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OPEN-FILE REPORT 97-UR

INVESTIGATION OF INDUCED RIVER RECHARGE IN THE LEWIS AND CLARK REGIONAL WATER SYSTEM WELLFIELD

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2022

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INTRODUCTION

The Lewis and Clark Regional Water System (LCRWS) is a provider of water to cities and rural water systems in southeast South Dakota, northwest Iowa, and southwest Minnesota. The water is sourced from 11 production wells in the Elk Point management unit of the Missouri aquifer (Missouri: Elk Point aquifer), located south of Vermillion, South Dakota, adjacent to the Missouri River (fig. 1). These wells collectively make up the Mulberry Bend wellfield for LCRWS and in 2021 supplied an average of 19.91 million gallons per day (MGD) to 15 cities and rural water systems.

The purpose of this report is to quantify the amount of water the Missouri River contributes to the Mulberry Bend wellfield. A numerical model was created using the computer software Groundwater Modeling System (GMS) by Aquaveo (Aquaveo, 2020) which is a Graphical User Interface for MODFLOW and other analytical codes. This program solves for MODFLOW, the United States Geological Survey’s (USGS) modular three-dimensional finite difference ground water flow modeling program (Harbaugh, 2005). MODFLOW yields the distribution of hydraulic head in a flow system. The model was used to estimate the percentage of induced flow to production wells from the Missouri River.

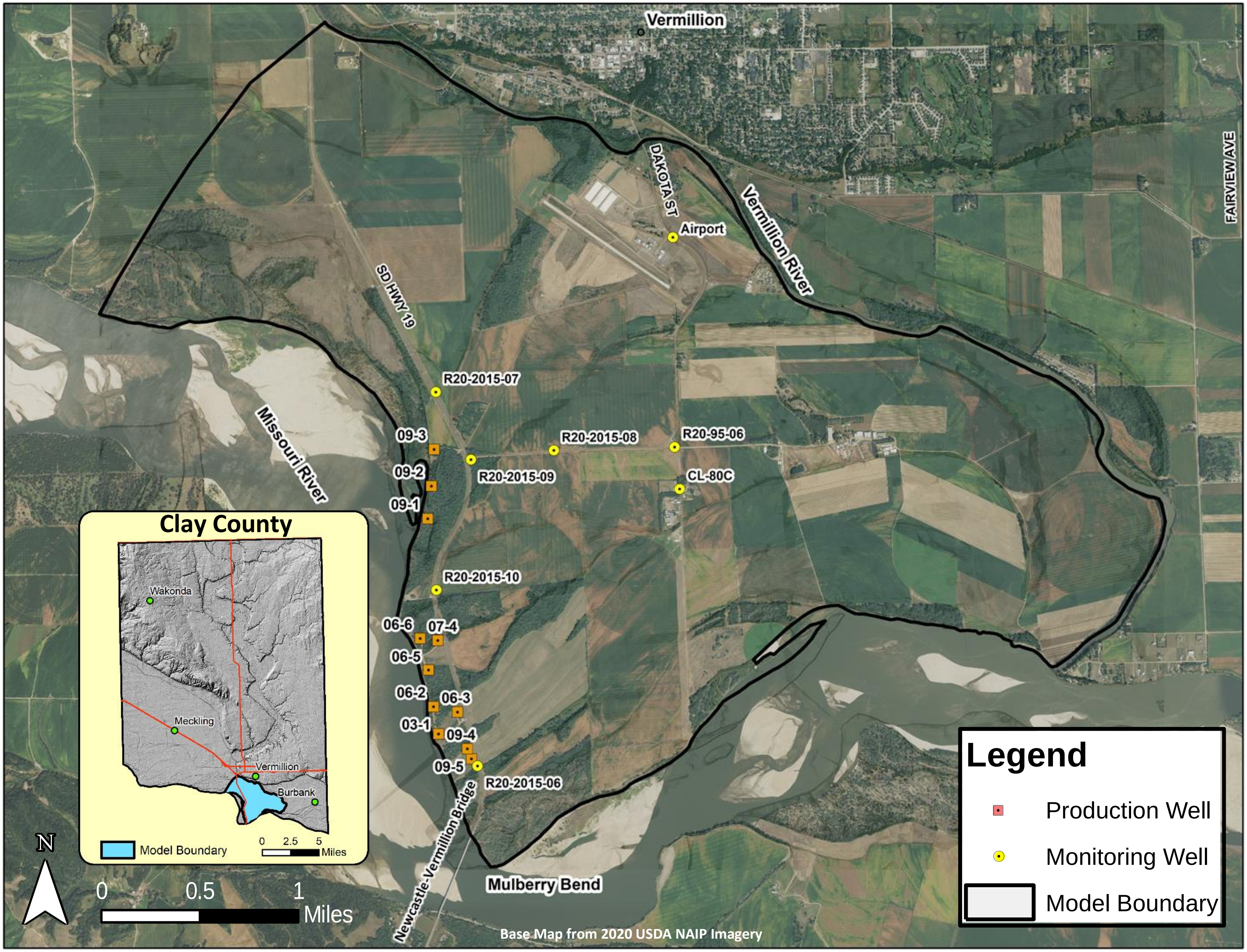
Previous Investigations

The aquifer properties of the LCRWS Mulberry Bend wellfield were previously investigated by Wittman Hydro Planning Associates (WHPA) (2008) and by Layne Hydro (2011). Impacts on the water table from pumping of the production wells were assessed by the South Dakota Geological Survey (SDGS) between February 2015 and September 2015 (Filipovic, 2016). The SDGS installed five monitoring wells, monitored water levels in eight monitoring wells (fig. 1) and measured the stage of the Missouri River. The SDGS report also included a compilation of data from the WHPA and Layne Hydro wellfield investigation reports. Filipovic (2016) concluded that the impact from pumping the 11 LCRWS production wells does not extend beyond 0.4 miles from the wellfield.

Numerical Model Development

A numerical model calculates a water budget for the model domain which can be analyzed to determine the sources of water that supply a well. A transient finite difference ground water flow model was created using MODFLOW. In addition to MODFLOW, the packages MODPATH (Pollock, 2017) and ZONEBUDGET (Harbaugh, 1990) were used in the numerical model.

MODFLOW 2005, an updated version of the original MODFLOW, was used with the Block-Centered Flow (BCF) package and the Preconditioned Conjugate-Gradient (PCG) solver (Harbaugh, et. al., 2017). The PCG solver is used to solve the finite difference equations in each step of a MODFLOW stress period, and the BCF package is used to specify flow properties between cells. MODPATH is the USGS particle tracking program which was used to create capture zones for this model. The capture zones were used to create zones for ZONEBUDGET, a program that



Base Map from 2020 USDA NAIP Imagery

Figure 1. Location of production wells, monitoring wells, and the model boundary.

computes sub-regional water budgets using results from MODFLOW (Harbaugh, 1990). The results from ZONEBUDGET were used to calculate the percentage of Missouri River water contribution to a capture zone. The finite difference grid was generated using GMS.

Calibration and Sensitivity Analysis

Calibration is the process of adjusting input parameters within a range of acceptable values determined in the conceptual model. The purpose of calibration is to match hydraulic heads observed in the field to those simulated by the numerical model. Hydraulic heads were calibrated to measurements taken in 8 monitoring wells within the model domain (Filipovic, 2016). Parameter Estimation (PEST), an automated parameter estimation code, was used to calibrate the model and to calculate parameter sensitivities of the aquifer's hydraulic properties and recharge to the aquifer.

Site Location and Model Boundaries

The study area is located south of the city of Vermillion, South Dakota and near the Mulberry Bend segment of the Missouri River (fig. 1). Model boundaries were drawn mainly from existing geographic features, except the northwestern boundary which is drawn far enough from the production wells as to not influence the model's solution. The Vermillion River is the northern and eastern boundary of the model. The Missouri River is the southern and western boundary of the model (fig. 1). Both rivers act as sources and sinks for the model.

HYDROGEOLOGY

Geology

The Missouri: Elk Point aquifer is composed of glacial outwash. The aquifer contains some clay and silt deposits which occur as lenses, with the bulk of the aquifer material being composed of sand and gravel. The glacial outwash deposits overlie Cretaceous formations including the Greenhorn Limestone and Graneros Shale.

The Missouri: Elk Point aquifer is under unconfined to semiconfined conditions throughout the study area (Rich, 2006). The general direction of ground water flow is to the south and east towards the confluence of the Vermillion and Missouri Rivers where the aquifer naturally discharges into these rivers.

The aquifer ranges from about 45 to 125 feet thick across the study area (fig. 2). Most LCRWS production wells are positioned within the portion of the aquifer that ranges from 100 to 125 feet thick. There is a bedrock high in the central region of the aquifer, thus a slight reduction in aquifer thickness was represented in this area of the model. The aquifer also thins towards the south.

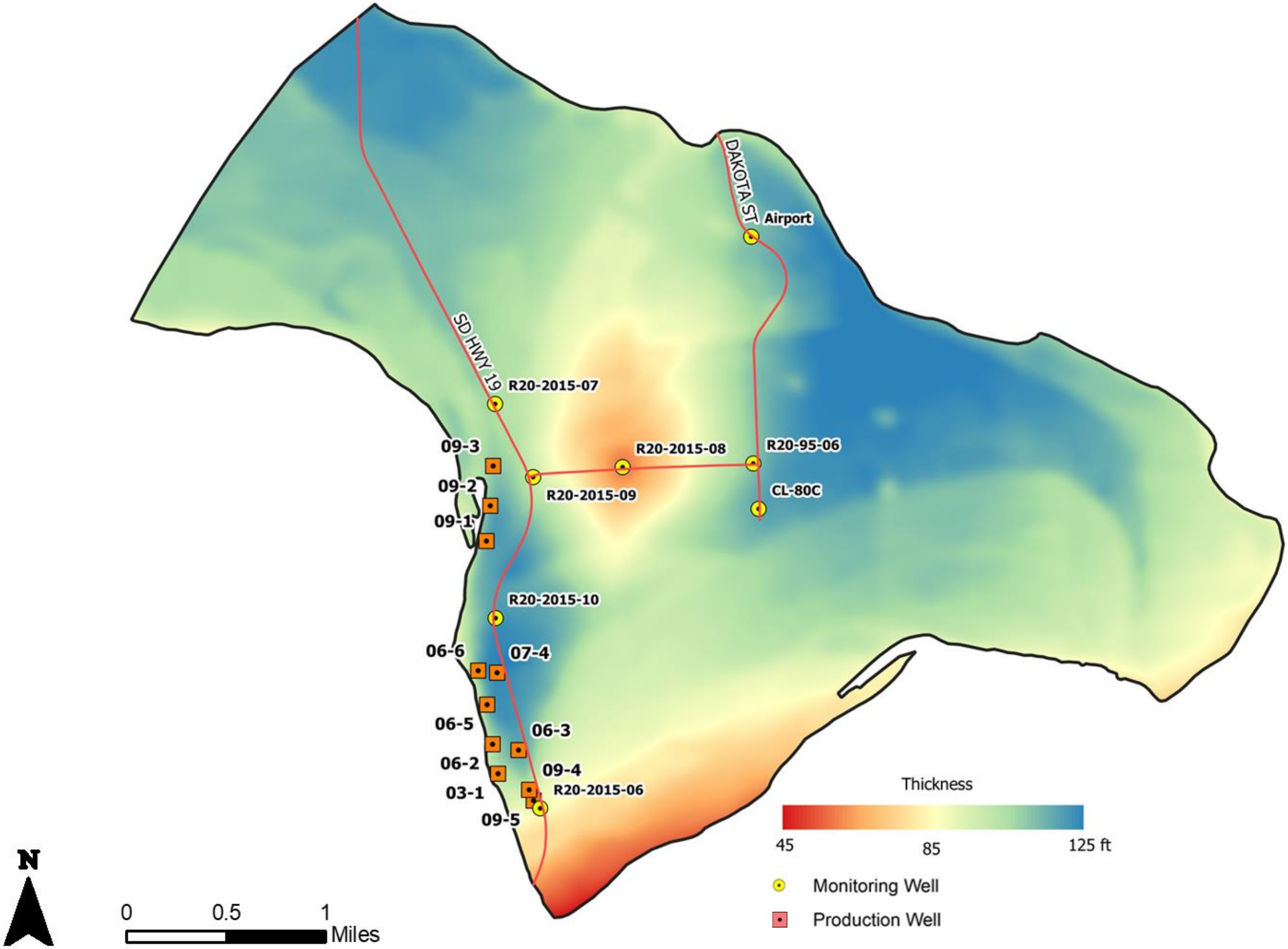


Figure 2. Aquifer thickness.

Hydraulic Conductivity and Transmissivity

Hydraulic conductivity and transmissivity values for the LCRWS production wells are shown in table 1 below. The data in table 1 are from the two wellfield analysis reports (WHPA, 2008 and Layne Hydro, 2011) conducted for the LCRWS and compiled in Filipovic (2016). The data shows that the hydraulic conductivity is within the range of well sorted gravels, well sorted sands, and glacial outwash (Fetter, 2001).

Table 1. Hydraulic conductivity and transmissivity values. Modified from Filipovic (2016)

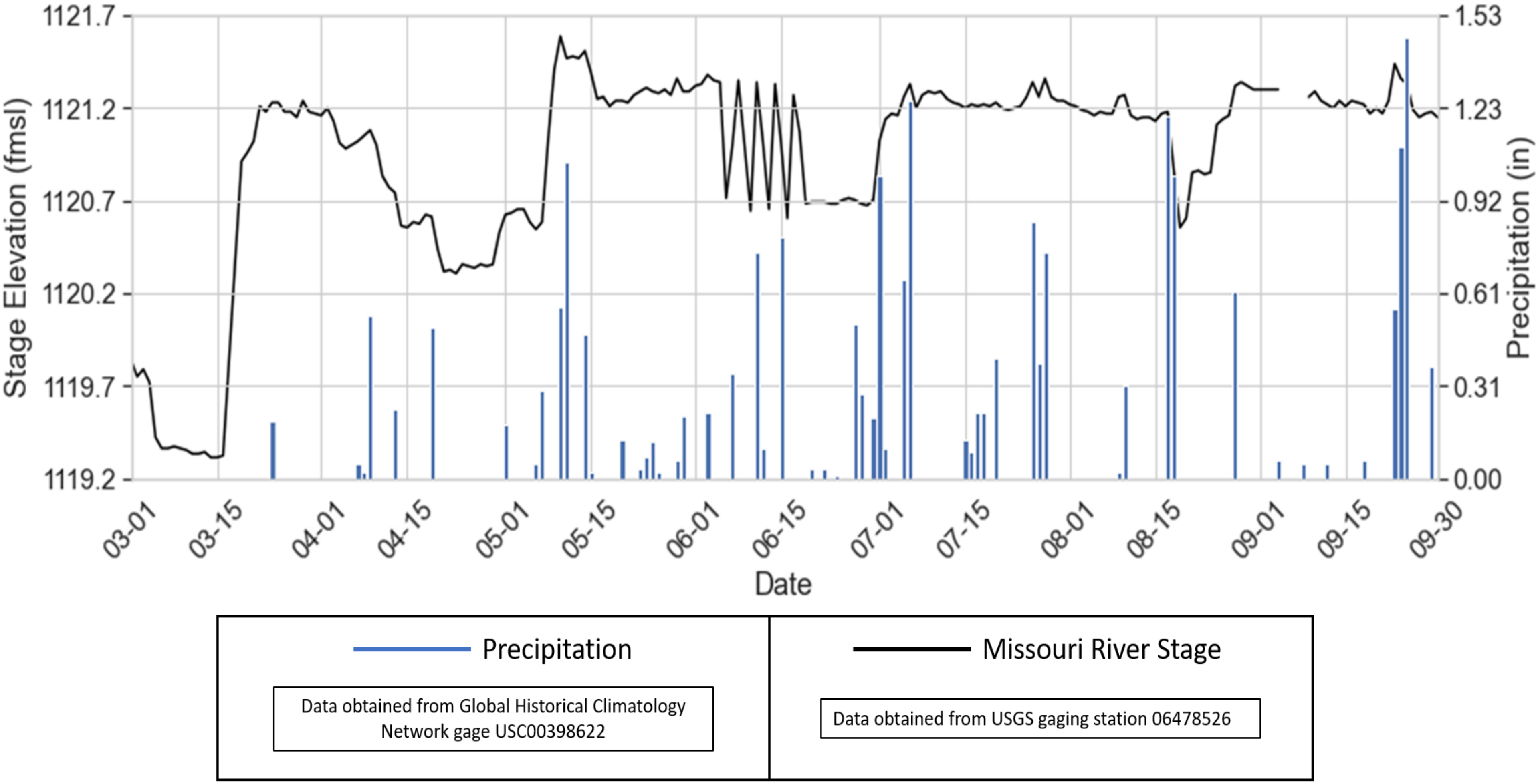
Well	Well Type	Hydraulic Conductivity (ft/day)	Transmissivity (ft^2/day)	Source
06-2	Angle	599	49100	WHPA (2008)
06-3	Vertical	654	69300	WHPA (2008)
06-5	Angle	699	74100	WHPA (2008)
06-6	Angle	233	24500	WHPA (2008)
07-4	Vertical	499	54900	WHPA (2008)
09-01	Vertical	643	64322	Layne Hydro (2011)
09-02	Vertical	322	30598	Layne Hydro (2011)
09-03	Vertical	221	18763	Layne Hydro (2011)
09-04	Vertical	287	35276	Layne Hydro (2011)
09-05	Vertical	172	12382	Layne Hydro (2011)
	Average	**433**	**43324**	
	Minimum	**172**	**12382**	
	Maximum	**699**	**74100**	

Recharge and Discharge

The major sources of recharge to the aquifer are from meteoric precipitation and infiltration from the Missouri River. Precipitation and Missouri River stage data from March 2015 to September 2015 are shown in figure 3. Discharge from the Missouri: Elk Point aquifer is through pumping from the LCRWS production wells, irrigation wells, evapotranspiration, and discharge to the Missouri and Vermillion Rivers.

Well Discharge and Monitoring Wells

There were 11 production wells collectively discharging 13.2 to 22.2 MGD, with an average pumping rate of 18.87 MGD in July of 2015. Daily pumping data was recorded from March 2015 to September 2015 and the pumping rates were combined into 3 groups and divided evenly amongst the wells in each group (Filipovic, 2016) (fig. 4). Irrigation wells were not included in the model because there is a lack of available data on pumping rates and times. The long-term average precipitation for July in this area is 3.3 inches. There was 6.06 inches of precipitation recorded in July 2015 (National Oceanic and Atmospheric Administration, 2022). Due to higher meteoric precipitation in July 2015, irrigation pumping was likely minimal.



Data obtained from Global Historical Climatology Network gage USC00398622

Data obtained from USGS gaging station 06478526

Figure 3. Daily precipitation and Missouri River stage in 2015.

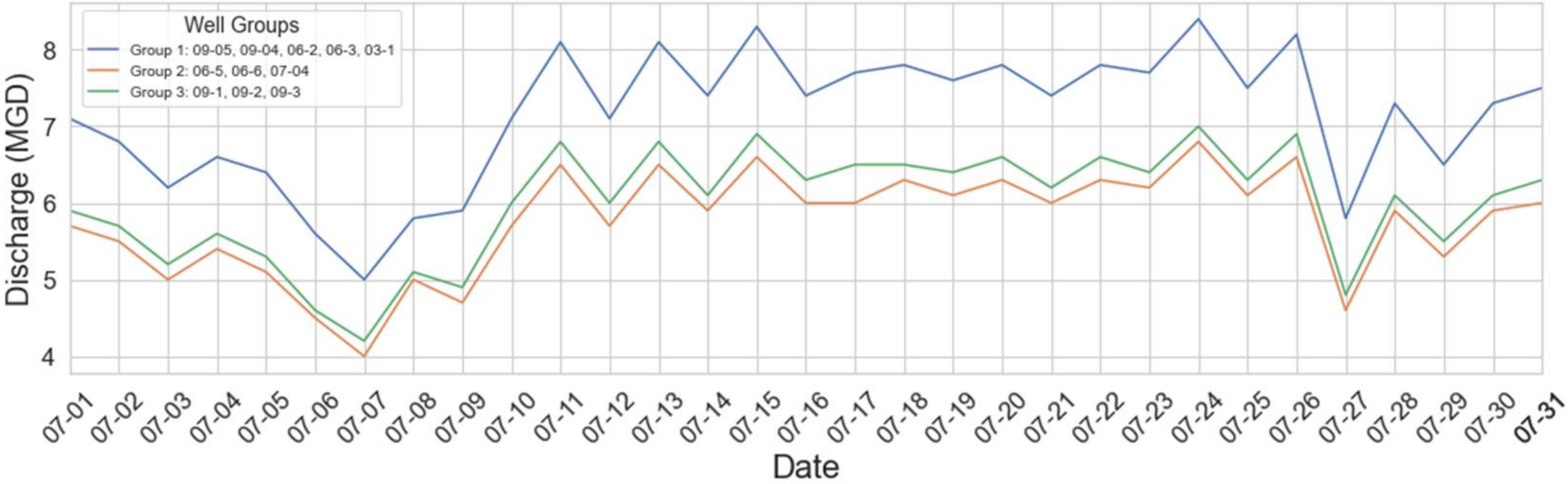


Figure 4. LCRWS production well discharge in July 2015.

NUMERICAL MODEL

Model Design

The hydrogeologic characteristics of the Missouri: Elk Point aquifer at the LCRWS wellfield were simplified into a two-layer homogenous numerical model. The model grid consists of 509 rows and 642 columns which contains 326,778 cells per layer. Each cell within the grid is 49.2 feet by 49.2 feet.

Filipovic (2016) recorded hydraulic head and pumping data from March 2015 through September 2015. Values for the month of July were used to calibrate the model. Hydraulic heads were high in July due to above average recharge to the aquifer by meteoric precipitation. This resulted in a smaller hydraulic gradient between the Missouri River and the aquifer. This provides a more conservative estimate of recharge induced from the Missouri River.

A steady-state model was created first, the resultant hydraulic heads were used as a starting point for the 31-day transient model. The first transient model iteration varied daily well discharge for calibration and the second transient model iteration varied well discharge and river stage.

Model Parameters

Acceptable ranges of values for model parameters were determined from previous work completed in the LCRWS Mulberry Bend wellfield. The following values were used as initial parameter inputs into the model.

Hydraulic Conductivity

Values for hydraulic conductivity range from 172 ft/day to 699 ft/day (table 1). An averaged value of 433 ft/day was used to start the calibration of the steady-state model.

Aquifer Recharge

The value for areal recharge was selected from a ground water resources report by Hedges and others, 1985. Recharge was set to 8.68×10^{-4} ft/day (3.8 in/yr).

Aquifer Discharge

There were 11 production wells collectively discharging 13.2 to 22.2 MGD in July of 2015. The combined pumping rates were divided evenly amongst the wells in each group (fig. 4).

River Stage

During the month of July, river stage was relatively stable which allowed for a constant maximum stage throughout the transient simulation (fig. 3). A measured river stage of 1121.26 feet and values from the USGS gaging station *Missouri River near Maskell, Nebr.* (USGS 06478526) were used to extrapolate the start and end stages of the Missouri River within the model domain. No river stage data was available for the Vermillion River near Vermillion, SD (USGS 06479010) stream gage during 2015, so LiDAR data and end stage values of the Missouri River (the confluence of both rivers) were used to extrapolate river stage values for the Vermillion River.

Storativity

WHPA (2008) calculated storativity values for several wells which were used to estimate values for specific yield for the transient model.

Conductance

The conductance of both riverbeds was determined through an interpretation of riverbed sediments, lithologic logs, manual calibration, and PEST calibration.

Calibration and Sensitivity Analysis

The model was calibrated using manual trial and error and PEST. The daily hydraulic head measurements recorded by Filipovic (2016) were used as calibration targets (fig. 5).

The Missouri River boundary was separated into three segments which were determined from an interpretation of the riverbed sediments and lithologic logs. The three segments are shown in figure 6, labeled North Segment, Middle Segment, and South Segment. The North Segment had little effect on model results, shown through the sensitivity analysis (fig. 7), but calibrated with PEST regardless. The Middle Segment is a backwater along the river where there is little to no current, allowing for finer grained sediments to deposit, which lowers the conductance value of the riverbed within the Middle Segment. The South Segment was designated along the stretch of river where most of the production wells are located. Lithologic logs recorded during the construction of the Newcastle-Vermillion Bridge across the Missouri River showed that the riverbed material is mostly comprised of sand and gravel, suggesting a high conductance value for the South Segment.

Model calibration was considered successful once simulated hydraulic heads arrived within 1 foot of observed hydraulic heads. The final calibrated model parameter values are shown in table 2.

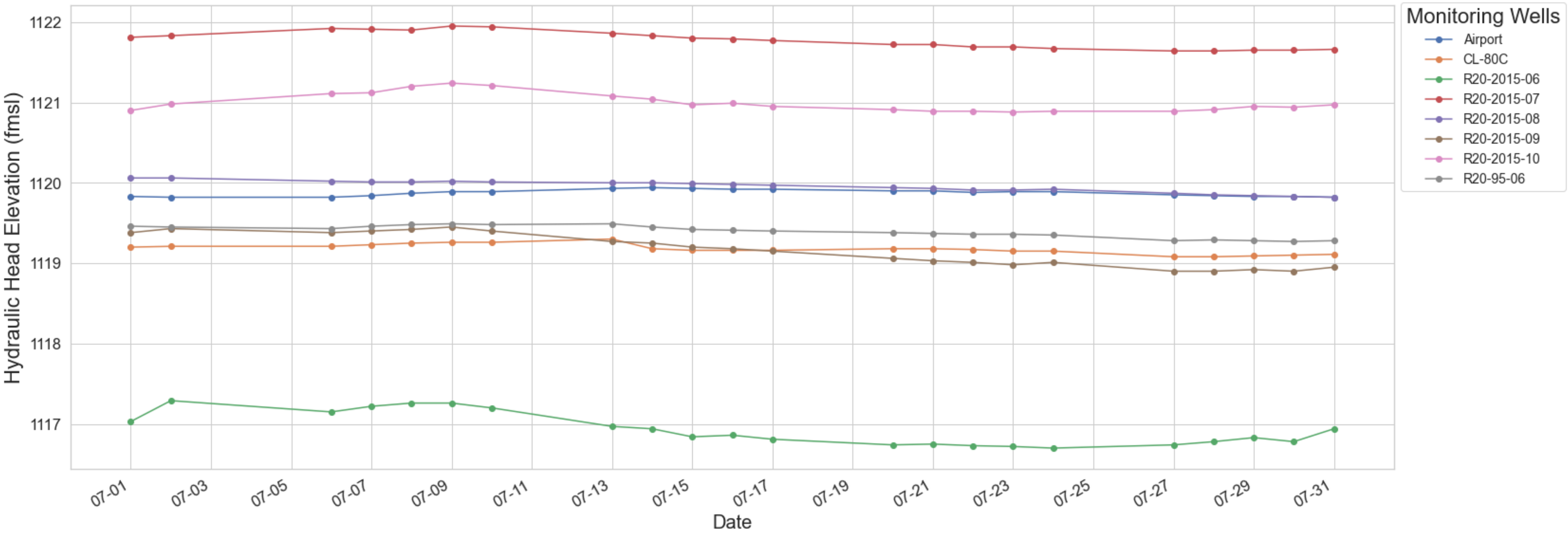


Figure 5. Hydraulic heads for monitoring wells.

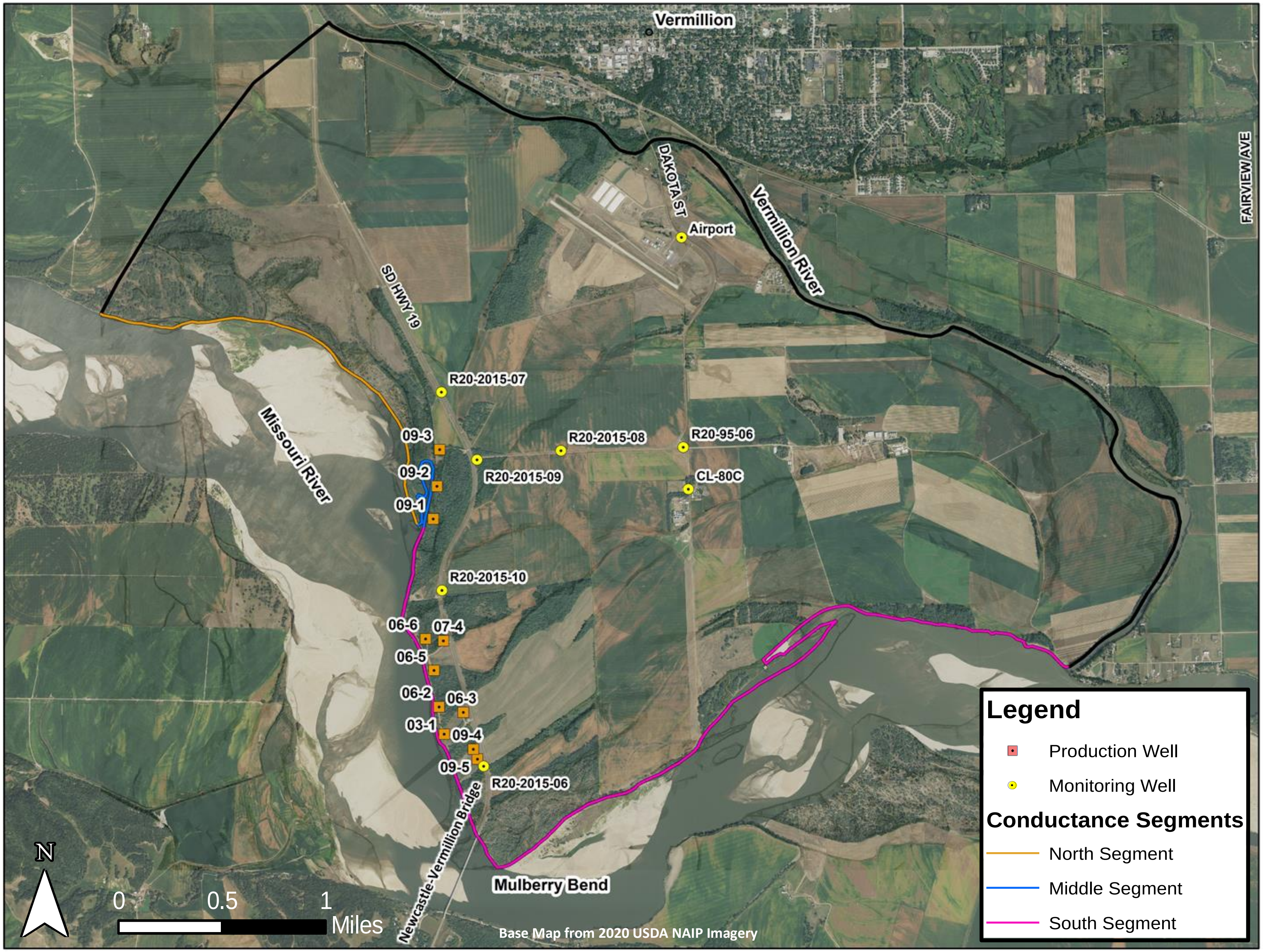


Figure 6. Missouri River conductance segments.

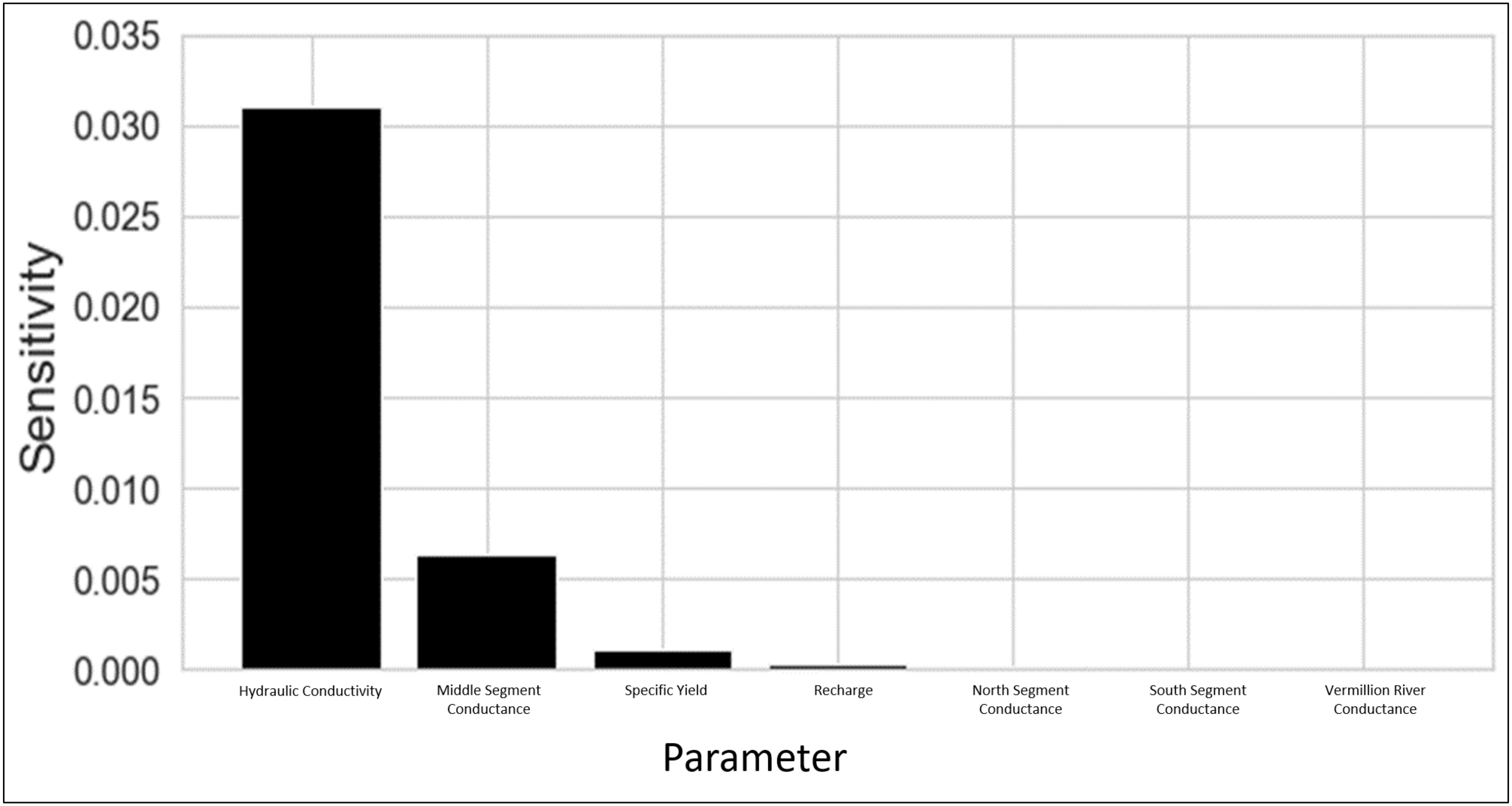


Figure 7. Model parameter sensitivities.

Table 2. Calibrated model parameter values.

Parameter	Value	Units
Hydraulic Conductivity (K)	303	ft/day
Recharge (R)*	3.8	in/yr
Specific Yield (SY)	0.3	unitless
North Segment Conductance (NSC)	5000	$(ft^2/d)/ft$
Middle Segment Conductance (MSC)	93	$(ft^2/d)/ft$
South Segment Conductance (SSC)	15000	$(ft^2/d)/ft$
Vermillion River Conductance (VRC)	10000	$(ft^2/d)/ft$

*Recharge was initially calibrated but deemed a low sensitivity parameter (figure 7), thus a recharge value of 3.8 in/yr was used from previous work conducted by Hedges, et al (1985).

Model sensitivity measures the effect in which a change in input parameters has on the model output. The change in values calculated at a target observation divided by the change of a parameter value is the sensitivity coefficient. A higher sensitivity coefficient refers to a more sensitive parameter. Sensitive values have the greatest effect on target calibration values. The sensitivity analysis showed hydraulic conductivity (K) to be the most sensitive parameter, followed by Middle Segment conductance (MSC), specific yield (SY), recharge (R), North Segment conductance (NSC), South Segment conductance (SSC), and Vermillion River conductance (VRC) (fig. 7).

MODEL ANALYSIS

31-Day Simulation

MODFLOW calculates a cell-by-cell flow budget. Flow in a water budget is dependent on the boundary conditions influencing a cell. River leakage from the Vermillion River, the Missouri River, and meteoric precipitation are the sources of recharge into the system. Flow out of the system is through discharge to both rivers and production wells. The resultant flows into and out of the system are calculated in the water budget.

This model calculated five separate water budgets for the Missouri: Elk Point aquifer at the LCRWS Mulberry Bend wellfield using ZONEBUDGET (fig. 8). To create each zone, particles were placed around each production well and reverse tracked for 31 days to determine capture zones. Capture zone polygons were drafted based on particles that originated from the Missouri River. Capture zones are three dimensional regions of an aquifer that supply water to a well over a specified time interval. ZONEBUDGET calculates the amount of water entering and exiting each zone, and the river contribution percentage is a function of river leakage into the zone divided by the total water into the zone. Zones 1 through 5 were created from the resulting particle tracks surrounding the production wells. Production wells with overlapping particle tracks were combined into one zone shown in table 3 and seen in figure 8.

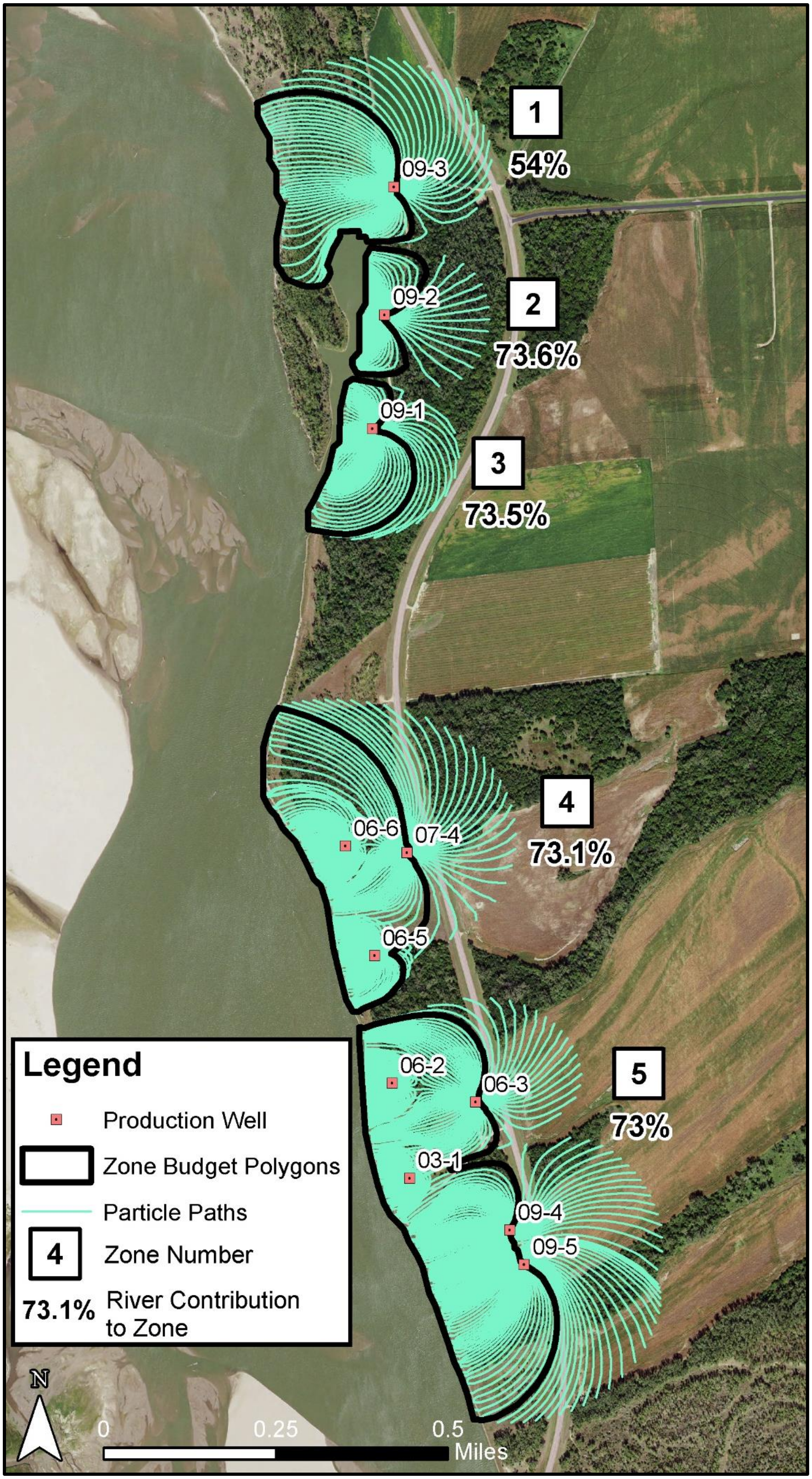


Figure 8. Average Missouri River contribution over 31 days.

Table 3. 31-day zone groupings of production wells.

31-Day Zones	Wells
1	09-3
2	09-2
3	09-1
4	06-6, 06-5, 07-4
5	06-2, 06-3, 03-1, 09-4, 09-5

The model discretized time into 31 days with 10 equally spaced increments throughout each day. The model computes a solution for all 10 time increments within a day. Figure 9 shows the time series of river inflow to the aquifer over 31 days. The production well discharge changes daily in the model. The data in figure 9 demonstrates the relationship between induced river leakage and discharge from the wellfield. Each capture zone intersects a portion of the Missouri River boundary in the model and the model calculates the respective river leakage into that zone.

River to aquifer interaction was calculated from the water budget outputs for each zone by taking the river leakage into the zone divided by total inflow from all sources. Percentages were calculated for each time increment and averaged to compute the average river contribution to total well discharge over 31 days for each zone. Figure 8 shows the average river contribution for each zone. A weighted average river contribution was calculated from weighting zones by the amount of production well discharge, so zones with higher discharge had higher weight factors. The resulting weighted average river contribution is 71.1% of the total water budget for the wellfield during this 31-day model solution.

365-Day Simulation

This simulation used the 31-day calibrated model to assess induced flow from the river for 365 days. The same methods and procedures were followed to calculate induced river flow. The only differences in this simulation are varied river stage and a time discretization of 365 days.

Daily average values for the Missouri River stage were computed from January 2013 to December 2021 from the USGS gaging station 06478526. Average river stage ranged from 1125 feet to 1129 feet throughout the year, with higher average stage readings between 1127 feet to 1129 feet from April to November of each year.

Daily average values for the Vermillion River stage were computed from the USGS gaging station 06479010. The period of record for river stage at this station begins in 2018, so daily average values were computed from January 2018 through December 2021. River stage ranged from 1121 feet to 1130 feet with the highest average stage readings occurring during March and April of each year. LCRWS provided daily pumping data from January 2018 through April 2022 for each production well. Daily average discharge values were computed for each well. The 31-day model used pumping rates from 2015 that ranged from 13.2 to 22.2 MGD. Between January of 2018 and April of 2022, the pumping rates ranged from 7.9 to 32.2 MGD.

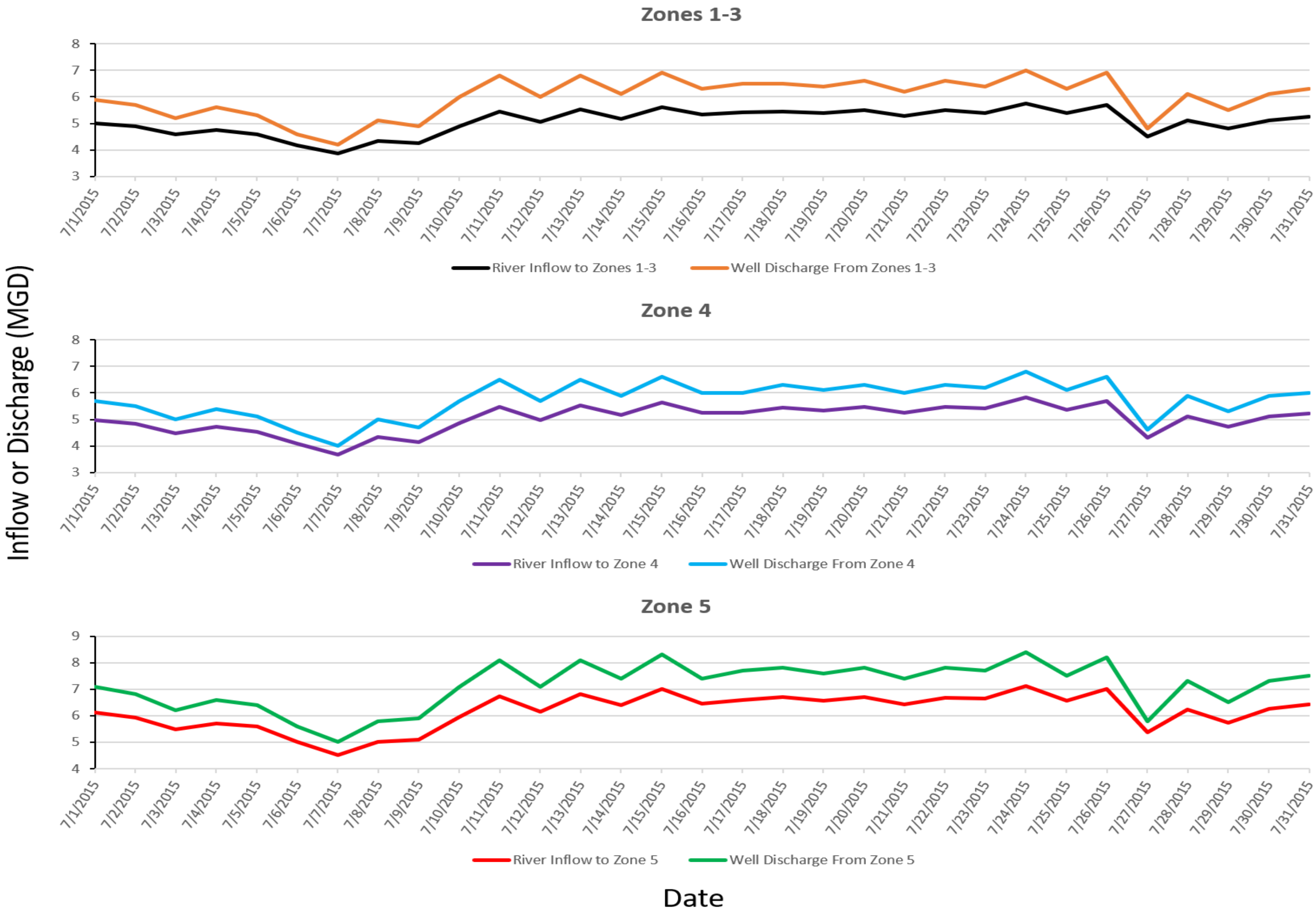


Figure 9. Time series of river inflow to the aquifer and well discharge over 31 days.

The average pumping rate during this time was 18.3 MGD. Larger capture zones are seen on the 365-day simulation due to initial storage of the aquifer contributing a lower percentage of total water over the course of a year compared to a month.

The results of this simulation showed higher river contributions compared to the 31-day simulation (fig. 10). Production wells were placed within three separate zones that were utilized in ZONEBUDGET (table 4). Capture zones did not extend more than a mile from the river. Figure 11 shows a time series of river inflow and well discharge. River inflow increases and decreases along with discharge. A weighted average river contribution was calculated from weighting zones by the amount of production well discharge, so that zones with higher discharge amounts had higher weight factors. The resulting weighted average river contribution is 84.6% of the total water budget for the wellfield during the 365-day simulation.

Table 4. 365-day zone groupings of production wells.

365-Day Zones	Wells
1	09-3, 09-2, 09-1
2	06-6, 06-5, 07-4
3	06-2, 06-3, 03-1, 09-4, 09-5

Model Behavior

Several attempts to create zones of hydraulic conductivity to better constrain the heterogeneity of the aquifer were made while keeping conductance of the Missouri River constant, but this only changed the flow budgets by 2-3% and created calibration problems. Holding the hydraulic conductivity of the aquifer constant and allowing the conductance of the Missouri River to vary in three places (NSC, MSC, and SSC) resulted in a better calibration, especially at calibration targets near the wellfield.

The 365-day simulation also showed that the induced flow from the river is significant. The average daily river stages are higher than the water levels in the aquifer near the wellfield which creates a large hydraulic gradient between the river and the production wells. This induces flow from the river into the aquifer. From these simulations it is determined that if production wells are close enough to the river, significant portions of the flow can be induced by pumping.

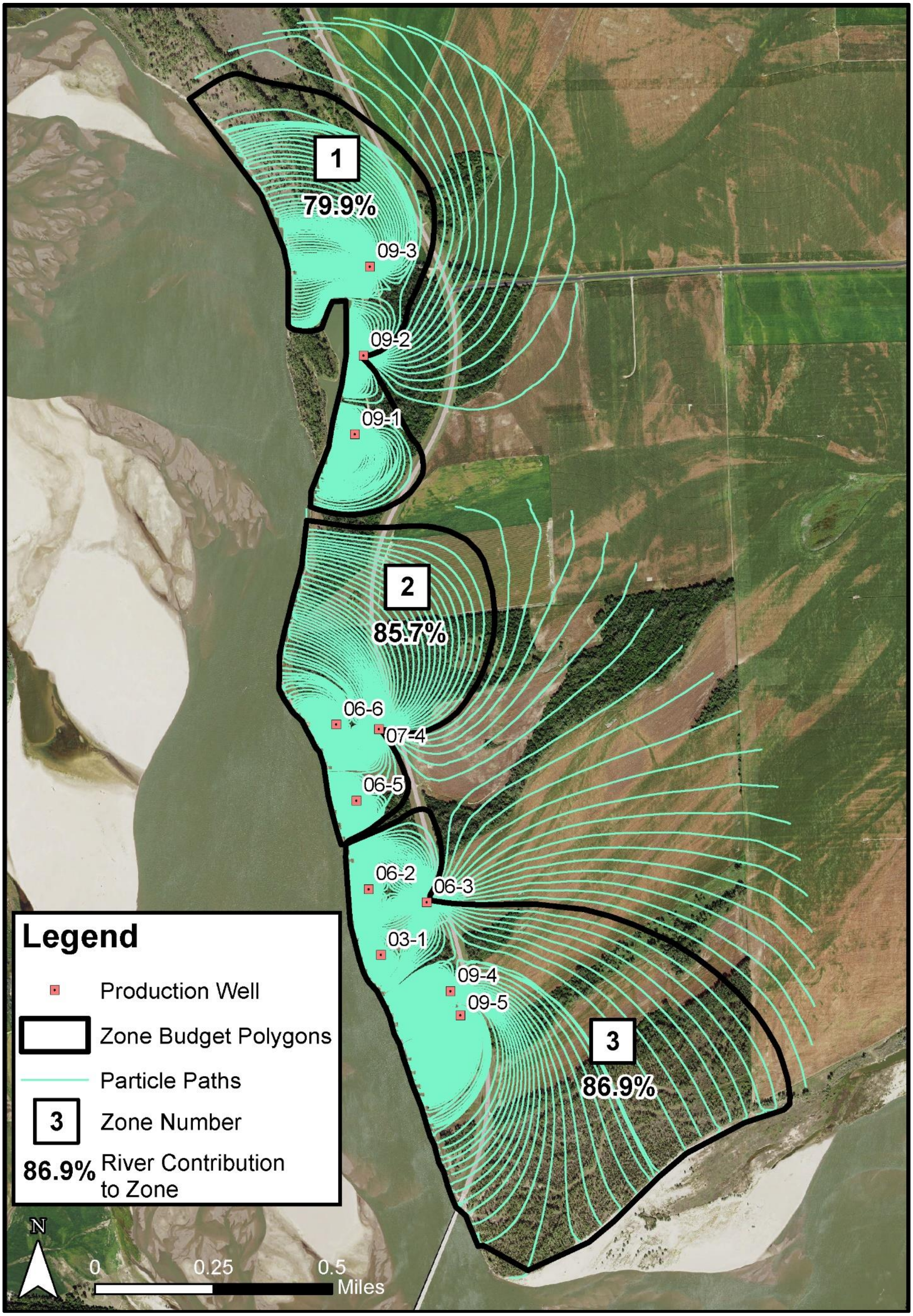


Figure 10. Average Missouri River contribution over 365 days.

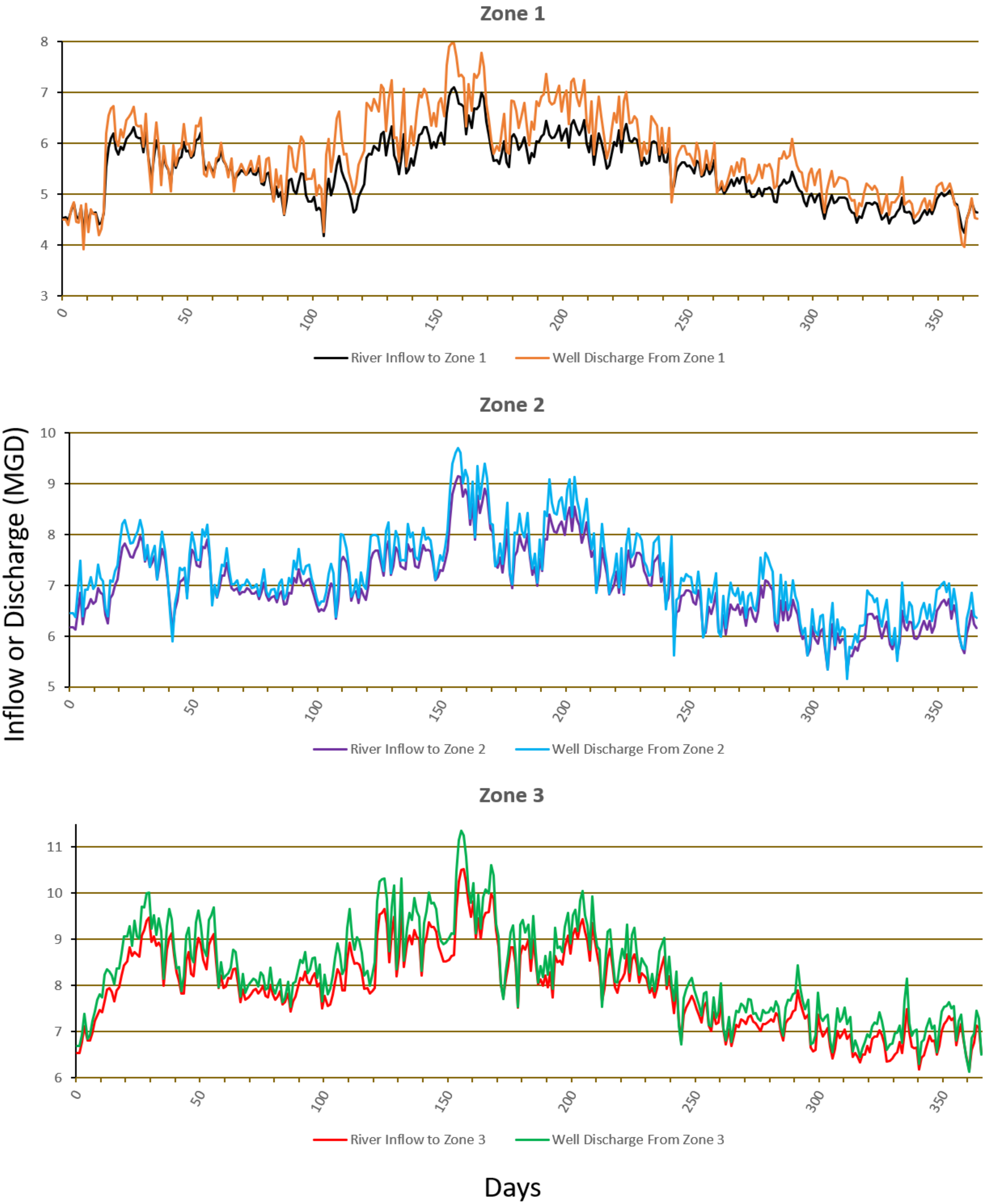


Figure 11. Time series of river inflow to aquifer and well discharge over 365 days.

SUMMARY

Results from previous work were used to define hydraulic parameters for the Missouri: Elk Point aquifer at the LCRWS Mulberry Bend wellfield. A transient numerical model was developed to assess the amount of water that the Missouri River contributes to production wells at the wellfield. Several model variations were analyzed, and the best solutions are presented in this report. The 31-day model weighted average river contribution was calculated as 71.1%, while the 365-day model showed a weighted average river contribution of 84.6% of the total water budget for the wellfield. The results of this model are useful for estimating the percentage of river water entering the capture zones established for the LCRWS Mulberry Bend wellfield. This model can be adapted to answer other questions regarding impacts on the aquifer from changes in pumping rates or the addition of new production wells.

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