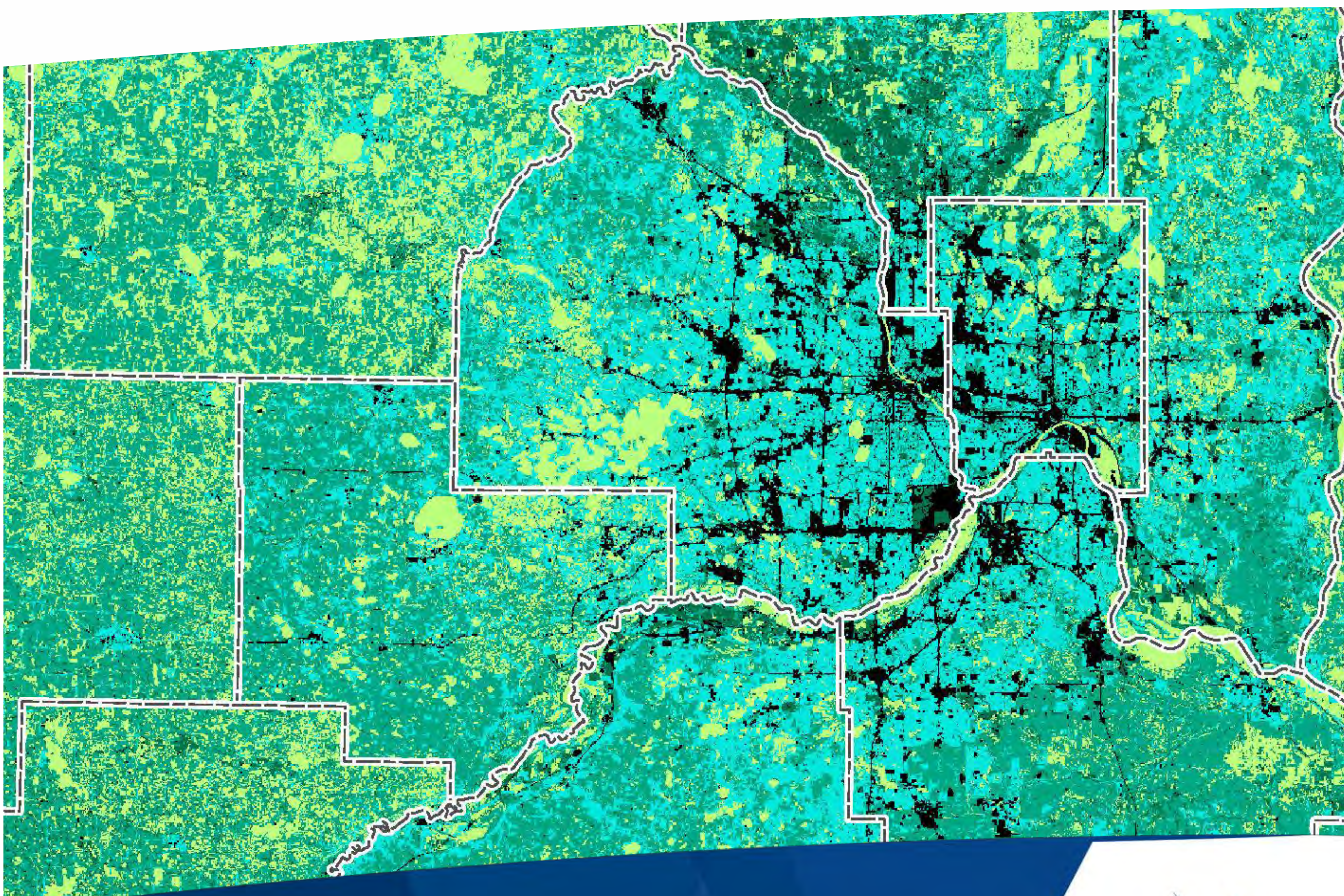
Appendix A

Updated Daily Soil Water Balance (SWB) Model

USING A SOIL WATER BALANCE (SWB) MODEL TO ESTIMATE RECHARGE FOR VERSION 3 OF THE TWIN CITIES METROPOLITAN AREA GROUNDWATER MODEL



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1 Introduction

In order to develop recharge estimates for input to the updated Twin Cities metropolitan area regional groundwater model (Metro Model 3), the U.S. Geological Survey (USGS) Soil-Water Balance (SWB) computer code was used to calculate spatial and temporal variations in surface water infiltration for eleven counties surrounding and including the Minneapolis – St. Paul metropolitan area in Minnesota. The input data used were obtained from readily available sources and integrated into the model using ARC/GIS tools. Calculated infiltration rates generally compared well with calculations performed using other techniques. The infiltration output from the SWB model varied over the domain according to soil properties, land use, and spatially variable, daily climate data.

This SWB modeling expands upon work done in 2008 to estimate recharge to the water table across the seven county Twin Cities metropolitan area, which supported the Metro Model 2.

Throughout this report the output from the SWB model will be referred to as “infiltration” as opposed to “recharge.” While generally the model output has been termed recharge, SWB does not consider the vertical distance and mechanisms for flow between the bottom of the root zone and the water table. So where there is significant distance between the surface and the water table, the SWB result may not match actual groundwater recharge in time or in space. Where the water table is close to the surface (within a few meters) infiltration and recharge would be expected to coincide. Because the water table is generally not close to the surface in the domain of the Metro Model 3, an additional groundwater flow package (MODFLOW-UZF, Niswonger et al., 2006) will be used to estimate the flow between the bottom of the root zone and the water table for input to the groundwater model, and output from SWB will be referred to as infiltration in this report.

1.1 Model Description

Accurate estimates of the spatial and temporal distribution of recharge are important for many types of hydrologic assessments, including water quality protection, stream flow and riparian ecosystem management, aquifer replenishment, groundwater flow, and contaminant transport. Recharge estimates are often key to understanding the effects of development in urban, industrial, and agricultural regions.

Groundwater recharge can vary greatly over time and space, but site-specific data are not generally available or applicable to regional-scale problems. Because of the difficulty in quantifying recharge directly, groundwater modelers often assume that a simple fraction of precipitation is converted to recharge, or use recharge as a calibration parameter. However, for many groundwater modeling problems the use of a physically-based, spatially variable recharge boundary condition has been found to improve model performance (Jyrkama and Sykes, 2007). The SWB code is intended to fill the gap in estimation techniques for transient, spatially-varied groundwater recharge.

For the Twin Cities Metro Model 3, the SWB code was chosen to estimate infiltration. While providing results based on relevant physical data, the SWB model is much simpler and less time-intensive to apply than a fully-coupled groundwater and surface water model (Markstrom and others, 2008;

Jyrkama, Sykes, and Normani, 2002). For a detailed description of the SWB model see Westenbroek et al., 2010.

The SWB code calculates components of the water balance on a daily basis, based on a modified version of the Thornthwaite-Mather soil-moisture balance approach (Thornthwaite, 1948; Thornthwaite and Mather, 1957). Data requirements include a number of commonly available tabular and gridded data types: 1) daily precipitation, daily minimum and maximum temperatures; 2) land use classifications; 3) hydrologic soil group; 4) soil water capacity and; 5) surface flow direction. The data and formats required are designed to take advantage of widely available geographic information systems (GIS) datasets and file structures.

Infiltration is calculated separately for each grid cell in the model domain (note: these grid cells do not necessarily need to correspond to the grid cells of a groundwater flow model). Sources and sinks of water within each grid cell are determined based on the input climate data and landscape characteristics. Infiltration is calculated on a daily basis as the difference between the change in soil moisture and these sources and sinks.

For greater theoretical detail the reader is directed to Dripps (2003), Dripps and Bradbury (2007), Steenhuis and van der Molen (1986), and Westenbroek et al. (2010).

2 Changes from the previous SWB Model

The following changes were made to the 2008 SWB model:

- Expanded model domain – 2008 domain (7,150 square miles) was only 57% of the area covered by the 2012 model domain (12,635 square miles)
- New land use data source, based on local planning information provided by metropolitan area communities, which changes over time
- Spatially variable climate input - The climate data used in 2008 came from a single station located near the center of the model domain; multiple stations were used in the 2012 set of simulations
- Modified code, based on results of beta testing done using the 2008 SWB model and other USGS modeling work
- The 2008 gridded data were compiled and modeled on 30 meter x 30 meter grids interpolated based on available GIS mapping; the 2012 gridded data were compiled and modeled on 90 meter x 90 meter grids (the resolution was lowered to maintain workability of the much larger model domain with standard computer resources)
- Different time period - The 2008 model was run using climate data for the period 1975–2003 while the 2012 model used data from 1988-2011

3 Model Limitations and Assumptions

The original concept behind the SWB code was to allow for the spatial distribution of infiltration to be calculated based on readily available data and a standardized set of parameters (Dripps, 2003). Although the SWB code can certainly be applied using only available data and a “standard” set of curve numbers, it is prudent to treat the results with caution as one should with any model output. In addition, there are underlying theoretical limitations that should be kept in mind when interpreting the SWB model output. These limitations are discussed below.

The SWB model is designed for application to regional, rather than site-specific problems. Due to the regional scale of the input data and nature of the hydrologic process models incorporated in it, the application of the SWB to site-specific cases would provide at best an imprecise result lacking true site-specific characteristics.

3.1 Runoff Curve Method

Much of the local imprecision of SWB stems from the use of the runoff curve method. The SWB model assumes that infiltration is the sum of precipitation, snowmelt, and inflow, minus the runoff calculated by means of the USDA-NRCS curve number method. The curve numbers used for the SWB model range from 36 to 100, with higher numbers representing more runoff versus infiltration, and lower numbers representing less runoff versus infiltration. High numbers generally represent areas of high imperviousness and low numbers are most appropriate for areas with low imperviousness. The list of perceived flaws associated with the curve number method includes (Garen and Moore, 2005):

- the inability to identify runoff processes, source areas, or flow paths
- use of a watershed scale method that should not be applied at a plot or field scale
- the method was developed to evaluate flood events and was not designed to simulate daily flows of ordinary magnitude

In addition, it has been suggested that the curve number is not constant, but varies from event to event, and that the antecedent runoff condition only explains a portion of this variability (Hjelmfelt, 1991).

3.2 Travel Time to Water Table

The infiltration estimates produced by the SWB model are likely more reliable when averaged over time scales on the order of months to years. Although the code calculates infiltration on a daily basis, there is no consideration of unsaturated zone flow. In locations where the depth to water table is substantial (more than several meters), there may be a significant lag between the time when SWB predicts infiltration, and the time when that infiltration actually reaches the water table to become recharge.

3.3 Rejected Infiltration

In areas with wetlands, springs, lakes, or other landscape features where the water table is close to the land surface, the SWB code can be expected to perform poorly as there is currently no provision for infiltration rejection via saturation excess, other than by specifying a maximum infiltration rate for a particular land use and soil type combination. In most areas covered by the Metro Model 3, the depth to groundwater is deep enough to make this problem negligible.

3.4 Surface Water Routing

The surface routing facility in SWB means that some account is made for runoff flowing to downhill grid cells and enhancing infiltration in them. However, all the runoff from a cell is assumed to infiltrate in downhill cells or be routed out of the model domain the same day it was originated as runoff and therefore storage of water is not simulated. Once water is routed to a closed surface depression and evapotranspiration and soil moisture demands are met the only loss mechanism is infiltration. This can result in cases where very high and unrealistic maximum infiltration rates occur. This is limited by specification of a maximum infiltration rate in the model input but may still cause unrealistically high rates within depressions.

In urban areas where piped storm sewers carry water out of a watershed the SWB routing routine can be expected to produce some error in the results. A piped storm sewer system typically removes water received from the surface where infiltration might occur. While the runoff curve numbers in SWB may account for a piped watershed at each cell, the routing routine reintroduces non infiltrated runoff at the next downstream cell. If evapotranspiration and soil moisture demands are met there, it will become infiltration. This might produce infiltration estimates in urban areas that are higher than actual values, especially for large rain events.

Despite the above limitations, the SWB model approach should be capable of generating reasonable mean annual or monthly infiltration estimates at the scale of a small catchment and for larger areas. In order to do so, however, the SWB authors recommend up-scaling the daily results offered by the SWB model to months or years, and averaging or filtering the results over large areas (Dripps and Bradbury, 2007).

4 SWB Model Input

The SWB model requires the user to provide the following data:

1. climatological data (array)
    a. daily precipitation (inches)
    b. daily maximum air temperature (°F)
    c. daily minimum air temperature (°F)
2. land use / land cover (array)
3. hydrologic soil group (array)
4. available soil water capacity (array)
5. surface flow direction (array)
6. lookup table for each combination of soil hydrologic group and land cover type (table)
    a. runoff curve numbers
    b. plant root zone depths
    c. maximum daily recharge values

The arrays listed above data were compiled and entered into the SWB model using 90 meter x 90 meter grid cells in a rectangular domain of 1810 columns and 2232 rows totaling 4,039,920 cells representing 32,723 km^2 (12,635 mi^2). The coordinate system for all input data was UTM NAD83 Zone 15N.

The SWB model input and options used for the Metro Model groundwater model calculations are detailed below.

4.1 Climatological Input

Climatological input was derived from the Global Historical Climatology Network (GHCN). Daily GHCN data were downloaded from NOAA's National Climatic Data Center for the period of 1988-2011 by calendar year. Daily precipitation, daily minimum temperature, and daily maximum temperature data were used to develop raster (gridded) data used as input to the SWB Model. Precipitation was converted from millimeters to inches and temperatures were converted from degrees Celsius to Fahrenheit. A total of 191 weather stations were used to develop the daily rasters, 53 of them within the model domain. Because of irregularity in data reports, only a portion of the 191 gages had data available for any given day. **Figure 1** shows the locations of weather stations used.

The climate data used for the SWB model simulations used a total of 191 weather stations. Data were interpolated to develop daily rasters, or grid files, for precipitation, maximum temperature, and minimum temperature for the period 1988-2011. Weather stations outside the SWB model domain were included to eliminate edge effects that might occur during interpolation of the data for input.

Daily climatological files containing station coordinates (in Universal Transverse Mercator (UTM) North American Datum 1983 (NAD83), meters) along with daily precipitation, daily minimum temperature, and daily maximum temperature were created for the period of 1988-2011. A script developed for the Surfer Version 10 (Golden Software, 2012) was used to interpolate rasters using kriging with 5,000 (5 km) meter cell size and the default kriging parameters. For the daily precipitation data, negative interpolated values in the resulting raster were set to zero.

The output from Surfer was a series of text grids with 5,000 meter (5 km) grid spacing. A geoprocessing script in ArcMap 10.0 (ESRI, 2010) was developed that resampled these 5,000 meter grids to 90 meters. The cell configuration was set so the resulting grids resolution matched those of the other grids used in the model as required by the SWB model code.

4.2 Land Use/Land Cover Input

The SWB code relies on runoff curve numbers and interception values from a land cover lookup table based on land use/land cover mapping. For this version of SWB, Metropolitan Council land use data (**Table 1**) were used and where that was not available, US Geological Survey (USGS) 2006 Land Use Land Cover data (**Table 2**) were added to create a hybrid data set. The hybrid data were converted from ESRI polygon shape files to 90 meter grids. Values in the Met Council datasets representing "Park," "Recreational" or "Preserve" were assigned values from the USGS data set to improve the accuracy of land cover properties within widely variable park areas. Otherwise, the Metropolitan Council mapped values had priority over the USGS values.

The Metropolitan Council periodically updates its land use mapping. In order to take advantage of this periodic land use mapping and account for changing land use in the infiltration simulations, it was incorporated into the model for the correlated periods of SWB simulation. **Table 3** shows the metropolitan land use data dates along with the time periods they were used in the SWB simulations.

Areas mapped by the Metropolitan Council as open water were defined in the land use table as open water and infiltration was not calculated for those areas. Because of the complexity of estimating recharge for lakes in general, recharge for these areas will be left as calibration parameters for the MODFLOW groundwater model and recharge for these zones will be fit to the calibration targets used for the groundwater model calibration.

Areas not mapped as open water in the Met Council data but that are mapped as wetlands in the USGS land cover mapping were identified as wetlands in the land use table. For these areas infiltration was calculated based on the soil properties with an assumed Soil Conservation Service (SCS) curve number of 60 (**Table 4**). This number was chosen as an intermediate value of runoff fractionation in the absence of specific information for wetland infiltration rates.

Wetland infiltration can vary from almost zero contribution to recharge to large values where direct exposure of the water table exists. Using the soil properties to estimate recharge might account for these wetlands using SWB, which is desirable for this modeling study because MODFLOW does not have an explicit wetlands boundary condition. SWB has no method for accounting for wetlands that might have negative net infiltration due to evapotranspiration, runoff to streams, or other processes.

Outflow (or surface runoff) from a cell in the SWB code is calculated using a Soil Conservation Service (SCS) curve-number rainfall-runoff relationship (Cronshey, 1986). This rainfall-runoff relationship relates rainfall to runoff based on four basin properties: soil type, land use, surface condition, and antecedent runoff condition. The curve number method defines runoff in relationship to the difference between precipitation and an “initial abstraction” term. Conceptually, this initial abstraction term represents the summation of all processes that might act to reduce runoff, including interception by plants and fallen leaves, depression storage, and infiltration (Woodward and others, 2003).

The runoff curve numbers used for the Metro Model 3-SWB model were taken from Technical Release 55, Table 2-2 (USDA, 1986). Generally the runoff curves predict runoff best in rural settings that have more uniform properties than urban areas. For urbanized areas the curve numbers assume that impervious areas (assigned a curve number of 98) are directly connected to a drainage system such as storm sewer, and pervious areas are equivalent to open space in good condition (with curve number ranging from 39-80 depending on soil type). **Table 4** shows the assumed impervious area fraction for the 3 urbanized land use types used for the model.

In the SWB code the SCS curve numbers are adjusted upward or downward depending on how much precipitation has occurred in the previous 5-day period. Based on precipitation, three classes of moisture conditions are defined, and are called antecedent runoff condition I, II, and III. When soils are nearly saturated, as in antecedent runoff condition III, the curve number for a grid cell is adjusted upward from antecedent runoff condition II to account for generally higher observed runoff amounts experienced when precipitation falls on saturated soil. Conversely, when soils are dry, as in antecedent runoff condition I, curve numbers are adjusted downward from antecedent runoff condition II in an attempt to reflect the increased infiltration rates of dry soils (Mishra and Singh, 2003). Interception of precipitation may be specified independently in SWB and for this set of simulations interception was set to 0 due to the use of the curve numbers described above which generally account for interception processes. **Table 4** below shows various properties used for the Metro Model 3-SWB model.

Table 1. Metropolitan Council land use with corresponding categories used for SWB.

2000-2010 Metropolitan Council Land Use Description and ID	*1990-1997 Metropolitan Council Land Use Description and ID*	*2005 SWB Model Input Land Use Description and ID*
Agricultural (100)	Agricultural (8)	Row Crops (Shallow-Rooted Agriculture) (82)
Farmstead (111)	Farmstead (11)	Low density Residential (21)
Seasonal/Vacation (112)	No Data (0)	Urban/Recreational Grasses (85)
Single Family Detached (113)	Single Family Res (1)	Low density Residential (21)
Single Family Attached (114_		High density Residential (22)
Multifamily (115)	Multi-Family Res (2)	High density Residential (22)
Manufactured Housing Parks (116)		High density Residential (22)
Retail and Other Commercial (120)	Commercial (3)	Commercial/Industrial/Transportation (23)
Office (130)		Commercial/Industrial/Transportation (23)
Mixed Use Residential (141)		High density Residential (23)
Mixed Use Industrial (142)	Industrial (4)	Commercial/Industrial/Transportation (23)
Mixed Use Commercial (143)		Commercial/Industrial/Transportation (23)
Industrial and Utility (151)	Public Industrial (54)	Commercial/Industrial/Transportation (23)
Extractive (153)	Extractive (12)	Quarries/Gravel Pits
Institutional (160)	Public Semi-Public (5)	Commercial/Industrial/Transportation (23)
Park, Recreational, or Preserve (170)	Parks (7)	USGS NLCD was used here
Golf Course (173)	Vacant (51)	Urban/Recreational Grasses (85)
Major Highway	Major Highways (9)	Commercial/Industrial/Transportation (23)
Railway (202)		Commercial/Industrial/Transportation (23)
Airport (203)	Airports (6)	Commercial/Industrial/Transportation (23)
Undeveloped	Not Developed (41)	Urban/Recreational Grasses (85)
Open Water (220)	Open water (10)	Open water (11)

Table 2. USGS land cover categories with corresponding categories used for the SWB.

USGS NLCD 2006 ID	USGS NLCD 2006 Description	SWB Model Input ID	SWB Model Input Description
11	Open Water	11	Open Water
21	Developed Open Space	85	Urban/Recreational Grasses
22	Developed Low Intensity	21	Low Density Residential
23	Developed Medium Intensity	22	High Density Residential
24	Developed High Intensity	23	Commercial Industrial Transport
31	Barren Land (Rock/Sand/Clay)	31	Bare Rock
41	Deciduous Forest	41	Deciduous Forest
42	Evergreen Forest	42	Evergreen Forest
43	Mixed Forest	43	Mixed Forest
52	Shrub/Scrub	51	Shrubland
71	Grassland/Herbaceous	71	Grass/Herbs
81	Pasture/Hay	81	Pastures
82	Cultivated Crops	82	Row Crops
90	Woody Wetlands	92	Wetland
95	Emergent Herbaceous Wetlands	92	Wetland

Table 3. Metropolitan Council periodic land use data application.

Metropolitan Council Land Use Data Year	Years of SWB Simulation Input
1990	1988-1993
1997	1994-1998
2000	1999-2002
2005	2003-2007
2010	2008-2011

Table 4. SWB model land cover categories with corresponding runoff and root zone properties.

SWB #	Description	Assumed % Impervious Cover	Curve #[A,B], Soil Class A	Curve #[A,B], Soil Class B	Curve #[A,B], Soil Class C	Curve #[A,B], Soil Class D	Max Recharge (in/day)[C], Soil Class A	Max Recharge (in/day)[C], Soil Class B	Max Recharge (in/day)[C], Soil Class C	Max Recharge (in/day)[C], Soil Class D	Root Zone Depth (ft)[D], Soil Class A	Root Zone Depth (ft)[D], Soil Class B	Root Zone Depth (ft)[D], Soil Class C	Root Zone Depth (ft)[D], Soil Class D
11	Open water	n/a	100	100	100	100	9	5.5	2.4	0.7	0	0	0	0
21	Low dens Res	25%	54	70	80	85	9	5.5	2.4	0.7	1.67	2.08	1.33	0.83
22	High dens Res	65%	77	85	90	92	9	5.5	2.4	0.7	1.11	1.39	0.89	0.55
23	Comm/Ind/Tran	85%	89	92	94	95	9	5.5	2.4	0.7	0.74	0.93	0.59	0.37
31	Bare Rock/Sand	n/a	89	92	94	95	9	5.5	2.4	0.7	0.5	0.5	0.5	0.5
32	Quarries/Pits	n/a	89	92	94	95	9	5.5	2.4	0.7	0.5	0.5	0.5	0.5
41	Deciduous Forest	n/a	36	60	73	79	9	5.5	2.4	0.7	6.66	6.66	5.33	3.9
42	Evergreen Forest	n/a	36	60	73	79	9	5.5	2.4	0.7	6.66	6.66	5.33	3.9
43	Mixed Forest	n/a	36	60	73	79	9	5.5	2.4	0.7	6.66	6.66	5.33	3.9
51	Shrub land	n/a	39	61	74	80	9	5.5	2.4	0.7	3.33	4.17	3.33	2.22
71	Grass/Herbs	n/a	39	62	74	85	9	5.5	2.4	0.7	3.33	4.17	3.33	2.22
81	Pasture	n/a	39	61	74	80	9	5.5	2.4	0.7	3.33	4.17	3.33	2.22
82	Row Crops	n/a	67	78	85	89	9	5.5	2.4	0.7	1.67	2.08	1.33	0.83
85	Urban/Rec Grass	n/a	39	61	74	80	9	5.5	2.4	0.7	3.33	4.17	3.33	2.22
92	Wetlands	n/a	60	60	60	60	9	5.5	2.4	0.7	1.67	2.08	1.33	0.83

Notes:

A. SCS base curve numbers for hydrologic soil groups A, B, C, D associated with antecedent runoff condition II.

B. Curve numbers for the Metro Model 3 simulations were taken directly or derived from the US Department of Agriculture Technical Release (TR) 55 (USDA, 1986).

C. Typical root zone depths were taken from Thornthwaite, Mather, 1957.

D. Maximum recharge (or infiltration) rate was derived considering multiple sources of estimates for infiltration rates in the four soil categories used.

4.3 Soil Hydrologic Group

The model uses hydrologic soil group (A-B-C-D) as input and then applies runoff coefficients from the land cover lookup table for each soil type and land cover type. The soil data were interpolated to 90 meter x 90 meter grid cells for the entire area.

Natural Resource Conservation Service Soil Survey Geographic Database (SSURGO) data were used to map soils for all counties within the model domain with the exception of a small portion of Pine County where it was not available. Natural Resource Conservation Service State Soil Geographic Database (STATSCO) data were used in areas of Pine County within the model area. The hydrologic soil group class was extracted from these data for each county.

These data were merged into one polygon vector GIS feature class. Each of the polygons were assigned integer values based the value of the Hydrologic Soil Group using the following relationship: A=1, A/D = 1, B=2, B/D = 2, C=3, C/D =3, and D=4. For features that did not contain a hydrologic soil group value (typically urban areas), the type B was assumed due to the intermediate value of its hydraulic properties. The polygon data were then converted to grid using a 90 meter cell size.

4.4 Available Soil Water Capacity

The SWB model uses soil information, together with land cover information, to calculate a maximum soil water holding capacity for each grid cell. The maximum soil water capacity is calculated as:

maximum soil water capacity = available soil water capacity x root zone depth

The available water capacity of a soil is typically given as inches of water holding capacity per foot of soil thickness. For example, if a soil type has an available water capacity of 2 inches per foot, and the root zone depth of the cell under consideration is 2.5 feet, the maximum water capacity of that grid cell would be 5.0 inches. This is the maximum amount of soil water storage that can take place in the SWB grid cells. Water added to the soil column in excess of this value will become infiltration.

For this model Natural Resource Conservation Service SSURGO data were used to map soil water capacity for all counties within the model domain with the exception of a small portion of Pine County where it was not available. Natural Resource Conservation Service STATSCO data were used in areas of Pine County within the model area. These data were merged into one polygon vector GIS feature class and converted from centimeters to inches. The polygon data were then converted to a grid using a 90 meter cell size.

4.5 Surface Flow Direction

The SWB model requires a digital elevation model (DEM) to route surface water flows. When a cell produces runoff or outflow, it becomes inflow to the downslope cell based on the DEM. If capacity for infiltration exists in the downslope cell it will occur and excess is again routed downslope, and so on. The calculation begins at the high points and proceeds downslope. At the end of each day, water that is in excess at the lowest cell is removed from the model domain. Physically, this can be interpreted as water that has left the domain via surface flow, in this case via the Mississippi River.

To develop the flow direction grid, National Elevation Data (NED) were used (USGS, 2012a). The data were projected into UTM NAD83, Zone 15 (meters) coordinates. The data were then resampled to 90 meter grid cells. To account explicitly for streams and known flow courses, DEM reconditioning was performed using high resolution National Hydrography Dataset flowlines as the “AGREE” stream (USGS, 2012b). This served to “burn” the stream flowlines into the DEM.

A depression analysis was performed on the reconditioned DEM. This identified all depressions and depression watersheds in the model area. Any depressions touching the National Hydrography Dataset flowlines were designated as open to the flowline. The flow direction grid was then created.

4.6 Other SWB Options

4.6.1 Evapotranspiration

The SWB code can use any one of five commonly-applied methods to estimate potential evapotranspiration (PET) from portions of the soil zone that are not included in the interception calculation. The method chosen for this model was the so-called Hargreaves (1985) method. This method uses daily maximum and minimum temperatures, along with latitude, to estimate PET and does not consider land cover. It is the only method currently available in the SWB model that can use daily precipitation and temperature grids as were used here.

4.6.2 Recharge (infiltration) limits

The inclusion of overland flow routing in the code ensures that runoff from an upslope grid cell has one or more opportunities to contribute to infiltration in the cells that are downslope from it. However, all runoff from a cell is assumed to infiltrate in downslope cells or be routed out of the model domain on the same day in which it originated as rainfall or snowmelt. In addition, once water is routed to a closed surface depression, and evapotranspiration and soil moisture demands are met, the only loss mechanism is infiltration. This results in cases where maximum infiltration values of hundreds or thousands of inches per year can be calculated. These extremely high values are unrealistic and are likely due to the fact that surface storage of water is not accounted for. For the Metro Model 3 simulations a maximum infiltration per day was specified to minimize this error. **Table 5** presents the values used for the simulations.

Table 5. Maximum recharge (or infiltration) per day specified for the SWB model.

Soil Hydrologic Group	Maximum Recharge Allowed per Day (inches)
A	9
B	5.5
C	2.4
D	0.7

4.6.3 Precipitation – Snow versus Rain

In the SWB model, snow is allowed to accumulate and/or melt on a daily basis. The daily mean, maximum and minimum air temperatures are used to determine whether precipitation takes the form of rain or snow. Precipitation that falls on a day when the mean temperature minus one-third the difference between the daily high and low temperatures is less than or equal to 32°F is considered to fall as snow. Snowmelt takes place based on a temperature-index method. In the SWB code it is assumed that 1.5 millimeters (0.059 inches) of water-equivalent snow melts per day per average degree Celsius that the daily maximum temperature is above the freezing point (Dripps and Bradbury, 2007).

5 Model Results

The (SWB) computer code was used to calculate spatial and temporal variations in infiltration for the eleven (11) county Minneapolis–St. Paul metropolitan area in Minnesota. Climate data used included daily spatial grids of precipitation and temperature in a rectangular domain representing 32,723 km^2 (12,635 mi^2). The model was run using climate data for the period January 1, 1988–December 31, 2011 for each calendar year.

For the modeled period 1988-2011 the average annual infiltration over the entire domain of the SWB model was 8.2 inches per year. The maximum annual domain-wide infiltration result was for 2002 in the amount of 13 inches, while the minimum annual domain-wide infiltration result occurred for 2000 in the amount of 2.7 inches. **Section 6** presents comparisons of the SWB estimates compared to other methods and applications.

The updated Twin Cities metropolitan area groundwater model, Metro Model 3, will use monthly results. The monthly grids were translated from a 90m x 90m grid to create a 500m x 500m grid to match the groundwater model resolution.

Figure 2 illustrates average infiltration over the entire period simulated. **Table 6** presents the annual infiltration results for the full time period.

Figures 3-26 present the annual infiltration totals for the model domain for each simulated year. In these figures, wide ranging temporal variability in the spatial distribution of the infiltration can be seen. While the geology and land cover dictate spatial variation, temporal variation is due to the variation of precipitation in time and space. As might be expected, very strong correlation can be seen in comparisons of mapped precipitation patterns and modeled infiltration patterns.

Tables 7A and **7B** present the mass balance for the model annually and for the entire term of the simulations.

5.1 Infiltration by Land Use Type and Soil Class

Table 8 below shows the average annual infiltration rate and area for each land use class used for input to the SWB model. The relative infiltration rates for the land use categories reflect primarily the soil hydrologic class and the rooting depths of plants for each land use. For example, the high infiltration rates in residential development areas reflect the shallow root zone for turf grass, most commonly planted there.

While the hydraulic conductivity of the four soil groups ranges high to low, from A to D, the infiltration results show approximately equal infiltration rates in soil groups B and C. Based on conductivity alone we would expect that infiltration in group B soils would be higher than group C. But soil rooting depths generally are larger in B soils than in C because of optimal growing conditions in B soils (Thornthwaite, Mather, 1957). This means less water escapes the plant uptake zone in B soils resulting in less water reaching the base of the root zone and becoming infiltration. Or stated another way, the greater rate of flow into the root zone of the B soils is offset by greater ET from the thicker B soil root zone.

Table 6. Average annual infiltration in inches as estimated by the Metro Model 3 - SWB model.

Year	Average Infiltration for Full Model Domain (in)	Precipitation Sum (rainfall + snowmelt) for Full Model Domain (in)
1988	5.4	20.7
1989	3.9	23.6
1990	7.2	35.0
1991	10.3	39.8
1992	8.8	28.9
1993	12.1	38.2
1994	7.9	32.5
1995	8.1	32.7
1996	7.8	30.0
1997	10.9	30.4
1998	8.0	31.9
1999	6.4	31.4
2000	2.7	28.4
2001	11.0	32.6
2002	13.0	40.1
2003	5.9	25.3
2004	7.8	34.3
2005	10.0	36.6
2006	6.1	26.4
2007	9.6	31.5
2008	5.9	27.3
2009	7.3	28.3
2010	8.9	38.1
2011	10.9	29.4
1988-2011 Average	**8.2**	**31.4**

Table 7A. Mass balance summary for 24 years of simulation in inches over the entire domain.

Year	Rainfall (inches)	Change in Snow Storage (inches)	Snowmelt (inches)	Change in Soil Moisture Storage (inches)	Surface Flow Out of Domain (inches)	Rejected Infiltration (inches)	Evapo-transpiration (inches)	Infiltration (inches)
1988	16.3	-1.6	6.1	-0.9	0.9	0.0	17.1	5.4
1989	19.1	-0.3	4.8	-1.1	1.0	0.0	20.2	3.9
1990	31.2	0.2	3.6	0.6	1.6	0.0	25.4	7.2
1991	32.1	1.7	6.0	1.5	1.8	0.1	24.5	10.3
1992	23.4	-1.2	6.7	-0.5	1.4	0.0	20.4	8.8
1993	32.7	-0.5	6.1	0.4	2.0	0.1	24.2	12.1
1994	27.8	-0.3	5.1	-0.1	1.4	0.0	23.7	7.9
1995	28.3	0.9	3.5	0.1	1.4	0.0	22.4	8.1
1996	19.9	3.2	6.9	-0.4	1.1	0.0	18.4	7.8
1997	25.1	-4.1	9.3	0.0	2.0	0.1	21.4	10.9
1998	28.2	-0.2	3.9	-0.4	1.5	0.0	23.0	8.0
1999	27.9	-0.2	3.7	-1.1	1.4	0.0	24.9	6.4
2000	23.4	2.3	2.7	0.9	1.2	0.0	21.4	2.7
2001	27.2	-1.9	7.3	0.4	1.9	0.1	21.2	11.0
2002	35.7	-0.3	4.8	0.6	2.3	0.1	24.4	13.1
2003	21.5	0.2	3.6	-1.6	1.2	0.0	19.7	5.9
2004	30.8	-0.1	3.6	1.5	1.5	0.0	23.6	7.8
2005	31.4	0.8	4.3	0.2	1.8	0.1	23.8	10.0
2006	22.7	-0.7	4.3	-0.5	1.2	0.0	20.4	6.1
2007	26.7	1.1	3.8	-0.5	1.6	0.0	19.9	9.6
2008	22.6	0.1	4.7	0.2	1.1	0.0	20.1	5.9
2009	23.6	0.6	4.1	0.3	1.3	0.0	18.9	7.3
2010	33.0	1.3	3.9	0.4	1.9	0.1	25.7	8.9
2011	25.2	-3.2	7.5	-2.6	1.6	0.0	22.8	10.9
Total	**635.8**	**-2.3**	**119.9**	**-2.5**	**36.1**	**1.0**	**527.5**	**196.1**
Mean	**26.5**	**-0.1**	**5.0**	**-0.1**	**1.5**	**0.0**	**22.0**	**8.2**

Table 7B. Mass balance summary for 24 years of simulation in millions of acre-feet over the entire domain.

Year	Rainfall (millions of acre-feet)	Change in Snow Storage (millions of acre-feet)	Snowmelt (millions of acre-feet)	Change in Soil Moisture Storage (millions of acre-feet)	Surface Flow Out of Domain (millions of acre-feet)	Rejected Infiltration (millions of acre-feet)	Evapo-transpiration (millions of acre-feet)	Infiltration (millions of acre-feet)
1988	10.98	-1.11	4.08	-0.64	0.62	0.01	11.51	3.63
1989	12.88	-0.17	3.20	-0.76	0.66	0.00	13.64	2.61
1990	21.03	0.13	2.39	0.44	1.10	0.03	17.10	4.84
1991	21.64	1.13	4.03	1.02	1.22	0.04	16.52	6.95
1992	15.79	-0.78	4.48	-0.31	0.95	0.02	13.72	5.96
1993	22.02	-0.36	4.10	0.30	1.37	0.04	16.30	8.18
1994	18.70	-0.20	3.41	-0.07	0.94	0.01	15.98	5.34
1995	19.08	0.60	2.37	0.06	0.92	0.01	15.07	5.47
1996	13.43	2.17	4.66	-0.24	0.76	0.01	12.37	5.24
1997	16.94	-2.77	6.30	0.03	1.38	0.09	14.44	7.38
1998	18.99	-0.10	2.60	-0.26	1.03	0.02	15.51	5.36
1999	18.79	-0.12	2.46	-0.77	0.97	0.01	16.80	4.32
2000	15.77	1.52	1.82	0.59	0.80	0.01	14.42	1.83
2001	18.35	-1.31	4.94	0.28	1.28	0.05	14.32	7.42
2002	24.04	-0.20	3.22	0.39	1.54	0.08	16.46	8.86
2003	14.46	0.14	2.46	-1.06	0.79	0.02	13.27	3.95
2004	20.78	-0.05	2.41	1.03	1.03	0.01	15.92	5.28
2005	21.19	0.53	2.92	0.10	1.20	0.06	16.04	6.72
2006	15.32	-0.47	2.91	-0.34	0.81	0.01	13.72	4.12
2007	17.97	0.73	2.55	-0.34	1.05	0.03	13.38	6.47
2008	15.21	0.05	3.14	0.11	0.77	0.00	13.56	3.98
2009	15.90	0.40	2.75	0.22	0.85	0.02	12.71	4.92
2010	22.26	0.85	2.60	0.27	1.26	0.04	17.34	5.99
2011	16.95	-2.15	5.02	-1.74	1.05	0.03	15.38	7.34
Total	**428.47**	**-1.54**	**80.82**	**-1.69**	**24.34**	**0.65**	**355.49**	**132.15**
Mean	**17.85**	**-0.06**	**3.37**	**-0.07**	**1.01**	**0.03**	**14.81**	**5.51**

Table 8. Average annual SWB infiltration by land use and soil class.

Land Use Class or Soil Hydrological Group Description	24 year Average Annual Infiltration (in)	1990 Area (square miles)	2010 Area (square miles)
Bare Rock & Sand	9.7	6.3	7.8
Commercial Industrial	8.9	209.8	265.5
Deciduous Forest	6.9	1,417.6	1,400.2
Evergreen Forest	7.8	137.3	78.3
Grass & Herbs	8.2	360.8	334.7
High Density Residential	10.1	91.3	142.9
Low Density Residential	10.4	610.5	763.3
Mixed Forest	7.6	7.4	10.7
Pastures	7.5	515.7	548.4
Open Water	0.0	1,625.7	1,565.8
Quarries & Pits	11.0	0.0	10.6
Row Crops	8.8	6,496.8	5,496.3
Shrub land	8.6	76.2	104.9
Urban Recreational Grass	8.2	483.8	1,177.4
Wetlands	9.9	595.3	727.7
Soil Group A	9.8	2,387.6	2,387.6
Soil Group B	7.8	8,453.3	8,453.3
Soil Group C	7.8	1,239.6	1,239.6
Soil Group D	7.3	554.0	554.0

6 Comparison of Results

In order to check the consistency of the SWB results with other methods used to calculate recharge, the 2012 SWB results were compared with 3 other studies: the 2008 SWB simulations, the Little Rock Creek Soil and Water Assessment Tool model, and a statewide Regional Recharge Regression study. An overview of these methods and results of the comparison are described below.

6.1 Comparison of SWB simulated infiltration to 2008 SWB Results

In 2008, the Soil-Water Balance (SWB) code was used to calculate spatial and temporal variations in groundwater recharge for the seven county Minneapolis – St. Paul metropolitan area in Minnesota.

For the modeled period (1975-2003) the average annual infiltration from the 2008 SWB model was 6.4 inches per year with average annual precipitation of 30.6 inches, as compared to the 2012 SWB Model (time period 1988-2011) with an average infiltration of 8.2 inches per year with 29.6 average annual precipitation (at the MSP Airport Station).

Figure 27 shows a comparison of the annual average results from the 2008 SWB model and the 2012 SWB model. The two models compare well considering the differences between the model inputs. Some of the differences in model input that would be expected to impact this comparison include:

1. Numerous weather station data sets interpolated in space for 2012 (single station in 2008).
2. Larger model domain for 2012 (from 7 to 11 counties).
3. Higher resolution soil data for 2012.
4. Time varying land use/land cover for 2012 (the 2008 model used 2005 land use throughout).

6.2 Comparison of SWB simulated infiltration to SWAT simulated infiltration

The Little Rock Creek watershed is located along the boundary of Benton and Morrison County in the northwestern area of the SWB modeled domain (**Figure 28**). Groundwater pumping within and around the Little Rock Creek watershed has been steadily increasing over the last several decades. In order to assess the relationship between groundwater pumping and stream flow in Little Rock Creek, Barr Engineering (2012) used the surficial hydrologic model Soil & Water Assessment Tool (SWAT) (Neitsch et al., 2011) in conjunction with the groundwater flow model MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996; Harbaugh et al. 2000).

The SWAT model is physically based meaning that rather than incorporating regression equations to describe the relationships between input and output variables, it requires specific information about weather, soil properties, topography, vegetation, and land use practices in the watershed, and then mathematically models the physical processes such as water movement, crop growth, and nutrient cycling based on the input. The SWAT model simulates surficial processes well but only considers groundwater flow in a simple “black-box” perfunctory fashion. MODFLOW is the industry standard finite difference, 3-D, groundwater flow model. It does an excellent job at simulating groundwater flow but does a poor job at simulating surficial processes. These two models (SWAT and MODFLOW) were used in tandem, allowing for the strengths of each model to substitute for the weaknesses of the other. Essentially, SWAT was used to calculate surface-water runoff, evapotranspiration, and infiltration. MODFLOW was used to simulate groundwater flow in the aquifer, baseflow to the creek, and withdrawal of water from the aquifer via high capacity wells. Together these two models were calibrated to hydraulic head, baseflow, and surface-water runoff based on data collected over a period of six years (2005-2010).

The entire watershed of Little Rock Creek is within the domain of the SWB model developed for this study (**Figure 28**), providing an opportunity to compare infiltration estimates from two different modeling methods. Monthly and annual comparisons of infiltration over the Little Rock Creek watershed from 2005 to 2010, simulated using the SWAT-MODFLOW and the SWB model, are shown on **Figure 29**. Generally, the results from the two modeling methods agree well, particularly for annual values. In March and April the two models often produced significantly different infiltration values, where the SWB model simulates more infiltration in March and the SWAT model simulates more infiltration in April.

Differences are believed to be primarily a result of how each model simulates snow melt. The SWAT model considers estimated snow pack temperature, time of year (amount of daylight), and air temperature in estimating snow melt. The SWB model considers only the temperature in estimating snow melt. Differences in the two models also occur in the late summer months, with the SWAT model simulating slightly higher recharge. This is believed to result primarily from the ability of SWAT to more accurately account for crop irrigation during those months.

6.3 Comparison of SWB simulated infiltration to Regional Recharge Regression (RRR) Results

The regional regression recharge (RRR) method of Lorenz and Delin (2007) yields an estimate of spatial variability of annual recharge rates within a region. The RRR method is based on a regression of RORA recharge rate estimates combined with climate and soil data for the region. RORA (Rutledge, 1998) is an automated method for estimating the average recharge rate in a basin from analysis of stream flow records, and is based on the recession-curve-displacement method of Rorabaugh (1960) for whom it is named. RORA accounts for the effects of PET, underflow (the flow of groundwater beneath and bypassing a stream), and other losses or gains of groundwater after a precipitation event. The accuracy of the RRR estimates are representative of the soils data, which were collected over areas ranging from about 2 to 150 square miles.

Recharge rates estimated on the basis of the RRR method done for area of the State of Minnesota (**Figure 30**) compared favorably with results from the 2012 SWB simulations for the Metro Model 3 domain. The average for the SWB domain using the RRR method was 6.3 inches compared to the SWB average value of 8.2, yielding a difference of about 25%.

Figure 31 shows a comparison of the RRR and SWB results on 1,108 grid points within the SWB model domain. The 25% difference in estimates can be seen on the plot values which group generally above the 1:1 red line on the figure.

7 SWB Infiltration Sensitivity Analysis

Changes in the model results due to the parameter sensitivities were developed and compiled with a relative ranking of each parameter for the model's sensitivity to changes in that parameter. To develop an estimate of uncertainty in the model due to uncertainty in the input parameters, the 16 parameters with the highest sensitivity were identified. Literature values for these parameters were used to estimate the expected range in their values that might occur. The high and low values of these expected ranges were used to map the range of values in the SWB model output that might occur due to this input variability.

The output from SWB (estimated infiltration below the bottom of the root zone) will be used as input to the MODFLOW-UZF package to simulate flow through the unsaturated material between the bottom of the root zone and the water table. This sensitivity analysis will also be used to determine appropriate ranges for the infiltration model inputs for the UZF package of the Metro Model 3.

7.1 Ranking the SWB Parameter Sensitivities

In order to test the SWB model output sensitivity to changes in individual parameters, numerous model runs were performed, each with an adjustment to an individual parameter. Model results were compiled and a relative ranking of each parameter for the model's sensitivity to changes in that parameter were calculated.

These sensitivity model runs simulated a single year using a single year's climate data (2001), at a single weather station, and land use that was held constant. The parameters tested for sensitivity (116) included:

1. Runoff Curve Numbers: 14 Land use x 4 soil types = 56 parameters

2. Maximum Daily Recharge: 4 parameters (one per soil type)

3. Root Zone Depths: 14 Land use categories x 4 soil types = 56 parameters

Observations tracked for sensitivity (1066) included:

1. Minimum, mean, and maximum simulated infiltration over the model domain for the entire year and by month (39)

2. Mean simulated infiltration for each of the combinations of land uses and soil types for the entire year and by month (780)

3. Mean simulated infiltration for each of the soil types for the entire year and by month (52)

4. Mean simulated infiltration for each of the land uses for the entire year and by month (195)

The 1066 observations produced by the SWB model for the 2001 simulation were divided into 13 observation groups: those observations calculated for the entire year (annual means) and those observations calculated for each month. The automated model calibration and uncertainty analysis software PEST (Doherty, 2010 and 2011), was used to facilitate calculation of the sensitivities of each observation with respect to each parameter. PEST calculates the composite sensitivity of each parameter with respect to all observations based on Equation 1.

$$s_i = \frac{1}{m}\left(\sum_{k=1}^{m}\left(\frac{\partial o_k}{\partial p_i} w_k\right)^2\right)^{1/2} \qquad \text{(Eq. 1)}$$

where:

s_i is the composite sensitivity for the i^{th} parameter (p_i)

m is the number of observations

$\partial o_k/\partial p_i$ is the partial derivative of the k^{th} observation with respect to the i^{th} parameter

w_k is the weight assigned to the k^{th} observation (all observations were assigned a weight of 1)

PEST was used to calculate the partial derivative of each observation with respect to each parameter using incremental changes to each of the SWB parameters. The composite sensitivities were calculated for each parameter based on all of the 1066 observations listed above and for each of the observation groups (annual and monthly means).

Figure 32 shows a plot of the composite sensitivities of all of the SWB output to the values of the input parameters based on this sensitivity analysis. The bars plotted in this graph are defined using the formula max(10^{-6}, s_i). In other words, sensitivities ranging from zero to 10^{-6} plot as if the sensitivity were 10^{-6}.

The most sensitive parameters were selected based on ranking the composite sensitivities for all observations along with ranked sensitivities for the annual, March, and April observation groups. The latter two observation groups were used because the mean recharge in March and April ranked 1 and 2 among monthly mean recharge in 2001. The 16 highest ranking parameters were selected for variation in the sensitivity analysis. The maximum recharge for B soils was also included in the sensitivity analysis based on previous feedback from the Technical Advisory Committee.

Generally the analyses show that the root zone depths, specified within SWB for each land use by soil type, dominate the relative sensitivity results. The specified maximum recharge rate for A and D soils were also indicated as having relatively high sensitivity for the model result.

7.2 SWB Output (Infiltration) Sensitivity Analysis

Sensitivity of the SWB output infiltration estimates can be used to gage uncertainty in them that is due to the uncertainty in the input parameters. To examine the output sensitivities, the 16 SWB parameters selected as described in **Section 7.1** were systematically adjusted through their expected ranges. Expected parameter ranges were established based on available literature (**Table 9**). Five values were tested (simulated) with SWB for each parameter: the initial, minimum and maximum values indicated in **Table 9,** the average of the minimum and initial value, and the average of the initial and maximum value. The mean (μ) and standard deviation (σ) were calculated for the 2001 annual infiltration rates for each of the combinations of land uses and soil types.

The multipliers represent the uncertainty in the infiltration parameter values based on the sensitivity analysis. It is common for the allowed range for a parameter's value in a model calibration to represent the 95-percent confidence interval (for example, see Doherty, 2011 pp. 12 and 199), consequently, the values (μ - 1.96 σ)/μ and (μ + 1.96 σ)/μ will be used as the lower and upper bounds, respectively for the multipliers.

The result of the infiltration parameter sensitivity analysis is summarized as a map of the range in variation of infiltration estimated with SWB that considers the variation in the parameter inputs. To create the map the SWB-simulated annual infiltration array for 2001 was multiplied by an array consisting of the maximum minus the minimum multiplier for the combined land use/soil type for that year. The resulting map is presented in **Figure 33.** The higher the range of variation mapped in **Figure 33**, the higher the expected uncertainty in the infiltration estimate.

The average expected uncertainty over the model domain for the predicted annual infiltration is 3 inches with a standard deviation of 3.7 inches. The lowest uncertainty levels tend to occur where land cover has less impervious surface such as forests and grasslands. Highest uncertainty occurs where land use is more urbanized such as residential and is especially high for the SWB land category #23: Commercial-Industrial-Transportation. The largest factor in this trend is probably the relatively high variability of the root zone depth estimates for these urban land uses.

The range in simulated infiltration due to sensitive parameters, and for each combination of land use and soil type, will be used as the range of freedom for infiltration values in the Metro Model 3 calibrations. Simulated infiltration using SWB will be multiplied by values (multipliers) related to each of the combinations of land uses and soil types prior being input into the UZF package for Metro Model 3.

7.3 Recommendations for Field Verification

In areas where modeled infiltration uncertainty shown in **Figure 33** is greatest, field verification of physical data may be used to constrain model parameters to a higher degree and thereby increase confidence in the final model result. In this case the model input uncertainty would be improved most with additional information regarding representative values for root zone depths, especially in urbanized areas. Currently little root zone depth data are available for urban areas and existing research is dominated by agricultural studies on this topic. This large uncertainty is reflected in this analysis.

Root zone depths could be measured for urban land uses and for each hydrologic soil type across the model domain. Land use categories for High Density Residential (#22) and Commercial-Industrial-Transportation (#23) have high sensitivity and uncertainty and would yield the most improvement to model accuracy (**Figure 34**).

Table 9. Summary of parameter value ranges for the 16 most sensitive SWB parameters varied during the sensitivity analysis.

SWB Parameter Description	Initial Value	Minimum Value	Maximum Value	Source for range for range of values
Curve number for soil type B in land use Comm/Ind/Tran	92	88	100	TR-55 Table 2-2a urban districts; raised max to higher than initial
Maximum recharge for D soils	0.7	0.35	1.4	TR-55 Appendix A (USDA, 1986)
Root zone depth for soil type A in land use Comm/Ind/Tran	0.74	0.668	2.96	Initial is 2/3 of high density residential; lowered minimum to less than initial
Root zone depth for soil type A in land use HidenyRes	1.11	1.002	4.44	2/3 of Table 10, TM 1957; lowered min to less than initial
Maximum recharge for A soils	9	7	18	TR-55 Appendix A (USDA, 1986)
Root zone depth for soil type A in land use Shrubland	3.33	1.67	6.66	Table 10, TM 1957
Root zone depth for soil type A in land use Urban/RecGrass	3.33	1.67	6.66	Table 10, TM 1957
Root zone depth for soil type B in land use Row Crops	2.08	1.872	6.66	Table 10, TM 1957; lowered min to less than initial
Root zone depth for soil type B in land use DeciduousForest	6.66	2.08	7.326	Table 10, TM 1957; raised max to higher than initial
Root zone depth for soil type B in land use Quarries/Pits	0.5	0.45	6.66	Table 10, TM 1957; lowered min to less than initial
Root zone depth for soil type B in land use Comm/Ind/Tran	0.93	0.832	2.96	Initial is 2/3 of high density residential; lowered minimum to less than initial
Root zone depth for soil type B in land use HidenyRes	1.39	1.248	4.44	Initial is 2/3 of high density residential; lowered minimum to less than initial
Root zone depth for soil type A in land use LowdenRes	1.67	1.503	6.66	Table 10, TM 1957; lowered min to less than initial
Root zone depth for soil type A in land use Grass/Herbs	3.33	1.67	6.66	Table 10, TM 1957
Root zone depth for soil type B in land use Shrubland	4.17	2.08	6.66	Table 10, TM 1957
Maximum recharge for B soils	5.5	4.8	7	TR-55 Appendix A (USDA, 1986)

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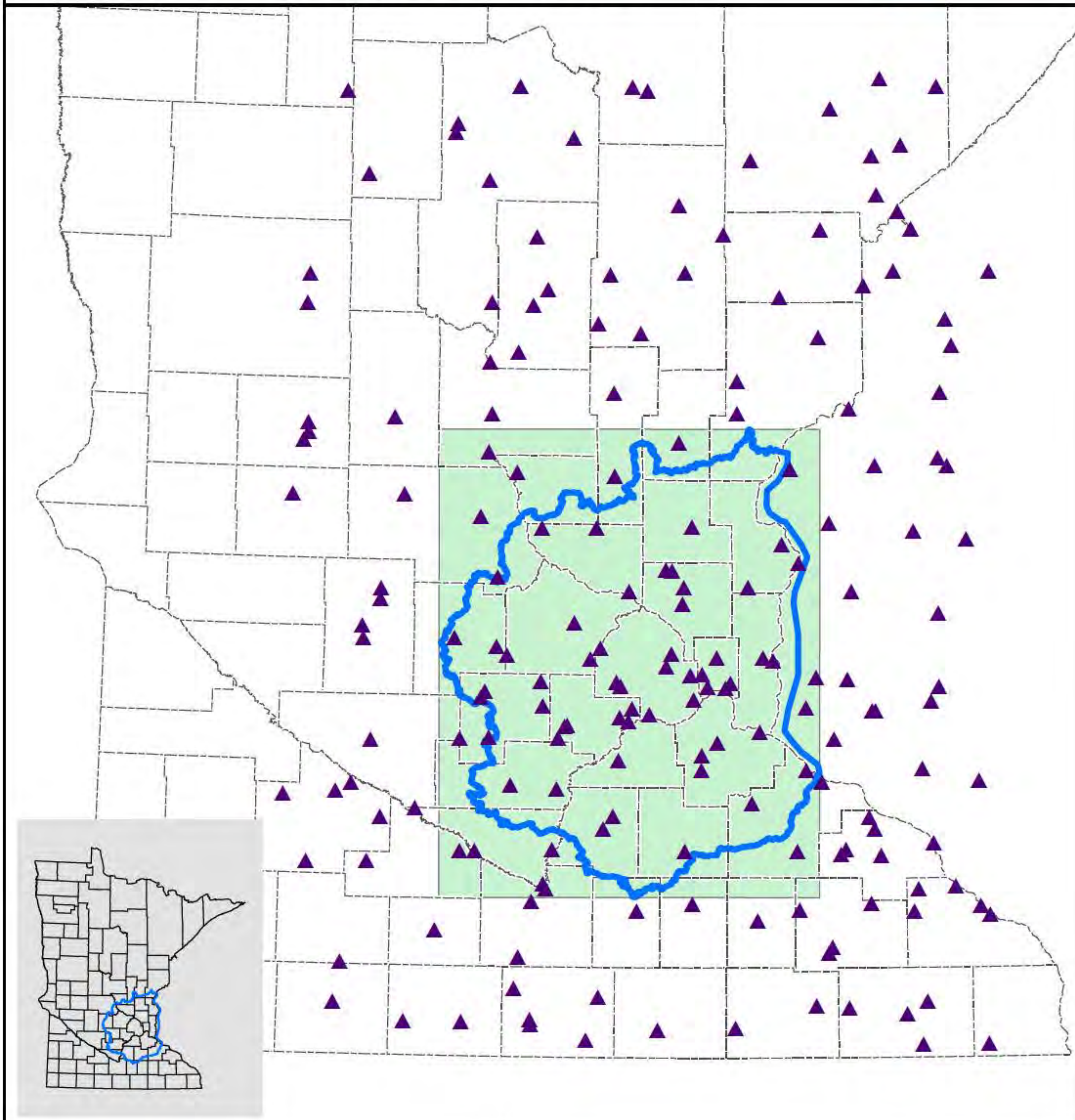
9 Figures



Legend

- GHCN Weather Stations
- GW Model
- Counties
- SWB Domain

0 10 20
Miles

0 15 30
Kilometers

FIGURE 1
Weather Stations
Used for Model Input

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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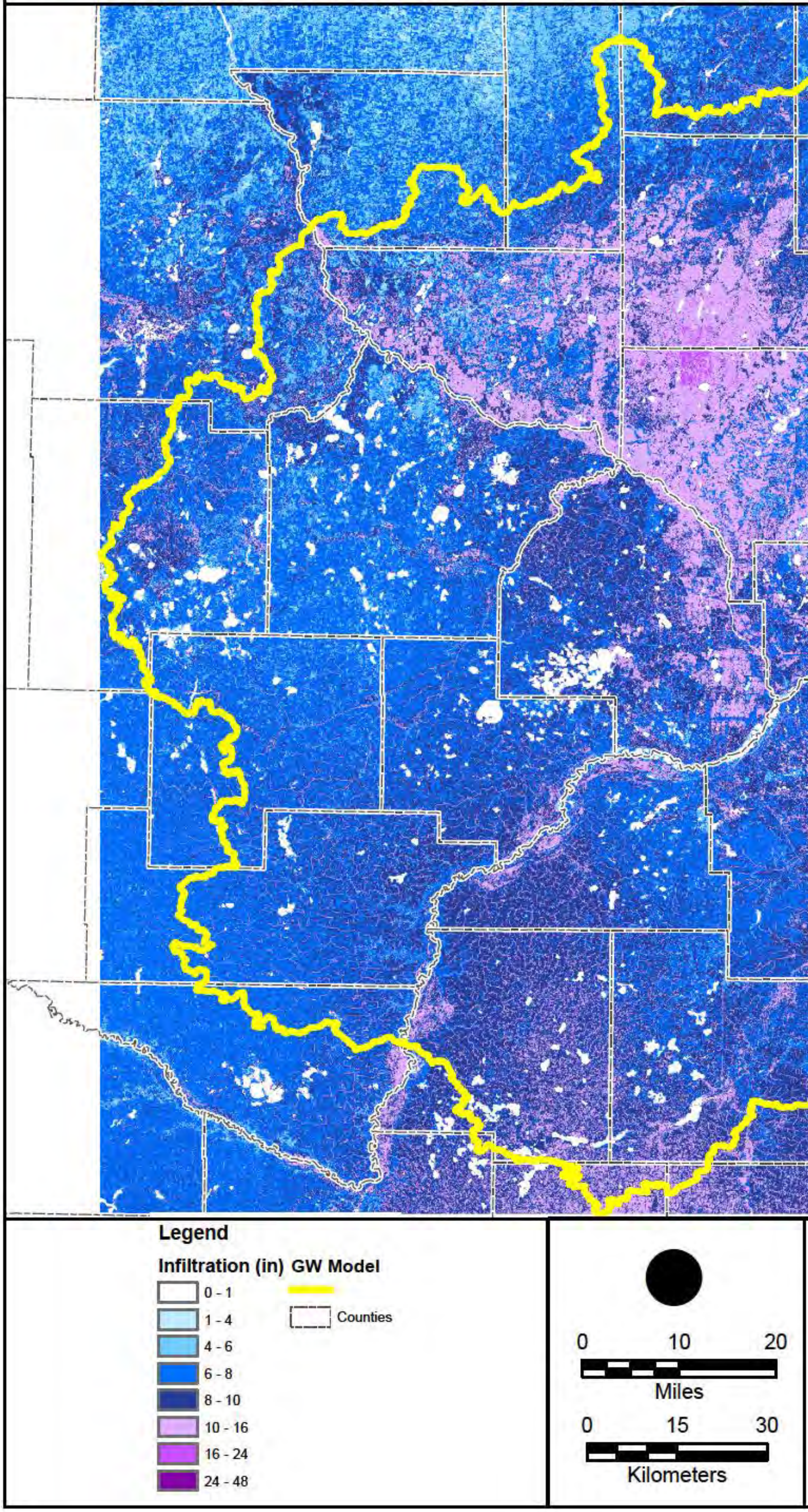

FIGURE 2
Average Annual SWB Infiltration For 1988-2011

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

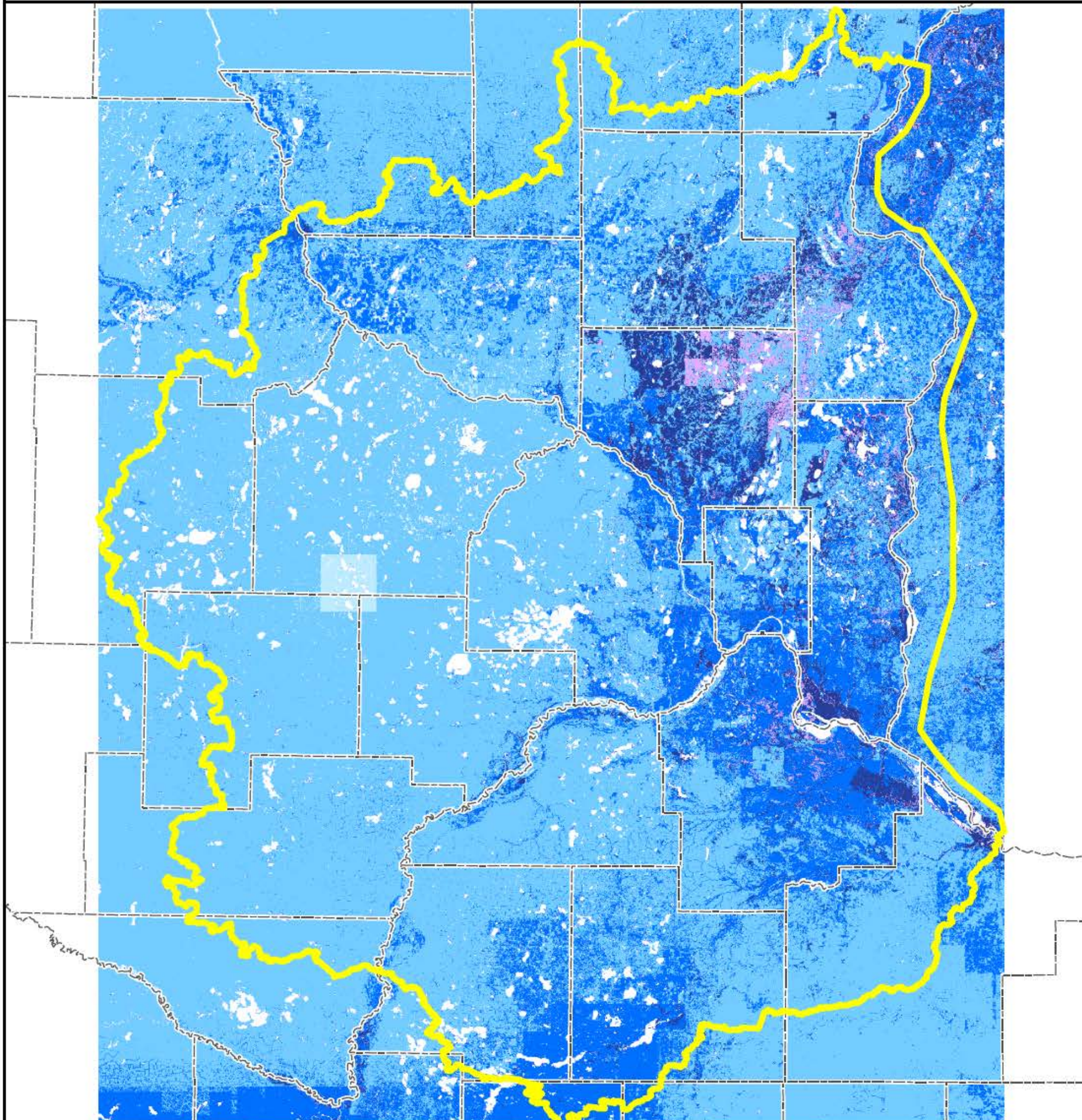
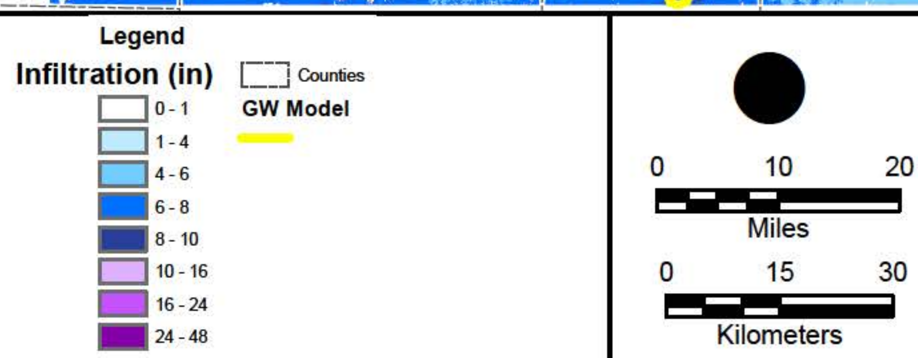
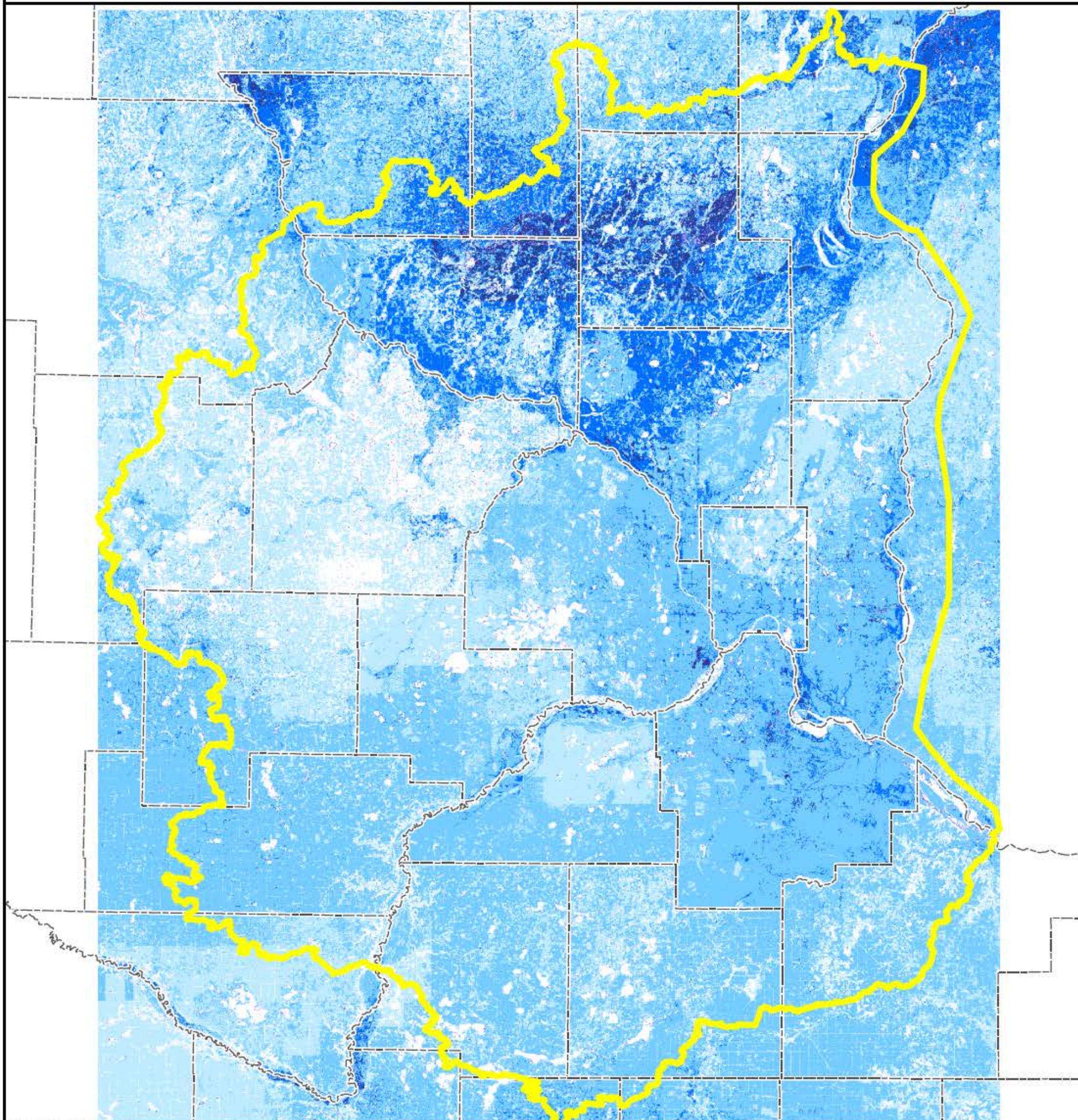


FIGURE 3
Annual SWB Infiltration in inches for 1988



Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

METROPOLITAN COUNCIL



Legend

Infiltration (in)

- 0 - 1
- 1 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 16
- 16 - 24
- 24 - 48

Counties

GW Model

0 10 20

Miles

0 15 30

Kilometers

FIGURE 4
Annual SWB Infiltration in inches for 1989

BARR

Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3

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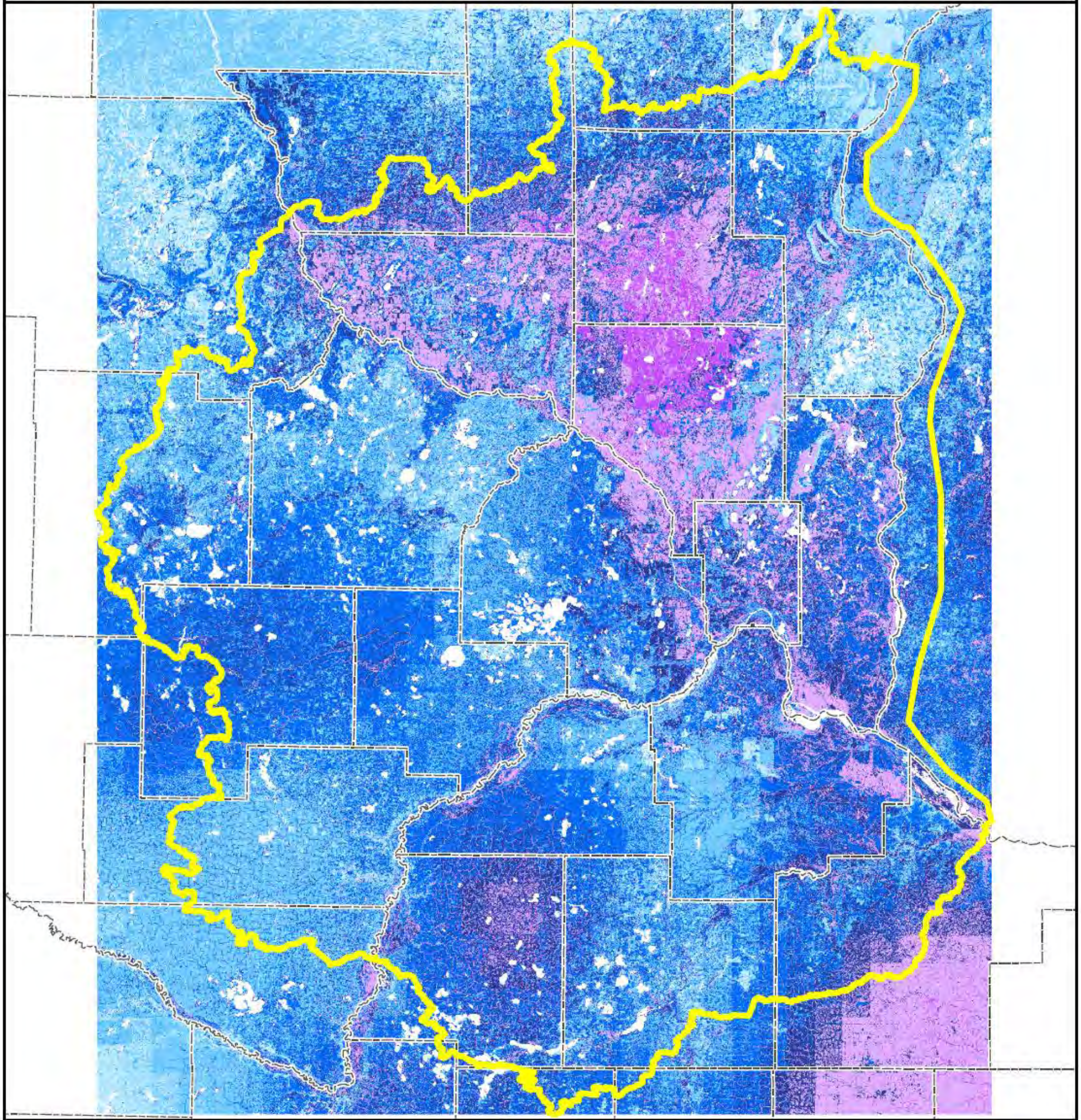

Legend

Infiltration (in)

- 0 - 1
- 1 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 16
- 16 - 24
- 24 - 48

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 5
Annual SWB Infiltration in inches for 1990

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Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3

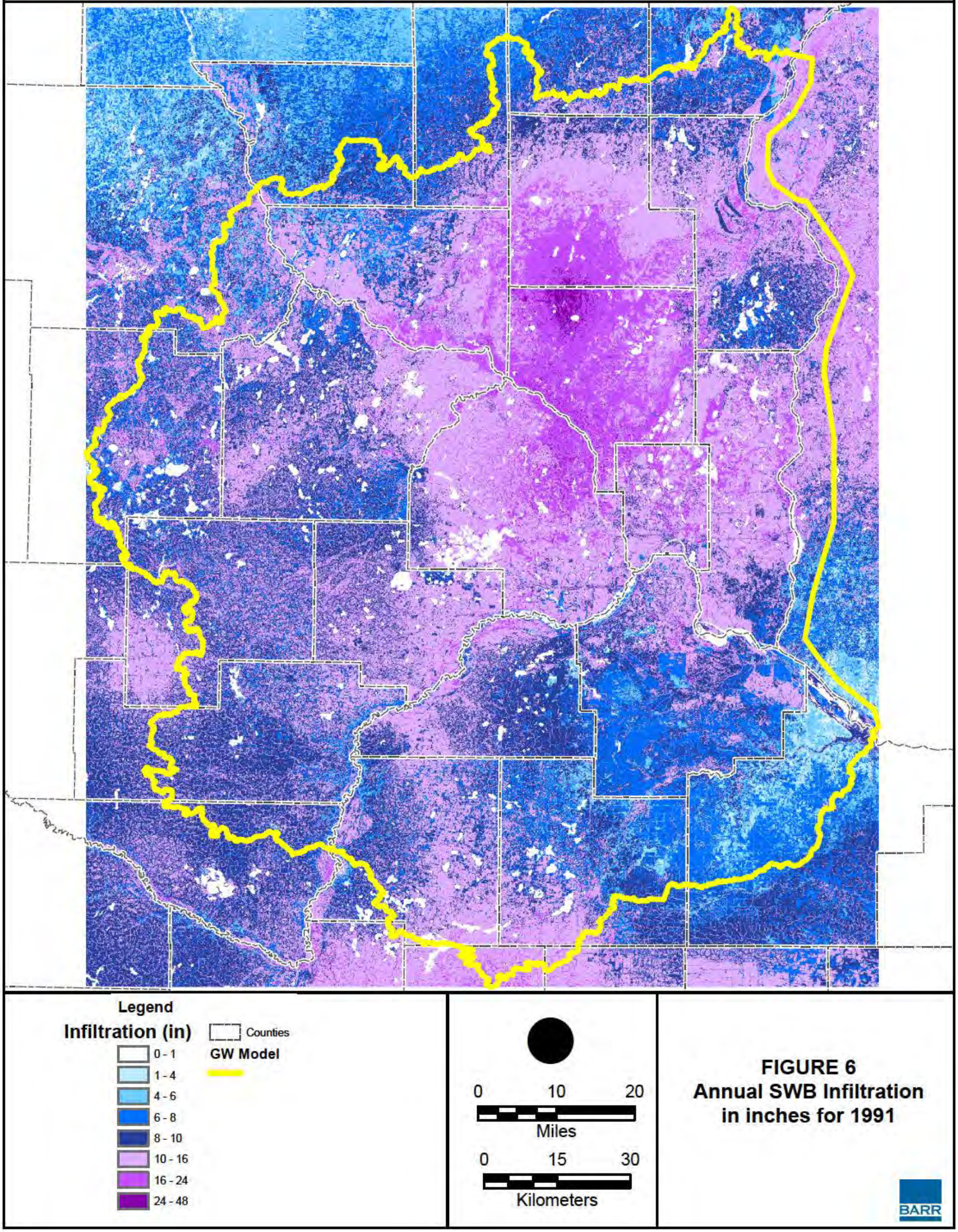

FIGURE 6
Annual SWB Infiltration in inches for 1991

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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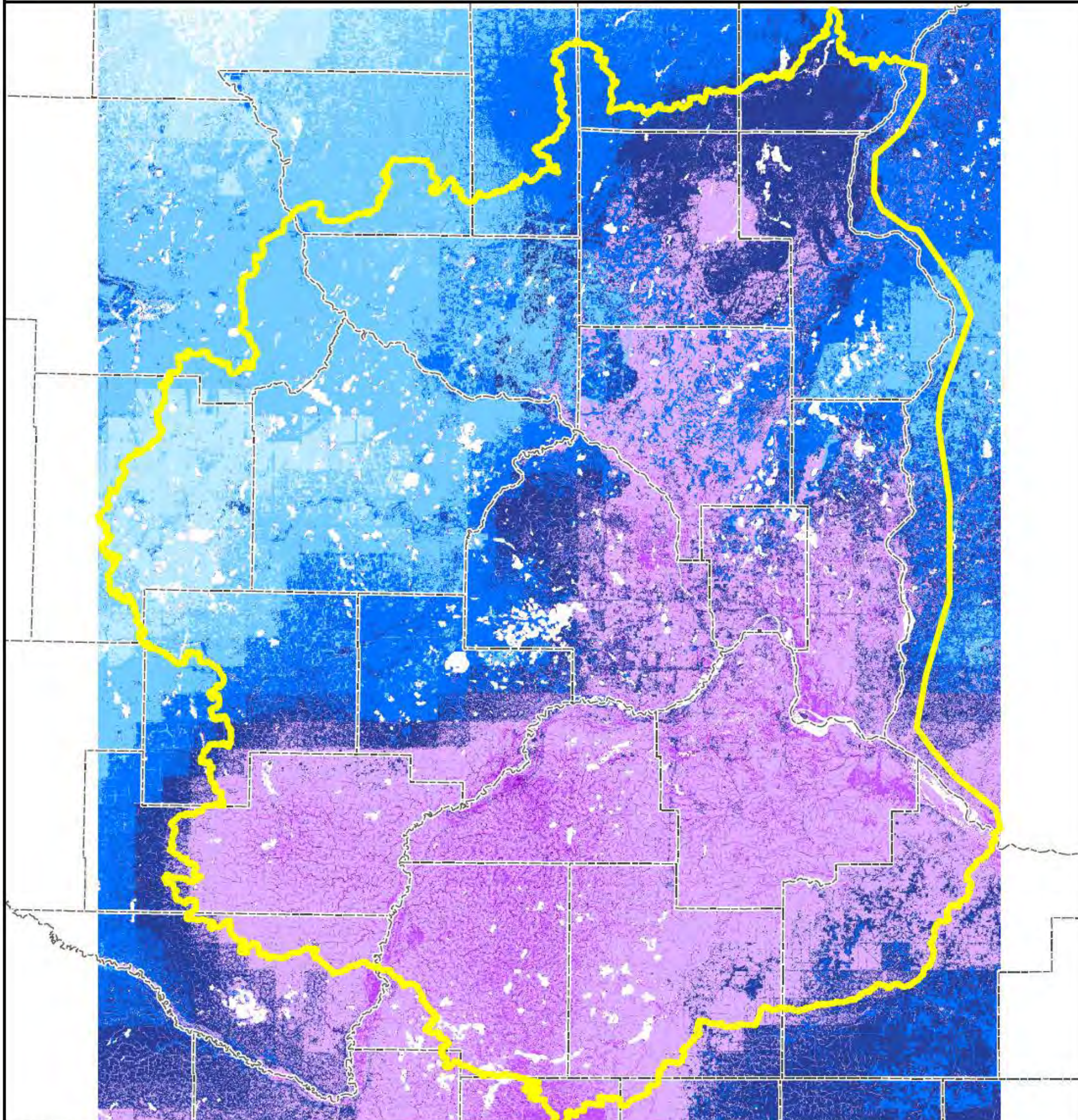

Legend

Infiltration (in)

0 - 1
1 - 4
4 - 6
6 - 8
8 - 10
10 - 16
16 - 24
24 - 48

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 7
Annual SWB Infiltration in inches for 1992

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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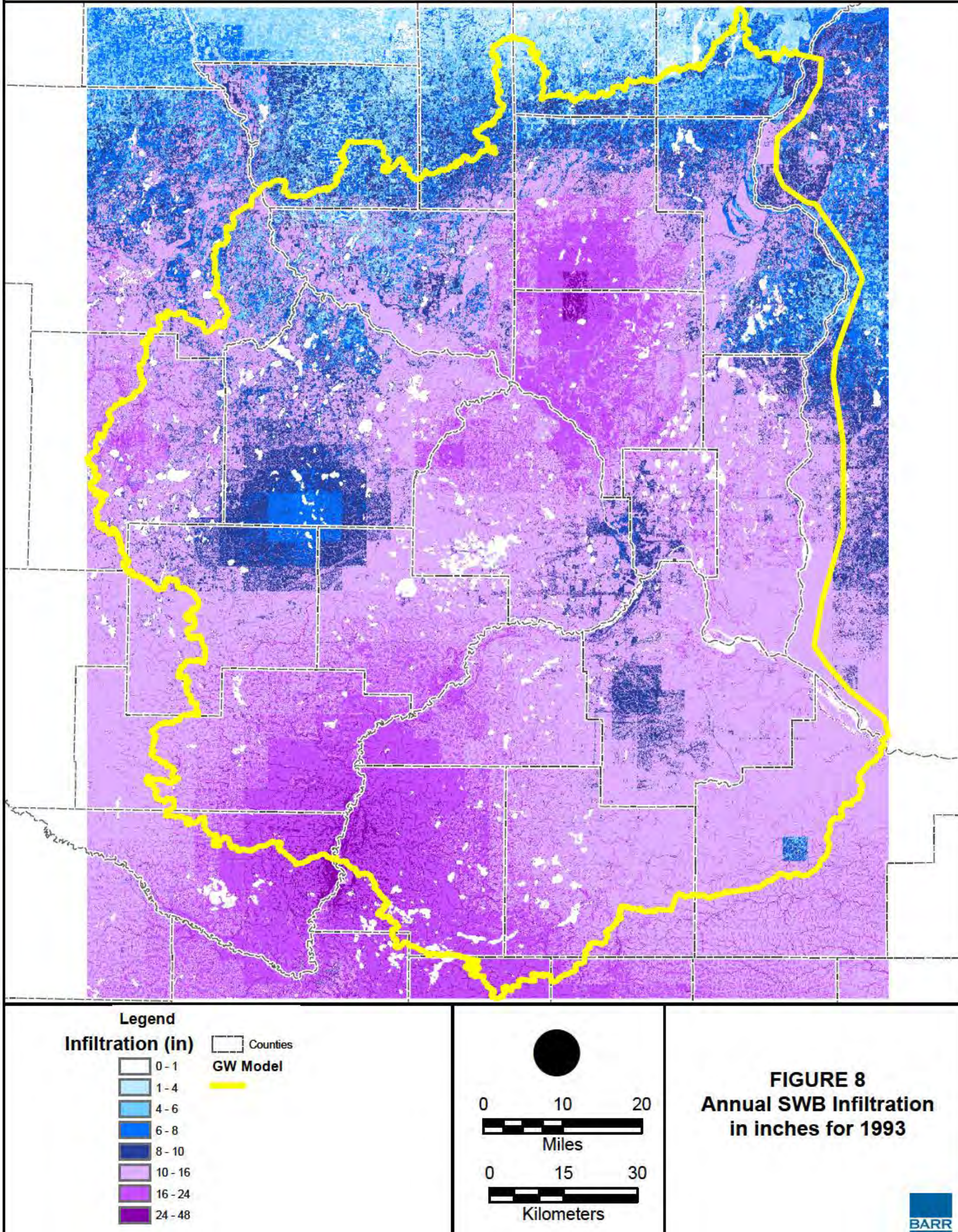

FIGURE 8
Annual SWB Infiltration in inches for 1993

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Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3

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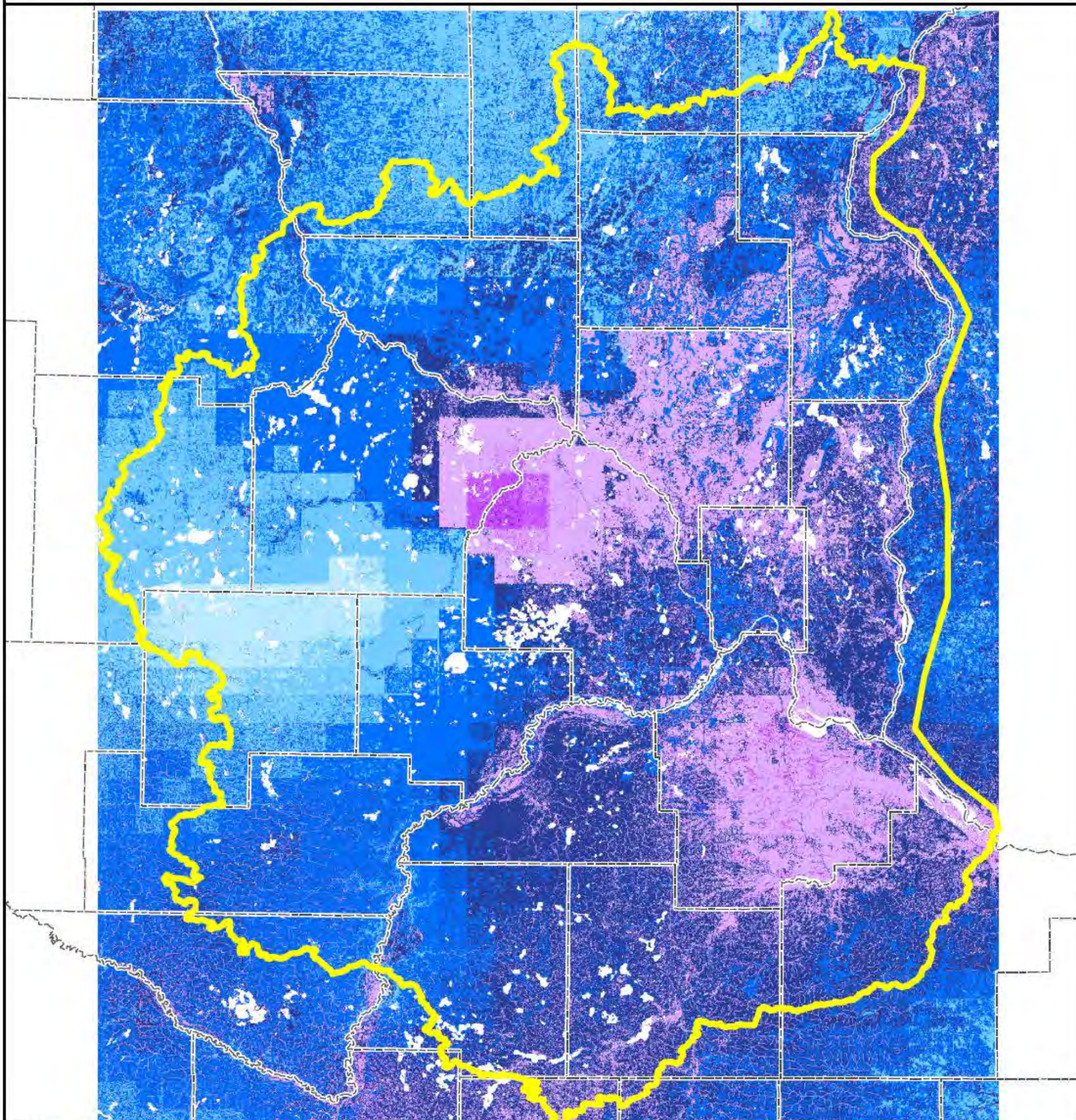

Legend

Infiltration (in)

- 0 - 1
- 1 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 16
- 16 - 24
- 24 - 48

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 9
Annual SWB Infiltration in inches for 1994

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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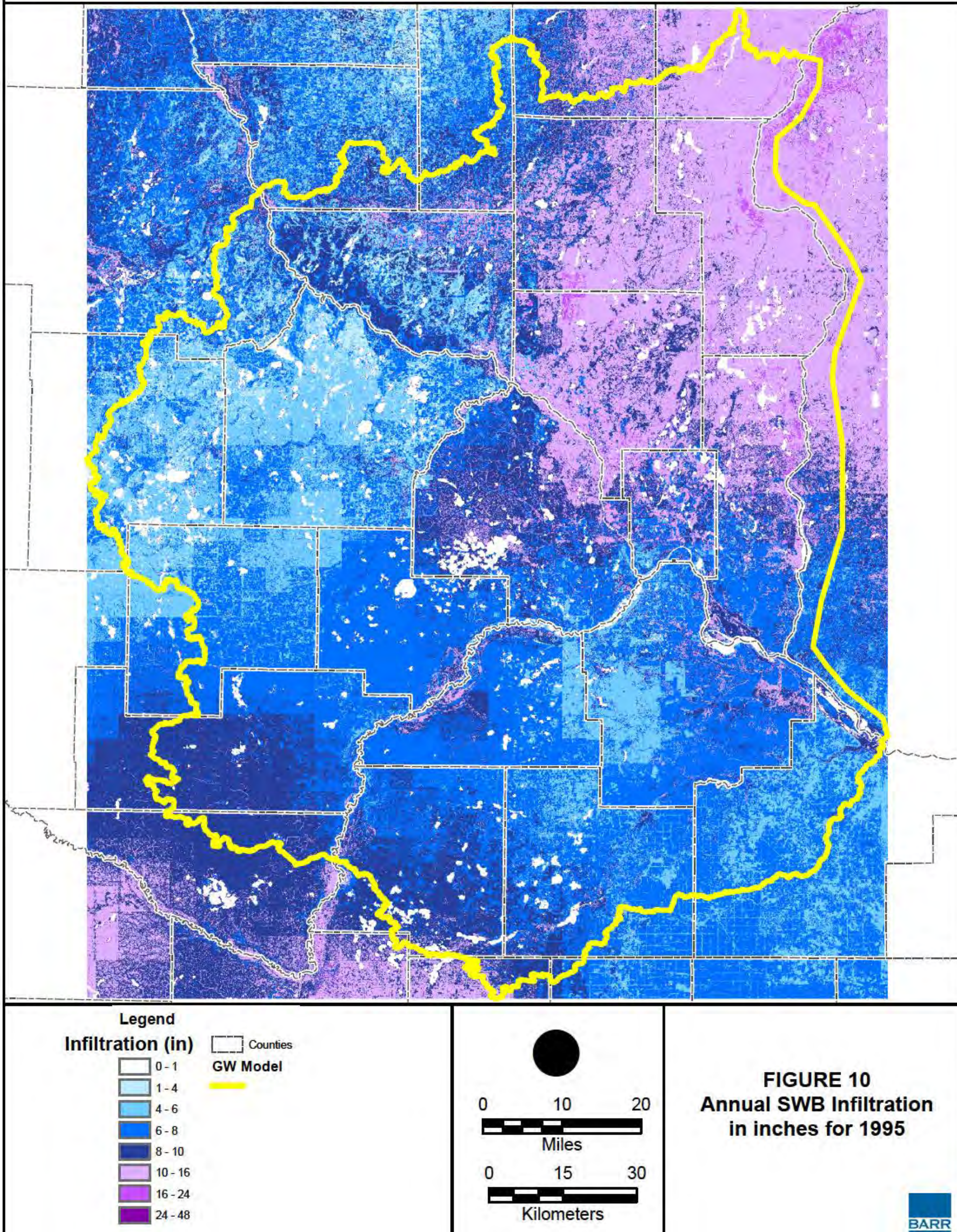

FIGURE 10
Annual SWB Infiltration in inches for 1995

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

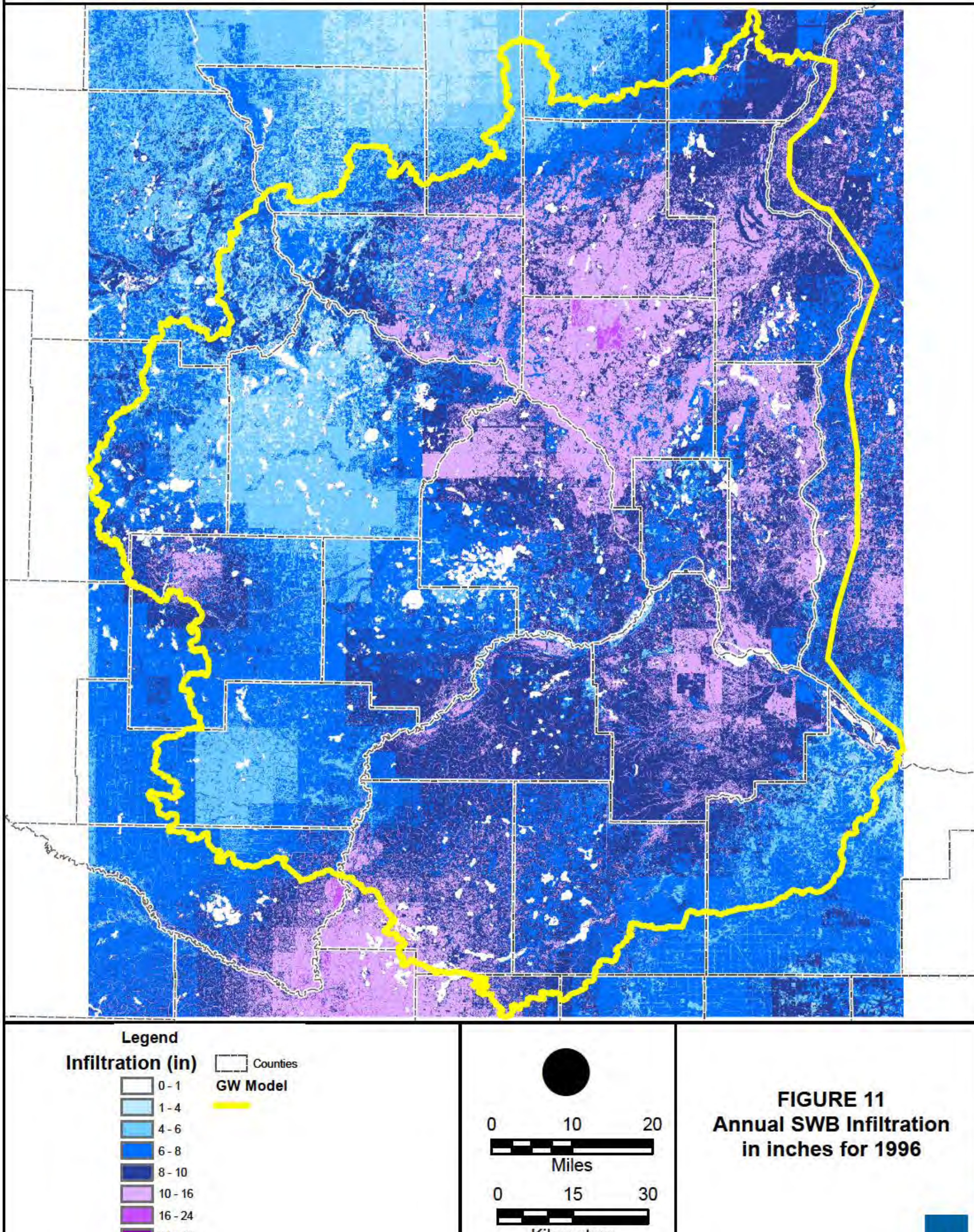


FIGURE 11
Annual SWB Infiltration in inches for 1996

Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3

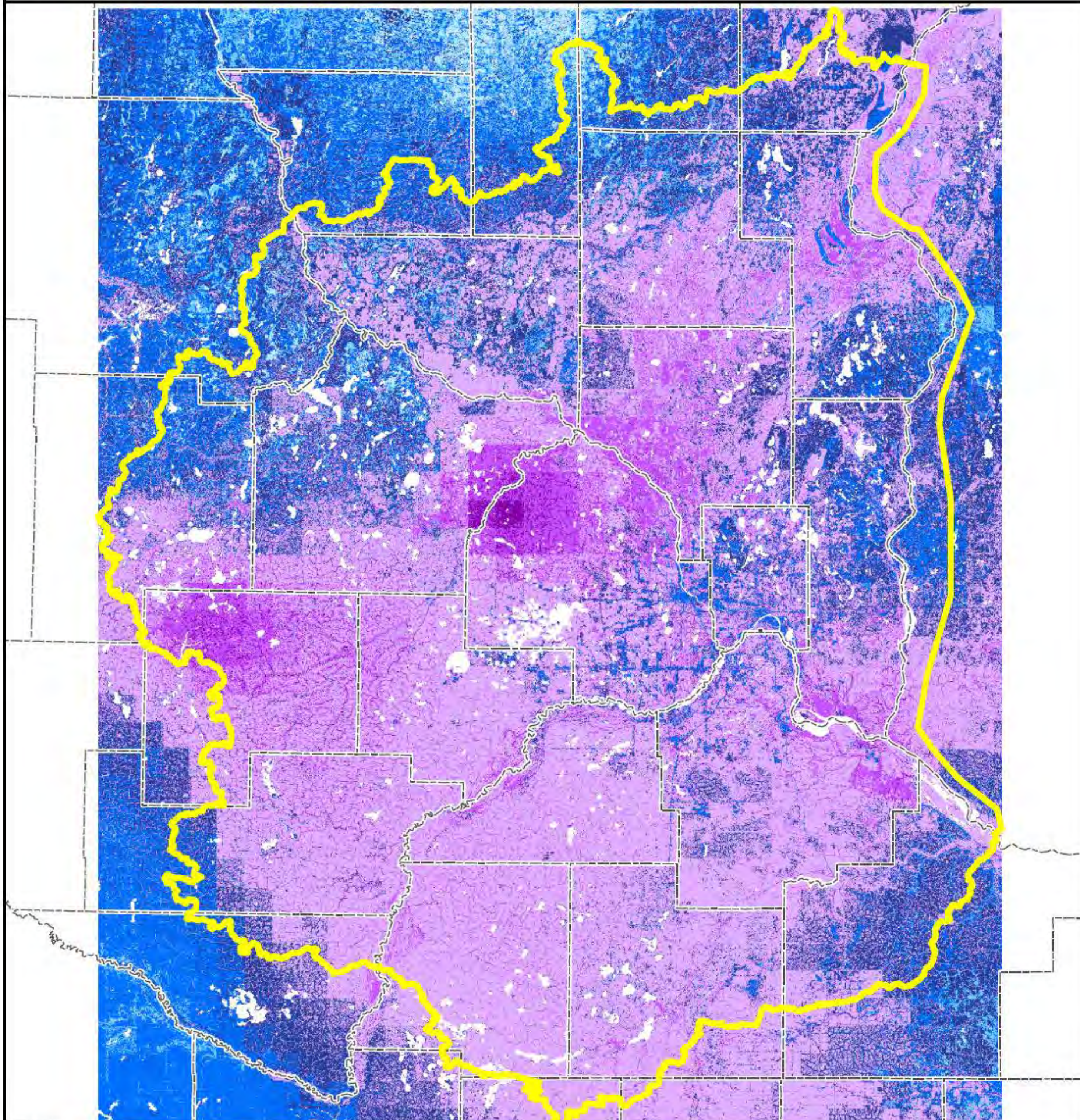
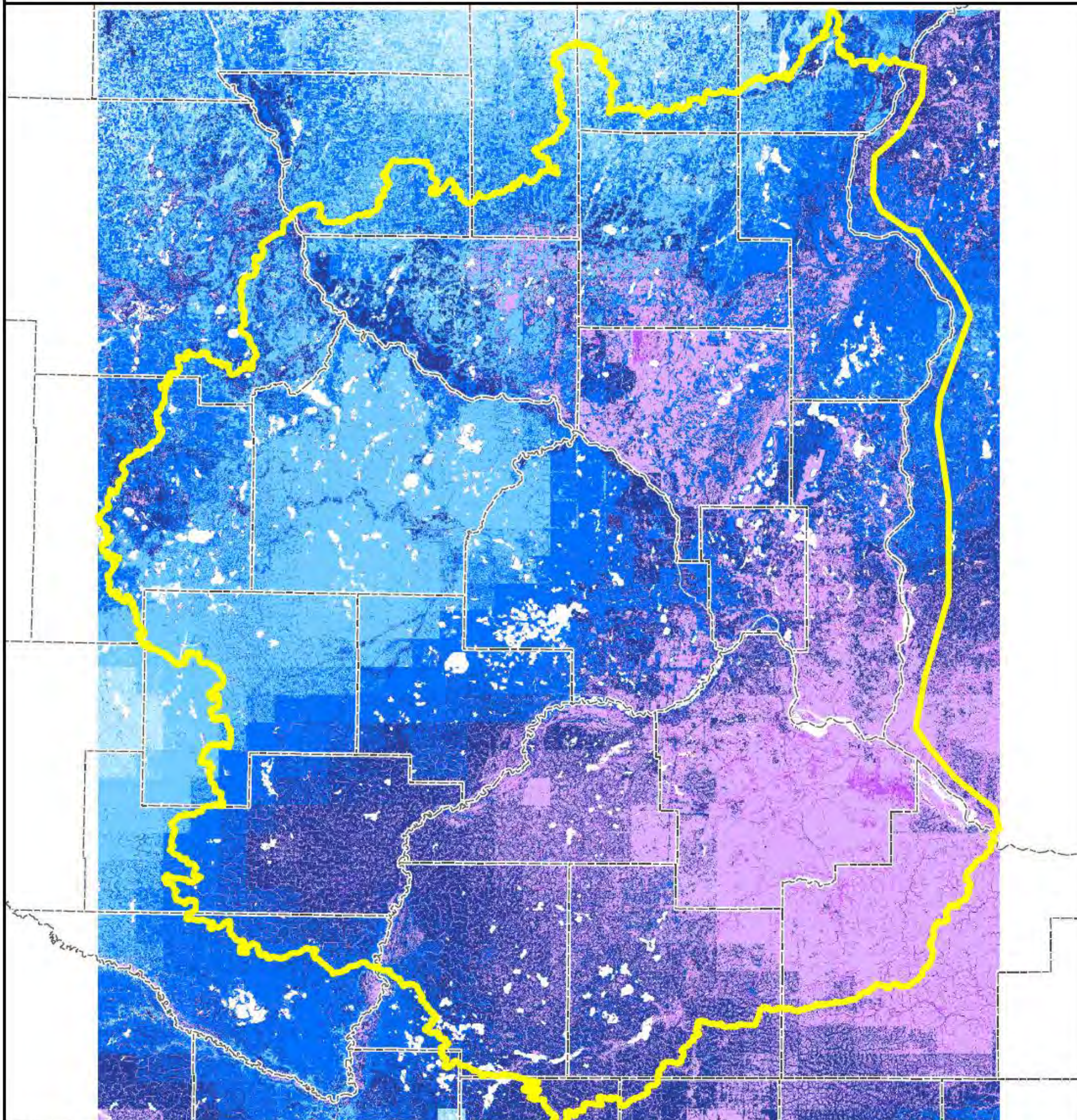


FIGURE 12
Annual SWB Infiltration in inches for 1997

Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3



Legend

Infiltration (in)

- 0 - 1
- 1 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 16
- 16 - 24
- 24 - 48

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 13
Annual SWB Infiltration in inches for 1998

BARR

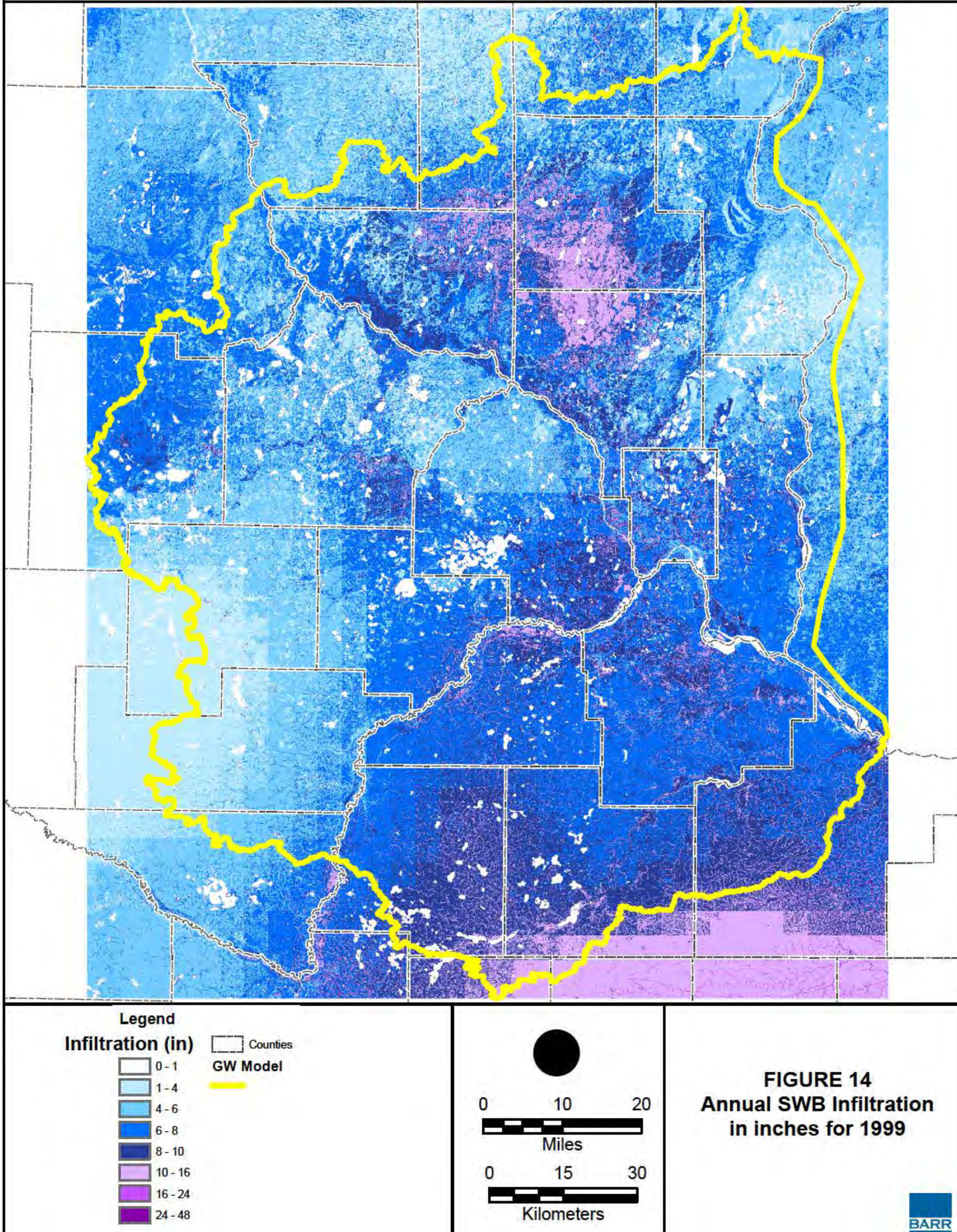
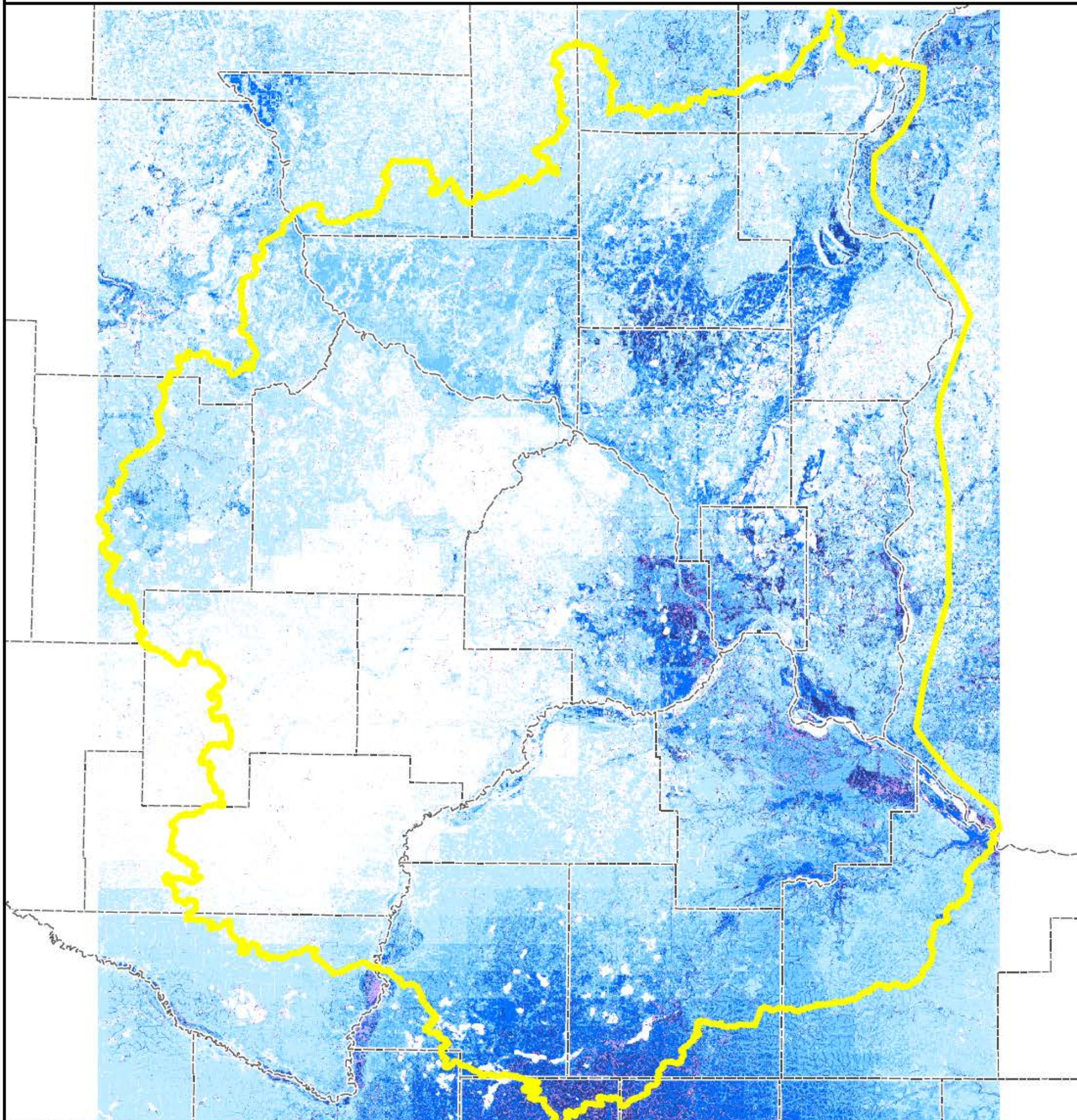


FIGURE 14
Annual SWB Infiltration in inches for 1999



Legend

Infiltration (in)

- 0 - 1
- 1 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 16
- 16 - 24
- 24 - 48

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 15
Annual SWB Infiltration in inches for 2000

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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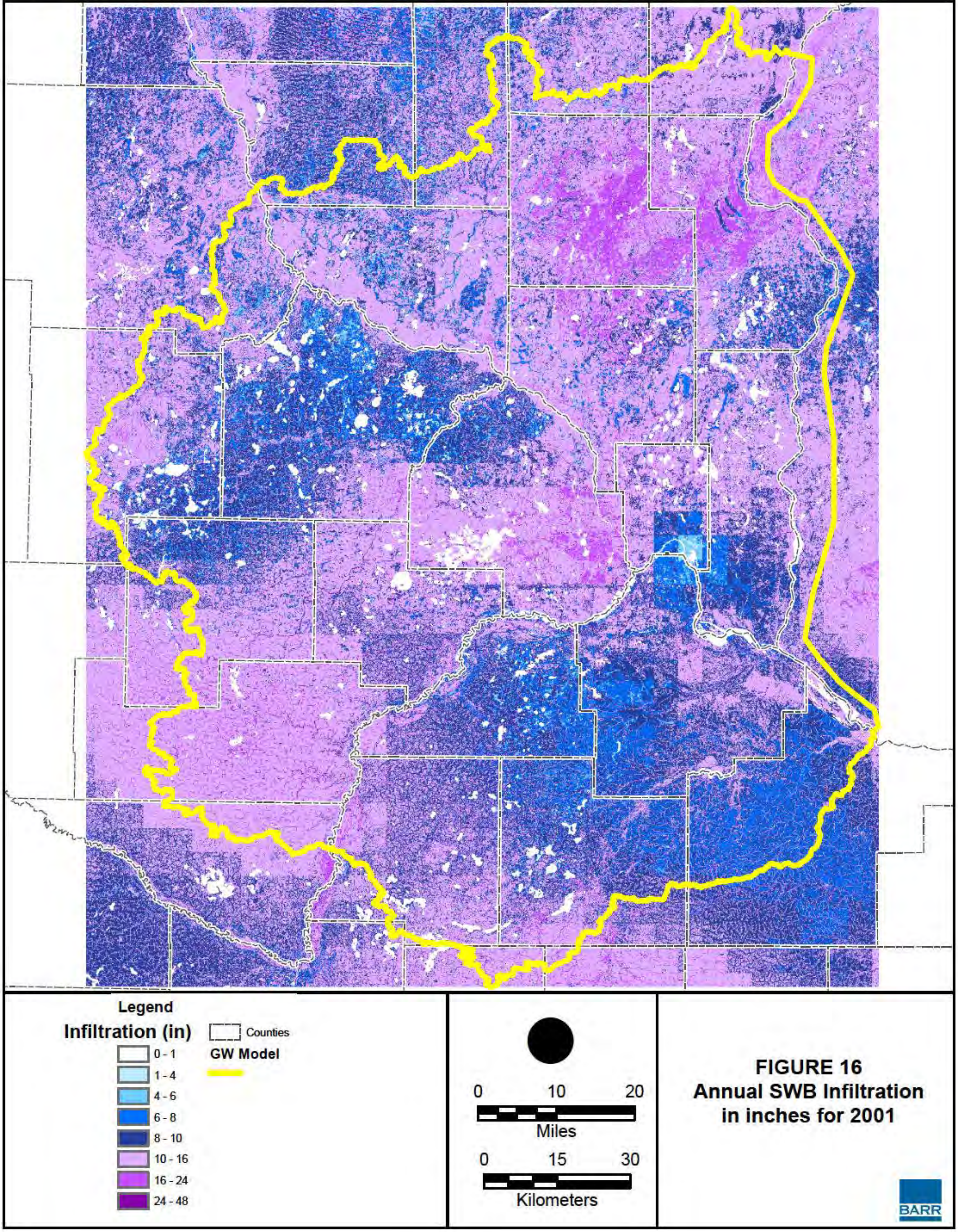

FIGURE 16
Annual SWB Infiltration in inches for 2001

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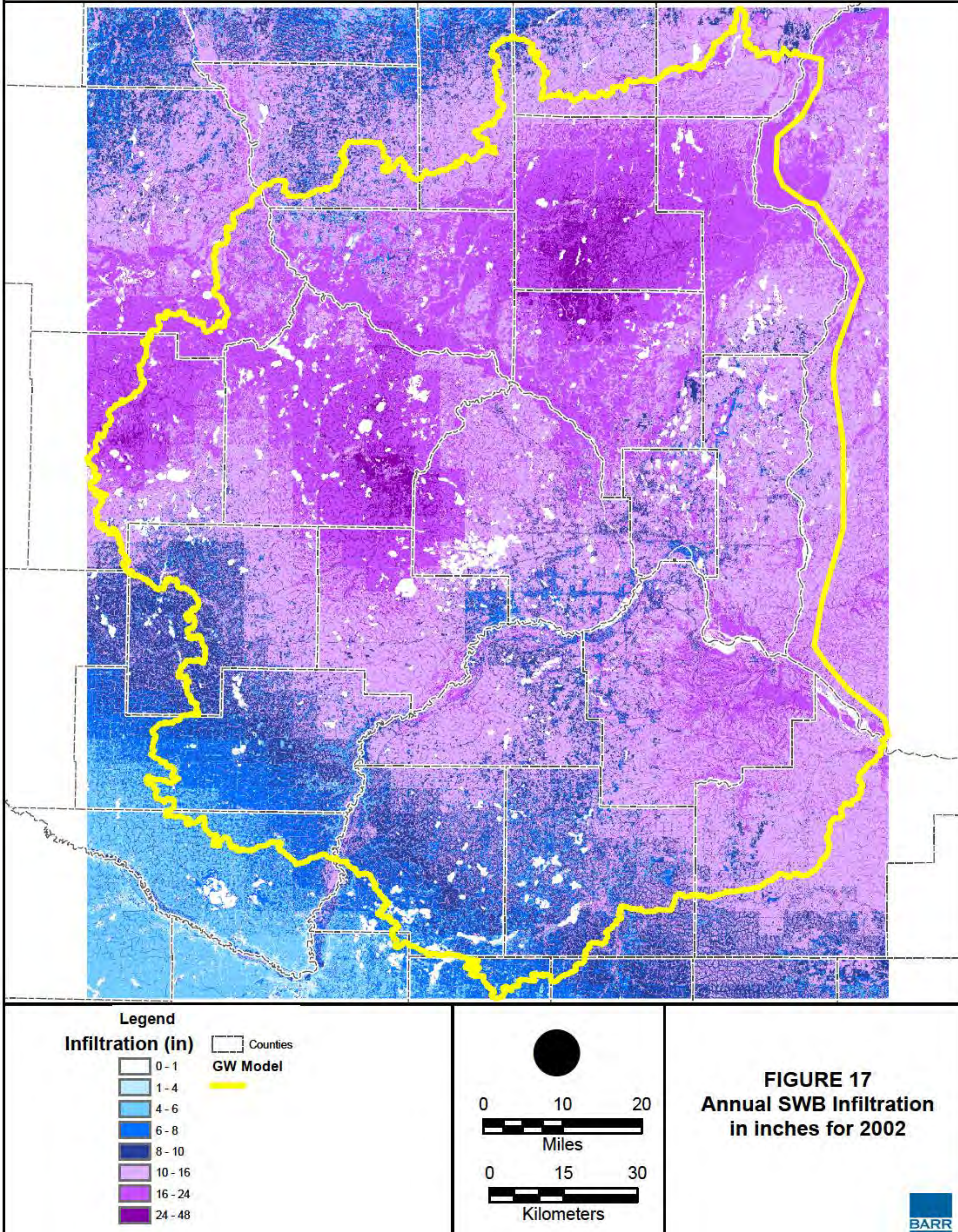


FIGURE 17
Annual SWB Infiltration in inches for 2002

BARR

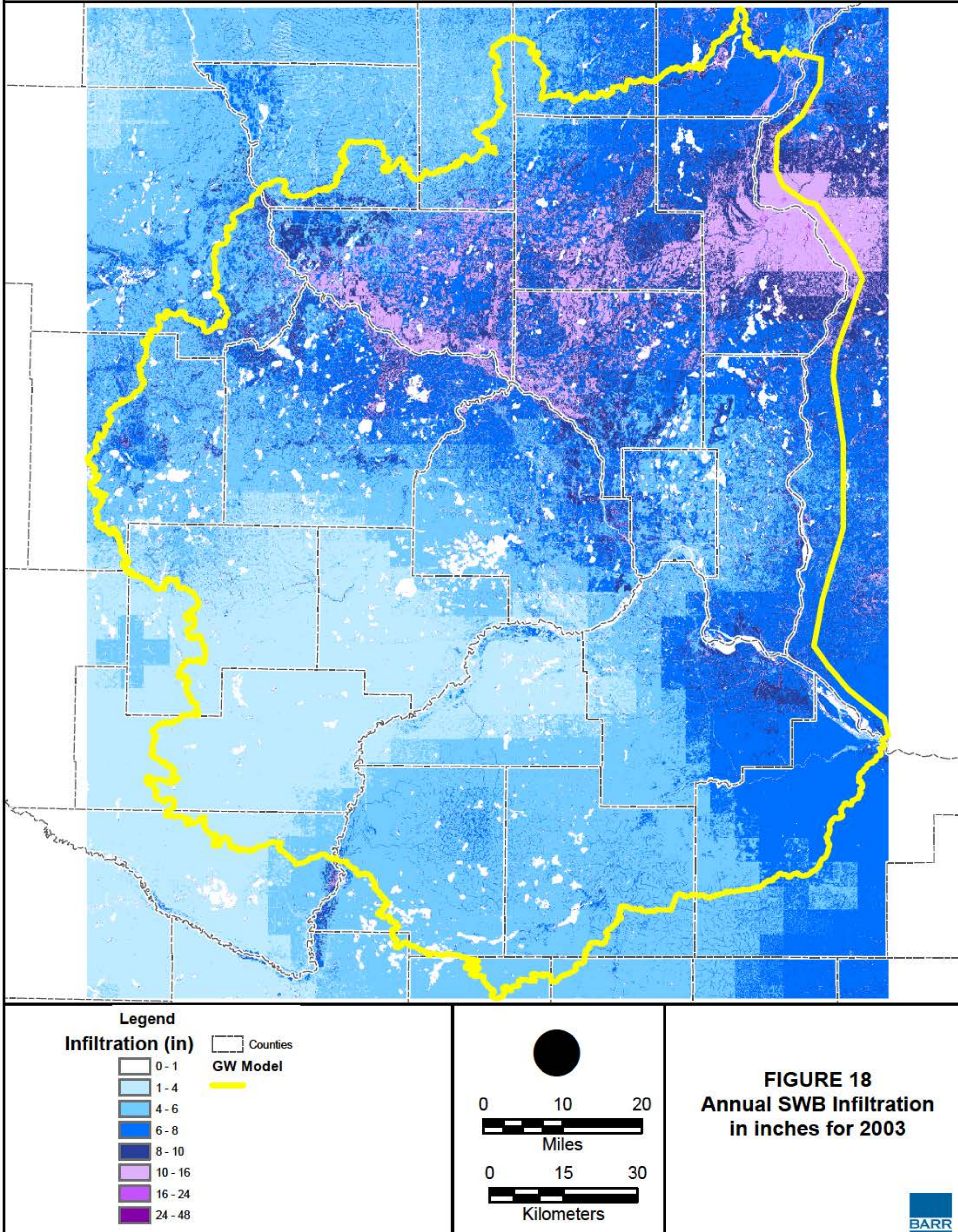


FIGURE 18
Annual SWB Infiltration in inches for 2003

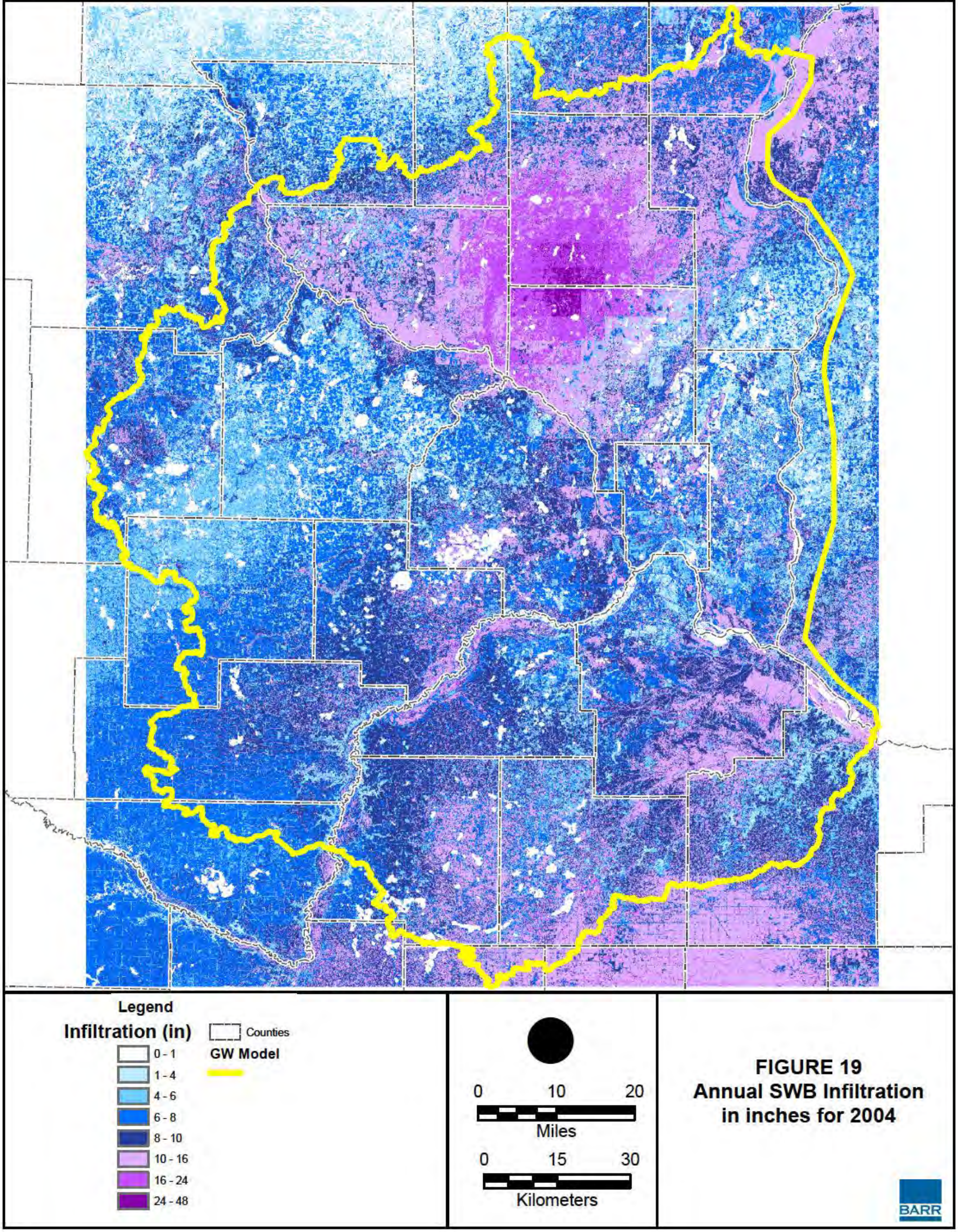
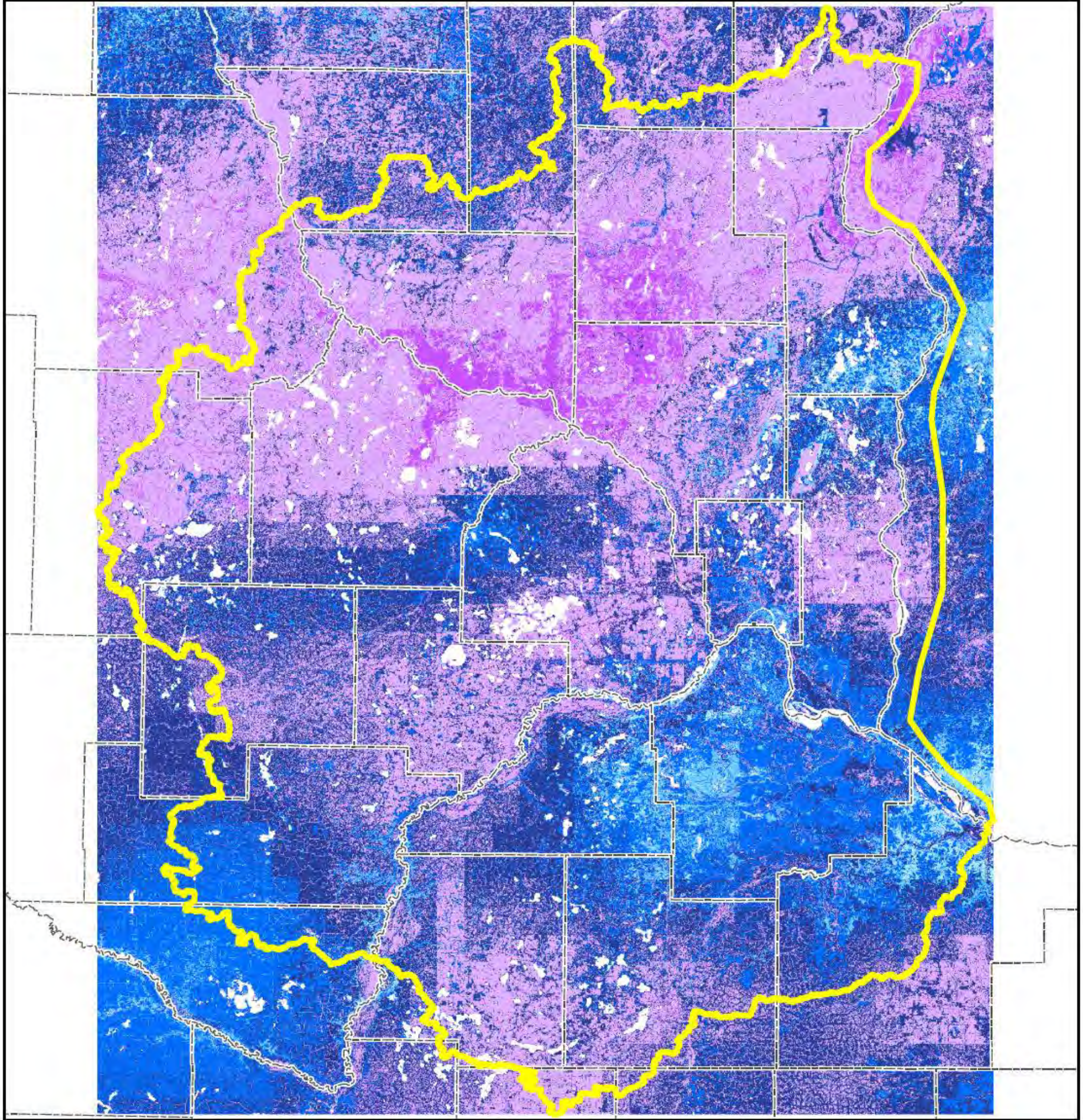


FIGURE 19
Annual SWB Infiltration in inches for 2004



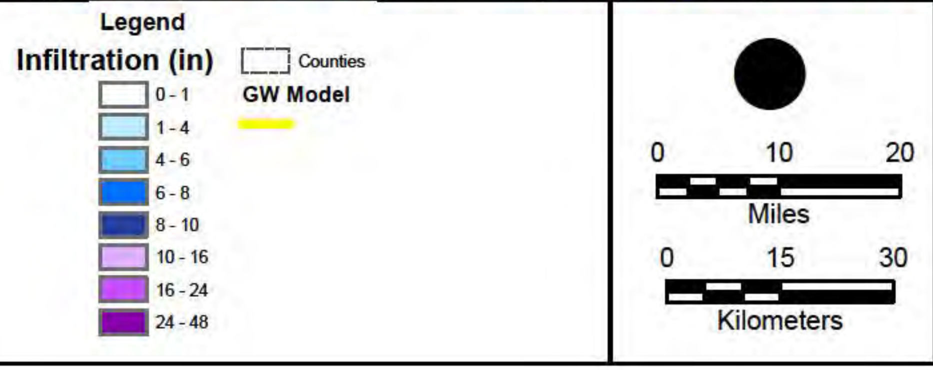


FIGURE 20
Annual SWB Infiltration in inches for 2005

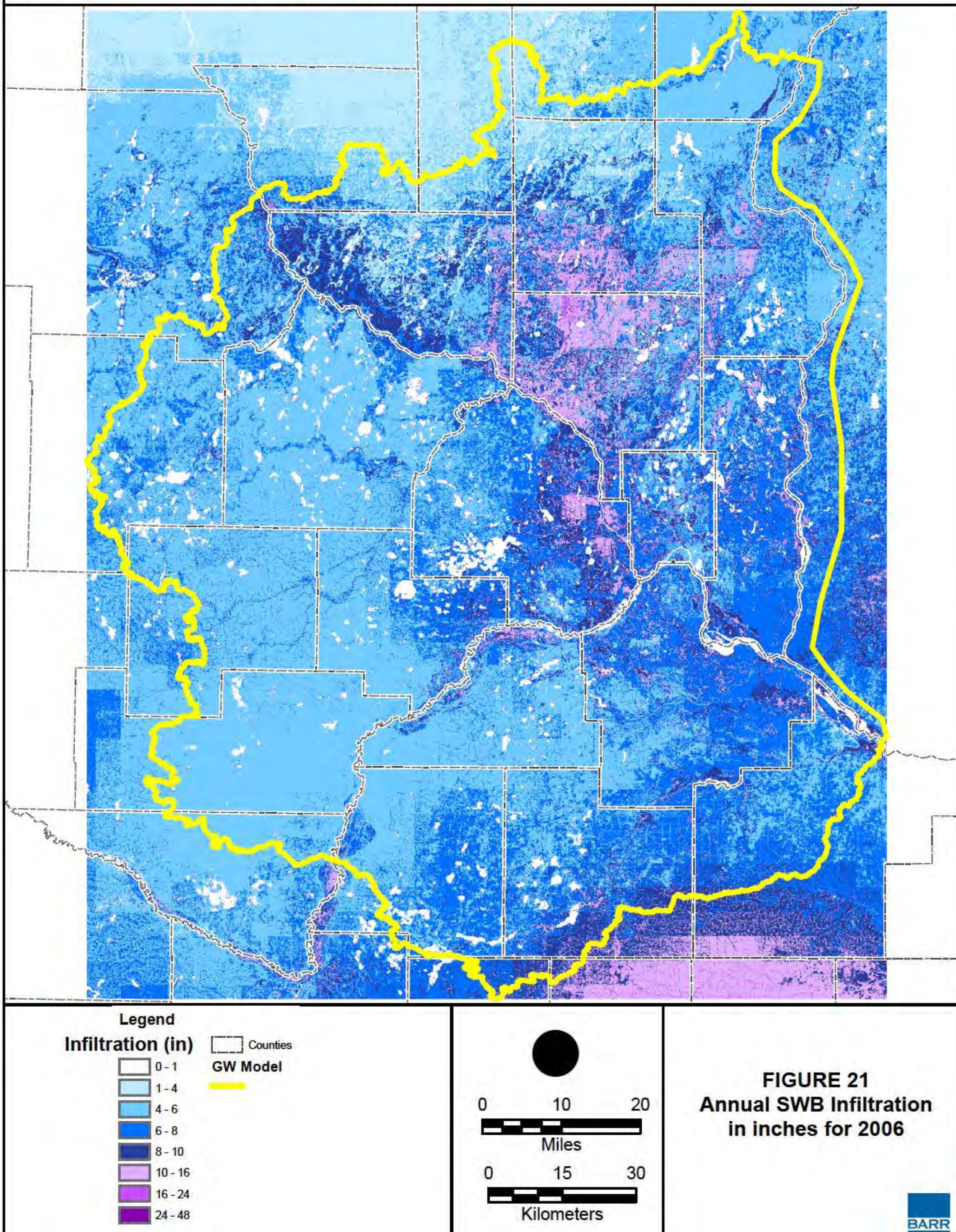


FIGURE 21
Annual SWB Infiltration in inches for 2006

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

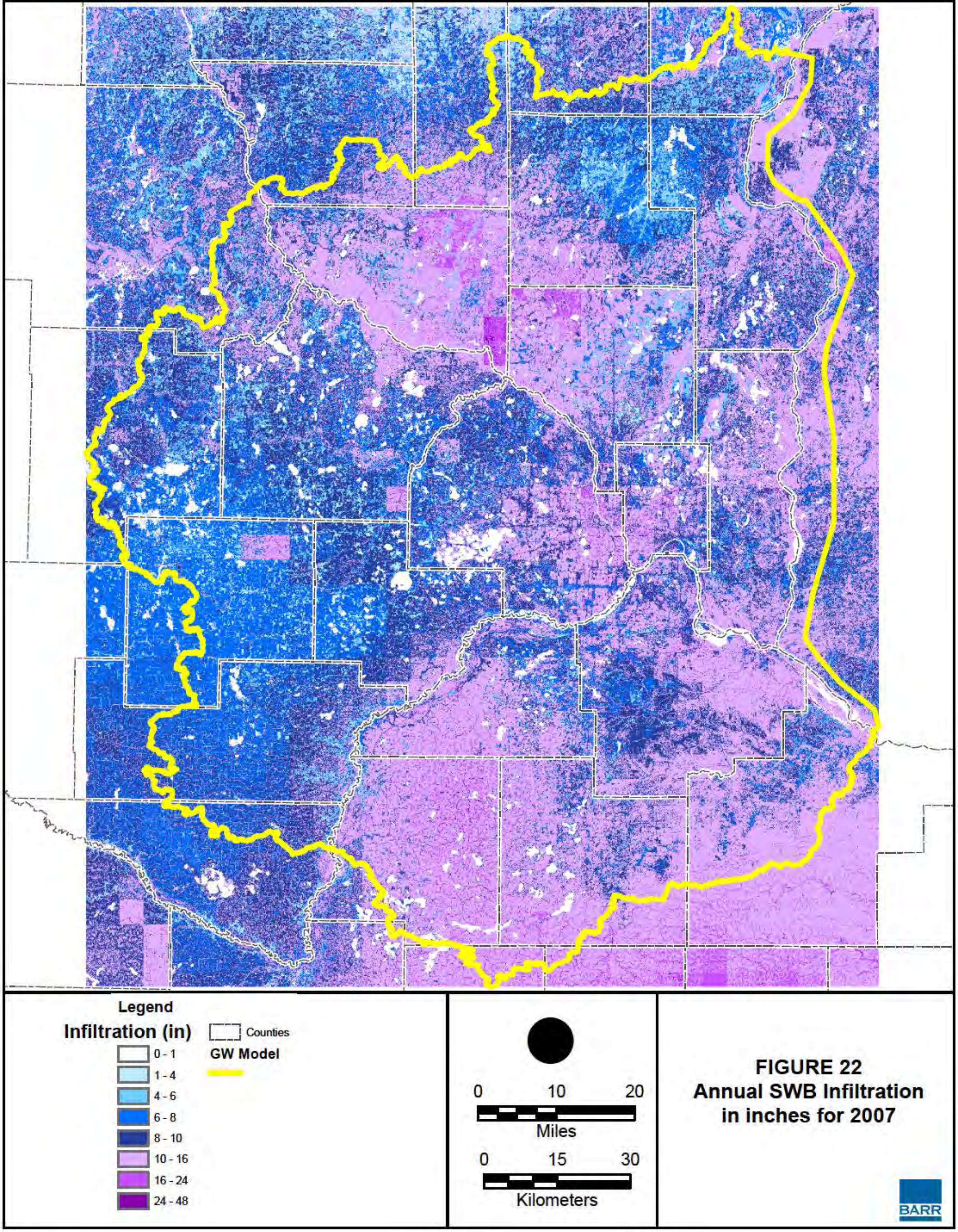


FIGURE 22
Annual SWB Infiltration in inches for 2007

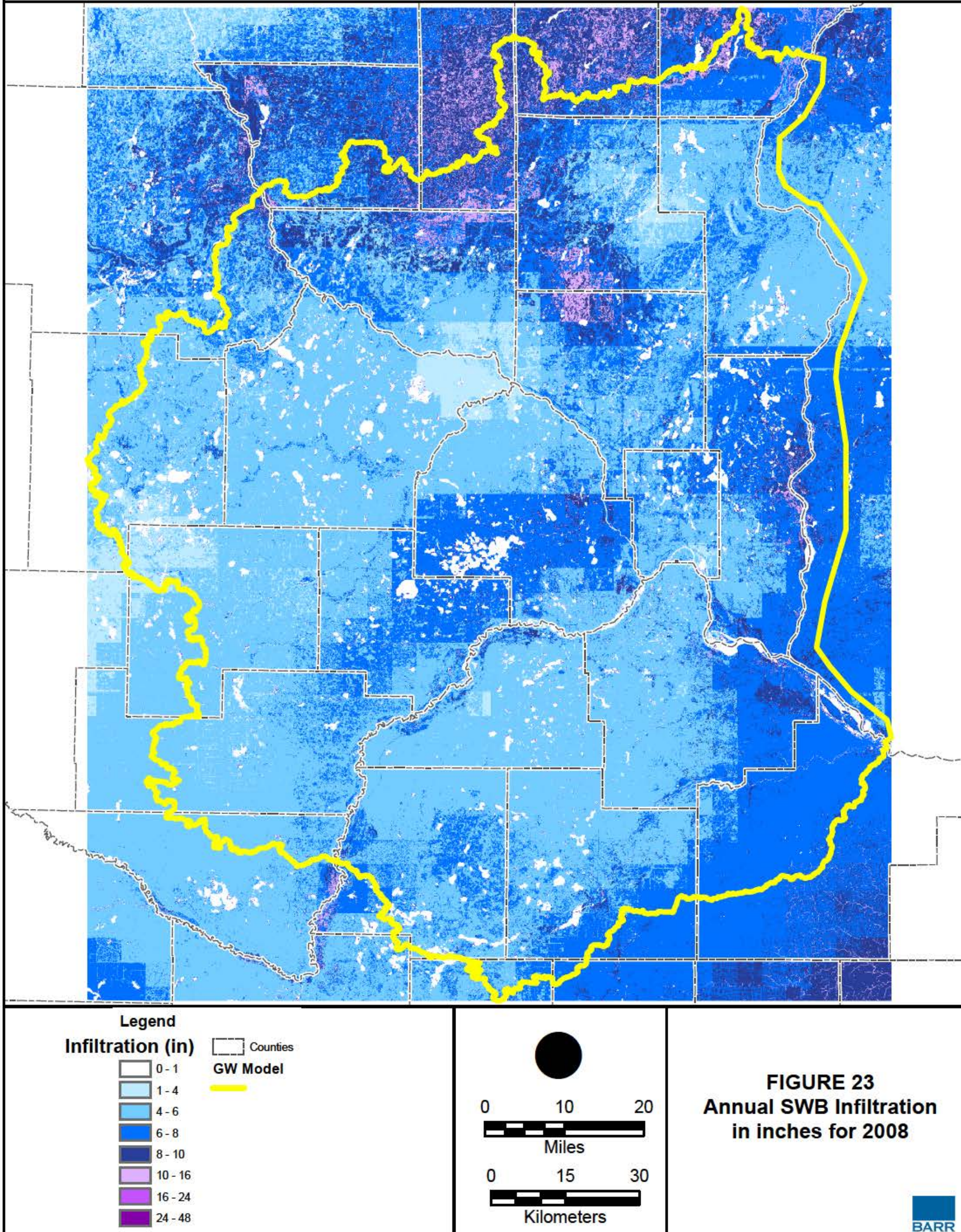


FIGURE 23
Annual SWB Infiltration in inches for 2008

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

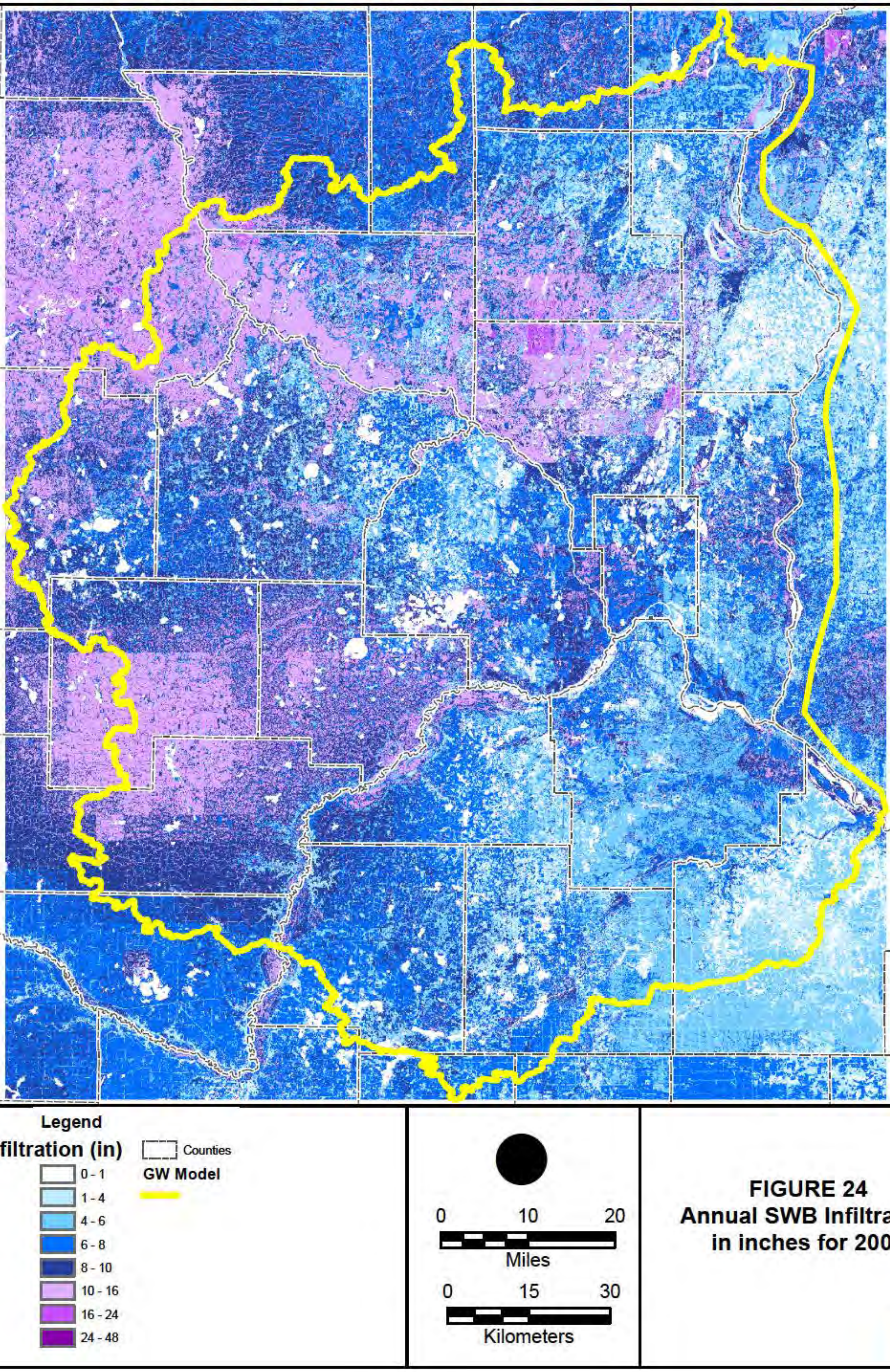


FIGURE 24
Annual SWB Infiltration in inches for 2009

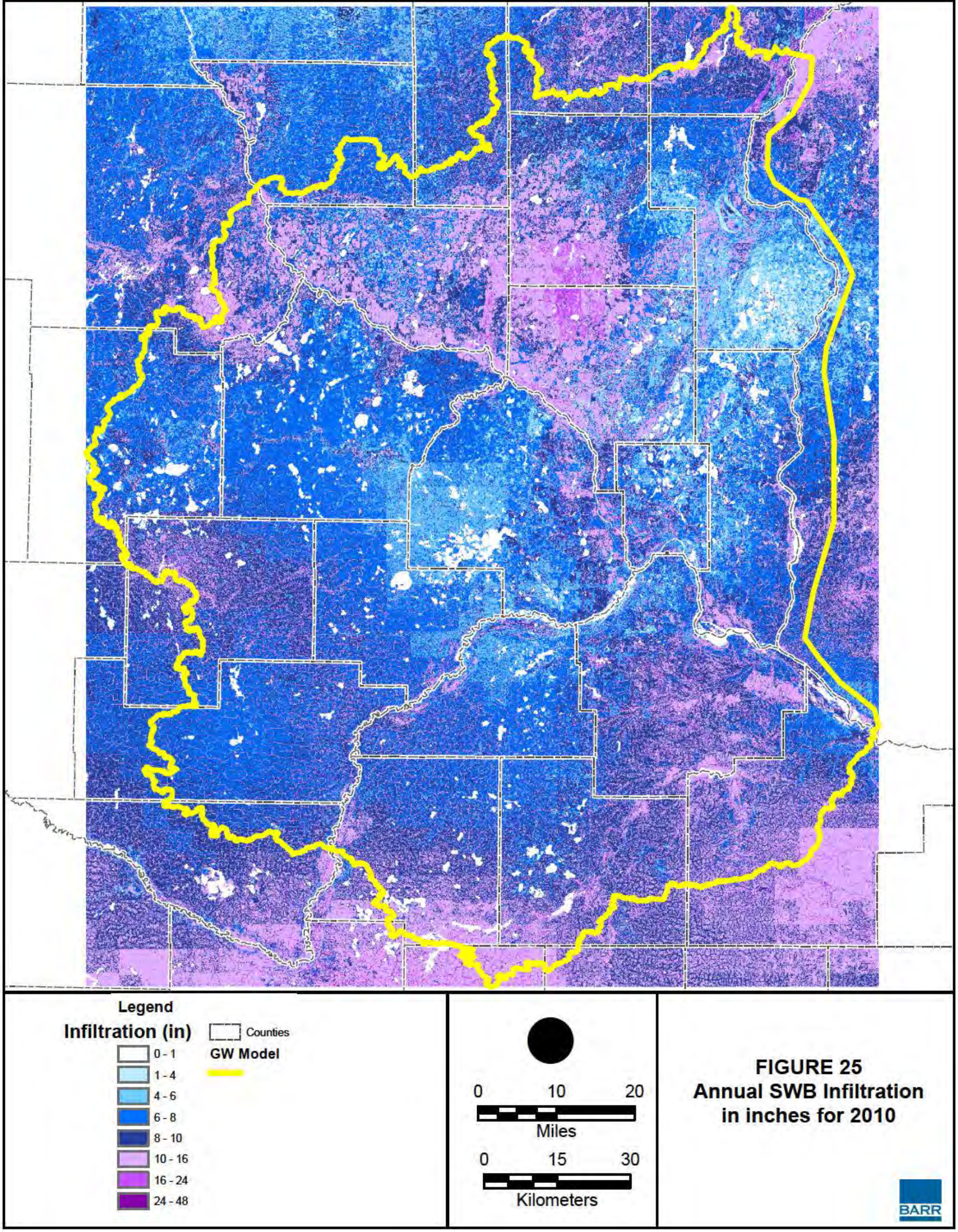


FIGURE 25
Annual SWB Infiltration in inches for 2010

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

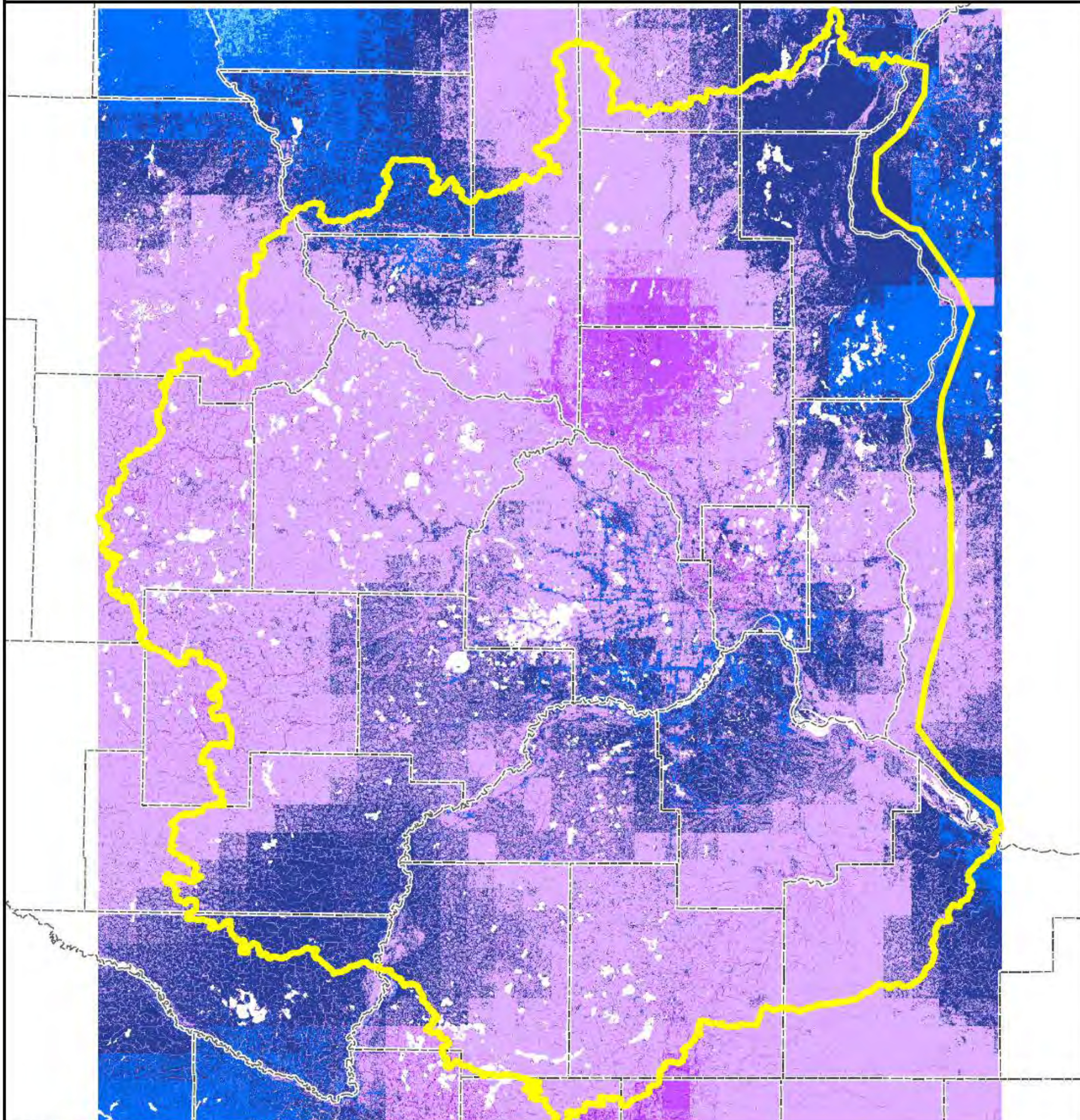


FIGURE 26
Annual SWB Infiltration in inches for 2011

BARR

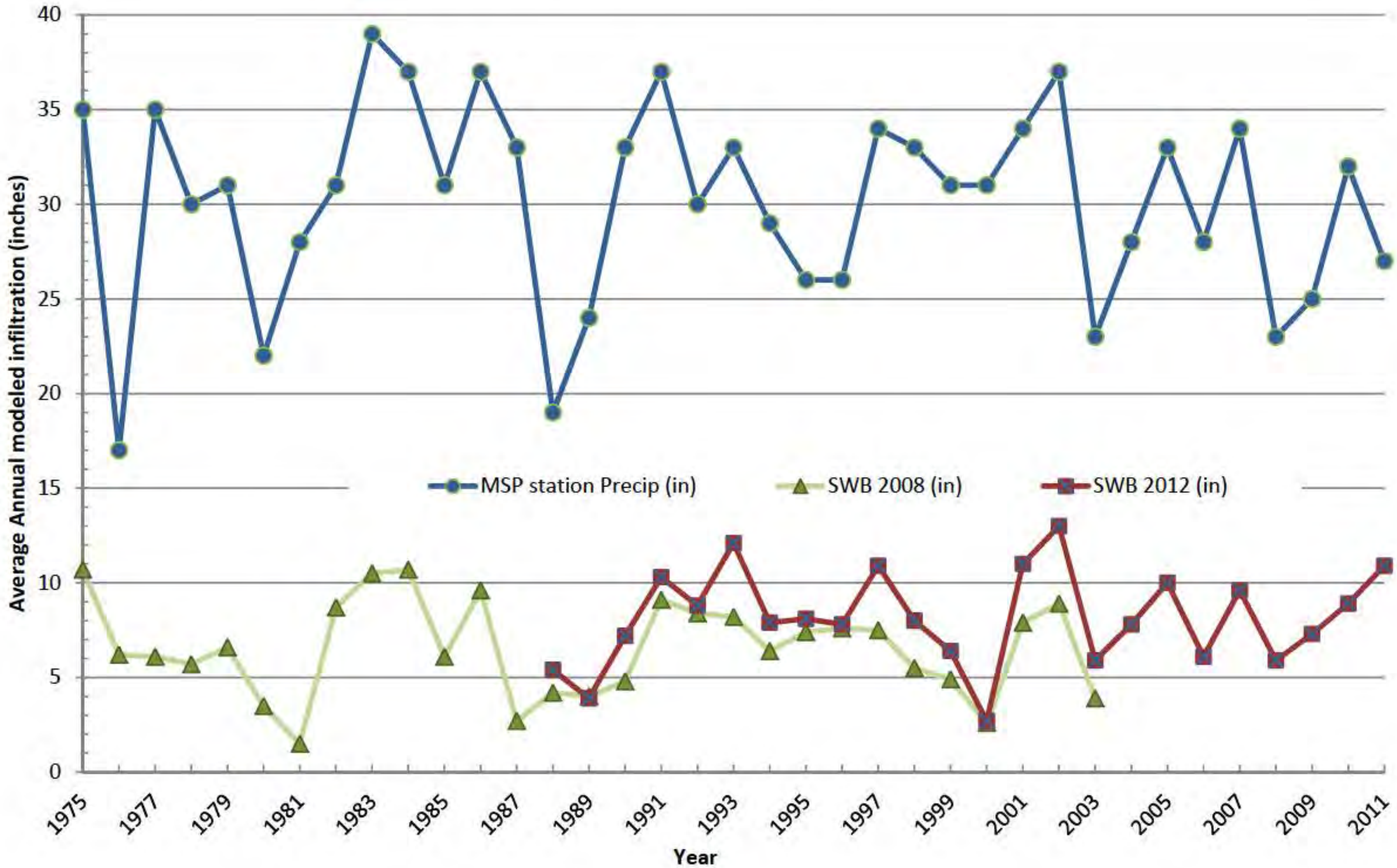
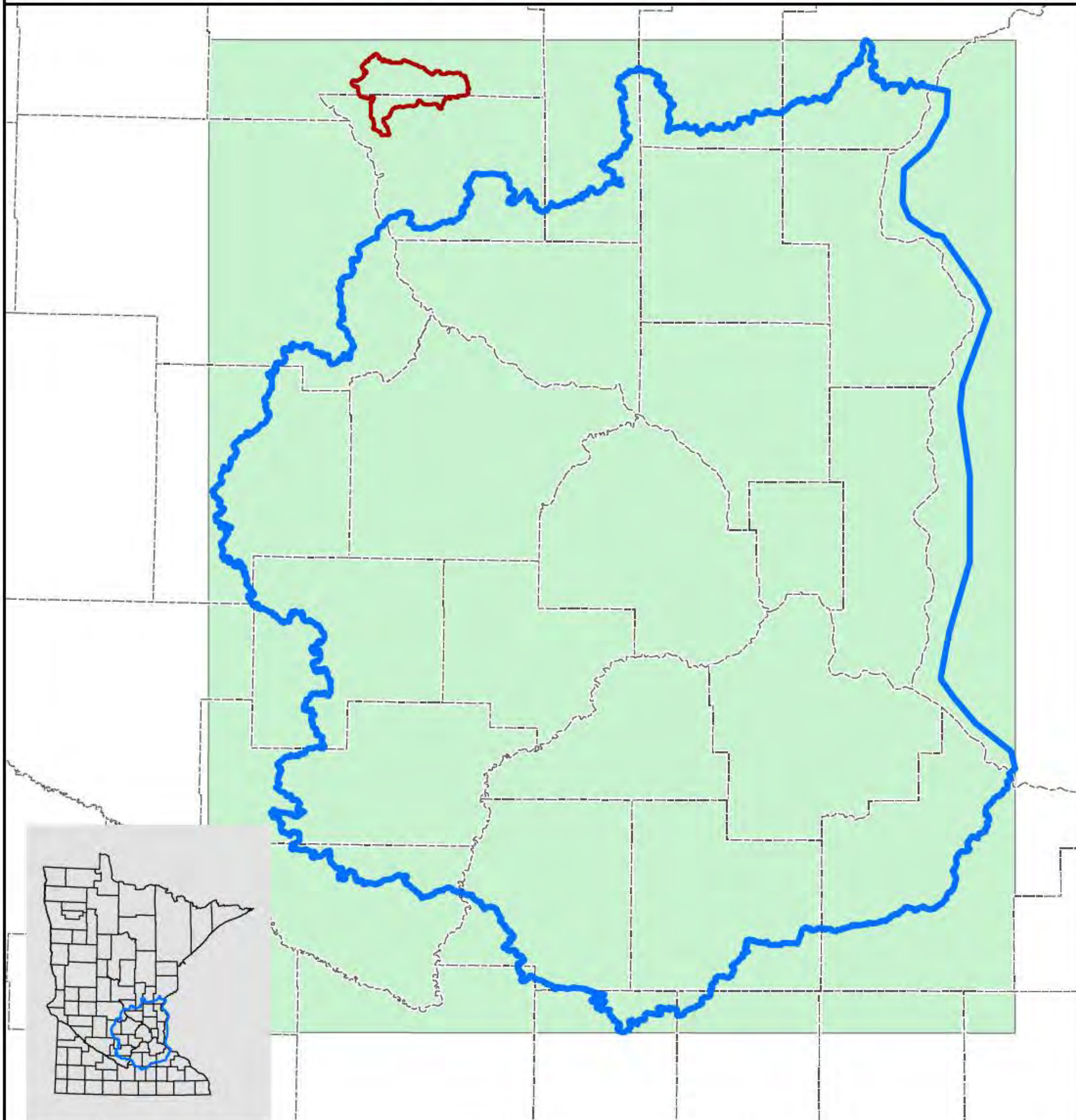


Figure 27

Comparison of 2008 SWB Result
to the 2012 Result

Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3



Legend

- Groundwater Model Domain
- Little Rock Creek Watershed
- Counties
- SWB Domain

0 10 20
Miles
0 15 30
Kilometers

FIGURE 28
Location of the Little Rock Creek SWAT Study

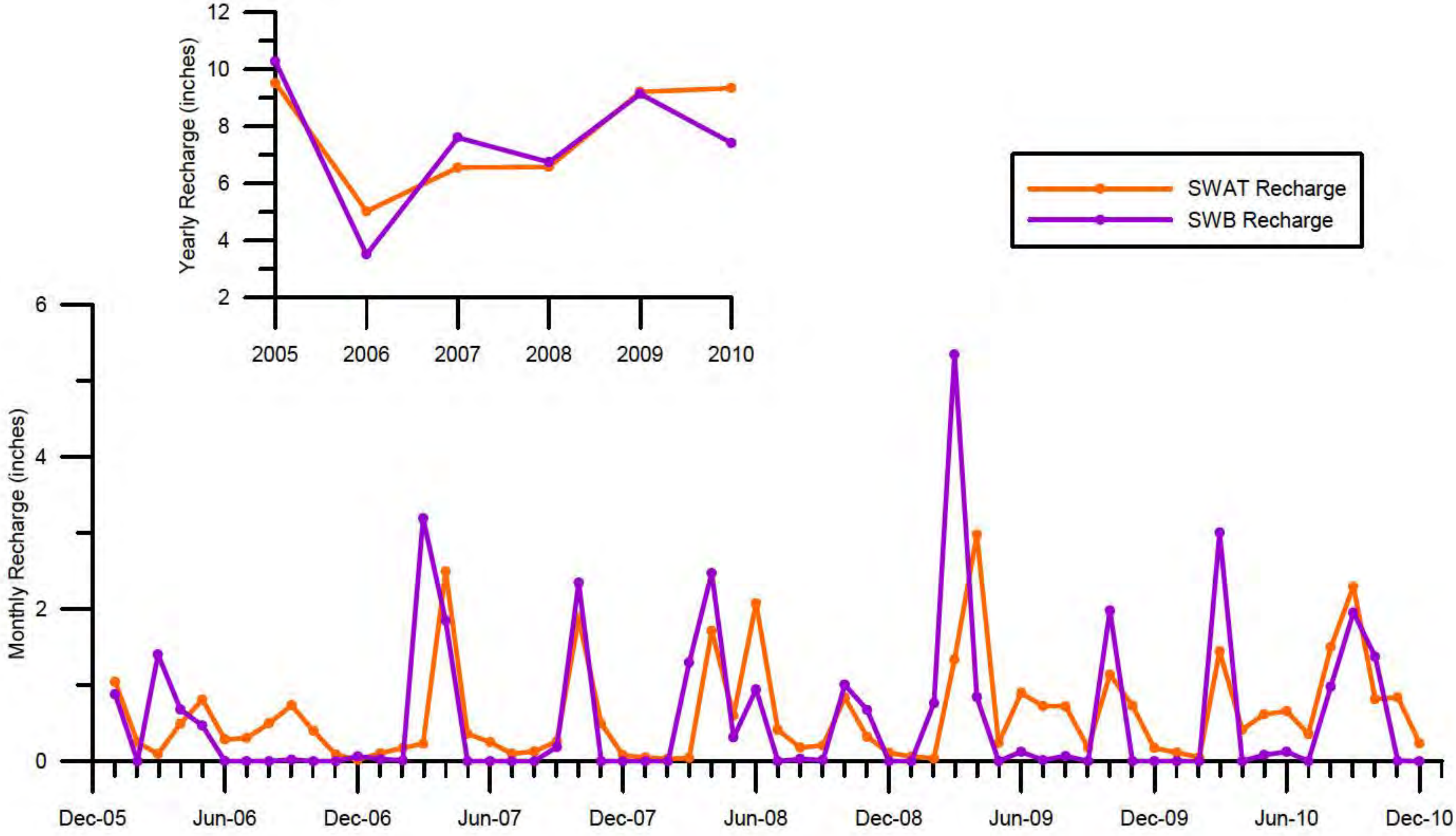


Figure 29

Comparison of SWB derived recharge
to SWAT derived recharge
Little Rock Creek Watershed

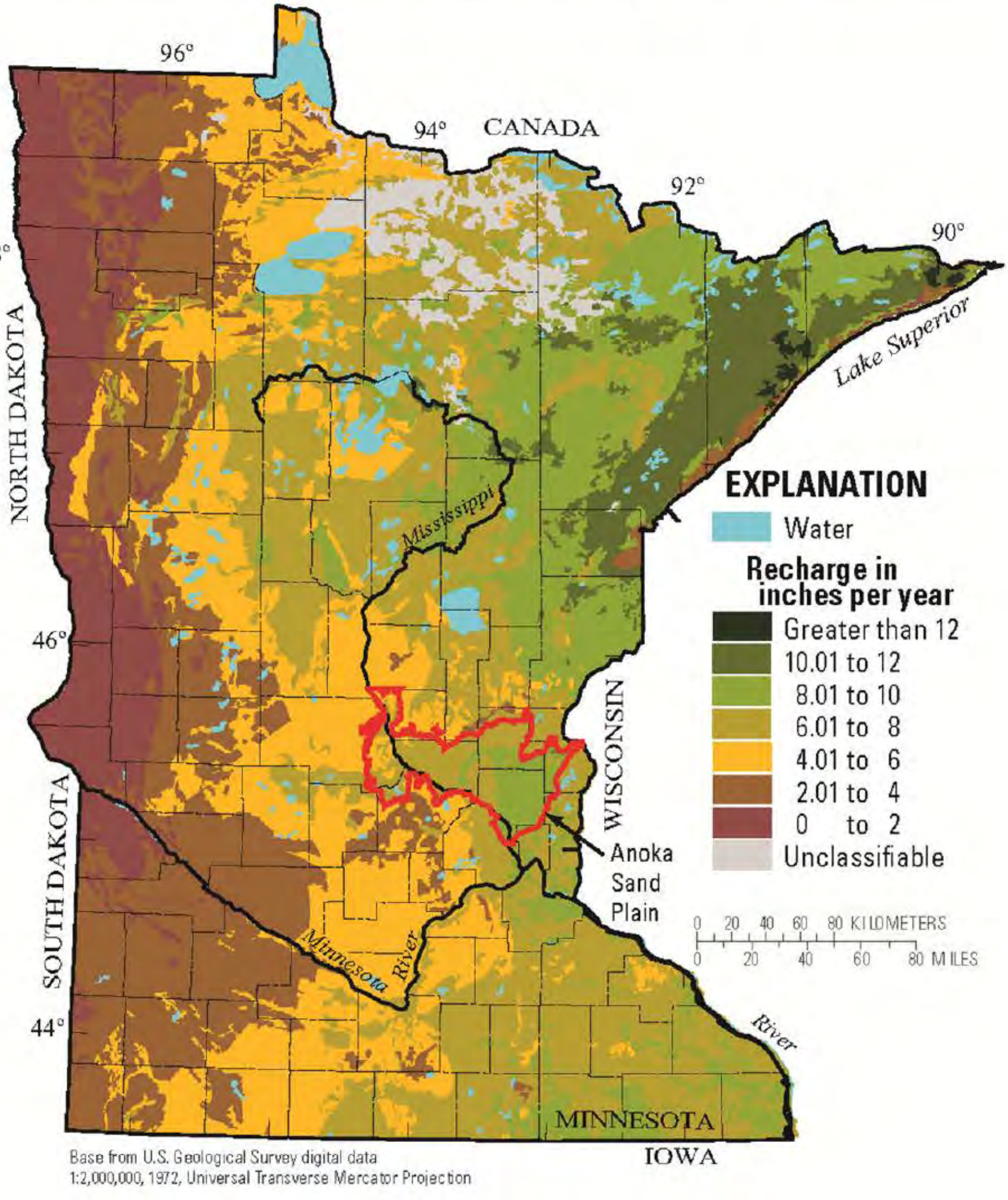


FIGURE 30

Average annual recharge rate to surficial materials in Minnesota (1971–2000) estimated on the basis on the regional regression recharge method (modified from Lorenz and Delin, 2007).

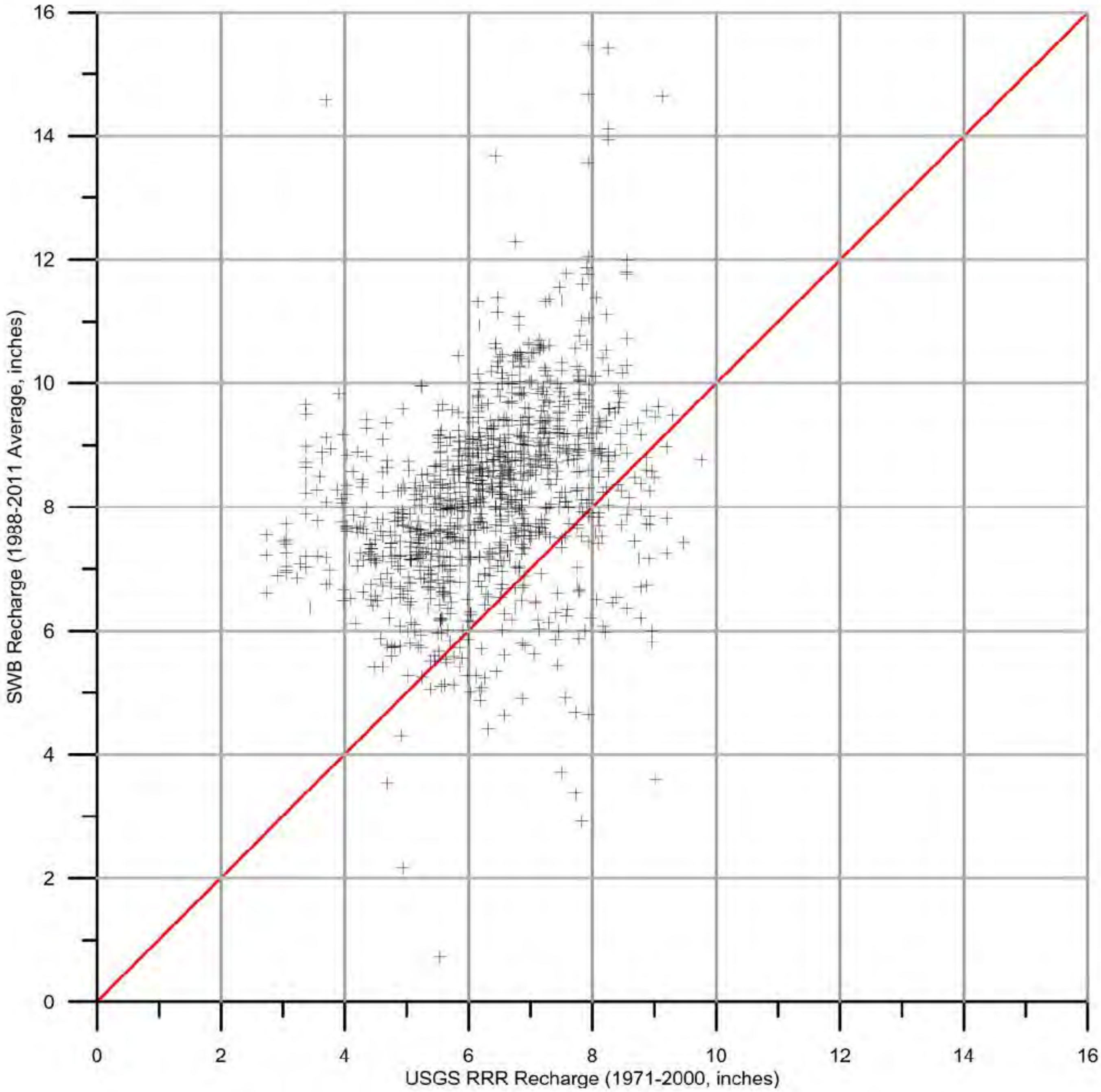


FIGURE 31

Comparison of the SWB results to the
RRR method on a grid of 1108 point values.

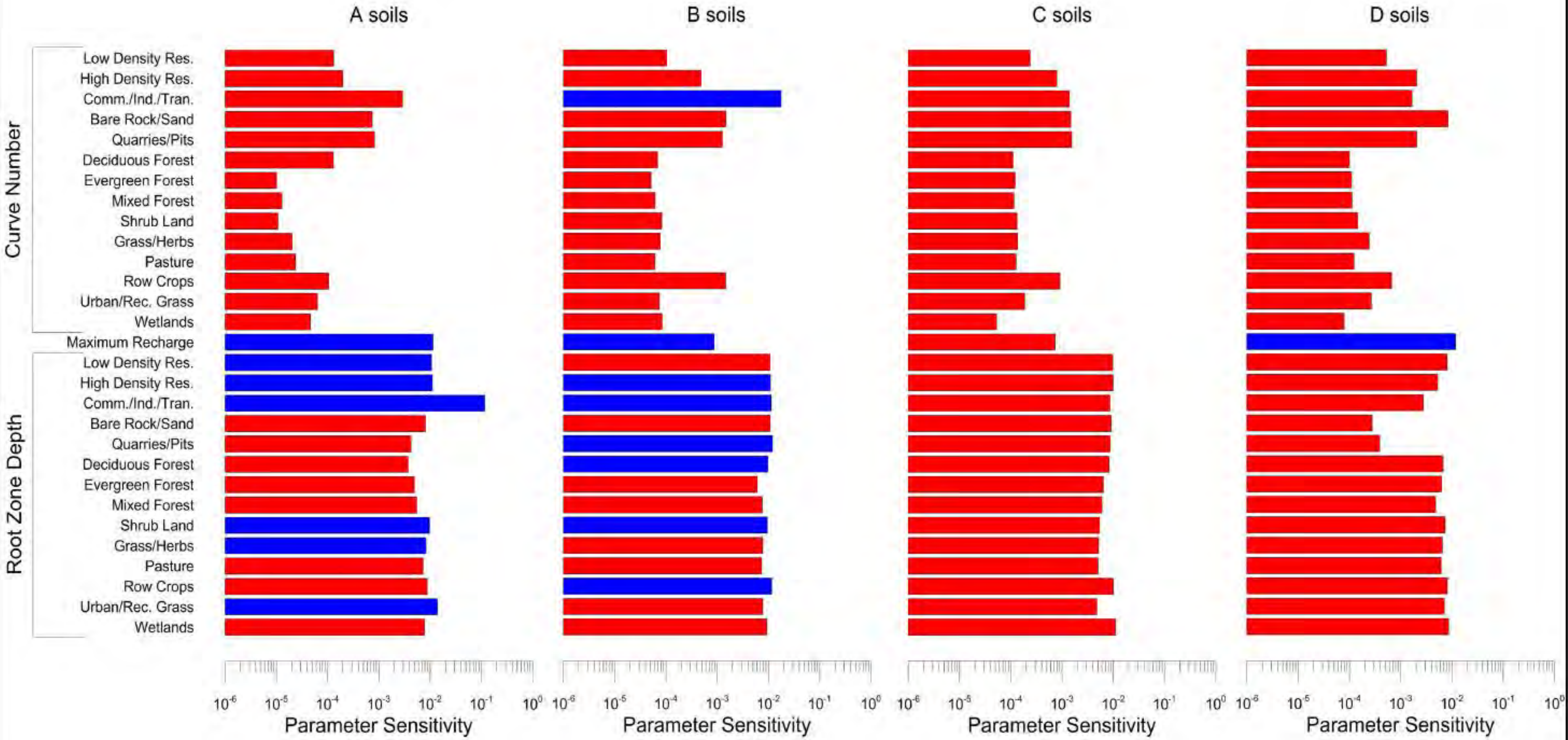


Figure 32

Composite SWB Parameter Sensitivities for SWB Mean Annual and Monthly Infiltration (for 2001 by combined land use and soil type). Blue bars represent parameters that were varied for the uncertainty analysis.

Using the Soil Water Balance Model (SWB) to Estimate Recharge
for the Twin Cities Metropolitan Area Groundwater Model Version 3

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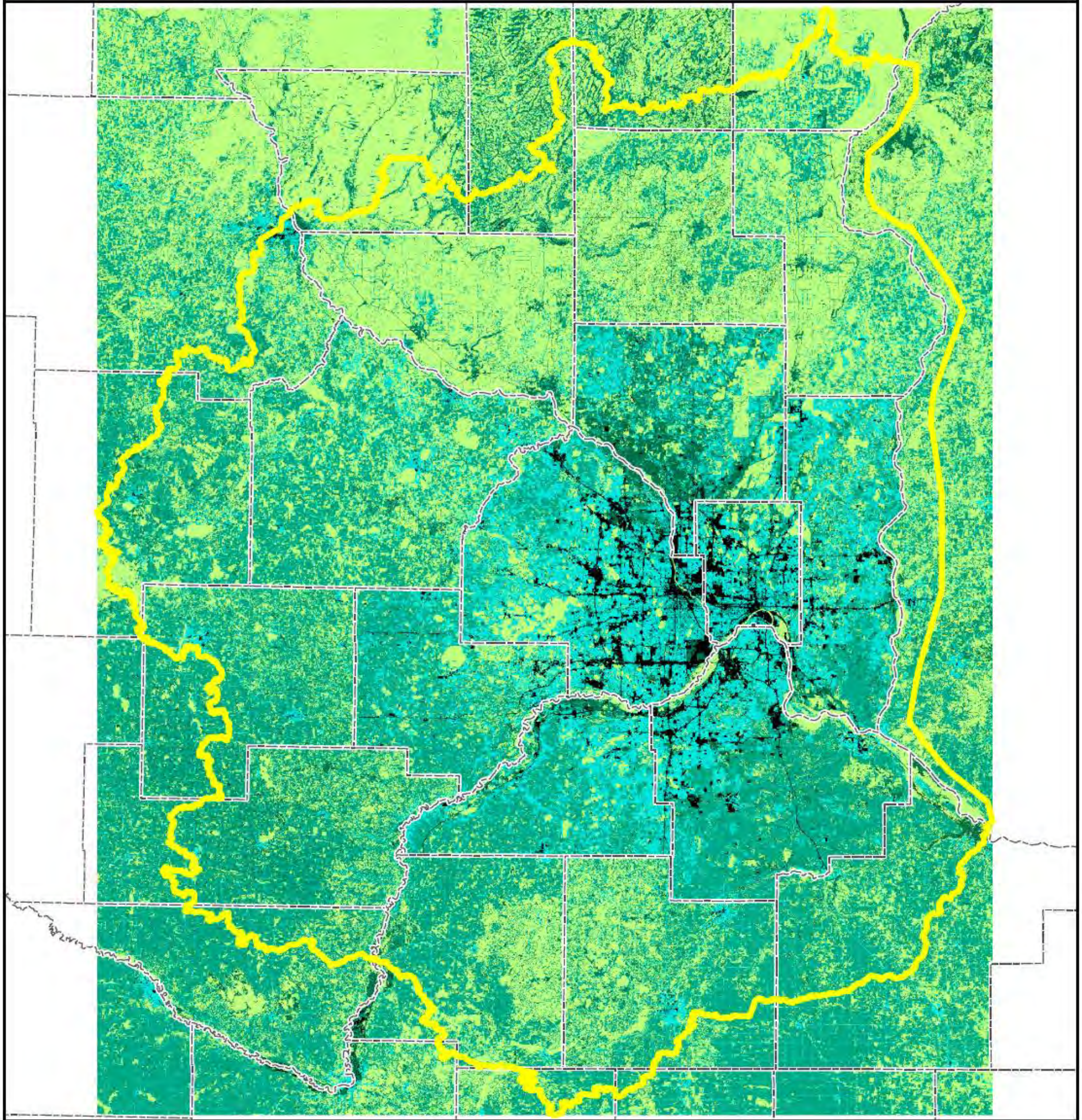

Legend

Variation (inches)

- 0 - 1
- 1 - 3
- 3 - 6
- 6 - 12
- 12 +

Counties

GW Model

0 10 20
Miles

0 15 30
Kilometers

FIGURE 33
Estimated SWB Model Infiltration Estimate Uncertainty in Inches

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Using the Soil Water Balance Model (SWB) to Estimate Recharge for the Twin Cities Metropolitan Area Groundwater Model Version 3

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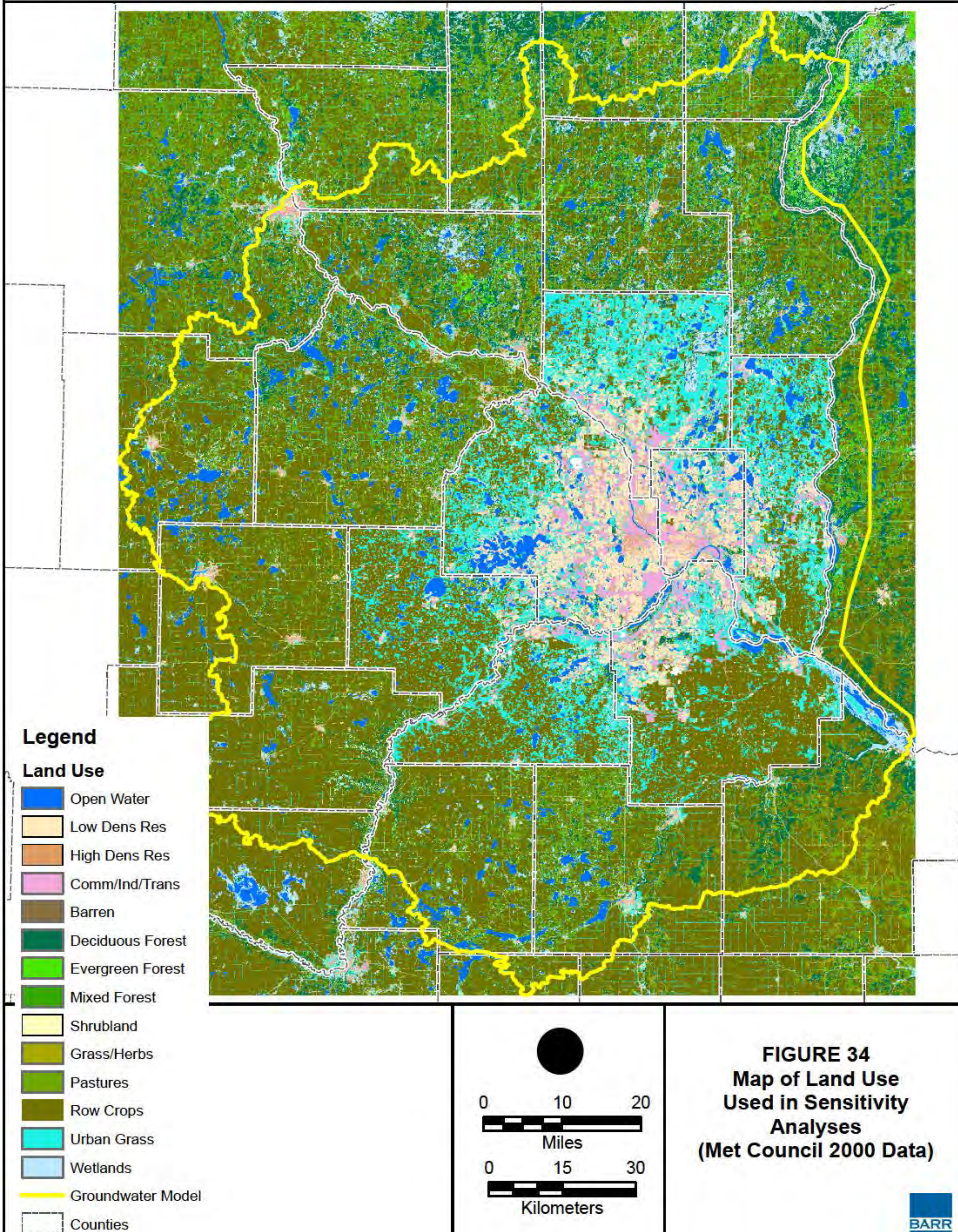

FIGURE 34
Map of Land Use Used in Sensitivity Analyses (Met Council 2000 Data)

BARR

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