Appendix G

Soil Water Balance (SWB) Model

1.0 Soil Water Balance (SWB) Recharge Model

Recharge estimates established for the Twin Cities Metropolitan Area Regional Groundwater Flow Model 2 (Metro Model 2; Metropolitan Council, 2008) using the SWB recharge model were applied in this study. The following is a description of the SWB model as used in development of the Metro Model 2.

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) precipitation and temperature; 2) land use classification; 3) hydrologic soil group; 4) flow direction; and 5) soil water capacity. The data and formats required are designed to take advantage of widely available geographic information systems (GIS) datasets and file structures. Recharge 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. Recharge is calculated 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), and Steenhuis and van der Molen (1986).

1.1 SWB Model Input

The SWB model requires the user to provide tabular climatological data including:

1. daily precipitation (in inches),
2. daily average air temperature (in °F),
3. daily maximum air temperature (in °F), and
4. daily minimum air temperature (in °F).

The climate data used for the Metro Model 2 – SWB model runs came from a single station located near the center of the model domain with a daily record.

The model also requires four grid data sets:

1. land use / land cover,

2. hydrologic soil group,
3. available soil water capacity and,
4. surface flow direction.

The above land data were complied and entered into the SWB model using 30 meter x 30 meter grids interpolated from available GIS data.

Finally, a lookup table must be supplied in order to assign runoff curve numbers, interception values, rooting depths, and maximum daily recharge values to each combination of soil hydrologic group and land cover type.

Details on the SWB model input and options used for the Metro Model 2 groundwater model calculations are detailed below.

1.1.1 Climatological Input

For the Metro Model 2-SWB model runs, precipitation data was input on a daily basis from a single gage. Data used was obtained from the US National Weather Service for the Downtown St. Paul Holman Field Airport station located in the central portion of the modeled groundwater domain. The data included the required information on a daily basis for the period January 1, 1975 – December 31, 2003.

1.1.2 Land Use Land Cover Input

The SWB code takes runoff curve and interception values from a land cover lookup table. For the Metro Model 2 case, GIS data of land cover from the United States Geological Survey (USGS) were used and categorized to correspond to available hydrologic data. Table G-1 presents the mapped USGS categories with the corresponding land cover categories used for this model.

The land cover categories are then coupled with the hydrologic characteristics needed by the SWB model to calculate the water balance for each grid cell. These categories and their respective properties are presented in Table G-2.

Outflow (or surface runoff) from a cell in the SWB code is calculated using a Soil Conservation Service (SCS) curve-number rainfall-runoff relationship (USDA, 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)

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 is treated simply using a "bucket" model approach—a user specified amount of rainfall in inches is assumed to be trapped and used by vegetation and evaporated or transpired from plant surfaces. Daily precipitation values must exceed the specified interception amount before any water is assumed to reach the soil surface. Interception values are specified for each land use type.

1.1.3 Soil Hydrologic Group

The model uses the 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 was interpolated to 30 meter x 30 meter grid cells for the entire area.

The soil data used in this model was obtained from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) where available. This included the counties of Stearns, Sherburne, Mille Lacs, Chisago, Polk (WI), Wright, Anoka, Washington, St Croix (WI), Carver, Hennepin, Ramsey, Pierce (WI), Sibley, Nicollet, Le Sueur, Scott, Dakota, Rice and Goodhue. For non-open water areas in Minnesota where hydrologic soil group data were not provided in the SSURGO data (e.g. urban areas), the Minnesota State Soil Atlas data were used to define the hydrologic soil group (Department of Soil, Water and Climate, University of Minnesota, and Land Management Information Center, 1975).

A mosaic was made from the SSURGO grid and the State Soil Atlas grid (with cell priority given to the SSURGO values) to fill in "no data" values in the SSURGO grid. SSURGO data for Wisconsin had significant gaps. For these areas, soil data digitized from 1:250,000-scale compilation sheets of a 1968 soils map of Wisconsin was used (WI DNR, USGS, WI Geological & Natural History Survey and University of Wisconsin, 1987). This data used a soil classification similar to the A-B-C-D model, but did not visually pair well with the previous grids produced. These data were further simplified into just 2 classes combining A with B, and C with D.

The SWB model will not accept “no data” values and after a mosaic was made from all the grids areas still existed with “no data”. Most of these areas appeared to occur where open water exists in which case the SWB does not calculate a water balance. To accommodate the program, all remaining “no data” values were converted to B type, the most common soil type in the domain.

1.1.4 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 recharge.

For this model we used a direct conversion from soil group to available water capacity. The input grid was created by converting the soil hydrologic group grid created from GIS soil mapping described above. The available water capacities were translated directly from the A-B-C-D mapping so that A soils = 1.2, B soils =2, C soils =2.8 and D soils =3.6, all in inches per foot.

1.1.5 Surface Flow Direction

The SWB model requires a digital elevation model (DEM) to route surface water flows. Based on the DEM when a cell produces runoff or outflow, it becomes inflow to the downslope cell. If capacity for recharge 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.

1.1.6 Other SWB Options

The SWB code can use any one of five commonly-applied methods to estimate potential evapotranspiration (ET) 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 ET and does not consider land cover. It is generally acknowledged as one of the better of many methods, especially when limited data is available.

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 recharge. This results in cases where maximum recharge 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. A maximum recharge per day was specified to minimize this error.

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).

1.1.7 SWB Model Limitations and Assumptions

The original concept behind the SWB code was to allow for the spatial distribution of groundwater recharge 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 would be 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 soil water balance 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 models incorporated in it, the application of the SWB to site specific cases would provide at best an imprecise result lacking any true site specific characteristics. Much of this local imprecision is derived from 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 list of perceived flaws associated with the curve number method include (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, and
- 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).

The recharge 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 recharge 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 generates recharge, and the time when that recharge actually reaches the water table.

In areas with wetlands, springs, lakes, or other landscape features where the groundwater table is close to the land surface, the SWB code can be expected to perform poorly as there is currently no provision for recharge rejection via saturation excess, other than by specifying a maximum recharge rate for a particular land use and soil type combination. In most areas covered by the Metro Model 2, the depth to groundwater is deep enough to make this problem negligible.

The SWB model results are very sensitive to the soil hydrologic properties. The accuracy of the model results will depend heavily on the quality of the mapped soil properties used as input. For this project, the lack of uniform data over the relatively large domain modeled, required patching together data from several sources. The apparent lack of uniformity in soil mapping methodology between certain areas (see discussion above) probably introduces some error in the result. From this standpoint, the SWB model is probably most accurate when the soil data for the domain comes from a single reliable source.

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

1.1.8 Overview of Model Results

The (SWB) computer code was used to calculate spatial and temporal variations in groundwater recharge for the seven county Minneapolis – St. Paul metropolitan area in Minnesota. The climate data used came from a single station located near the center of the model domain with a daily record. The gridded data were complied and modeled on 30 meter x 30 meter grids interpolated based on available GIS mapping. The model was run using the climate data for the period January 1, 1975 – December 31, 2003.

For the modeled period the averaged annual recharge from the SWB model was 6.4 inches per year. The maximum annual result was for 1984 in the amount of 10.7 inches, while the minimum occurred for 1981 at the amount of 1.5 inches. These annual recharge values generally compare well with calculations done using other techniques (USGS, 2002). Table G-3 presents the annual recharge results for 1974-2003.

2.0 References

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Table G-1

USGS land cover categories with corresponding categories used for SWB model

USGS NLCD 2001 Values		SWB Model Input Values	
NLCD ID	*Description*	*SWB ID*	*Description*
11	Open Water	5	Open Water
21	Developed Open Space	13	Golf Course
22	Developed Low Intensity	12	Low Intensity
23	Developed Medium Intensity	11	High Intensity
24	Developed High Intensity	11	High Intensity
31	Barren Land (Rock/Sand/Clay)	7	Barren
41	Deciduous Forest	4	Forest
42	Evergreen Forest	4	Forest
43	Mixed Forest	4	Forest
52	Shrub/Scrub	8	Shrubland
71	Grassland/Herbaceous	3	Grassland
81	Pasture/Hay	3	Grassland
82	Cultivated Crops	2	Agriculture
90	Woody Wetlands	6	Wetland
95	Emergent Herbaceous Wetlands	6	Wetland

Table G-2

SWB model land cover categories with corresponding runoff and interception properties

ID	Description	SCS Curve Numbers by soil type[1] (1/in)				Maximum Recharge by soil type (in/day)				Interception [2] (in)	Root Zone Depth (ft)				Reference (Curve Numbers)	Reference (Root Depth)
		A	B	C	D	A	B	C	D		1	2	3	4		
11	High Intensity	89	92	94	95	2	0.6	0.6	0.3	0.09	1.67	1.67	1.67	2.08	USDA, 1986	Thornthwaite and Mather, 1957; table 10, shallow-rooted crops
12	Low Intensity	61	75	83	87	2	0.6	0.6	0.3	0.09	1.67	1.67	1.67	2.08	USDA, 1986	Thornthwaite and Mather, 1957; table 10, shallow-rooted crops
13	Park (or Golf)	39	61	74	80	2	0.6	0.6	0.3	0.09	3.33	3.33	3.33	4.17	USDA, 1986	Thornthwaite and Mather, 1957; table 10, deep-rooted crops
2	Agriculture	65	75	82	86	2	0.6	0.6	0.3	0.09	0.84	2.5	3.33	3.33	USDA, 2004	Thornthwaite and Mather, 1957; table 10, deep and shallow-rooted crops
3	Grassland	49	69	79	84	2	0.6	0.6	0.3	0.09	3.33	3.33	3.33	4.17	USDA, 2004	Thornthwaite and Mather, 1957; table 10, deep-rooted crops
4	Forest	30	55	70	77	2	0.6	0.6	0.3	0.1	6	5.4	4.86	4.37	USDA, 1986	Thornthwaite and Mather, 1957; table 10, closed mature forest
5	Open Water	100	100	100	100	2	0.6	0.6	0.3	0.09	0	0	0	0	Dripps, 2001	
6	Wetland	30	58	71	78	2	0.6	0.6	0.3	0	1.67	1.67	1.67	2.08	Dripps, 2001	Thornthwaite and Mather, 1957; table 10, shallow-rooted crops
7	Barren	74	83	88	90	2	0.6	0.6	0.3	0	0.5	0.5	0.5	0.5	USDA, 2004	Assumed value
8	Shrubland	35	56	70	77	2	0.6	0.6	0.3	0.09	3.9	5	5.55	5	USDA, 2004	Thornthwaite and Mather, 1957; table 10, orchard
9	Cloud Cover	39	61	74	80	2	0.6	0.6	0.3	0.09	3.33	3.33	3.33	4.17	Assumed Value	Assumed Value

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

[2] Interception given for growing season, values for non-growing season assumed to be zero.

Table G-3

SWB Model average reacharge values over Twin Cities Metropolitan Area 1975-2003

Year	Average recharge for full domain (in)
1975*	10.7*
1976	6.2
1977	6.1
1978	5.7
1979	6.6
1980	3.5
1981	1.5
1982	8.7
1983	10.5
1984	10.7
1985	6.1
1986	9.6
1987	2.7
1988	4.2
1989	4
1990	4.8
1991	9.1
1992	8.4
1993	8.2
1994	6.4
1995	7.4
1996	7.6
1997	7.5
1998	5.5
1999	4.9
2000	2.6
2001	7.9
2002	8.9
2003	3.9

* Assumed initial conditions result in recharge values that are artificially high for year 1 of simulation.

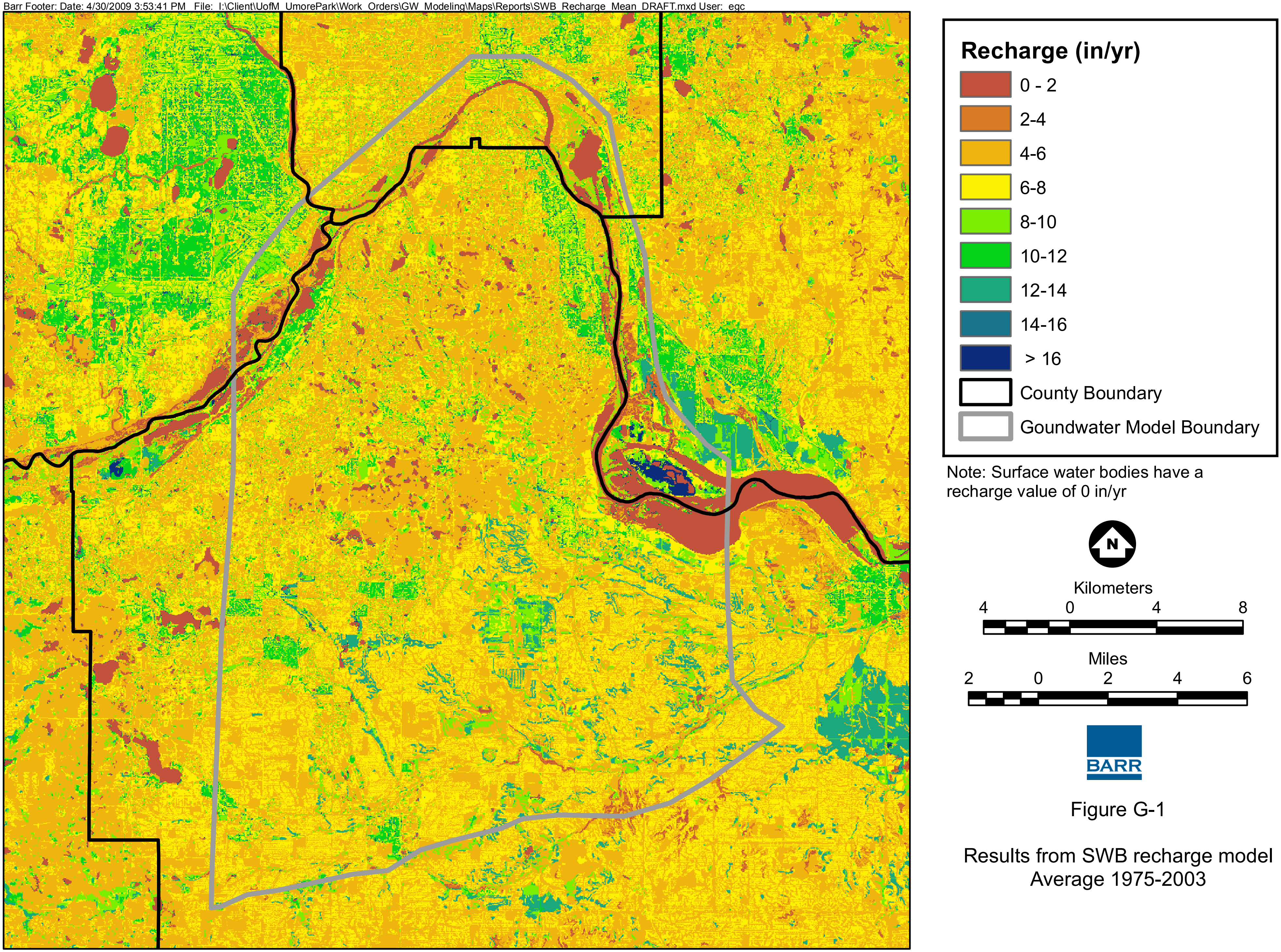

Figure G-1

Results from SWB recharge model
Average 1975-2003