2014 Project Abstract
For the Period Ending June 30, 2017

PROJECT TITLE: Watershed Water Budgets for Managing Minnesota's Groundwater
PROJECT MANAGER: Erik A. Smith
AFFILIATION: U.S. Geological Survey
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FUNDING SOURCE: Environment and Natural Resources Trust Fund)
LEGAL CITATION: M.L. 2014, Chp. 226, Sec. 2, Subd. 03i

APPROPRIATION AMOUNT: $ 129,000.00
AMOUNT SPENT: $ 129,000.00
AMOUNT REMAINING: $ 0.00

Overall Project Outcomes and Results

A new visual mapping technique that illustrates the relative and cumulative streamflow contributions from across a large watershed was developed for two pilot areas in Minnesota: Cannon River and St. Louis River. Both areas were selected because of mining-related activities. For the Cannon River, for the surficial sand mining, and for the St. Louis River, for the ongoing iron ore mining of the Mesabi Iron Range. Each large watershed (Cannon, St. Louis) was sub-divided into a series of much smaller sub-watersheds (Cannon: 153; St. Louis: 353). For each sub-watershed, the estimated groundwater (as baseflow) and surface runoff fluxes flowing into all surface-water features was summed under different typical conditions, such as drought or flood conditions. Downstream sub-watersheds aggregate upstream surface-water flows in addition to baseflow and surface runoff directly from the sub-watershed. These maps, termed as streamflow distribution maps, can help illustrate sub-watersheds that are vulnerable due to either groundwater or surface-water appropriations, particularly under drought conditions.

For each pilot watershed, a series of the streamflow distribution maps were developed at selected flow regimes: extreme drought conditions, drought conditions, an average condition, and a flood condition. Each pilot watershed is displayed as a single map sheet with the four flow regimes as separate panels for ease of comparison. The selected streamflow distribution maps illustrate streamflow contributions from different parts of the watershed for typical conditions, not necessarily the contribution for any particular time. These maps will provide a tool for State cooperators, such as the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency, for proactive water management and water-use sustainability. Furthermore, by highlighting the sub-watersheds in terms of surface-water flows, the streamflows can be evaluated in the context of meeting specific ecological flows under different flow regimes and potentially assist with decisions regarding groundwater and surface-water appropriations.

Project Results Use and Dissemination

The new visual mapping technique will be summarized in a U.S. Geological Survey Scientific Investigations Map (SIM). The SIM series includes map sheets and an accompanying report to discuss the methodology for creating the map products. In the case of this study, the SIM will include the following: (1) separate map sheets for each watershed (Cannon River, St. Louis River) that includes four panels of selected flow regimes: extreme drought, drought, mean flow, and flood; (2) the accompanying report with included tables and figures that support the map construction; (3) three separate model archives related to the mapping work. The web locations for the Scientific

Investigations Map and model archives will be included with the final report, expected to be completed by November 2017. With this final workplan update/progress report, a complete draft of the SIM and the accompanying map sheets has been included. By the requirement of U.S. Geological Survey guidelines, all materials used in the construction of these maps will be made available through public webpage (https://www.usgs.gov/) upon release of the final SIM report.

The U.S. Geological Survey also organized two phone calls during the project timeline to interface with key partners from the Minnesota Department of Natural Resources (MNDNR) and the Minnesota Pollution Control Agency (MPCA). These meetings were meant to ensure that the mapping products produced from the project would meet their needs, and the USGS project team did adapt some of the final products to make the maps more useful. Keen interest was shown in the final products, and upon release of the final Scientific Investigations Map, the lead project managers (Erik Smith and Chris Sanocki) will be meeting again with key MNDNR and MPCA to develop next steps for other watersheds in the State.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2014 Work Plan

Date of Report: August 11, 2017

Date of Next Status Update Report: N/A

Date of Work Plan Approval: June 4, 2014

Project Completion Date: June 30, 2017

Does this submission include an amendment request? No

PROJECT TITLE: Watershed Water Budgets for Managing Minnesota's Groundwater

Project Manager: Erik Smith

Organization: U.S. Geological Survey

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City/State/Zip Code: Mounds View, MN 55112

Telephone Number: (612) 419-4777

Email Address: easmith@usgs.gov

Web Address: http://mn.water.usgs.gov/index.html

Location: St. Louis and Goodhue, Rice, and Steele with some additional small areas in neighboring counties.

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$129,000.00**
	Amount Spent:	**$129,000.00**
	Balance:	**$ 0.00**

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 03i

Appropriation Language:
$129,000 the second year is from the trust fund to the commissioner of natural resources for an agreement with the United States Geological Survey to create a pilot study to calculate complete watershed water budgets for two counties in Minnesota for enhanced groundwater management. This appropriation is available until June 30, 2017, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Watershed Water Budgets for Managing Minnesota's Water

II. PROJECT STATEMENT:

Responsible groundwater management requires knowledge the water budget. The water budget is the quantity of water that is flowing through the hydrologic system as well as the amount of groundwater in aquifers (storage). We often have a good idea of groundwater storage (from a county atlas, for example); we have good knowledge of surface-water flow (from USGS and DNR streamflow gages); but we seldom know groundwater flow. This project will tie together those pieces of information.

Problem: The surficial aquifer system is intimately tied to surface-water flow and to flow to and from deeper, buried aquifers. The connection among those systems is poorly understood across much of Minnesota. The lack of understanding of those connections hinders the state's efforts to define the sustainability of water use from surficial aquifers as well as streams and rivers through the state.

Benefits: The water budget information obtained from this study will assist the state in planning for long-term water-use sustainability. The proposed study will provide the Minnesota Department of Natural Resources with information necessary to protect wetlands and ensure streamflows for ecological needs. It should also provide information to the Minnesota Pollution Control Agency information necessary to better understand the interaction between surface- and groundwater.

Scope and Objective: The objective of the proposed pilot study is to calculate the water budgets, including the groundwater flow component, for selected watersheds in St. Louis and Goodhue counties. The goal of the proposed project is to provide information for proactive water management in two areas undergoing mining exploration.

Water budgets would be computed primarily using soil-water-balance (SWB). A current USGS project that uses SWB calculates only recharge for the state; the proposed project would extend those computations to include calibrated evapotranspiration and runoff, giving the water balance. Other data inputs into the watershed water budgets would include data from the USGS synthetic hydrograph project to help understand and map general flowpaths from surficial aquifers to streams.

III. PROJECT STATUS UPDATES:

Project Status as of 12/31/2014:

A detailed project work plan and budget were prepared and approved by the LCCMR. A corresponding technical project proposal was prepared, reviewed and approved by the USGS. A Joint Funding Agreement was prepared for review by the USGS headquarters and by the Minnesota Department of Natural Resources. That agreement was not signed until November 4, 2014. Off-budget time was spent planning this project.

For Activity 2, the GIS and climatological data from the statewide SWB study were extracted and down-scaled for the St. Louis and Cannon River basins.

For Activity 3, water-use data from 2000-2012 were compiled for the St. Louis and Cannon River basins.

Project Status as of 06/30/2015:

For Activity 1, progress does include identifying the characteristics that explain spatial distribution have been identified, but not yet applied specifically to the entire basins. The spatial distribution for groundwater discharge has been computed as a pilot for one tributary in the Cannon River basin.

For Activity 2, all of the remaining input files (in particular the flow direction grid) were compiled for the greater Cannon River SWB model. The SWB calibration began for the Cannon River watershed. As part of the greater Cannon River SWB model, the following calibration targets have been included: USGS 05355200 (Cannon River at Welch, MN) and USGS 05353800 (Straight River near Faribault, MN). Hydrograph separation will be used on all of these records, and the SWB calibration targets will include the baseflow-separated component as well as total flow.

No progress on Activity 3 was made during this reporting period. None was scheduled.

Project Status as of 12/31/2015:

For Activity 1, progress included identifying the characteristics that explain spatial distribution of the flow-duration curves, for both the St. Louis and Cannon River basins. Furthermore, the flow-duration curves were calculated for both basins for each of the DNR sub-watersheds.

For Activity 2, minor progress was made for further calibration of the Cannon River watershed SWB model, but this work is still not completed.

For Activity 3, water-use data from 2000-2012 were compiled for the St. Louis and Cannon River basins.

Amendment Request (12/14/2015)

This amendment request is to change the project manager from Dave Lorenz to Erik Smith, due to Dave Lorenz's retirement from the U.S. Geological Survey in January 2016. Also, on the Work Plan Budget, the name was changed over to Erik Smith and the specific names were crossed out. The roles remain the same, but due to retirements and staff leaving, some of the specific people have changed.

Project Status as of 06/30/2016**:**

For Activity 1, additional low flow frequency statistics were calculated using the regional regression models developed by USGS. All the flow statistics have now been calculated for all watersheds and sub-watersheds.

For Activity 2, preliminary SWB model results were analyzed to identify portions of the watersheds where the initial "flow correction" of the digital elevation models (DEMs) was inadequate. Additional adjustments, corrections, to the DEMs have been made and model calibrations are in progress. Further adjustment of these input datasets may be necessary pending subsequent calibration results.

No progress was made on Activity 3 this period, once calibration of the SWB models is deemed as acceptable this task will begin.

Amendment Request (06/29/2016)

This amendment request is to change the project manager from Erik Smith to Jason Roth, due to Erik Smith's promotion to a supervisory role at MNWSC. Also, on the Work Plan Budget, the name was changed over to Jason Roth and the specific names were crossed out.

Project Status as of 12/31/2016:

For Activity 1, the low-flow statistics calculated for both watersheds have been integrated into ArcGIS maps in order to begin the merger of these results with the SWB results from Activity 2.

For Activity 2, soil-water-balance (SWB) model has been run and the refined recharge grid resolution for the Cannon River watershed has been finalized. At this time, the refined St. Louis River SWB recharge grid is in progress, with the refined grid resolution finalized in early January 2017.

No progress was made on Activity 3 this period. With the newly refined recharge grids available for both watersheds by early January 2017, this task will continue for the final months of the project including the final deliverables.

Amendment Request (12/30/2016)

This amendment request is to change the project manager from Jason Roth back to Erik Smith, due to Jason Roth's acceptance of a position outside of the U.S. Geological Survey. Also, as the new project manager, Erik Smith would like to request a no-cost extension of the project deadline to June 30, 2018. **LCCMR approval of the project manager change – 1-18-17. Request for extension withdrawn.**

Overall Project Status as of 08/11/2017**:**

A new visual mapping technique that illustrates the relative and cumulative streamflow contributions from across a large watershed was developed for two pilot areas in Minnesota: Cannon River and St. Louis River. Both areas were selected because of mining-related activities. For the Cannon River, for the surficial sand mining, and for the St. Louis River, for the ongoing iron ore mining of the Mesabi Iron Range. Each large watershed (Cannon, St. Louis) was sub-divided into a series of much smaller sub-watersheds (Cannon: 153; St. Louis: 353). For each sub-watershed, the estimated groundwater (as baseflow) and surface runoff fluxes flowing into all surface-water features was summed under different typical conditions, such as drought or flood conditions. Downstream sub-watersheds aggregate upstream surface-water flows in addition to baseflow and surface runoff directly from the sub-watershed. These maps, termed as streamflow distribution maps, can help illustrate sub-watersheds that are vulnerable due to either groundwater or surface-water appropriations, particularly under drought conditions.

For each pilot watershed, a series of the streamflow distribution maps were developed at selected flow regimes: extreme drought conditions, drought conditions, an average condition, and a flood condition. Each pilot watershed is displayed as a single map sheet with the four flow regimes as separate panels for ease of comparison. The selected streamflow distribution maps illustrate streamflow contributions from different parts of the watershed for typical conditions, not necessarily the contribution for any particular time. These maps will provide a tool for State cooperators, such as the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency, for proactive water management and water-use sustainability. Furthermore, by highlighting the sub-watersheds in terms of surface-water flows, the streamflows can be evaluated in the context of meeting specific ecological flows under different flow regimes and potentially assist with decisions regarding groundwater and surface-water appropriations.

Overall Project Outcomes and Results:

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Estimate groundwater contribution to streamflow
Description:
The groundwater contribution to streamflow throughout each area will be estimated from the relations among low streamflows, landscape characteristics, and climate identified in the synthetic hydrograph project. Multiple linear regressions will be used to fit selected points of the flow-duration curve to physical characteristics that can be mapped as part of the synthetic hydrograph project. The overall contribution will be computed from those regression analyses to construct a series that cover a range of base-flow conditions, corresponding to the points on the flow-duration curve.

The product will be a series of maps, and corresponding GIS data, that cover a range of base-flow conditions. The maps will represent the relative contribution from the surficial aquifer system to streamflow under various flow conditions. They will be similar to the specific yield map in Lorenz and Delin (2007) shown in figure 1 (section IX), but will cover only the area of the watershed and be relative contribution rather than the actual value of the variable.

Summary Budget Information for Activity 1: **ENRTF Budget: $ 33,500.00**
Amount Spent: $ 33,500.00
Balance: $ 0.00

Activity Completion Date: 06/30/2015

Outcome	**Completion Date**	**Budget**
1. Spatial distribution of the average amount of groundwater discharge to rivers.	06/30/2015	$28,500

2. Identify landscape characteristics that explain the spatial distribution of groundwater discharge to streams.	06/30/2015	$5,000

Activity Status as of 12/31/2014:
No activity during this period.

Activity Status as of 06/30/2015:
Neither outcome that was scheduled for completion by 06/30/2015 was completed due to a delay in the completion of the project on which these outcomes rely (the USGS synthetic hydrograph project). Actual progress does include identifying the characteristics that explain spatial distribution have been identified, but not yet applied specifically to the entire basins. The spatial distribution for groundwater discharge has been computed as a pilot for one tributary in the Cannon River basin.

Activity Status as of 12/31/2015:
Progress included identifying the characteristics that explain spatial distribution of the flow-duration curves, for both the St. Louis and Cannon River basins. Furthermore, the flow-duration curves were calculated for both basins for each of the DNR sub-watersheds.

Activity Status as of 06/30/2016**:**
Low flow frequency statistics (LFFS) were calculated for all DNR level 9 sub-watersheds in the St. Louis and Cannon River watersheds. These calculations indicate the relative contributions of the sub-watersheds to overall flow within the larger watershed at low flows and provide further insight, with respect to the previously calculated flow duration curves (FDR), as to the spatial contributions of different portions of the larger water sheds at low flows. Ultimately, select results from the LFFS and/or FDR will be merged with the products from task 2 to form the final deliverable during task 3.

Activity Status as of 12/31/2016:
Low flow frequency statistics calculated for all DNR level 9 sub-watersheds in the St. Louis and Cannon River watersheds have been integrated into ArcGIS maps in order to begin the merger of these results with the SWB results from Activity 2.

Final Report Summary:
All the flow-duration curve (FDC) statistics, which ultimately became the mapping product rather than the LFFS, were imported into ArcGIS 10.4. A total of 505 sub-watersheds (Cannon: 152; St. Louis, 353) had separate FDC statistics for all 13 of the exceedance-probability quantiles that define the FDC. All the FDC statistics were re-adjusted, based on a comparison between the mean FDC streamflow and the mean Soil-Water-Balance (SWB) flow.

ACTIVITY 2: Estimate groundwater recharge for each area
Description:
Recharge will be calculated across two selected watersheds in St. Louis and Goodhue counties utilizing the SWB – Soil-Water-Balance Code (Westenbroek and others, 2010). The SWB application will incorporate spatial and temporal variability by using commonly available geographic information system (GIS) data layers and daily, gridded climatological data. As components of the soil-water-balance approach are calculated at daily time steps, recharge estimates can be output as daily, monthly, and/or annual estimates.
Within the SWB approach, recharge is calculated within each grid cell of the model domain based on the difference between soil moisture and the sources (precipitation, snowmelt, inflow) and sinks (interception, outflow, evapotranspiration (ET)) (eq. 1):

$$\text{Recharge} = (\text{precip} + \text{snowmelt} + \text{inflow}) - (\text{interception} + \text{outflow} + \text{ET}) - \Delta\text{soil moisture} \qquad (1)$$

Input for the sources and sinks is provided by climate data and landscape characteristics. Output is only limited by the resolution of the climatological data and available land use, land cover, and soil cover data layers. The first step in the approach is to assemble all the required gridded data sets for the state, including the following:

1. Land use / land cover
2. Surface water flow direction
3. Hydrologic soil group
4. Available soil-water capacity

Several data sources will be key for building these statewide grids. The National Land Cover Data (NLCD) will be used as the source for land use/land cover data. A 30-meter Digital Elevation Model (DEM) will be used to determine cell-by-cell flow direction. The Soil Survey Geographic (SSURGO) database will be used to determine the hydrologic soil group and available soil-water capacity.

The daily, gridded climate datasets available from DAYMET (Oak Ridge National Laboratory, 2014) will be the primary sources of information for populating the climate data tables for the model. The minimum data requirements for SWB include daily precipitation, daily minimum air temperature, and daily maximum air temperature. The final required data set, the matrix of soil-water retention for given accumulated potential water loss, is an included part of the SWB code and is derived from Thornthwaite and Mather (1957).

After all the required data sources have been collected, the next step is to build and format the input files (i.e., control files) for running the SWB code. Also, all the initial conditions need to be set in addition to setting options, such as the surface water routing method and the evapotranspiration method. Upon completion of these steps, the SWB will be run for a period of at least 10 years to incorporate climatic variability. Results from the SWB method will be used to create daily, monthly, and/or annual recharge estimates for the two selected watersheds.

Output for the selected watersheds will be similar to Figure 2, except a summary of recharge across the two selected watersheds in St. Louis and Goodhue counties.

Summary Budget Information for Activity 2:		
	ENRTF Budget:	**$ 28,500.00**
	Amount Spent:	**$ 28,500.00**
	Balance:	**$ 0.00**

Activity Completion Date: 12/31/2015

Outcome	**Completion Date**	**Budget**
1. Compile and produce GIS and climatological datasets.	12/31/2014	$5,000
2. Calculate groundwater recharge and produce preliminary distribution maps.	12/31/2015	$23,500

Activity Status as of 12/31/2014:

The GIS and climatological data from the statewide SWB study were extracted and down-scaled for the St. Louis and Cannon River basins. The GIS data include land use/land cover, surface water flow direction, hydrologic soil group, and available soil-water capacity. The climatological data include daily precipitation, daily minimum air temperature, and daily maximum air temperature. The data were resampled or down-scaled to 30-meter resolution, which is appropriate for the scale of the basins.

Activity Status as of 06/30/2015:

For Activity 2, all of the remaining input files (in particular the flow direction grid) were compiled for the greater Cannon River SWB model. The SWB calibration began for the Cannon River watershed. As part of the greater Cannon River SWB model, the following calibration targets have been included: USGS 05355200 (Cannon

River at Welch, MN) and USGS 05353800 (Straight River near Faribault, MN). Hydrograph separation will be used on all of these records, and the SWB calibration targets will include the baseflow-separated component as well as total flow.

Activity Status as of 12/31/2015:
Minor progress was made for further calibration of the Cannon River watershed SWB model, but this work is still not completed.

Activity Status as of 06/30/2016**:**
Previous SWB calibration efforts were analyzed for areas within the watersheds having inappropriate hydrologic routing within the Digital Elevation Models (DEM) i.e. flow direction grids. The DEM's were then "flow corrected" in areas deemed to have inappropriate routing ensuring the runoff computed in the SWB simulations is appropriately routed throughout the basins to ensure best possible calibration and water budgets are obtained from the simulations. This is a trial and error process and calibration of the SWB models is still in progress.

Activity Status as of 12/31/2016:
The refined resolution Cannon River watershed SWB results were finalized, with some initial progress for the St. Louis River watershed's SWB model. The St. Louis River watershed's SWB results should be completed by early January 2017.

Final Report Summary:
Both the Cannon River and St. Louis River SWB models were completed, refining the earlier published statewide Minnesota SWB model (Smith and Westenbroek, 2015), for better fits specific to these watersheds. Additionally, the new SWB models have refined resolution at 100-meters rather than 1-kilometer. Final model archival has been completed, with all model materials freely available for download by the public.

ACTIVITY 3: Analysis and map production
Description:
Integrate the results from activities 1 and 2 to reconcile differences and calculate all components of the surface- and groundwater budgets in the watersheds. The integration process takes the recharge data and applies it to the relative contribution information from activity 1 to produce the actual contribution to streamflow at selected flow regimes. The integration also incorporates surface runoff, estimated by the recharge estimates in activity 2, to estimate the contribution to flow at higher flow regimes, floods for example. The resulting products represent the contribution for typical conditions, not necessarily the contribution for any particular time.

Figure 3 shows the current watershed budget for the Cannon River watershed, which covers part of Goodhue County. It is a very crude representation of the watershed budget, showing only average flow. The updated product will show the streamflow for selected flow regimes, like average, drought, and severe drought; and the aquifers that contribute to the streamflow at those flow regimes. The data can be extracted from the GIS products, which will be useful to watershed planners and mangers.

Summary Budget Information for Activity 3: **ENRTF Budget: $ 67,000.00**
Amount Spent: $ 67,000.00
Balance: $ 0.00

Activity Completion Date: 06/30/2017

Outcome	Completion Date	Budget
1. Compile water-use data.	12/31/2014	$5,000
2. Produce final distribution maps.	12/31/2016	$31,000
2. Produce map reports.	06/30/2017	$31,000

Activity Status as of 12/31/2014:
Water-use data from 2000-2012 were compiled for the St. Louis and Cannon River basins. The water use data for this project included consumptive uses, including public supply, domestic supply, agricultural, industrial, and mining uses from both surface- and groundwater sources. The water-use data will be integrated into the final over-all water budget for each basin.

Activity Status as of 06/30/2015:
No activity during this period.

Activity Status as of 12/31/2015:
No activity during this period.

Activity Status as of 06/30/2016**:**
No activity during this period.

Activity Status as of 12/31/2016:
No activity during this period.

Final Report Summary:
The final streamflow distribution maps integrate the recharge data from activity 2 and applies it to the relative contribution information from activity 1 to produce the actual contribution to streamflow at selected flow regimes. All mapping products have been completed and will be a part of the pending USGS Scientific Investigations Map (SIM), set to be release by November 2017. A series of four panels for each watershed illustrate the streamflow distribution at selected flow regimes: extreme drought, drought, a mean flow condition, and a flood condition. [The integration also incorporates surface runoff, estimated by the recharge estimates in activity 2, to estimate the contribution to flow at higher flow regimes, floods for example.]

V. DISSEMINATION:

Description: A USGS Scientific Investigations Map and the corresponding GIS data will be published by June 30, 2017. The report and supporting data will be hosted on the USGS publications website: http://pubs.er.usgs.gov/. In addition to the report, a group composed of staff of the USGS and the MDNR will monitor the progress and help direct the final product to improve its usefulness. That group will also be instrumental in keeping other interested parties informed of the progress and the final product.

Status as of 12/31/2014:
No activity during this period.

Status as of 06/30/2015:
No activity during this period.

Status as of 12/31/2015:
No activity during this period.

Status as of 06/30/2016**:**
No activity during this period.

Status as of 12/31/2016:
No activity during the period.

Status as of 06/30/2017**:**
A draft USGS Scientific Investigations Map (SIM) and the corresponding GIS data has been completed.

Final Report Summary:
A draft USGS Scientific Investigations Map (SIM) and the corresponding GIS data has been completed. Along with the final work plan update, a draft copy of the USGS SIM has been included as a separate attachment along with the accompanying map sheets for Cannon and St. Louis River watersheds.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Explanation
Personnel:	$129,000	
TOTAL ENRTF BUDGET:	**$129,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 1.0

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
USGS	$63,700	$63,700	All activities—USGS administrative and indirect costs
TOTAL OTHER FUNDS:	**$63,700**	**$63,700**	

VII. PROJECT STRATEGY:

A. Project Partners:

Minnesota Department of Natural Resources and Minnesota Pollution Control Agency. Both are interested in the project and a project guiding task force will be formed by representatives from both agencies and the U.S. Geological Survey so that the final product will be most useful to the state agencies.

B. Project Impact and Long-term Strategy:

The water budget information obtained from this study will assist the state in planning for long-term water-use sustainability. The proposed study will provide the Minnesota Department of Natural Resources with information necessary to protect wetlands and ensure streamflows for ecological needs. It should also provide information to the Minnesota Pollution Control Agency information necessary to better understand the interaction between surface- and groundwater.

This project is a proof-of-concept study in two watersheds in Minnesota. It is intended to research and find the most practical methods to produce the GIS products. The long-term goal would be to extend the results to all watersheds in Minnesota.

C. Spending History:

Funding Source	M.L. 2008 or FY09	M.L. 2009 or FY10	M.L. 2010 or FY11	M.L. 2011 or FY12-13	M.L. 2013 or FY14
LCCMR-ENRTF	NA	NA	NA	NA	NA
USGS Cooperative Water Program	NA	NA	NA	NA	NA

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. VISUAL ELEMENT or MAP(S):

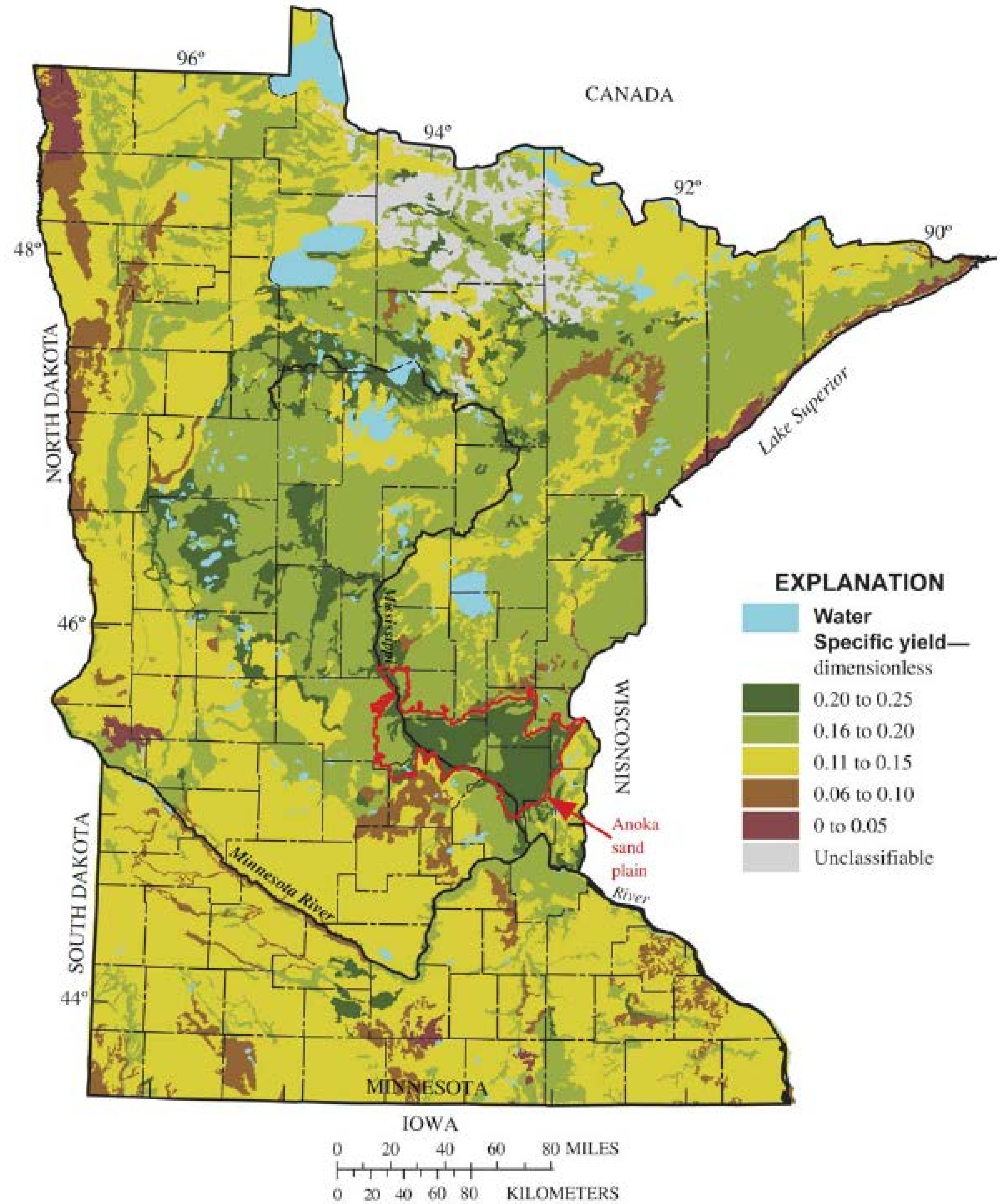

Figure 1. Specific yield of surficial materials in Minnesota.

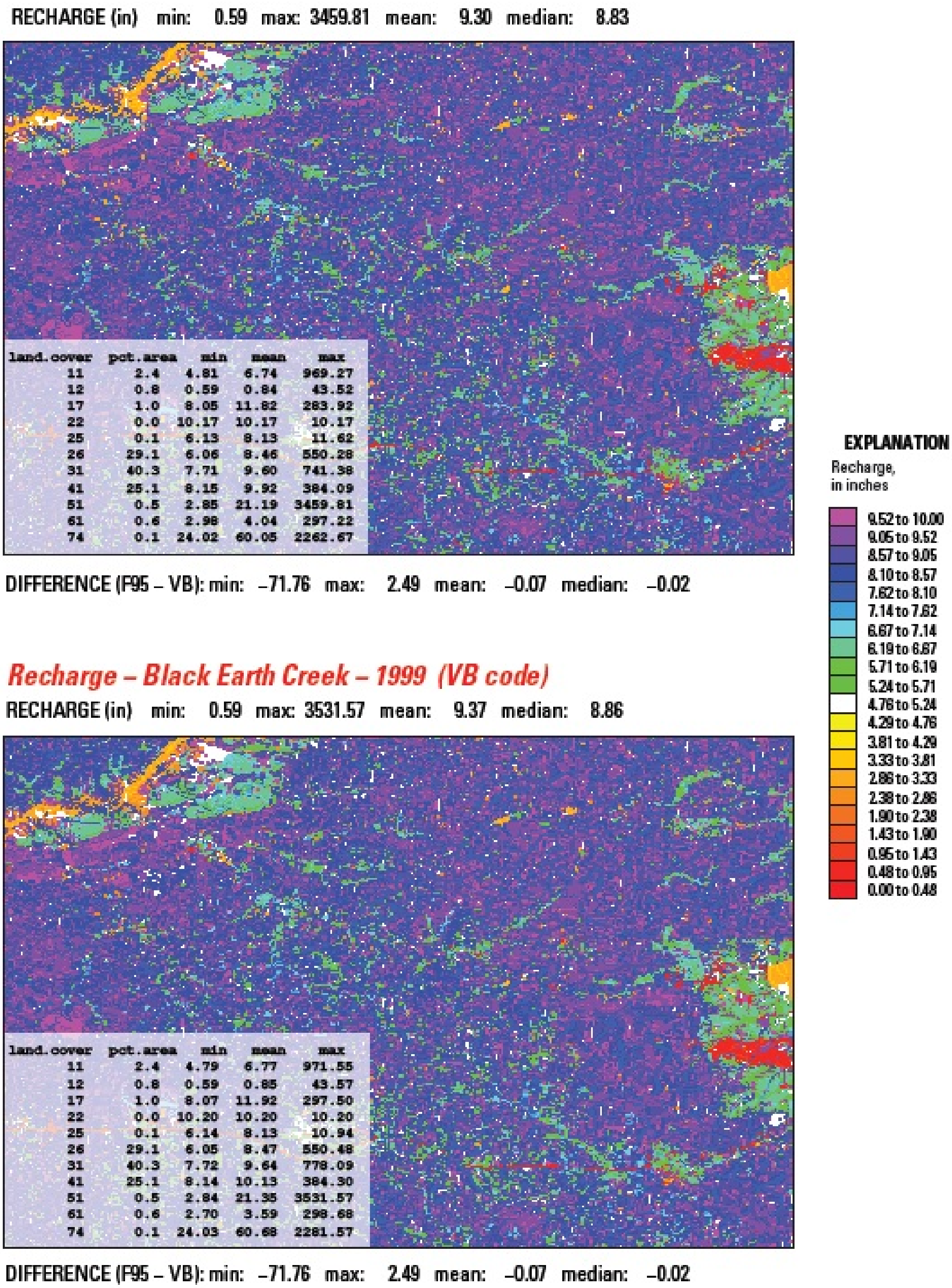

Figure 2. Recharge across an example watershed, Black Earth Creek, WI (copied from Westenbroek and others, 2010).

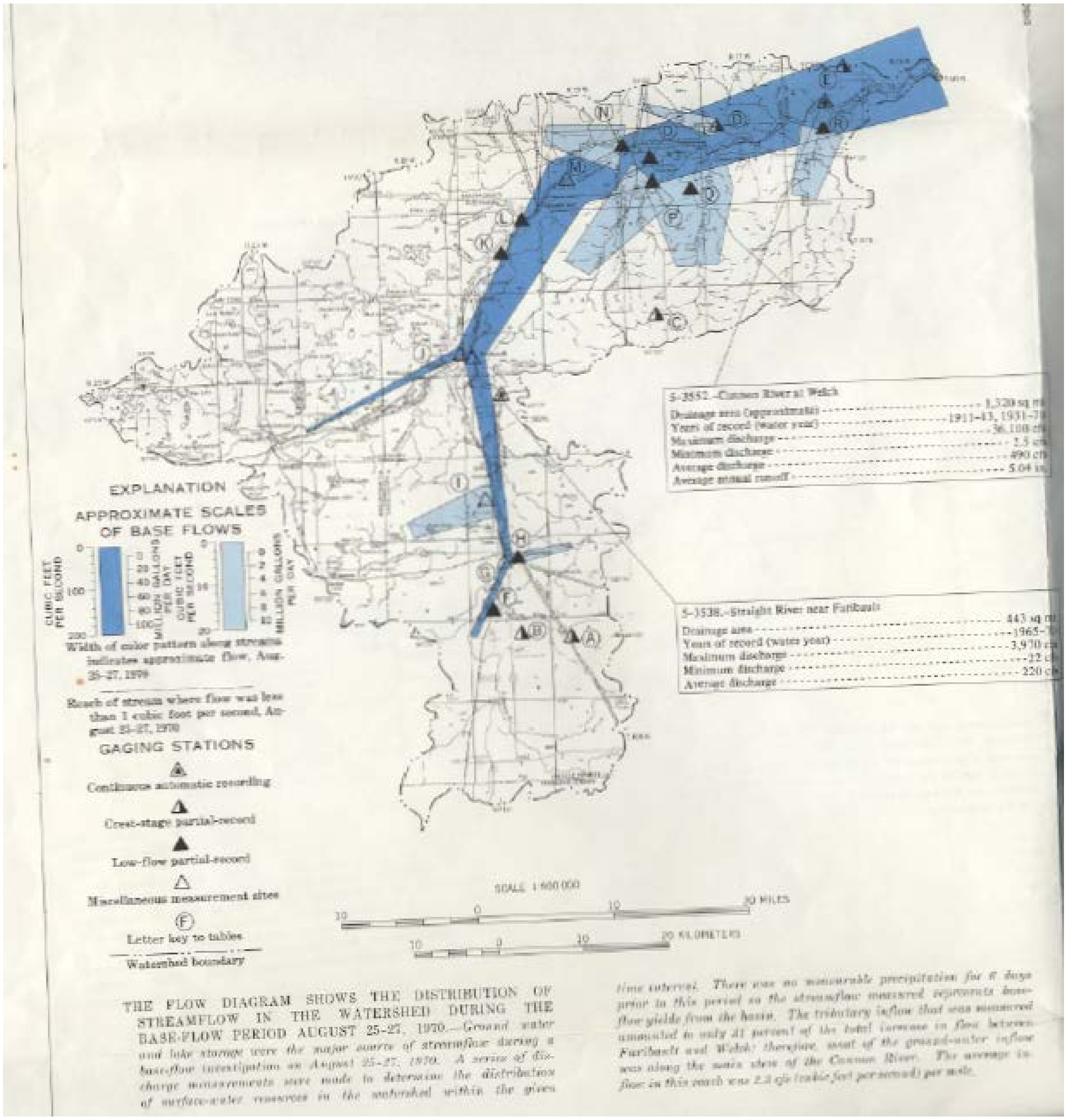

Figure 3. Water budget from Anderson and others, 1974.

X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: N/A

XI. RESEARCH ADDENDUM:

The U.S. Geological Survey will conduct internal peer reviews of this detailed proposal and will be revised based on those USGS peer review comments. The proposal will then be approved by the USGS and added to this document. The expected date of proposal approval is April 30, 2014.

XII. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than June 30, 2015; June 30, 2016; and June 30, 2017. A final report and associated products will be submitted by June 30, 2017.

XIII REFERENCES:

Anderson, H.W., Jr., Farrell, D.F., Broussard, W.L., and Felsheim, P.E., 1974, Water resources of the Cannon River watershed, southeastern Minnesota: U.S. Geological Survey Hydrologic Atlas HA-522, 3 sheets, scales 1:250,000 and 1:500,000.

Lorenz, D.L., and Delin, G.N., 2007, A regression model to estimate regional ground-water recharge in Minnesota: Ground Water, v. 45, no. 2, 10.1111/j.1745-6584.2006.00273.x.

Oak Ridge National Laboratory, 2014, Daily Surface Weather and Climatological Summaries: accessed January 9, 2014, at http://daymet.ornl.gov/gridded.

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Environment and Natural Resources Trust Fund

M.L. 2014 Project Budget

Project Title: Watershed Water Budgets for Managing Minnesota's Groundwater

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 03i

Project Manager: Erik Smith

Organization: U.S. Geolgical Survey

M.L. 2014 ENRTF Appropriation: $ 129,000

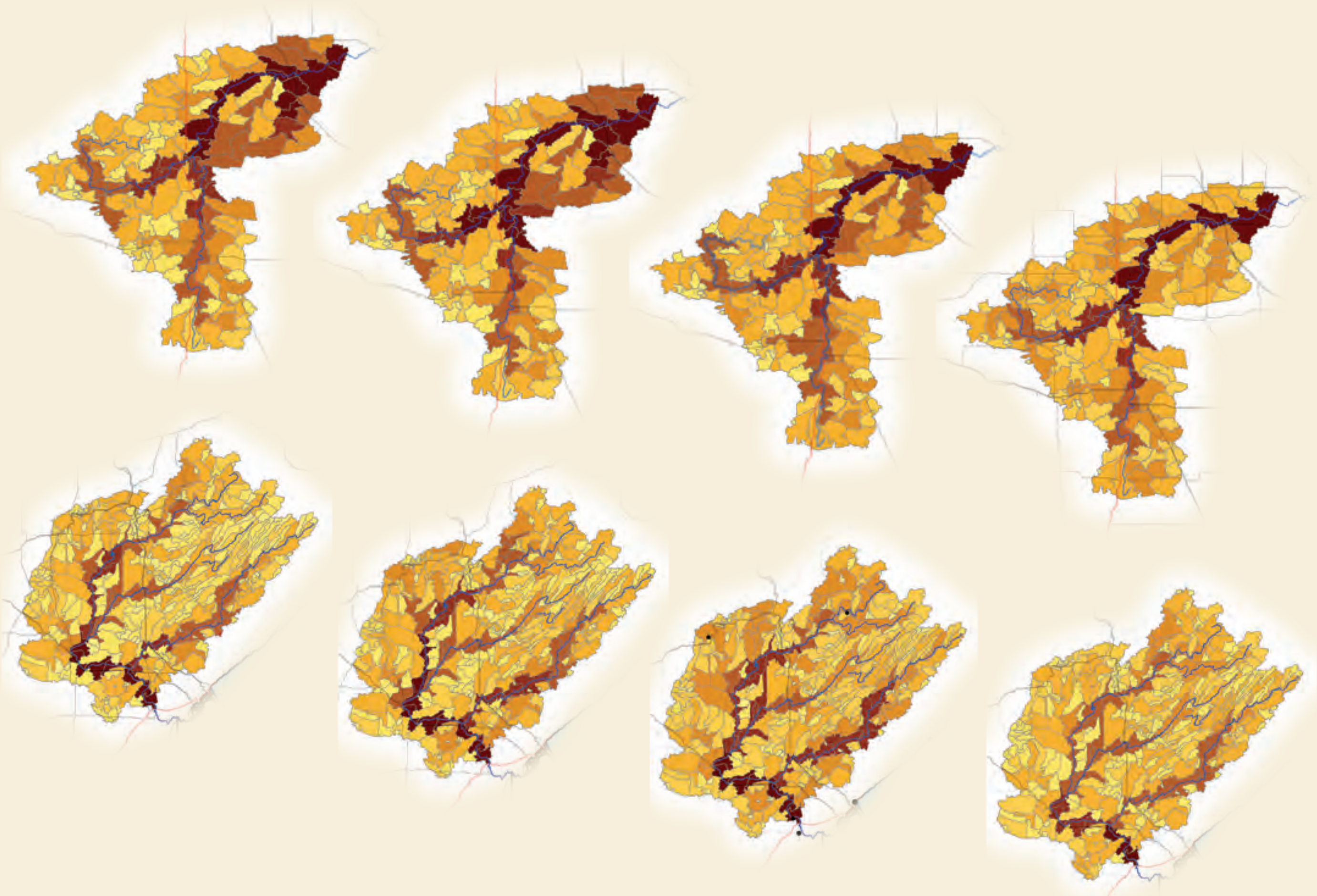
Project Length and Completion Date: 3 Years, June 30, 2017

Date of Report: December 30, 2016

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	**Estimate groundwater contribution to streamflow**			**Estimate groundwater recharge for each area**			**Analysis and map production**				
Personnel (Wages and Benefits)	$33,500.00	$33,500.00	$0.00	$28,500.00	$28,500.00	$0.00	$67,000.00	$67,000.00	$0.00	$129,000.00	$0.00
USGS Project Chief 267 hours, 78%salary, 22%benefits ($17,800)											
USGS Hydrologist 425 hours, 73% salary, 27% benefits ($26,000)											
USGS Hydrologist 828 hours, 73% salary, 27% benefits ($53,500)											
USGS Water-Use Specialists 160 hours, 73% salary, 27% benefits ($10,000)											
USGS Technical Administration (2 staff) 180 total hours, 69% salary, 31% benefits ($7,000)											
USGS Project Administration and Oversight (2 staff) 50 total hours, 69% salary, 31% benefits ($4,200)											
USGS Technical Specialists (2staff) 150 hours total, 73% salary, 27% benefits ($10,500)											
COLUMN TOTAL	$33,500.00	$33,500.00	$0.00	$28,500.00	$28,500.00	$0.00	$67,000.00	$67,000.00	$0.00	$129,000.00	$0.00

Prepared in cooperation with the Legislative-Citizen Commission on Minnesota Resources

Streamflow Distribution Maps for the Cannon River Drainage Basin, Southeast Minnesota, and the St. Louis River Drainage Basin, Northeast Minnesota



Pamphlet to accompany

Scientific Investigations Map 3390

U.S. Department of the Interior
U.S. Geological Survey

Cover. Streamflow distribution maps for the Cannon River and St. Louis River drainage basins.

Streamflow Distribution Maps for the Cannon River Drainage Basin, Southeast Minnesota, and the St. Louis River Drainage Basin, Northeast Minnesota

By Erik A. Smith, Chris A. Sanocki, David L. Lorenz, and Katrin E. Jacobsen

Prepared in cooperation with the Legislative-Citizen Commission on Minnesota Resources

Scientific Investigations Map 3390

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
exercising the authority of the Director

U.S. Geological Survey, Reston, Virginia: 2017

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Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meters per kilometer (m/km)	5.28	foot per mile (ft/mi)
kilometer (km)	0.6215	mile (mi)
millimeter (mm)	25.4	inch (in)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeters per year (mm/yr)	0.03937	inches per year (in/yr)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), unless otherwise indicated.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

<	less than
ET	evapotranspiration
FDC	flow-duration curve
HSPF	Hydrologic Simulation Program-FORTRAN
LUC	land-use classification
Minn.	Minnesota
NLCD	National Land Cover Database
SSURGO	Soil Survey Geographic [database]
STATSGO	State Soil Geographic [database]
SWB	Soil Water Balance [model]
USGS	U.S. Geological Survey
WRAPS	watershed restoration and protection strategies

Streamflow Distribution Maps for the Cannon River Drainage Basin, Southeast Minnesota, and the St. Louis River Drainage Basin, Northeast Minnesota

By Erik A. Smith, Chris A. Sanocki, David L. Lorenz, and Katrin E. Jacobsen

Abstract

Streamflow distribution maps for the Cannon River and St. Louis River drainage basins were developed by the U.S. Geological Survey, in cooperation with the Legislative-Citizen Commission on Minnesota Resources, to illustrate relative and cumulative streamflow distributions. The Cannon River was selected to provide baseline data to assess the effects of potential surficial sand mining, and the St. Louis River was selected to determine the effects of ongoing Mesabi Iron Range mining. Each drainage basin (Cannon, St. Louis) was subdivided into nested drainage basins: the Cannon River was subdivided into 152 nested drainage basins, and the St. Louis River was subdivided into 353 nested drainage basins. For each smaller drainage basin, the estimated volumes of groundwater discharge (as base flow) and surface runoff flowing into all surface-water features were displayed under the following conditions: (1) extreme low-flow conditions, comparable to an exceedance-probability quantile of 0.95; (2) low-flow conditions, comparable to an exceedance-probability quantile of 0.90; (3) a median condition, comparable to an exceedance-probability quantile of 0.50; and (4) a high-flow condition, comparable to an exceedance-probability quantile of 0.02.

Streamflow distribution maps were developed using flow-duration curve exceedance-probability quantiles in conjunction with Soil-Water-Balance model outputs; both the flow-duration curve and Soil-Water-Balance models were built upon previously published U.S. Geological Survey reports. The selected streamflow distribution maps provide a proactive water management tool for State cooperators by illustrating flow rates during a range of hydraulic conditions. Furthermore, after the nested drainage basins are highlighted in terms of surface-water flows, the streamflows can be evaluated in the context of meeting specific ecological flows under different flow regimes and potentially assist with decisions regarding groundwater and surface-water appropriations. Presented streamflow distribution maps are foundational work intended to support the development of additional streamflow distribution maps that include statistical constraints on the selected flow conditions.

Introduction

Water resource management in a drainage basin requires knowledge of the water budget. The water budget states that the rate of change of water volume in a drainage basin is balanced by the flow in and out of all the surface water bodies (for example, lakes, streams, reservoirs, and wetlands) and underlying groundwater that make up the drainage basin (Healy and others, 2007). In Minnesota, the County Geologic Atlas program provides basic information on surficial and buried aquifers, including maps that detail the distribution and the lithologic and hydrogeologic properties of rock and sediments that lie below the land surface (Setterholm, 2014); this information can help estimate the volume of groundwater in storage within a particular geological unit. For streams and rivers with active streamgage networks, the volume and rate of surface-water flows at a streamgaged location are well quantified. For surficial aquifers, the volume and rate of groundwater flow in and out of surface water bodies are affected by the amount of surface-water flow and flow to and from deeper aquifers (Winter and others, 1998).

Water budgets provide a means for evaluating water availability and sustainability in the absence of robust groundwater modeling to determine sustainable groundwater yields within a basin or long-term monitoring of streamflow to determine continuous surface-water flows. These water budgets can be an important initial step for determining the water balance; however, predevelopment water budgets should not be used as the sole source of information for determining the amount of groundwater withdrawal that can happen in a watershed or to preserve minimum ecological streamflows (Bredehoeft, 1997).

The initial water budget generally requires accurate estimates of the spatial and temporal distribution of the water budget components, including potential recharge, surface runoff, evapotranspiration (ET), inflow from surface-water bodies and groundwater, and outflow from surface-water bodies and groundwater. The Soil-Water-Balance (SWB) model was developed to estimate the volume of potential recharge using widely available geographic information system datasets (Westenbroek and others, 2010) and includes estimates of ET and surface runoff. The SWB modeling assumes most potential recharge eventually flows into nearby surface-water systems as base flow. Combined with surface runoff, this analysis can be the first step for a water budget.

Another common problem with developing water budgets is that streamgages are not available to compute streamflow at every stream location; however, methods have been developed to estimate flow-duration curve (FDC) statistics at stream locations in Minnesota (Ziegeweid and others, 2015) with little or no long-term monitoring data, such as the upper reaches of large drainage basins. An FDC is a cumulative frequency curve that shows the fraction of time that specified streamflow is equaled or exceeded (Searcy, 1959). An FDC is built by sorting streamflow observed during a given period by magnitude and calculating the probability that a specified streamflow value will be equaled or exceeded. The fraction of time that the streamflow is calculated to have been equaled or exceeded is termed exceedance probability. At an ungaged location, the FDC is constructed from regression-based estimates of streamflow for 13 exceedance probabilities (0.9999, 0.999, 0.99, 0.95, 0.9, 0.75, 0.5, 0.25, 0.1, 0.05, 0.02, 0.001, and 0.0001) that cover the range of streamflow (Lorenz and Ziegeweid, 2016). The FDC statistics define exceedance probabilities, and they are not a substitute for calculating continuous streamflow; instead, the FDC can provide a mechanism to assess water availability and determine initial estimates for sustained flow requirements (Unthank and others, 2012).

The contribution of base flow to total streamflow can be calculated for lower flow conditions, such as droughts, by integrating the SWB water budget components and the FDC exceedance probabilities. Additionally, the combined contribution of base flow and surface runoff at higher flow conditions, such as floods, can be estimated with this approach. To help guide the efforts made by the State of Minnesota to define water use sustainability from surficial aquifers and effectively manage streamflow during low-flow conditions, the U.S. Geological Survey (USGS), in cooperation with the Legislative-Citizen Commission on Minnesota Resources, combined SWB and FDC components to create a series of streamflow distribution maps for two pilot drainage basins. The selected streamflow distribution maps represent the relative contribution of base flow and surface runoff to total volume of streamflow for typical conditions, not necessarily the contribution for any particular time. These maps will help guide potential State cooperators such as the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency for proactive water management, ensure streamflows meet ecological needs at different flow conditions, and assist with decisions for groundwater appropriations at low-flow conditions.

Purpose and Scope

The purpose of this report is to describe the development of a series of estimated streamflow distribution maps at selected low-flow conditions and one high-flow condition for the Cannon River and St. Louis River drainage basins in Minnesota. The scope of the streamflow distribution maps was limited to the entire drainage basin above the farthest downstream continuous USGS streamgage. For the Cannon River, the maps included the entire drainage basin above the Cannon River at Welch, Minnesota (USGS station number 05355200). For the St. Louis River, the maps included the entire drainage basin above the St. Louis River at Scanlon, Minn. (USGS station number 04024000). Tasks specific to the estimated streamflow distribution maps were (1) analyzing the flow data collected at both gages (table 1); (2) generating FDC statistics for 505 smaller drainage basins within the 2 larger drainage basins using the Minnesota regional regression equations (Ziegeweid and others, 2015); (3) constructing and calibrating SWB models for each drainage basin for the period of January 1, 1996, through December 31, 2010, primarily based on the published Minnesota statewide Soil-Water-Balance model (Smith and Westenbroek, 2015); (4) adjusting the FDC statistics based on the results of the SWB models; and (5) producing estimated streamflow distribution maps based on selected flow conditions representative of approximately median, low flow, extreme low flow, and high flow conditions.

Study Area Description

The Cannon River drainage basin in southeastern Minnesota consists of the Cannon River and the Straight River (Wotzka and Watkins, 2016). The drainage basin above the Cannon River at Welch, Minn., streamgage is 3,471 square

Table 1. Site information for the U.S. Geological Survey streamgages used for this study in the Cannon River and St. Louis River drainage basins, Minnesota.

[See figure 1 for station location; USGS, U.S. Geological Survey; Minn., Minnesota; ft³/s, cubic foot per second]

Station name	USGS station number	Drainage area (square miles)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Continuous period of record	Maximum recorded streamflow at streamgage and date
Cannon River at Welch, Minn.	05355200	1,340	44° 33′ 50″	92° 43′ 55″	1931 to current year (2017)	36,100 ft^3/s April 8, 1965
St. Louis River at Scanlon, Minn.	04024000	3,430	46° 42′ 12″	92° 25′ 07″	1908 to current year (2017)	45,300 ft^3/s June 21, 2012

kilometers (km^2) (1,340 square miles [mi^2]) (U.S. Geological Survey, 2017). The Cannon River flows northeast towards the Mississippi River near Red Wing, Minn., and the Straight River joins the Cannon River in Faribault, Minn. (fig. 1; table 1). The Cannon River drainage basin covers parts of nine counties (fig. 1), including Blue Earth, Dakota, Freeborn, Goodhue, LeSueur, Rice, Scott, Steele, and Waseca.

The Cannon River drainage basin overlies two groundwater provinces (Minnesota Department of Natural Resources, 2017; fig. 2): the south-central province (groundwater province 2) and the southeastern province (groundwater province 3). The upstream sections of both the Cannon River and the Straight River are underlain by the south-central province, a glacial drift dominated landscape classified as thick clayey till overlying Paleozoic sandstone, limestone, and dolostone aquifers (Minnesota Department of Natural Resources, 2017). The glacial drift has a strong effect on infiltration and runoff, and the infiltration pathways are more diffuse through intermittent sand and gravel bodies, whereas the fine-grained units in this area impede infiltration (Runkel and others, 2014). Discharge to surface waters in the upstream part of the drainage basin follows a more diffuse network of preferential groundwater flow pathways (Runkel and others, 2014).

The more downstream parts of the Cannon River, in addition to the lower parts of the Straight River near the confluence of the two rivers, are underlain by the southeastern province. The southeastern province is an area with thin clayey till overlying Paleozoic bedrock and has karst characteristics, particularly in the eastern section of the drainage basin (Runkel and others, 2014; Minnesota Department of Natural Resources, 2017). The downstream parts of the Cannon River have a more pronounced connection to limestone and dolostone aquifers, in particular the Prairie du Chien Group (Groten and Alexander, 2013). High-purity sands within the St. Peter Sandstone exist in a substantial proportion of the Cannon River drainage basin (not shown). These high-purity sands are often extracted for use in hydraulic fracturing.

The St. Louis River drainage basin is one of the largest in northern Minnesota (fig. 2; Anderson and others, 2013). The drainage basin above the St. Louis River at Scanlon, Minn., streamgage is 8,884 km^2 (3,430 mi^2) (U.S. Geological Survey, 2017). The St. Louis River flows for 323 kilometers (km) (201 miles [mi]) towards Lake Superior before discharging into Lake Superior at Duluth, Minn. (fig. 3; table 1). The last 24 km (15 mi) of the St. Louis River comprise the St. Louis River estuary. Several tributaries join the St. Louis River along its reach, including the Embarrass River (not shown), Whiteface River, Floodwood River (not shown), and the Cloquet River (fig. 3) (Lindholm and others, 1979). The St. Louis River drainage basin covers parts of five counties (fig. 3), including Aitkin, Carlton, Itasca, Lake, and St. Louis; however, most of the basin is contained within St. Louis County.

The St. Louis River drainage basin overlies the central groundwater province (groundwater province 4) and the arrowhead province (groundwater province 6; fig. 2). The upstream part of the St. Louis River drainage basin is underlain by the arrowhead province, which is made up of Precambrian rocks exposed at the surface or covered by less than 9.2 meters (30 feet) of glacial till (Minnesota Department of Natural Resources, 2017). Groundwater in this region typically flows through faults and fractures within the Precambrian bedrock, although sand and sandstone aquifers are present in small areas. The lower parts of the St. Louis River drainage basin are underlain by the central province. The central province is an area with sand aquifers and thicker sand and clay glacial drift overlying the Precambrian and Cretaceous bedrock. Both the sand deposits within the glacial till and the bedrock deposits function as aquifers (Minnesota Department of Natural Resources, 2017). St. Louis River gradients are highly variable, ranging from 0.1 to 6.5 meters per kilometer (Lindgren and others, 2006). Much of the upper and middle sections of the St. Louis River drainage include shallow gradients, resulting in a highly fragmented stream network made up of small, short tributaries (Lindgren and others, 2006). In the lower reaches, gradients increase to near 6.5 meters per kilometer, particularly in a 24-km (15-mi) reach below Cloquet, Minn. (fig. 3) (Lindholm and others, 1979).

The St. Louis River estuary, the final 24 km (15 mi) of the St. Louis River, has been listed as an Area of Concern by the International Joint Commission (Lindgren and others, 2006) because of the effects of heavy industry (for example, mining) and untreated urban effluent since the 19th century. Mining activity has happened within the St. Louis River drainage basin in the past 150 years. The Mesabi Iron Range (not shown), noted for rich deposits of iron ore, parallels much of the northern drainage basin boundary (Lindholm and others, 1979). Ongoing (2017) and potential future expansion of iron ore mining along the Mesabi Iron Range has been noted as an area of study and concern within the St. Louis River drainage basin (Fletcher and Christin, 2015).

Previous Studies

Several water-resource reports that include parts of the Cannon River drainage basin have been published during the last 45 years. A preliminary water budget that accounted for precipitation, ET, runoff, and a general compilation of water usage was included as part of a characterization of the Cannon River surface-water and groundwater resources by Anderson and others (1974). The high-purity silica sand deposits from the Middle Ordovician age were mapped across several midwestern states, including the Cannon River drainage basin in southeastern Minnesota by Ketner (1979). More recently, a comprehensive regional analysis of geologic controls on nitrate concentrations, in the context of the hydrogeologic attributes of surficial and bedrock deposits, was completed by Runkel and others (2014). Synoptic dye traces in a Cannon River tributary, Trout Brook, concluded that 30 to 40 percent of all Trout Brook streamflow was spring fed (Groten and Alexander, 2013). As part of the statewide watershed restoration and protection strategies (WRAPS) process, a Hydrologic

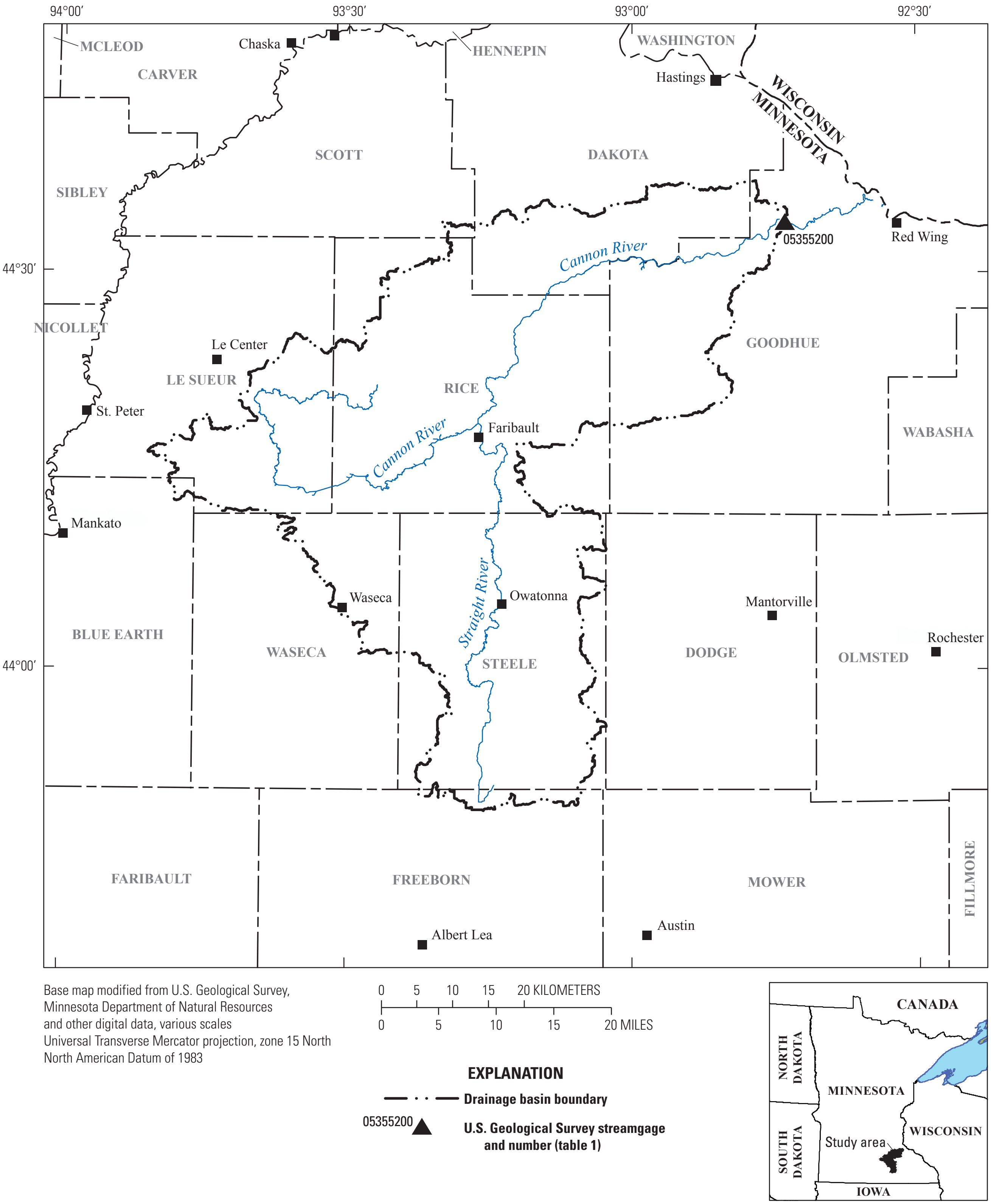

Figure 1. The Cannon River study area, including the entire drainage basin above the Cannon River at Welch, Minnesota, streamgage (U.S. Geological Survey station number 05355200), main stem of the Cannon River and the Straight River, major cities/towns, and other administrative boundaries.

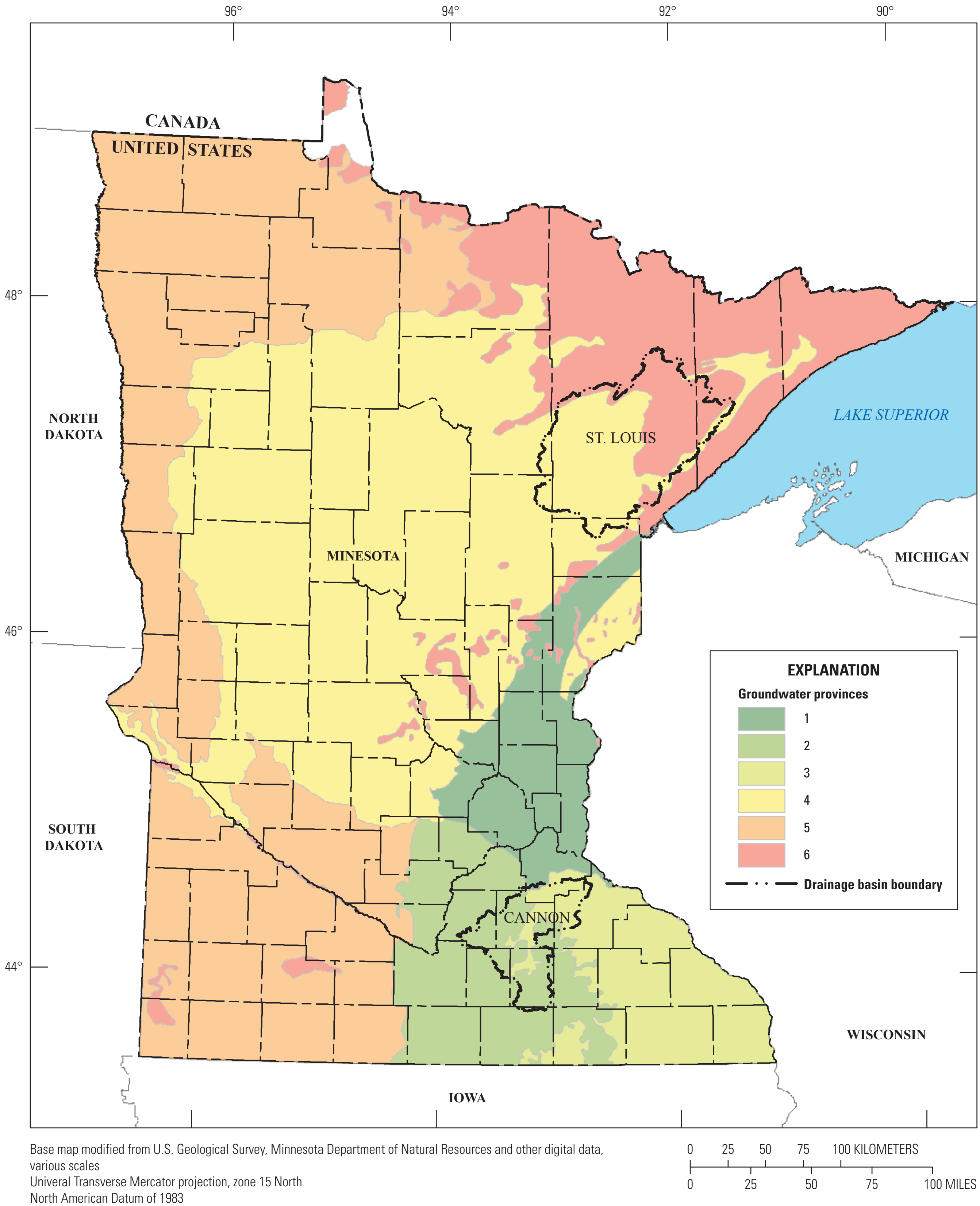

Figure 2. The six Minnesota groundwater provinces, as outlined by the Minnesota Department of Natural Resources (2017), along with the Cannon River drainage basin (above the Cannon River at Welch, Minnesota, streamgage [U.S. Geological Survey station number 05355200]) and the St. Louis River drainage basin (above the St. Louis River at Scanlon, Minnesota, streamgage [U.S. Geological Survey station number 04024000]).

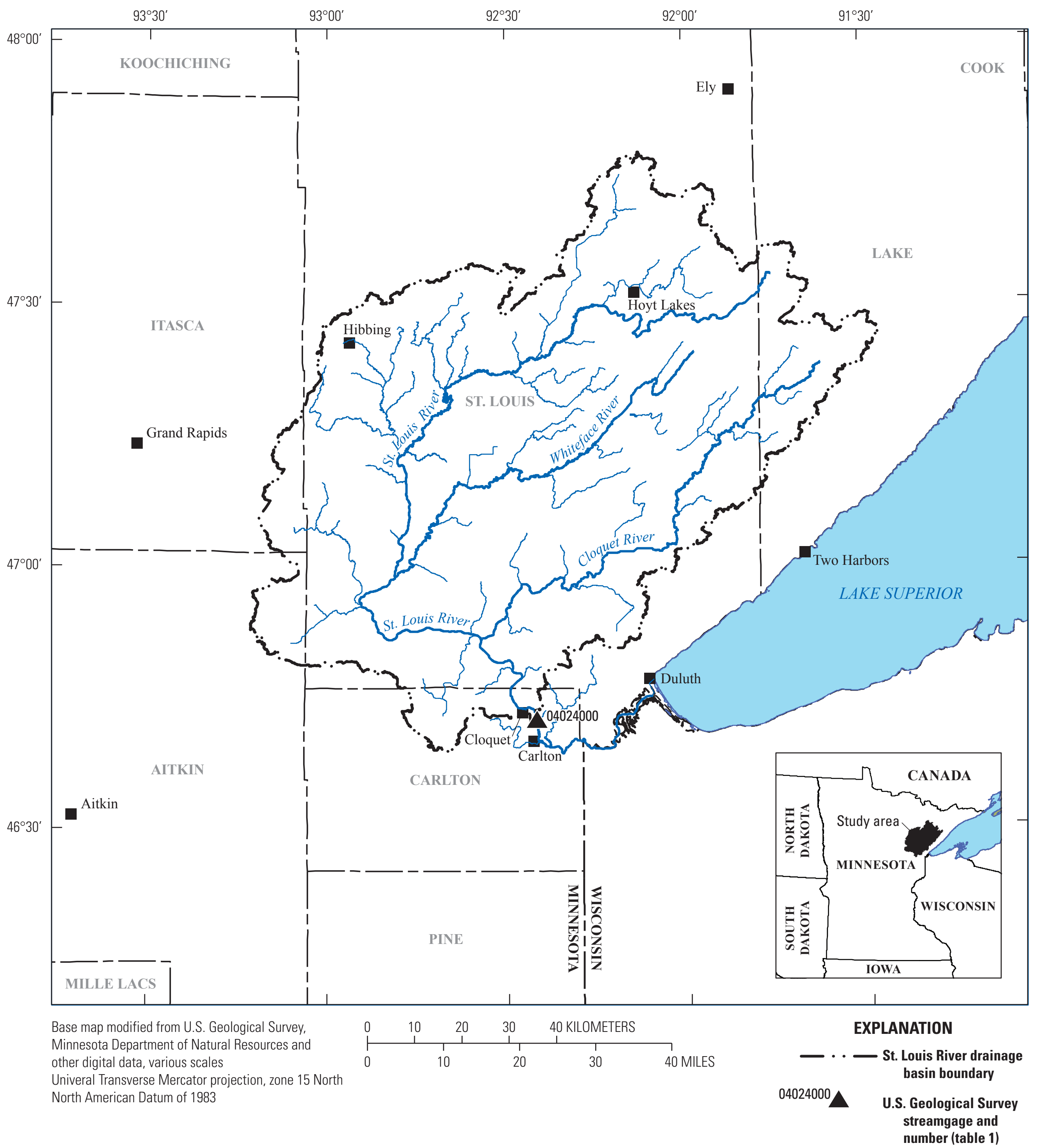

Figure 3. The St. Louis River study area, including the entire drainage basin above the St. Louis River at Scanlon, Minnesota, streamgage (U.S. Geological Survey station number 04024000), main stem of the St. Louis River, the Whiteface River, and the Cloquet River, major cities/towns, and other administrative boundaries.

Simulation Program-FORTRAN (HSPF) model that simulated drainage basin hydrology and water quality was constructed, calibrated, and validated by LimnoTech (2015) for the Cannon River WRAPS (Wotzka and Watkins, 2016).

The St. Louis River drainage basin also has had several reports published in the last 4 decades. Similar to the Cannon River, a preliminary water budget was included as part of a characterization of the St. Louis River surface-water and groundwater resources by Lindholm and others (1979). Additionally, the Fond du Lac Indian Reservation water resources were characterized by Ruhl (1989). The physical characteristics and comprehensive water quality synopses for the St. Louis River were summarized by Lindgren and others (2006); similar to the Lindgren and others (2006) report, a separate Minnesota Pollution Control Agency-led summary monitoring and assessment report was published by Anderson and others (2013). After the severe flooding of the St. Louis River in 2012, Czuba and others (2012) characterized the high-water marks for several communities in and around the St. Louis River, also creating flood-peak inundation maps and water-surface profiles for several of the most affected communities. Similar to the Cannon River, an HSPF model that simulated drainage basin hydrology and water quality was constructed, calibrated, and validated by Tetra Tech (2016).

Streamflow Distribution Maps

Methods used generally are cited from previously published reports (Smith and Westenbroek, 2015; Ziegeweid and others, 2015; Lorenz and others, 2016). The SWB model developed for Minnesota at a 1-km^2 resolution (Smith and Westenbroek, 2015) was used as a baseline model for the Cannon River and St. Louis River SWB models. Regression equations developed in Ziegeweid and others (2015) were used to estimate the FDC quantiles, based on hydrologic regions developed in Lorenz and Ziegeweid (2016). If techniques varied substantially from previously documented methods because of available data, model domain resolution, or time periods, those techniques are described in detail in this report. Estimated streamflow distribution maps were produced for four flow conditions as referenced to the long-term discharge characteristics for the streamgages on the Cannon River at Welch, Minn. (USGS station number 05355200), and the St. Louis River at Scanlon, Minn. (USGS station number 04024000). These profiles covered the following flow conditions: (1) extreme low-flow conditions, comparable to an exceedance-probability quantile of 0.95; (2) low-flow conditions, comparable to an exceedance-probability quantile of 0.90; (3) median flow, comparable to an exceedance-probability quantile of 0.50; and (4) a high-flow condition, comparable to an exceedance-probability quantile of 0.02.

The FDC statistics were generated using the estFDC method, part of the DVstats package (Lorenz, 2016) for the R statistical environment (RStudio Team, 2016). The estFDC method estimates streamflow at selected exceedance probabilities for ungaged sites in Minnesota, based on the regression equations developed from Ziegeweid and others (2015). The SWB model executable used for this study was compiled by Steve Westenbroek of the USGS on June 8, 2015; the SWB lookup table was based on the published Minnesota statewide Soil-Water-Balance model (Smith and Westenbroek, 2015), with minor modifications described in the "Soil-Water-Balance Models" section.

Flow-Duration Curve Statistics

The FDC statistics were calculated to predict streamflow at selected exceedance-probability quantiles. The two drainage basins, the Cannon River and the St. Louis River, were subdivided into 152 nested drainage basins in the Cannon River above the Welch, Minn., streamgage, and 353 nested drainage basins in the St. Louis River above the Scanlon, Minn., streamgage. The selected exceedance-probability quantiles (0.95, 0.90, 0.50, and 0.02) were used as a representation of the spatial streamflow contribution from different parts of the drainage basins. The 13 exceedance probabilities were developed in Ziegeweid and others (2015) using the weighted left-censored regression method (Helsel and Hirsch, 2002). Regional regression equations were developed for five hydrologic regions in Minnesota; the Cannon and St. Louis drainage basins contain three of the five regions, including region BC that combines regions B and C (Lorenz and others, 2010). An illustration of the regional boundaries, regions D and E were present in the Cannon River and region BC was present in the St. Louis River, is shown in figure 4.

The regional regression equations for the flow-duration curves rely upon explanatory variables related to basin characteristics. The regional regression equations used in this study are based on five basin characteristics (Ziegeweid and others, 2015): (1) drainage area, in square miles (DRNAREA); (2) percentage of drainage basin area consisting of lakes and wetlands (STORAGE); (3) percentage of drainage basin area consisting of hydrologic soil group C (SOILC); (4) percentage of mean basin low-lying flatland (PFLATLOW); and (5) percentage of area of forested land (FOREST). The FDC statistics for the 505 nested drainage basins were calculated from the imported explanatory basin characteristics using the estFDC method from the R package DVstats (Lorenz, 2016). Once the 13 exceedance-probability quantiles that define the FDC were calculated for each of the 505 nested drainage basins, these quantiles were exported from R into Microsoft® Excel for further postprocessing; all the FDC statistics are available on USGS ScienceBase (Smith, 2017a, 2017b).

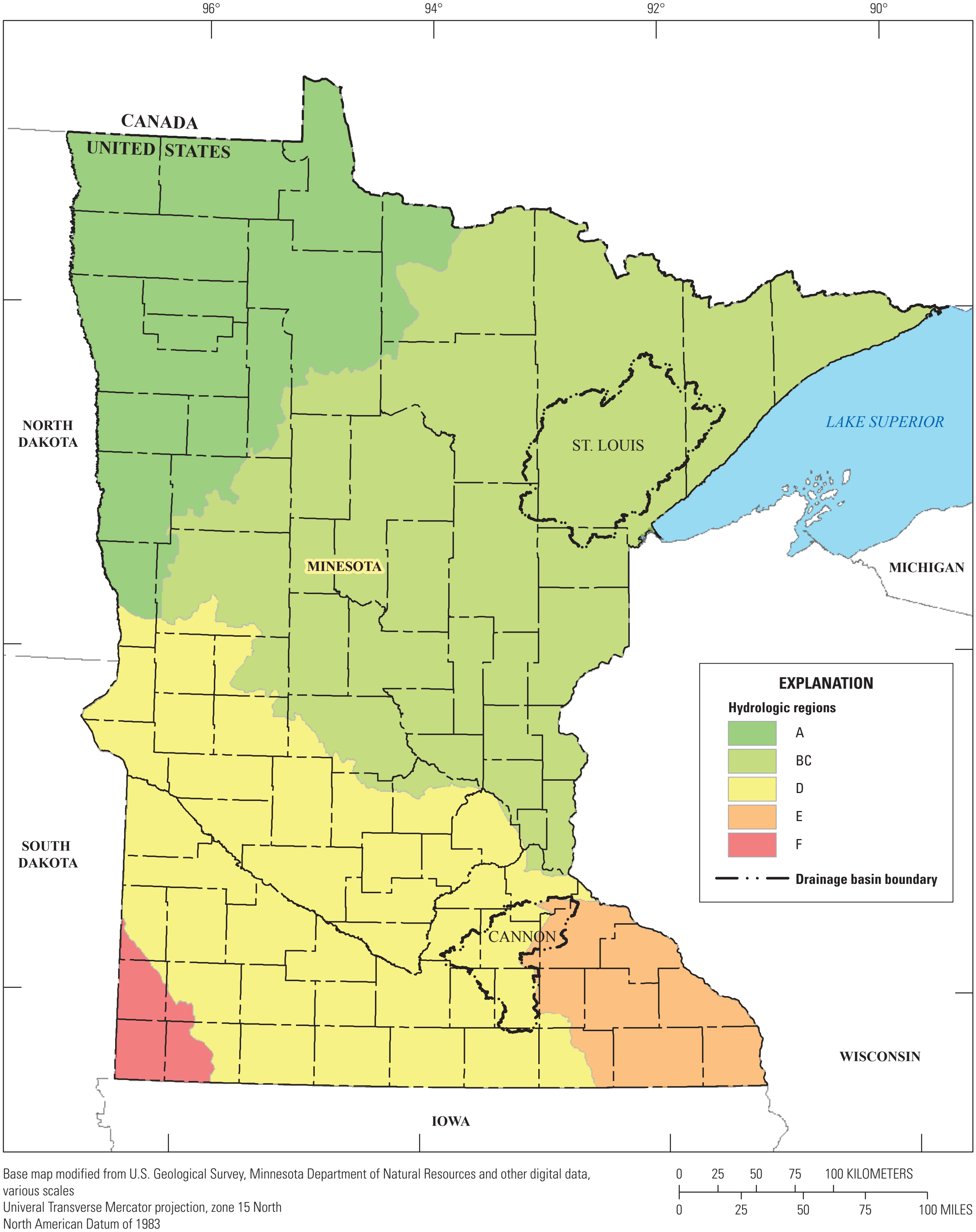

Figure 4. The five hydrologic regions in Minnesota, as defined by the regional regression equations from Ziegeweid and others (2015), along with the Cannon River drainage basin (above the Cannon River at Welch, Minnesota [U.S. Geological Survey station number 05355200]), and the St. Louis River drainage basin (above the St. Louis River at Scanlon, Minnesota [U.S. Geological Survey station number 04024000]).

Soil-Water-Balance Models

The SWB model uses a modified Thornthwaite-Mather SWB accounting method (Thornthwaite and Mather, 1955, 1957) to estimate potential recharge to groundwater and surface runoff on a daily basis (Westenbroek and others, 2010). The SWB approach calculates the values of the water-budget components based on relations among surface runoff, land cover, hydrologic soil group, maximum soil-water capacity, ET estimates, and temperature. Each of the water-budget components is handled by one or more modules within the SWB model. Within the SWB approach, potential recharge is calculated within each grid cell of the model domain separately based on the differences among sources (precipitation, snowmelt, inflow), sinks (interception, outflow, ET), and changes in soil moisture (Δsoil moisture). Outflow from each grid cell, also known as surface runoff, is calculated by the U.S. Department of Agriculture Natural Resources Conservation Service curve number rainfall-runoff relation, also known as the curve number method (Cronshey and others, 1986).

The SWB model uses the soil and land-cover lookup table to assign model cell properties related to soils and land cover (Westenbroek and others, 2010). The soil and land-cover lookup table cross-references the 15 land-cover classes in Minnesota, as derived from the National Land Cover Database (NLCD) classification (Homer and others, 2007; Fry and others, 2011) to five soil classes (four hydrologic soil group classes plus a special organic soil class) to assign the curve number, daily maximum recharge (in inches per day), and the root-zone depth (in feet). Hydrologic soil group data used in the SWB model were obtained from two separate soil geographic databases, both distributed by and available for download from the U.S. Department of Agriculture Natural Resources Conservation Service (Natural Resources Conservation Service, 2014): (1) the Soil Survey Geographic (SSURGO) database and (2) the State Soil Geographic (STATSGO) database.

Individual SWB models were used as a method for estimating potential recharge and surface runoff for the Cannon River and St. Louis River drainage basins. The SWB models calibrated for this study were largely based on the Smith and Westenbroek (2015) SWB model, which estimated the average potential groundwater recharge across Minnesota from 1996 through 2010 at a 1-km^2 resolution. Further calibration simulations for this study compared the potential recharge estimate from the SWB model to annual base-flow estimates derived from hydrograph separation techniques using the USGS groundwater toolbox (Barlow and others, 2015). Additionally, the sum of annual potential recharge and runoff from the individual SWB models was compared to the annual mean flow for the two drainage basins at the previously mentioned streamgages.

For this report, the published statewide SWB model (Smith and Westenbroek, 2015) was rerun for the period 1996–2010 (Smith, 2017a, 2017b). All meteorological data were provided by the Daymet dataset, which provided key climatological data such as daily precipitation, minimum daily temperature, and maximum daily temperature (Thornton and others, 1997). The grid was refined to a 100-square meter resolution, rather than the original 1-km^2 resolution, including the other inputs such as the hydrologic soil groups and available soil-water capacity. The soil and land-cover lookup table from the published statewide SWB model (Smith and Westenbroek, 2015) was used for the Cannon and St. Louis River drainage basin SWB models with only slight adjustments as explained in the next two sections. One feature of the soil and land-cover lookup table of the statewide model, interception, was zeroed out for all values; interception for SWB was defined as the part of precipitation intercepted by the plant canopy and lost to ET but was a minimal component of the statewide model and technically has overlap with curve numbers.

Cannon River Drainage Basin

Further refinement of the Cannon River SWB model (Smith, 2017a) consisted of manual calibrations comparing the potential recharge estimates to the annual base-flow estimates from the Cannon River at Welch, Minn., streamgage (USGS station number 05355200). The annual base-flow estimates were generated using three different hydrograph separation techniques: PART (Rutledge, 1998), HYSEP fixed-interval method (Sloto and Crouse, 1996), and HYSEP sliding method (Sloto and Crouse, 1996). Additionally, the combined potential recharge and surface runoff estimates were compared to annual mean streamflow from the same streamgage. As a baseline SWB model, the published statewide SWB model with the increased 100-m resolution was used, and manual adjustments were completed only on the soil and land-cover lookup table. The construction of the original model was preserved as much as possible; only multiplier adjustments were made to parts of the lookup table.

For an individual iteration, subgroups of curve numbers and root-zone depths within the lookup table were altered by a multiplier to determine if the new set of parameter values improved the difference between the SWB model results and both the base-flow estimates (from the hydrograph separation techniques) and total flow. Improvements in the SWB model calibration from the statewide model were evaluated using relative errors. The relative error between the 15-year mean annual potential recharge estimates from SWB and the 15-year mean annual base flow estimates from the three different hydrograph separation techniques was considered with little emphasis on individual years. The relative error (dimensionless) of the potential recharge estimate from the SWB model for each drainage basin in table 2 was calculated by using equation 1:

$$relative\ error = \frac{potential\ recharge - (mean\ base - flow\ estimate)}{mean\ base - flow\ estimate} \quad (1)$$

where the *potential recharge*, in inches per year, is obtained from the SWB model and the *mean base-flow estimate* is the mean of the three base-flow estimates determined using hydrograph separation techniques, in inches per year.

After several iterations, the final calibration yielded relative errors for the overall mean base-flow estimate and total flow estimate of less than (<) 0.01 ft^3/s; for the individual years,

Table 2. Annual mean base flow estimates rates (from 1996 to 2010) using three hydrograph separation techniques for the Cannon River at Welch, Minnesota (U.S. Geological Survey station number 05355200), used in model calibration analysis in comparison to the Soil-Water-Balance model estimated annual potential recharge rates. Additional comparison shown between the annual mean streamflow and the Soil-Water-Balance model estimated annual sum of potential recharge and surface runoff rates.

[in/yr, inch per year; <, less than]

Year	Base-flow estimate (in/yr)				Soil-Water-Balance model (in/yr)		Annual mean streamflow (in/yr)	Relative error	
	PART[a] (in/yr)	HYSEP fixed-interval method[b]	HYSEP sliding method[b]	Mean base-flow estimate	Potential recharge rate	Potential recharge rate and surface runoff		Mean base-flow estimate[c]	Total flow estimate[d]
1996	5.79	5.34	5.38	5.50	5.18	6.79	7.11	−0.06	−0.04
1997	8.99	8.72	8.52	8.74	8.82	11.31	11.85	0.01	−0.05
1998	9.11	8.20	8.26	8.52	7.61	9.46	11.98	−0.11	−0.21
1999	8.53	8.21	7.81	8.18	7.92	10.24	10.73	−0.03	−0.05
2000	6.04	5.44	5.46	5.65	4.62	6.97	8.00	−0.18	−0.13
2001	8.77	9.04	8.46	8.76	9.10	13.12	12.24	0.04	0.07
2002	6.37	5.93	5.84	6.05	7.08	10.00	8.05	0.17	0.24
2003	4.53	4.19	4.12	4.28	1.52	2.84	5.42	−0.64	−0.48
2004	7.10	6.76	6.28	6.71	8.36	11.44	9.88	0.24	0.16
2005	6.77	6.07	6.11	6.32	5.82	8.80	8.75	−0.08	0.01
2006	6.10	5.77	5.73	5.87	5.41	7.57	7.68	−0.08	−0.01
2007	7.80	6.45	6.66	6.97	10.68	13.93	10.17	0.53	0.37
2008	5.88	5.49	5.51	5.63	3.75	5.32	7.19	−0.33	−0.26
2009	3.14	2.98	2.96	3.03	4.56	6.34	3.82	0.51	0.66
2010	10.21	9.04	8.55	9.27	9.26	13.03	13.94	−0.00	−0.07
1996–2010	7.01	6.51	6.38	6.63	6.65	9.14	9.12	<0.01	<0.01

[a]Rutledge (1998).

[b]Sloto and Crouse (1996).

[c]The relative error is the soil-water-balance potential recharge estimate to the mean of the three different base-flow estimates (equation 1).

[d]The relative error is the soil-water-balance estimate (potential recharge and surface runoff) to the annual mean streamflow (equation 1).

the mean base-flow estimate relative errors ranged from -0.64 to 0.53 ft^3/s, and the total flow estimate ranged from -0.48 to 0.66 ft^3/s (table 2). Compared to the original Minnesota statewide SWB model, the following differences were made for the Cannon River for the soil and land-cover lookup table: (1) all curve numbers for the NLCD land-use classifications (LUCs) of grassland/herbaceous (LUC 71), pasture/hay (LUC 81), and cultivated crops (LUC 82) were multiplied by 1.08; and (2) all root-zone depths for the NLCD LUCs of grassland/herbaceous (LUC 71), pasture/hay (LUC 81), and cultivated crops (LUC 82) were multiplied by 0.82. Besides these changes and the zeroing out of the interception values mentioned earlier, all other features of the Cannon River SWB model (Smith, 2017a) were identical to the published Minnesota statewide SWB model (Smith and Westenbroek, 2015).

St. Louis River Drainage Basin

Similar to the Cannon River SWB model, further refinement of the St. Louis River SWB model (Smith, 2017b) consisted of manual calibrations comparing the potential recharge estimates to the annual base-flow estimates from the St. Louis River at Scanlon, Minn. (USGS station number 04024000). The same annual base-flow estimates were generated, and the combined potential recharge and surface runoff estimates were compared to annual mean streamflow from the Scanlon streamgage. The baseline St. Louis River SWB model was run with the published statewide SWB model using an increased 100-m resolution, and manual adjustments were completed only on the soil and land-cover lookup table and the SWB control file.

For an individual iteration, subgroups of curve numbers and root-zone depths within the lookup table, in addition to the rainfall and snowfall multipliers from the control file, were altered to determine improvements in the fit between the same calibration criteria outlined for the Cannon River SWB model. Model calibration improvements were evaluated using relative errors.

After several iterations, the final calibration yielded relative errors for the overall mean base flow estimate and total flow estimate of <0.01 ft^3/s; for the individual years, the mean base flow estimate relative errors ranged from -0.53 to 0.70 ft^3/s, and the total flow estimate ranged from -0.21 to 0.63 ft^3/s (table 3). Compared to the original Minnesota statewide SWB model, the following differences were made for the St. Louis River in the soil and land-cover lookup table: (1) all curve numbers for the NLCD LUCs of deciduous forest (LUC 41), evergreen forest (LUC 42), and mixed forest (LUC 43) were multiplied by 1.25; and (2) all curve numbers for the NLCD LUCs of woody wetlands (LUC 90) and emergent herbaceous wetlands (LUC 95) were increased from 60 to 83. Within the SWB control file, the rainfall and snowfall correction factors were increased from 1.00 to 1.092. In addition to the zeroing out of the interception values, all other features of the St. Louis River SWB model (Smith, 2017b) were identical to the published Minnesota statewide SWB model (Smith and Westenbroek, 2015).

Adjusting the Flow-Duration Curve Statistics using the Soil-Water-Balance Model Output

The SWB components of potential recharge and outflow were used as surrogates for base flow and surface runoff, respectively; therefore, the sum of the 15-year means for these two SWB water budget components was used to calculate the long-term mean total flow from the SWB model. In ArcGIS 10.4 (Esri, 2017), the mean SWB flow for each of the 505 drainage basins was calculated and exported to Microsoft® Excel. The 13 exceedance-probability quantiles that define the FDC, previously calculated for each of the 505 drainage basins, were further processed to determine the mean FDC flow (Smith, 2017a, 2017b).

The mean FDC flow is defined as the area underneath the FDC curve. The mean FDC flow was calculated by multiplying each flow percentile by the respective FDC statistic. Each flow percentile was assumed to represent the flow at the halfway point between the surrounding percentiles (or 0 or 100 in the two end-members); for example, in the 13 FDC statistics for this study, the 5th percentile (0.05) represents the mean flow value for 0.035 to 0.075 percent, the 10th percentile (0.10) represents the mean flow value for 0.075 to 0.175 percent, and so forth. So, if the FDC exceedance probability for the 5th percentile was 1,000 ft^3/s, 1,000 ft^3/s would be multiplied by 0.04 (difference between 0.035 and 0.075); if the FDC exceedance probability for the 10th percentile was 750 ft^3/s, 750 ft^3/s would be multiplied by 0.10 (the difference between 0.075 and 0.175). These calculations for all 13 FDC exceedance probabilities would be carried out and summed to calculate the mean FDC flow. This calculation was completed for all 505 drainage basins.

The next step was to calculate the ratio of mean SWB total flow to mean FDC flow. The ratios differed for each nested drainage basin and ranged from 0.075 to 1.757. The ratio was multiplied by the previously calculated FDC exceedance probabilities, thereby defining an adjusted set of 13 FDC exceedance probabilities. From these adjusted FDC exceedance probabilities, a subset of four flow conditions was selected for the streamflow distribution maps; however, any of the 13 FDC exceedance probabilities could be mapped as a typical flow condition across the drainage basin for a given exceedance probability. The four chosen flow conditions, (1) extreme low-flow conditions, comparable to an exceedance-probability quantile of 0.95; (2) low-flow conditions, comparable to an exceedance-probability quantile of 0.90; (3) median flow, comparable to an exceedance-probability quantile of 0.50; and (4) a high-flow condition, comparable to an exceedance-probability quantile of 0.02, were selected for illustrative purposes and were based upon feedback from Minnesota Department of Natural Resources and Minnesota Pollution Control Agency personnel (sheets 1 and 2).

Table 3. Annual mean base flow estimates rates (from 1996 to 2010) using three hydrograph separation techniques for the St. Louis River at Scanlon, Minnesota (U.S. Geological Survey station number 04024000), used in model calibration analysis for comparison to the Soil-Water-Balance model estimated annual potential recharge rates. Additional comparison shown between the annual mean streamflow and the Soil-Water-Balance model estimated annual sum of potential recharge and surface runoff rates.

[in/yr, inch per year; <, less than]

Year	Base-flow estimate (in/yr)				Soil-Water-Balance model (in/yr)		Annual mean streamflow (in/yr)	Relative error	
	PART[a] (in/yr)	HYSEP fixed-interval method[b]	HYSEP sliding method[b]	Mean base-flow estimate	Potential recharge rate	Potential recharge rate and surface runoff		Mean base-flow estimate[c]	Total flow estimate[d]
1996	10.89	9.78	9.74	10.14	8.98	11.66	14.31	−0.11	−0.19
1997	8.97	8.01	8.05	8.34	6.76	9.74	11.24	−0.19	−0.13
1998	6.05	5.78	5.78	5.87	7.59	10.41	8.63	0.29	0.21
1999	11.15	10.10	9.95	10.40	10.18	14.53	16.00	−0.02	−0.09
2000	5.92	5.49	5.53	5.65	4.05	6.67	7.81	−0.28	−0.15
2001	9.66	9.44	8.77	9.29	9.74	12.86	13.23	0.05	−0.03
2002	6.25	5.89	5.75	5.96	5.54	8.72	9.29	−0.07	−0.06
2003	4.45	4.14	4.20	4.26	2.01	4.38	5.54	−0.53	−0.21
2004	6.35	5.65	5.69	5.90	5.54	7.72	8.03	−0.06	−0.04
2005	6.40	6.01	6.08	6.16	6.19	8.52	8.44	0.00	0.01
2006	4.89	4.30	4.31	4.50	3.33	5.22	6.47	−0.26	−0.19
2007	5.58	5.12	5.07	5.26	8.92	11.99	7.34	0.70	0.63
2008	7.61	6.73	6.70	7.01	7.26	9.42	9.65	0.03	−0.02
2009	6.18	5.71	5.76	5.88	7.00	9.58	7.56	0.19	0.27
2010	4.48	3.89	4.04	4.14	5.41	8.03	5.85	0.31	0.37
1996–2010	6.99	6.40	6.36	6.58	6.57	9.30	9.29	<0.01	<0.01

[a]Rutledge (1998).

[b]Sloto and Crouse (1996).

[c]The relative error is the soil-water-balance potential recharge estimate to the mean of the three different base-flow estimates (equation 1).

[d]The relative error is the soil-water-balance estimate (potential recharge and surface runoff) to the annual mean streamflow (equation 1).

Limitations and Assumptions

The limitations and assumptions for the streamflow distribution maps inherently depend on the underlying FDC statistics and SWB model results. A full understanding of model limitations and assumptions is necessary to better evaluate the performance of any hydrologic model. The SWB model was originally developed to allow for recharge calculations based on readily available data and standardized parameters for short-term periods (Westenbroek and others, 2010). Both SWB models used in this study were intended to obtain estimates of the amount of potential recharge and surface runoff; however, in this study, mean potential recharge and surface runoff estimates (that is, the mean for the 15-year period 1996–2010) were calculated for the 15-year period from 1996 to account for climate cycles and variability in surficial aquifer groundwater flow rates.

The SWB conceptual model for this study assumed that the base-flow component from the hydrograph separation technique was correct, even though this base-flow estimate was a simulated result. For comparisons made in this study, all SWB potential recharge was assumed to become base flow to the respective streamgaged drainage basin; furthermore, all groundwater exchange between the surficial aquifer and deeper aquifers was assumed to be at steady state. Finally, drainage basin boundaries of the streamgaged surface-water bodies were assumed to coincide with the boundaries of contributing recharge areas to the surficial aquifer, even though these boundaries do not always coincide (Kanivetsky, 1979).

General limitations and assumptions of the SWB model are discussed in great detail in the conceptual SWB report (Westenbroek and others, 2010) and the Minnesota statewide SWB model (Smith and Westenbroek, 2015). First, potential recharge is assumed to eventually become actual recharge.

Next, because the path or distance to the water table is not known, the SWB model only represents water leaving the root zone. The model assumes that recharge is instantaneous within the daily time step, but actual recharge can sometimes take months or even years. Even if the recharge reaches the water table in days to weeks, it can take much longer for the same recharge water to become base flow to the nearest surface-water body. Theoretical limitations to the SWB model also relate to the aggregation of meteorological data to daily time steps; however, except for groundwater-flow models for small areas, daily time steps are considered reasonable and are recommended for water-budget tabulations (Healy and Scanlon, 2010).

Several limitations warrant consideration when using the FDC statistics presented in this report. The applicability and accuracy of the underlying regional equations depend on if the basin characteristics calculated for an ungaged stream location are within the range of the values for variables used to develop the regression equations. Inconsistencies may happen because regional regression equations were developed separately and have variable estimation intervals depending on the size and variability of the datasets used to develop regression equations (Ziegeweid and others, 2015). Additionally, adjustments to the regression equations based on the mean flow from the SWB model assumes that the bias in the regression equation estimates are constant across the FDC. Estimates at the extremes often exhibit more bias than estimates at the mean flow, so manipulation of the low-flow estimates would lead to a higher bias.

Several factors affect the estimation accuracy of the underlying regression equations to develop the FDC statistics. Estimation accuracy depends on the sample size, the accuracy of each recorded streamflow, and how well the chosen distribution fits the actual distribution of the data (Lorenz and others, 2010). The accuracies of regression estimates are affected by errors in explanatory variables, and systematic errors in the computation of the response variable can bias estimates.

Special attention must be given to censored values and the number of significant figures used. Because of the uncertainty in measuring and estimating flows less than 0.1 ft^3/s, the censoring threshold used to develop the left-censored regression equations was set at 0.1 ft^3/s; thus, any regression estimates that were 0.1 ft^3/s or less were reported as less than 0.1 ft^3/s. Because the precision of response and explanatory variable data used to develop the equations commonly was limited to three significant figures, selected-statistic streamflows estimated from the regression equations also were limited to three significant figures. The discussion from Ziegeweid and others (2015) is recommended for a further summary of limitations and assumptions for FDC statistics.

Summary

Streamflow distribution maps for the Cannon River and St. Louis River drainage basins were developed by the U.S. Geological Survey, in cooperation with the Legislative-Citizen Commission on Minnesota Resources, to illustrate relative and cumulative streamflow distributions. The Cannon River was selected to provide baseline data to assess the effects of potential surficial sand mining, and the St. Louis River was selected to determine the effects of ongoing Mesabi Iron Range mining. These maps (available at https://doi.org/10.3133/sim3390) can help guide potential State cooperators such as the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency for proactive water management, ensure streamflows meet ecological needs at different flow conditions, and assist with decisions for groundwater appropriations at low-flow conditions.

These maps were developed using flow-duration curve (FDC) statistics in conjunction with Soil-Water-Balance (SWB) model output, specifically potential recharge and surface runoff. The mean flow calculated from the FDC statistics was compared to the mean total flow (potential recharge estimates and the surface runoff estimates) from the SWB models. The ratio of mean SWB total flow to mean FDC flow was calculated, and these ratios were used to readjust the 13 FDC exceedance probabilities. The selected streamflow distribution maps illustrate streamflow contributions from different parts of the drainage basin for typical conditions, not necessarily the contribution for any particular time.

A subset of the FDC exceedance probabilities defining the following flow conditions was mapped for 505 nested drainage basins (152 nested drainage basins in the Cannon River and 353 nested drainage basins in the St. Louis River): (1) extreme low-flow conditions, comparable to an exceedance-probability quantile of 0.95; (2) low-flow conditions, comparable to an exceedance-probability quantile of 0.90; (3) a median condition, comparable to an exceedance-probability quantile of 0.50; and (4) a high-flow condition, comparable to an exceedance-probability quantile of 0.02.

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Smith and others— Streamflow Distribution Maps for the Cannon River Drainage Basin and the St. Louis River Drainage Basin, Minnesota—SIM 3390

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U.S. Department of the Interior
U.S. Geological Survey

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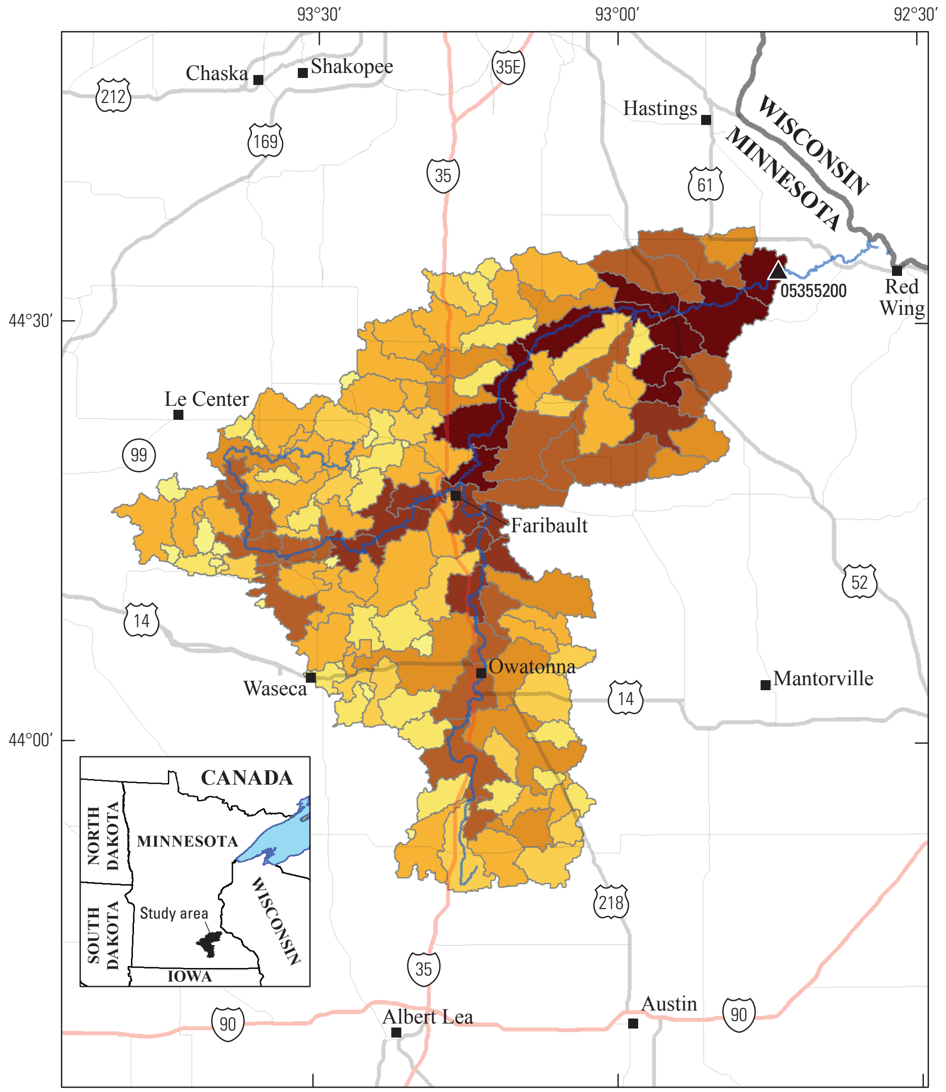
Scientific Investigations Map 3390
Sheet 1 of 2
Pamphlet accompanies map



Base map modified from U.S. Geological Survey, Minnesota Department of Natural Resources and other digital data, various scales
Universal Transverse Mercator projection, zone 15 North
North American Datum of 1983

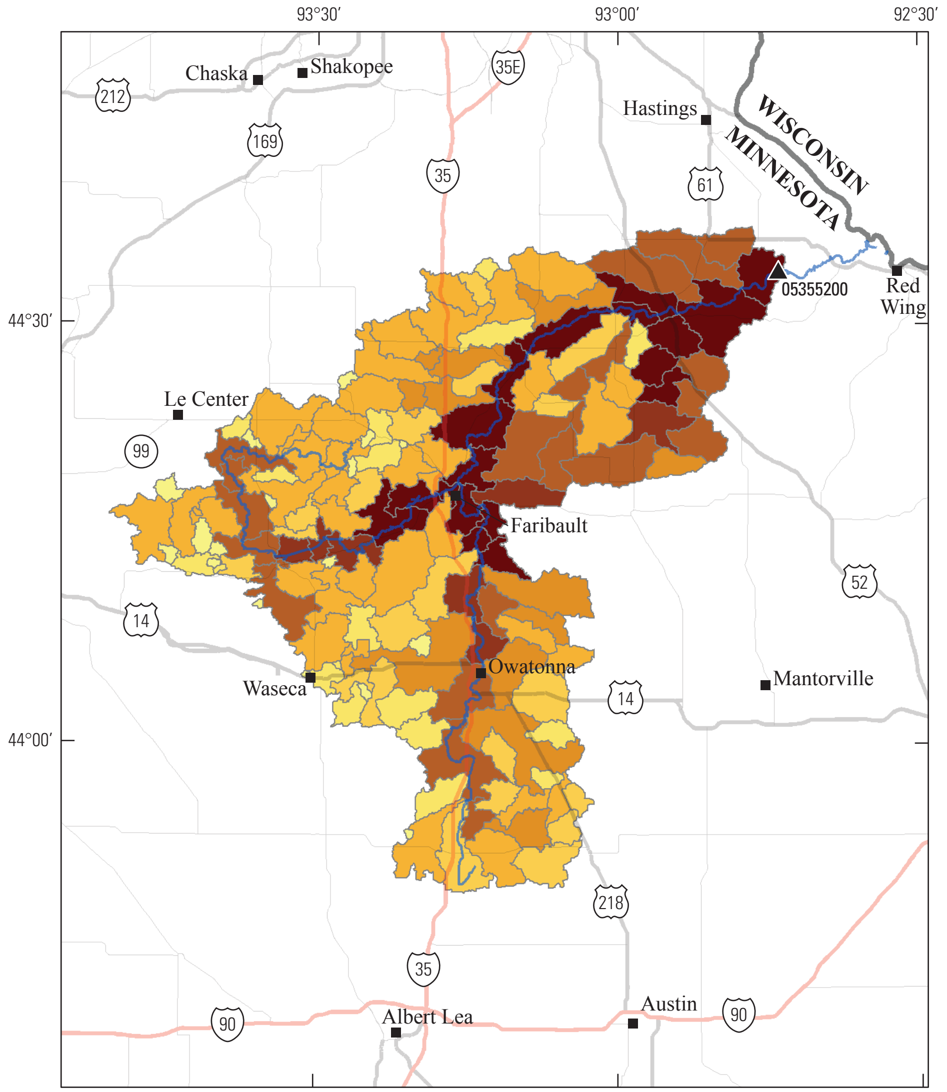
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 95 percent of the time

0.000262 to 0.0100	0.501 to 1.00
0.0101 to 0.0500	1.01 to 5.00
0.0501 to 0.100	5.01 to 10.0
0.101 to 0.500	10.1 to 45.0

Interstate highway
U.S. highway
Minnesota State highway
05355200 ▲ U.S. Geological Survey streamgage and number (table 1)



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Universal Transverse Mercator projection, zone 15 North
North American Datum of 1983

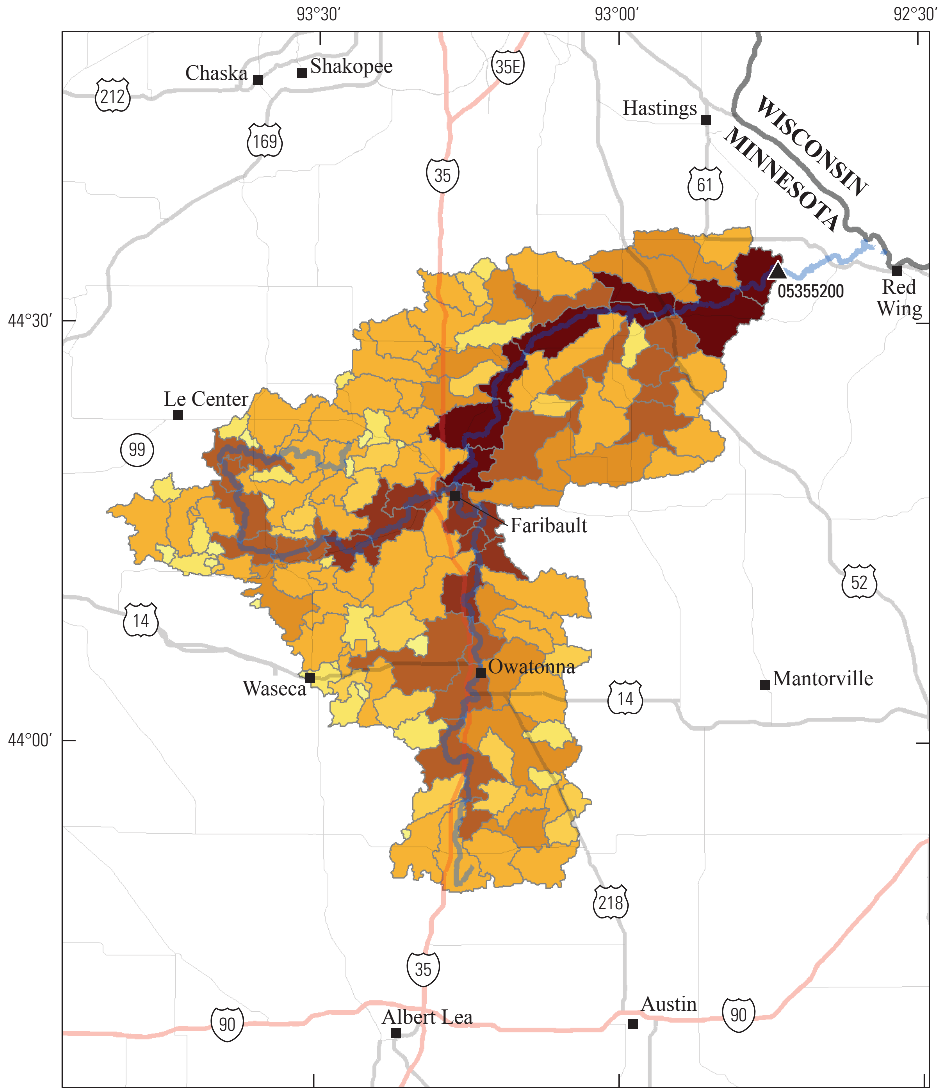
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 90 percent of the time

0.000569 to 0.0100	0.501 to 1.00
0.0101 to 0.0500	1.01 to 5.00
0.0501 to 0.100	5.01 to 10.0
0.101 to 0.500	10.1 to 79.5

Interstate highway
U.S. highway
Minnesota State highway
05355200 ▲ U.S. Geological Survey streamgage and number (table 1)



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Universal Transverse Mercator projection, zone 15 North
North American Datum of 1983

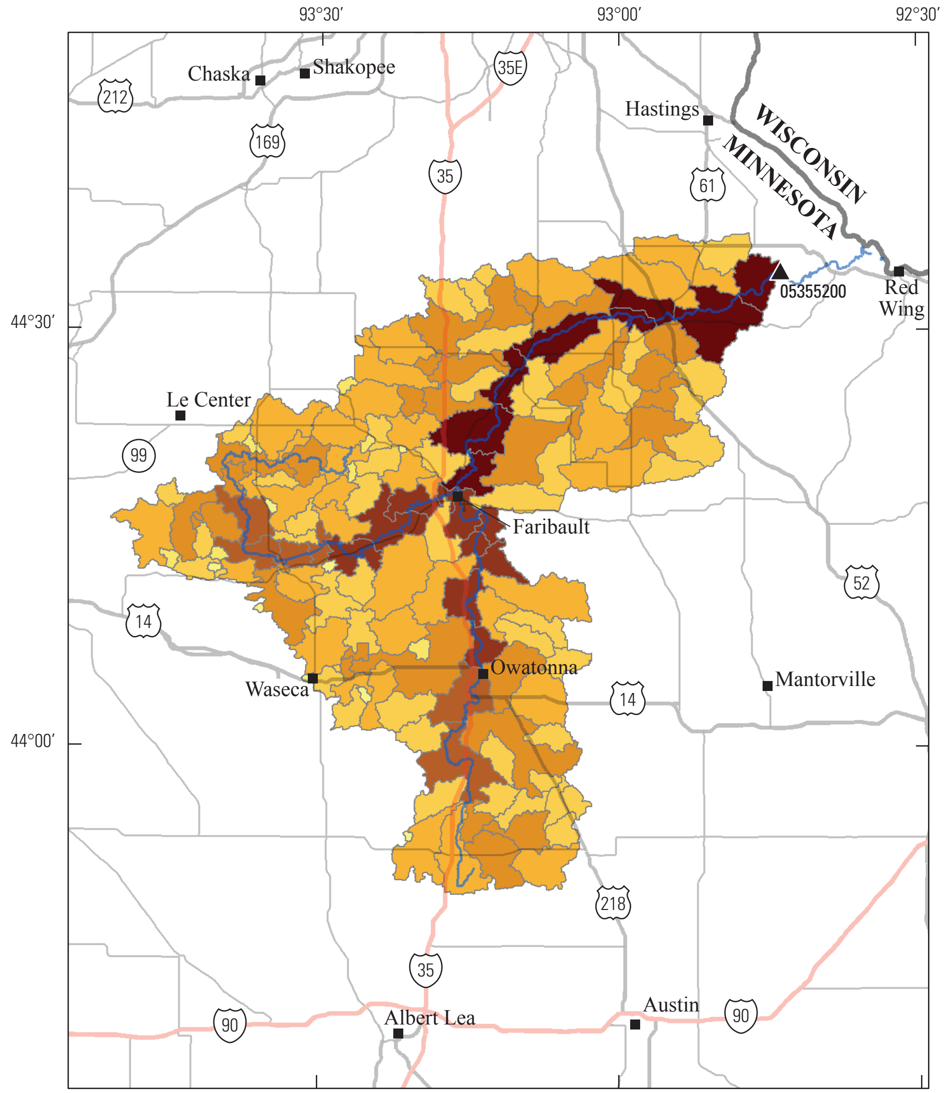
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 50 percent of the time

0.0143 to 0.100	5.01 to 10.0
0.101 to 0.500	10.1 to 50.0
0.501 to 1.00	50.1 to 100
1.01 to 5.00	101 to 404

Interstate highway
U.S. highway
Minnesota State highway
05355200 ▲ U.S. Geological Survey streamgage and number (table 1)



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North American Datum of 1983

0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 2 percent of the time

1.91 to 5.00	101 to 500
5.01 to 10.0	501 to 1,000
10.1 to 50.0	1,010 to 2,000
50.1 to 100	2,010 to 4,600

Interstate highway
U.S. highway
Minnesota State highway
05355200 ▲ U.S. Geological Survey streamgage and number (table 1)

The streamflow distribution maps should not be used for regulatory, permitting, or other legal purposes. The USGS provides these maps "as-is" for a quick-reference, but assumes no legal liability or responsibility resulting from the use of this information.

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U.S. Department of the Interior
U.S. Geological Survey

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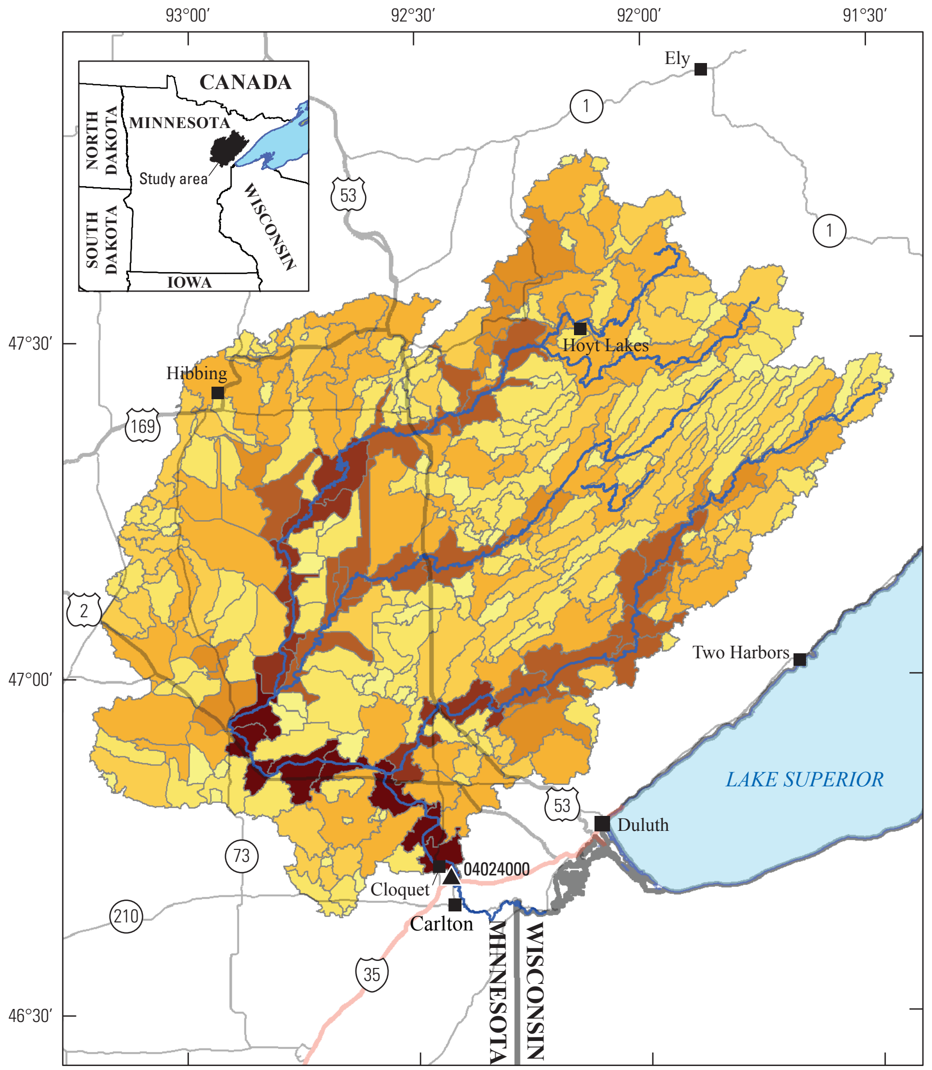
Scientific Investigations Map 3390
Sheet 2 of 2
Pamphlet accompanies map



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Universal Transverse Mercator projection, zone 15 North
North American Datum of 1983

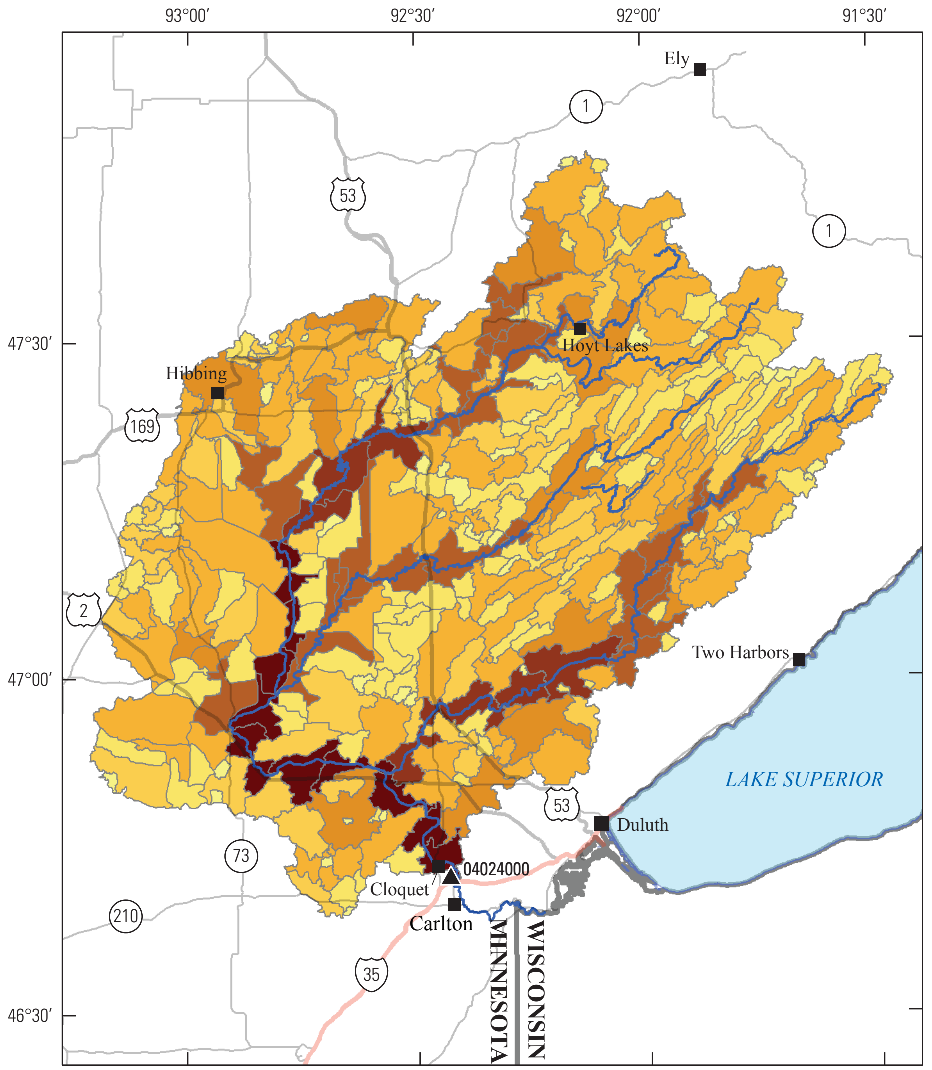
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 95 percent of the time

0.00877 to 0.100	5.01 to 10.0
0.101 to 0.500	10.1 to 50.0
0.501 to 1.00	50.1 to 100
1.01 to 5.00	101 to 261

Interstate highway
U.S. highway
Minnesota State highway
04024000 ▲ U.S. Geological Survey streamgage and number (table 1)



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North American Datum of 1983

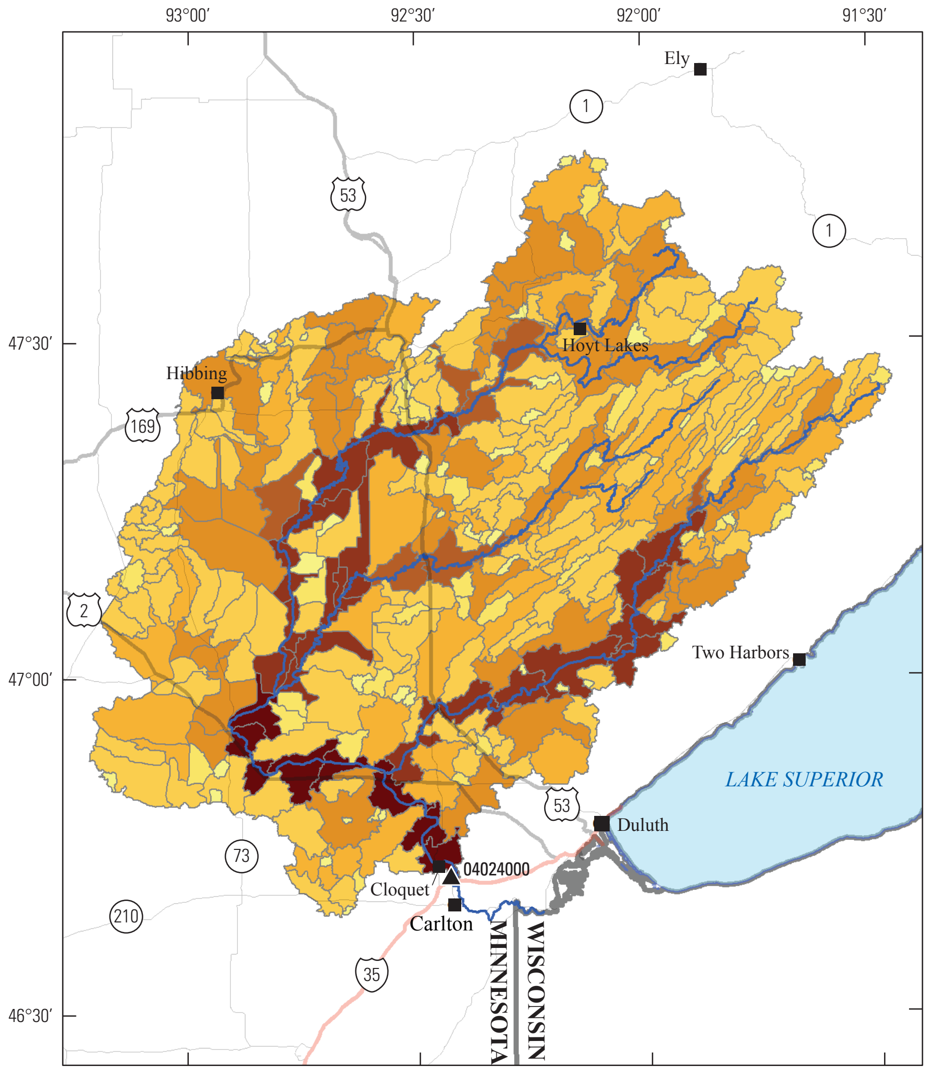
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 90 percent of the time

0.0191 to 0.100	5.01 to 10.0
0.101 to 0.500	10.1 to 50.0
0.501 to 1.00	50.1 to 100
1.01 to 5.00	101 to 346

Interstate highway
U.S. highway
Minnesota State highway
04024000 ▲ U.S. Geological Survey streamgage and number (table 1)



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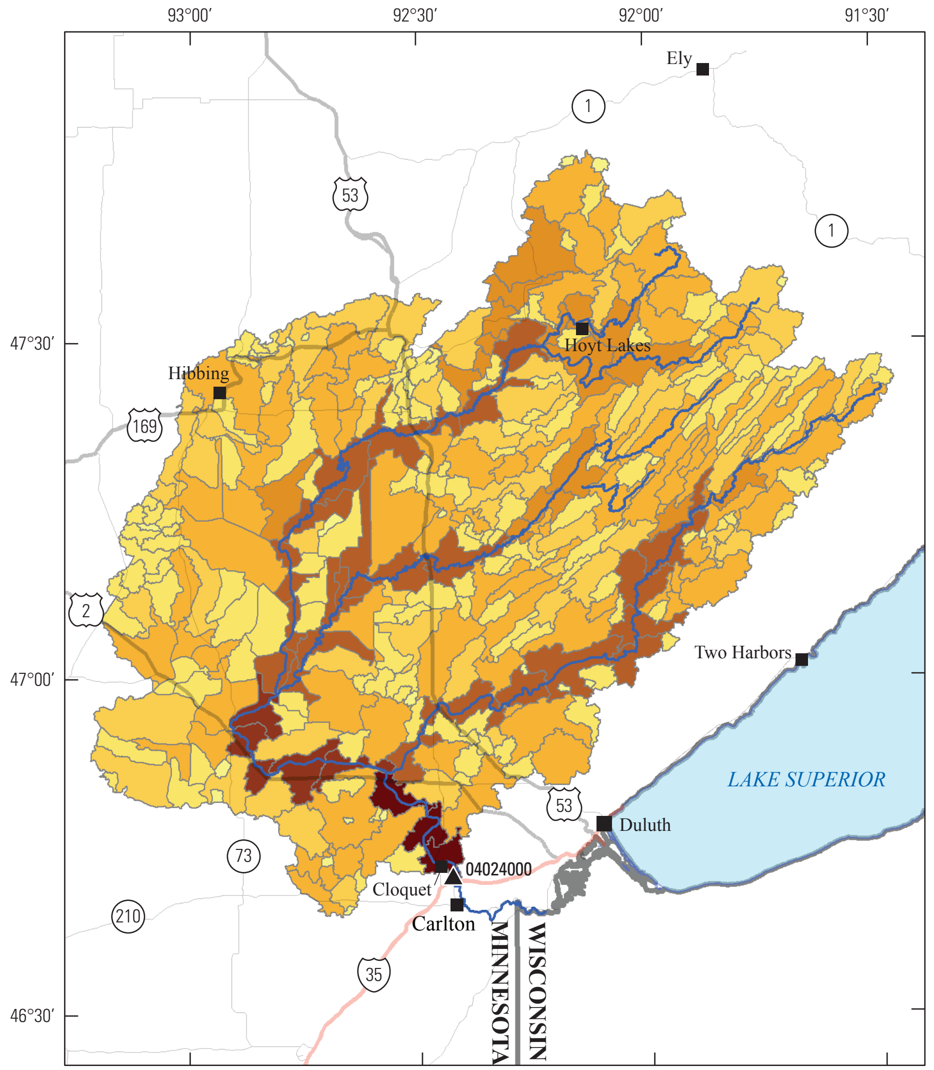
0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 50 percent of the time

0.116 to 0.500	10.1 to 50.0
0.501 to 1.00	50.1 to 100
1.01 to 5.00	101 to 500
5.01 to 10.0	501 to 1,110

Interstate highway
U.S. highway
Minnesota State highway
04024000 ▲ U.S. Geological Survey streamgage and number (table 1)



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North American Datum of 1983

0 10 20 KILOMETERS
0 10 20 MILES

EXPLANATION

Estimated flow, in cubic feet per second, exceeded 2 percent of the time

2.35 to 10.0	501 to 1,000
10.1 to 50.0	1,010 to 5,000
50.1 to 100	5,010 to 10,000
101 to 500	10,100 to 11,500

Interstate highway
U.S. highway
Minnesota State highway
04024000 ▲ U.S. Geological Survey streamgage and number (table 1)

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