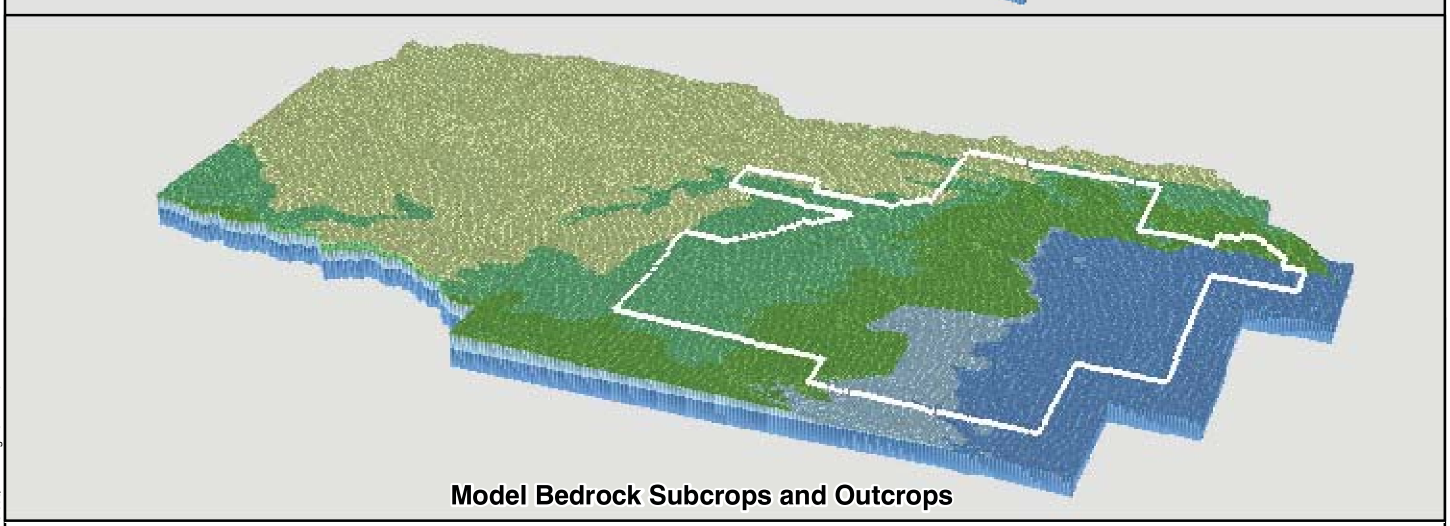
- Specified Flow Boundary Condition
- Constant Head Boundary Condition
- Head-Dependent Flow (Stream Cells)
- Head-Dependent Flow (ET Cells)

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure26.mxd

FIGURE 26. Boundary Conditions





5/19/2010 ses/WPB Figure27.mxd

FIGURE 27. Hydrologic Unit Flow Package Solids Model (Exploded View)

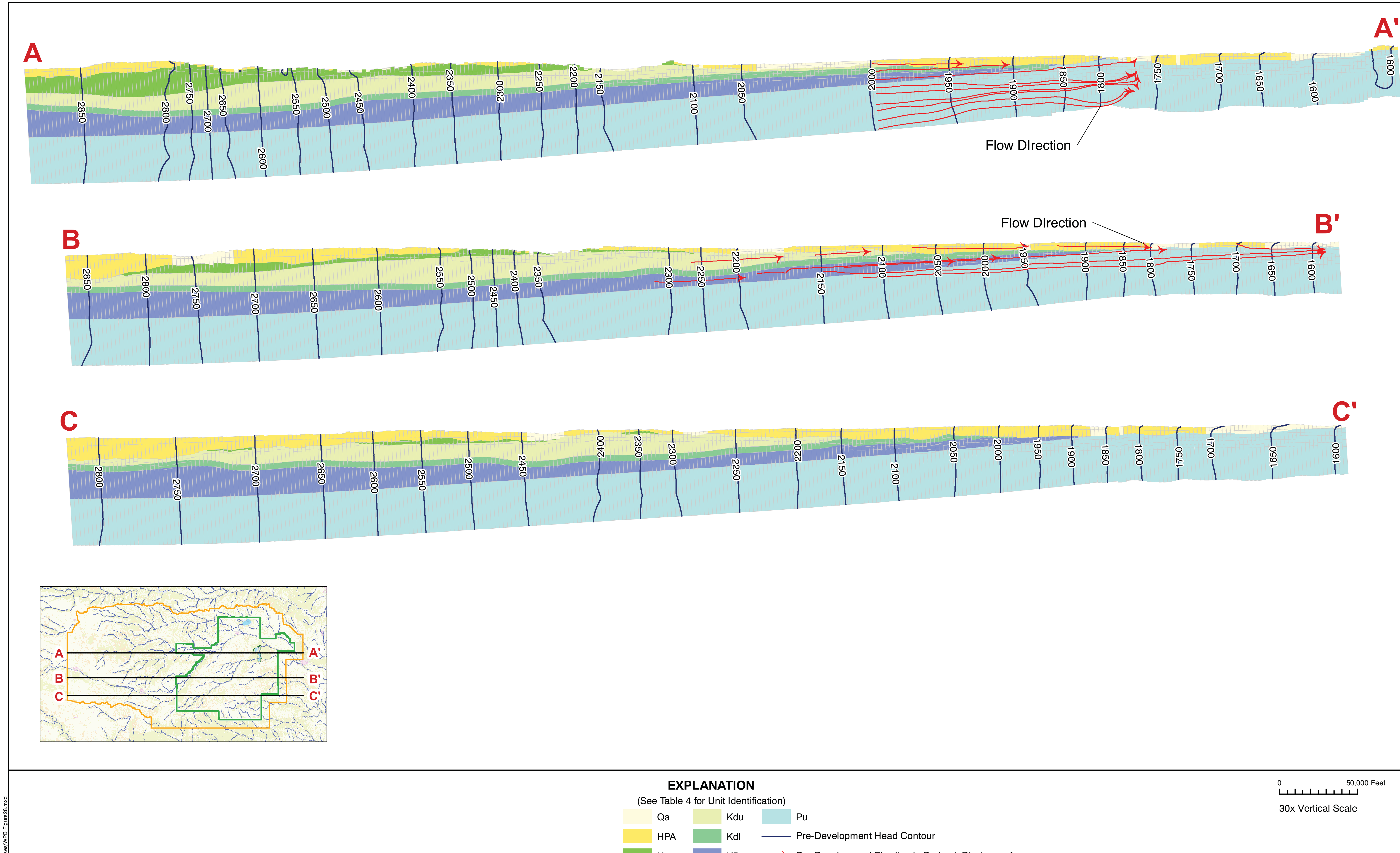
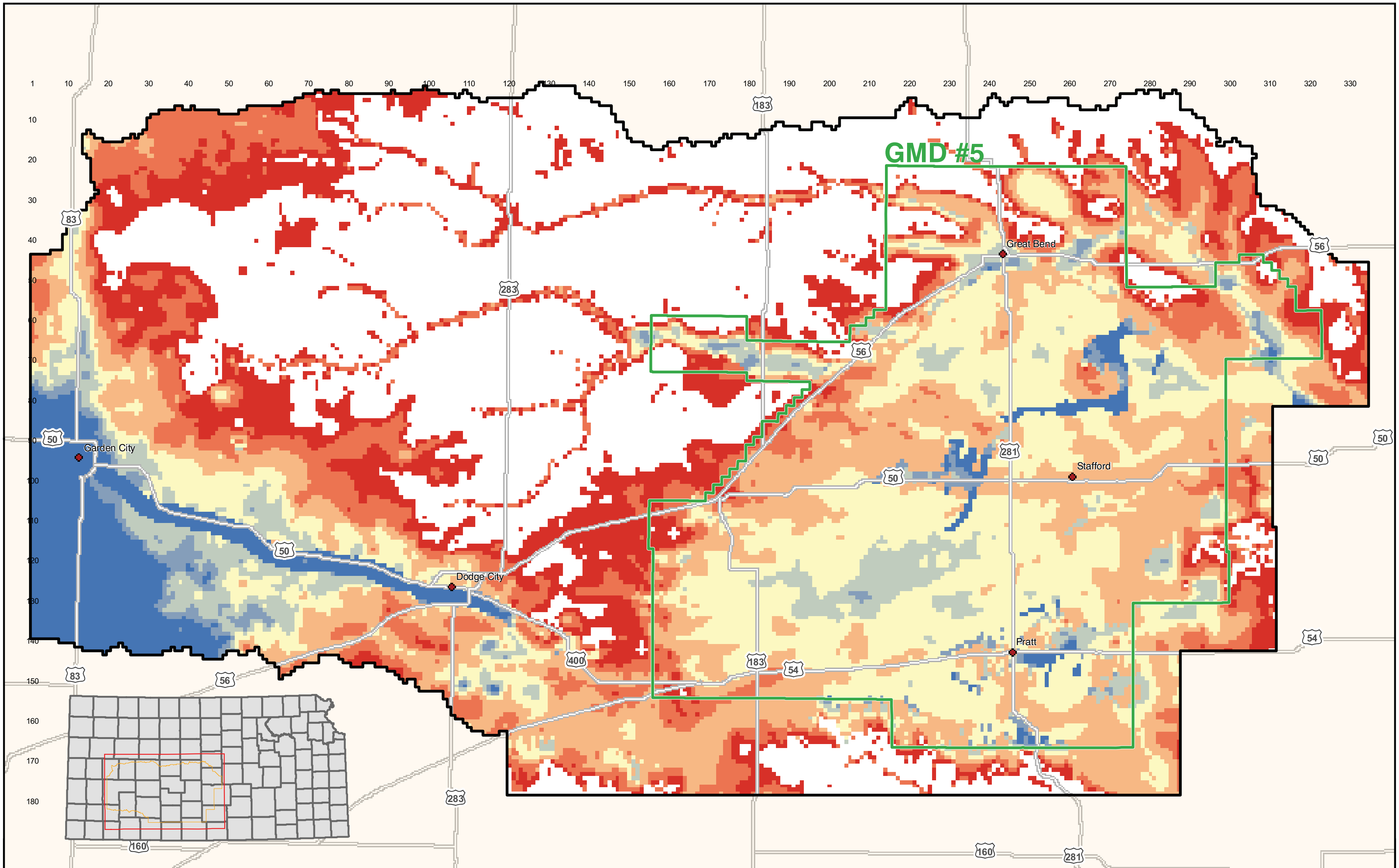
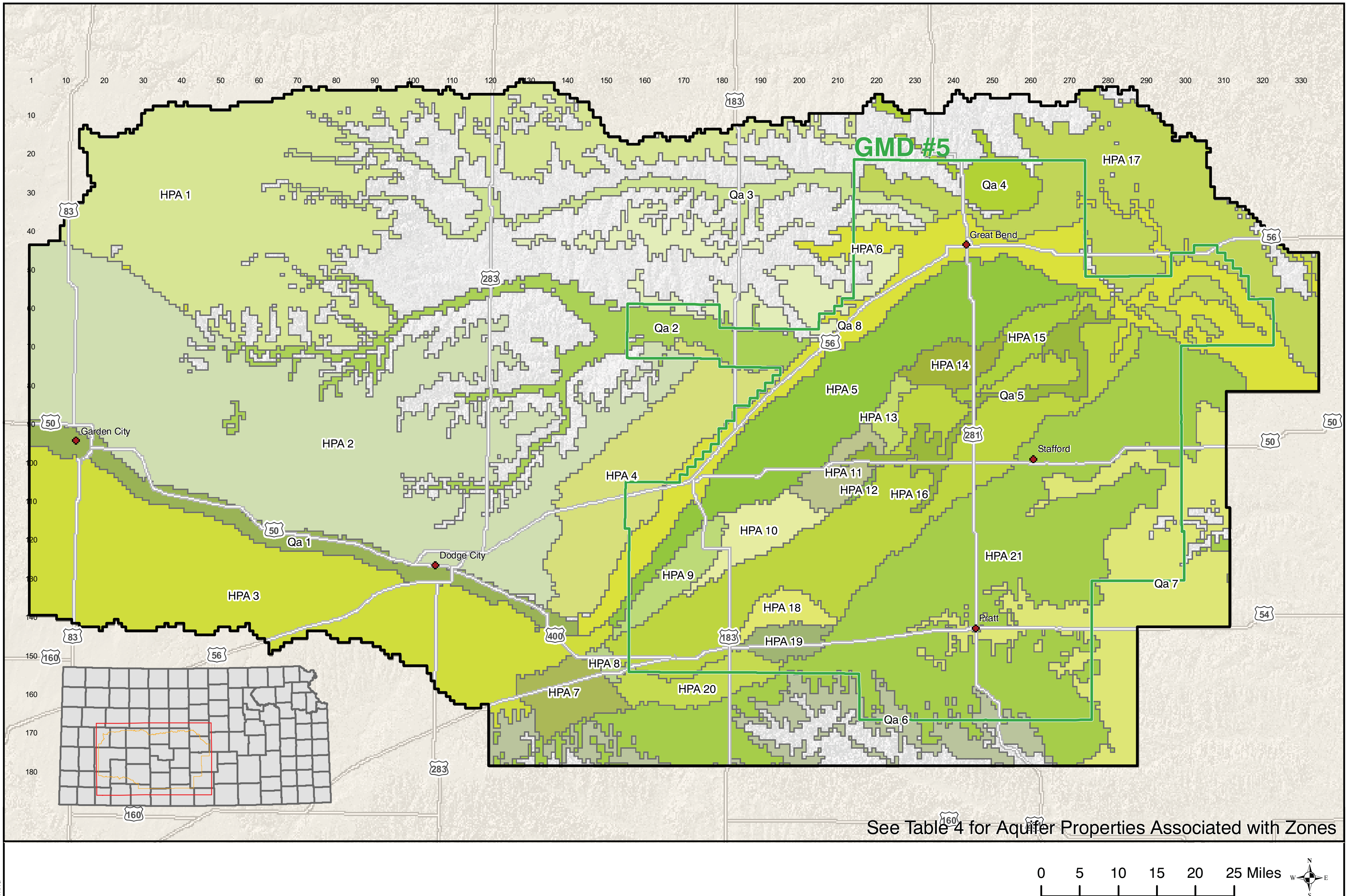


FIGURE 28. Model Cross Sections



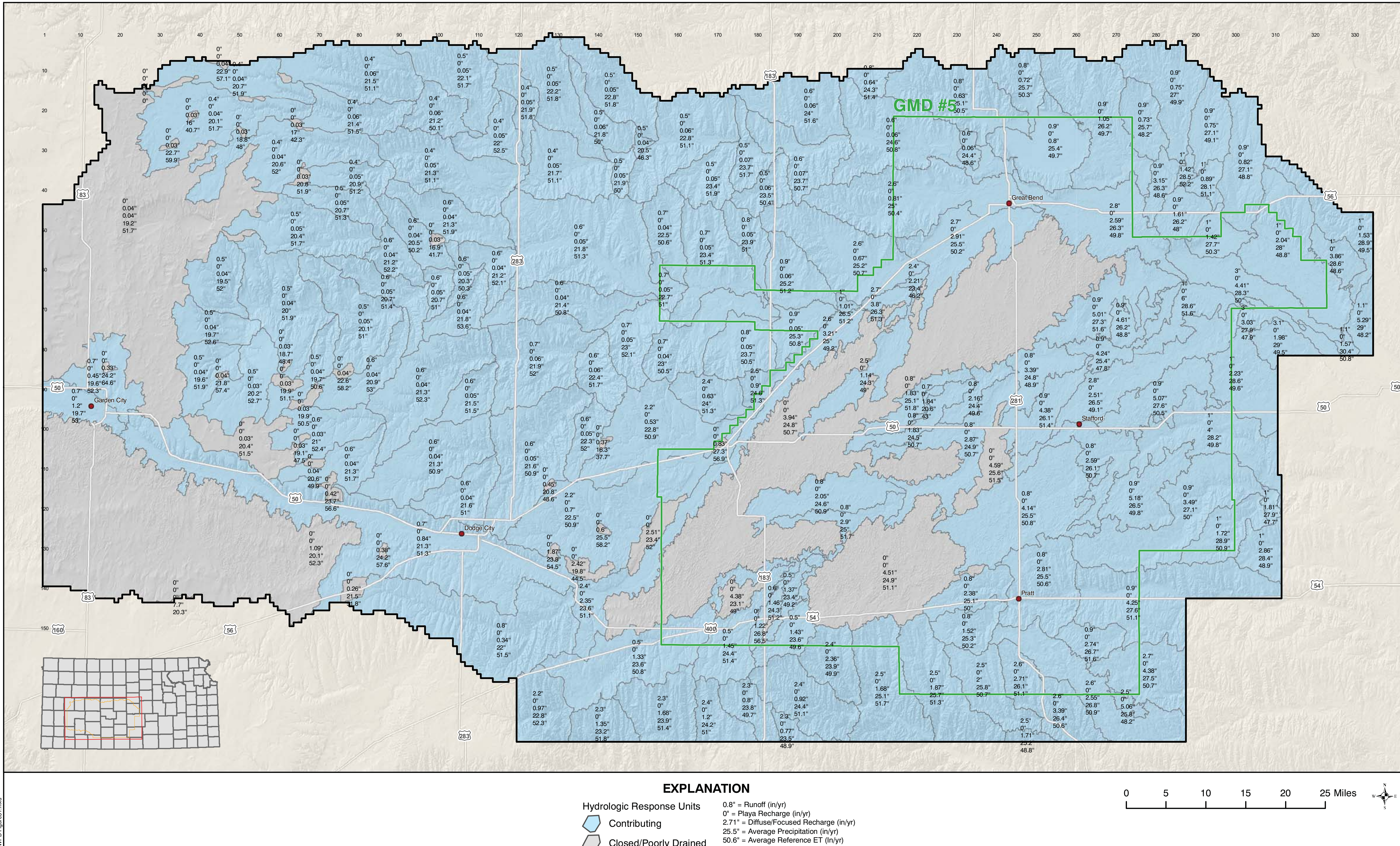
5/19/2010 ses/WPB Figure29.mxd

FIGURE 29. Modeled Transmissivity



5/19/2010 ses/WPB Figure30.mxd

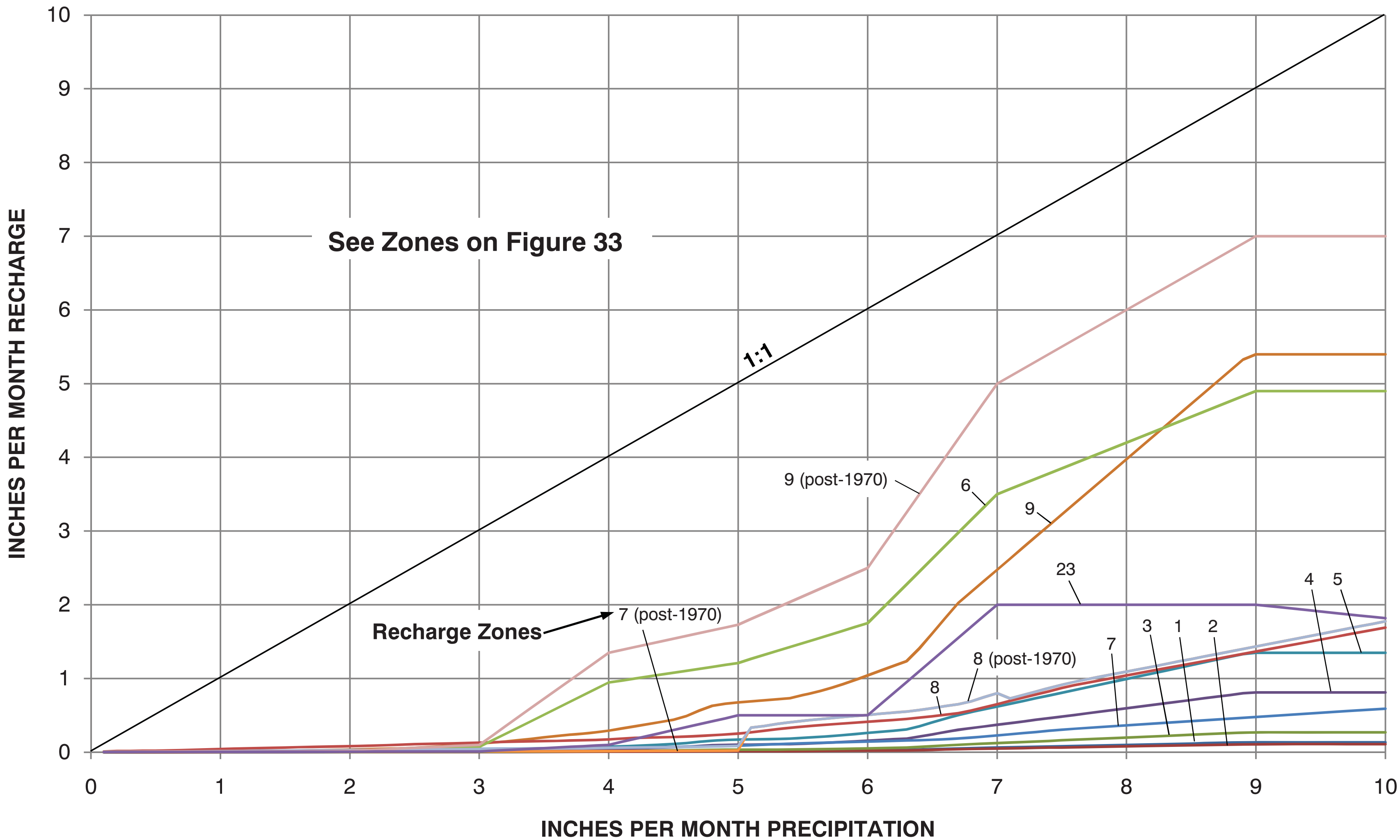
FIGURE 30. Simulated Aquifer Property Zones

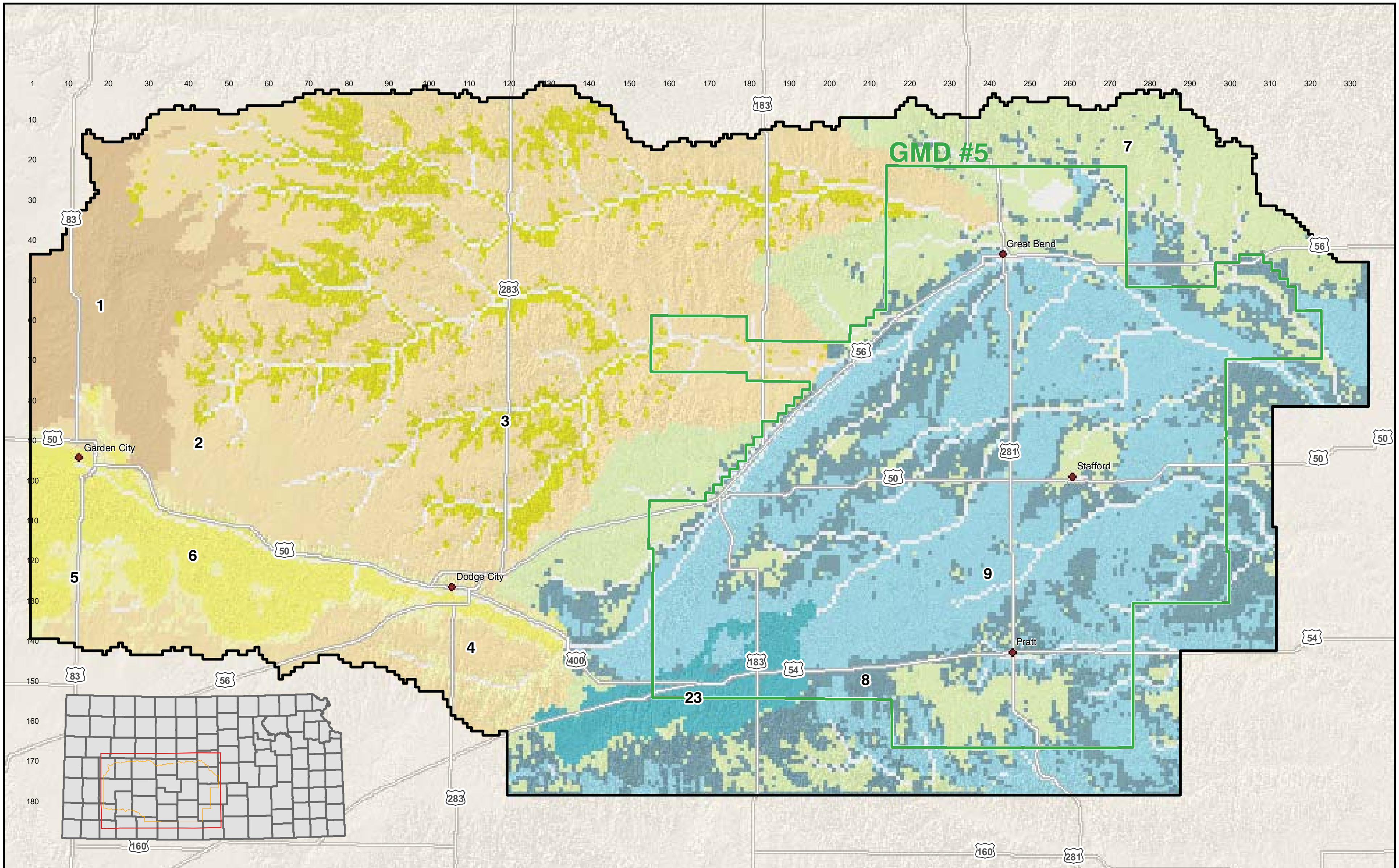


5/19/2010 ses/WPB Figure31.mxd

FIGURE 31. Average Water Loading/Runoff and Water Accounting for Hydrologic Response Units (1940 through 2007)

FIGURE 32
MONTHLY PRECIPITATION-RECHARGE RELATIONSHIPS





EXPLANATION

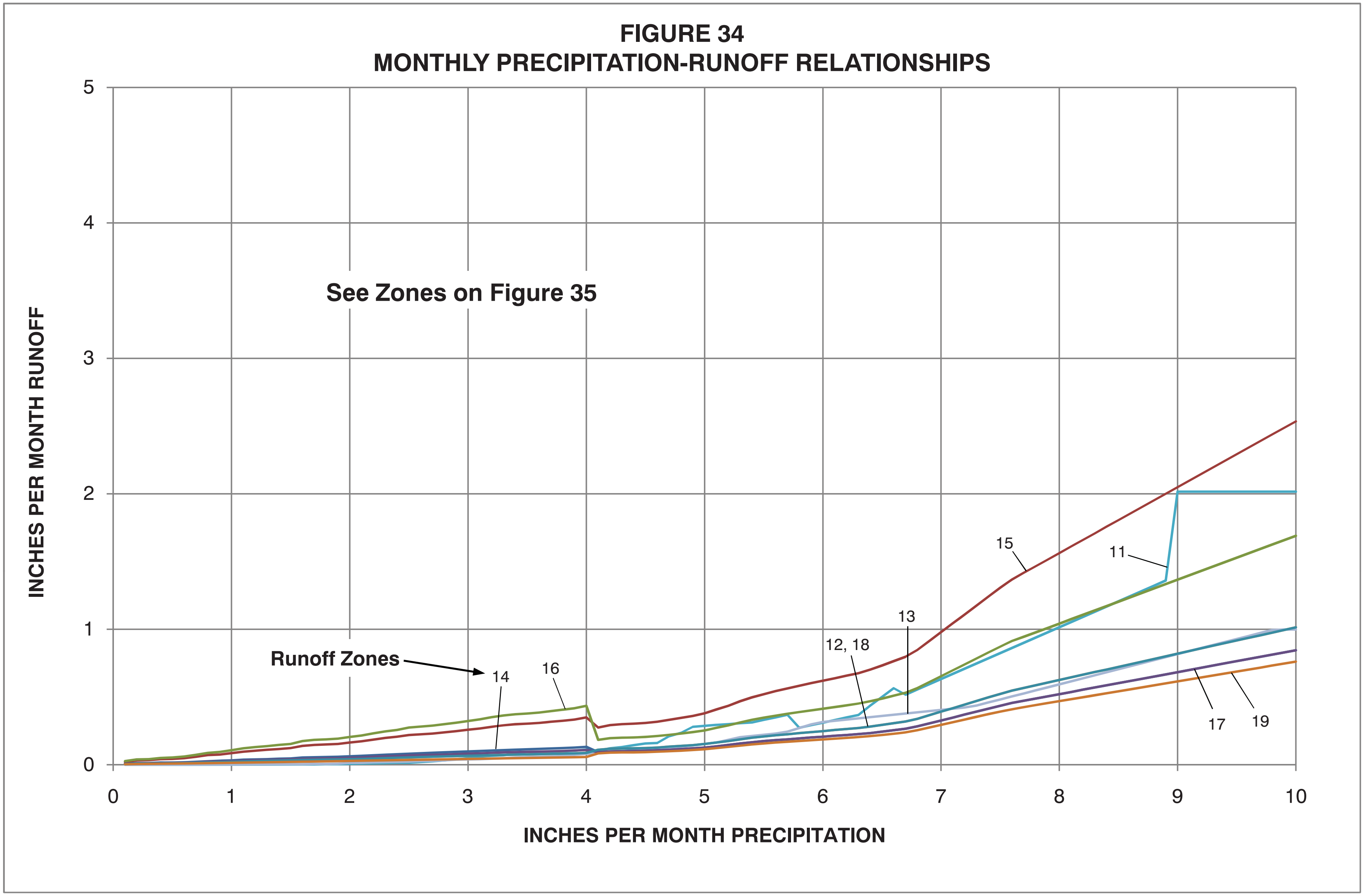
Recharge Zones (See Curves on Figure 32)

1, 2, 3, 4, 5, 6, 7, 8, 9, 23

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure33.mxd

FIGURE 33. Modeled Recharge Zones



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BY
5/19/2010

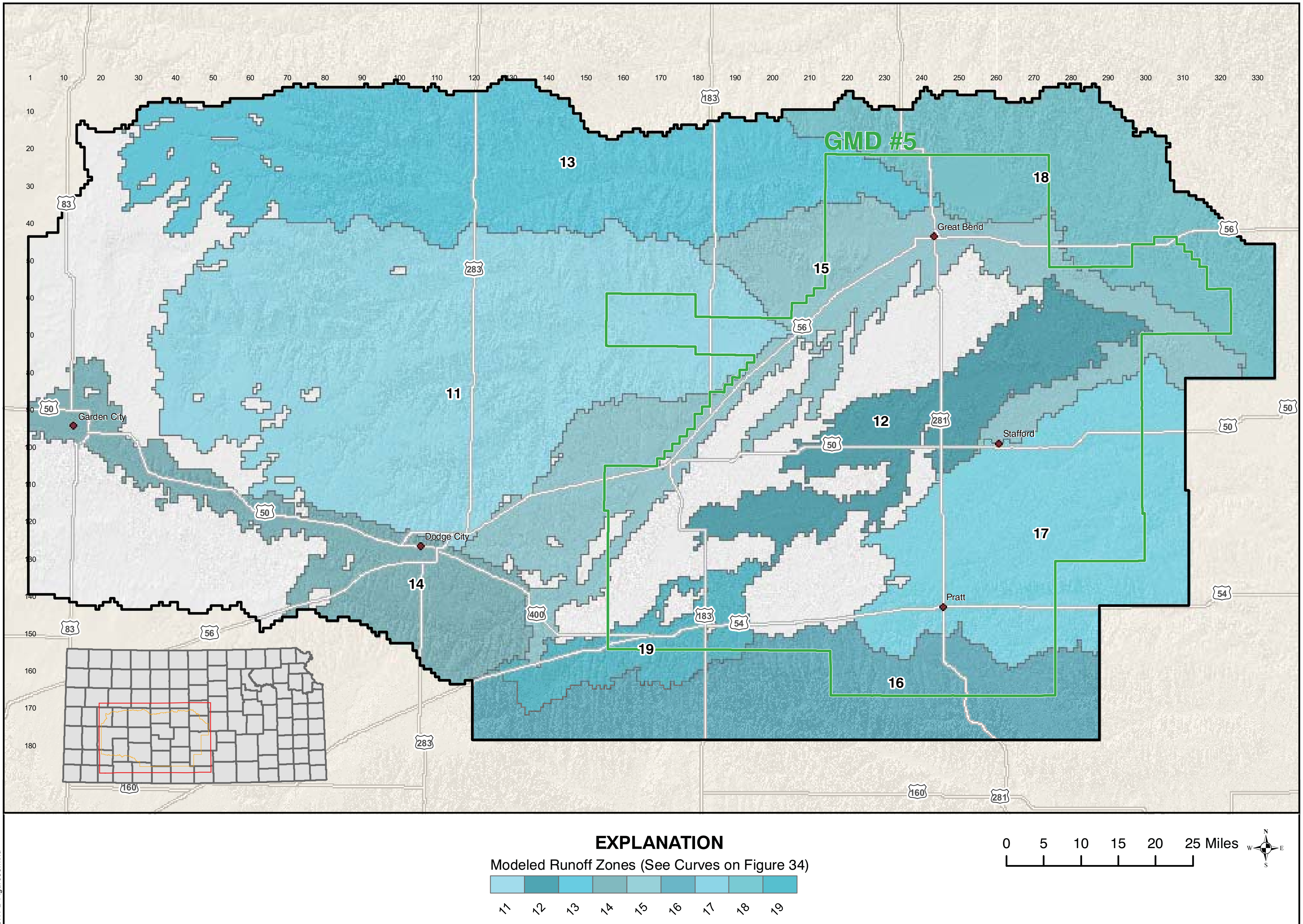


FIGURE 35. Modeled Runoff Zones

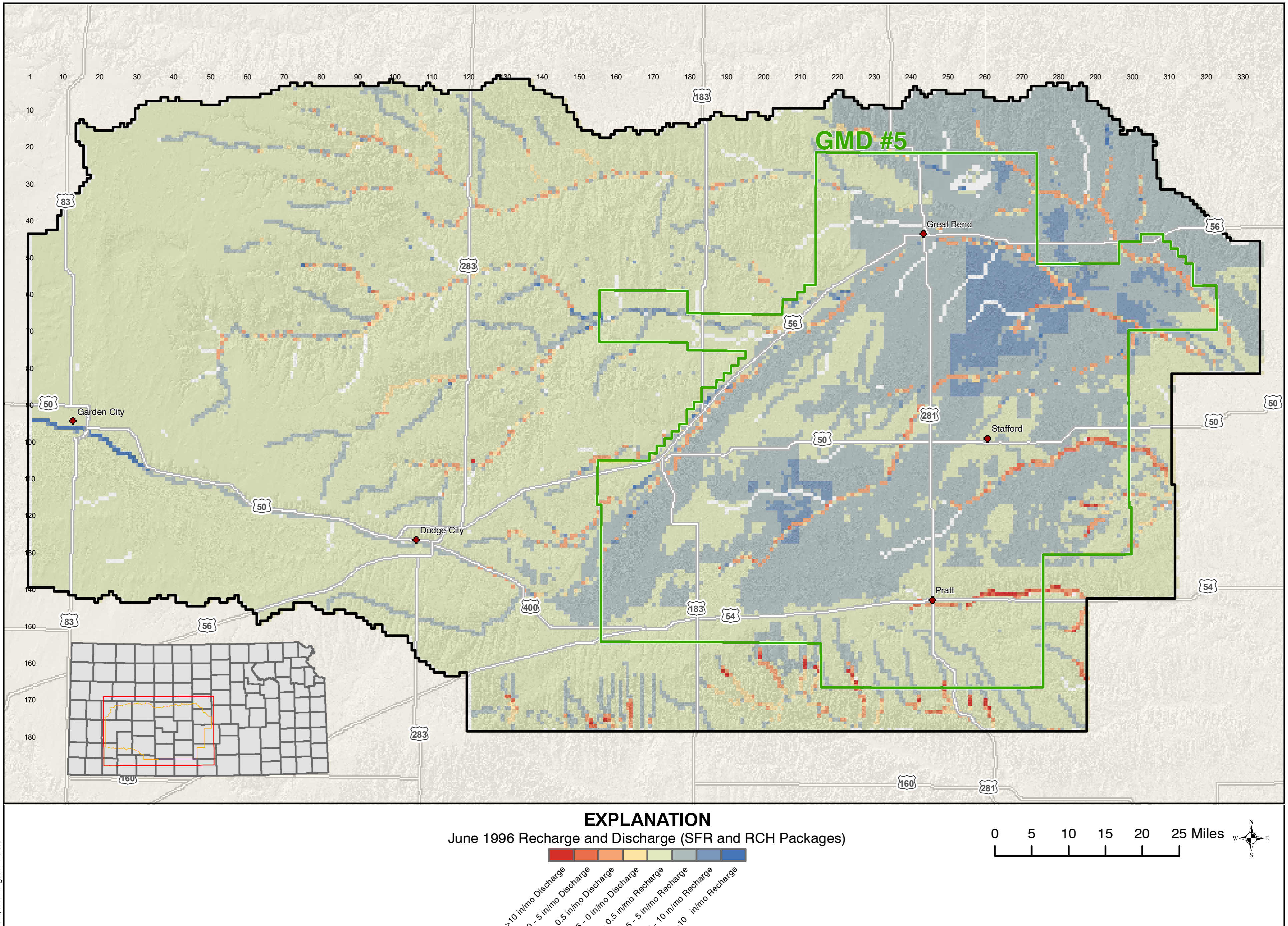
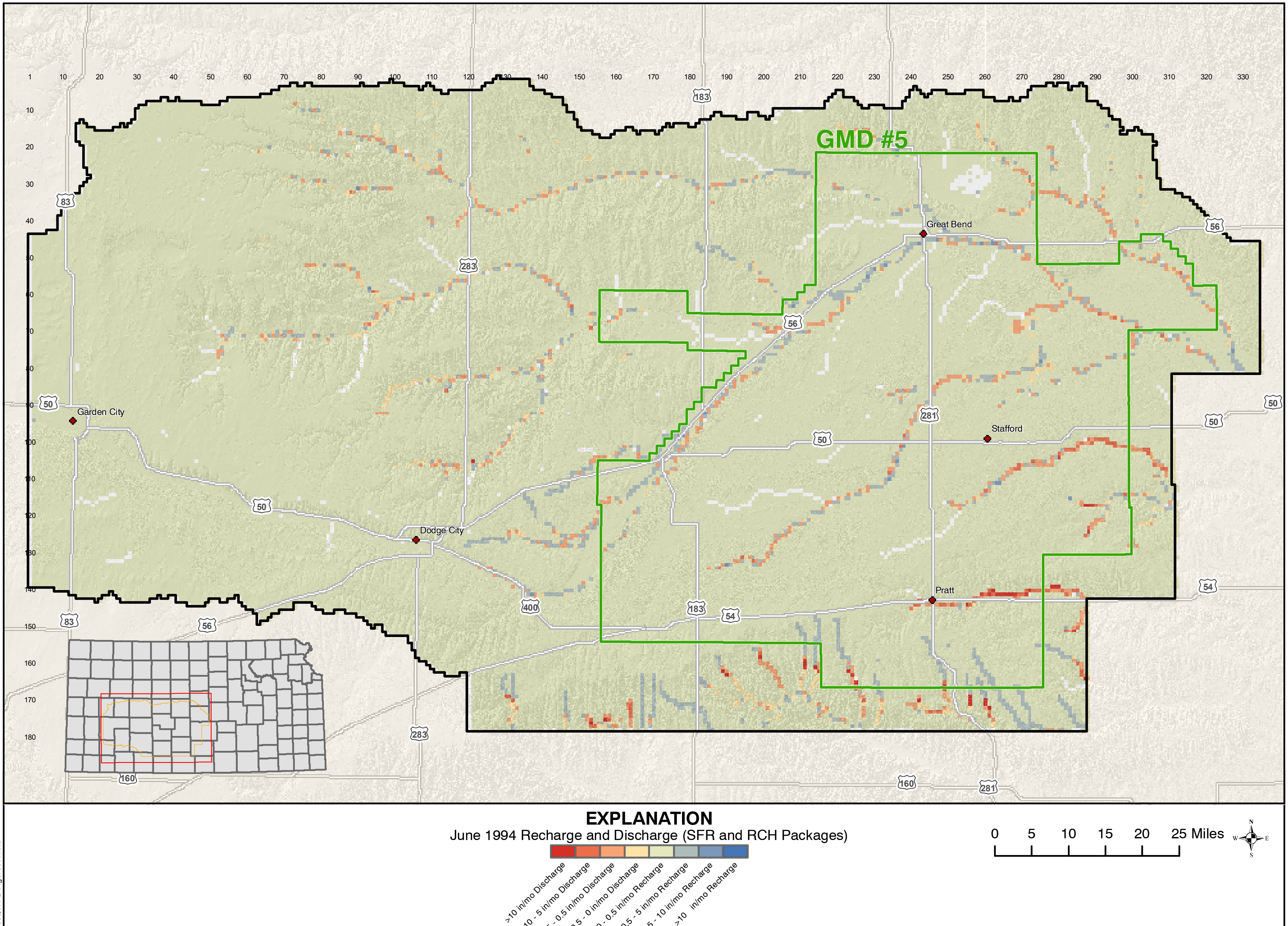


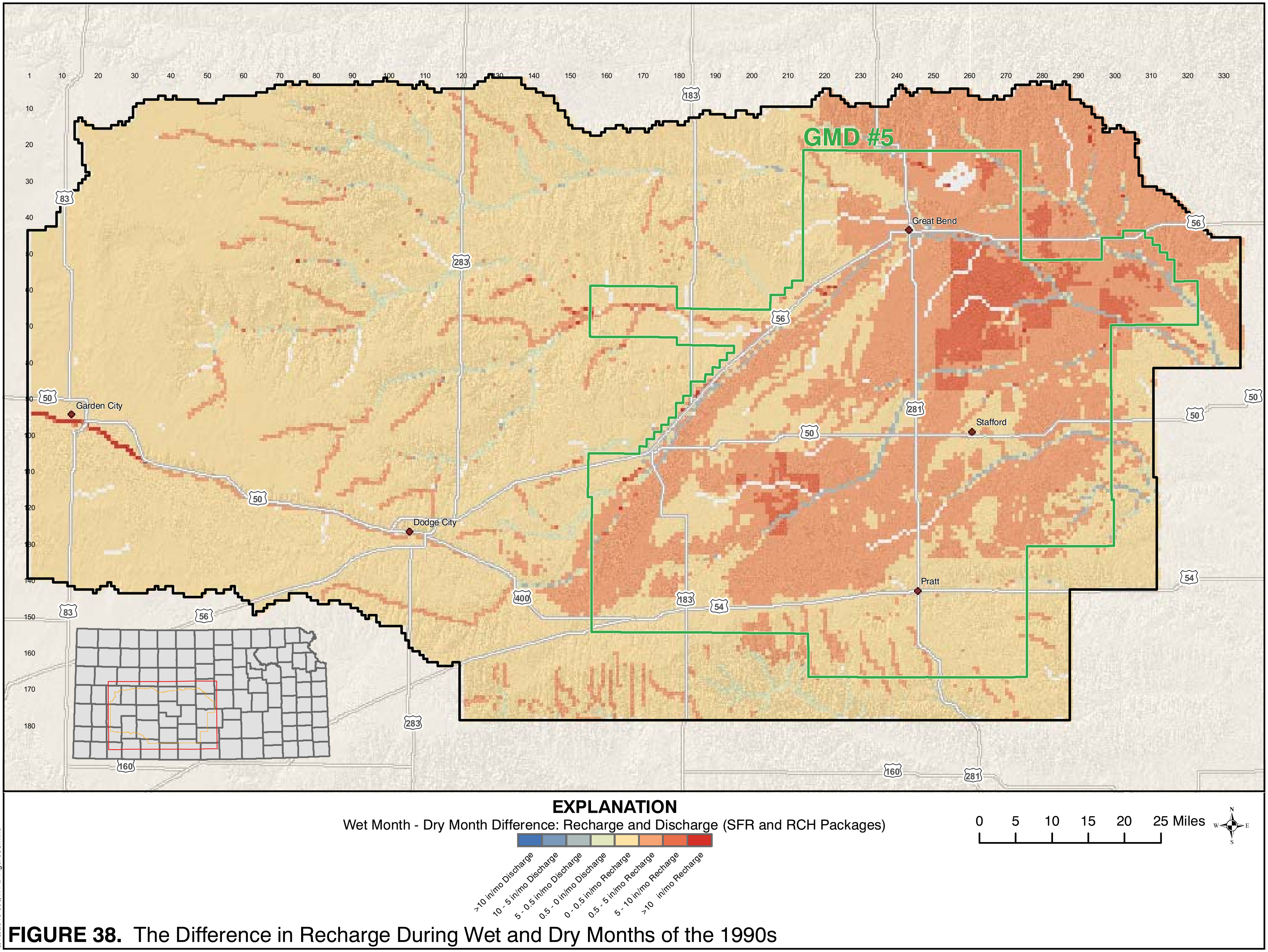
FIGURE 36. Areas Simulated as Net Recharge and Net Discharge During a Wet Month (June 1996) of the Decade of 1990s

5/19/2010 ses/WPB Figure36.mxd



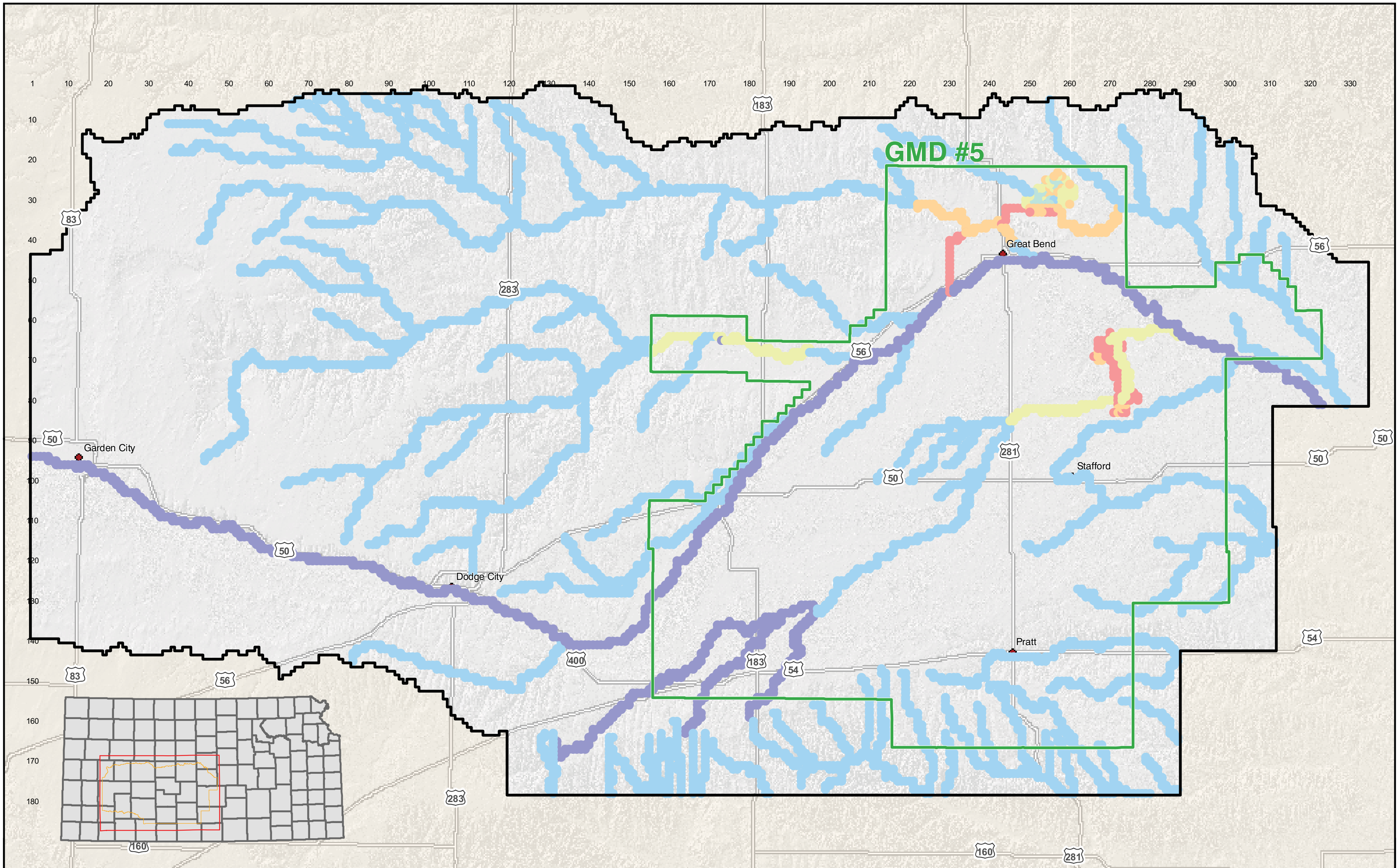
5/19/2010 ses/WPB Figure37.mxd

FIGURE 37. Areas Simulated as Net Recharge and Net Discharge During a Dry Month (June 1994) of the Decade of 1990s



5/19/2010 ses/WPB Figure38.mxd

FIGURE 38. The Difference in Recharge During Wet and Dry Months of the 1990s



EXPLANATION

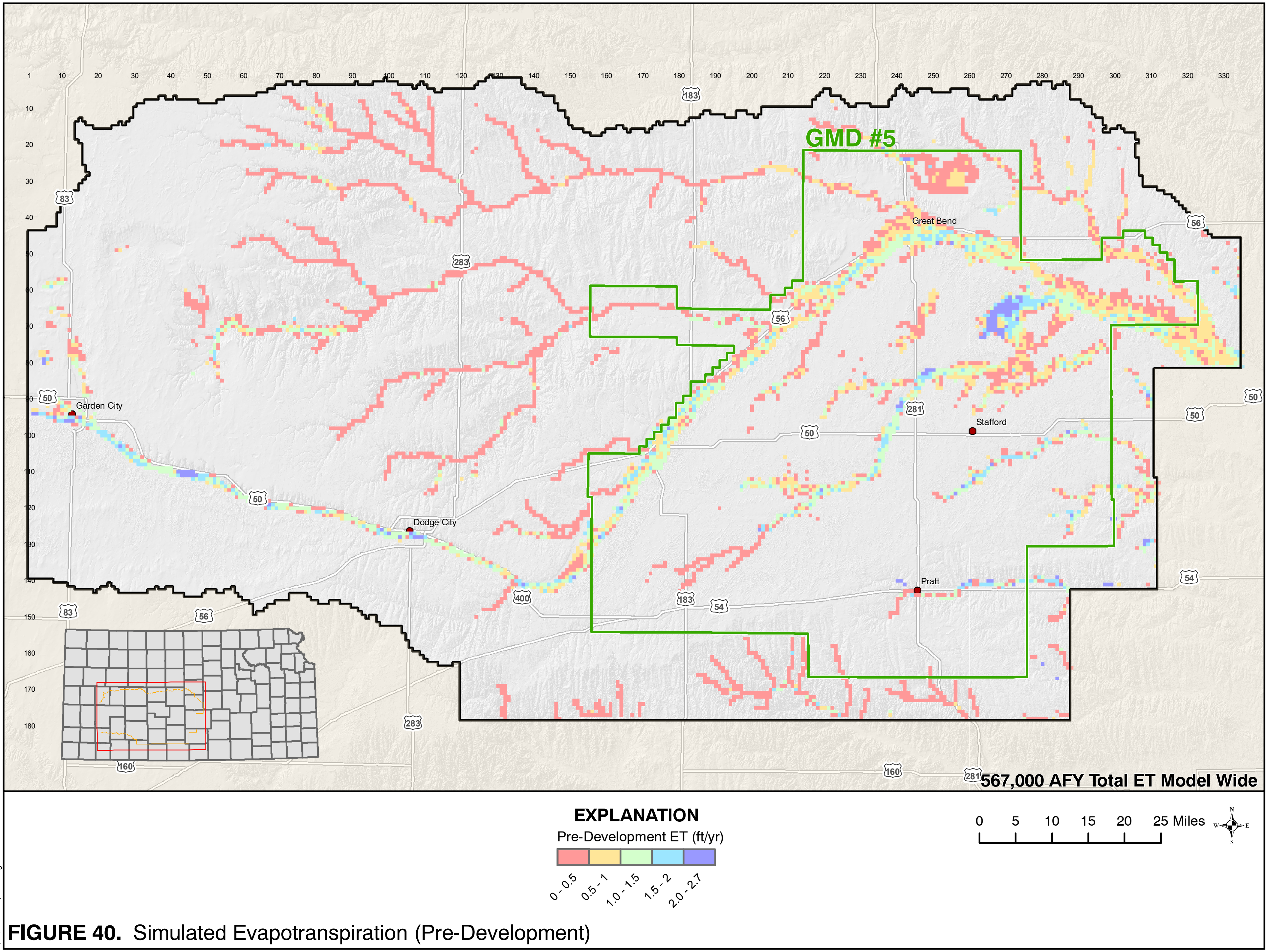
Maximum Stream Leakage (cfs/mi)

< 0.1 | 0.1 - 0.5 | 0.5 - 1.5 | 1.5 - 3.0 | 3.0 - 7.25 | 7.25 - 9.04

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure39.mxd

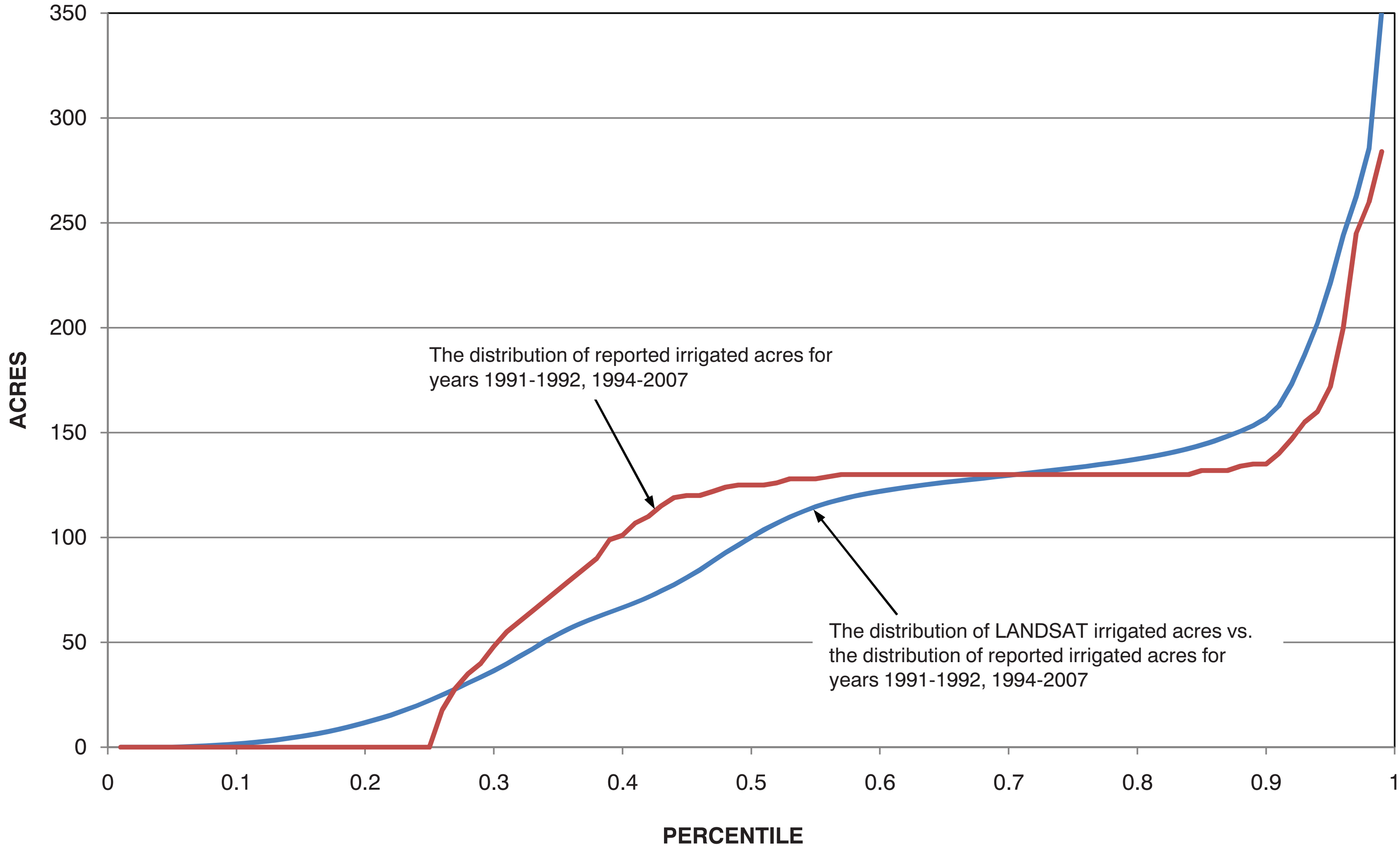
FIGURE 39. Simulated Stream Network



5/19/2010 ses/WPB Figure40.mxd

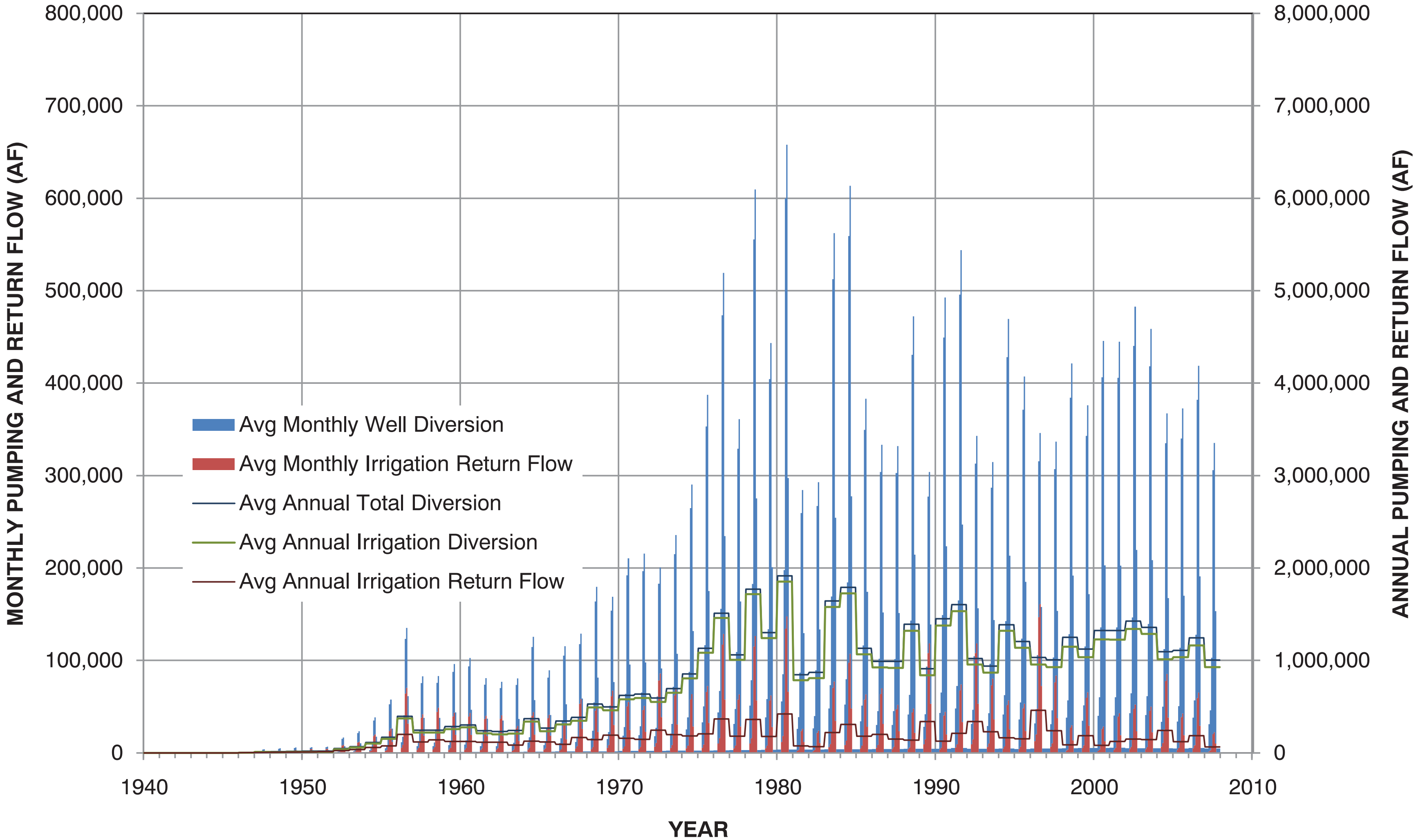
FIGURE 40. Simulated Evapotranspiration (Pre-Development)

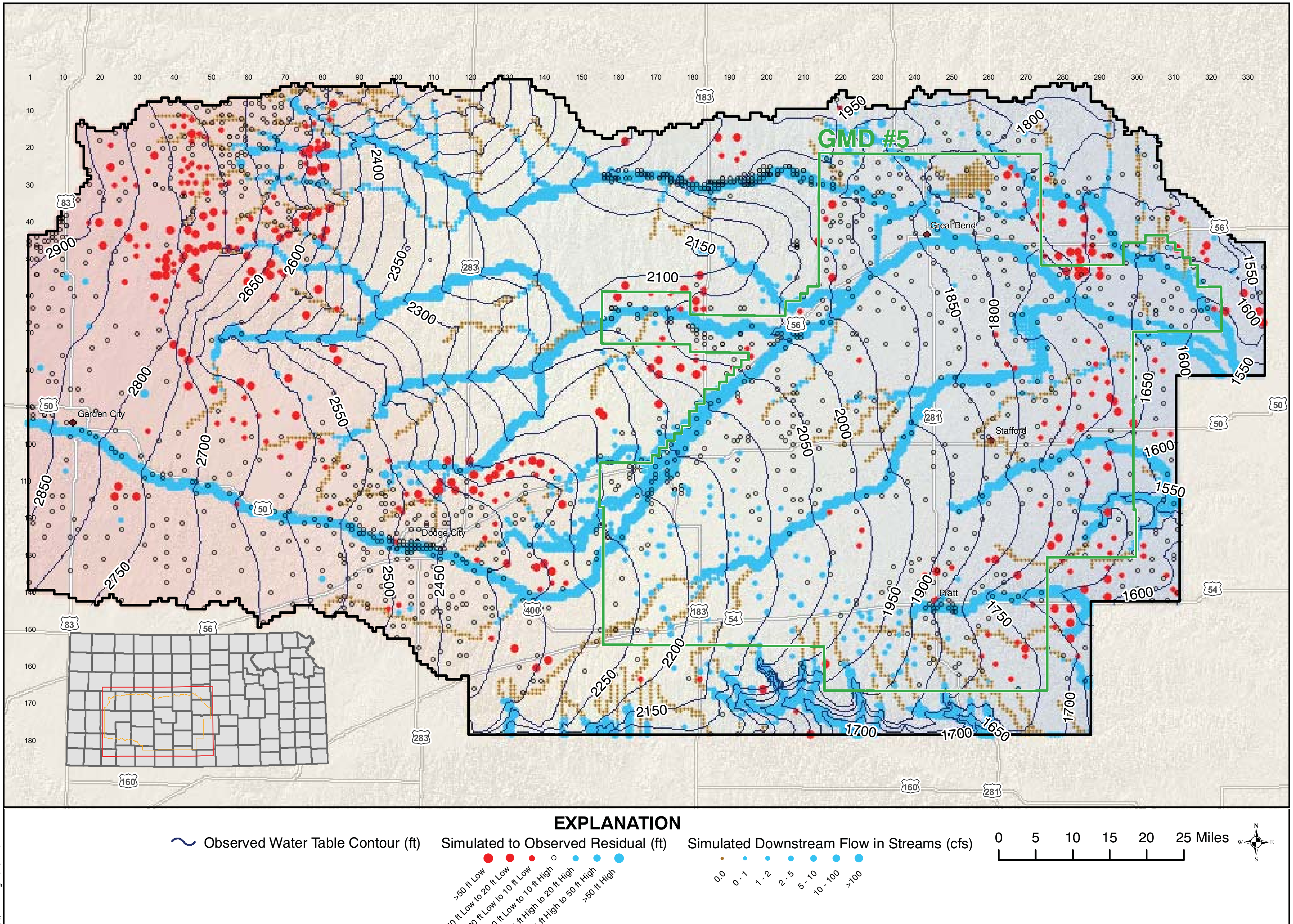
FIGURE 41
RELATIONSHIP OF IMAGE IRRIGATED ACRES TO REPORTED IRRIGATED ACRES



fur.xls
SES
6/23/2010

FIGURE 42
SIMULATED WATER-USE TREND OF IRRIGATION AND RETURN FLOW

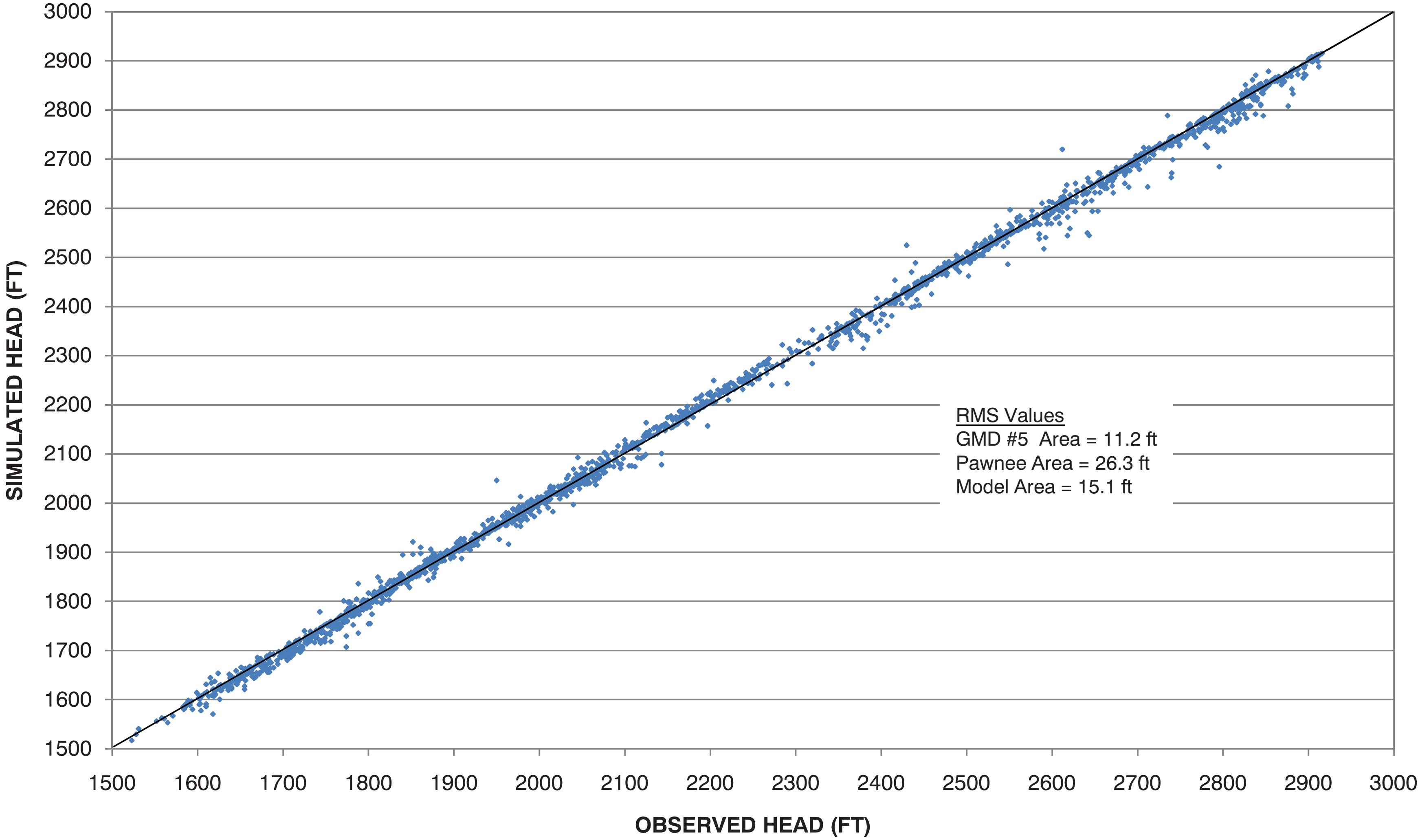




5/19/2010 ses/WPB Figure43.mxd

FIGURE 43. Pre-Development Observed Heads with Simulated Residuals

FIGURE 44
PRE-DEVELOPMENT HEAD CORRELATION



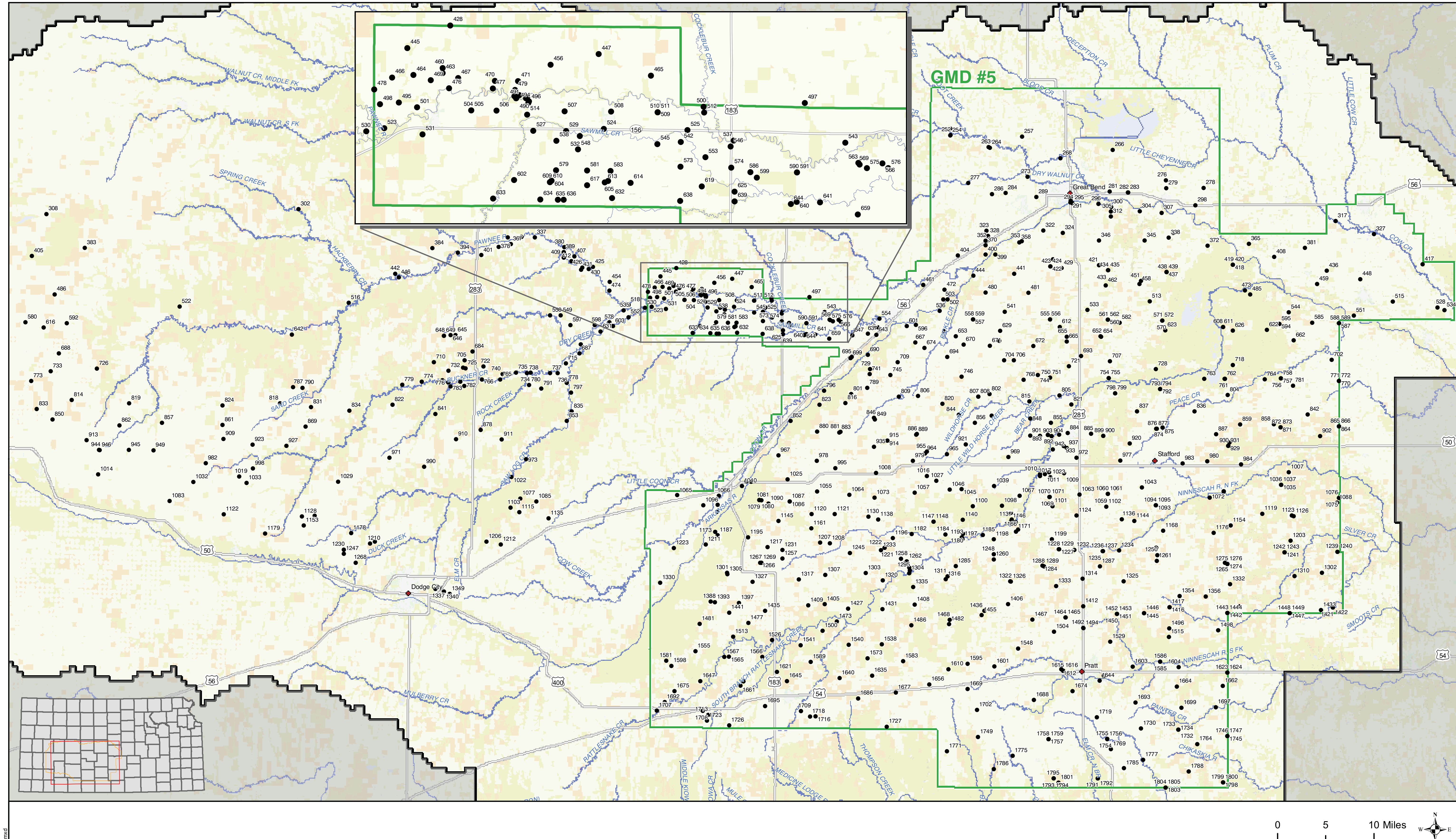
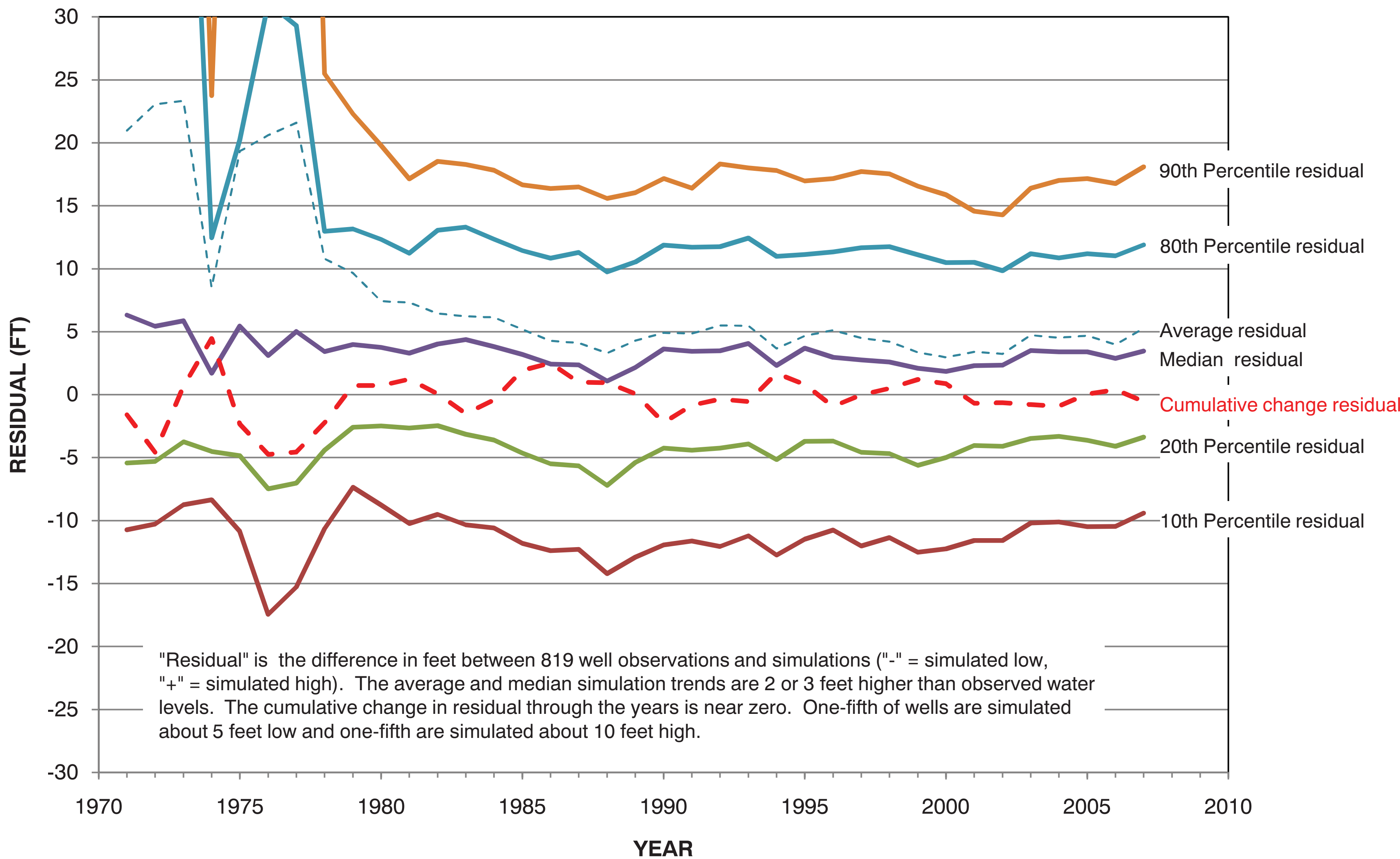
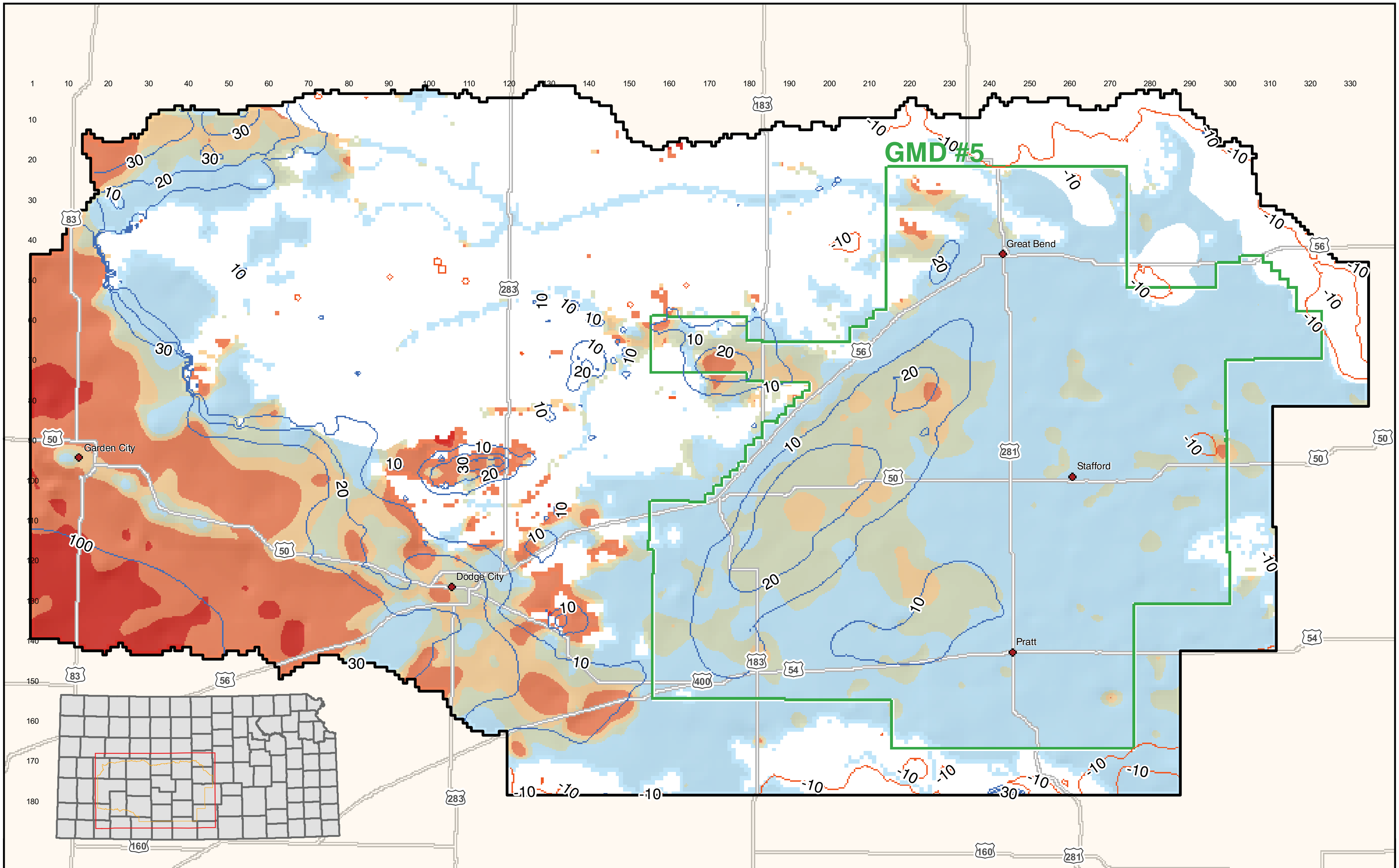


FIGURE 45. Groundwater Hydrograph Locations

5/18/2010 ses/WPB Figure45.mxd

FIGURE 46
COMPARISON OF OBSERVED AND SIMULATED WATER-LEVEL TRENDS





EXPLANATION

White Area = Water-level change not calculated or not presented because of low data density or low coincident data density.

Observed Pre-Development to 2000s Water-Level Change (ft)
<10, 10 - 20, 20 - 30, 30 - 100, >100

Simulated Water-Level Change (ft)
Buildup
Drawdown

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure47.mxd

FIGURE 47. Observed and Simulated Water-Level Change Contours from 1940 through 2007

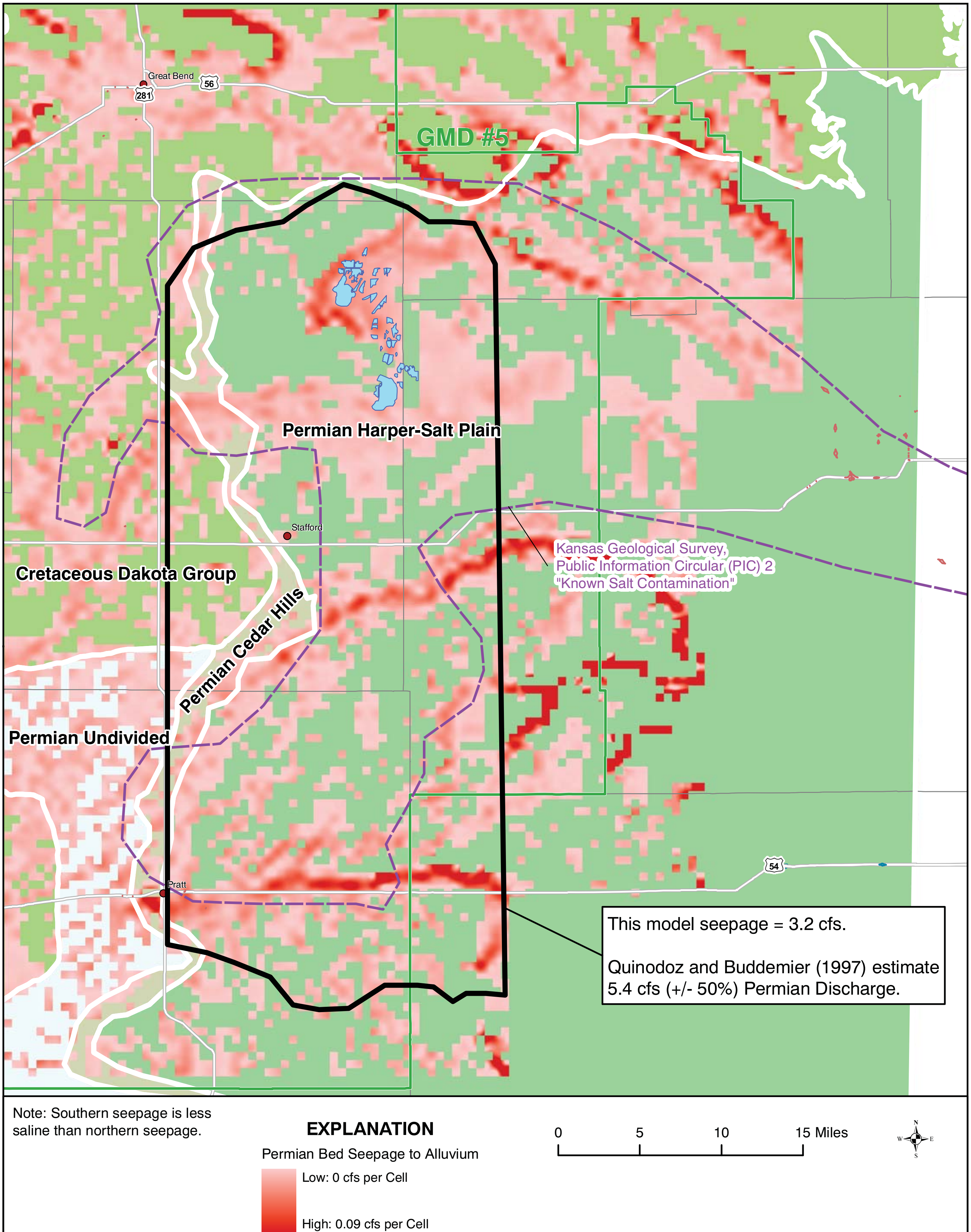
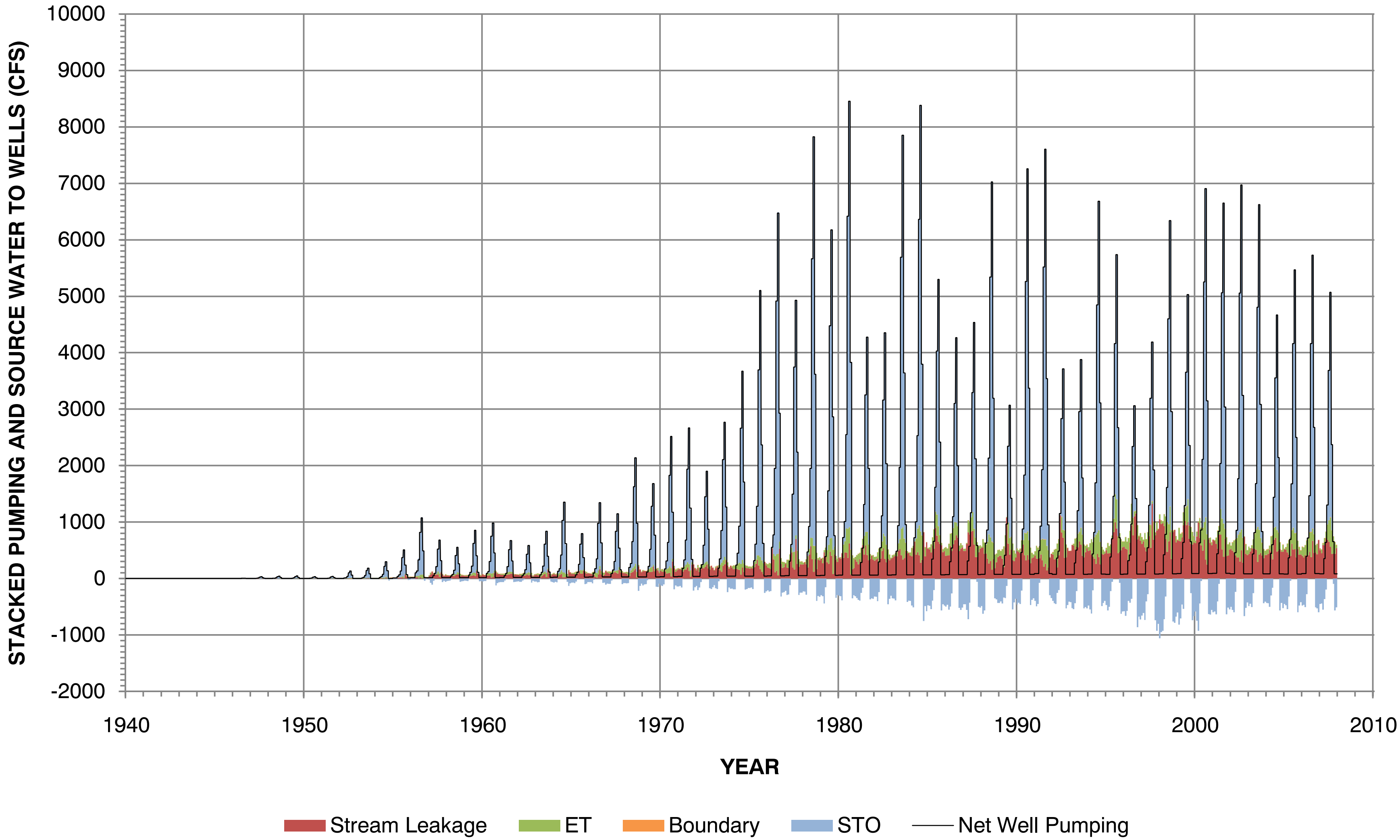


FIGURE 48. Simulated Permian-Bed Seepage

MODEL

FIGURE 49A
MONTHLY SOURCES OF WATER TO WELLS FROM 1940 THROUGH 2007



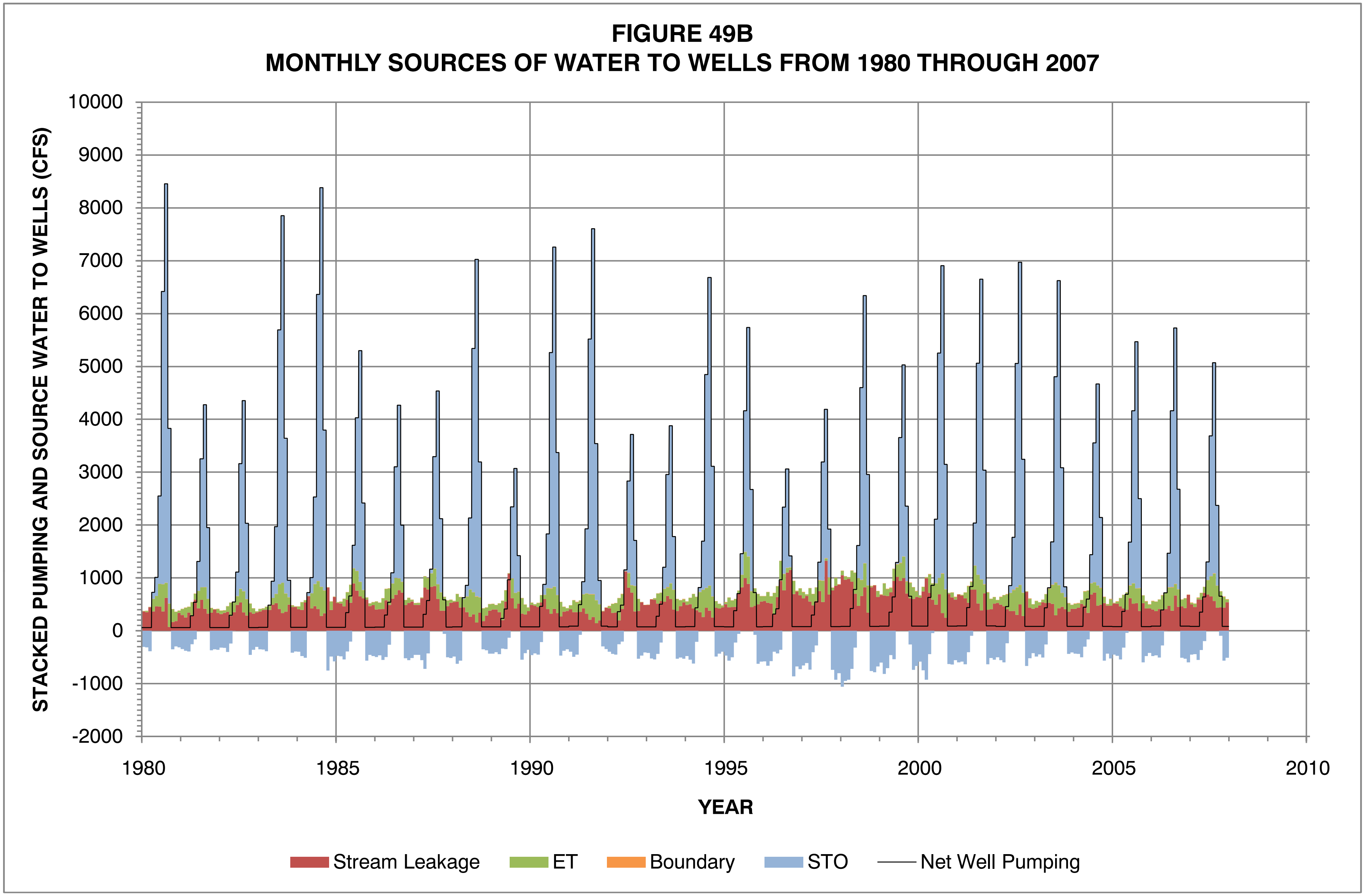
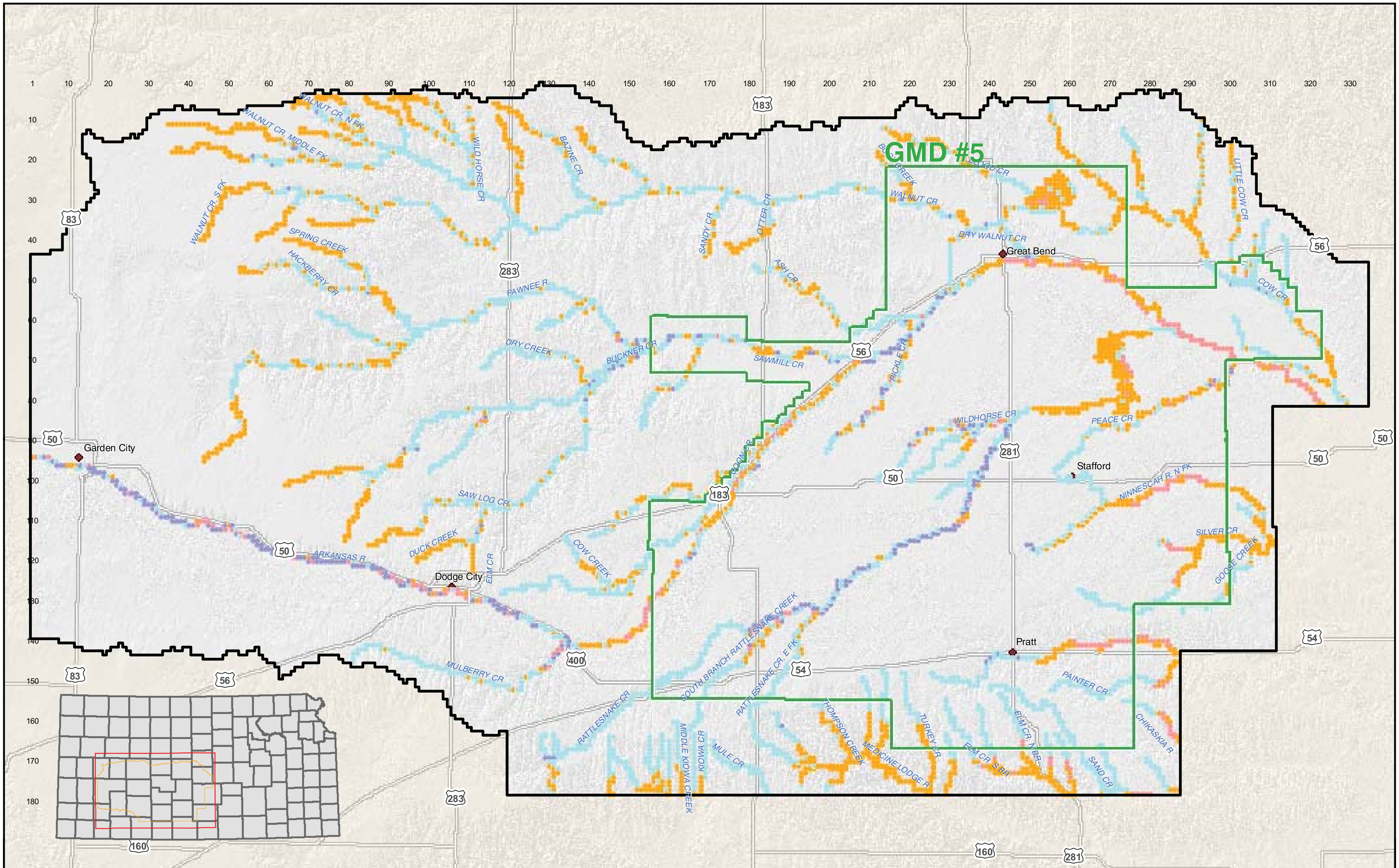


FIGURE 49B
MONTHLY SOURCES OF WATER TO WELLS FROM 1980 THROUGH 2007
STACKED PUMPING AND SOURCE WATER TO WELLS (CFS)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
1980
1985
1990
1995
2000
2005
2010
YEAR
Stream Leakage
ET
Boundary
STO
Net Well Pumping



EXPLANATION

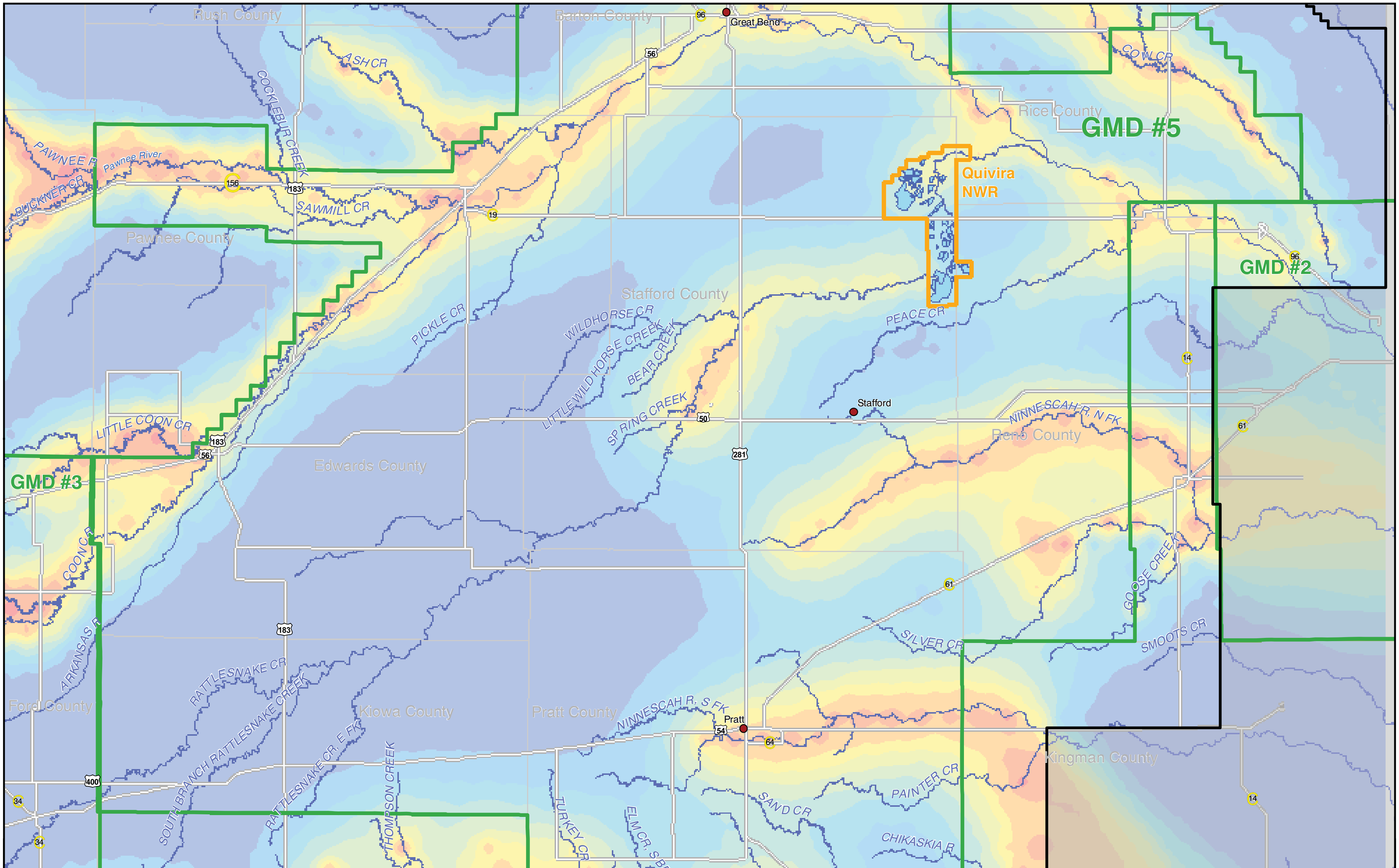
Change in Stream Leakage (cfs per cell)
(Average 2000s stream leakage minus average 1960s leakage)

- -1.9 to -0.25
- -0.25 to 0.0
- 0.0 to 0.25
- 0.25 to 2.0

0 5 10 15 20 25 Miles

5/19/2010 ses/WPB Figure50.mxd

FIGURE 50. Simulated Change in Stream Leakage



EXPLANATION

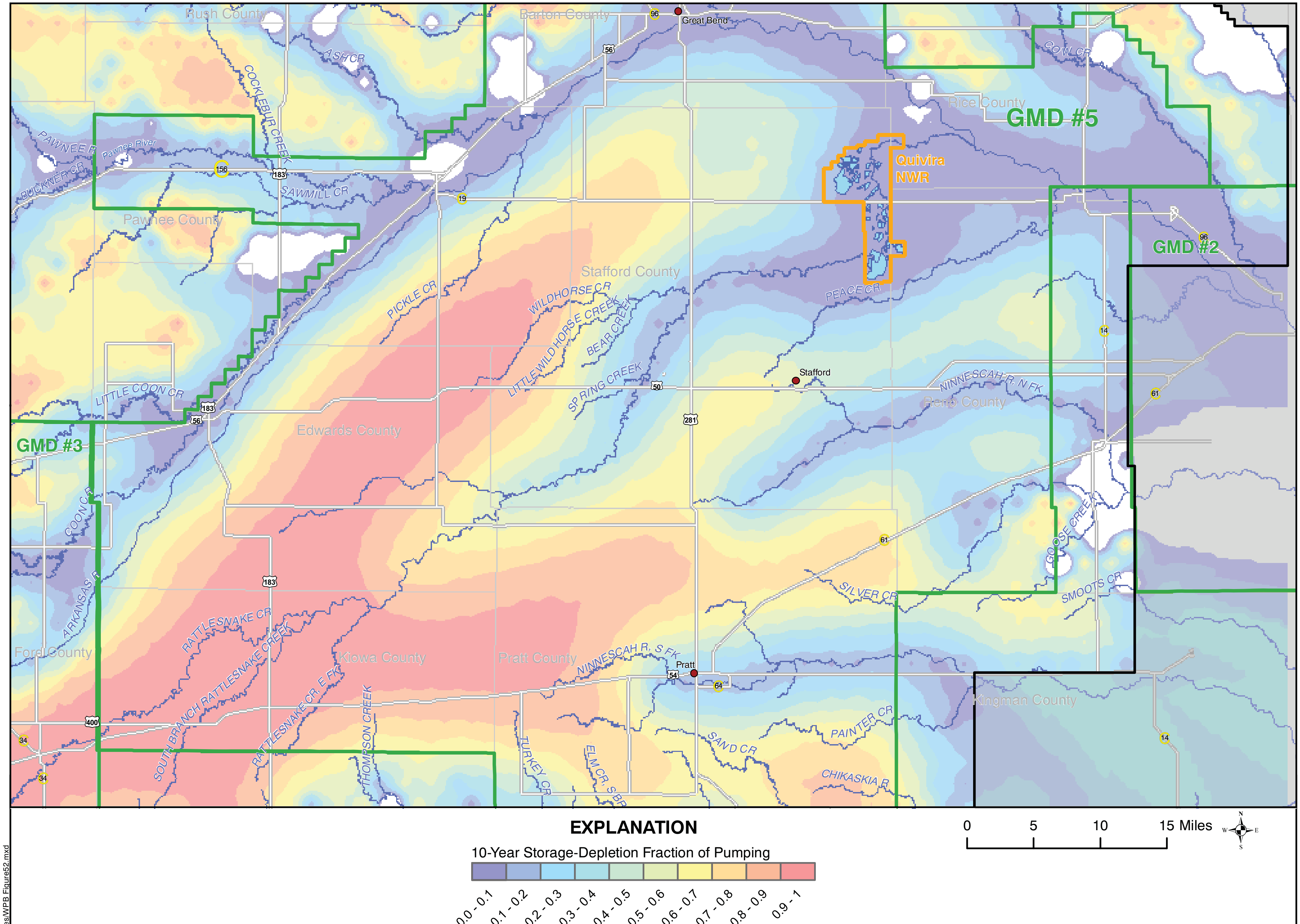
10-Year Stream-Depletion Fraction of Pumping

0.0 - 0.1 | 0.1 - 0.2 | 0.2 - 0.3 | 0.3 - 0.4 | 0.4 - 0.5 | 0.5 - 0.6 | 0.6 - 0.7 | 0.7 - 0.8 | 0.8 - 0.9 | 0.9 - 1

0 5 10 15 Miles

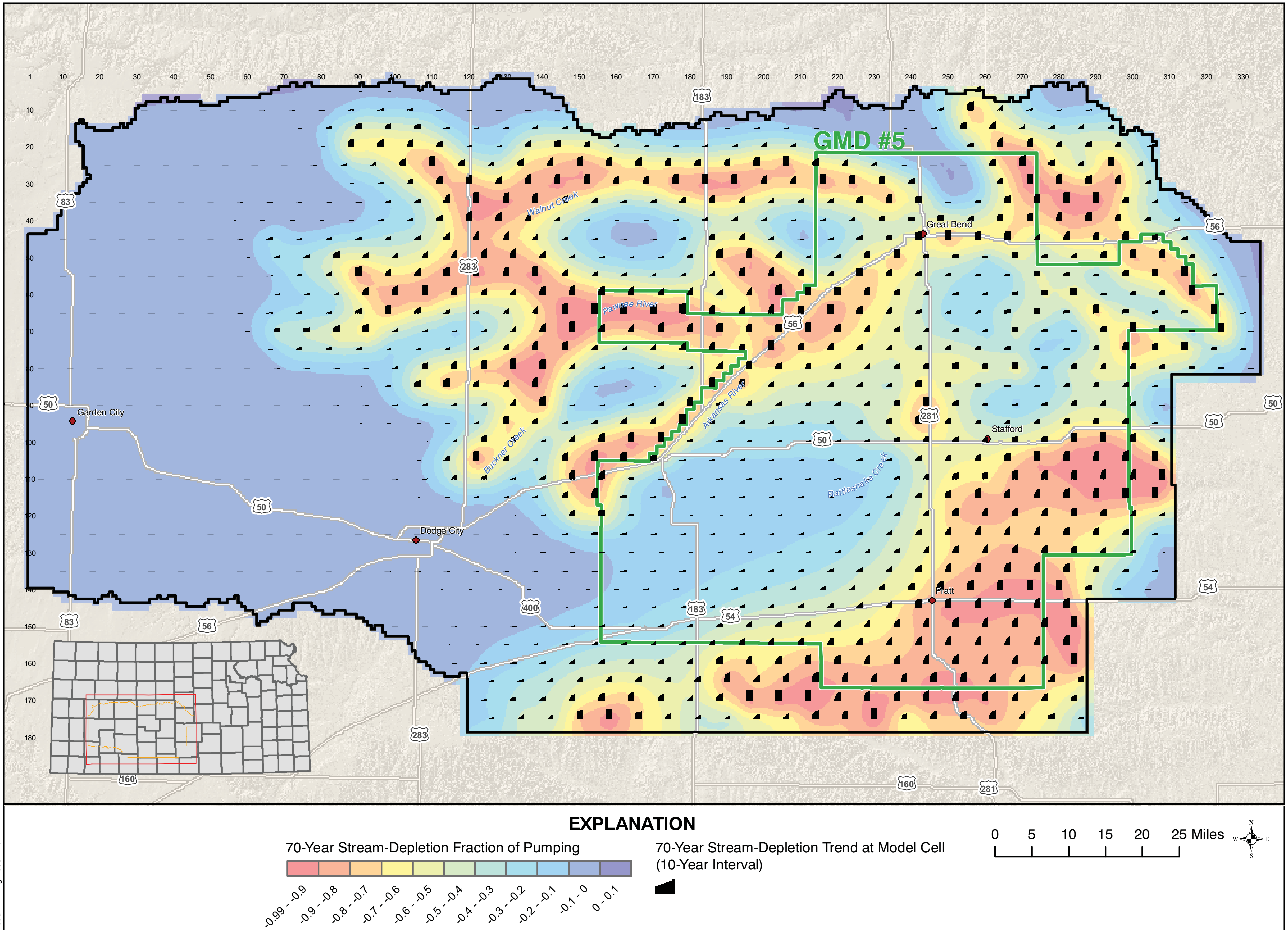
6/11/2010 ses/WPB Figure51.mxd

FIGURE 51. Ten-Year Stream-Depletion Fraction of Pumping (From Year 2020 Condition to Year 2030)



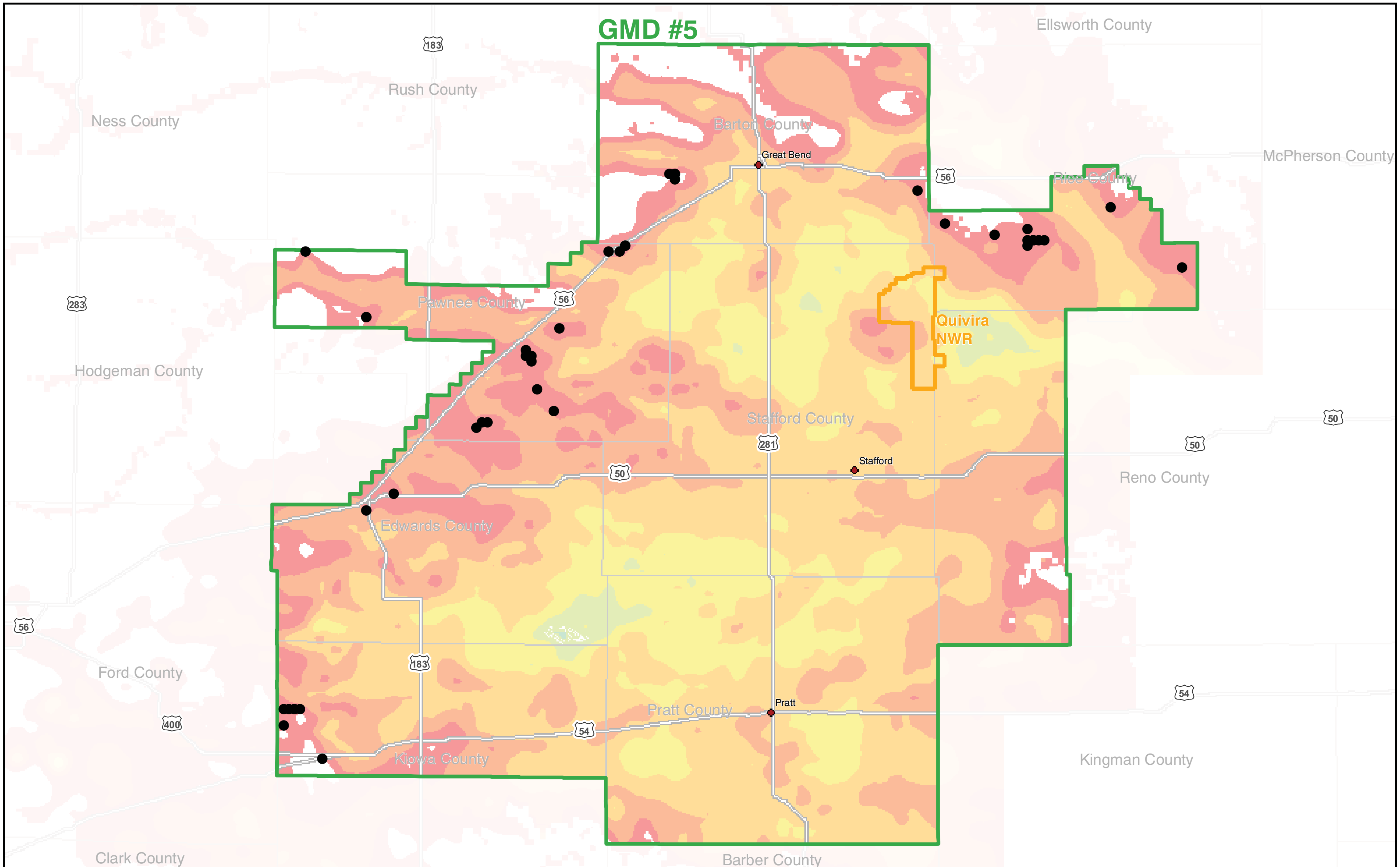
6/11/2010 ses/WPB Figure52.mxd

FIGURE 52. Ten-Year Storage-Depletion Fraction of Pumping (From Year 2020 Condition to Year 2030)



5/25/2010 ses/WPB Figure53.mxd

FIGURE 53. 70-Year Stream-Depletion Fraction of Pumping (From Long-Term Sustainable Condition)



EXPLANATION

● MNW with Reduced Yield at Long-Term Sustainable Condition

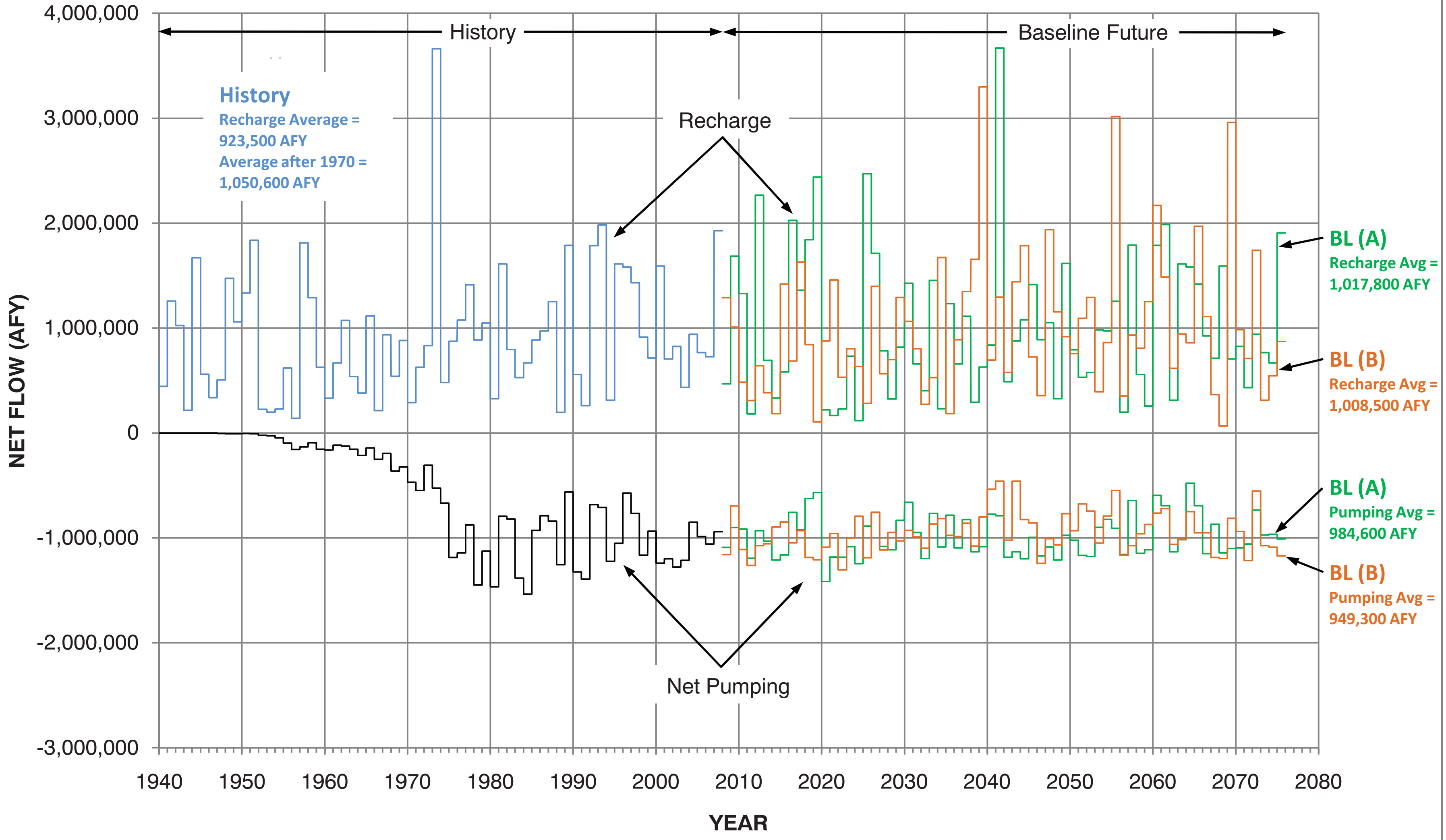
Ultimate Saturated Thickness (ft)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
>250

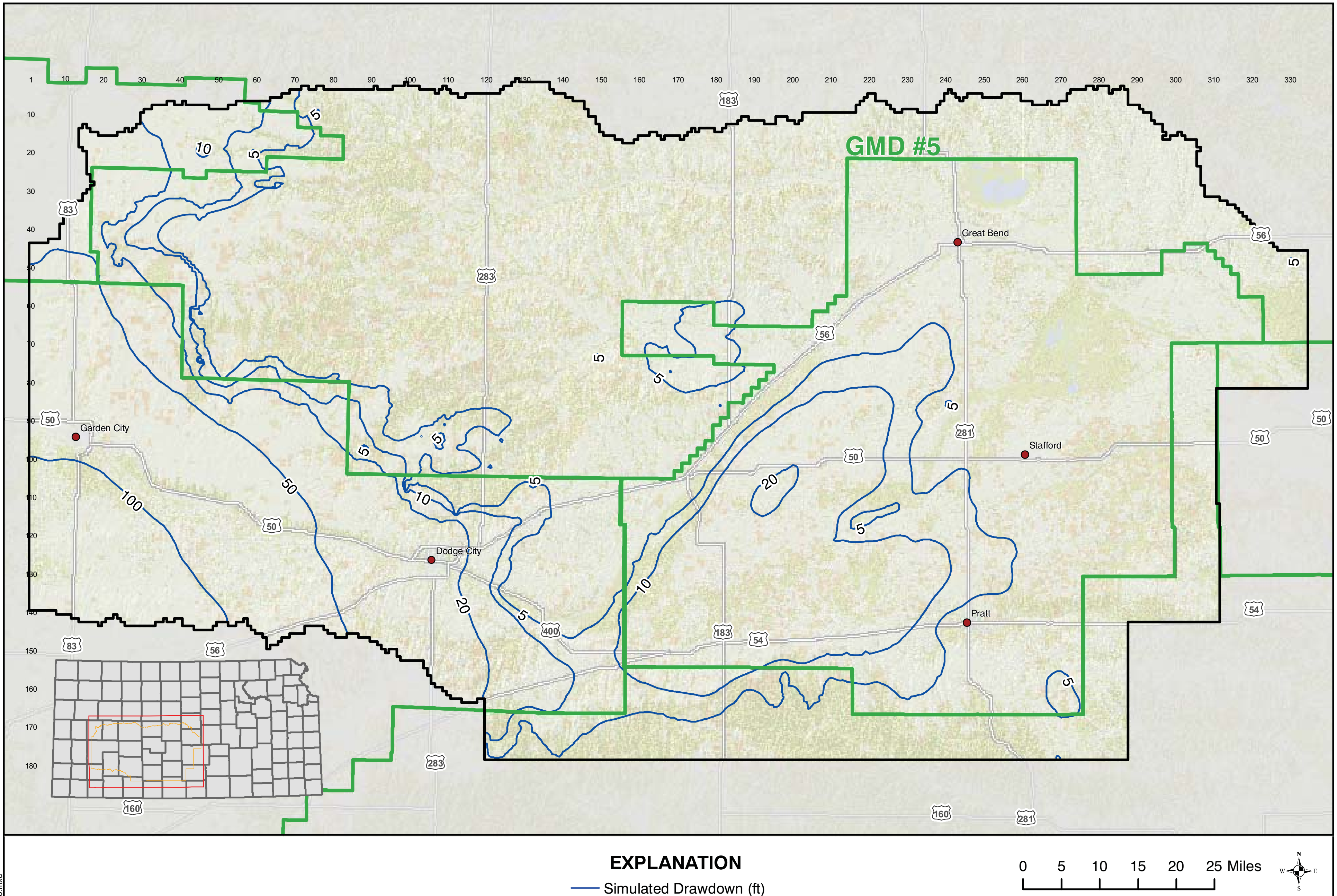
0 5 10 15 Miles

5/25/2010 ses/WPB Figure54.mxd

FIGURE 54. Long-Term Sustainable Saturated Thickness

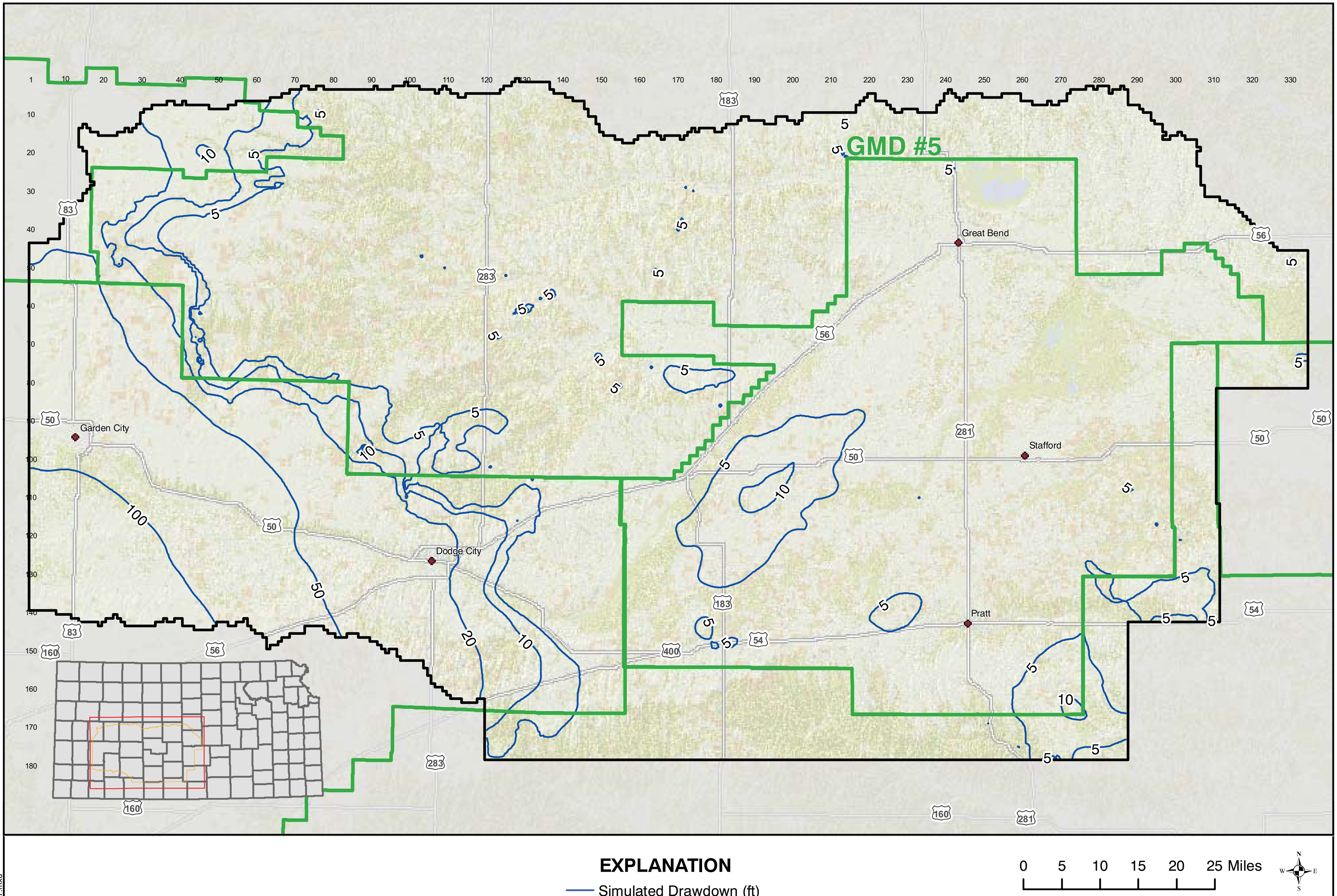
FIGURE 55
HISTORY AND BASELINE AVERAGE ANNUAL NET FLOW





6/11/2010 ses/WPB Figure56.mxd

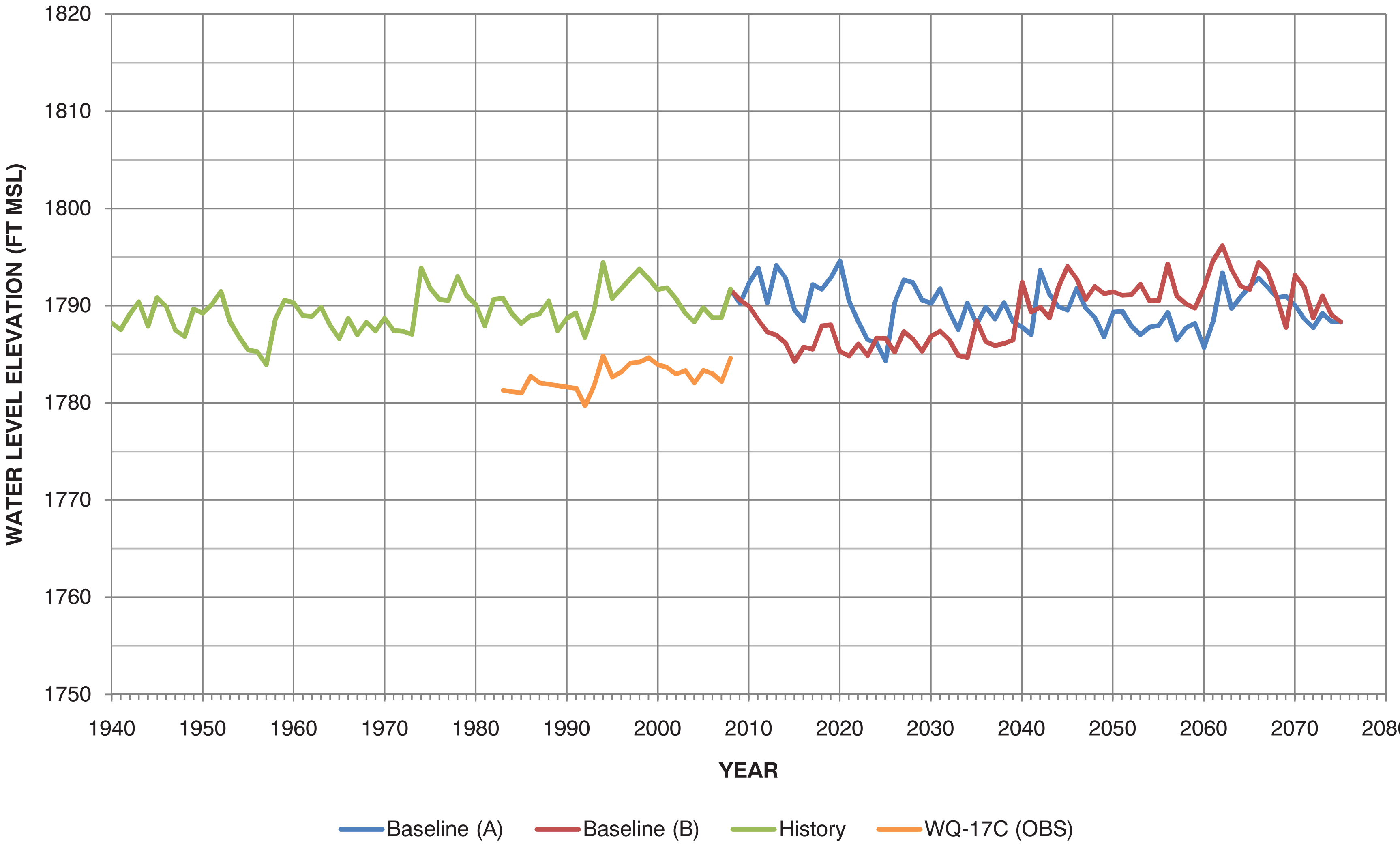
FIGURE 56. Baseline (A) Water-Level Change 68-Year Future



6/11/2010 ses/WPB Figure57.mxd

FIGURE 57. Baseline (B) Water-Level Change 68-Year Future

FIGURE 58
BASELINE A AND B HYDROGRAPH OF WELL WQ-17 (MAP ID 2)



MODEL

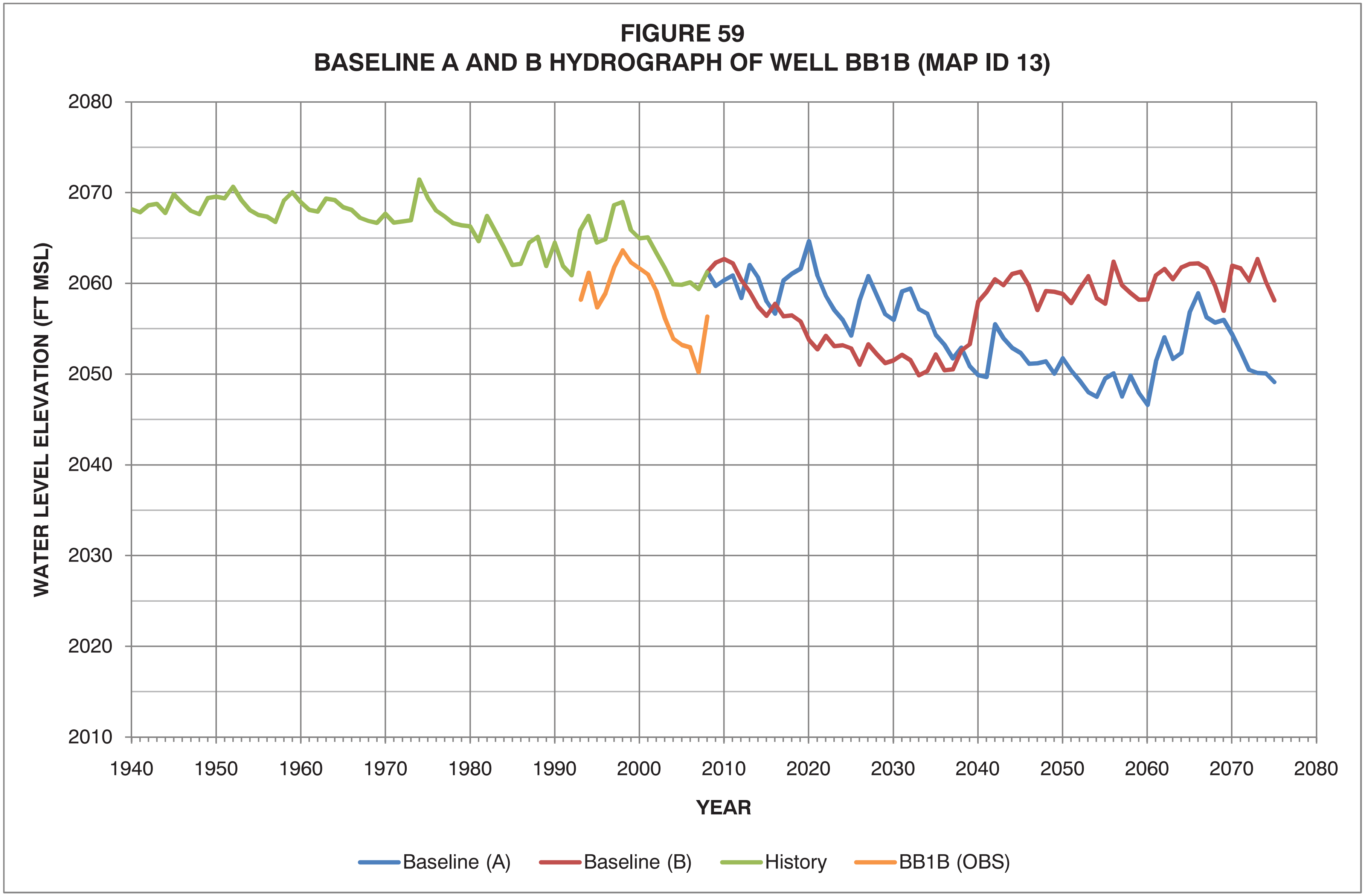


FIGURE 59
BASELINE A AND B HYDROGRAPH OF WELL BB1B (MAP ID 13)
2080
2070
2060
2050
2040
2030
2020
2010
WATER LEVEL ELEVATION (FT MSL)
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
YEAR
Baseline (A)
Baseline (B)
History
BB1B (OBS)

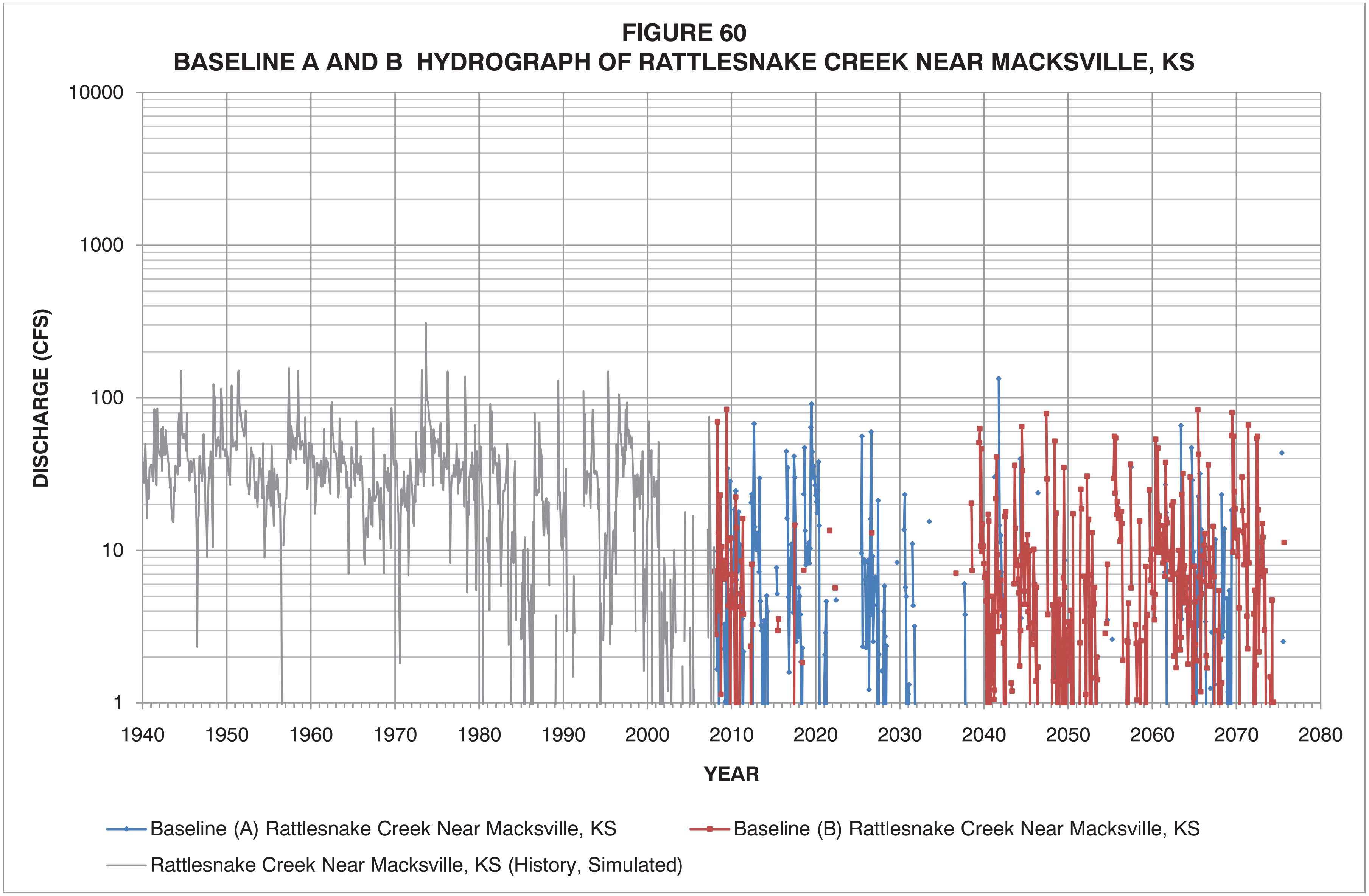


FIGURE 60
BASELINE A AND B HYDROGRAPH OF RATTLESNAKE CREEK NEAR MACKSVILLE, KS
DISCHARGE (CFS)
10000
1000
100
10
1
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
YEAR
Baseline (A) Rattlesnake Creek Near Macksville, KS
Baseline (B) Rattlesnake Creek Near Macksville, KS
Rattlesnake Creek Near Macksville, KS (History, Simulated)

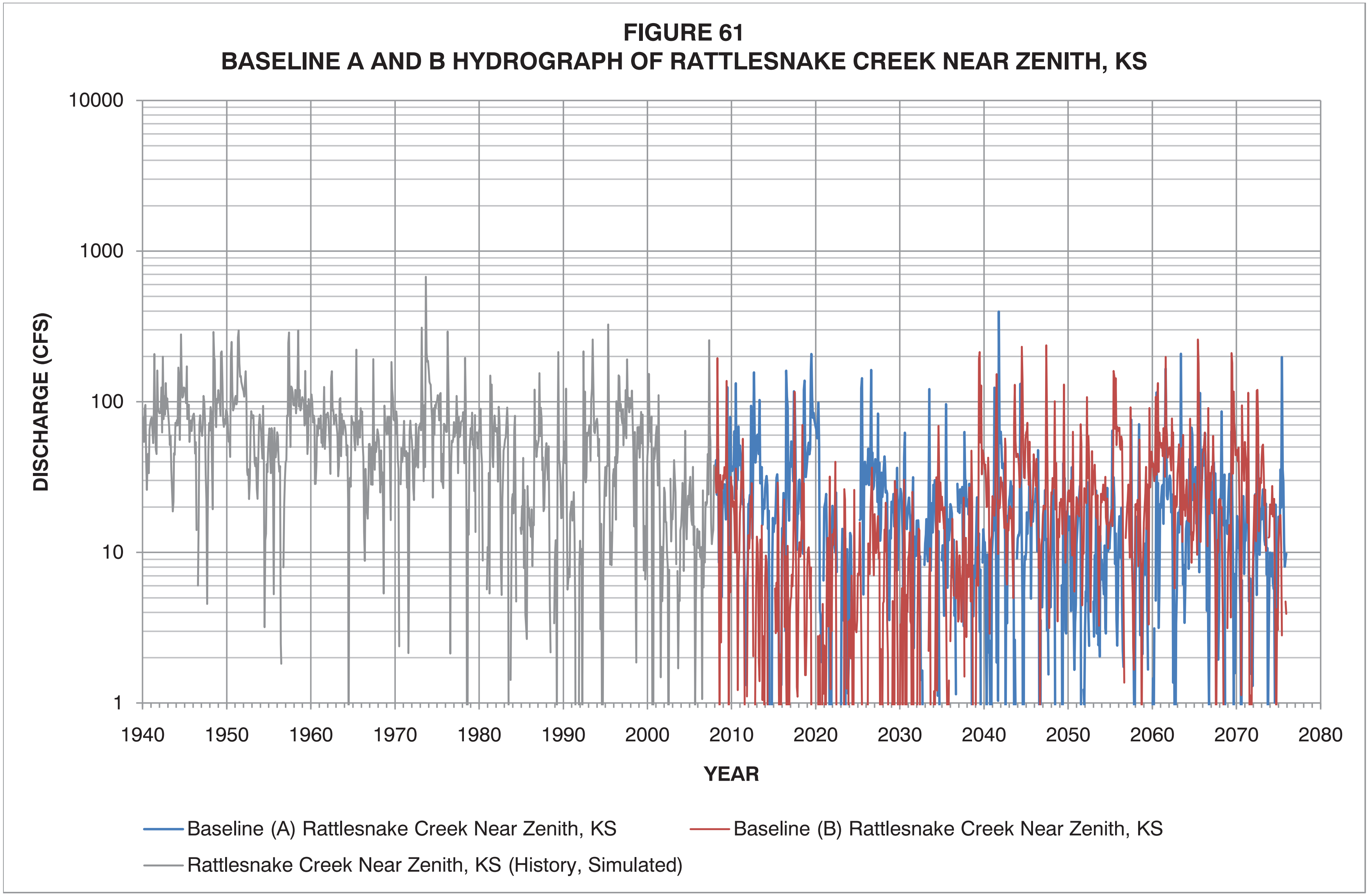


FIGURE 61
BASELINE A AND B HYDROGRAPH OF RATTLESNAKE CREEK NEAR ZENITH, KS
10000
1000
100
10
1
DISCHARGE (CFS)
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
YEAR
Baseline (A) Rattlesnake Creek Near Zenith, KS
Baseline (B) Rattlesnake Creek Near Zenith, KS
Rattlesnake Creek Near Zenith, KS (History, Simulated)

FIGURE 62
BASELINE A AND B DURATION CURVE OF RATTLESNAKE CREEK NEAR MACKSVILLE, KS

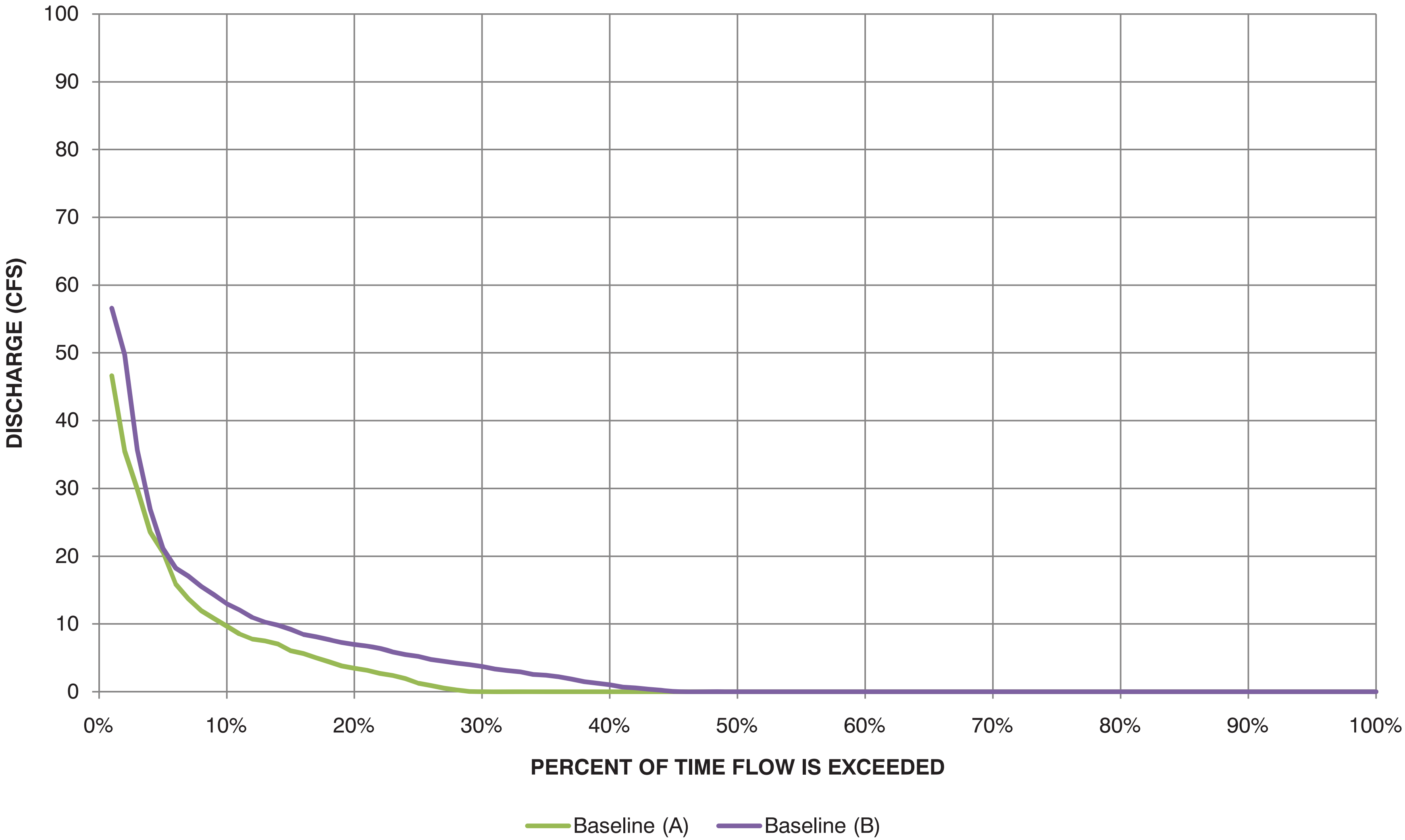
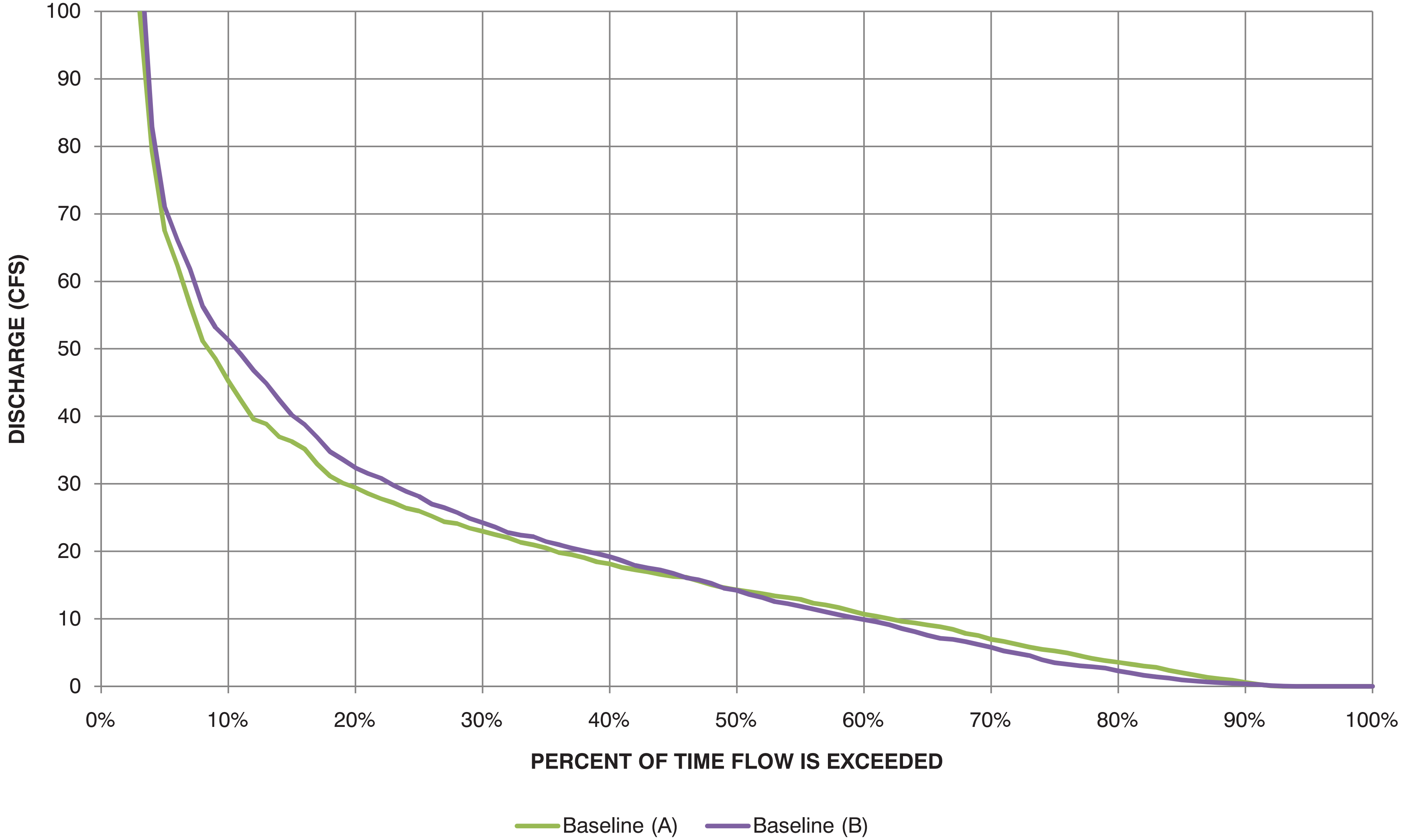
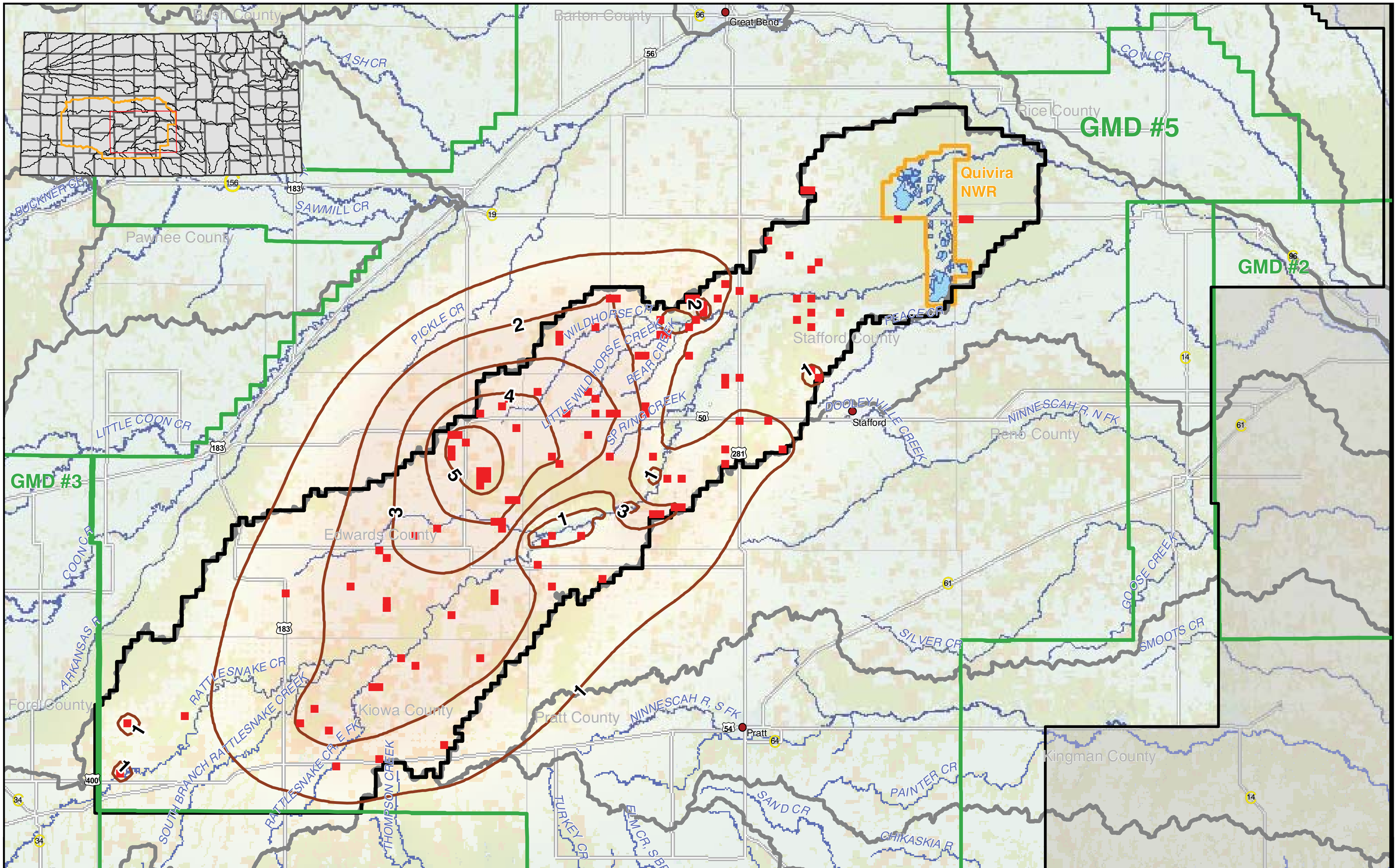


FIGURE 63
BASELINE A AND B DURATION CURVE OF RATTLESNAKE CREEK NEAR ZENITH, KS





EXPLANATION

- POD with post-April 12, 1984 priority with pumping in future baseline, off in scenario
- Buildup contour due to scenario (ft)

0 5 10 15 Miles

6/11/2010 ses/WPB Figure64.mxd

FIGURE 64. Water-Table Buildup at Year 2075 Due to Priority Curtailment

MODEL

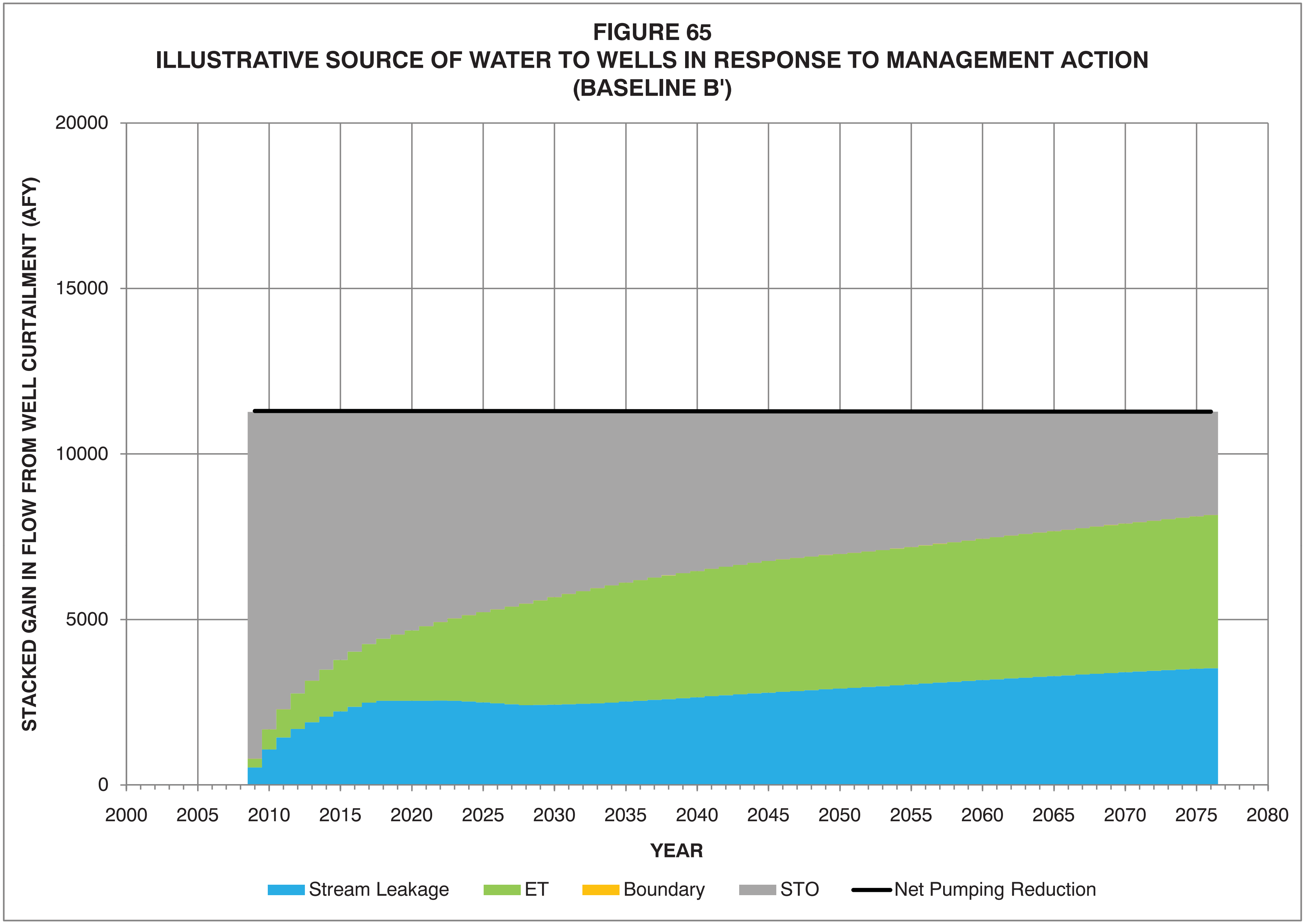


Fig65.xlsb
DR
6/16/2010

FIGURE 66
MANAGEMENT ACTION EFFECT AT WELL WQ-17 (MAP ID 2)

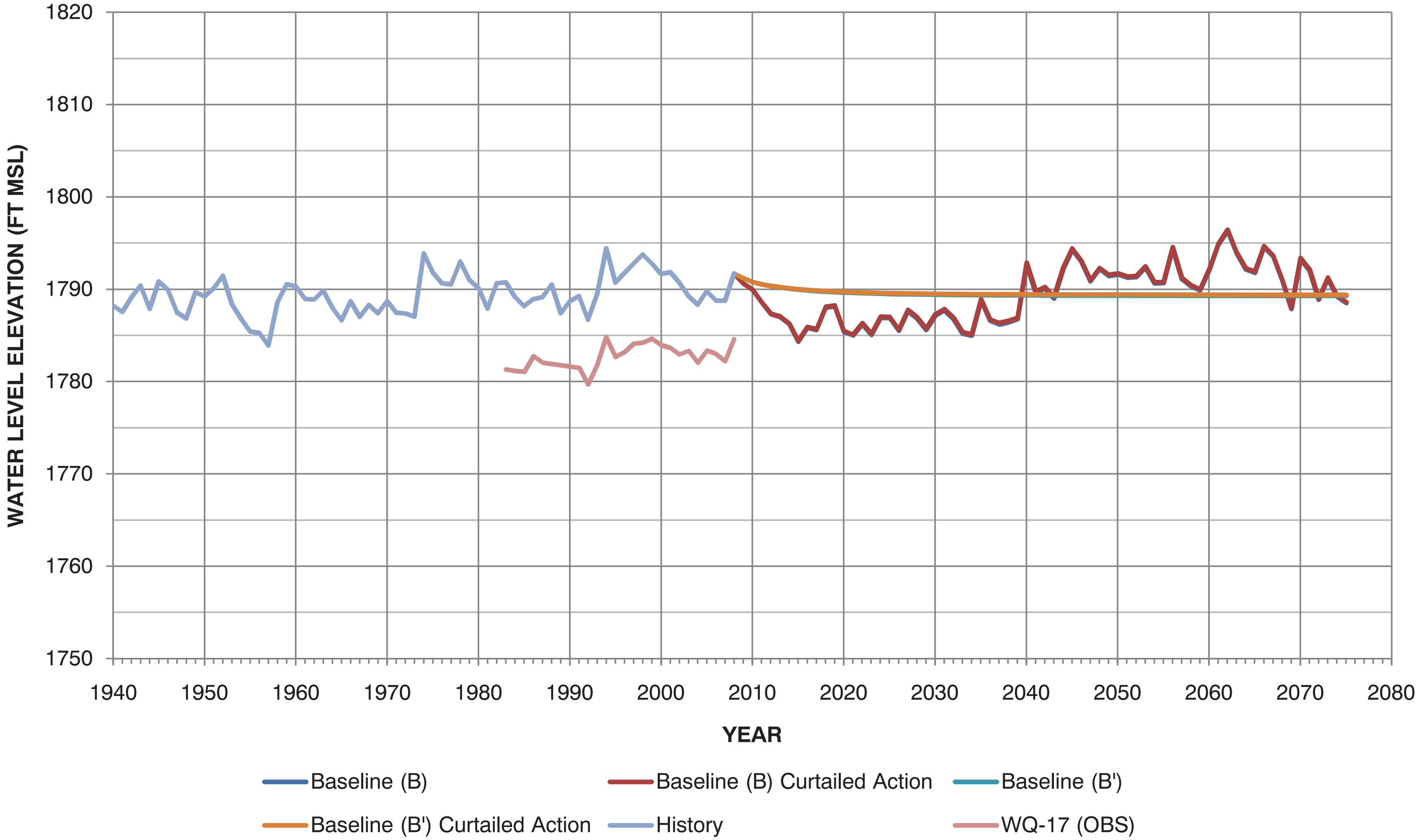


FIGURE 67
MANAGEMENT ACTION EFFECT AT WELL BB1B (MAP ID 13)

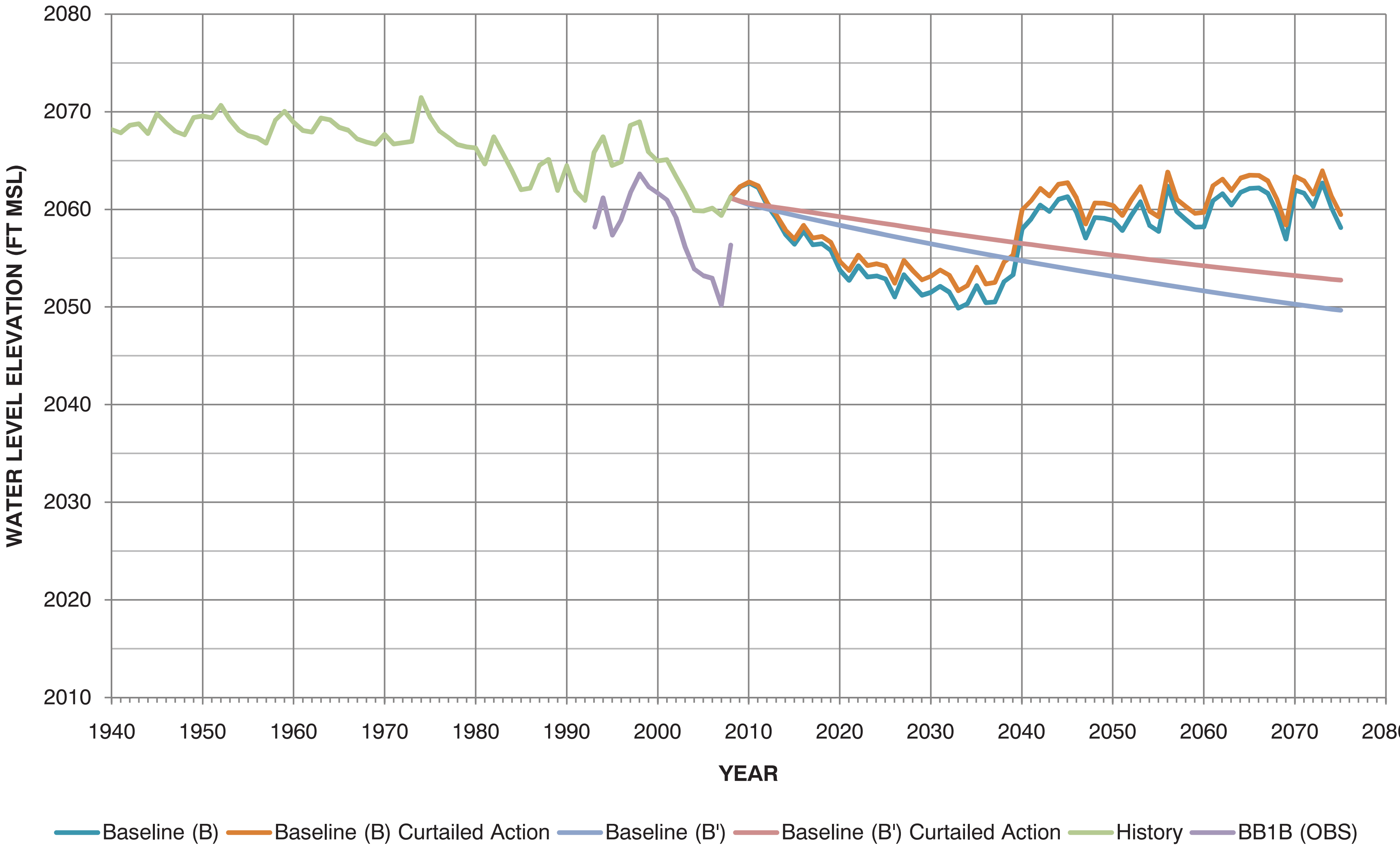
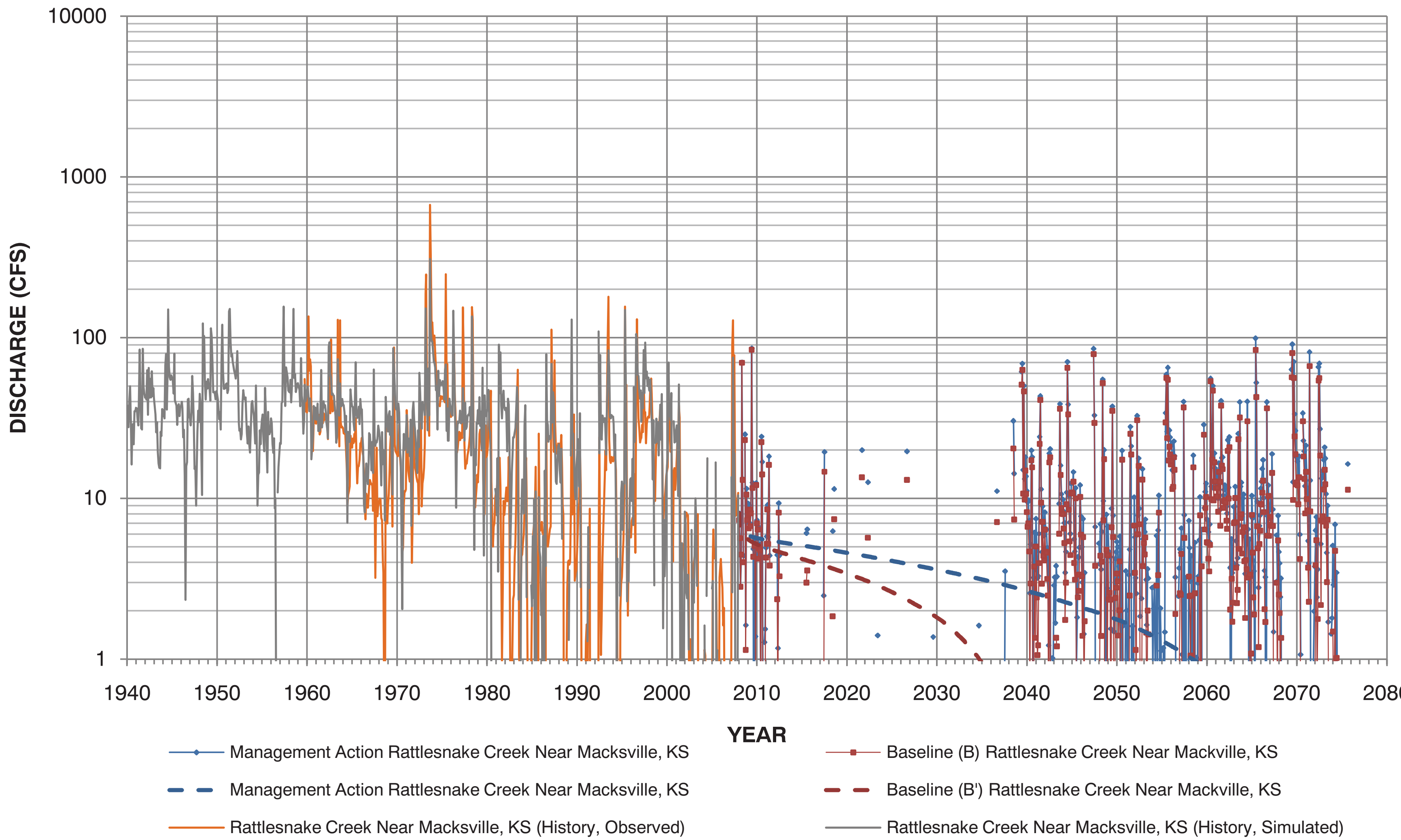


FIGURE 68
MANAGEMENT ACTION EFFECT AT RATTLESNAKE CREEK NEAR MACKSVILLE, KS



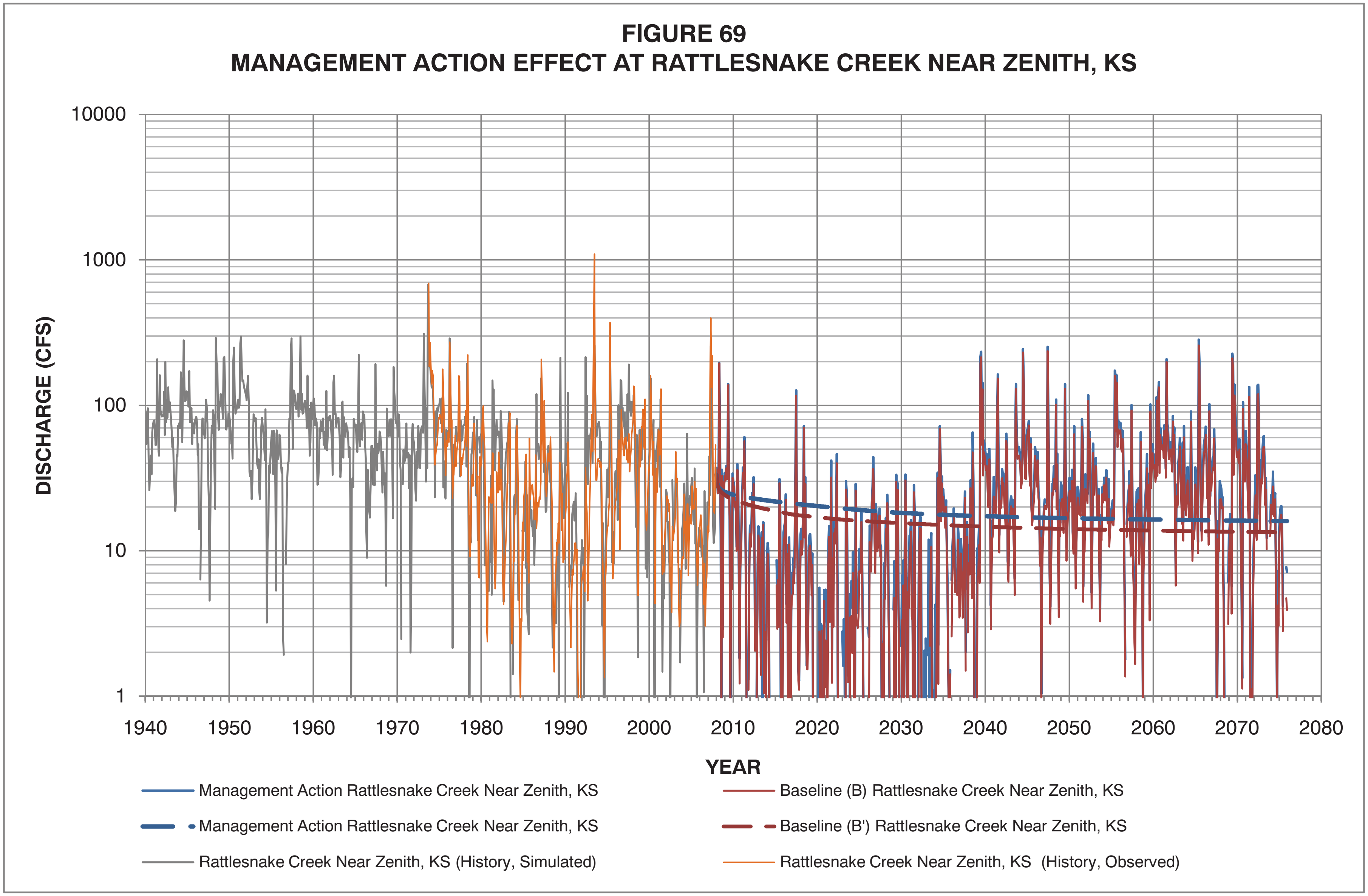


FIGURE 69
MANAGEMENT ACTION EFFECT AT RATTLESNAKE CREEK NEAR ZENITH, KS
DISCHARGE (CFS)
10000
1000
100
10
1
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
YEAR
Management Action Rattlesnake Creek Near Zenith, KS
Management Action Rattlesnake Creek Near Zenith, KS
Rattlesnake Creek Near Zenith, KS (History, Simulated)
Baseline (B) Rattlesnake Creek Near Zenith, KS
Baseline (B') Rattlesnake Creek Near Zenith, KS
Rattlesnake Creek Near Zenith, KS (History, Observed)

MODEL

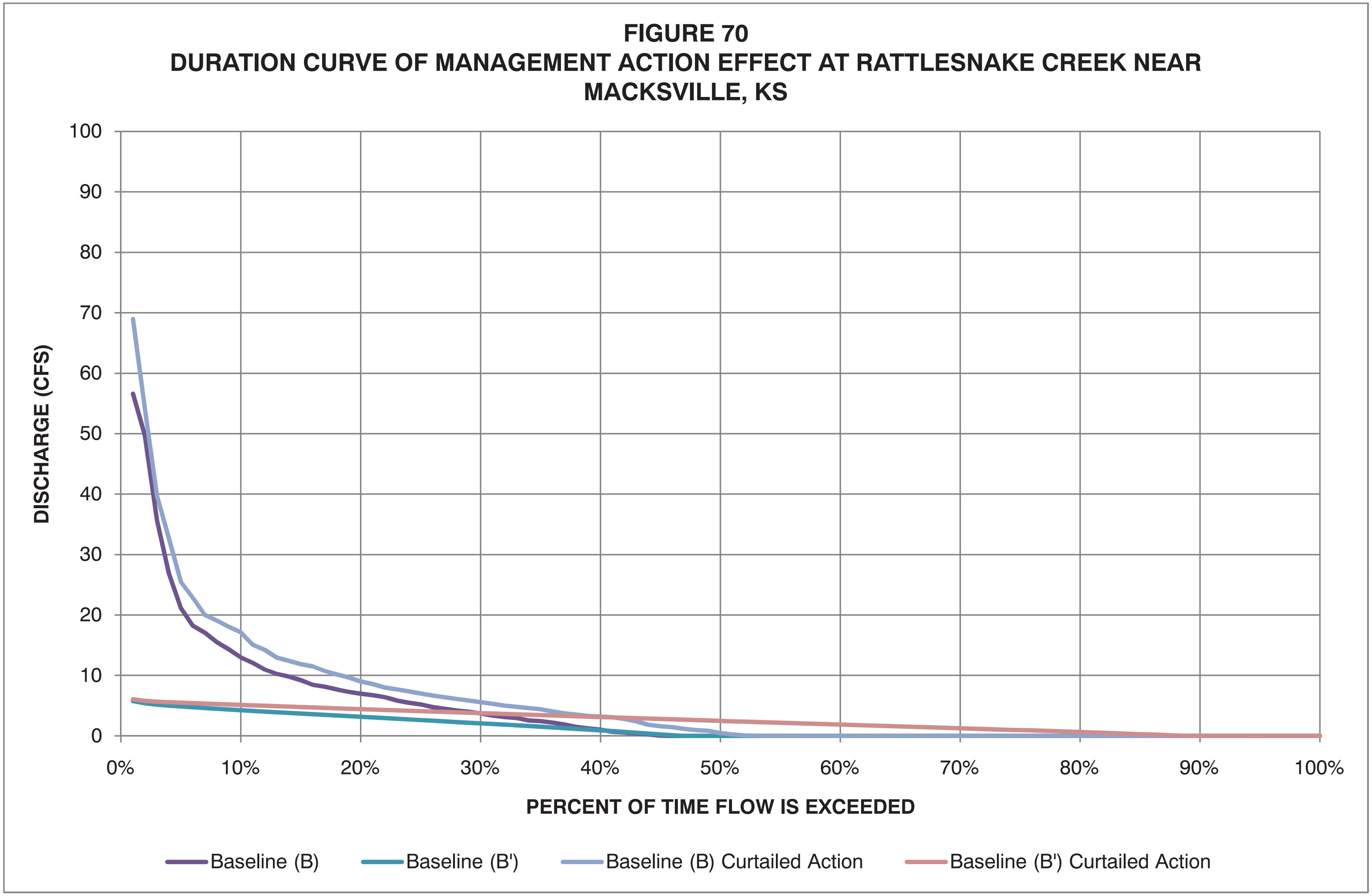
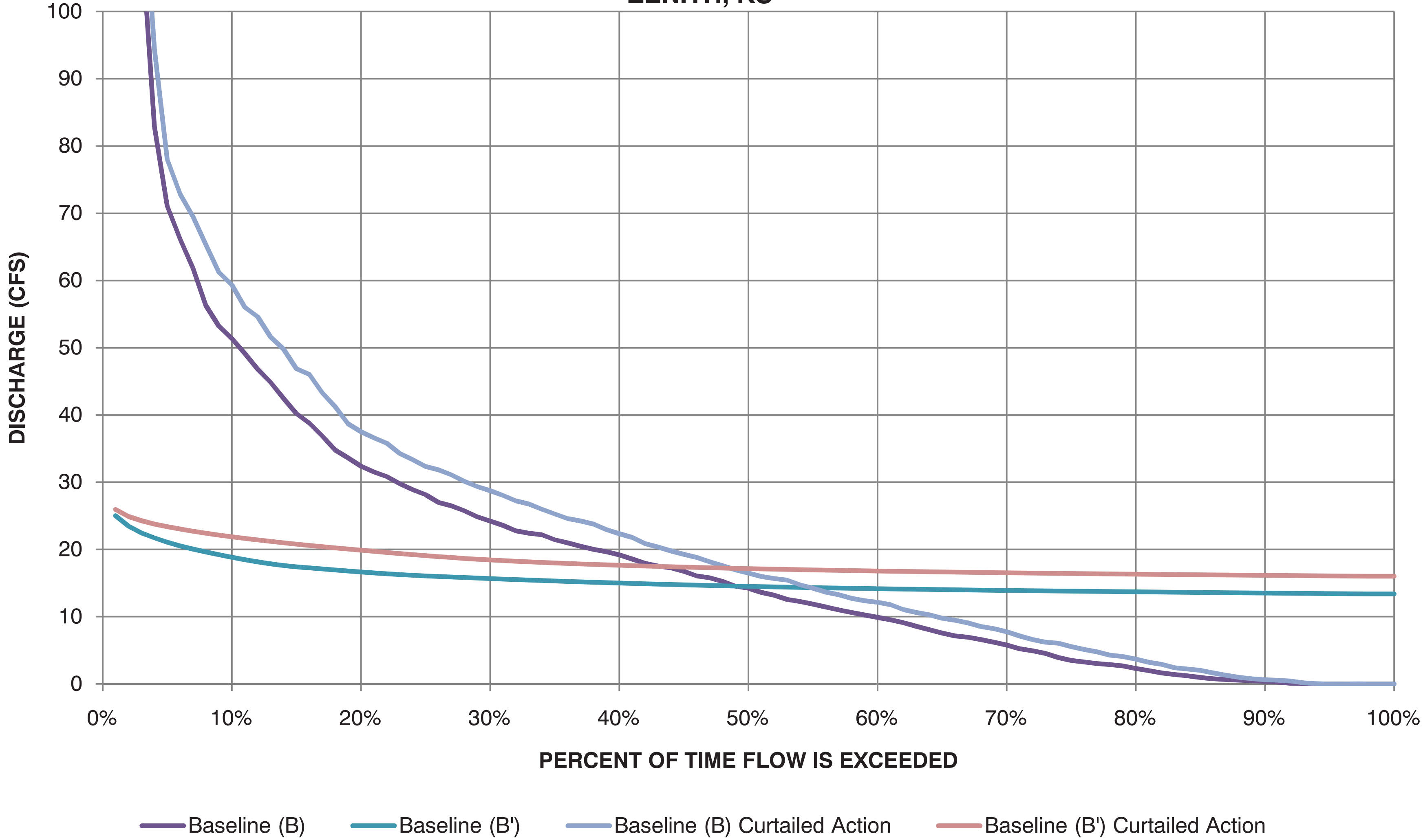


FIGURE 70
DURATION CURVE OF MANAGEMENT ACTION EFFECT AT RATTLESNAKE CREEK NEAR MACKSVILLE, KS
DISCHARGE (CFS)
100
90
80
70
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
PERCENT OF TIME FLOW IS EXCEEDED
Baseline (B)
Baseline (B')
Baseline (B) Curtailed Action
Baseline (B') Curtailed Action

FIGURE 71
DURATION CURVE OF MANAGEMENT ACTION EFFECT AT RATTLESNAKE CREEK NEAR ZENITH, KS



Figs65to70.xlsb
BY
6/15/2010