FIGURES

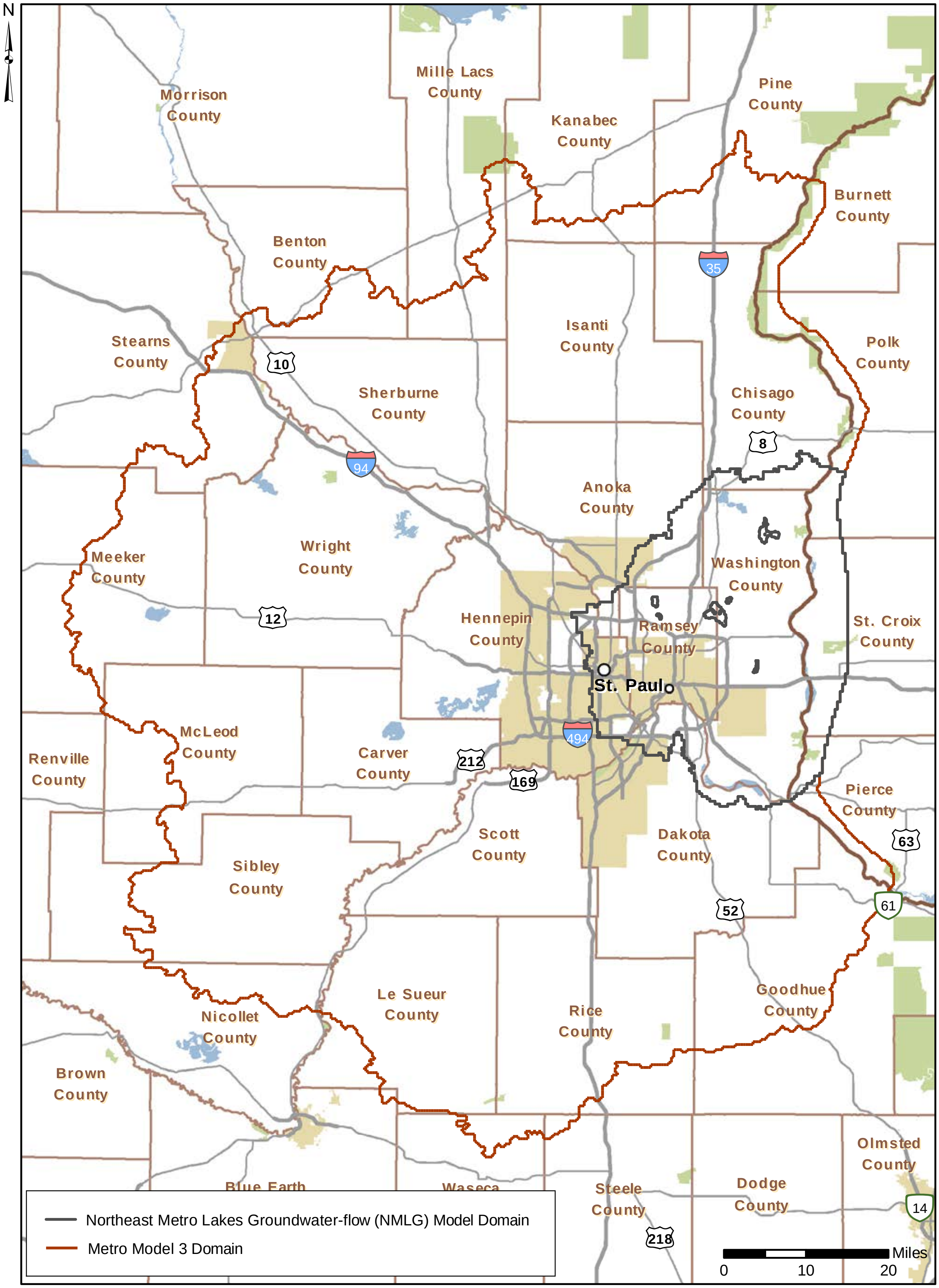


Figure 1-1 Study Area Location

Erathem	System	Formation or Group	General lithology	Thickness (in feet)	Hydrgoelogic unit and general water-beraring characteristics	Primary ground-water model layers numbers[1]
Cenozoic	Quaternary	Undifferentiated glacial drift		0-100	**Glacial aquifers** -- Glacial drift is generally a confining unit, but locally may supply water to wells. Drift consists primarily of till and outwash. Drift is thin or absent throughout much of the area, generally less than 50 feet thick.	1-4 (5-12)
Paleozoic	Ordovician	Decorah Shale		40	**Decorah-Platteville-Glenwood confining unit**--The vertical hydraulic conductivity ranges from about 10^{-5} to 10^{-4} feet/day; horizontal hydraulic conductivites for the Decorah Shale range from less than 10^{-6} to 60 feet/day; the Platteville Formation range from 10^{-2} to 98 feet/day, and the Glenwood Formation are approximately 10^{-2} feet/day.	1-4
		Platteville Formation		25		
		Glenwood Formation		5		
		St. Peter Sandstone		100	**St. Peter aquifer**--The aquifer is a major aquifer in southeastern Minnesota; horizontal hydraulic conductivities range from 10^{-3} to greater than 49 feet/day, vertical hydraulic conductivities range from $2x10^{-3}$ to 92 feet/day; effective porosity ranges from 0.28 to 0.3; storativity ranges from $9x10^{-5}$ to $9.8x10^{-3}$.	5
		Prairie du Chien Group: Shakopee Formation		130	**Prairie du Chien aquifer, Shakopee Formation**--The aquifer is a part of a major aquifer in southeastern Minnesota; has well-developed secondary porosity; horizontal hydraulic conductivities range from 1.0 to 160 feet/day; vertical hydraulic conductivities range from 0.03 to 35 feet/day; has a well-developed secondary porosity; effective porosity of 0.06, but highly variable; storativity ranges from $1.1x10^{-5}$ to $3.4x10^{-5}$.	6
		Prairie du Chien Group: Oneota Dolomite		170	**Prairie du Chien aquifer, Oneota Dolomite**--The aquifer is part of major aquifer in south-eastern Minnesota; horizontal hydraulic conductivities range from $1.5x10^{-4}$ to 740 feet/day, with the lower conductivities in the middle and lower parts of the unit; vertical hydraulic conductivities range from $1.5x10^{-4}$ to 10^{-3} feet/day; the uppermost part of the unit has a well-developed secondary porosity; effective porosity of 0.06, but highly variable; storativity ranges from $1.1x10^{-5}$ to $3.4x10^{-4}$.	
Paleozoic	Cambrian	Jordan Sandstone		100	**Jordan aquifer**--The aquifer is a major aquifer in southeastern Minnesota; horizontal hydraulic conductivities range from 10^{-2} to greater than 490 feet/day; vertical hydraulic conductivities range from 10^{-4} to 47 feet/day; effective porosity of 0.32; storativity ranges from $4.9x10^{-5}$ to $1.2x10^{-4}$.	7
		St. Lawrence Formation		75	**St. Lawrence Formation**--Parts of the formation are confining, other parts are used for water, horizontal hydraulic conductivities range from less than 10^{-2} to 46 feet/day; vertical hydraulic conductivities range from 10^{-5} to 1.8 feet/day; effective porosity ranges from 0.15 to 0.20.	8
		Tunnel City Group		155 - 160	**Tunnel City aquifer** --The upper part of the group is an aquifer and the lower part is considered a confining unit; hydraulic conductivities range from less than 1 to 340 feet/day, with conductivities varying with fracturing and depth, hydraulic conductivities are greater at shallower depths.	9
		Wonewoc Formation		40 - 45	**Wonewoc aquifer** -- A single aqufer with parts of the upper part of the formation considered confining; hydraulic conductivities range from 1 to 230 feet/day, varying with fracturing.	10
		Eau Claire Formation		200	**Eau Clarie confining unit** -- Vertical and horizontal hydraulic conductivities in deep bedrock settings range from 10^{-4} to 10^{-2} feet/day, hydraulic conductivities in shallow bedrock settings range from less than 1 to 400 feet/day, sandstones in the unit are used as local aquifers.	11
		Mount Simon Sandstone		200 or less	**Mount Simon aquifer** -- The aquifer is used by some large high-capacity wells in northeast Twin Citites Metropolitatn area. The fine clastic material in upper part of the formation are a confining unit in deep bedrock settings, the lower part of the formation consists of coarse clastic material that serves as an aquifer, hydraulic conductivities range from less than 1 to 200 feet/day, with the higher conductivities generally present in shallow bedrock settings, hydraulic conductivities in deep bedrock settings (greater than 200 feet below the land surface) generally range from less than 1 to 50 feet/day.	12

1 - The layer number for each hydrogeologic unit will vary with the presence and absence of other hydrogeologic units over the area. Units commonly are absent in areas where faulting and buried bedrock valleys are present.

EXPLANATION

Till, sand, and gravel | Limestone/dolomite | Shale | Sandstone | Siltstone | Aquifer

Figure 3. Generalized hydrogeologic column of regional aquifers and confining units and their use in the groundwater-flow model, northeast Twin Cities Metropolitan Area, Minnesota [Geology modified from Balaban, (1988) and Lindgren (2001); water-bearing characteristics modified from Delin (1991), Runkel and others (2003), and Campion (2002).]

Figure 1-2 Generalized Hydrostratigraphy of the Twin Cities Metropolitan Area Aquifers (reproduced from U.S. Geological Survey (USGS), 2017, Draft Report)

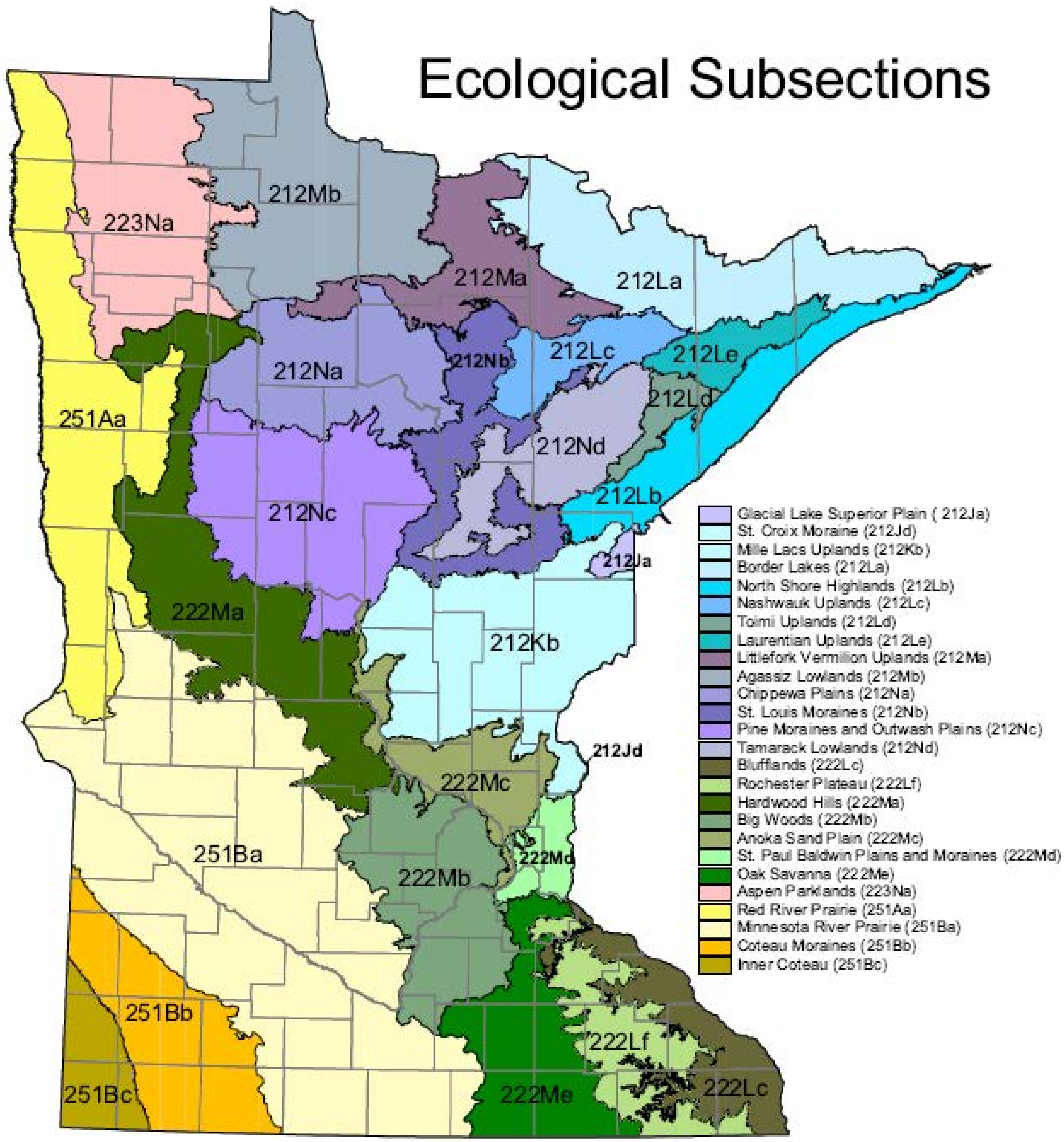


Figure 2-1 Ecological Subsections of Minnesota (Minnesota Department of Natural Resources 2017)

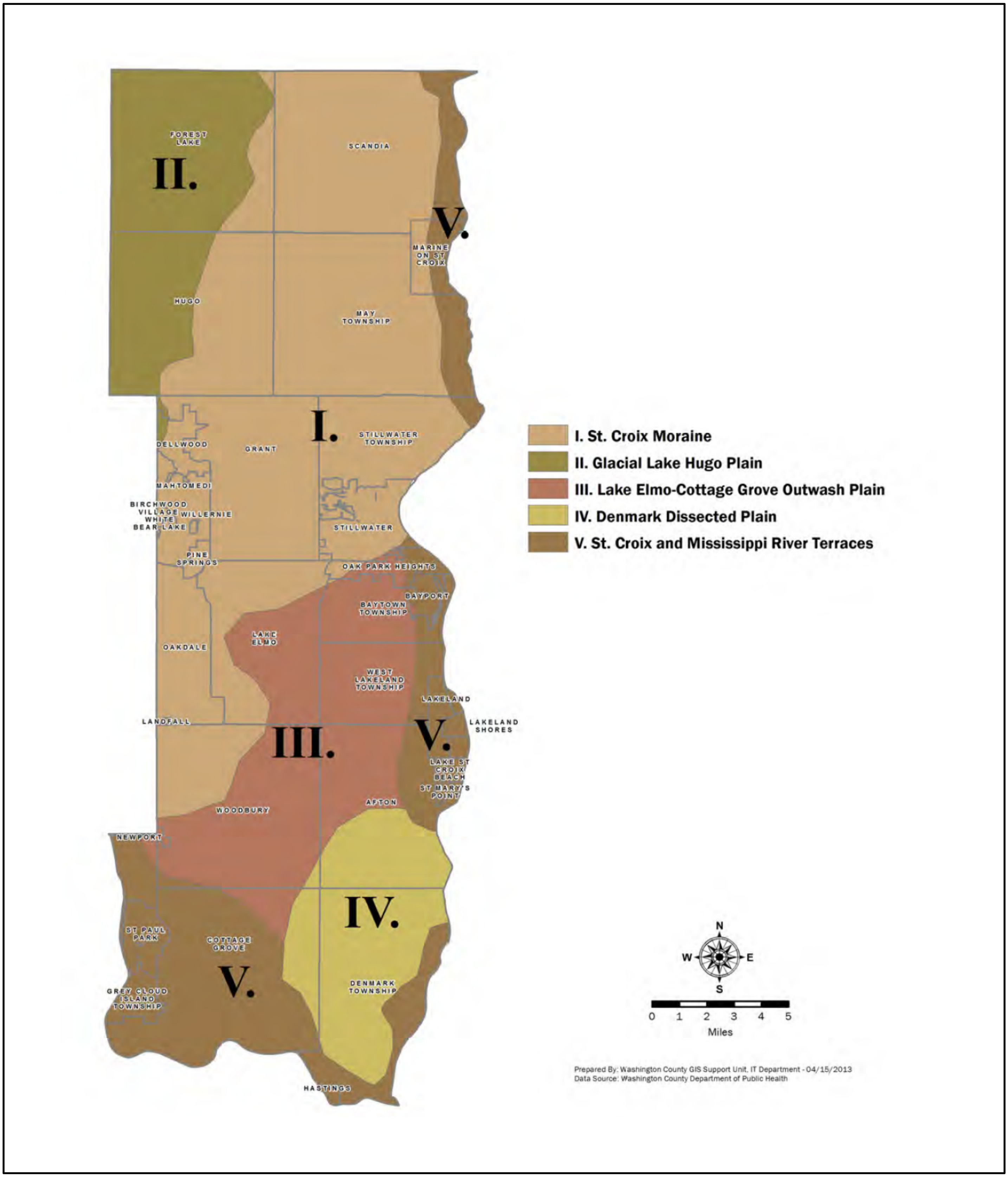


Figure 2-2 Geomorphic Regions of Washington County (Washington County 2014)

Figure 2-3 Example of Lakes and Wetlands (Closed Depressions) in Glacial Lake Hugo Plain

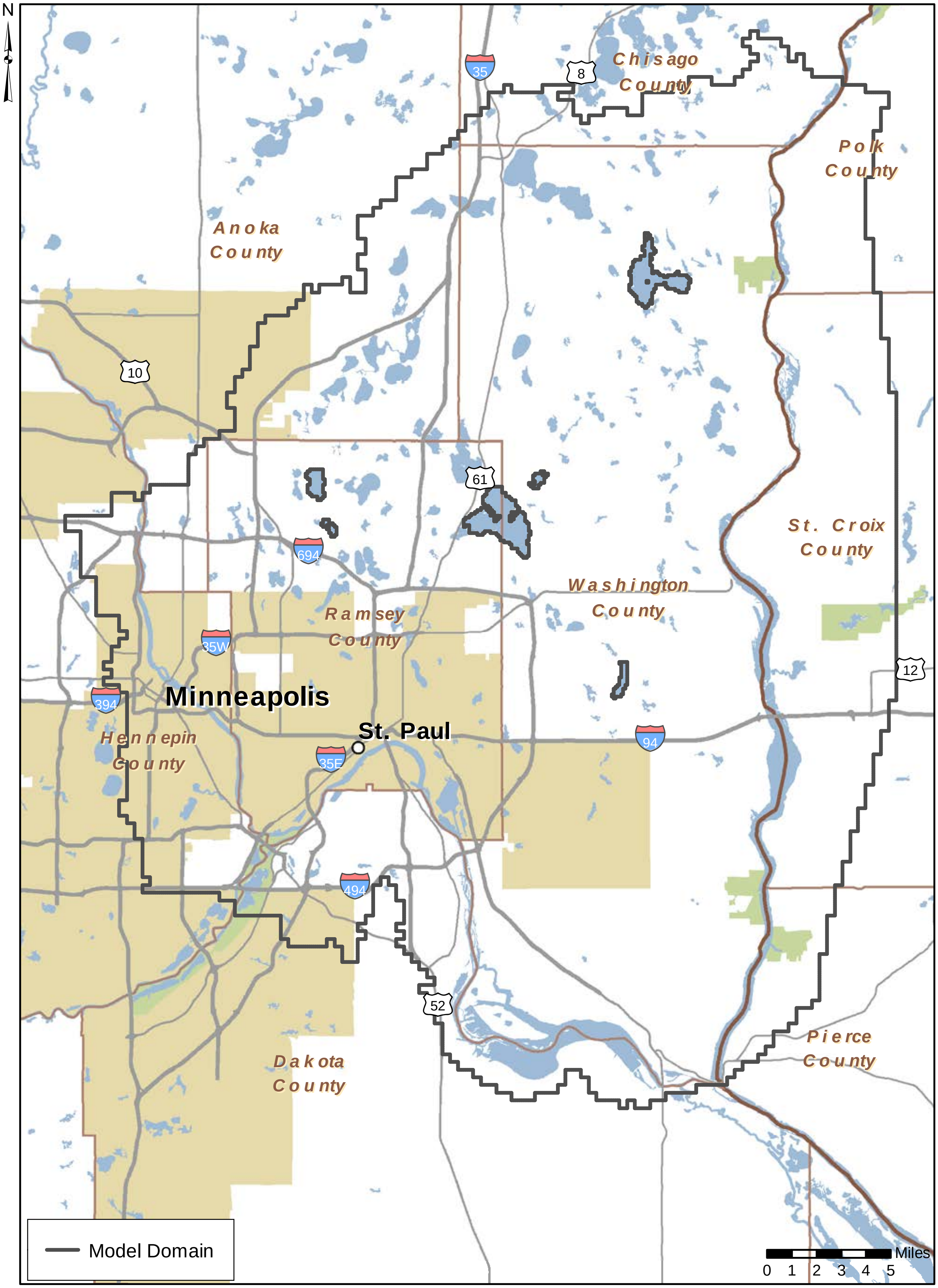


Figure 3-1 NMLG Model Domain Detail

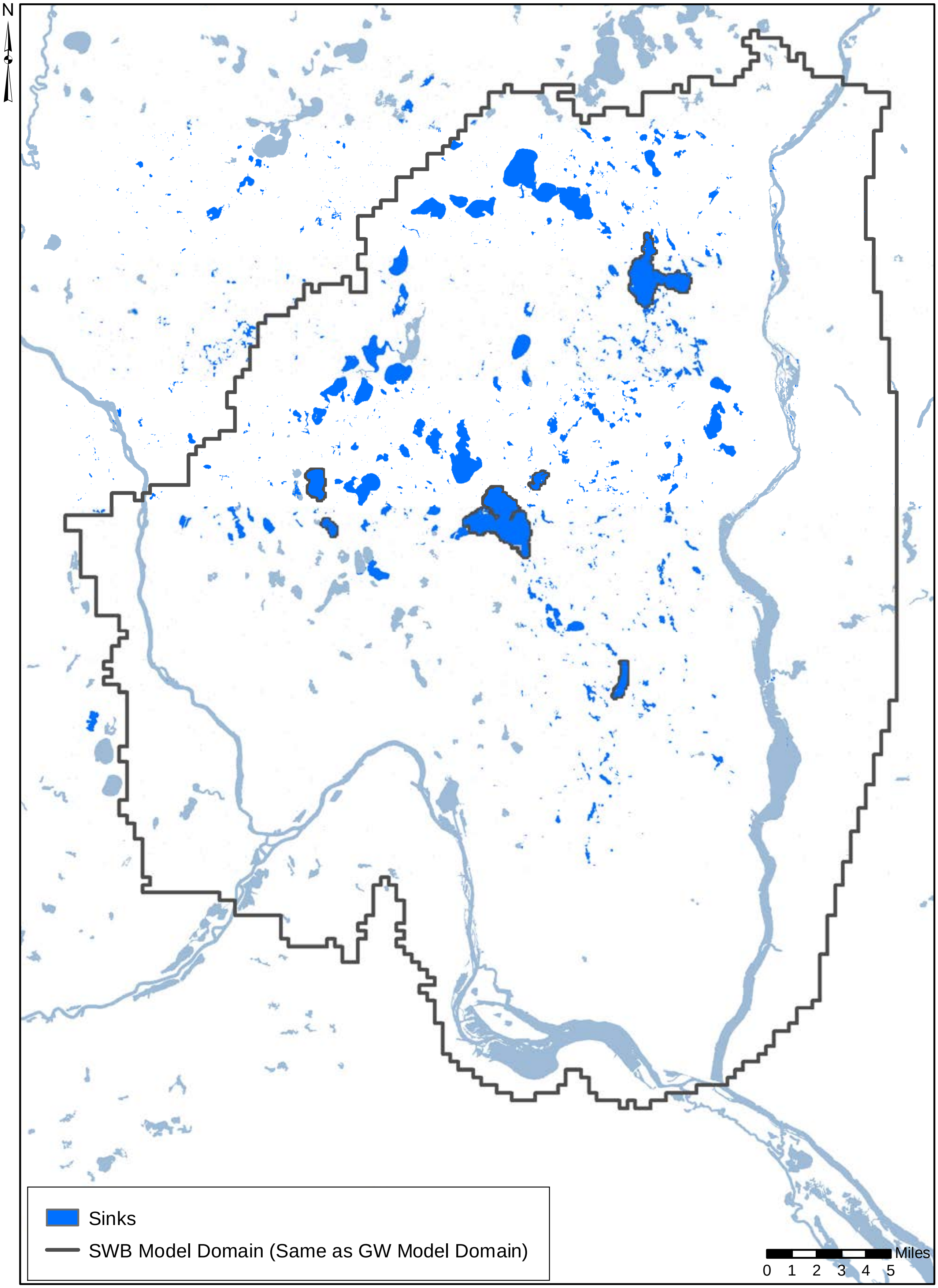


Figure 3-2 SWB Model Extent and Internal Features

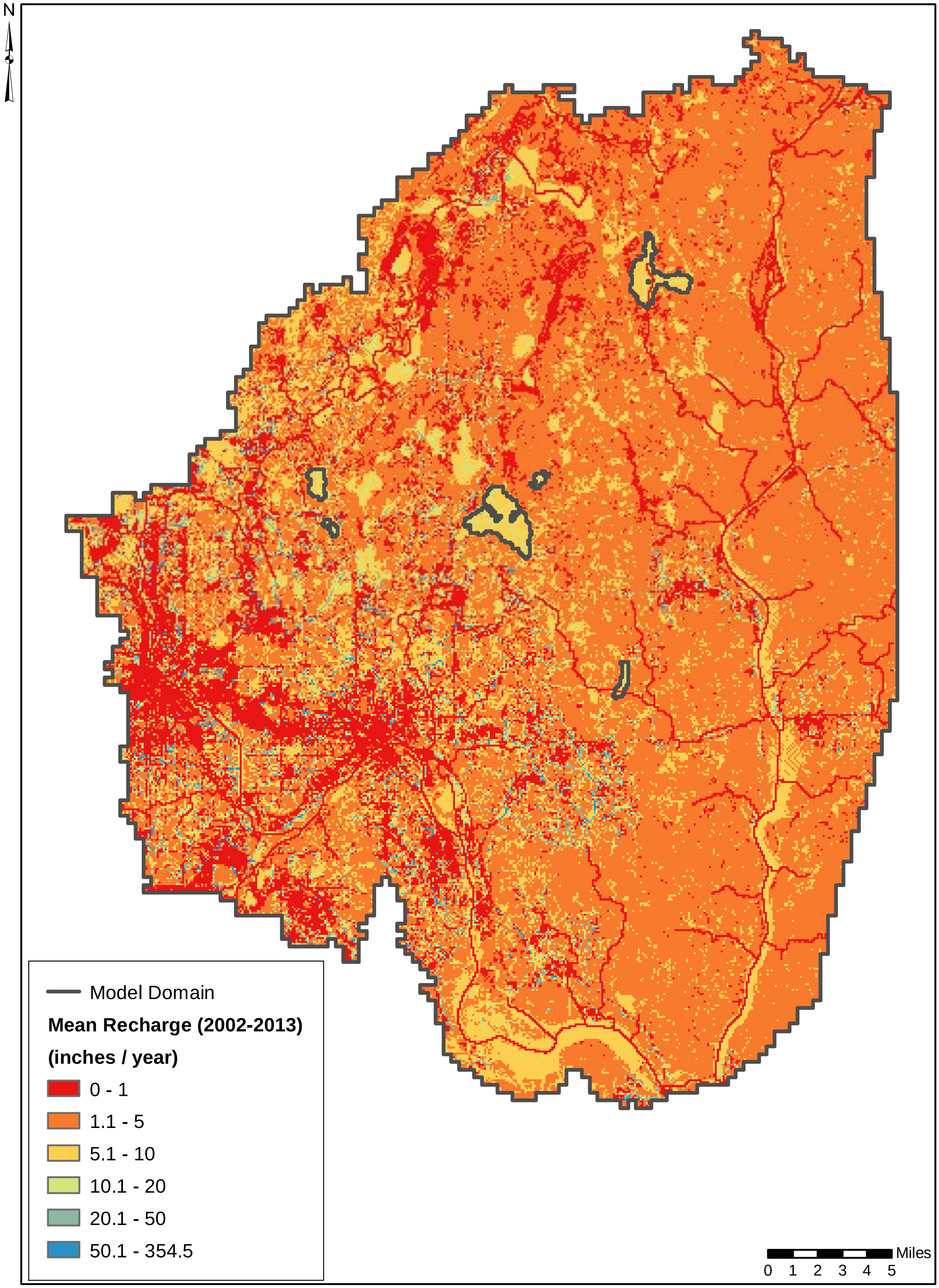


Figure 3-3 Average Groundwater Recharge Rates Simulated by the SWB Model (2003-2013)

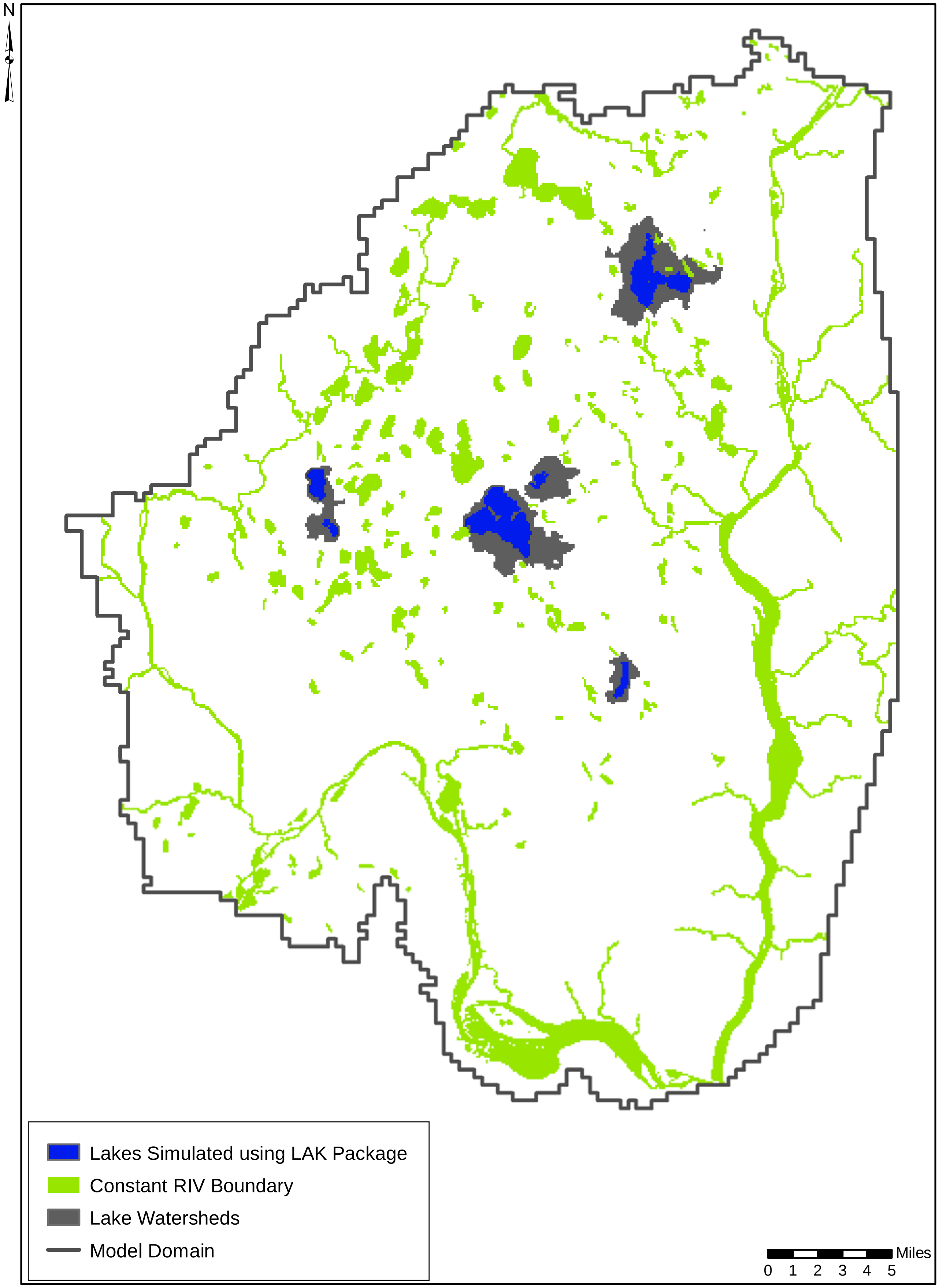


Figure 3-4 Groundwater Model Extent and Major Internal Features Including Model Cells Representing Lakes and Lake Watersheds

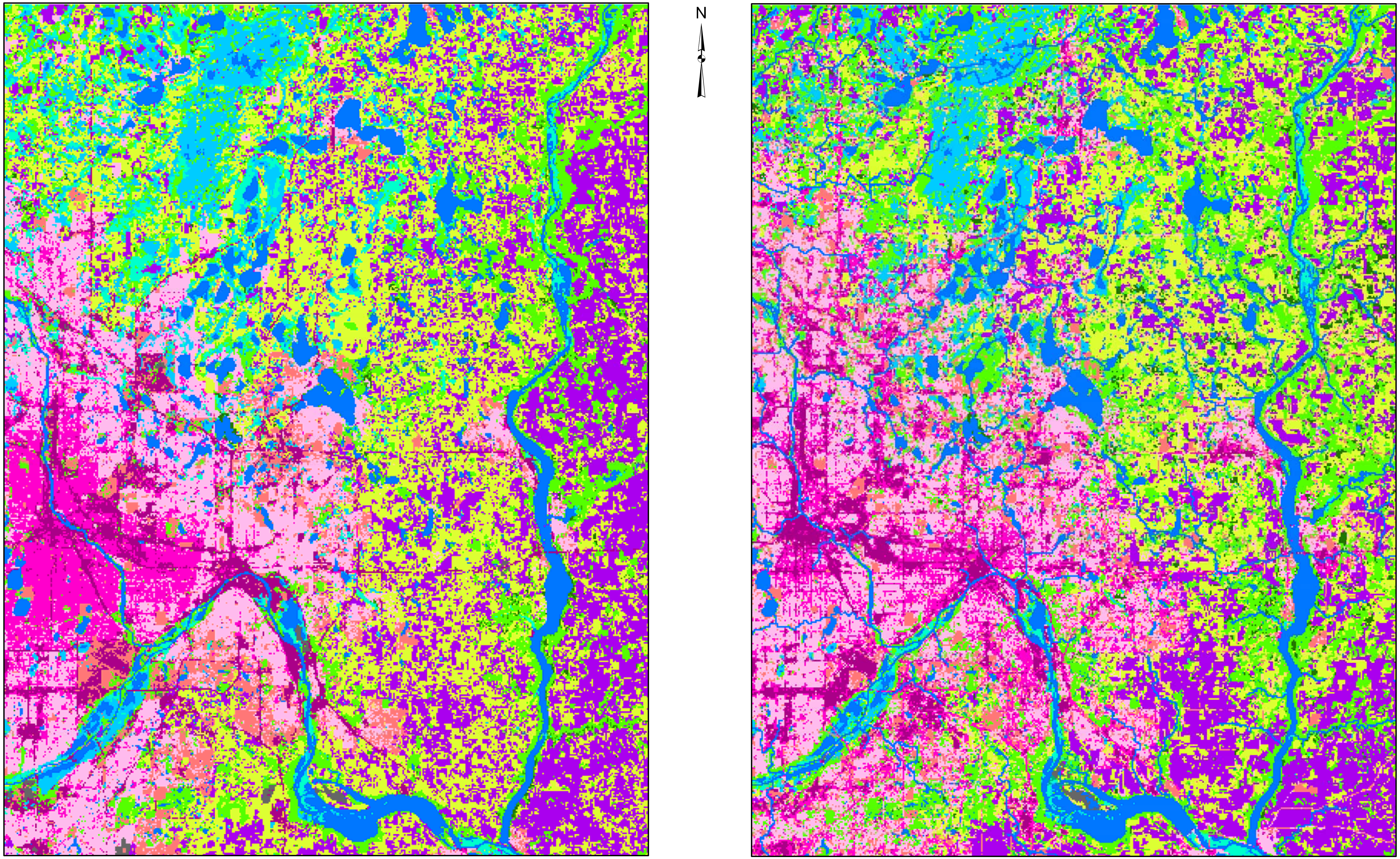


Figure 4-1 Land-Use Classification Maps used in SWB (A) 1992 for years 1980 to 1999, (B) 2006 for years 2000 to 2016

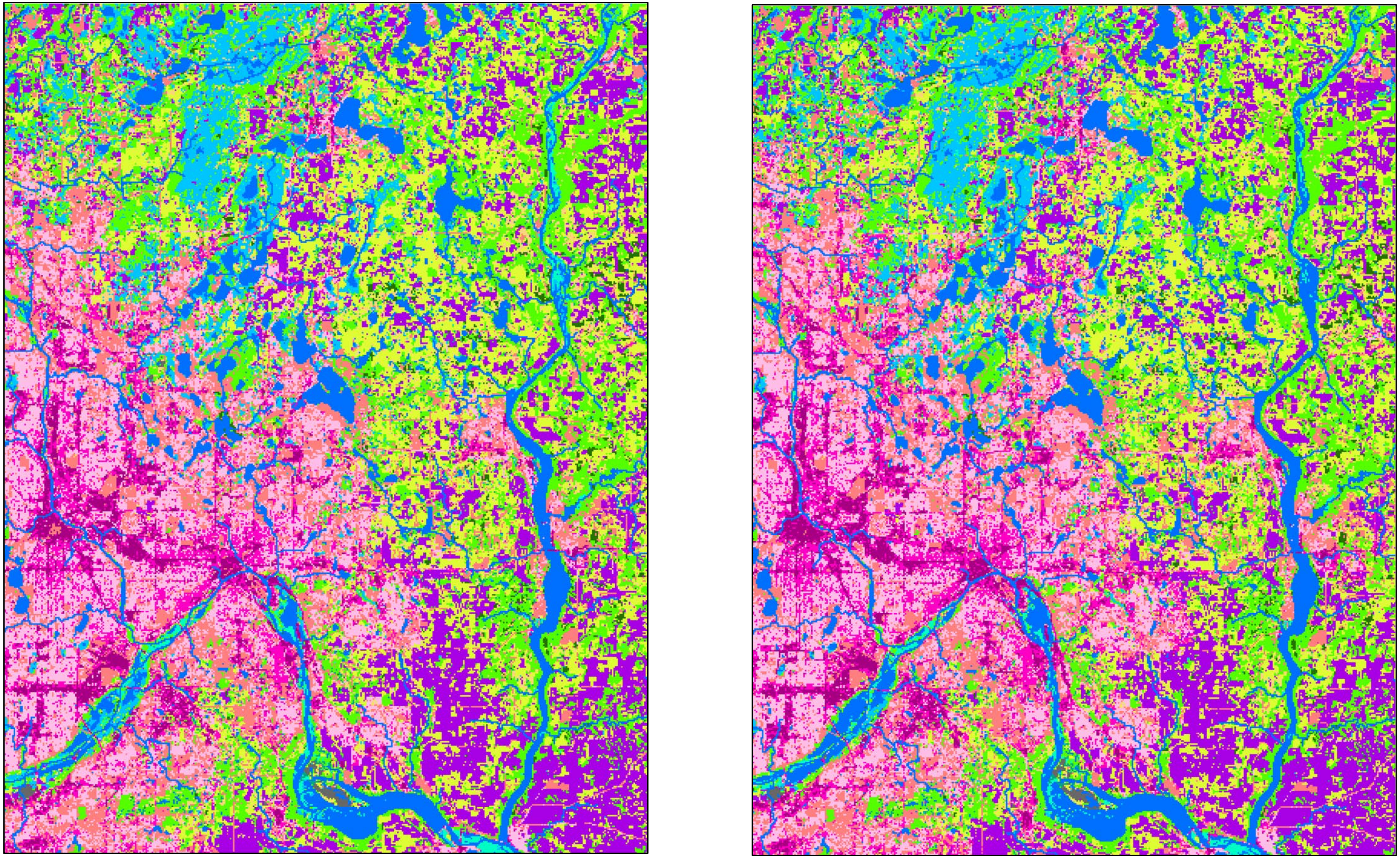


Figure 4-1 Land-Use Classification Maps not used in SWB (C) 2001, (D) 2011

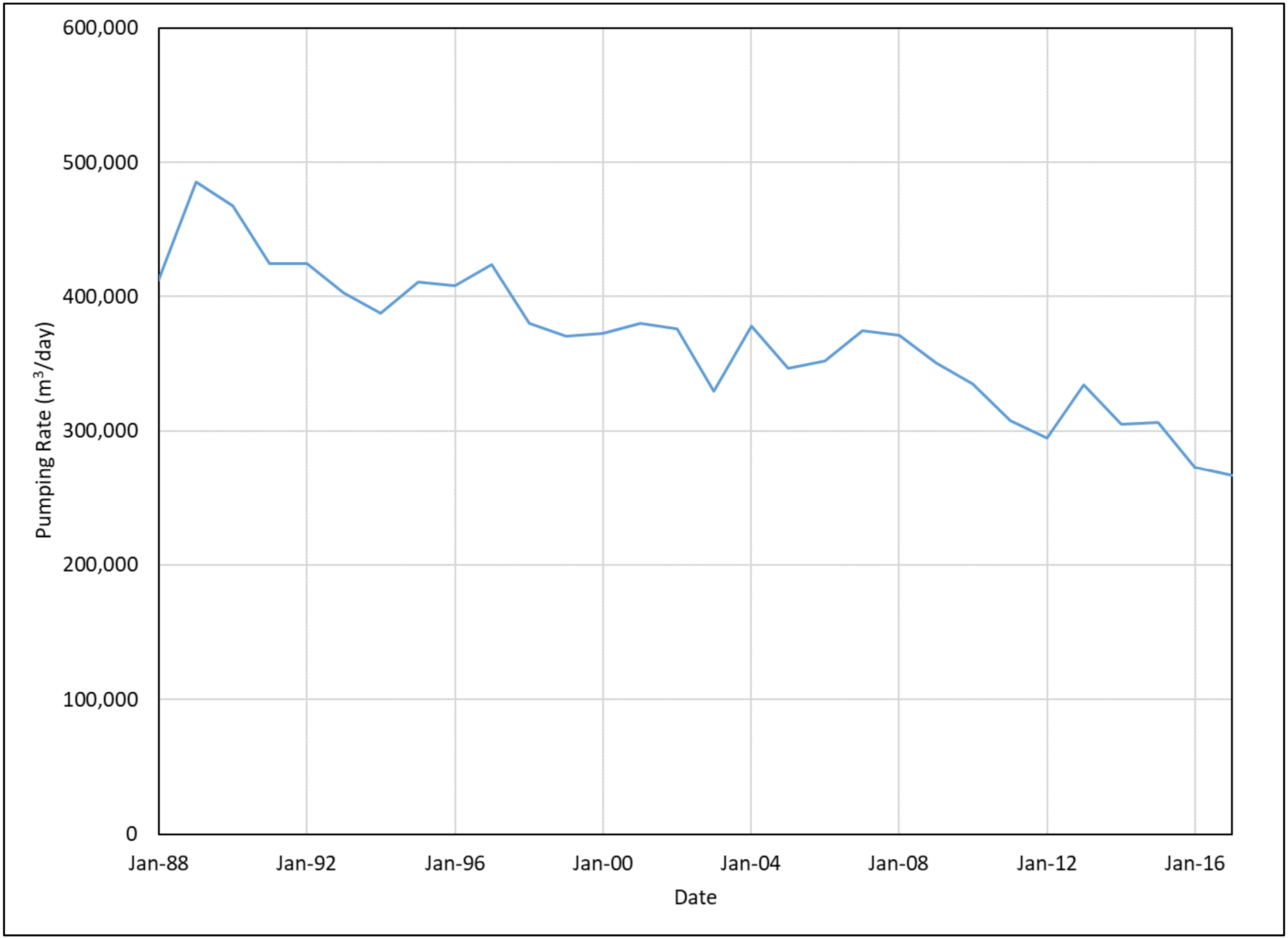


Figure 4-2 Transient Groundwater Pumping (1988-2016)

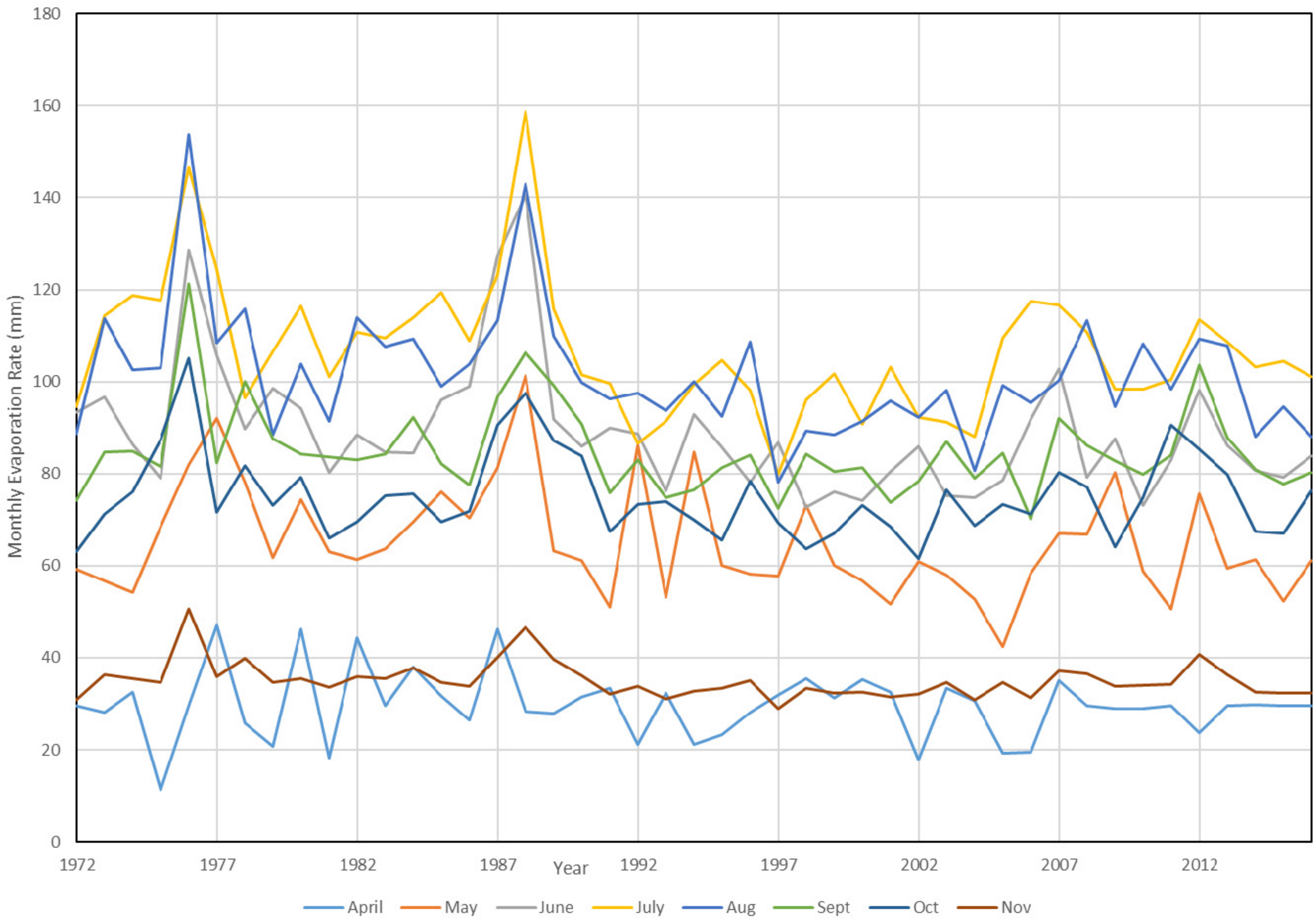


Figure 4-3 Monthly Calculated Evaporation Rates from White Bear Lake

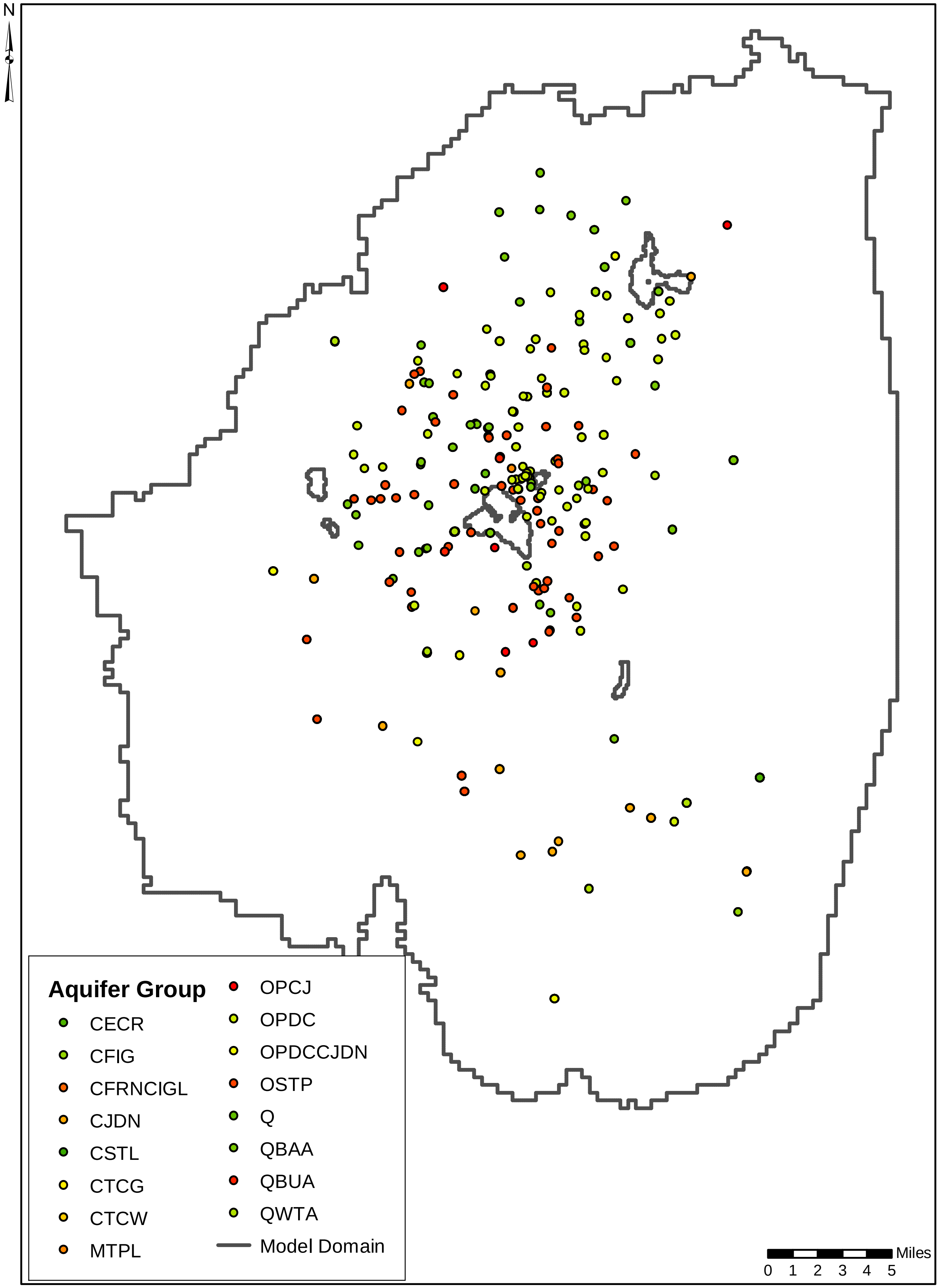


Figure 5-1 Location and Aquifer Unit of Groundwater Level Calibration Targets

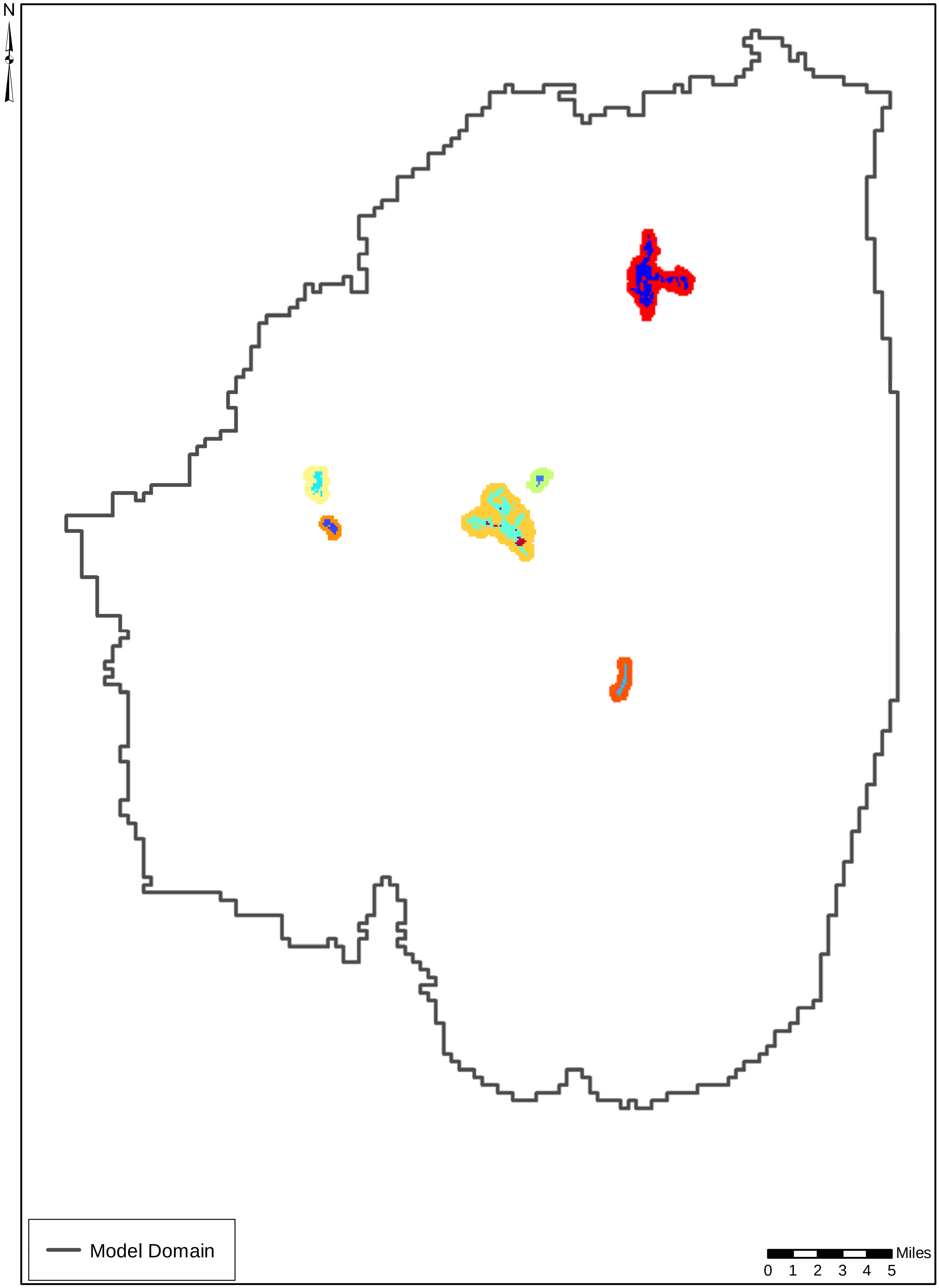


Figure 6-1 Lakebed Conductance Zones

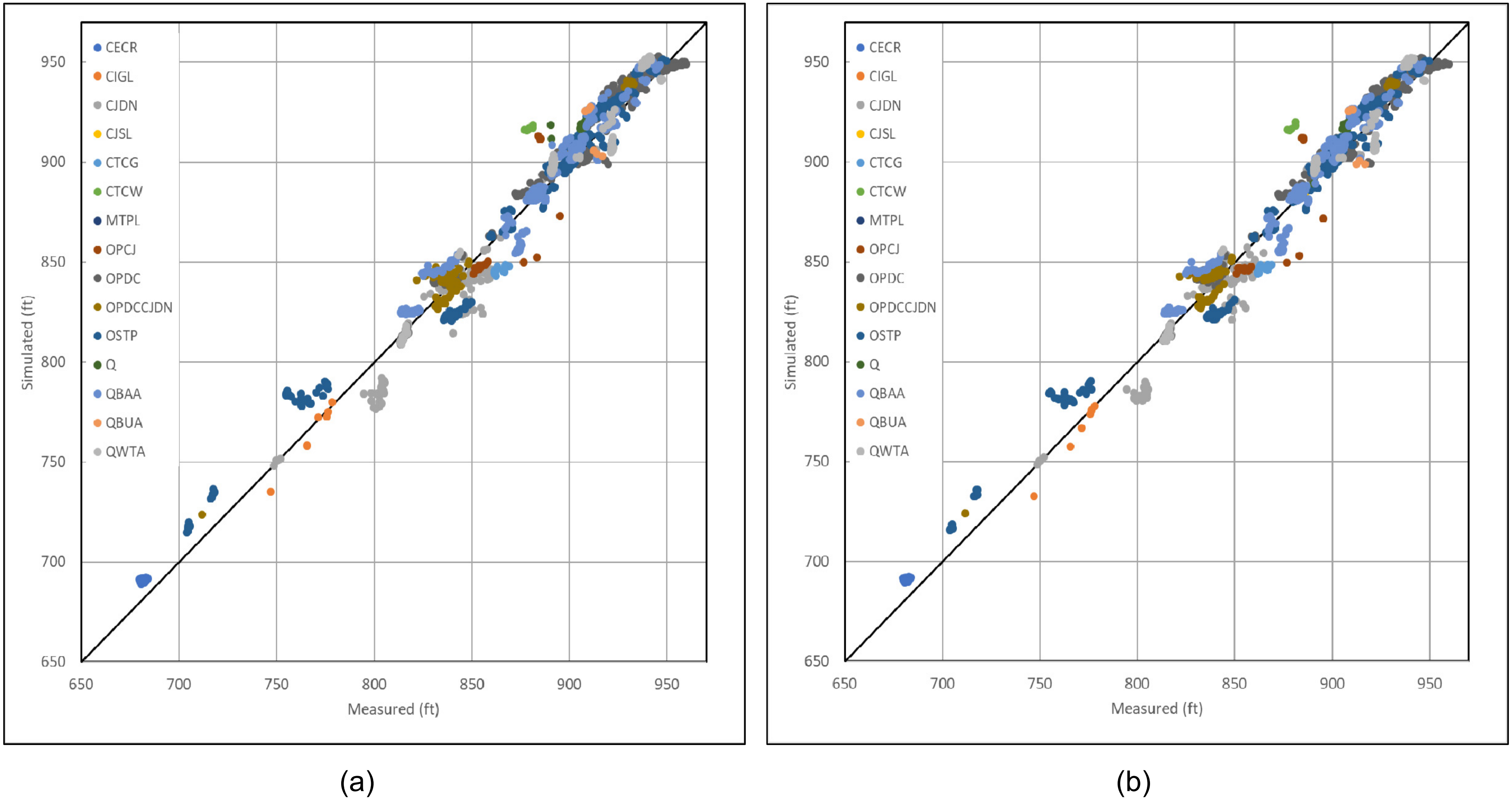
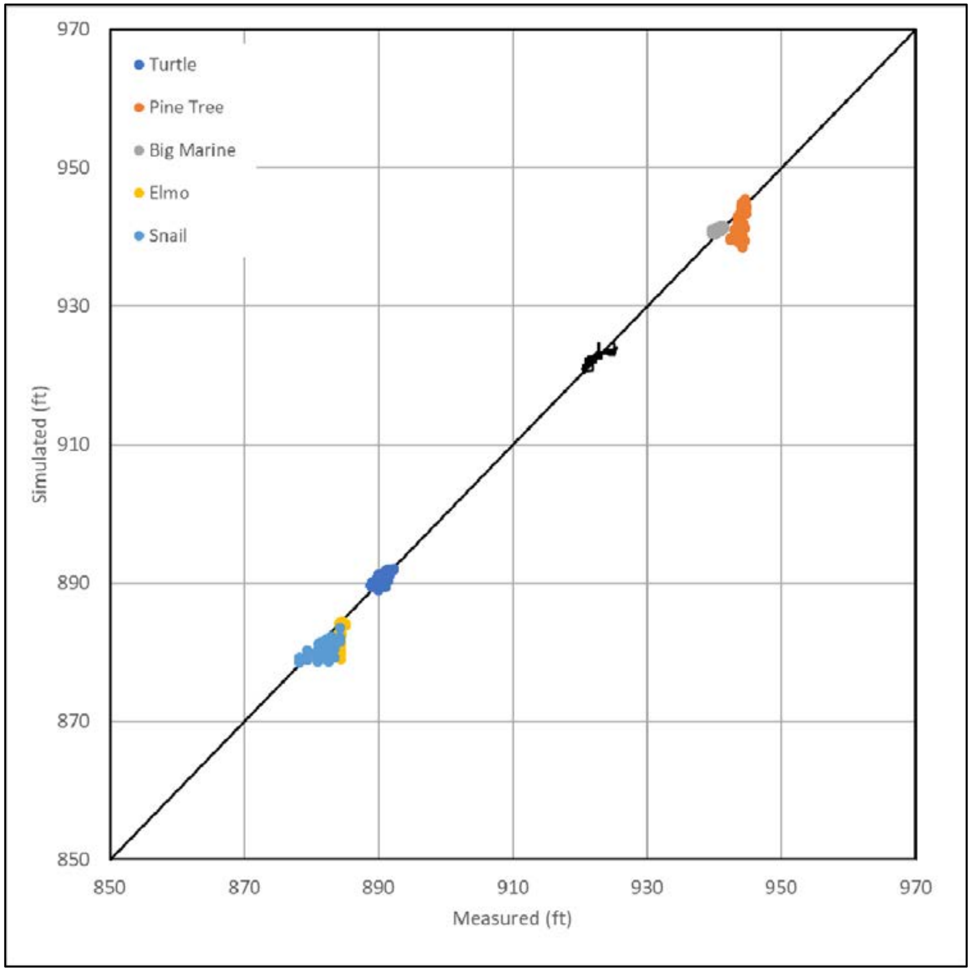
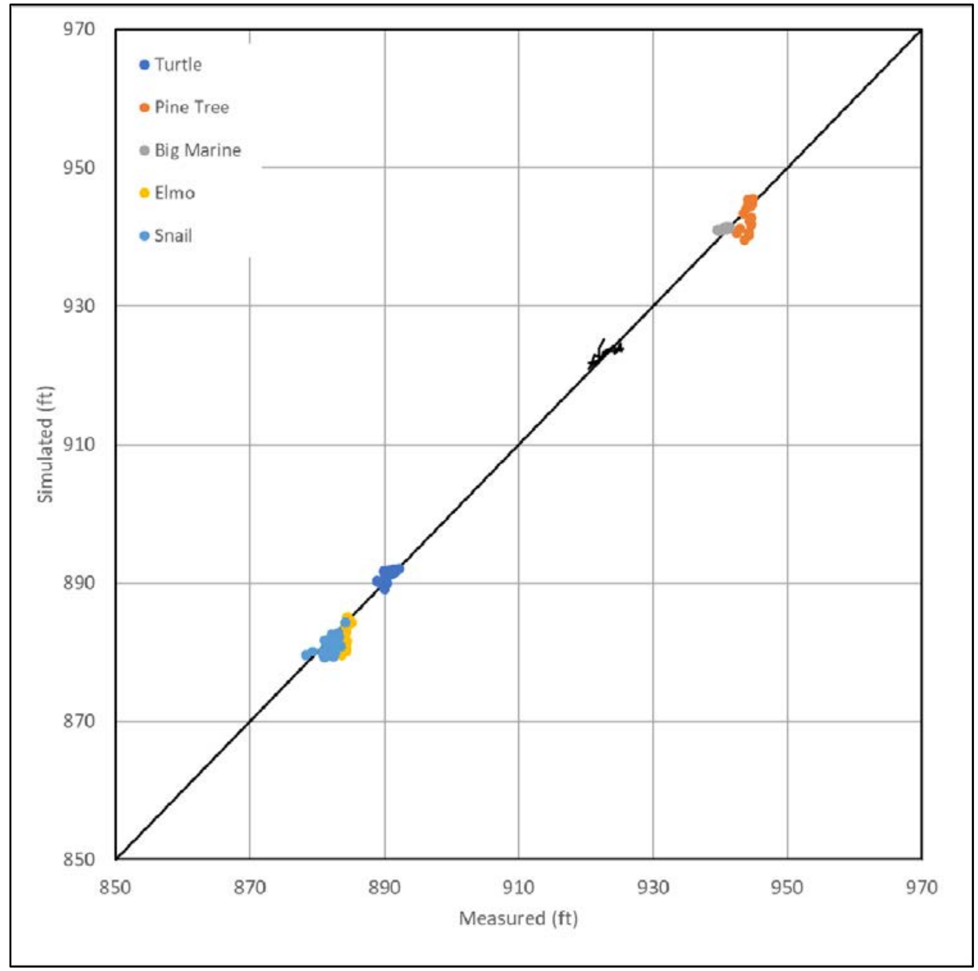


Figure 7-1 Calibration Scatter Plots for Aquifer Hydrographs: (a) Triannual Stress Periods and (b) Annual Stress Periods



(a)



(b)

Figure 7-2 Calibration Scatter Plots for Lake Stage Hydrographs: (a) Triannual Stress Periods and (b) Annual Stress Periods

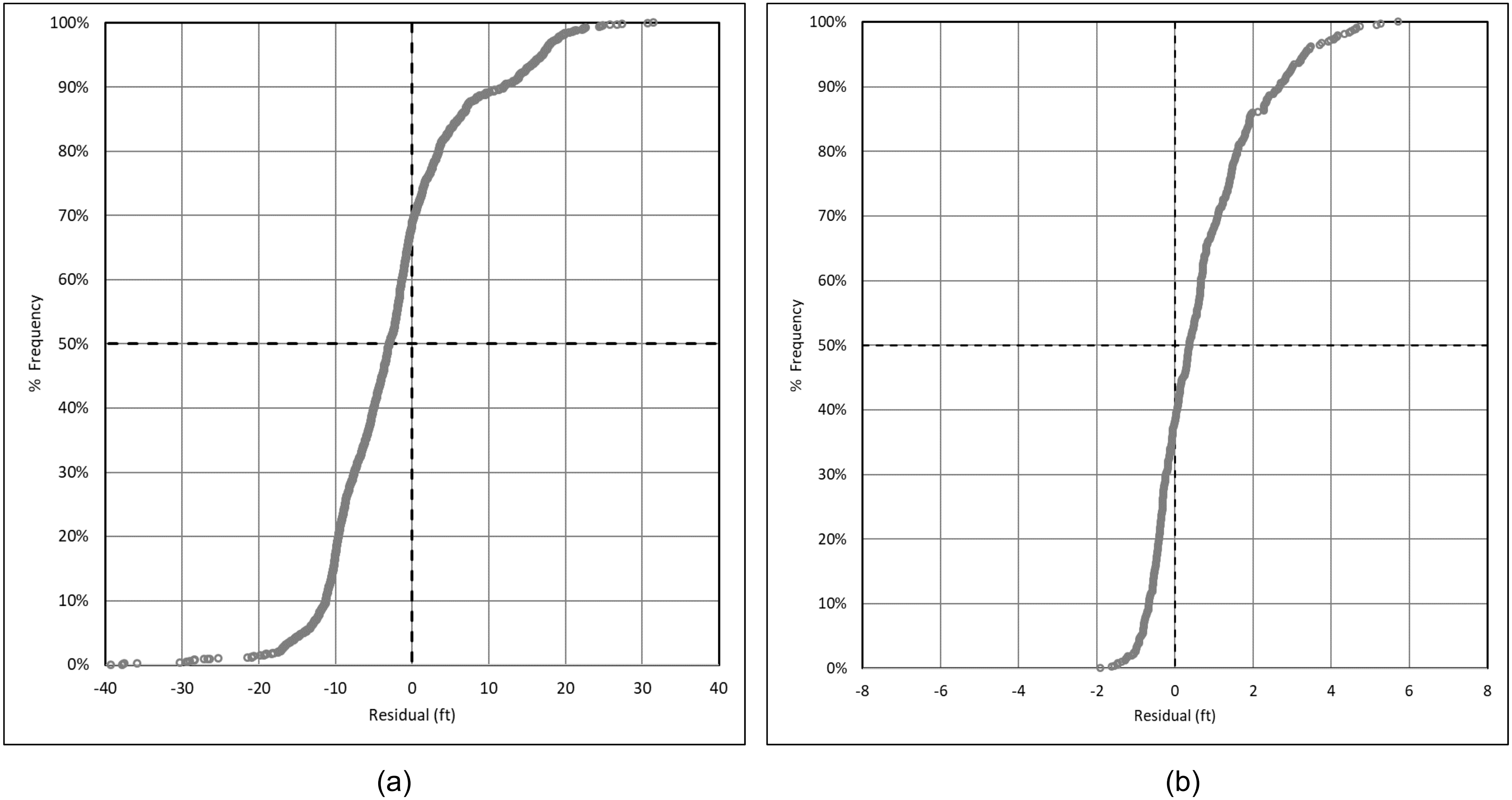


Figure 7-3 Calibration Residuals Cumulative Frequency, Triannual Stress Periods: (a) Groundwater Elevations and (b) Lake Stage Elevations

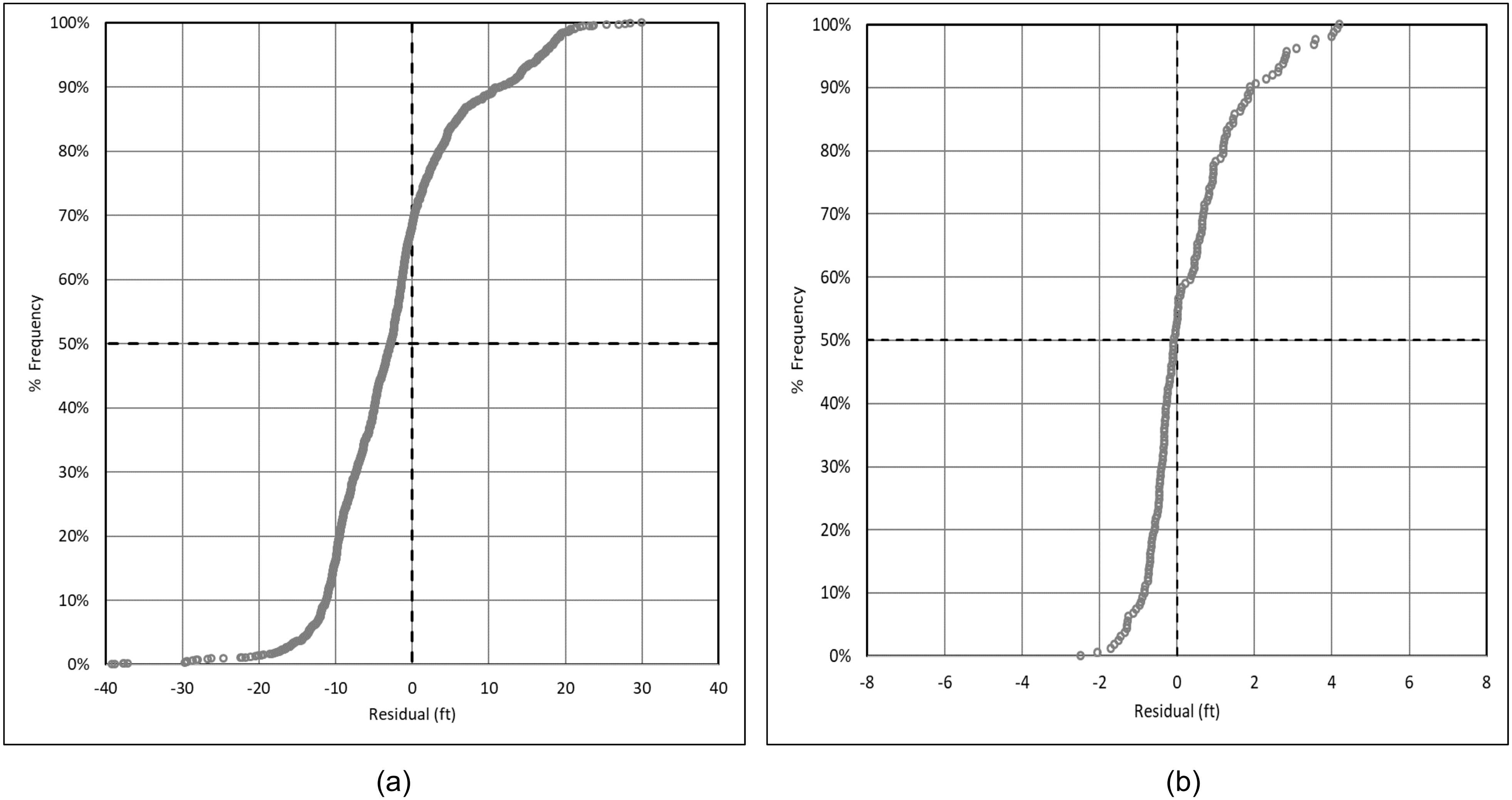


Figure 7-4 Calibration Residuals Cumulative Frequency, Annual Stress Periods: (a) Groundwater Elevations and (b) Lake Stage Elevations

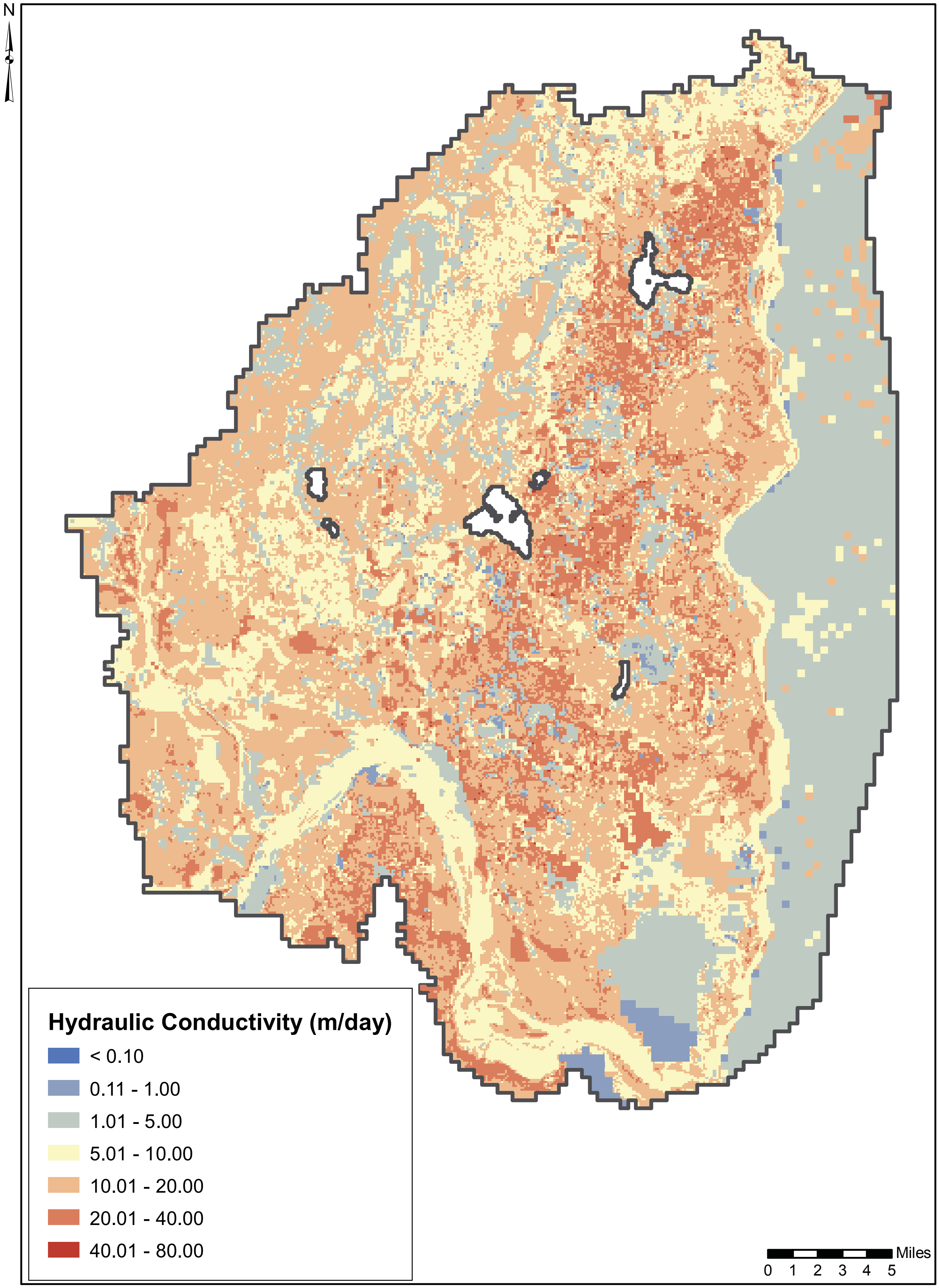


Figure 7-5 Horizontal Hydraulic Conductivity for Model Layer 1

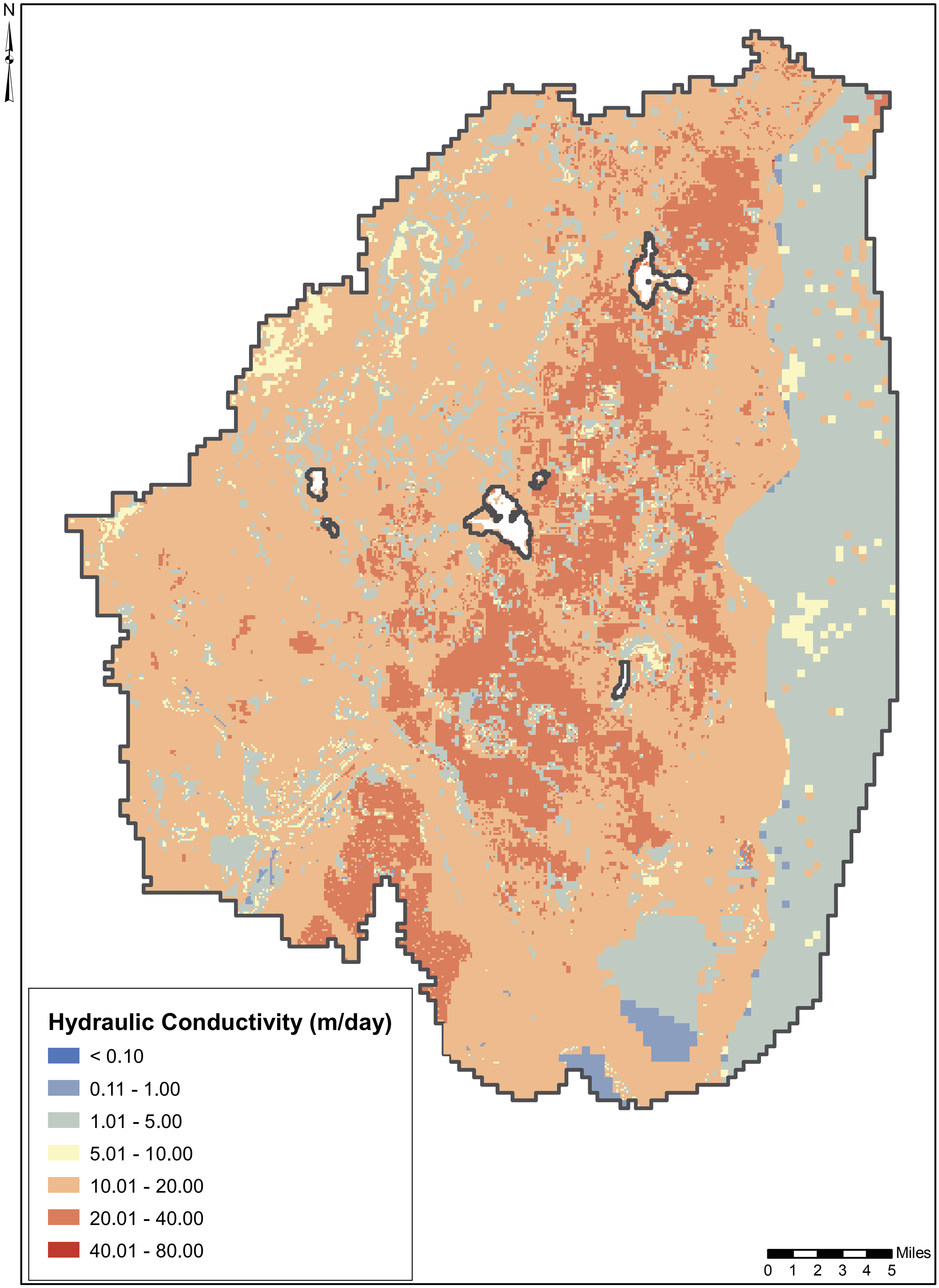


Figure 7-6 Horizontal Hydraulic Conductivity for Model Layer 2

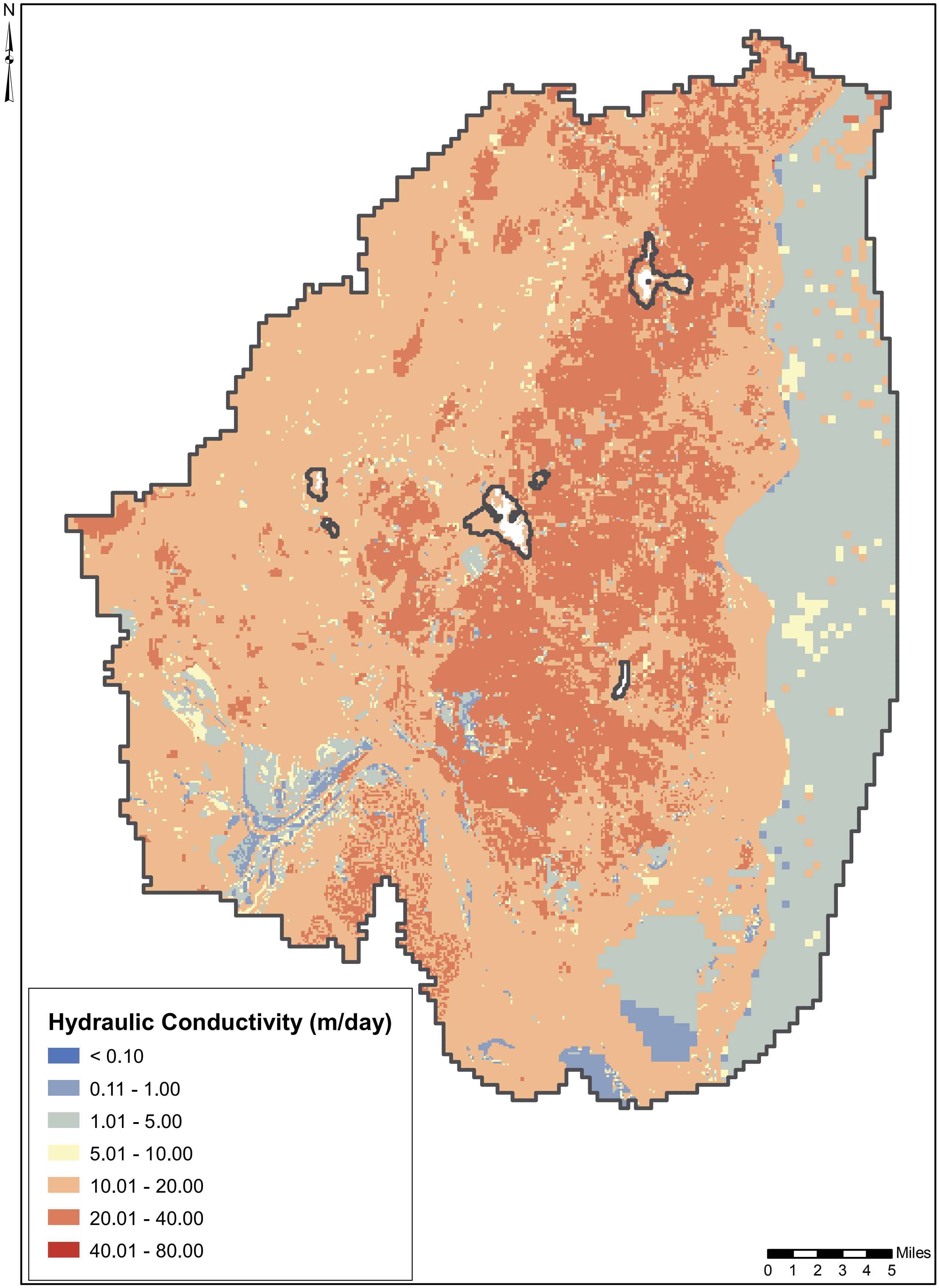


Figure 7-7 Horizontal Hydraulic Conductivity for Model Layer 3

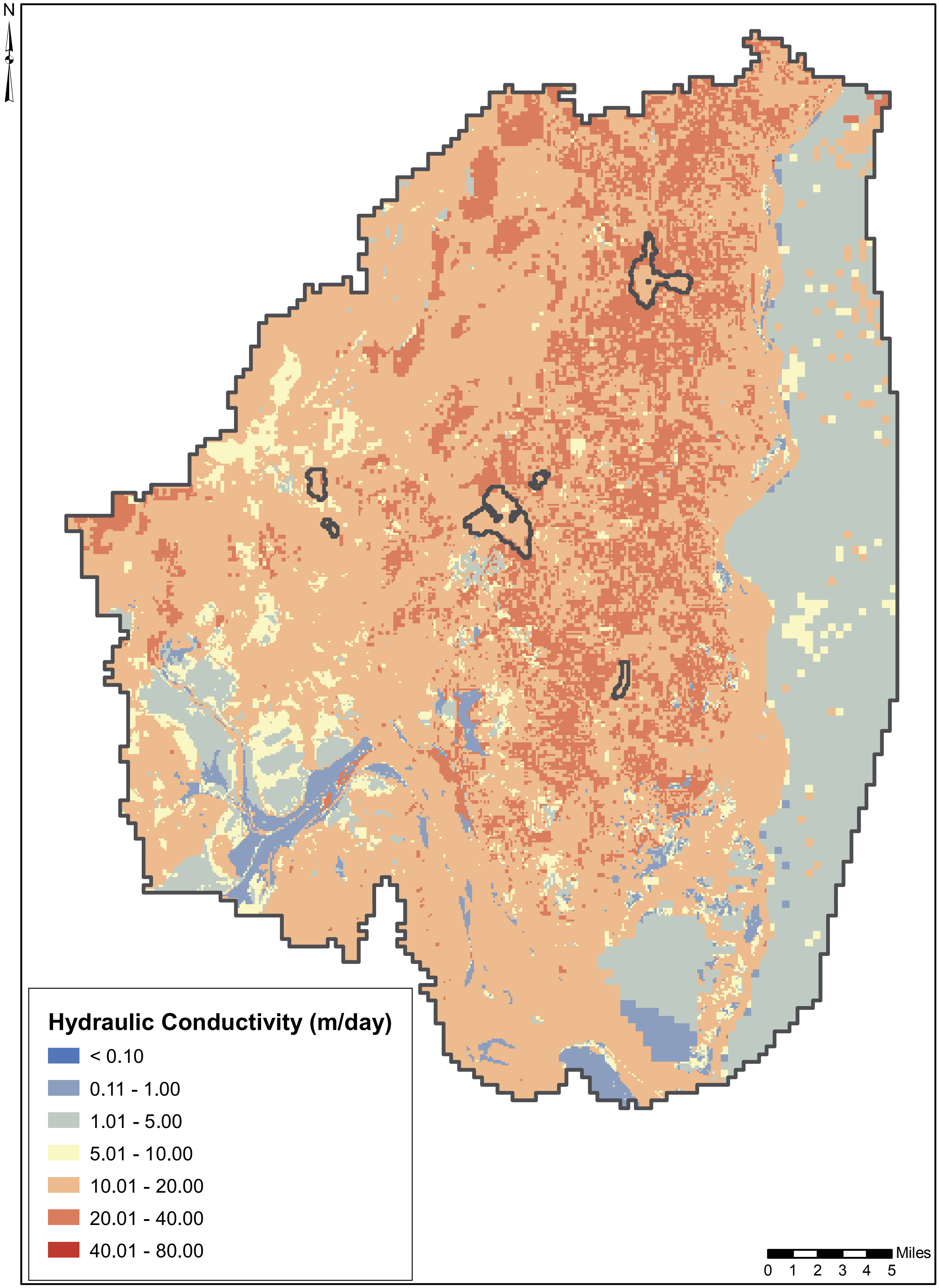


Figure 7-8 Horizontal Hydraulic Conductivity for Model Layer 4

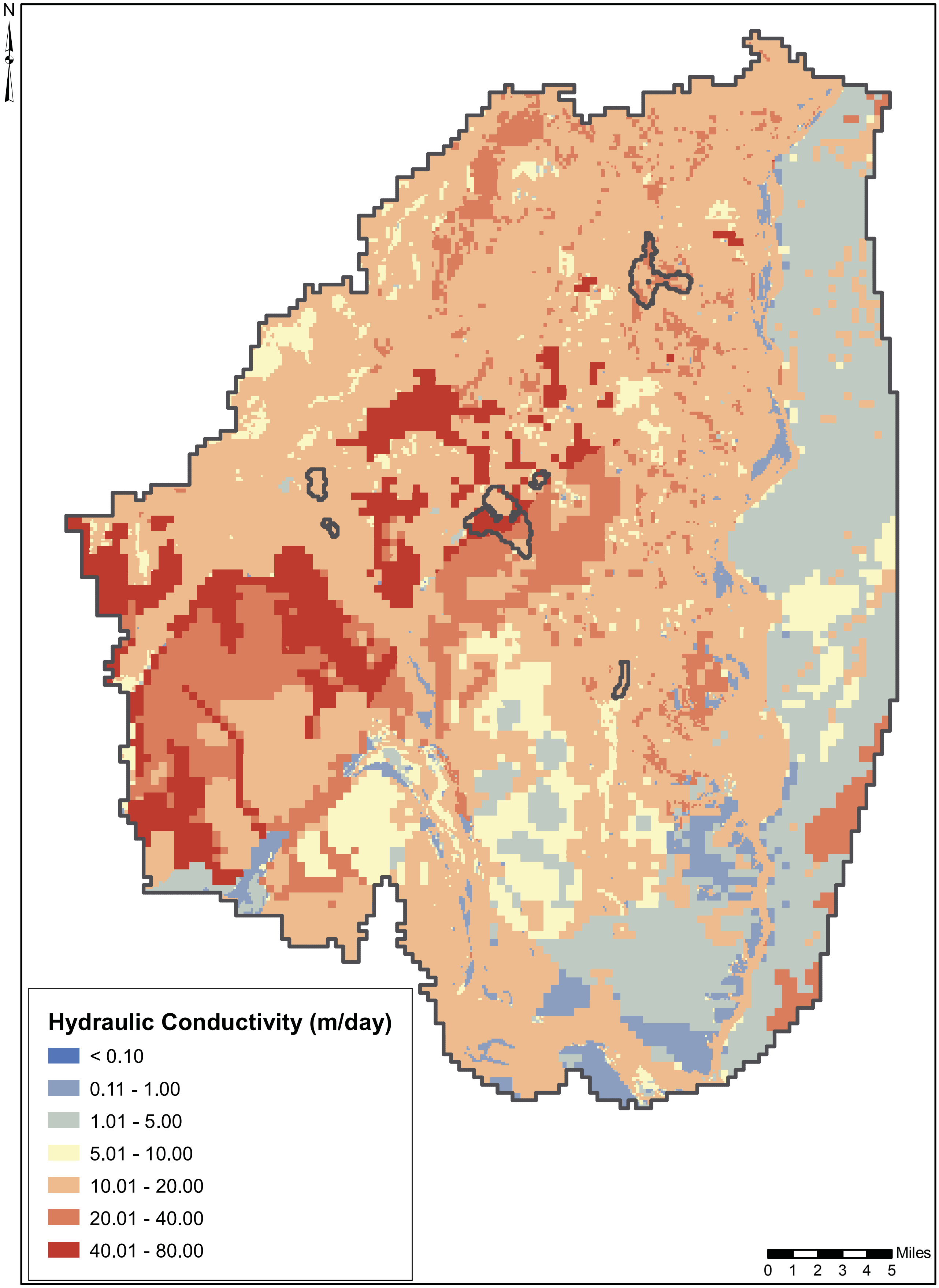


Figure 7-9 Horizontal Hydraulic Conductivity for Model Layer 5

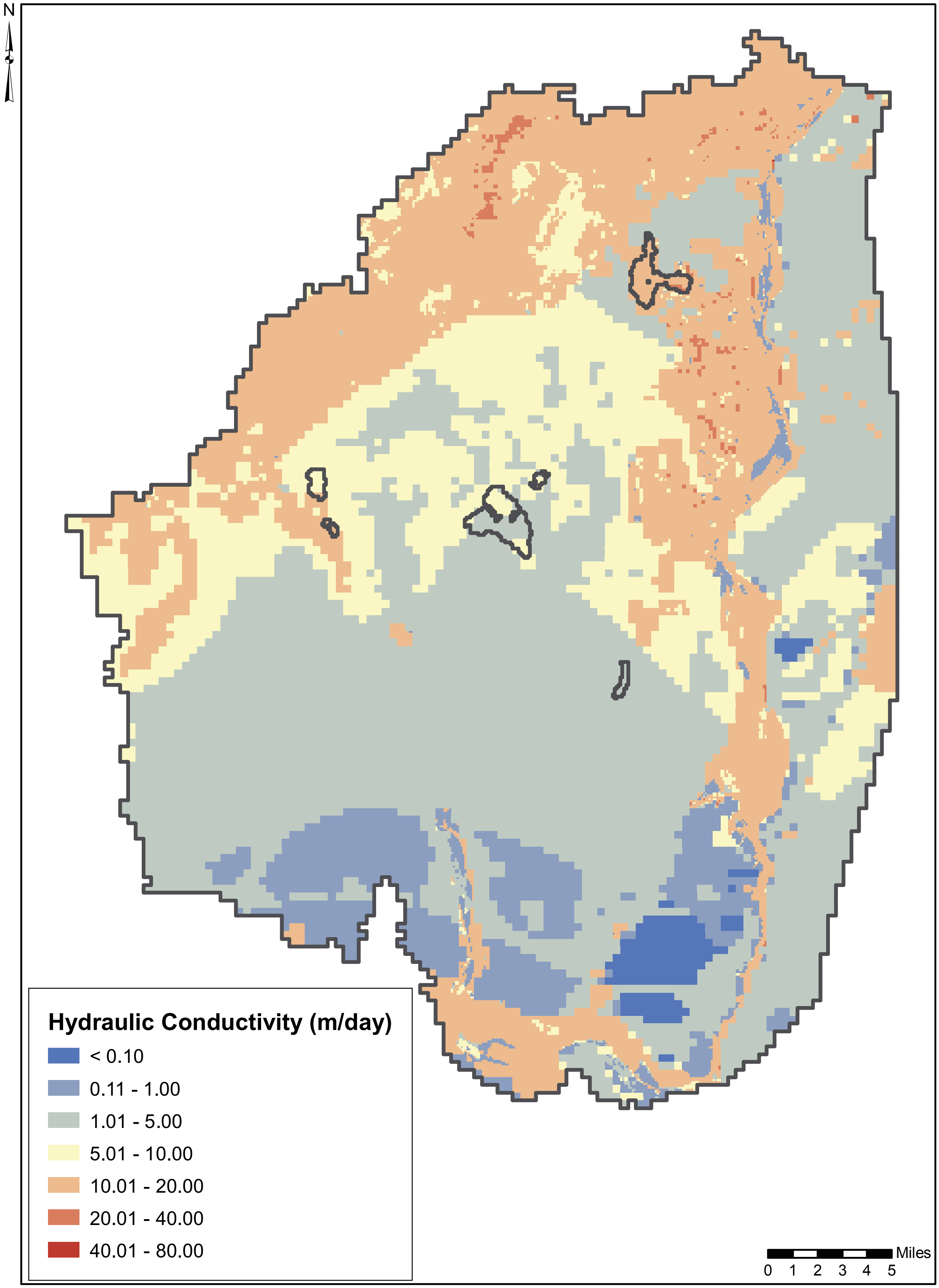


Figure 7-10 Horizontal Hydraulic Conductivity for Model Layer 6

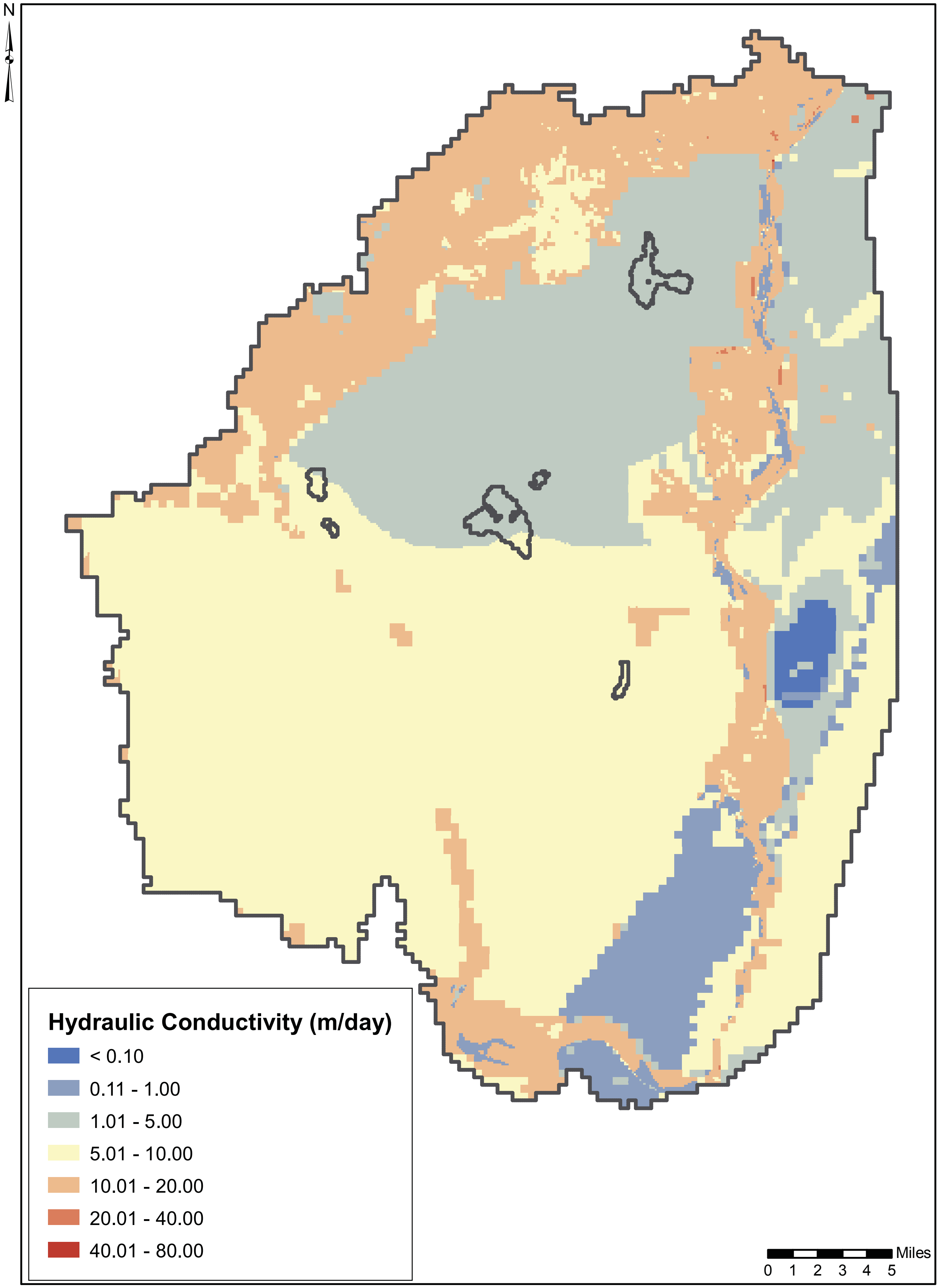


Figure 7-11 Horizontal Hydraulic Conductivity for Model Layer 7

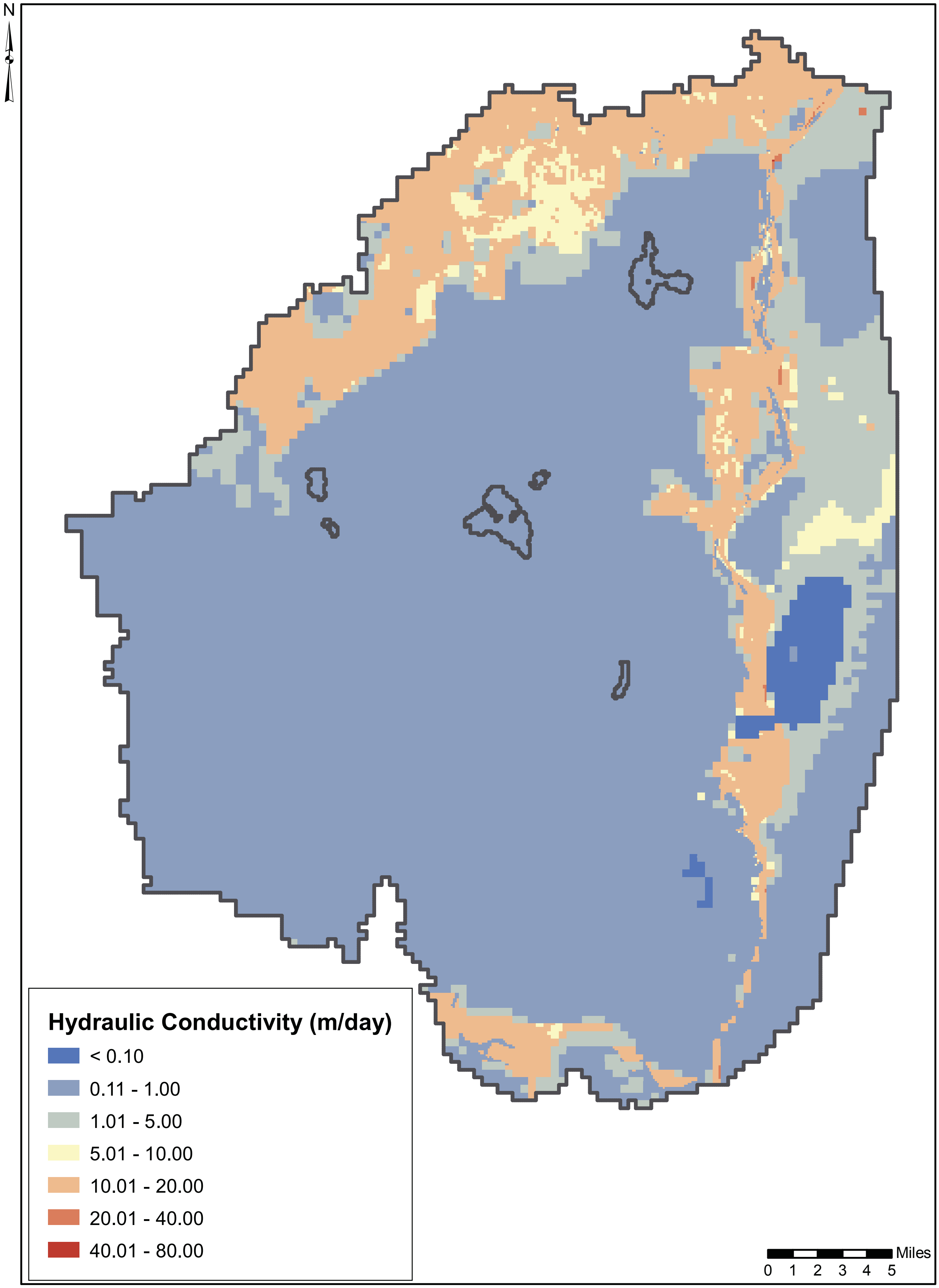


Figure 7-12 Horizontal Hydraulic Conductivity for Model Layer 8

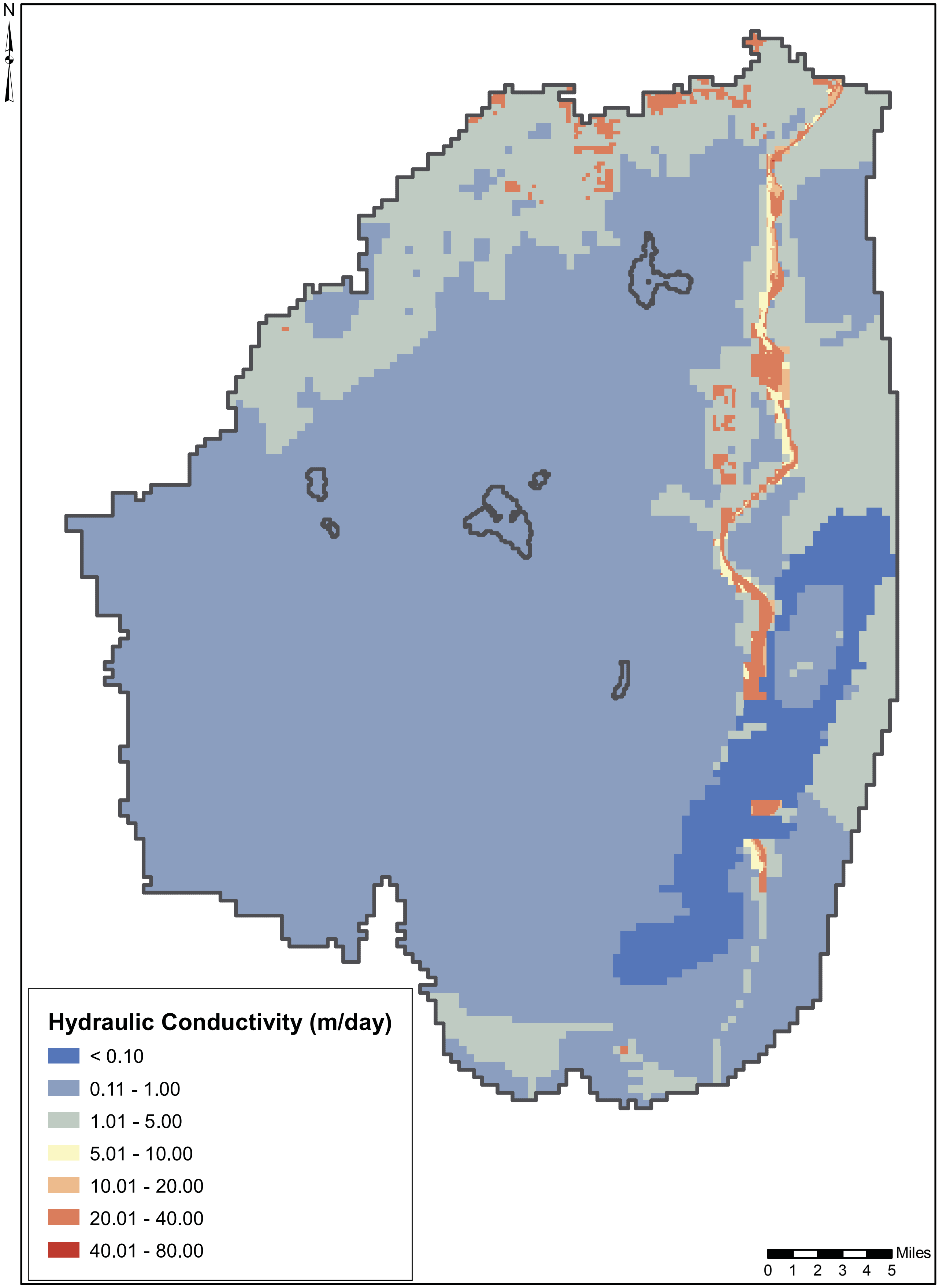


Figure 7-13 Horizontal Hydraulic Conductivity for Model Layer 9

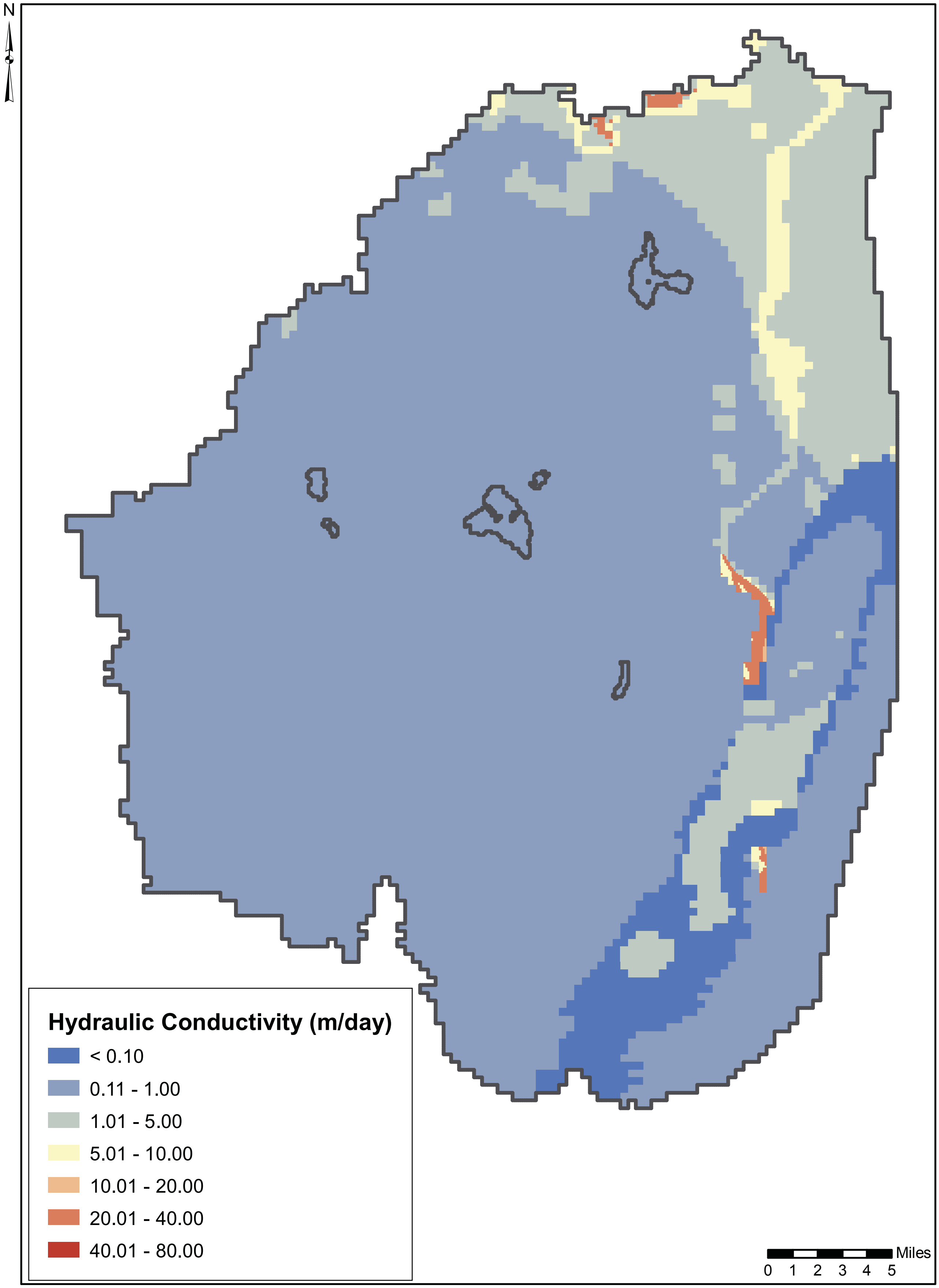


Figure 7-14 Horizontal Hydraulic Conductivity for Model Layer 10

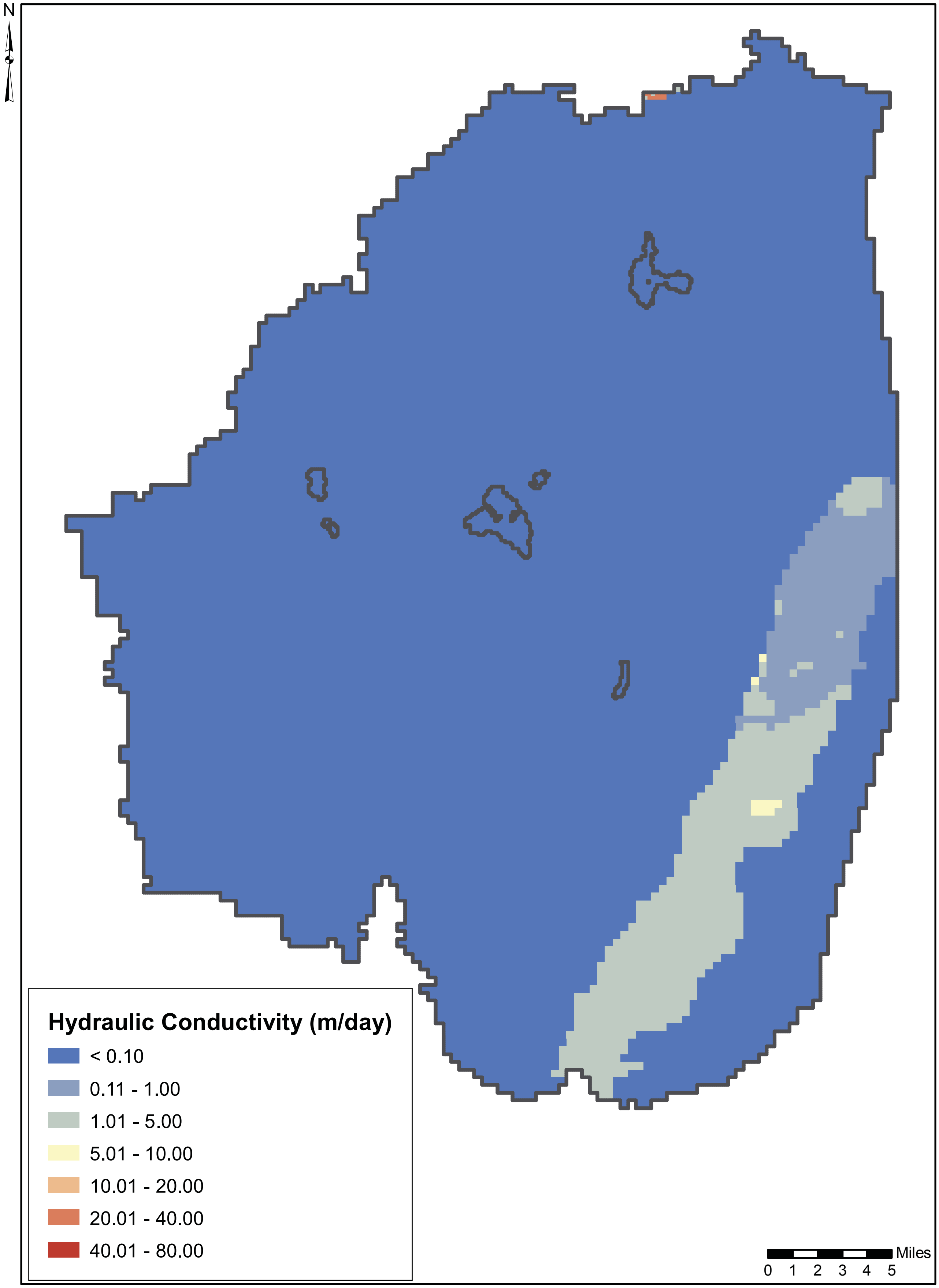


Figure 7-15 Horizontal Hydraulic Conductivity for Model Layer 11

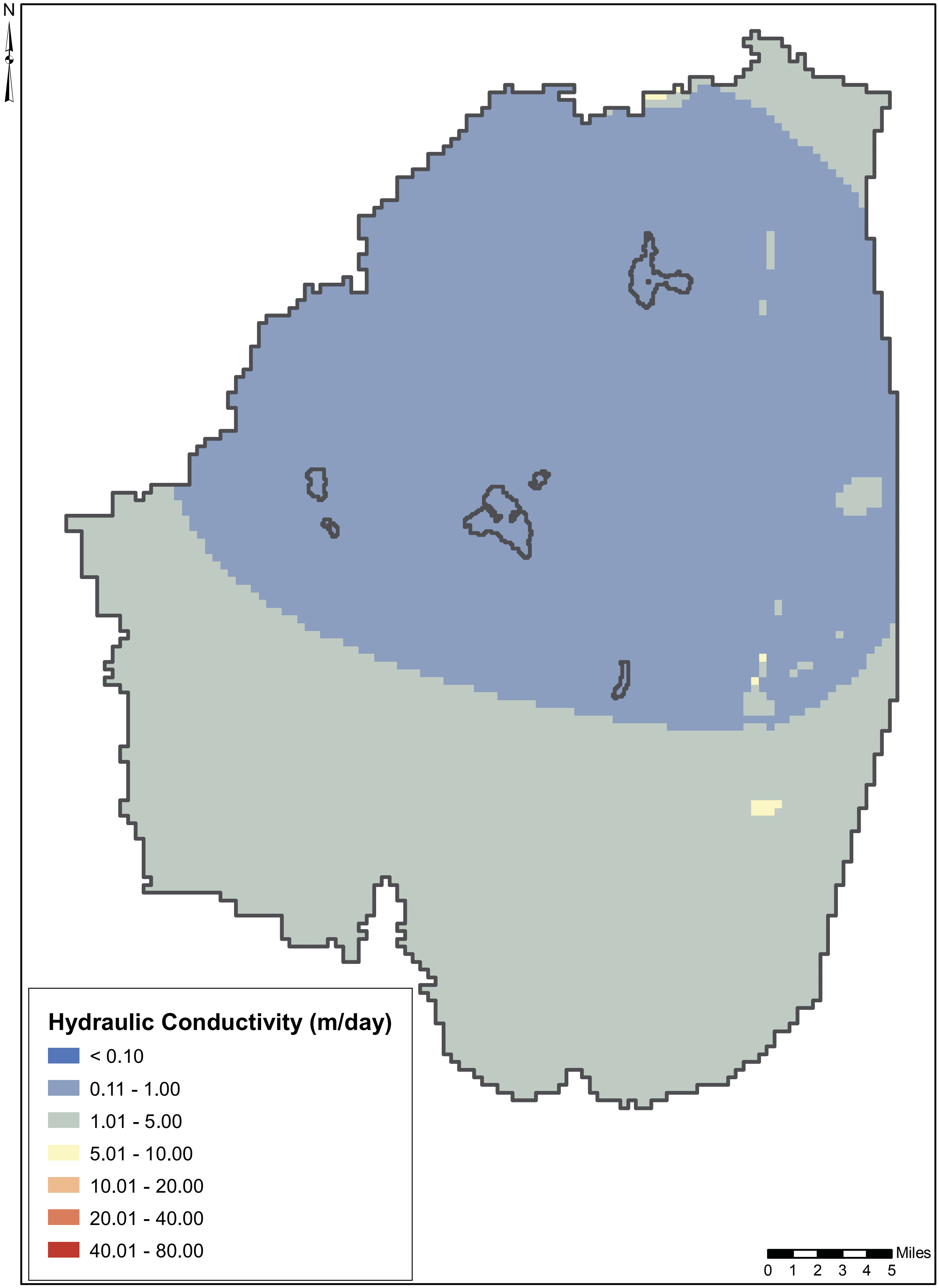


Figure 7-16 Horizontal Hydraulic Conductivity for Model Layer 12

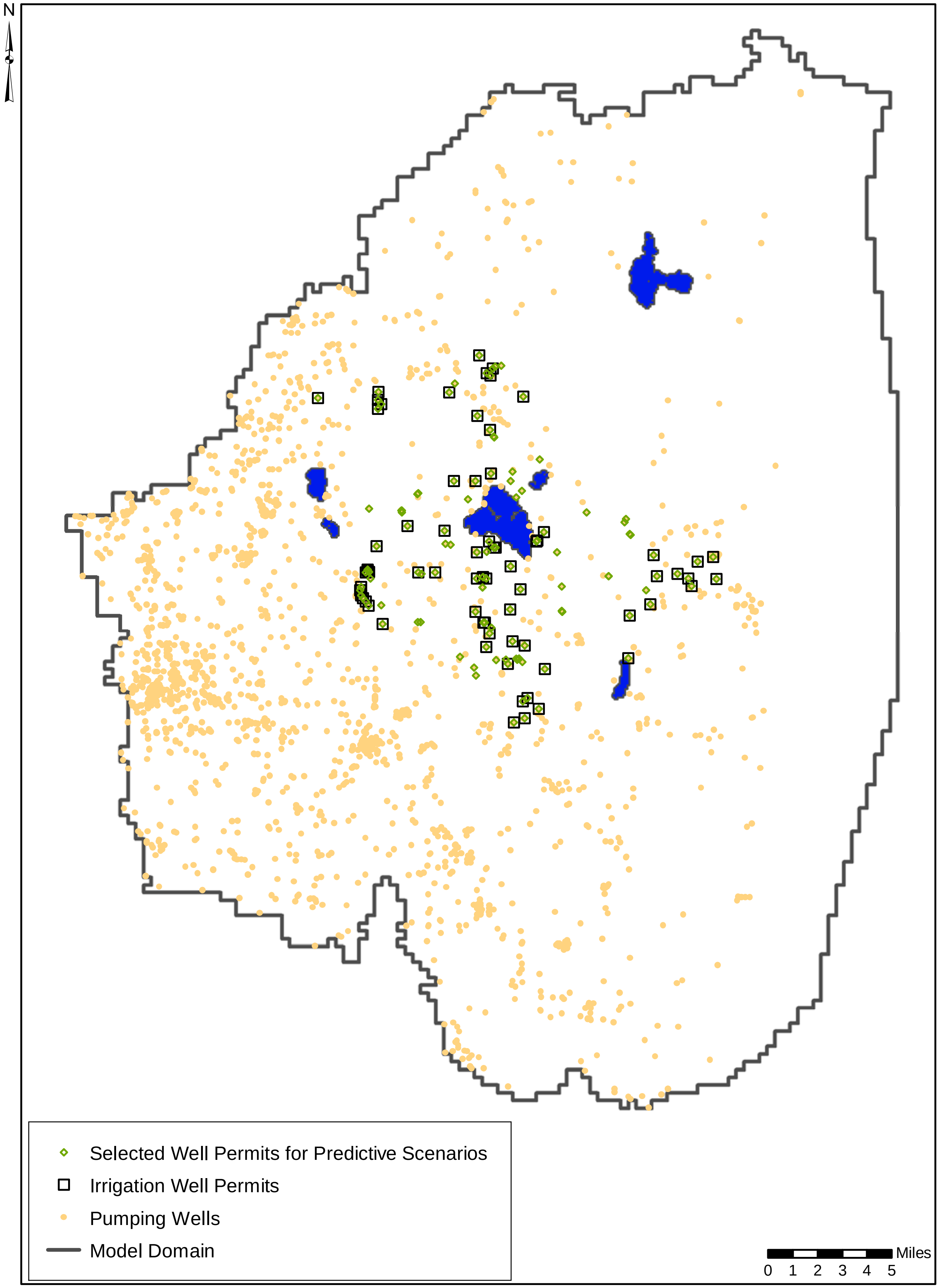


Figure 8-1 Location of Wells Associated with a Permit for which At Least One Well is Within 5 miles of White Bear Lake

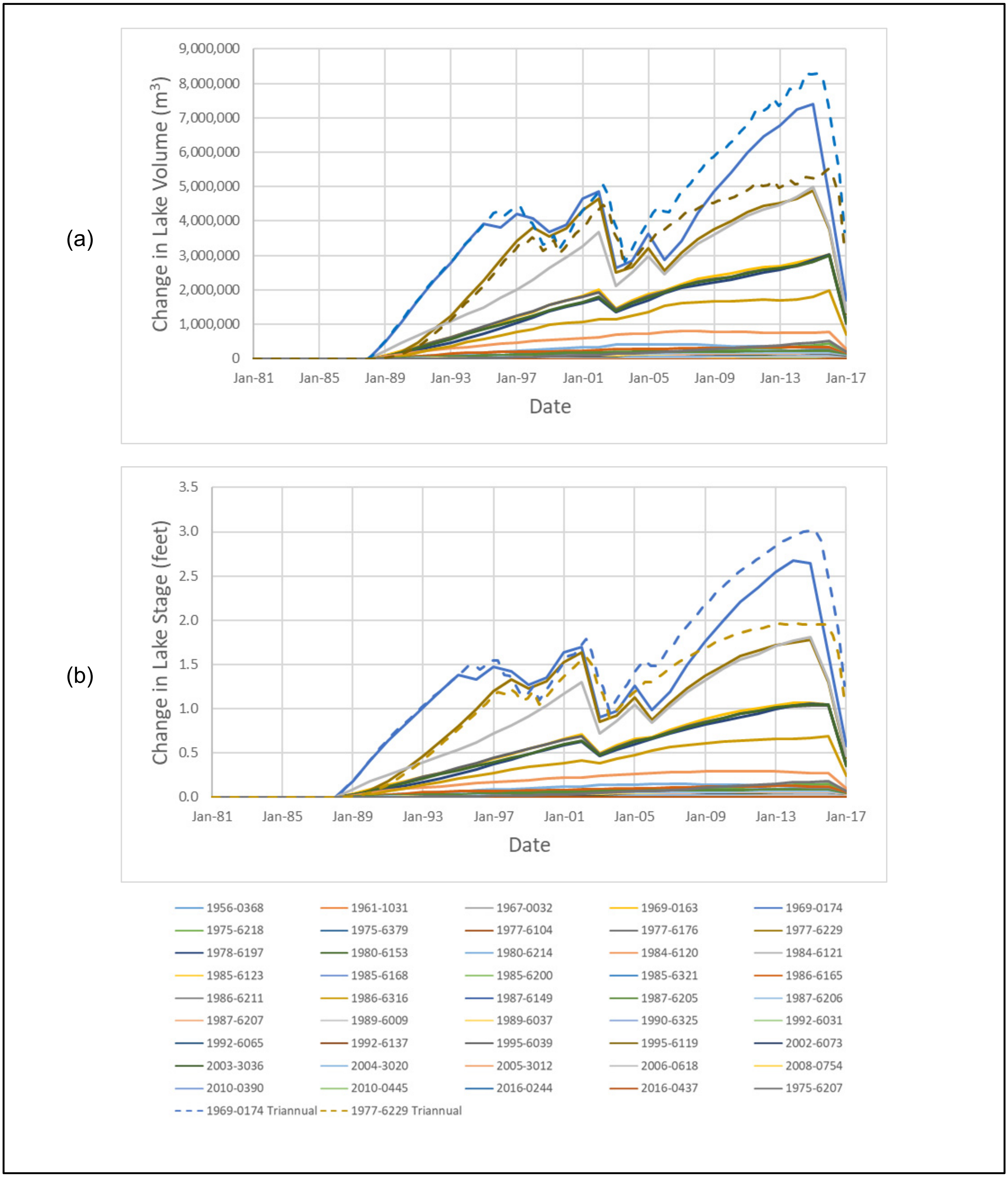


Figure 8-2 Simulation Results from Scenario 1: (a) Simulated Changes in Lake Volume, and (b) Simulated Changes in Lake Stage

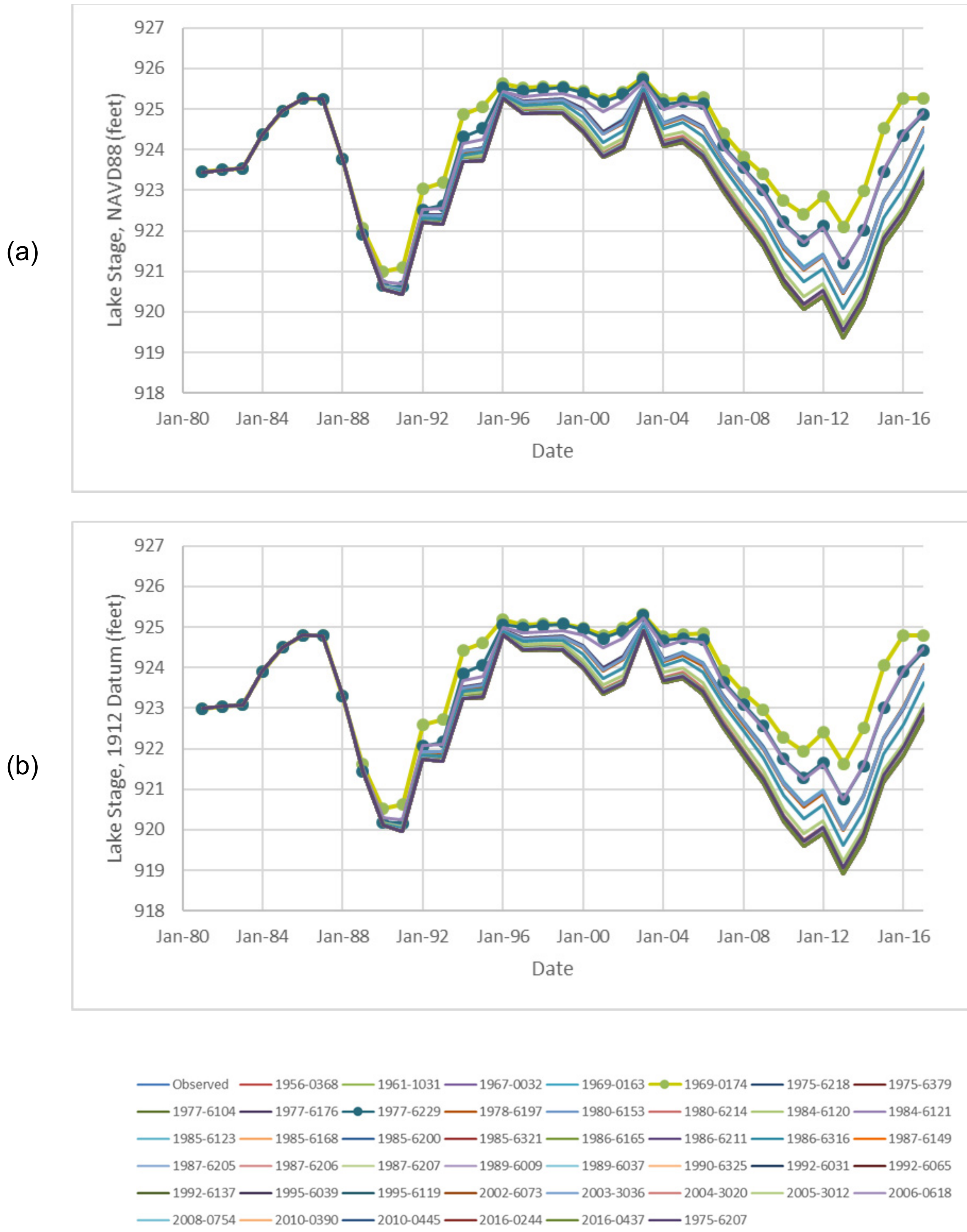


Figure 8-3 Estimated Lake Stages for Scenario 1 Annual Simulations: (a) NAVD88 Datum; (b) 1912 Datum

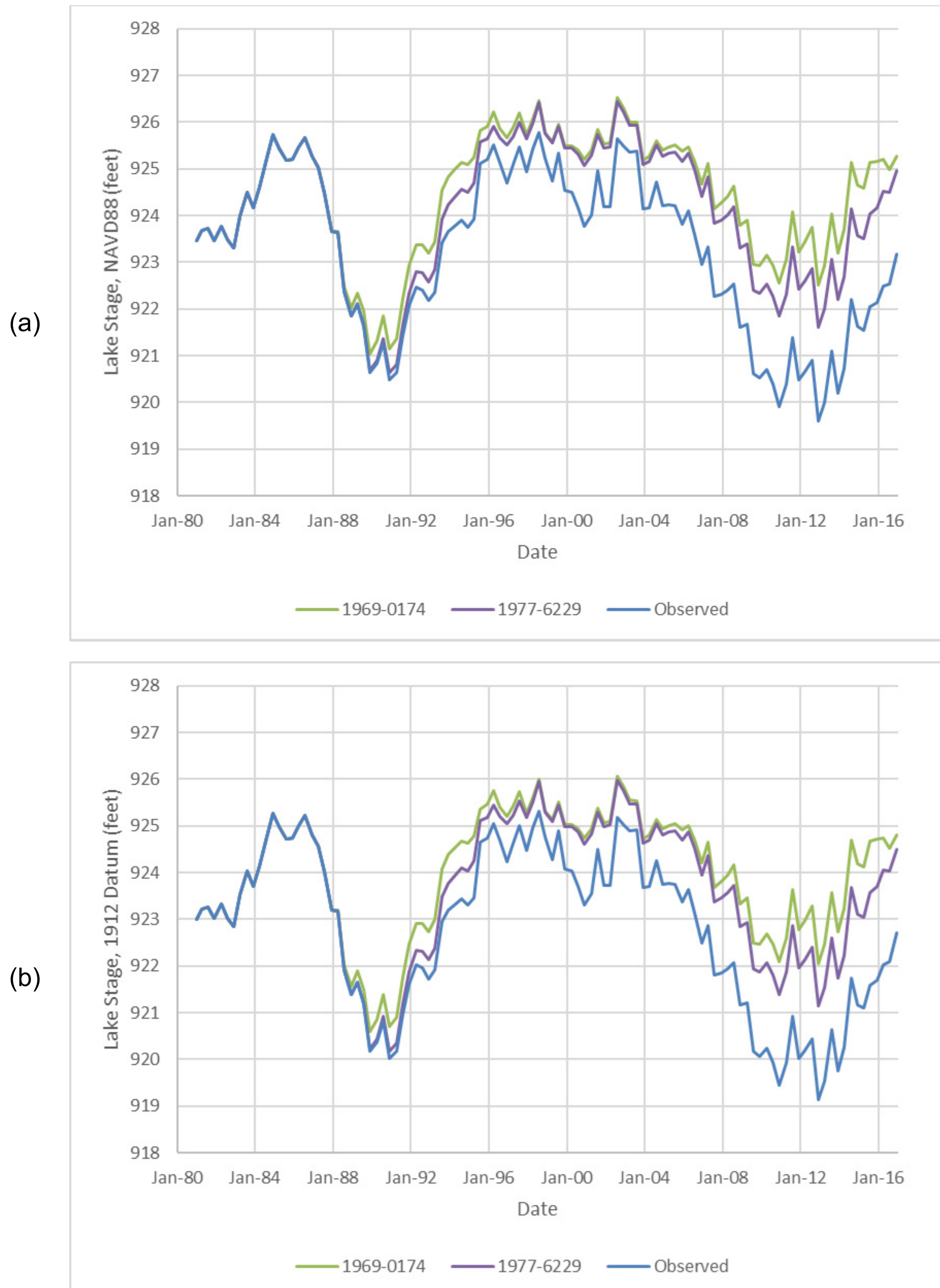
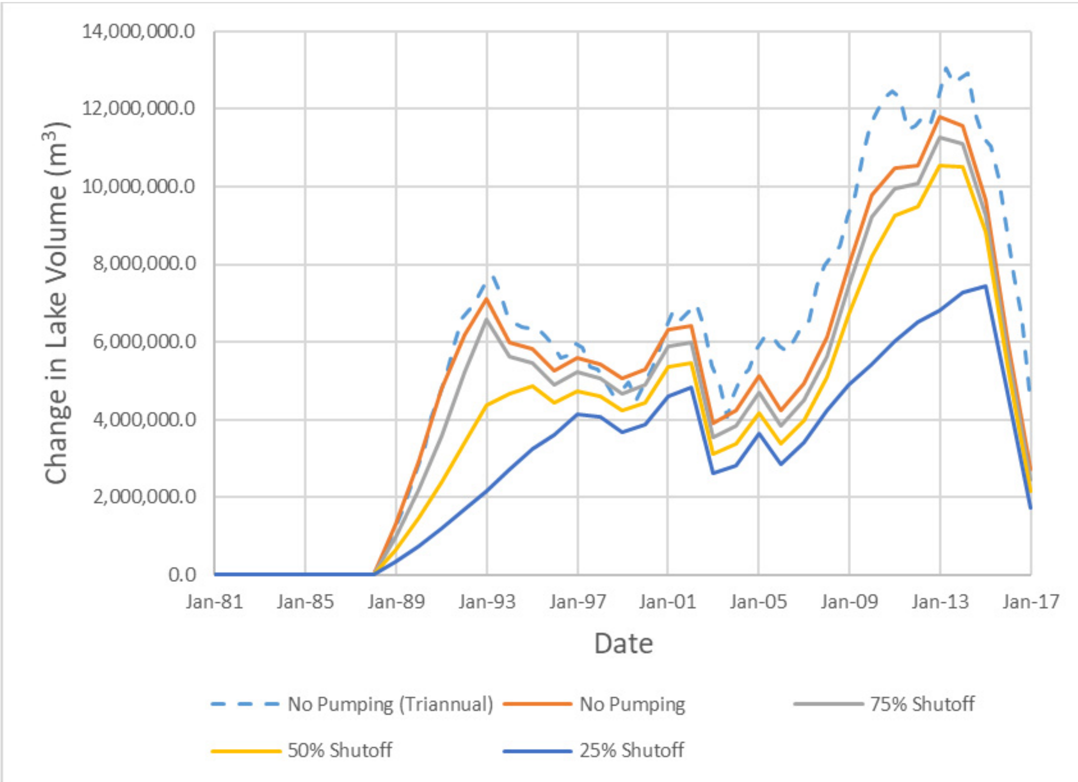


Figure 8-4 Estimated Lake Stages for Scenario 1 Triannual Simulations: (a) NAVD88 Datum; (b) 1912 Datum

(a)



(b)

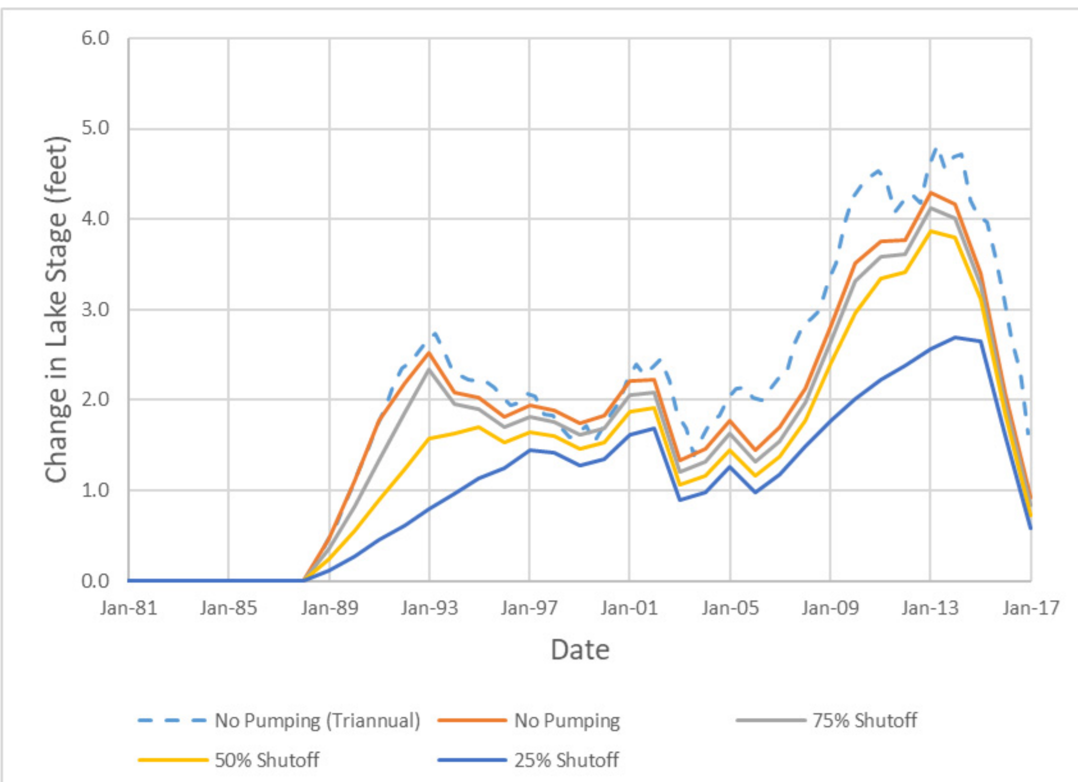
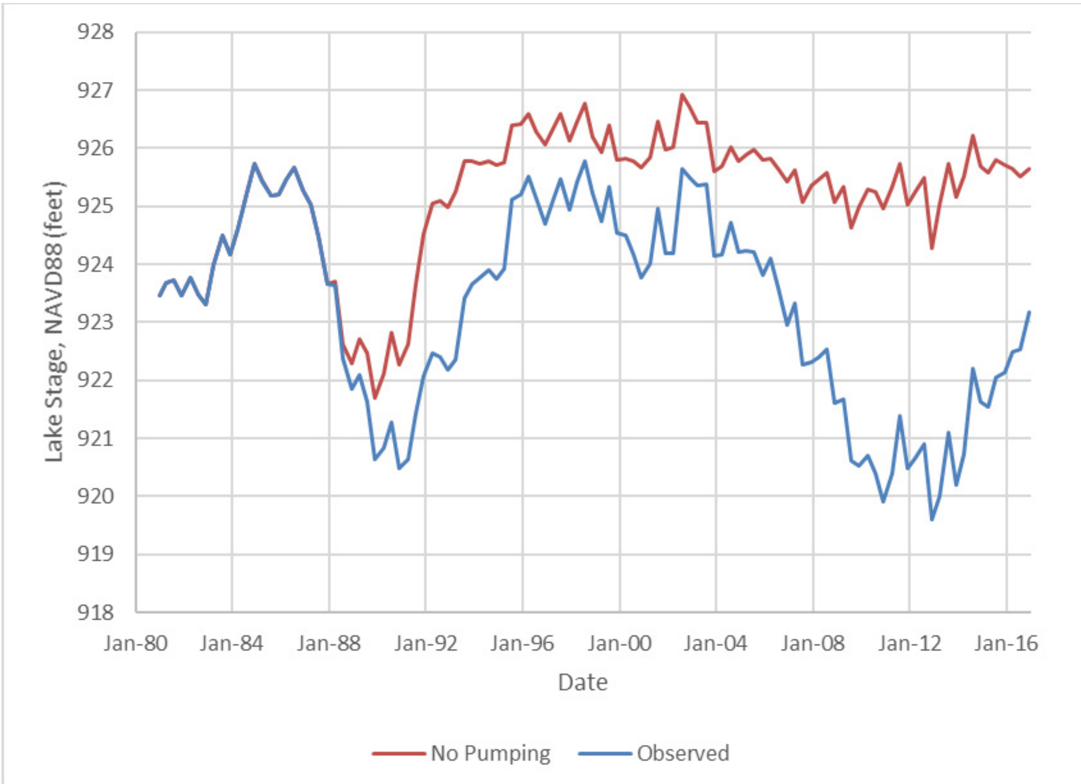


Figure 8-5 Simulation Results from Scenario 2: (a) Simulated Changes in Lake Volume, and (b) Simulated Changes in Lake Stage

Figure 8-6 Estimated Lake Stages for Scenario 2 Annual Simulations: (a) NAVD88 Datum; (b) 1912 Datum

(a)



(b)

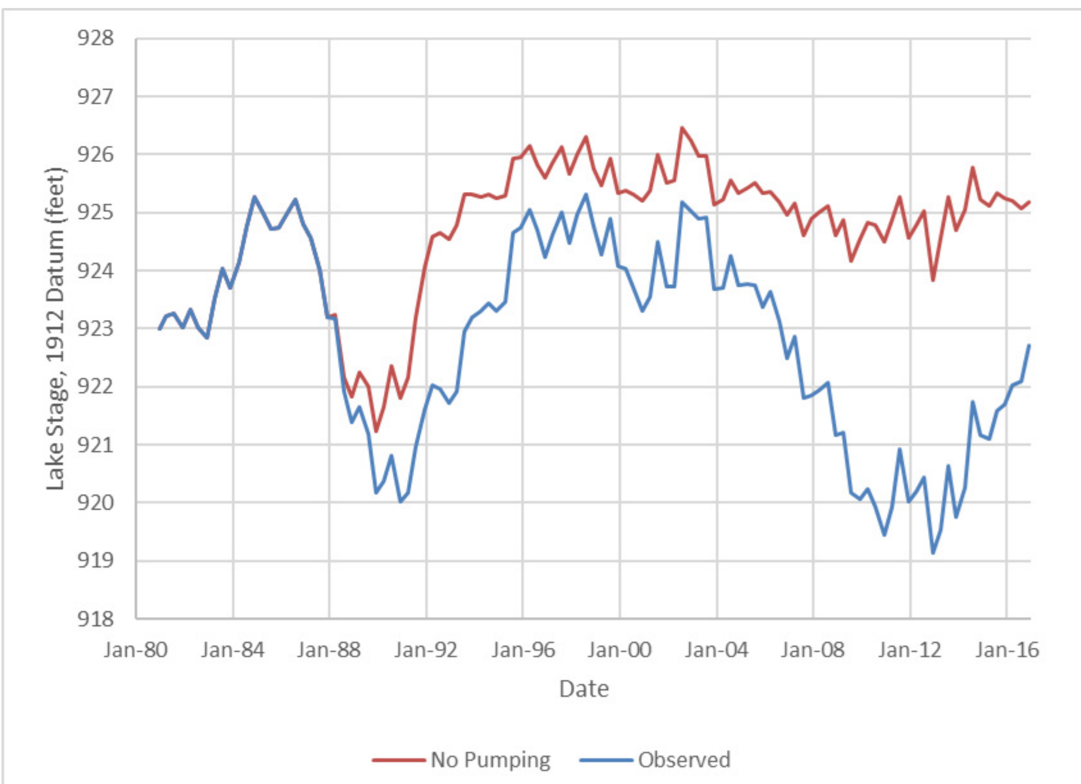


Figure 8-7 Estimated Lake Stages for Scenario 2 Triannual Simulations: (a) NAVD88 Datum; (b) 1912 Datum

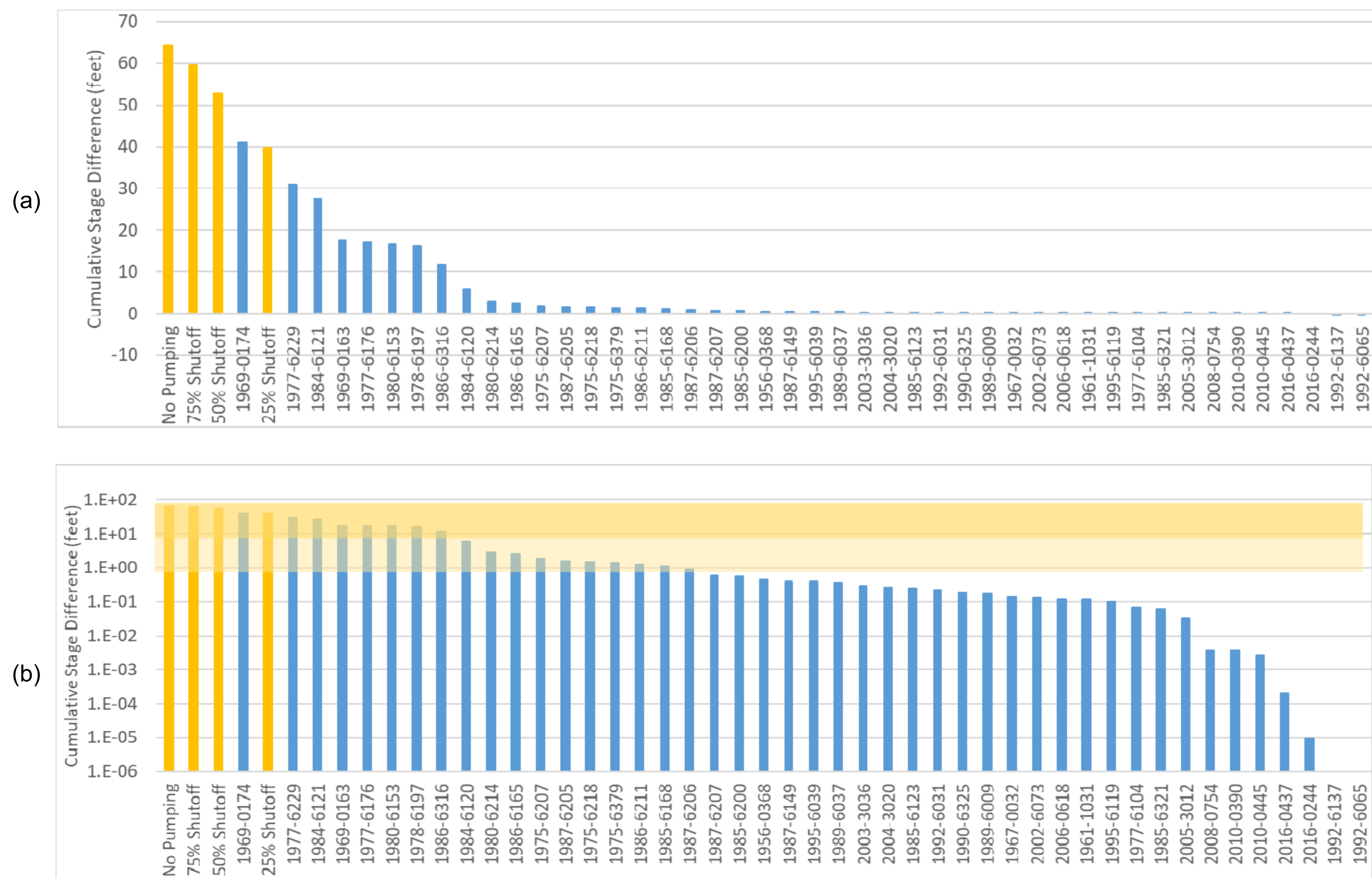


Figure 8-8 Comparison of Transient Response Functions Calculated for Scenario 1 with those for Scenario 2: (a) Linear Scale, and (b) Logarithmic Scale

(a)

(b)

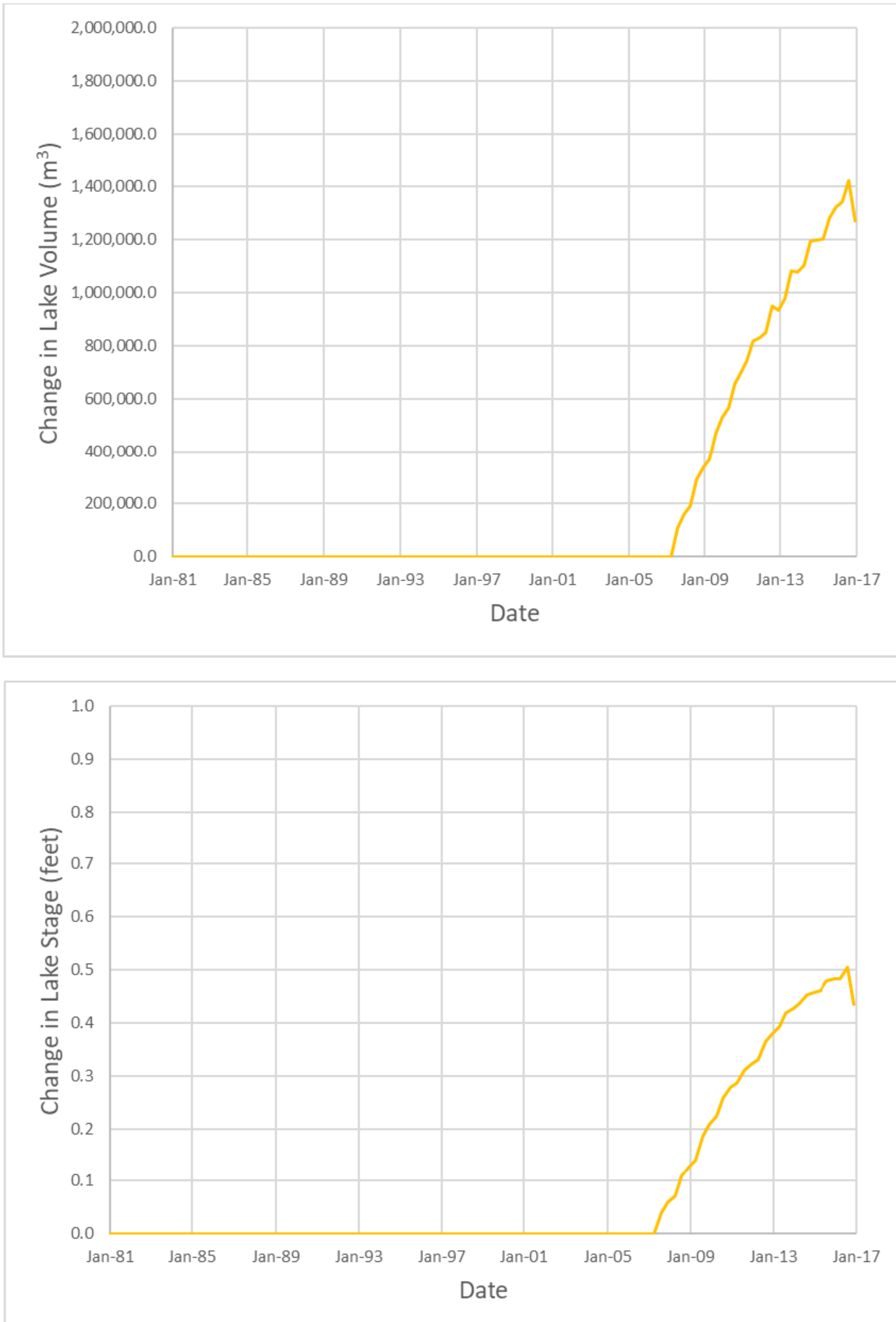
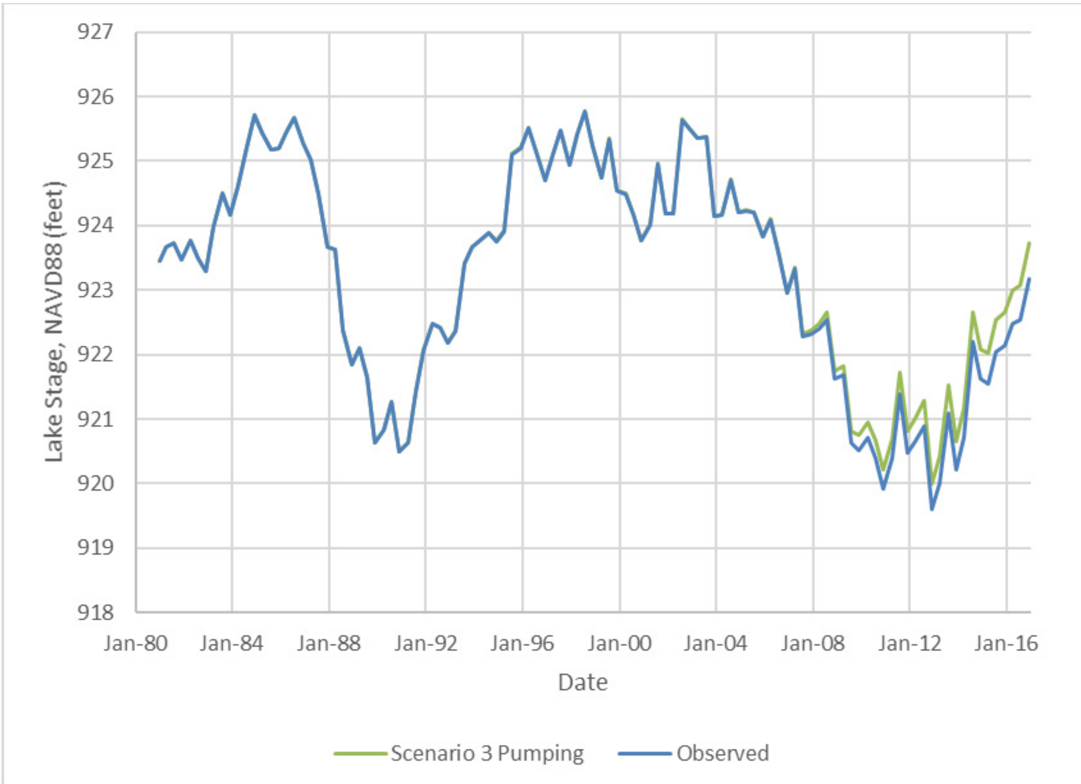


Figure 8-9 Simulation Results from Scenario 3: (a) Simulated Changes in Lake Volume, and (b) Simulated Changes in Lake Stage

(a)



(b)

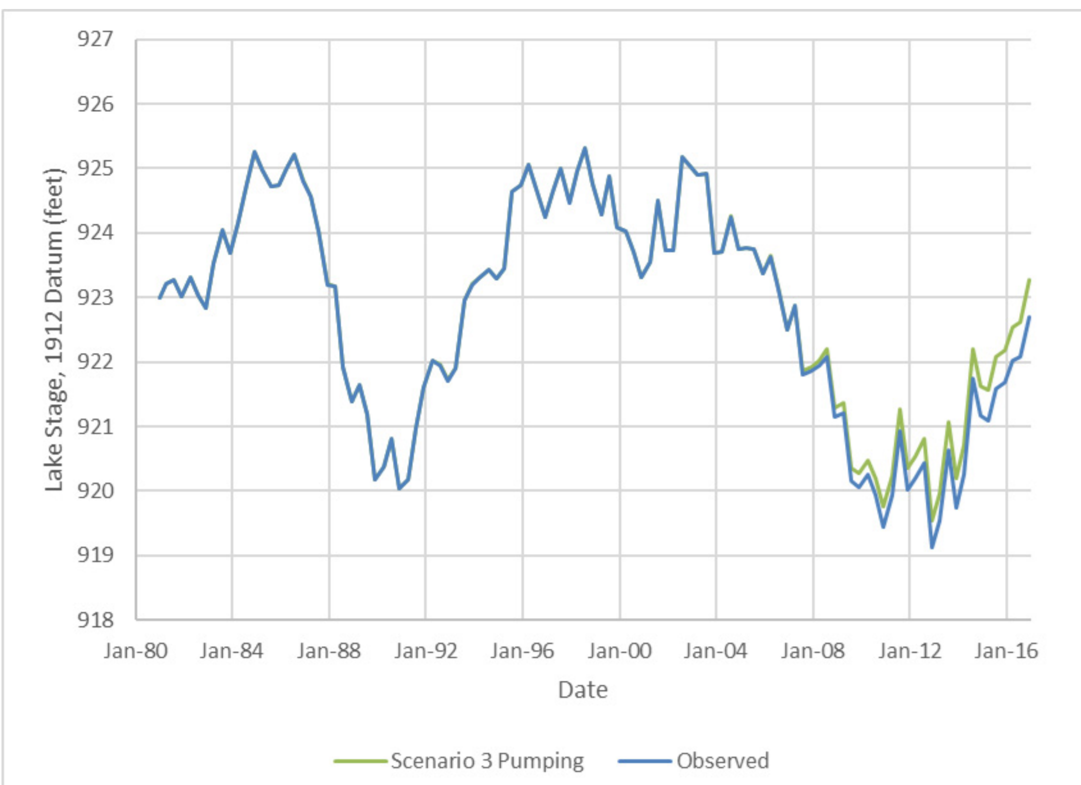


Figure 8-10 Estimated Lake Stages for Scenarios 3: (a) NAVD88 Datum; (b) 1912 Datum

Figure 9-1 Ramsey Washington Judicial Ditch #1 within Shuneman Marsh

TABLES

Table 2-1

Calibrated SCS Runoff Curve Numbers for Various Hydrological Soil Groups in the Steady- State NMLG Model

Description Assumed Imperviousness	A	B	C	D
Pasture/Hay	-5	35	58	66
Grassland/Herbaceous	16	49	69	75
Evergreen Forest	24	52	69	74
Developed, Open Space	32	51	62	66
Mixed Forest	33	58	73	78
Cultivated Crops	41	65	79	84
Deciduous Forest	43	64	77	82
Shrub/Scrub	45	66	78	82
Barren Land (Rock/Sand/Clay)	69	82	89	92
Woody Wetlands	76	78	80	80
Developed, Low Intensity	78	85	89	91
Emergent Herbaceous Wetlands	83	85	86	86
Developed, High Intensity	97	98	99	99
Developed, Medium Intensity	100	100	100	100

Table 4-1

Adjusted Land Classification Codes for1992
(reproduced from: USGS Open-File Report 2008-1379)

Description	NLCD 1992 class code	NLCD 2001 class code	Modified Anderson Level 1 class code
Open water	11	11	1
Perennial ice, snow	12	12	8
Urban, recreational grasses	85	21	2
Low intensity residential	21	22	2
High intensity residential	22	23	2
Commercial, industrial, roads	23	24	2
Bare rock, sand	31	31	3
Quarry, strip mine, gravel pit	32	31	3
Transitional barren	33	31	3
Deciduous forest	41	41	4
Evergreen forest	42	42	4
Mixed forest	43	43	4
Shrubland	51	52	5
Orchards, vineyards, other	61	82	6
Grasslands, herbaceous	71	71	5
Pasture, hay	81	81	6
Row crops	82	82	6
Small grains	83	82	6
Fallow	84	82	6
Woody wetlands	91	90	7
Emergent, herbaceous wetland	92	95	7

Table 4-2

Percentage of Each Land Class used in the SWB Model

Land-Use Classification	1992	2001	2006	2011
Pasture, hay	24.2%	14.5%	14.3%	13.4%
Orchards, vineyards, other	18.8%	13.8%	13.4%	13.2%
Low intensity residential	13.2%	13.1%	15.4%	13.3%
Deciduous forest	11.0%	15.2%	16.8%	14.6%
Open water	7.5%	10.1%	10.1%	11.0%
High intensity residential	5.9%	6.2%	8.0%	7.7%
Emergent, herbaceous wetland	5.7%	5.6%	5.6%	5.0%
Commercial, industrial, roads	4.7%	3.2%	4.2%	3.5%
Urban, recreational grasses	4.7%	13.2%	7.0%	13.4%
Woody wetlands	3.5%	0.7%	0.7%	0.6%
Evergreen forest	0.3%	1.2%	1.3%	1.1%
Grasslands, herbaceous	0.1%	2.5%	2.4%	2.4%
Shrubland	0.0%	0.6%	0.6%	0.6%

Table 4-5

Lakes Represented using the MODFLOW Lake (LAK) and MODFLOW River (RIV) Packages

Lake Name	Lake Number	MODFLOW Package
White Bear Lake	82016700	LAK
Lake Elmo	82010600	LAK
Pine Tree Lake	82012200	LAK
Big Marine Lake	82005200	LAK
Snail Lake	62007300	LAK
Turtle Lake	62006100	LAK
Bald Eagle (62-2 P)	62000200	RIV
Birch (62-24 P)	62002400	RIV
DeMontreville	82010100	RIV
Echo	82012900	RIV
Echo	82013500	RIV
Fish	82013700	RIV
Gilfillan	62002700	RIV
Goose	62003400	RIV
Jane (82-104 P)	82010400	RIV
Long	82011800	RIV
Long	82013000	RIV
Mann (82-121 W)	82012100	RIV
Olson	82010300	RIV
Otter (2-3 P)	2000300	RIV
Round	82013600	RIV
Sunnybrook (82-133 W)	82013300	RIV
Sunset (82-153 P)	82015300	RIV
Willow (62-40 P)	62004000	RIV

Table 4-6

Lake Invert (Overflow) Elevations

Lake Name	Lake Number	Outlet Elevation (ft NAVD88)
White Bear Lake	82016700	924.8
Lake Elmo	82010600	883.93
Pine Tree Lake	82012200	945.3
Big Marine Lake	82005200	940.8
Snail Lake	62007300	886.6
Turtle Lake	62006100	891.7

Table 6-1

Groundwater Model Parameters Included in Calibration Process

Model Parameter	Description
River Conductance	Values for river conductance in those RIV package cells that represent (a) Rivers; (b) Lakes not represented by LAK package; (c) Tributaries; and (d) Wetlands.
Lake Conductance	Values for lake conductance varying over lake depth used in the LAK package.
Specific Yield	Specific yield in unconfined units.
Horizontal Hydraulic Conductivity	Horizontal hydraulic conductivity is calibrated using multiple parameters including: (a) spatially distributed multiplier based on soil-type for quaternary formation; (b) point values of hydraulic conductivity at pilot point locations for quaternary formation; and (c) point values of multipliers applied to conductivity values at pilot point locations for deeper formations.
Vertical Hydraulic Conductivity	Vertical hydraulic conductivity is calibrated using multiple parameters including: (a) spatially distributed multiplier based on soil-type for quaternary formation; (b) point values of hydraulic conductivity at pilot point locations for quaternary formation; (c) point values of multipliers applied to conductivity values at pilot point locations for deeper formations; and (d) point values of multipliers applied to vertical conductivity values at pilot point locations for confining beds.

Table 7-1

Calibrated SCS Runoff Curve Numbers in the Transient NMLG Model

Land-Use Type	CN
Developed with Vegetation (Open, Low, [illegible]	69
Developed with no Vegetation (High, [illegible]	72
Forest/Shrub (Deciduous, Evergreen, Mixed)	36
Grassland/Pasture/Crop	49
Wetland	100

Table 7-2

Lake Calibration Summary Statistics:
(a) Annual Stress Period Model and (b) Triannual Stress Period Model

(a)

Lake Name	Snail (62-73 P)	Elmo (82-106 P)	Big Marine (82-52 P)	Pine Tree (82-122 P)	Turtle (62-61 P)	White Bear (82-167 P)
Lake ID	**62007300**	**82010600**	**82005200**	**82012200**	**62006100**	**82016700**
Correlation	0.53	0.59	-0.02	0.50	0.79	0.75
Residual Min	-3.10	-4.20	-2.42	-4.06	-0.90	-1.69
Residual Max	1.26	0.50	1.50	1.29	1.69	2.48
Average Residual	-0.49	-1.45	0.11	-0.88	0.42	0.14
Std. Deviation	1.11	1.17	0.89	1.66	0.51	1.07
Sum of Squared Residuals	56.28	131.56	26.41	70.29	16.63	43.88
Mean Square Error	1.48	3.46	0.80	3.51	0.44	1.15
Root Mean Square Error	1.22	1.86	0.89	1.87	0.66	1.07
Observation Range	5.90	4.29	3.46	2.38	3.33	5.25
Root Mean Square Error / Observation Range	0.21	0.43	0.26	0.79	0.20	0.20
Coefficient of Determination (R2)	0.28	0.35	0.00	0.25	0.63	0.56

(b)

Lake Name	Snail (62-73 P)	Elmo (82-106 P)	Big Marine (82-52 P)	Pine Tree (82-122 P)	Turtle (62-61 P)	White Bear (82-167 P)
Lake ID	**62007300**	**82010600**	**82005200**	**82012200**	**62006100**	**82016700**
Correlation	0.42	0.62	0.29	0.52	0.83	0.81
Residual Min	-4.34	-5.28	-2.42	-5.72	-1.72	-2.12
Residual Max	1.00	-0.01	1.45	0.91	1.27	1.90
Average Residual	-1.09	-1.65	0.14	-1.50	0.21	-0.12
Std. Deviation	1.23	1.21	0.77	1.71	0.49	0.96
Sum of Squared Residuals	298.42	460.30	58.68	309.67	31.74	102.73
Mean Square Error	2.71	4.18	0.62	5.16	0.29	0.93
Root Mean Square Error	1.65	2.05	0.79	2.27	0.54	0.97
Observation Range	5.90	4.29	3.46	2.38	3.33	5.25
Root Mean Square Error / Observation Range	0.28	0.48	0.23	0.95	0.16	0.18
Coefficient of Determination (R2)	0.18	0.38	0.08	0.27	0.69	0.65

The correlation coefficient is a measure of strength of a linear relationship between two variables. In this instance, the correlation measures how well the modeled values match the simulated values, with a perfect score being 1. Residuals are calculated as the difference between a simulated value and an observed value. A negative residual therefore reflects the model underestimating the observed value, while a positive residual reflects the model overestimating. The minimum and maximum residuals are most negative and most positive residuals, respectively. The average residual is the arithmetic mean of all of theresiduals. The standard deviation is a measure of the variation of the residuals from the average. The sum of squared residuals is measure of the linear distance
of each simulated value from its corresponding observed value, summed over all values, and the mean square error is the arithmetic average of those distances. The root mean square error is the square root of the mean square error and represents the sample standard deviation of the residuals. The observation range is the difference between the highest and lowest observed values. Root mean square error divided by the observation range normalized the values. The coefficient of determination (R2) is a measure of model fit with a value of 1 being a perfect model fit.

Table 7-3

Groundwater Elevation Calibration Summary Statistics:
(a) Annual Stress Period Model and (b) Triannual Stress Period Model

(a)

Statistic	Value
Correlation	0.9870
Residual Min	-39.21
Residual Max	29.94
Average Residual	-2.18
Std. Deviation	9.12
Sum of Squared Residuals	125247.46
Mean Square Error	87.95
Root Mean Square Error	9.38
Observation Range	279.96
Root Mean Square Error / Observation Range	0.03
Coefficient of Determination (R2)	0.97

(b)

Statistic	Value
Correlation	0.9868
Residual Min	-39.32
Residual Max	31.52
Average Residual	-2.23
Std. Deviation	9.23
Sum of Squared Residuals	128295.50
Mean Square Error	90.10
Root Mean Square Error	9.49
Observation Range	279.96
Root Mean Square Error / Observation Range	0.03
Coefficient of Determination (R2)	0.97

The correlation coefficient is a measure of strength of a linear relationship between two variables. In this instance, the correlation measures how well the modeled values match the simulated values, with a perfect score being 1. Residuals are calculated as the difference between a simulated value and an observed value. A negative residual therefore reflects the model underestimating the observed value, while a positive residual reflects the model overestimating. The minimum and maximum residuals are most negative and most positive residuals, respectively. The average residual is the arithmetic mean of all of the residuals. The standard deviation is a measure of the variation of the residuals from the average. The sum of squared residuals is measure of the linear distance of each simulated value from its corresponding observed value, summed over all values, and the mean square error is the arithmetic average of those distances. The root mean square error is the square root of the mean square error and represents the sample standard deviation of the residuals. The observation range is the difference between the highest and lowest observed values. Root mean square error divided by the observation range normalized the values. The coefficient of determination (R2) is a measure of model fit with a value of 1 being a perfect model fit.