**2007 Project Abstract**
For the Period Ending June 30, 2009

**PROJECT TITLE:** Water Resources Sustainability

**Project Manager**: John L. Nieber
**Affiliation:** Department of Bioproducts and Biosystems Engineering, University of Minnesota
**Mailing Address:** 1390 Eckles Ave.
**City / State / Zip :** St. Paul, MN 55045
**Telephone Number:** 612-625-6724
**E-mail Address:** nieber@umn.edu
**FAX Number:** 612-624-3005
**WEBSITE:** www.bbe.umn.edu
**FUNDING SOURCE:** Environment and Natural Resources Trust Fund
**LEGAL CITATION:** ML 2007, [Chap._30___], Sec.[__2__], Subd._5(i)____.

**Appropriation Language:** $292,000 is from the trust fund to the University of Minnesota to quantify sustainable supplies of surface and groundwater by integrating surface water, vadose zone, and groundwater systems into defined hydrologic units.

**APPROPRIATION AMOUNT: $**292,000

**Overall Project Outcome and Results**

To assure that our use of freshwater within Minnesota is sustainable into the indefinite future it is necessary to know beforehand the rate of renewal of our freshwater supplies on an annual basis. The rate of renewal of freshwater supplies is a measure of the limits of the natural system to sustain both human needs as well as the needs of nature (ecological services). This project quantified this rate of renewal across the state and related the rate to various characteristics of the local landscape. This quantification was achieved using streamflow records for gauged watersheds located throughout Minnesota. The final result is in the form of atlases of mean minimum annual groundwater recharge (the rate of annual renewal of the freshwater resource) at three different geographical scales; statewide, regional, and county. Regional atlases were developed for the east central, southeast, and south central regions of the state. County atlases were created for Pope, Lac Qui Parle and Olmsted counties. Based on these atlases and the MNDNR water permits a database was produced that will allow the quantitative comparison of renewable freshwater supply and the water demand for human use down to the scale of individual township sections. The database provides the information needed to assess freshwater sustainability on any desired geographical scale. The atlases and the database supplied by this project will be of value to water planners at all geographical levels. One limitation of the current results provided is that they do not account for changes that occur in time, and therefore do not account for possible effects of future climate change. This aspect is needed to provide additional information to water planners for consideration of the risks posed by climate change.

**Project Results Use and Dissemination**

1. To date the project results have been used for an assessment of siting of a gas-fired power plant in Chisago County. In this case John Nieber was requested by 'The Friends of the Sunrise' to speak to their group, and other interested citizens regarding to the availability of groundwater resources for projected use by the power plant. The Minnesota Environmental Quality Board used results from the precursor study in helping to formulate the EQBs 2008 report on water resources sustainability, and it is expected that the results of the current study will be used for similar statewide assessments in the future. Of course it is the hope of the PI and co-PI of the project that the results will be used by the MNDNR, the MPCA, and by other agencies in conducting water resource planning activities.
2. A website for the project exists at https://wiki.umn.edu/view/Water_Sustainability.
3. Many presentations have been made regarding this project every since the project began in 2007. A list of the presentations, both oral presentations and poster presentations, is given below.

J. Nieber, R. Kanivetsky, B. Shmagin, B. Wilson, and D. Mulla, Multi-scale quantitative mapping of recharge/discharge to ground water systems as related to freshwater sustainability in Minnesota, 2007 Minnesota Waters Conference, October 23-24. Results presented as a poster.

J. Nieber, Quantifying Water Resources Sustainability, Texas A&M University, Distinguished Speakers Series in the Department of Biological and Agricultural Engineering, October 16-18, 2007. No cost to project as TAMU provided complete funding for the trip.

J. Nieber, R. Kanivetsky, B. Shmagin, B. Wilson, and D. Mulla, Quantification of Water Resources Sustainability in Minnesota, 52nd Annual South Dakota Water Resources Conference, Sioux Falls, October 28-30, 2007. *This meeting provided the opportunity for us to present the methodology to a broader group of water resource managers and hydrogeologist coming from the upper Midwest region. Discussions stimulated by the presentations provided us with a means to further fine-tune the message regarding the methodology and justification for the work. An important presentation at the meeting given by Bill Allie (USGS, Reston, VA) was valuable to our effort since he spoke about the effects of mining of groundwater on flows in surface waters connected to aquifers. Cost to the project was $800. Roman Kanivetsky and John Nieber also met with Boris Shmagin (project partner) at the meeting to discuss the ongoing work.*

J. Nieber, R. Kanivetsky, B. Shmagin, B. Wilson, and D. Mulla, Regional hydrologic synthesis using a system model of watersheds: a new integrative tool to advance knowledge and predictability of hydrologic systems, 2007 Fall meeting of the American Geophysical Union, December 11-15. *At this meeting we were able to present to a national audience the conceptual development of the ideas of sustainability, and also a description of the methodology used for the project for quantifying water resource sustainability. The meeting also provided the opportunity for John Nieber to meet with Boris Shmagin (project partner) to discuss progress on the project. A presentation by a scientist from Sweden (Anders Worman) also gave some new ideas that we could use in the modeling the physical basis for hydrogeologic units. The cost was for John Nieber's travel, coming to $1,200.*

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Hydropedology, Pennsylvania State University, State College, PA, July 28 – July 31, 2008. Given as an oral presentation by John Nieber and a poster presentation by Heidi Peterson. Total cost of travel for Nieber and Peterson was $1,850 - no cost to the project.

H. Peterson, J. Nieber, R. Kanivetsky, D. Mulla, F. Lahoud, B. Wilson, and B. Shmagin, Multi-scale quantitative hydrologic analysis of water resources sustainability: An integration of vadose zone, ground water and surface water systems. Oral presentation at the 2008 Fall meeting of the American Geophysical Union, San Francisco, December 14-19. This was an invited presentation. Total cost for Nieber and Peterson was $1,655 – no cost to project.

J. Nieber, R. Kanivetsky, H. Peterson, F. Lahoud, D. Mulla, and B. Shmagin, 2008. Atlases of Minnesota water sustainability: Creation from models, analytical methods, and databases of watershed characteristics, Midwest Groundwater Association, Dubuque, IA, 9/29/08-10/02/08. $450 – no cost to project.

H. Peterson, J. Nieber, R. Kanivetsky, B. Shmagin, and J. Wells, 2009. Atlases of water resources for Minnesota as a tool for sustainable community planning, 52$^{nd}$ Annual Great Lakes Research Conference, Toledo, OH, May 18-22. $1,030 – no cost to project.

J. Nieber, H. Peterson, R. Kanivetsky and B. Shmagin. Water resources sustainability and climate change in the Twin Cities Metropolitan Area. Oral presentation at the annual meeting of the University Council on Water Resources, July 7-9, 2009. Total cost for Nieber was $530 – no cost to project.

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# Trust Fund 2007 Work Program Final Report

**Date of Report:** originally submitted September 11, 2009 – revised March 15, 2010
**Trust Fund 2007 Work Program Final Report**
**Date of Work program Approval:**
**Project Completion Date:** June 30, 2009

**I. PROJECT TITLE**: Water Resource Sustainability

**Project Manager**: John L. Nieber
**Affiliation:** Department of Bioproducts and Biosystems Engineering, University of Minnesota
**Mailing Address:** 1390 Eckles Ave.
**City / State / Zip :** St. Paul, MN 55045
**Telephone Number:** 612-625-6724
**E-mail Address:** nieber@umn.edu
**FAX Number:** 612-624-3005
**Web Page address:** https://wiki.umn.edu/view/Water_Sustainability

**Location:** University of Minnesota, St. Paul campus

| | | |
|---|---|---|
| **Total Trust Fund Project Budget:** | **Trust Fund Appropriation:** | **$** 292,000 |
| | **Minus Amount Spent:** | **$** 292,000 |
| | **Equal Balance:** | **$** 0 |

**Legal Citation: ML 2007, [Chap._30___], Sec.[__2__], Subd._5(i)____.**

**Appropriation Language:** $292,000 is from the trust fund to the University of Minnesota to quantify sustainable supplies of surface and groundwater by integrating surface water, vadose zone, and groundwater systems into defined hydrologic units.

## II. and III. Final Project Summary.

To assure that our use of freshwater within Minnesota is sustainable into the indefinite future it is necessary to know beforehand the rate of renewal of our freshwater supplies on an annual basis. The rate of renewal of freshwater supplies is a measure of the limits of the natural system to sustain both human needs as well as the needs of nature (ecological services). This project quantified this rate of renewal across the state and related the rate to various characteristics of the local landscape. This quantification was achieved using streamflow records for gauged watersheds located throughout Minnesota. The final result is in the form of atlases of mean minimum annual groundwater recharge (the rate of annual renewal of the freshwater resource) at three different geographical scales; statewide, regional, and county. Regional atlases were developed for the east central, southeast, and south central regions of the state. County atlases were created for Pope, Lac Qui Parle and Olmsted counties. Based on these atlases and the MNDNR water permits a database was produced that will allow the quantitative comparison of renewable freshwater supply and the water demand for human use down to the scale of individual township sections. The database provides the information needed to assess freshwater sustainability on any desired geographical scale. The atlases and the database supplied by this project will be of value to water planners at all geographical levels. One limitation of the current results provided is that they do not account for changes that occur in time, and therefore do not account for possible effect of future climate change. This aspect is needed to provide additional information to water planners for consideration of the risks posed by climate change.

## IV. OUTLINE OF PROJECT RESULTS*:*

**Result 1:** Development of hierarchical hydrologic units and estimation of associated ground water recharge

**Description:** Compilation of an hierarchy of flow fields based on ecological (surface water system), agroecological (vadose zone) and hydrogeological units (ground water system). Computation and analysis of runoff rates and ground water recharge/discharge rates and preparation of atlases of stream runoff and ground water recharge/discharge. Prepare state-wide maps of flow fields at the 1:3,000,000 scale, and similar maps for Southeastern Minnesota and the Twin Cities – St. Cloud Corridor at the 1:500,000 scale, and for Olmsted, Pope and Lac Qui Parle counties at the 1:100 000 to 1:200 000 scales. Using these flow field results we will develop estimates of surface runoff and ground water recharge/discharge at the same spatial scales. From these estimates we will develop atlases of stream runoff and ground water recharge/discharge at the same spatial scales. The developed atlases will be basic information for assessment of water resource sustainability. Note that detailed maps and atlases for other regions and counties of the state cannot be produced within the scope of the proposed budget. The counties selected for analysis in the present work will be used to demonstrate that the proposed approach does work as expected. It will require additional follow-up work (and funding) to complete maps for other counties and other regions of the state.

**Summary Budget Information for Result 1: Trust Fund Budget: $** 202,000
**Amount Spent: $** 202,000
**Balance: $** 0

| **Deliverable** | **Completion Date** | **Budget** | **Status** |
|---|---|---|---|
| **1.**Statewide atlas | 03/31/08 | $ 55,000 | $0 |
| **2**.Regional atlases | 09/30/08 | $ 95,000 | $0 |
| **3.**County scale atlases | 03/31/09 | $ 52,000 | $0 |

The statewide map for minimum recharge was produced by considering the variables including bedrock geology, quaternary geology, soil order, drainage density, as well as a number of other variables. Of these variables the ones that show a significant effect on the minimum recharge are the bedrock geology and quaternary geology. This is similar to the result that was found in the previous study by Kanivetsky and Shmagin (2001) where only 75 watersheds were used to derive the statewide map of minimum groundwater recharge. The atlas showing the statewide map is illustrated in Attachment 1. The recharge rates are given in $l/s/km^2$.. We note that there is also a climate effect manifested in this atlas but that effect has not been separated out within the overall distribution of recharge. The annual precipitation variability varies significantly across the state with the strongest trend being from the southeast (33 inches/year) to the northwest (20 inches/year), but this climate effect has not been separated out from the effect of geology. The geology effect is very strong however. We can see this by comparing the recharge for the very southeast part of Minnesota to the southwest part. The total precipitation changes by about 5 inches/year across that distance, but yet the recharge varies by an order of magnitude. The procedure for deriving the statewide atlas for recharge is described in Attachment 2.

The atlases for the East Central Minnesota region, the Southeast Region (karst region), and the Southcentral region are presented in Attachment 1 along with tables of estimates of recharge rates for various HHUs. The procedures for deriving the estimates of recharge for the region scale level are described in Attachment 2.

The atlases for the three counties, Olmsted, Lac Qui Parle and Pope, are presented in Attachment 1 along with tables of estimates of recharge rates for various HHUs. The procedure for deriving the estimates of recharge at the county scale level is fairly straight forward. Due to the fact that there are so few gauged watersheds within a given county, the estimates of recharge were taken from the HHU recharge characteristics derived from the analyses of the regions, ECM, Karst, and South Central. The procedure is described in more detail in Attachment 2.

A manuscript for publication in a scientific journal of the results developed for the regional scale analysis results has been prepared in a format to be submitted to the journal Water Resource Research, the premier journal of water resources. We hope to prepare a manuscript on the state-wide analysis for future submission.

**Result 2:** Development of materials for quantitative information system for freshwater sustainability.

**Description:** It is desirable to develop a Quantitative Information System (QIS) which will be an expert information and decision support system to compare sustainable supply with water use. To support the future development of this QIS, the water resources sustainability atlases will be converted as overlays onto GIS databases that will also include the spatial distribution of water use/demand.

**Summary Budget Information for Result 2:** **Trust Fund Budget:** **$** 42,500
**Amount Spent:** **$** 42,500
**Balance:** **$** 0

| Deliverable | Completion Date | Budget | Status |
| --- | --- | --- | --- |
| **1.** GIS databases on CD | 08/19/09 | $42,500 | $0 |

Using the atlases of HHUs, the estimates minimum recharge rates associated with the individual HHUs, and data from the DNR permits for the entire State of Minnesota we developed a database that can be used to quantify the minimum renewable flux and the permitted water demand for any area within the boundaries of the state. The minimum size of the area for estimation of water availability and permitted water demand is the area of a township section, one square mile.

The database for water availability and permitted water demand was derived by using township sections as the basis for the area of query. The idea being that anyone wishing to gain an estimate of water availability and water demand within specified boundaries, the township section would be the basic unit most easily identified. For instance, one could easily determine what townships and what portions of townships lie within a bounty boundary, or within the boundaries of a watershed. Given that the data on water availability and permitted water demand are organized by township sections, the cumulative water available and the cumulative water demand can be determined by summing the corresponding amounts for the sections contained within the boundaries of interest.

The database created for this project is in the form of a Microsoft Access file with a memory size of 28 megabytes. This file is available on CD but also at the freshwater sustainability website (https://wiki.umn.edu/view/Water_Sustainability) for internet download. Other pertinent data generated by GIS analysis will also be available upon request.

The procedures used to create the database files are described in Attachment 3. The created database file can be queried by a QIS, a program that can read the data, extract the required information, and summarize the results in a report format. Presumably this QIS program would also be capable of updating the information in the database as information become available. For example, if a new water use permit is added, or one is deleted from use, the user would be able to enter the information about the permitted use and update the database as a result. Likewise, if new information is gained that helps to improve the accuracy of the estimates of water availability, this information could also be added by the user.

**Result 3:** County level test of the sustainable supply estimation methodology.

**Description:** The water use and the estimated sustainable supply of water in Olmsted, Pope and Lac Qui Parle counties will be compared as case study tests of the methodology used here to estimate sustainable supply.

**Summary Budget Information for Result 3:** **Trust Fund Budget:** **$** 32,500
**Amount Spent:** **$** 32,500
**Balance:** **$** 0

| Deliverable | Completion Date | Budget | Status |
| --- | --- | --- | --- |
| **1.**Report detailing the test of the methodology | 08/19/09 | $32,500 | $0 |

Once the water availability and the permitted water use database was created, as in Result 2, that database could be applied to estimate the water use and water availability for the county level to demonstrate its use. This demonstration was conducted for the counties of Olmsted, Lac Qui Parle and Pope. The method was also demonstrated for selected watersheds to show that the method can be used for general areas and not only for areas bounded by political boundaries. The methodology for this application and the results are outlined in Attachment 4. It should be noted that we did not develop the QIS that would be used to query the database. However the logical steps used in doing the query are essentially identical to the algorithmic steps that would be incorporated into the QIS. We should add that anyone with basic knowledge of Microsoft Access should be able to query the databases created to do a sustainability assessment.

**Result 4:** Compare recharge estimates from alternative methodologies

**Description:** Compare the estimates of ground water recharge obtained with our regionalization procedure to estimates obtained with the regionalization reported by Delin et al. (2007). This comparison will be conducted for selected watersheds representing the breadth of variability within the state.

**Summary Budget Information for Result 4:** **Trust Fund Budget:** **$**15,000
**Amount Spent:** **$** 15,000
**Balance:** **$** 0

| Deliverable | Completion Date | Budget | Status |
|---|---|---|---|
| **1.** Report detailing the comparison of our method with alternative methods | 08/31/09 | $15,000 | $0 |

Estimated minimum mean annual recharge for selected watersheds in Olmsted County and Lac Qui Parle County was determined using the results of the regional atlases and county atlases developed within this project, and these estimates are compared to mean annual recharge derived from the regional regression recharge (RRR) method developed by the USGS. The procedures for estimating the minimum mean annual recharge from the developed atlases are outlined in Attachment 5. The estimates are compared to estimates using the RRR method.

## V. TOTAL TRUST FUND PROJECT BUDGET:

**Staff or Contract Services**:

Dr. Roman Kanivetsky, UofM, $67,666. 33%. Responsible for hierarchical conceptualization of the terrestrial hydrologic system resulted in creation of units and subsequent quantification of these units. Worked in concert with Boris Shmagin as well as John Nieber, David Mulla and Bruce Wilson to develop and quantify hierarchical units of vadose zone to compile the multi-scale maps showing sustainable water resources.

Dr. Boris Shmagin, SDSU, $38,000. 28%. The developer of the original statistical analyses used to develop multi-scale maps, he was primarily responsible to develop the statewide atlas of mean annual minimum groundwater recharge, and provided guidance to Heidi Peterson in learning the statistical analysis procedures for development of the regional and county level atlases.

Jason Ulrich, Research Associate, GIS specialization. $19,195. 33%. Developed the the Microsoft Access database for the QIS concept.

Graduate Research Assistants(2), Heidi Peterson and Francisco Lahoud. $82,859. 50%. Assisted with acquisition of data bases used for analyses and also provided substantial. Both students are studying at the Ph.D. level so they were expected to help with the regular project activities such as data acquisition, data processing, etc., but will also be required to develop an off-shoot project for their Ph.D. theses that will augment the proposed outcomes of the project. Since the project ended being closely related to the Ph.D. research of Heidi Peterson she took primary responsibility to learn the statistical methods for development of the regional and the county level atlases of recharge.

Undergrad Research Assistant, $9,194. Several undergraduate research assistants assisted with routine data acquisition, and also prepare GIS maps and other summary charts and illustrations needed for analysis and report presentation.

Fringe Benefits: Explanation for the fringe benefit charges.
32.8% of salary for Research Associate (GIS specialist), $6,296
13.4% of salary for Kanivetsky, $9,067
70% of salary for Graduate Research Assistants, $52,615
7.7% of salary for Undergrad Research Assistant, $708

**TOTAL TRUST FUND PROJECT BUDGET: $**292,000

## VI. OTHER FUNDS & PARTNERS:

**A. Project Partners:** Dr. Boris Shmagin, Research Associate Professor, Water Resources Institute and Dept of Agricultural & Biosystems Engineering, South Dakota State University; $38,000

**B. Other Funds Proposed to be Spent during the Project Period:** During the project period and after the project final date of June 30 the work was also supported by Minnesota Agricultural Experiment Station project, MN-12-046, "Characterizing Mass and Energy Transport at Different Scales". From July 1, 2007 until June 30, 2009 the 12-046 project provided support (salary and supplemented travel) for Nieber at about $11,500 per year. Additional work was conducted following the June 30, 2009 deadline to revise the final report and to do additional analyses to address review comments. Project MN-12-046 also supported those activities for Nieber, Peterson and Ulrich for an amount of approximately $10,550.

**C. Past Spending:** NA

**D. Time:** NA

**VII. DISSEMINATION**: Throughout the period of the project the results of the project were presented at scientific and professional society meetings, at other institutions (by invitation), and at public forums within Minnesota (the PI has given three such presentations even before the project began). At least one scientific article will be prepared and submitted to a scientific journal. A web site was established to highlight the results of the project. This web site will be maintained to update results even as the project has come to a close.

## Presented results of the research at the following venues:

J. Nieber, R. Kanivetsky, B. Shmagin, B. Wilson, and D. Mulla, Multi-scale quantitative mapping of recharge/discharge to ground water systems as related to freshwater sustainability in Minnesota, 2007 Minnesota Waters Conference, October 23-24. Results presented as a poster.

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## Project webpage, pamphlet.

A project web site at the U of M is operational and is currently being updated with the final project results. The website provides information about project results and outreach efforts. The website address is

https://wiki.umn.edu/view/Water_Sustainability

A pamphlet which describes the need for sustainability of water resources, and also provides information on the general concepts underlying the methodology. This pamphlet gives a layman's explanation for the research. A number of copies of the pamphlet have been distributed at professional meetings. A copy of the pamphlet is shown as Attachment 6**.**

## VIII. REPORTING REQUIREMENTS:

**Periodic work program progress reports were due on December 31, 2007, June 30, 2008, December 31, 2008. A final work program report and associated products was due on August 17, 2009.**

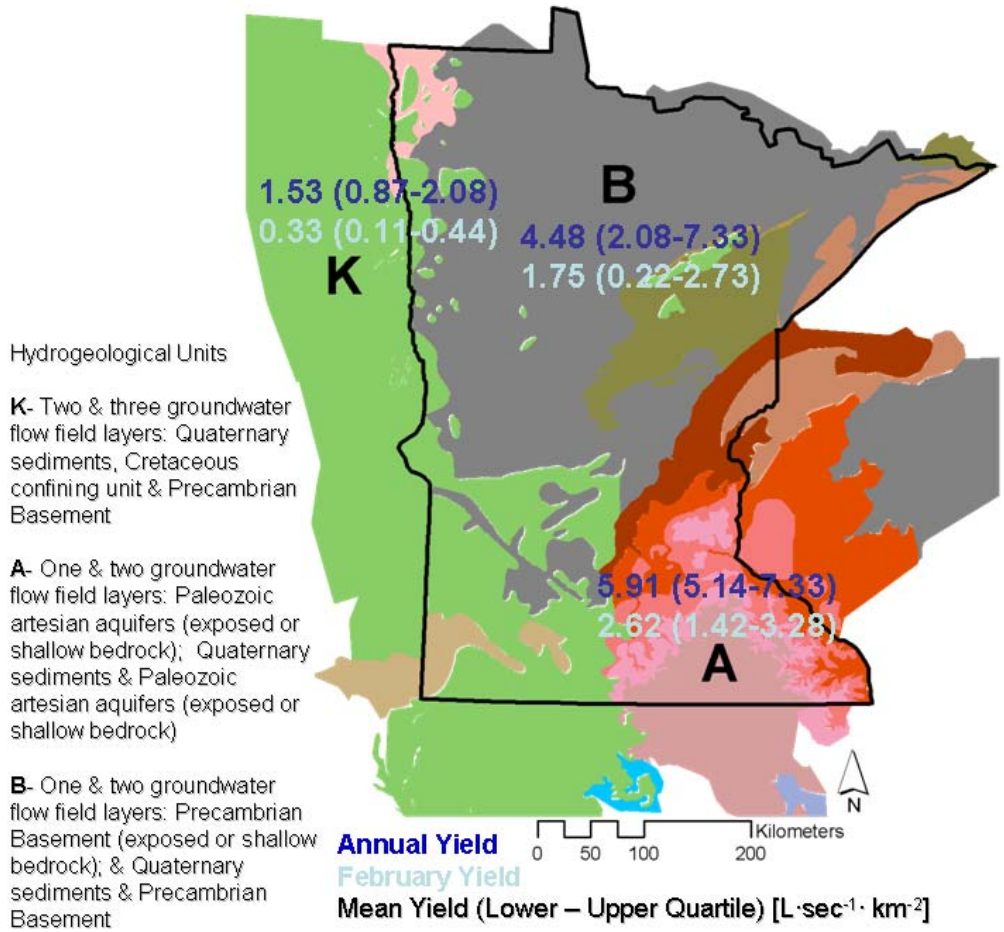
## IX. RESEARCH PROJECTS:

1. Two research documents that show methods for estimating ground water recharge similar to the approach used in the current research are given in Attachment 7.
2. The graduate students, Heidi Peterson and Francisco Lahoud, both supported by this project are currently working on their Ph.D. research activities. Heidi's work is closely related to this project as she will be quantifying the relationship between recharge and landscape features, that is, she will be deriving equations to predict the relationships. Francisco's project will involve the use of remote sensing techniques to monitor baseflow in streams, and as such is not directly related to the objectives of the Water Resources Sustainability project, but is an offshoot of it.

# Attachment 1

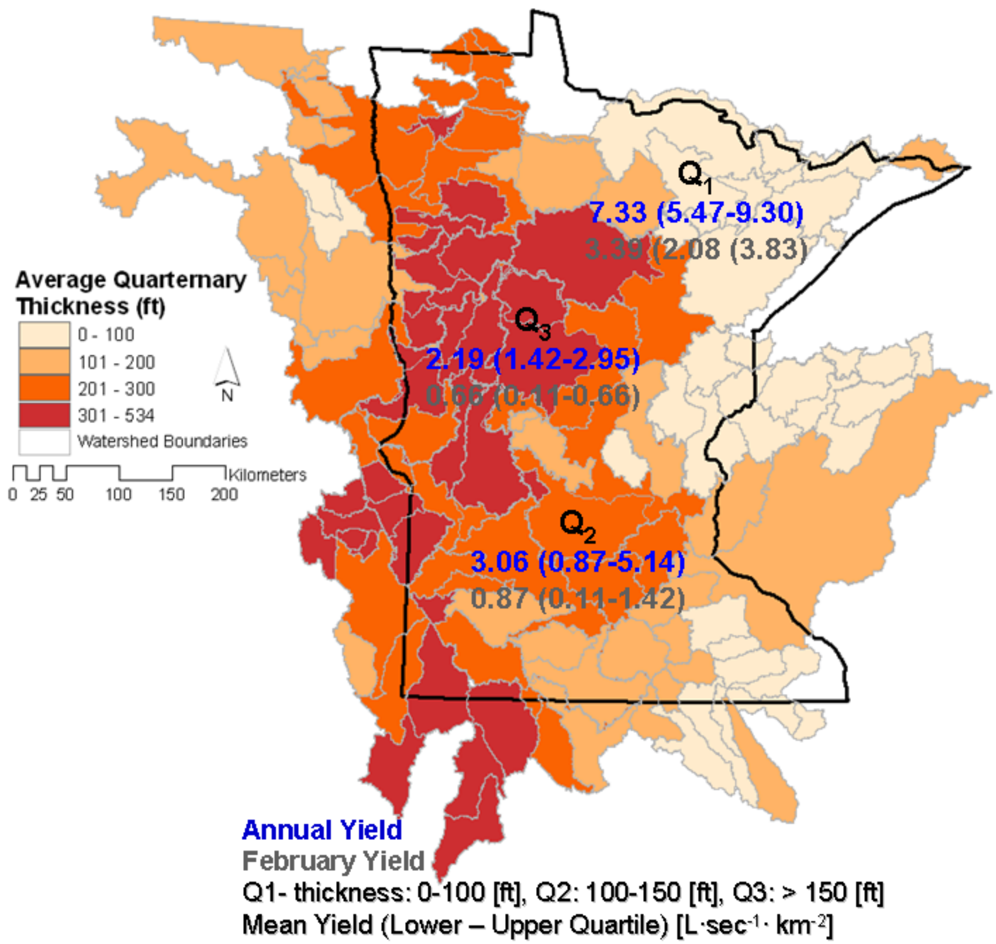
Recharge atlases, hierarchical hydrogeologic units, recharge tables

| Variables for Initial Analysis of Basin Characteristics | | | |
|---|---|---|---|
| **Variables** | **Regionalization Level** | **Data Use** | **Data Source** |
| **Soil** | | | |
| Available Water Capacity | Regional | Watershed average | Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2) for IA, MN, ND, SD & IA. [Available online at http://soildatamart.nrcs.usda.gov] |
| Available Water Storage (AWS)<br>AWS 0-25 cm<br>AWS 0-50 cm<br>AWS 0-100 cm<br>AWS 0-150 cm | Regional | Watershed average | STATSGO2 |
| Drainable Porosity | Regional | Watershed average | Calculated using total porosity and field capacity data layers. |
| Drainage Class | State | Composition by category | STATSGO2 |
| Field Capacity | Regional | Watershed average | STATSGO2 |
| Hydrologic Soil Class | State | Composition by category | STATSGO2 |
| Permeability | State | Composition by category | STATSGO2 |
| Slope | State | Composition by category | STATSGO2 |
| Soil Order | State, Regional | Composition by category | STATSGO2 |
| Soil Texture | Regional | Composition by category | STATSGO2 |
| Total porosity | Regional | Watershed average | Miller, D.A. and R.A. White. 1998: A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Earth Interactions, 2. [Available online at http://EarthInteractions.org] |
| **Ecoregions** | | | |
| Agroecoregions | State | Compotition by category | Data obtained from Professor David Mulla, University of Minnesota, 2007. |
| Bailey<br>Sections<br>Provinces | State | Compotition by category | USDA Forest Service, 200403, Bailey's Ecoregions and Subregions of the United States, Puerto Rico, and the U.S. Virgin Islands: National Atlas of the United States, Reston, VA. |
| Omernik Level III Ecoregions | State | Composition by category | U.S. Environmental Protection Agency, 200506, Omernik's Level III Ecoregions of the Continental United States: National Atlas of the United States, Reston, VA. |
| **Elevation** | | | |
| Altitude | State, Regional | Watershed average | Calculated from a 30-meter USGS Digital Elevation Mode (DEM)l. [Available online at http://edc2.usgs.gov/geodata/index.php] |
| Slope | State, Regional | Watershed average | Calculated from a 30-meter USGS DEM. |
| **Geology** | | | |
| Bedrock | State, Regional | Composition by category | Kanivetsky, R. 1978. Hydrogeologic Map of Minnesota: Bedrock Hydrogeology (Digital Version). Map S-2. 1:500,000. Minnesota Geological Survey. Digitized by: Land Management Information Center, 1985. [Available online at http://www.lmic.state.mn.us/chouse/metadata/bdrkhydr.html] |
| Depth to Bedrock | State, Regional | Watershed average | 50-meter grid supplied by Richard Lively, Minnesota Geological Survey, 2007.<br>Iowa Department of Natural Resources. 1993. Quaternary Isopach of Iowa. [Available online at http://www.igsb.uiowa.edu/nrgislibx/]<br>North Dakota Geological Survey. 1980. Surficial Geology. [Available online at http://web.apps.state.nd.us/hubdataportal/srv/en/main.home]<br>South Dakota Geological Survey. Contours for Bedrock - Eastern SD. [Available online at http://arcgis.sd.gov/IMS/sdgis/Data.aspx]<br>Schoephoester, P.R. 2001. Wisconsin Depth to Bedrock Map. 1:250,000. Wisconsin Geological and Natural History Survey. |
| Quaternary | State, Regional | Composition by category | Kanivetsky, R. 1979. Hydrogeologic Map of Minnesota: Quaternary Hydrogeology (Digital Version). Map S-3. 1:500,000. Minnesota Geological Survey. Digitized by: Land Management Information Center, 1985. [Available online at http://www.mngeo.state.mn.us/chouse/metadata/hydgeo.html]<br>*Additional data layers used for extending bedrock and quaternary data outside of Minnesota:*<br>U.S. Geological Survey. 200209. Aquifers of Alluvial and Glacial Origin: U.S. Geological Survey, Reston, VA. [Available online at http://nationalatlas.gov/atlasftp.html]<br>U.S. Geological Survey, 200310. Principal Aquifers of the 48 Conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands: U.S. Geological Survey, Madison, WI, USA. [Available online at http://nationalatlas.gov/atlasftp.html]<br>Olcott, Perry. 1992. Ground water atlas of the United States: Iowa, Michigan, Minnesota, Wisconsin. U.S. Geological Survey. HA 730-J. [Available online at http://pubs.usgs.gov/ha/ha730/ch_j/index.html]<br>Whitehead, R.L. 1996. Ground water atlas of the United States: Montana, North Dakota, South Dakota, Wyoming. U.S. Geological Survey. HA 730-I. [Available online at http://pubs.usgs.gov/ha/ha730/ch_i/index.html] |
| **Land Use** | | | |
| 2001 Land Cover | State | Composition by category | Homer, C. C. Huang, L. Yang, B. Wylie and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing, Vol. 70, No. 7, July 2004, pp. 829-840. [Available online at http://www.mrlc.gov/index.php] |
| **Drainage** | | | |
| Drainage Density<br>Intermittent<br>Perennial<br>Total | State, Regional | Watershed total | Calculated using flowline database from: U.S. Geological Survey and the U.S. Environmental Protection Agency. 2004. National Hydrography Dataset (NHD) Medium Resolution. [Available online at http://www.horizon-systems.com/nhdplus/data.php] |



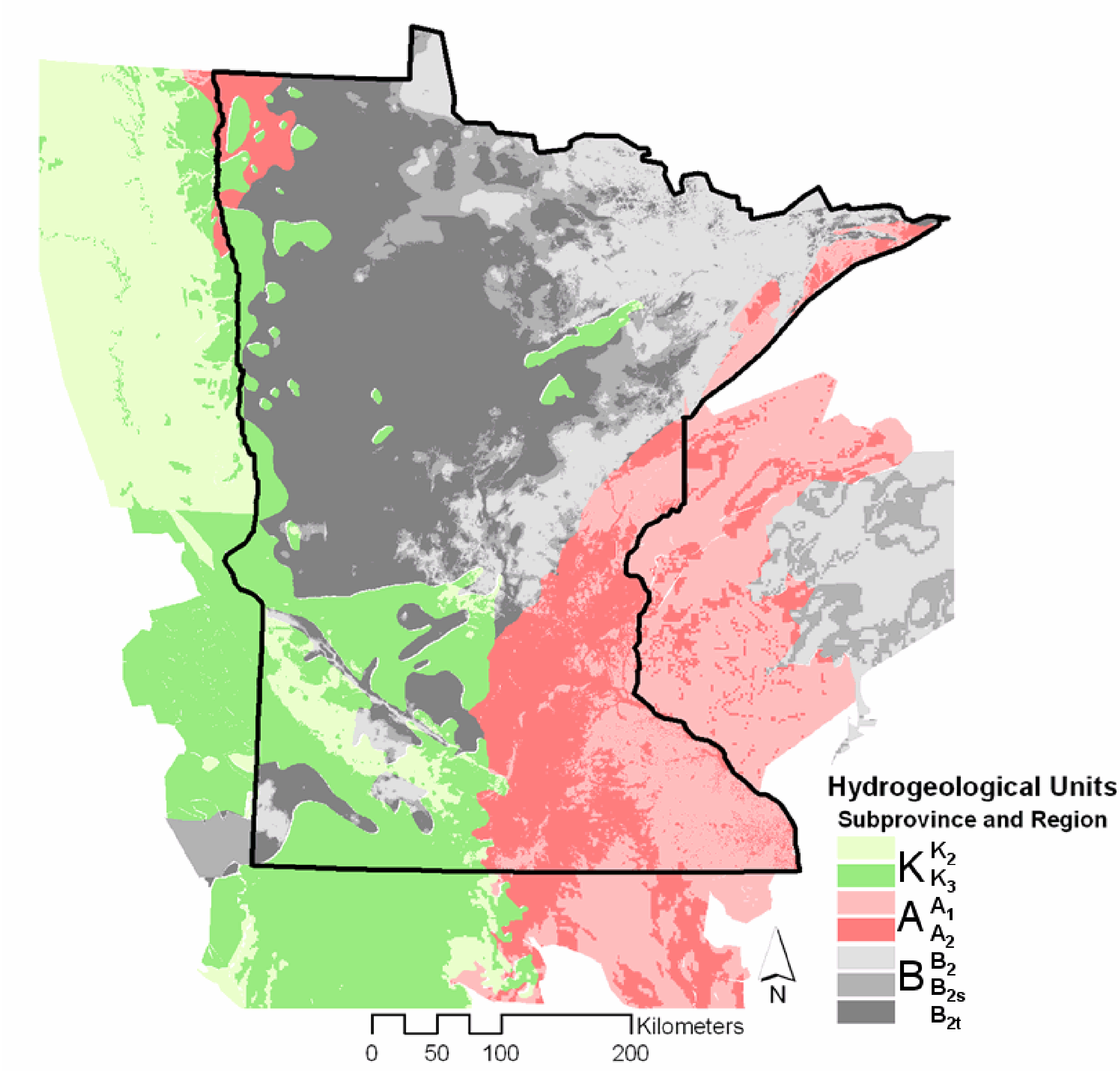

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

Distribution of mean minimum annual groundwater recharge for the state scale given by the February yield values as affected by bedrock geology.




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

Distribution of mean minimum annual groundwater recharge for the state scale given by the February yield values as affected by bedrock and quaternary geology.



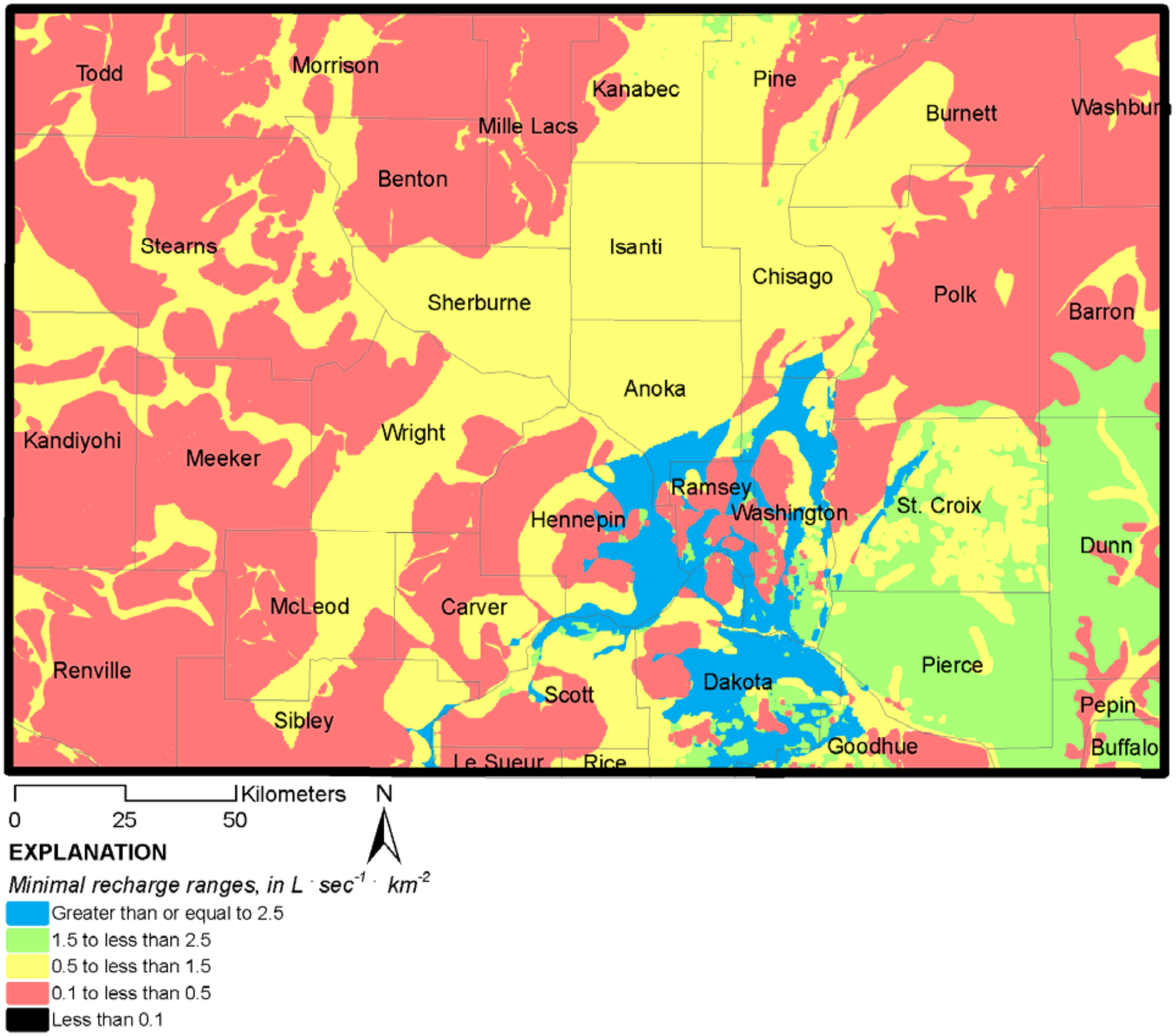

State scale map for minimum annual groundwater recharge. Hydrogeological units are shown on the map and are defined by the bedrock geology and the thickness of quaternary material. The values for each unit are given in the table for the statewide results.

**Table of average rates of annual and monthly (February) stream flow for units of hydrogeological hierarchical regionalization for Minnesota and surrounding areas.**

| Symbol - Subprovince | Mean Annual Stream Flow (L/s/$km^2$) | Mean February Recharge (L/s/$km^2$) | Symbol - Region | Mean Annual Stream Flow (L/s/$km^2$) | Mean February Recharge (L/s/$km^2$) |
|---|---|---|---|---|---|
| **K** - Two & three ground water flow field layers: Quaternary sediments, Cretaceous deposits & Precambrian Basement | 1.53 (0.88 - 2.08)[a] | 0.33 (0.11 - 0.44) | **$K_2$** (9)[b] - Two ground water flow field layers: Quaternary sediments < 130 ft thick (till, sand, silt, gravel, peat), Cretaceous deposits (shale, sandstone) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 0.798 (0.22-0.88) | 0.12 (0.00-0.11) |
| | | | **$K_3$** (22) - Three ground water flow field layers: Quaternary sediments > 130 ft thick (till, sand, silt, gravel, peat), Cretaceous deposits (shale, sandstone) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 1.85 (1.31-2.30) | 0.36 (0.11 - 0.44) |
| **A** - One & two ground water flow field layers: Paleozoic artesian aquifers (exposed or shallow bedrock); Quaternary sediments & Paleozoic artesian aquifers | 5.91 (5.14-7.33) | 2.62 (1.42 - 3.28) | **$A_1$** (12) - One ground water flow field layer: Quaternary sediments <100 ft thick (till, sand, silt, gravel, peat), Paleozoic artesian aquifers (sandstone, dolomite, limestone, shale) | 6.93 (5.47-8.64) | 3.43 (2.35-3.77) |
| | | | **$A_2$** (7) - Two ground water flow field layers: Quaternary sediments > 100 ft thick (till, sand, silt, gravel, peat) & Paleozoic artesian aquifers | 4.04 (1.09-5.36) | 1.19 (0.44-1.86) |
| **B** - One & two ground water flow field layers: Precambrian Basement (exposed or shallow bedrock); Quaternary sediments & Precambrian Basement | 4.48 (2.08 - 7.33) | 1.75 (0.22 - 2.73) | **$B_1$** (13) - One ground water flow field layer: crystalline, magmatic, metamorphic & volcanic rocks (Quaternary sediments <100 ft thick (till, sand, silt, gravel, peat) | 8.17 (7.33-9.62) | 3.70 (1.86-3.83) |
| | | | **$B_{2s}$** (4) - Two ground water flow field layers: Quaternary sediments 100-150 ft thick (till, sand, silt, gravel, peat) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 5.72 (4.10-7.33) | 1.64 (1.09-2.19) |
| | | | **$B_{2t}$** (26) - Two ground water flow field layers: Quaternary sediments > 150 ft thick (till, sand, silt, gravel, peat) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 2.53 (1.75-3.06) | 0.85 (0.11-0.98) |

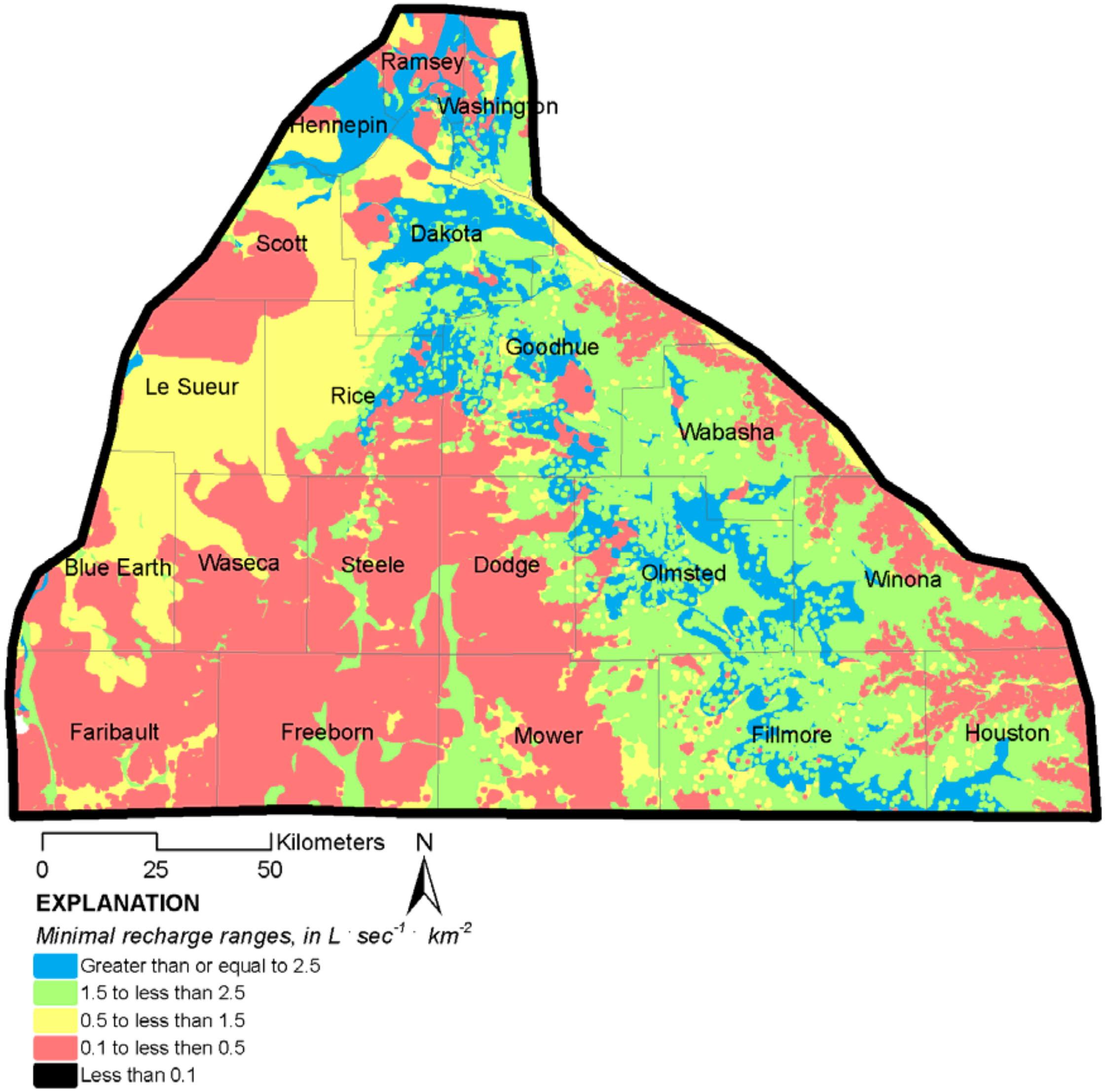
[a] *Range of the lower and upper quartile.*
[b] *(#) refers to the number of watersheds included in analysis.*

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24



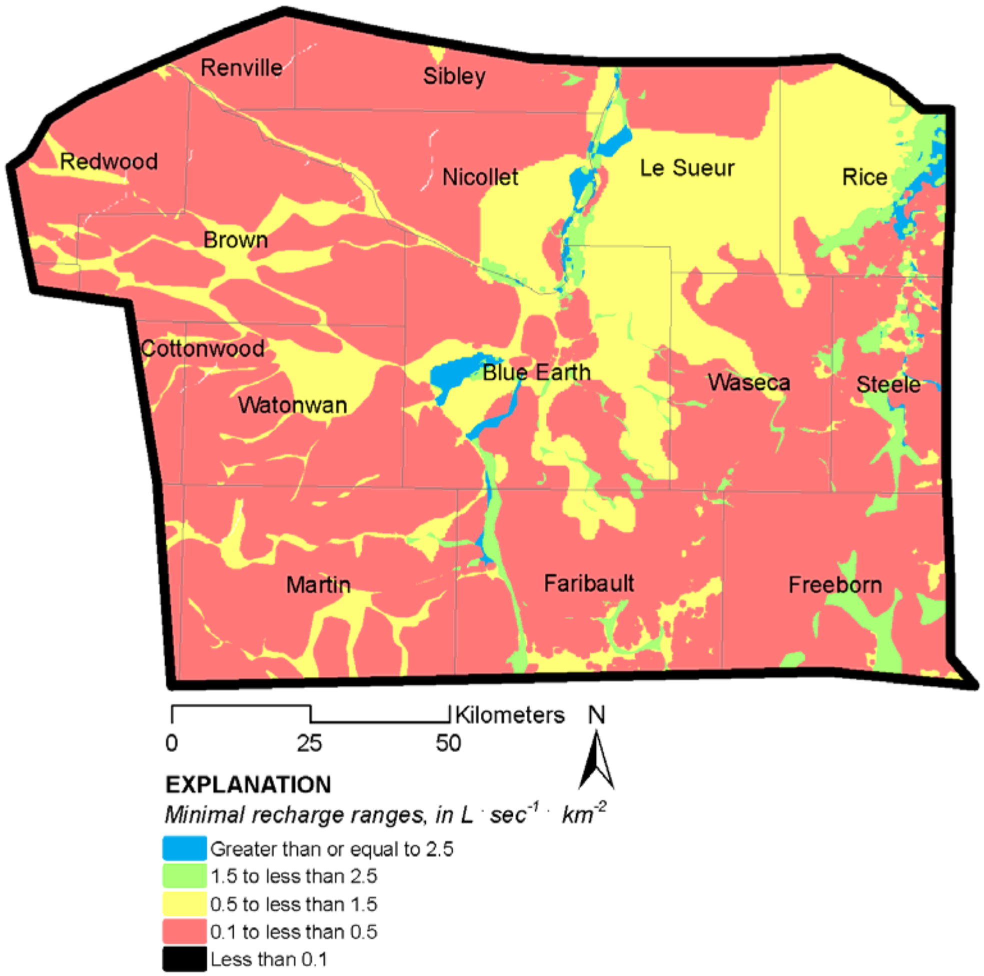

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

Recharge distribution atlas for the East Central Minnesota region.




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

Recharge distribution atlas for the Southeast Minnesota region.




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

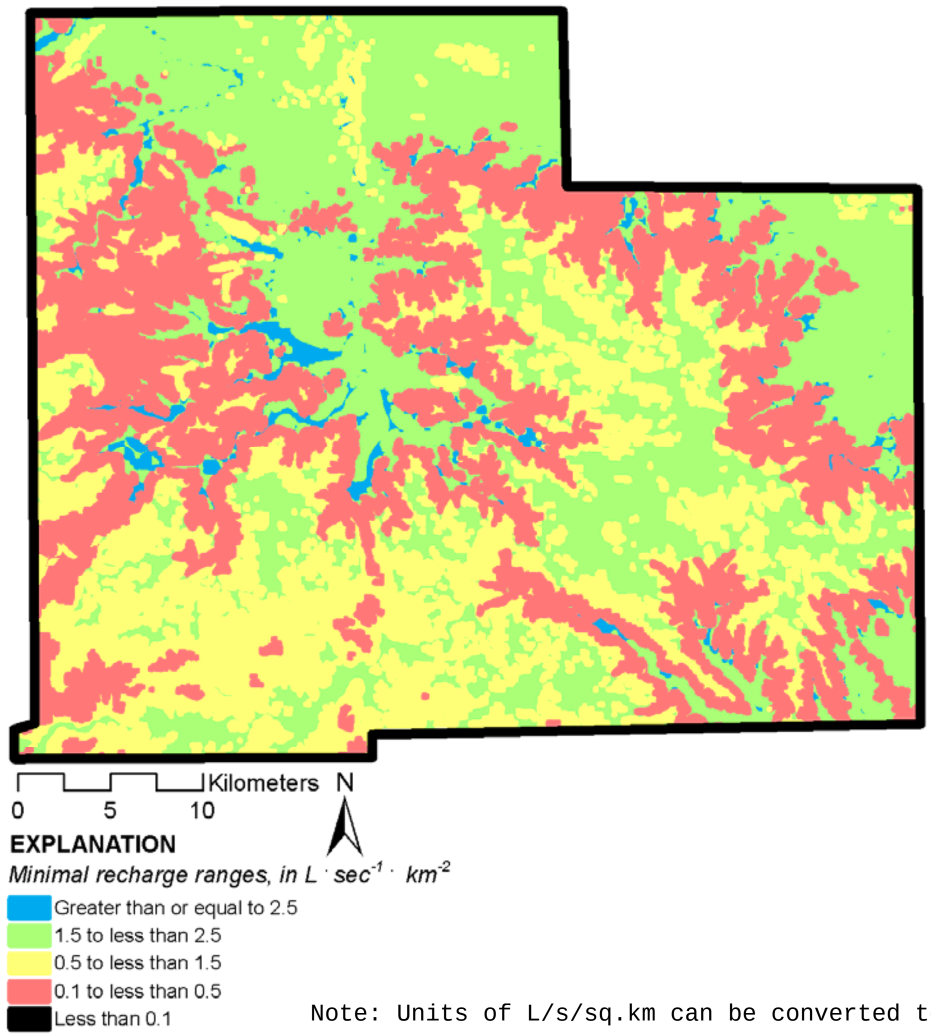
Recharge distribution atlas for the South Central Minnesota region.

**Table of average rates of minimal ground water discharge/recharge for units of hydrologic regionalization for Southern Minnesota.**

| Symbol - Subprovince | Mean Recharge ($L/s/km^2$) | Symbol - Region | Mean Recharge ($L/s/km^2$) | Symbol - Subregion | Mean Recharge ($L/s/km^2$) | Symbol - District | Mean Recharge ($L/s/km^2$) | Symbol - Subdistrict | Mean Recharge ($L/s/km^2$) |
|---|---|---|---|---|---|---|---|---|---|
| **K** - Two & three ground water flow field layers: Quaternary sediments, Cretaceous deposits & Precambrian Basement | | **$K_3$/Q** (38) - Three ground water flow field layers: Quaternary sediments > 50 ft thick (till, sand, silt, gravel, peat), Cretaceous deposits (shale, sandstone) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 0.37 (0.02-0.26) | | | | | **$K_3$/Q2** - gravel and sand quaternary sediment | 0.90* |
| | | | | | | | | **$K_3$/Q3** - sand and gravel quaternary sediment | 0.60* |
| | | | | | | | | **$K_3$/Q6** (37) - till quaternary sediment | 0.33 (0.02-0.24) |
| **A** (79[a]) - One & two ground water flow field layers: Paleozoic artesian aquifers (exposed or shallow bedrock); Quaternary sediments & Paleozoic artesian aquifers | 1.33 (0.28-2.08)[b] | **$A_1$** (27) - One ground water flow field layer: Quaternary sediments < 50 ft thick (till, sand, silt, gravel, peat), Paleozoic artesian aquifers (sandstone, dolomite, limestone, shale) | 2.00 (0.92-3.05) | **$A_1^1$** (2) - Cedar Valley-Maquoketa-Dubuque-Galena aquifer (limestone, dolomite) | 2.40 (1.00-3.80) | | | | |
| | | | | **$A_1^2$** (6) - St. Peter aquifer (sandstone) | 3.38 (2.76-3.29) | | | | |
| | | | | **$A_1^3$** (8) - Prairie du Chien Jordan aquifer (sandstone, limestone) | 2.07 (1.04-3.05) | | | | |
| | | | | **$A_1^4$** (6) - Franconia-Ironton-Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 1.65 (0.28-2.42) | | | | |
| | | | | **$A_1^5$** - Mt. Simon-Hinckley-Fond du Lac aquifer (sandstone) | 1.85* | | | | |
| | | | | **$A_1^6$** (5) - Keweenawan Volcanic Rocks aquifer (basaltic lava flows) | 0.50 (0.29-0.66) | | | | |
| | | **$A_2$/Q** (52) - Two ground water flow field layers: Quaternary sediments > 50 ft thick (till, sand, silt, gravel, peat) & Paleozoic artesian aquifers | 0.98 (0.20-1.47) | **$A_2$/Q1** - Primarily gravel quaternary sediment | 2.15* | | | **$A_2^2$/Q1** - St. Peter aquifer (sandstone) within Mississippi River Valley | 2.80* |
| | | | | | | | | **$A_2^3$/Q1** - Prairie du Chien Jordan aquifer (sandstone, limestone) within Mississippi River Valley | 2.60* |
| | | | | | | | | **$A_2^4$/Q1** - Franconia-Ironton-Galeville aquifer (mixed shale, sandstone, some shaly carbonates) within Mississippi River Valley | 1.15* |
| | | | | **$A_2$/Q2** (6) - Gravel and sand quaternary sediment | 1.59 (0.80-2.66) | | | **$A_2^1$/Q2** - Cedar Valley-Maquoketa-Dubuque-Galena aquifer (limestone, dolomite) | 2.15* |
| | | | | | | | | **$A_2^2$/Q2** - St. Peter aquifer (sandstone) | 2.60* |
| | | | | | | | | **$A_2^3$/Q2** - Prairie du Chien Jordan aquifer (sandstone, limestone) | 2.50* |
| | | | | | | | | **$A_2^4$/Q2** - Franconia-Ironton-Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 0.90* |
| | | | | | | | | **$A_2^5$/Q2** - Mt. Simon-Hinckley-Fond du Lac aquifer (sandstone) | 1.40* |
| | | | | | | | | **$A_2^1$/Q2** - Keweenawan Volcanic Rocks aquifer (basaltic lava flows) | 0.45* |
| | | | | **$A_2$/Q3** (1) - Sand and gravel quaternary sediment | 1.50* | | | **$A_2^1$/Q3** - Cedar Valley-Maquoketa-Dubuque-Galena aquifer (limestone, dolomite) | 1.95* |
| | | | | | | | | **$A_2^2$/Q3** - St. Peter aquifer (sandstone) | 2.40* |
| | | | | | | | | **$A_2^3$/Q3** - Prairie du Chien Jordan aquifer (sandstone, limestone) | 2.30* |
| | | | | | | | | **$A_2^4$/Q3** - Franconia-Ironton-Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 0.60* |
| | | | | | | | | **$A_2^5$/Q3** - Mt. Simon-Hinckley-Fond du Lac aquifer (sandstone) | 1.25* |
| | | | | | | | | **$A_2^6$/Q3** - Keweenawan Volcanic Rocks aquifer (basaltic lava flows) | 0.40* |
| | | | | **$A_2$/Q5** - Silt and sand quaternary sediment | 1.15* | | | **$A_2^4$/Q5** - Franconia-Ironton-Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 0.50* |
| | | | | | | | | **$A_2^6$/Q5** - Keweenawan Volcanic Rocks aquifer (basaltic lava flows) | 0.35* |
| | | | | **$A_2$/Q6** (45) - Till quaternary sediment | 0.84 (0.19-1.15) | **$A_2$/$Q_s$6** (16) - Quaternary sediment thickness < 100 feet | 1.55 (0.71-2.07) | **$A_2^1$/$Q_s$6** (8) - Cedar Valley-Maquoketa-Dubuque-Galena aquifer (limestone, dolomite) | 1.33(0.44-2.08) |
| | | | | | | | | **$A_2^2$/$Q_s$6** (3) - St. Peter aquifer (sandstone) | 1.77 (1.45-2.05) |
| | | | | | | | | **$A_2^3$/$Q_s$6** (2) - Prairie du Chien Jordan aquifer (sandstone, limestone) | 1.60 (1.14-2.08) |
| | | | | | | | | **$A_2^4$/$Q_s$6** (1) - Franconia- Ironton Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 0.30* |
| | | | | | | | | **$A_2^5$/$Q_s$6** (1) - Mt. Simon-Hinckley-Fond du Lac aquifer (sandstone) | 1.20* |
| | | | | | | | | **$A_2^6$/$Q_s$6** (1) - Keweenawan Volcanic Rocks (basaltic lava flows) | 0.30* |
| | | | | | | **$A_2$/$Q_t$6** (29) - Quaternary sediment thickness > 100 feet | 0.45 (0.12-0.60) | **$A_2^1$/$Q_t$6** (14) - Cedar Valley-Maquoketa-Dubuque-Galena aquifer (limestone, dolomite) | 0.38 (0.06-0.50) |
| | | | | | | | | **$A_2^2$/$Q_t$6** (4) - St. Peter aquifer (sandstone) | 0.23 (0.17-0.28) |
| | | | | | | | | **$A_2^3$/$Q_t$6** (5) - Prairie du Chien Jordan aquifer (sandstone, limestone) | 0.85 (0.25-1.49) |
| | | | | | | | | **$A_2^4$/$Q_t$6** (2) - Franconia- Ironton-Galesville aquifer (mixed shale, sandstone, some shaly carbonates) | 0.12 (0.06-0.17) |
| | | | | | | | | **$A_2^5$/$Q_t$6** (4) - Mt. Simon-Hinckley-Fond du Lac aquifer (sandstone) | 0.58 (0.42-0.74) |
| | | | | | | | | **$A_2^6$/$Q_t$6** - Keweenawan Volcanic Rocks (basaltic lava flows) | 0.25* |
| **B** - One & two ground water flow field layers: Precambrian Basement (exposed or shallow bedrock); Quaternary sediments & Precambrian Basement | | **$B_2$/Q** (38) - Two ground water flow field layers: Quaternary sediments > 50 ft thick (till, sand, silt, gravel, peat) & Precambrian Basement (crystalline, magmatic, metamorphic & volcanic rocks) | 0.45 (0.04-0.62) | | | **$B_2$/$Q_s$** (26) Quaternary sediment thickness < 200 feet | 0.59 (0.09-0.74) | **$B_2$/$Q_s$1** - gravel quaternary sediment | 1.60* |
| | | | | | | | | **$B_2$/$Q_s$2** (1) - gravel and sand quaternary sediment | 1.05* |
| | | | | | | | | **$B_2$/$Q_s$3** (1) - sand and gravel quaternary sediment | 0.85* |
| | | | | | | | | **$B_2$/$Q_s$6** (24) - till quaternary sediment | 0.48 (0.07-0.65) |
| | | | | | | **$B_2$/$Q_t$** (12) - Quaternary sediment thickness > 200 feet | 0.16 (0.02-0.18) | **$B_2$/$Q_t$1** - gravel quaternary sediment | 0.90* |
| | | | | | | | | **$B_2$/$Q_t$2** - gravel and sand quaternary sediment | 0.60* |
| | | | | | | | | **$B_2$/$Q_t$3** (1) - sand and gravel quaternary sediment | 0.50* |
| | | | | | | | | **$B_2$/$Q_t$6** (11) - till quaternary sediment | 0.11 (0.01-0.17) |

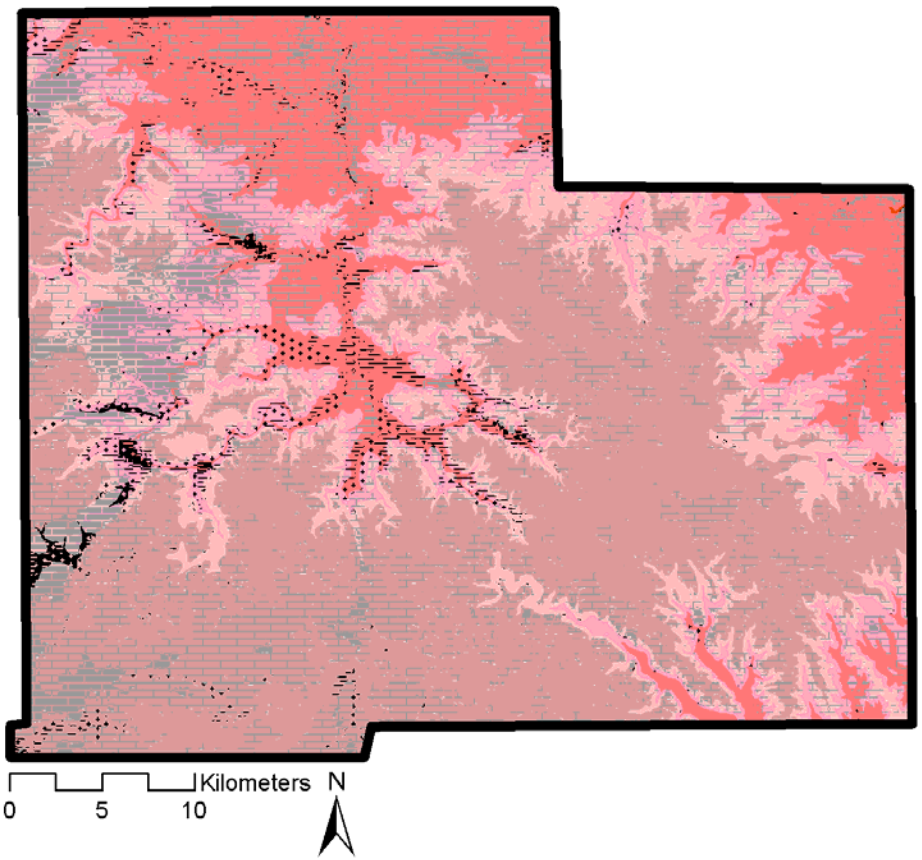
*[a] (#) refers to the number of watersheds included in analysis.*
*[b] Range of the lower and upper quartile.*
*[*] Mean recharge estimated through expert judgement, not statistical analysis, due to insufficient set of study watersheds falling within unit.*

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

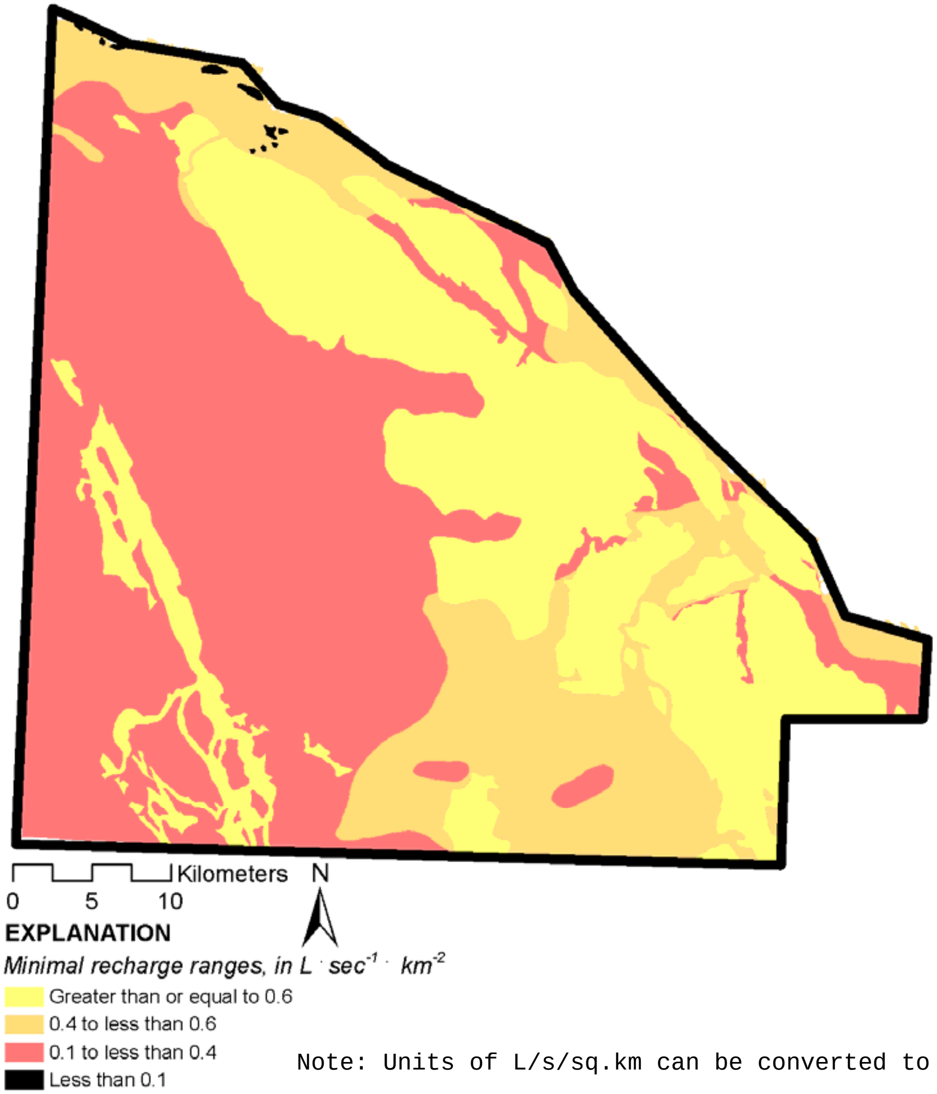
Recharge distribution atlas for Olmsted County.




Hierarchical Hydrogeologic Units for Olmsted County. The recharge table goes with this map.

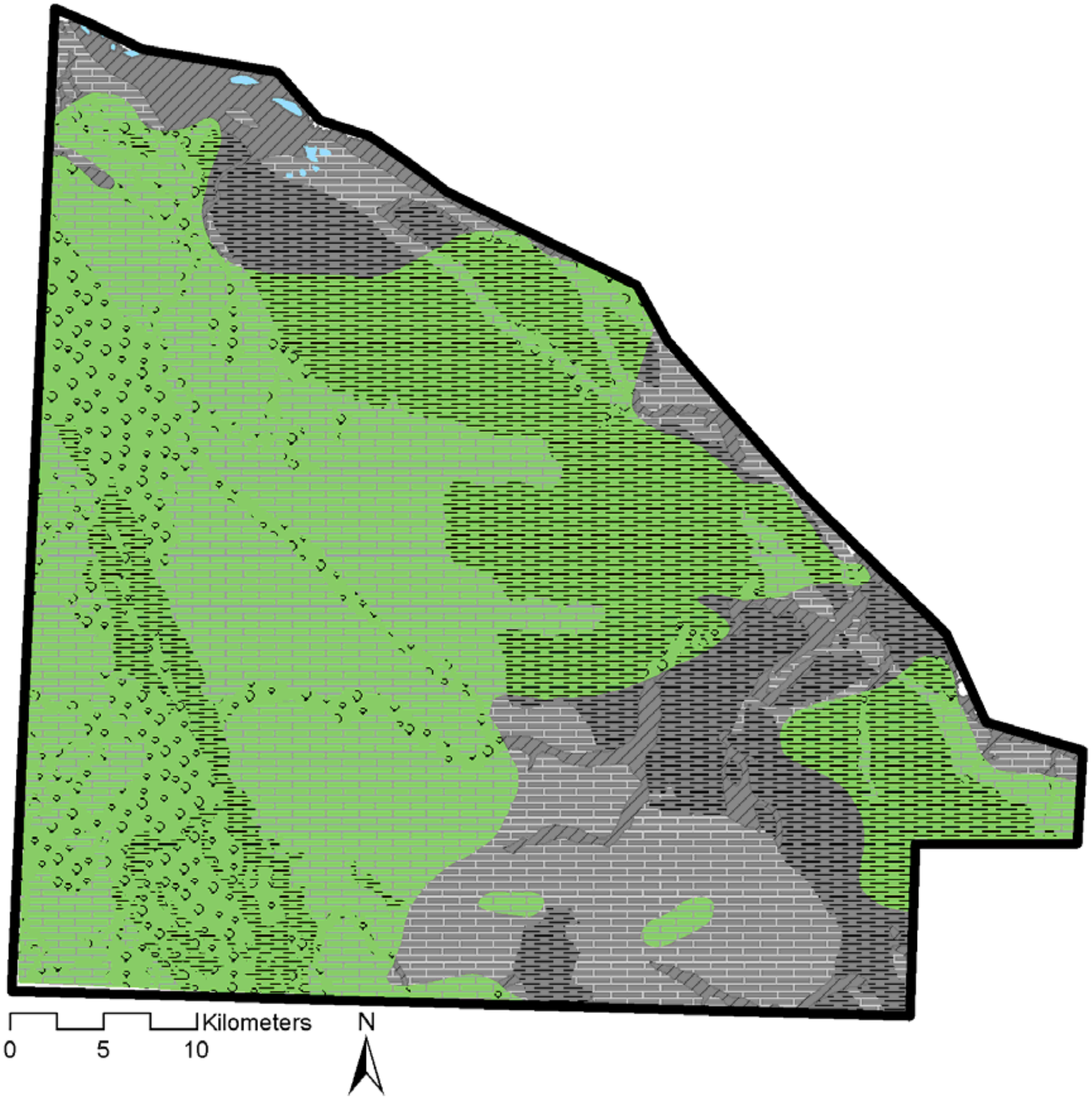
| Olmsted County Minimal Ground-Water Recharge Based on February Monthly Discharge Mean Measurements Period 1955-1978 | | | |
|---|---|---|---|
| **Subregion** | **Symbol** | **Unit Description** | **Recharge [L/s/km$^2$]** |
| $A_1^1$ | | Exposed or less than 30 feet quaternary material over Cedar Valley - Maquoketa - Dubuque - Galena Aquifer | 2.40 |
| $A_2^1$/Q2 | | Cedar Valley - Maquoketa - Dubuque - Galena Aquifer overlain by gravel and sand | 2.15 |
| $A_2^1$/Q3 | | Cedar Valley - Maquoketa - Dubuque - Galena Aquifer overlain by sand and gravel | 1.95 |
| $A_2^1$/Q6 | | Cedar Valley - Maquoketa - Dubuque - Galena Aquifer overlain by till | 1.33 |
| $A_1^2$ | | Exposed or less than 30 feet of quaternary material over St. Peter Aquifer | 3.39 |
| $A_2^2$/Q2 | | St. Peter Aquifer overlain by gravel and sand | 2.60 |
| $A_2^2$/Q3 | | St. Peter Aquifer overlain by sand and gravel | 2.40 |
| $A_2^2$/Q6 | | St. Peter Aquifer overlain by till | 1.77 |
| $A_1^3$ | | Exposed or less than 30 feet of quaternary material over Prairie du Chien - Jordan Aquifer | 2.07 |
| $A_2^3$/Q2 | | Prairie du Chien - Jordan Aquifer overlain by gravel and sand | 2.50 |
| $A_2^3$/Q3 | | Prairie du Chien - Jordan Aquifer overlain by sand and gravel | 2.30 |
| $A_2^3$/Q6 | | Prairie du Chien - Jordan Aquifer overlain by till | 1.60 |
| $A_1^4$ | | Exposed or less than 30 feet of quaternary material over Franconia - Ironton - Galesville Aquifer | 1.65 |
| $A_2^4$/Q2 | | Franconia - Ironton - Galesville Aquifer overlain by gravel and sand | 0.90 |
| $A_2^4$/Q6 | | Franconia - Ironton - Galesville Aquifer overlain by till | 0.30 |
| $A_1$c1 | | Exposed of less than 30 feet of quaternary material over Decorah - Platteville - Glenwood | 0.10 |
| $A_2$c1/Q2 | | Decorah - Platteville - Glenwood overlain by gravel and sand | 0.35 |
| $A_2$c1/Q3 | | Decorah - Platteville - Glenwood overlain by sand and gravel | 0.25 |
| $A_2$c1/Q6 | | Decorah - Platteville - Glenwood overlain by till | 0.10 |
| Q2/$A_2^1$ | | Sand and gravel predominant over Cedar Valley - Maquoketa - Dubuque - Galena Aquifer | 2.00 |
| Q2/$A_2$c1 | | Sand and gravel predominant over Decorah - Platteville - Glenwood | 0.30 |
| Q2/$A_2^2$ | | Sand and gravel predominant over St. Peter Aquifer | 2.50 |
| Q2/$A_2^3$ | | Sand and gravel predominant over Prairie du Chien - Jordan Aquifer | 2.40 |
| Q2/$A_2^4$ | | Sand and gravel predominant over Franconia - Ironton - Galesville Aquifer | 0.50 |
| Q3/$A_2^1$ | | Gravel and sand predominant over Cedar Valley - Maquoketa - Dubuque - Galena Aquifer | 2.20 |
| Q3/$A_2$c1 | | Gravel and sand predominant over Decorah - Platteville - Glenwood | 0.55 |
| Q3/$A_2^2$ | | Gravel and sand predominant over St. Peter Aquifer | 2.70 |
| Q3/$A_2^3$ | | Gravel and sand predominant over Prairie du Chien - Jordan Aquifer | 2.60 |
| Q6/$A_2^1$ | | Till predominant over Cedar Valley - Maquoketa - Dubuque - Galena Aquifer | 0.30 |
| Q6/$A_2$c1 | | Till predominant over Decorah - Platteville - Glenwood | 0.10 |
| Q6/$A_2^2$ | | Till predominant over St. Peter Aquifer | 0.20 |
| Q6/$A_2^3$ | | Till predominant over Prairie du Chien - Jordan Aquifer | 0.80 |
| Q6/$A_2^4$ | | Till predominant over Franconia - Ironton - Galesville Aquifer | 0.10 |

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

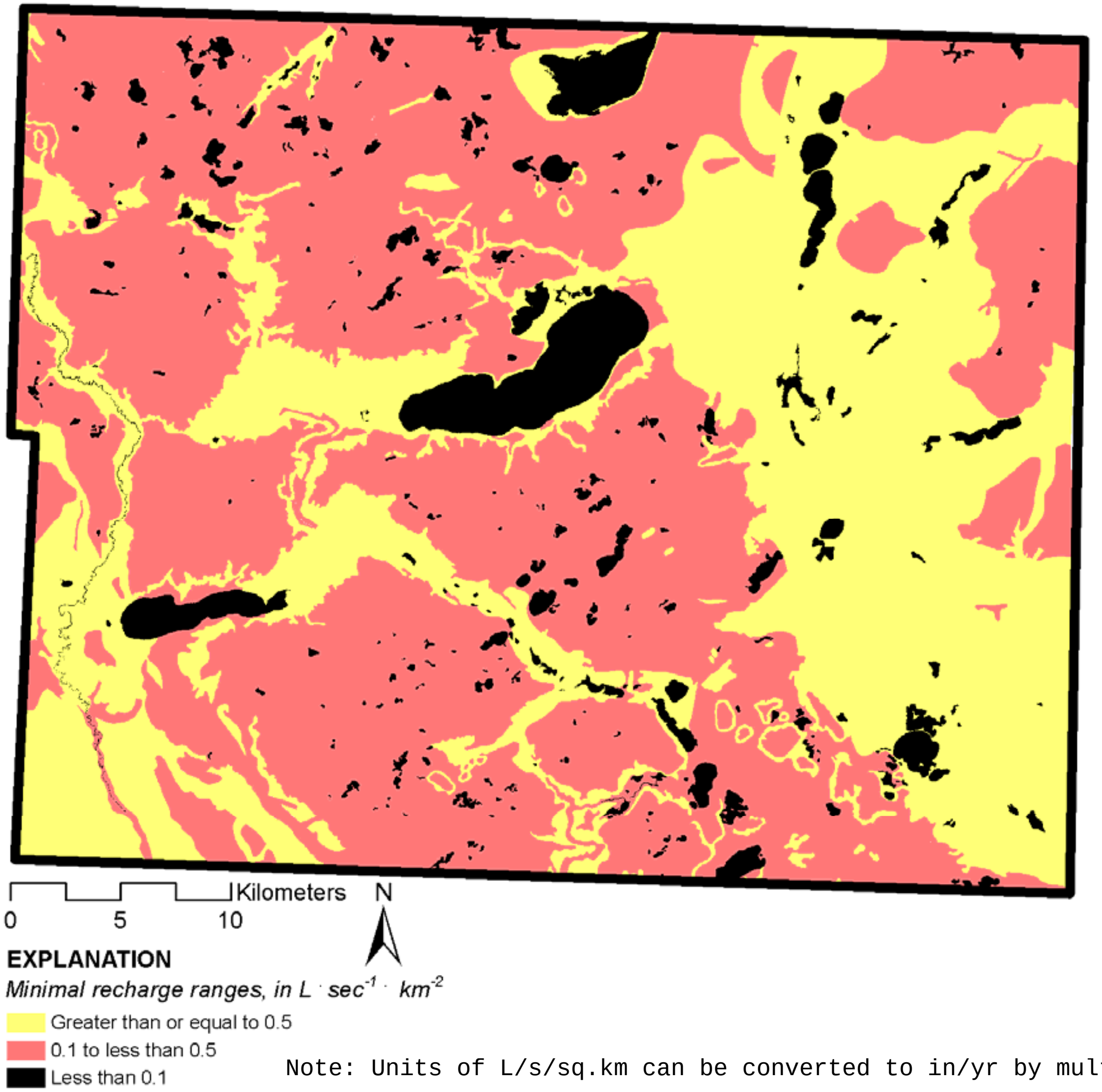
Recharge distribution atlas for Lac Qui Parle County.




Hierarchical Hydrogeologic Units for Lac Qui Parle County. The recharge table goes with this map.

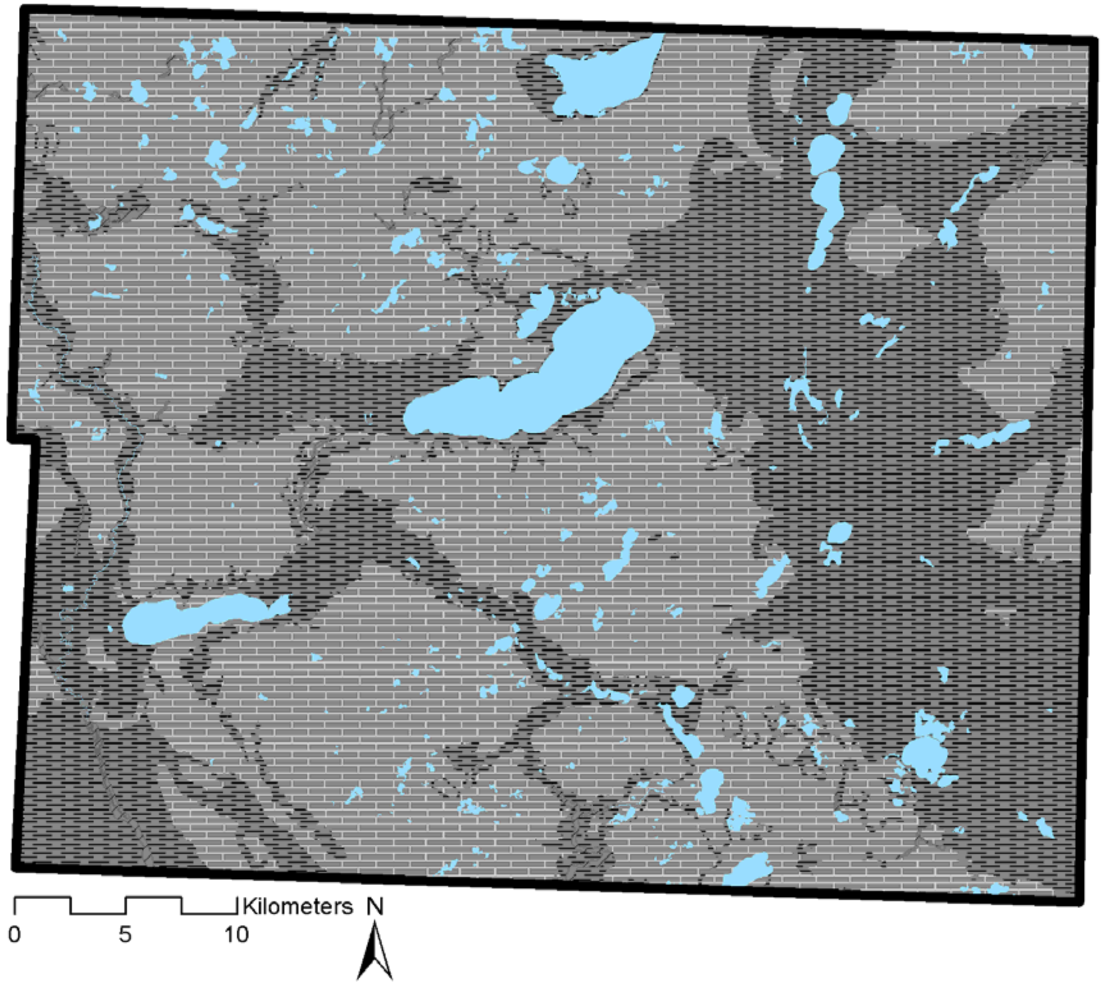
| Lac Qui Parle County Minimal Ground-Water Recharge Based on February Monthly Discharge Mean Measurements Period 1955-1978 | | | |
|---|---|---|---|
| **Subregion** | **Symbol** | **Unit Description** | **Recharge [L/s/km$^2$]** |
| **$B_2$/Q3** | | Precambrian Igneous and Metamorphic Rocks overlain by sand and gravel | 0.85 |
| **$B_2$/Q6** | | Precambrian Igneous and Metamorphic Rocks overlain by till | 0.48 |
| **$B_2$/Q10** | | Precambrian Igneous and Metamorphic Rocks overlain by sandy till | 0.40 |
| **$K_3$/Q3** | | Cretaceous Aquifer overlain by sand and gravel | 0.60 |
| **$K_3$/Q6** | | Cretaceous Aquifer overlain by till | 0.33 |
| **$K_3$/Q10** | | Cretaceous Aquifer overlain by sandy till | 0.28 |

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24




Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

Recharge distribution atlas for Pope County.




Hierarchical Hydrogeologic Units for Pope County. The recharge table goes with this map.

**Pope County Minimal Ground-Water Recharge Based on February Monthly Discharge**
**Mean Measurements Period 1955-1978**

| Subregion | Symbol | Unit Description | Recharge [L/s/km$^2$] |
|---|---|---|---|
| $B_2$/Q3 | | Precambrian Igneous and Metamorphic Rocks overlain by sand and gravel | 0.85 |
| $B_2$/Q6 | | Precambrian Igneous and Metamorphic Rocks overlain by till | 0.48 |
| $B_2$/Q10 | | Precambrian Igneous and Metamorphic Rocks overlain by sandy till | 0.44 |

Note: Units of L/s/sq.km can be converted to in/yr by multiplying by 1.24

# Attachment 2

# Methods for deriving estimates of minimum groundwater recharge for Minnesota at state, regional and county scales.

## General concepts for all spatial scales.

The methodology underlying the analysis used in this study is called the Watershed Characterization (WC) method. Previous applications of this method to groundwater recharge mapping have been presented by Shmagin and Kanivetsky (2002, 2006) and Kanivetsky and Shmagin (2005). The method is founded in the hydrogeological regionalization concepts described by Pinneker (1984) and the geophysical systems analysis described by Krcho (1978). Factor analysis, cluster analysis, and non-parametric statistical testing procedures play the part for the quantitative implementation of the basic concepts.

The basic idea underlying the WC method is that we can describe the landscape by various landscape characteristics and that within a whole landscape domain one can define subareas that appear to have relatively homogeneous landscape characteristics at some specified spatial scale. Examples of landscape characteristics that could be used include bedrock geology, quaternary geology, soil order, topographic slope, drainage density, vegetation, and landuse. With respect to defining hydrologic responses these subareas then are defined as being hydrologic response units. If the hydrologic responses or hydrologic response units are quantified at locations where hydrologic monitoring data are available, and those responses are related to the landscape characteristics of those response units, then it is possible to use those relations to predict the response of areas where no hydrologic data are available. In the present application the hydrologic response units are referred to as Hierarchical Hydrologic Units (HHUs) and the hydrologic response of interest is the minimum annual groundwater recharge.

The WC method can be applied at multiple scales, and is applied starting at the largest area of interest (e.g., global scale or continental), and then moving down to the smallest area for which data are available to quantify the responses of the HHUs. In the present application the largest area has boundaries extending outside the State of Minnesota, and the smallest area is the scale of an individual county.

**Application of the WC method to Minnesota.**

USGS gauging station locations and real time stream flow data (annual and monthly) for sites throughout MN and surrounding states were downloaded from the USGS Real-Time Water Data for the Nation website (http://waterdata.usgs.gov/nwis/rt). Data was sorted and sites were selected based on consistent consecutive available data and gauging station location.

To conduct the watershed characterization, a digital landscape database was constructed. The latitudinal and longitudinal coordinates for each gauging station were georeferenced in ArcGIS®, a Geographic Information System (GIS) database. Using Arc Hydro, GIS mapping software for water resources, catchment boundaries were delineated for each gauging station (e.g., at the statewide scale we have Figure 1) (Maidment, 2002). NHDPlus data, which is a compilation of the National Hydrography Dataset (NHD), National Elevation Dataset (NED), National Land Cover Dataset (NLCD) and Watershed Boundary Dataset (WBD) were formatted for the Arc Hydro delineations. Although the NHDPlus data were initially based on a 1:100,000-scale, most of the data incorporated into the database were developed at a higher resolution (USGS, 2009).

Soil data from the US General Soil Map (STATSGO2) Database, downloadable through the National Resources Conservation Service (NRCS), were formatted and compiled into the landscape database. STATSGO2 is a state-wide map at a scale of 1:250,000 (Soil Survey Staff, 2009). Some of the soil characteristics pertinent to this research, either in this NRCS database or derived from this database, include available water capacity, drainable porosity, field capacity, available water storage, particle-size and taxonomic soil order.

Bedrock hydrogeology, quaternary hydrogeology and depth to bedrock data layers from the MGS were formatted and incorporated into the landscape database. It should be noted that while this study was specific to Minnesota, whenever a delineated watershed crossed the boundaries between adjacent states, the data for this watershed lying within the adjacent state were acquired (LMIC, 2009).

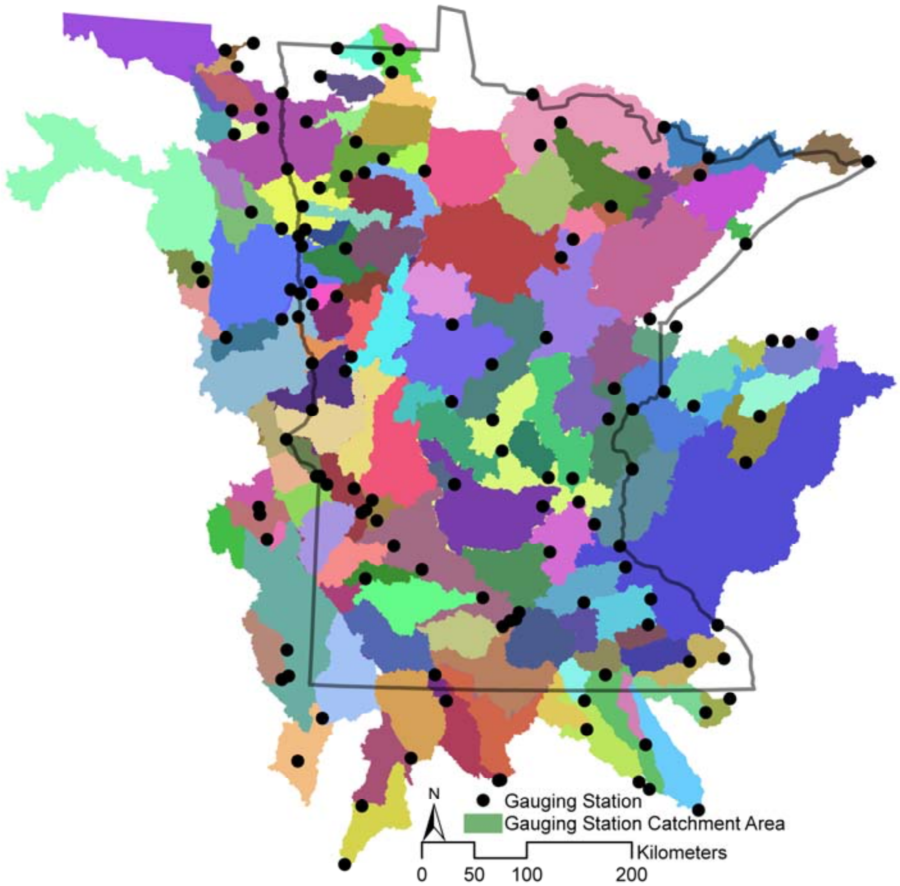



Figure 1. Minnesota regional map illustrating gauging station location and corresponding delineated watersheds.

A seamless, 30-meter resolution digital elevation model (DEM) was used for various topographic analyses. This DEM was compiled from the USGS National Map Seamless Server (2009b) and covers Minnesota and adjacent states. A number of additional data layers were acquired for the digital landscape database, and are summarized in a table included in Attachment 1. Some of these data layers include, landuse (MRLC, 2009), hydrologic soil group, and drainage classification. More than 80 characteristics were derived in total and maps are included on the project website (https://wiki.umn.edu/view/Water_Sustainability).

A watershed characterization for each watershed included in the hydrologic database was conducted using a compilation of the data layers discussed. The characterization involves overlaying the watershed boundaries that correspond to the stream gauge stations on the landscape characteristics and summarizing the fraction of each watershed that consists of a specific characteristic. A conceptualization of this overlay process showing the correspondence between the watershed boundaries, the gauging stations, and the landscape features is illustrated in Figure 2. These data were compiled into a set of matrices, to be used in a non-parametric analysis to facilitate segregation of the watersheds into distinct groups and thereby distinguish the hydrologic responses of the HHUs associated with the watersheds. This separation of the HHUs comprises the regionalization process.

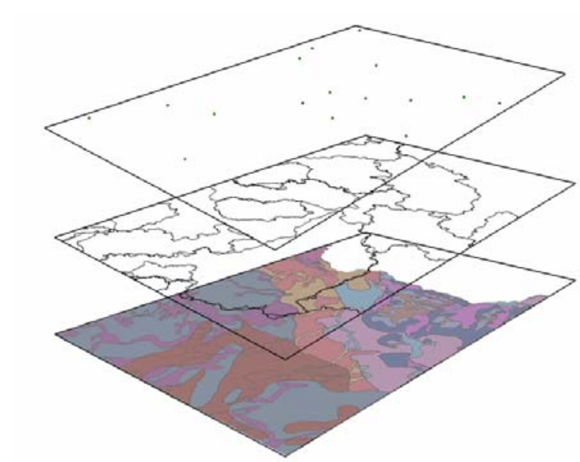


Figure 2. Diagram illustrating the overlay of GIS layer to extract values for the initial matrix used in the factor analysis.

Non-parametric statistical analysis, specifically the Kruskal-Wallis analysis of variance (ANOVA), was used to determine if streamflow was statistically different between basins, given different watershed characteristics. This analysis was used since the characteristics are not normally distributed, as basic parametric statistical analyses assume. In addition, non-parametric statistical analyses can be used with small data sets to identify differences between independent groups.

**Minimum groundwater recharge from stream discharge.**

Numerous methods have been used by hydrologist to estimate groundwater recharge. These methods are represented in the review by Scanlon et al. (2002). The method adopted in this project is to use the minimum flow in the month of February, which is known in Minnesota to be composed only of groundwater discharge to the surface stream system. Using streamflow to estimate groundwater recharge is not new but a recent advocacy was expressed by Bredehoeft (2007). Other methods using streamflow use baseflow recessions (e.g., Rorabaugh, 1964) and are not limited to time of year. However, we select to use the minimum flow in February because then the flow is known to be composed only of groundwater discharge and will not be affected by processes such as bank storage recession.

Using the minimum flow in February as the surrogate for minimum annual groundwater recharge is sensible because it is known that the water balance requires that groundwater discharge back to the surface at some point in the landscape, unless the water that does recharge is already completely allocated to human use or to ecological processes. The streamflow is therefore the signal for the groundwater recharge, and the minimum recharge can be viewed as being the stable baseflow, the part that is not affected by short-term events.

The groundwater discharge that occurs as part of the water balance of a watershed is illustrated in Figure 3 where there is a recharge area and a discharge area for the watershed. The net between the infiltration of precipitated water and evapotranspiration is the recharge to the groundwater shown in the figure as R. It is this quantity that we estimate with the streamflow gauging data.

The calculation of the aerial groundwater recharge from the minimum February flow is based on the assumption that the groundwater divide is approximated by the topographic divide (surface water divide) for the watershed associated with the streamflow measurement. The assumption of correspondence between the groundwater divide and the topographic divide is not flawless, but all reference books covering the topic of regional groundwater flow systems state that topography is an important driver of groundwater flow, at lease in humid areas.

An illustration of the multiscale nature of groundwater recharge and discharge is presented in Figure 4. Here we see that the scale of the groundwater flow field is related to the surface topography, and the scale of the surface topography relates to the size of watersheds. So for small watersheds the flow pathways are short, and for large watersheds the flow pathways are long, with intermediate sized watersheds and pathways in between. Even though the flow pathways operate over different length and time scales for the different size watersheds, the recharge through the surface is gradual and there is a link between the flows recharging the shallow groundwater system (local groundwater recharge and discharge) and the deeper groundwater system (regional groundwater recharge and discharge).

With the assumption that the groundwater divide corresponds to the surface water divide, the minimum groundwater recharge can be calculated by simply dividing the annual discharge volume associated with the minimum discharge by the watershed area. This recharge can be expressed in various common units such as inches/year, cfs/mi$^2$ or l/sec/km$^2$ .

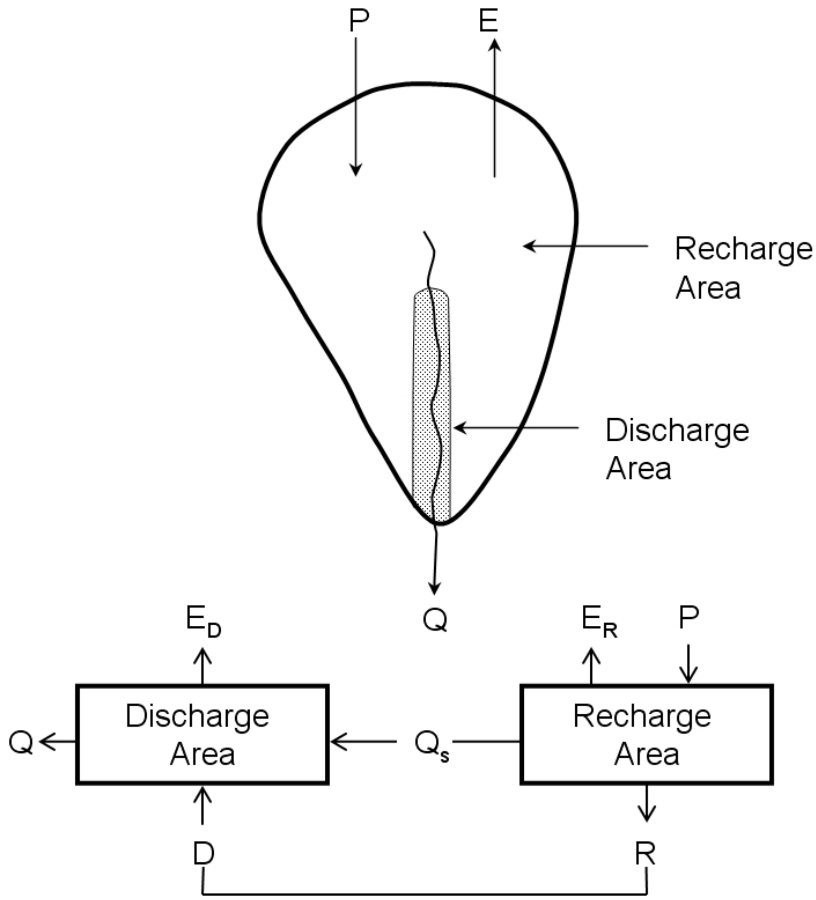



Figure 3. The water balance of a watershed showing the components of the balance and the recharge to the groundwater as a result of the excess between infiltrated water and evapotranspired water (from Freeze and Cherry, 1979).

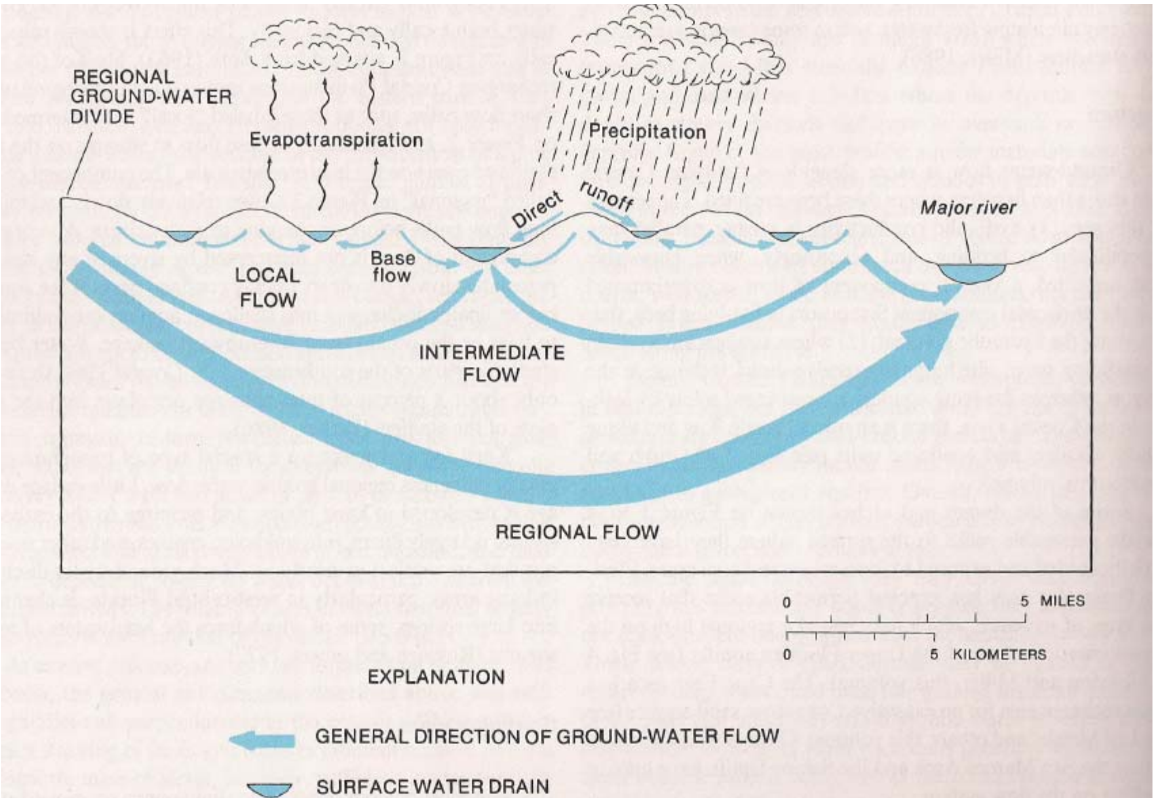



Figure 4. Illustration of groundwater flow fields in a vertical plane showing different spatial scales of flow ranging from local flow to regional flows. Local flow have to do with small watersheds, while regional flow are associated with large watersheds. (from Miller, 1988)

**Multivariate statistical analysis.**

Multivariate statistical analysis is commonly used to complete stream flow regionalization (Bartlein, 1982; Lins, 1985, 1997; Sophocleous, 1992; Mauer et al., 2004; Shmagin and Kanivetsky, 2002, 2006; and Kahya, et. al., 2008). It explains correlations in a large set of variables by reducing the number of underlying independent components or variables. In these studies regional stream flow behaviors were delineated to identify homogeneous hydrologic regions. These hydrologic regimes had distinct patterns of seasonality and persistence (Lins, 1985, 1997; Kahya et. al., 2008).

In the present research project we used factor analysis for completion of the regionalization of state-wide hydrologic units (watersheds). Factor analysis is a multivariate analysis technique used for data reduction or structure detection by reducing the number of variables and detecting structure in the relationships between variables (*classifying variables) (*Thurstone, 1931; StatSoft, 2007). It allowed us to indicate watersheds that fell within five specific hydrologic regimes representing similar flow trends. By looking at the boundaries of these regimes with the boundary of landscape characteristics across Minnesota, an initial understanding of the data is established.

When a factor analysis is performed, the correlation between two or more variables is summarized in a scatterplot. A regression line with the maximum variance is then fit to represent a linear relationship between the variables. This correlation is called the factor load. After this first factor has been extracted additional lines are drawn to maximize the remaining variability extracting consecutive factors.

Variance maximizing rotation is the method used to extract the additional factors. In essence, the maximum variance of each additional factor is obtained by rotating the original factor regression line to represent the X-axis. This maximizes the variability of the new factors, while minimizing the variance around the new variable. Since each consecutive factor is defined to maximize the variability that is not indicated by the preceding factor, consecutive factors are independent of each other, making them uncorrelated or orthogonal. Varimax rotation is the most common orthogonal method (Haan, 1977; Kahya et al., 2008).

**State scale.**

It is recognized that a number of factors control the recharge rate to groundwater systems. These factors include, but are not necessarily limited to, climate (precipitation and evapotranspiration potential), geology (both bedrock and quaternary layer characteristics), surface topography, vegetation (landuse), and soil type. As such, using GIS methodology we derived statewide maps of parameters that represent these characteristics. Examples of these maps are available on the project website (https://wiki.umn.edu/view/Water_Sustainability), and a summary of all data layers used to produce these maps are summarized in the table found in Attachment 1. . Figure 5 is an example of a state-wide data map representing the distribution of Soil Orders overlain by the watershed boundaries.

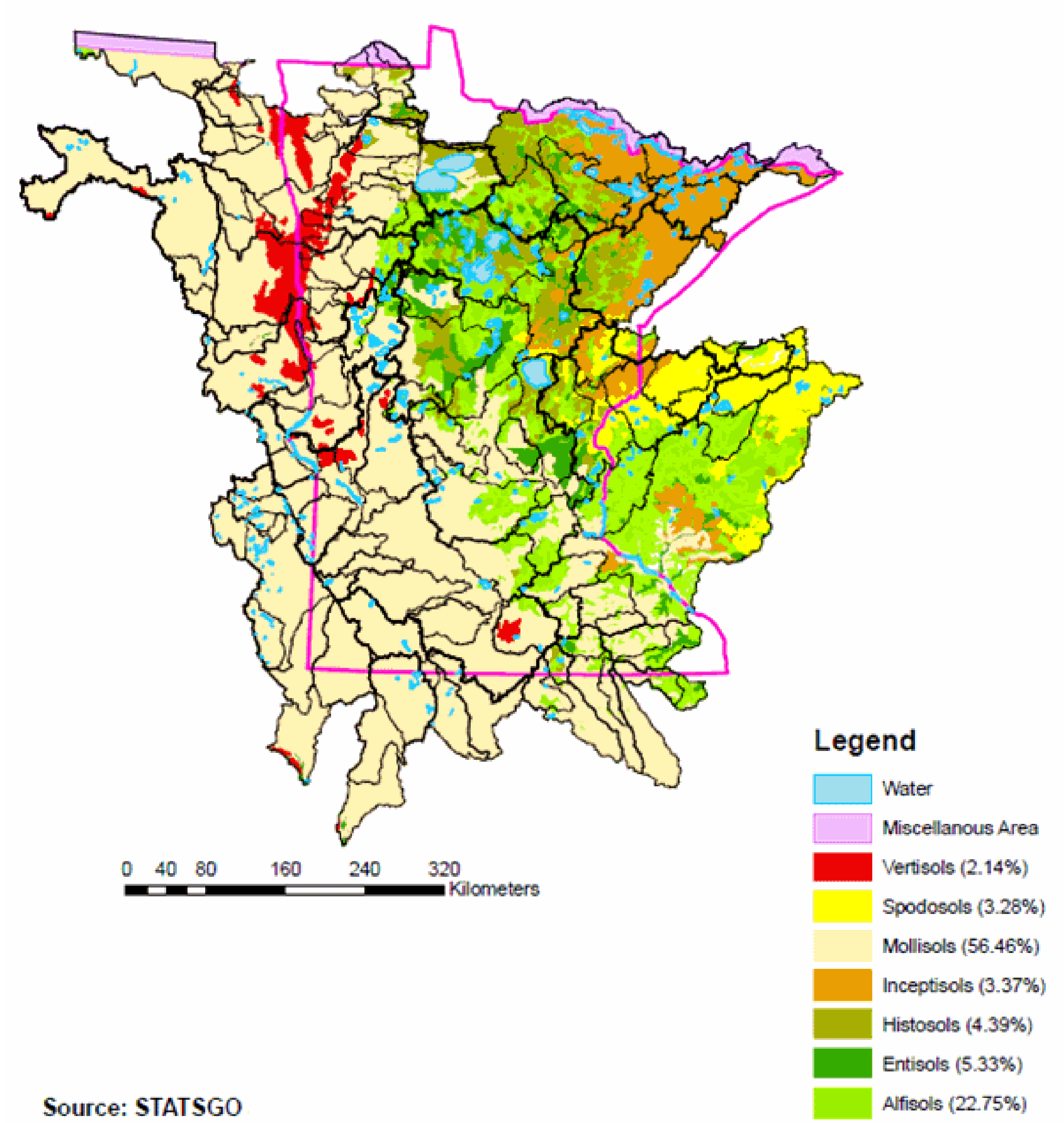



Figure 5. State-wide GIS map of Soil Orders overlain by watershed boundaries.

These maps could then be coordinated with the hydrologic characteristics derived for the watersheds outlined in Figure 1 in a fashion similar to the illustration given in Figure 2. That is, we identify the landscape characteristics that exist within the boundaries of a watershed, and correlations are then sought between the landscape characteristics and corresponding hydrologic characteristics. It is this identification of significant correlations that leads to the delineation of HHUs. By definition, HHUs are delineated landscape units that contain distinct landscape characteristics and distinct hydrologic response. The hydrologic response of interest to us at the state-wide scale is the minimum annual groundwater recharge. To quantify this recharge we use as a surrogate the minimum flow that occurs in February.

Before analyzing the recharge characteristics of different HHUs we first establish the fact that there are differences in hydrologic characteristics across the state, and that these characteristics can be regionalized. An analysis was conducted using the within-year distribution of monthly streamflows for all 129 watersheds. The monthly flow data for each of the 129 watersheds was entered into spreadsheets for application of factor analysis. The data ranged over the period from 1936 to 2006. Analyses were performed for three periods within the hydrologic record. The number of watersheds used in the analyses for these periods depended on the time period itself. The factor analyses distinguished watersheds lying within a given region of the state from watersheds lying within other regions as illustrated in Figure 6. Each of these regions has a distinct hydrologic regime in terms of the distribution of the annual flows and of the within-year distribution of flows. The distinctions shown in Figure 6 were found to be consistent among the three time periods analyzed, for both monthly and annual flow. Similar analysis of the annual minimum flows for the month of February showed that the behavior of those flows were similar to those for the annual and monthly hydrologic regimes.

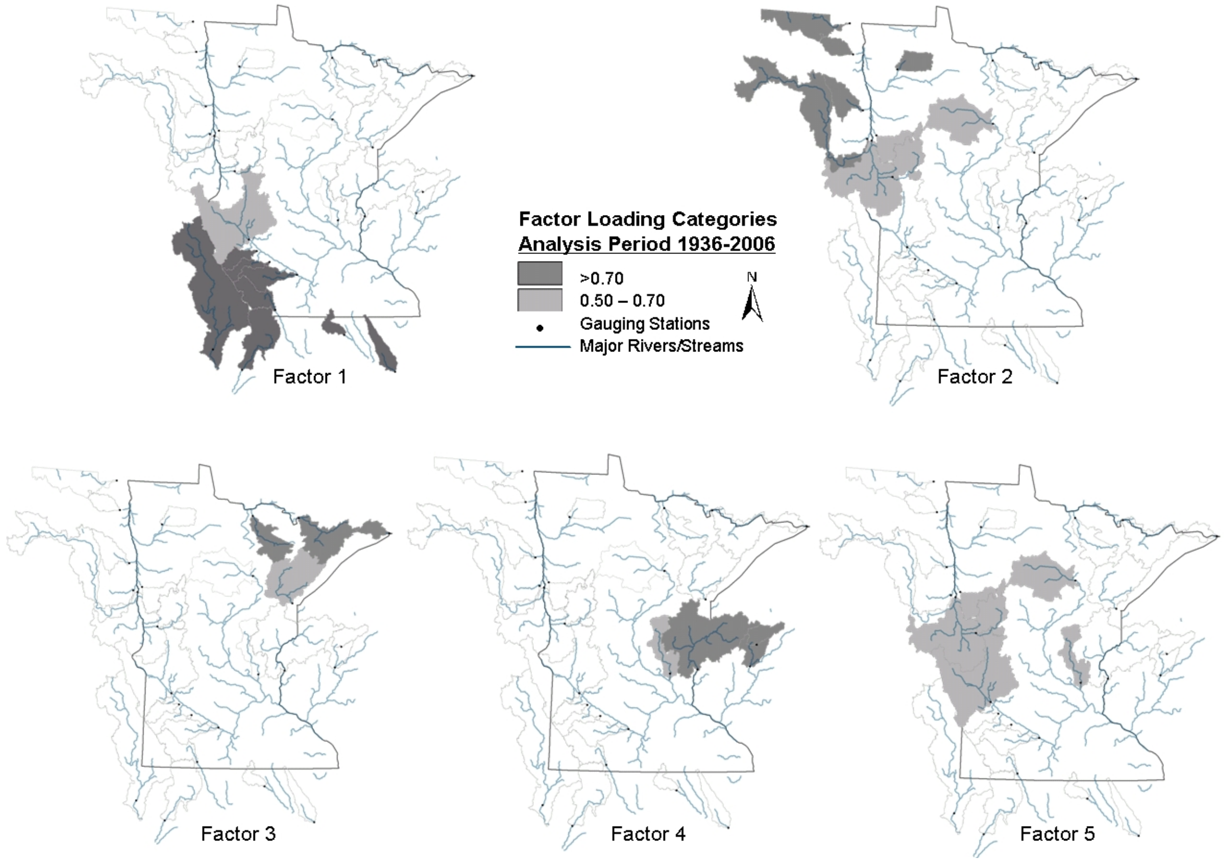



Figure 6. Illustration of the identification of the various regions of the state where the hydrologic regime is distinguished.

This result is then used as a visual guide to determine what areas of the state might divide up into regions of similar mean minimum annual groundwater recharge. For this the mean minimum February flows from the records for 129 watersheds were entered into tables along with coded landscape characteristics, such characteristics include but are not limited to, bedrock geology, quaternary geology, and soil order.

It was discovered from this analysis that the bedrock characteristics and the presence/absence of Quaternary layer were the variables that provide distinction in mean minimum annual groundwater recharge at the state scale. Other variables, such as soil order for instance, were not found to be significant. A map showing the spatial distribution of the mean minimum annual groundwater recharge at the state scale based on hydrogeologic boundaries is presented as the image on page 1-2 in Attachment 1, and in Figure 7. This map shows that there are three areas of the state with distinct recharge characteristics and those are identified as being Paleozoic Artesian Basin (referred to as A), Precambrian Basement (B), and Cretaceous Deposits (K). Further subdivision of this map was completed by overlaying Quaternary thickness on top of hydrogeologic boundaries (Figure 8). Although the thickness intervals which resulted in statistically significant recharge variations do not correspond directly to the coloration of the map used for Figure 8, this illustration provides a representation of the Quaternary distribution across the State of Minnesota. The final atlas (Figure 9) corresponds to the state-wide recharge table included on page 1-5 in Attachment 1.

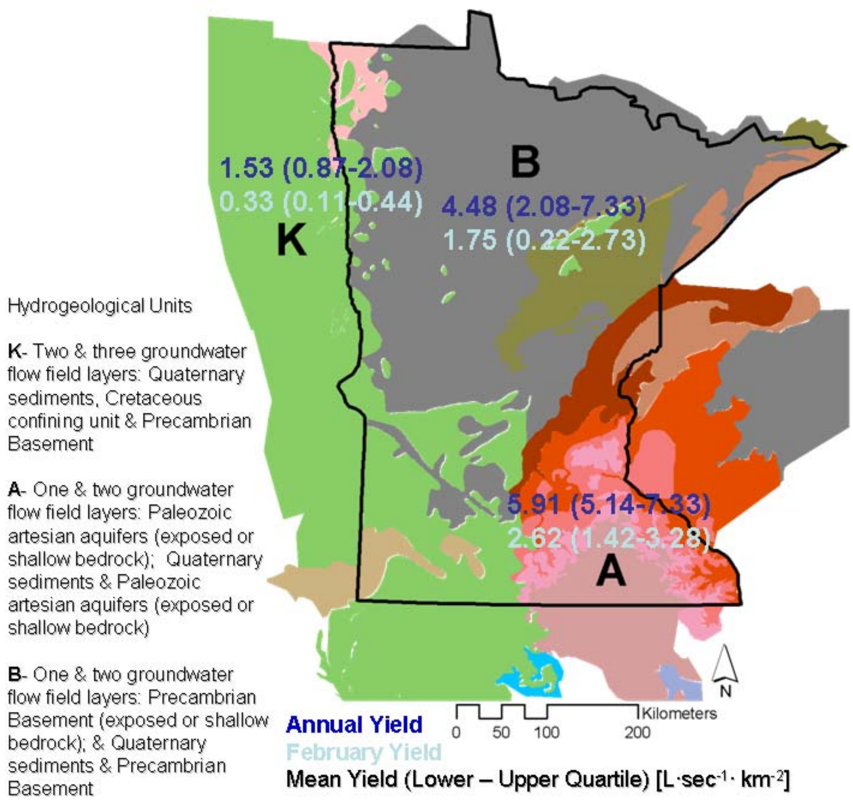



Figure 7. Distribution of mean minimum annual groundwater recharge for the state scale given by the February yield values. The regions are distinguished by the three hydrogeologic regimes, A, B, and K as defined in the legend. The recharges are given as mean values and the lower and upper 25% quartiles. To convert L/s/km$^2$ to in/yr multiply by 1.24.

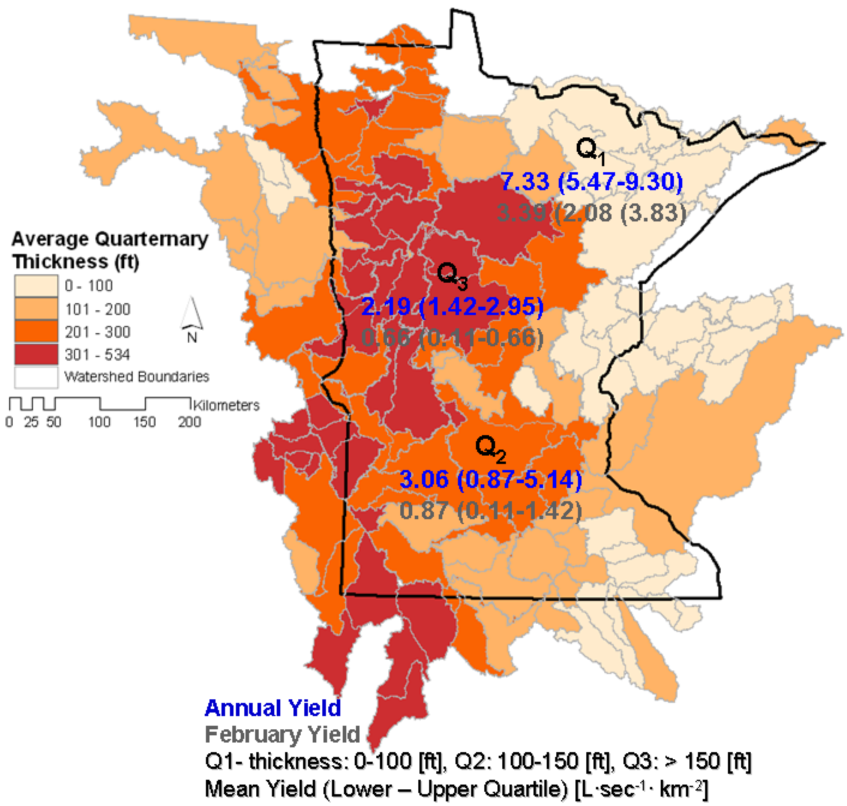



Figure 8. Distribution of mean minimum annual groundwater recharge for the state scale depicted by Quaternary thickness. Results of the non-parametric analysis indicated recharge variations for thicknesses of <100 ft, 100-150 feet and >150 ft. To convert L/s/km$^2$ to in/yr multiply by 1.24.

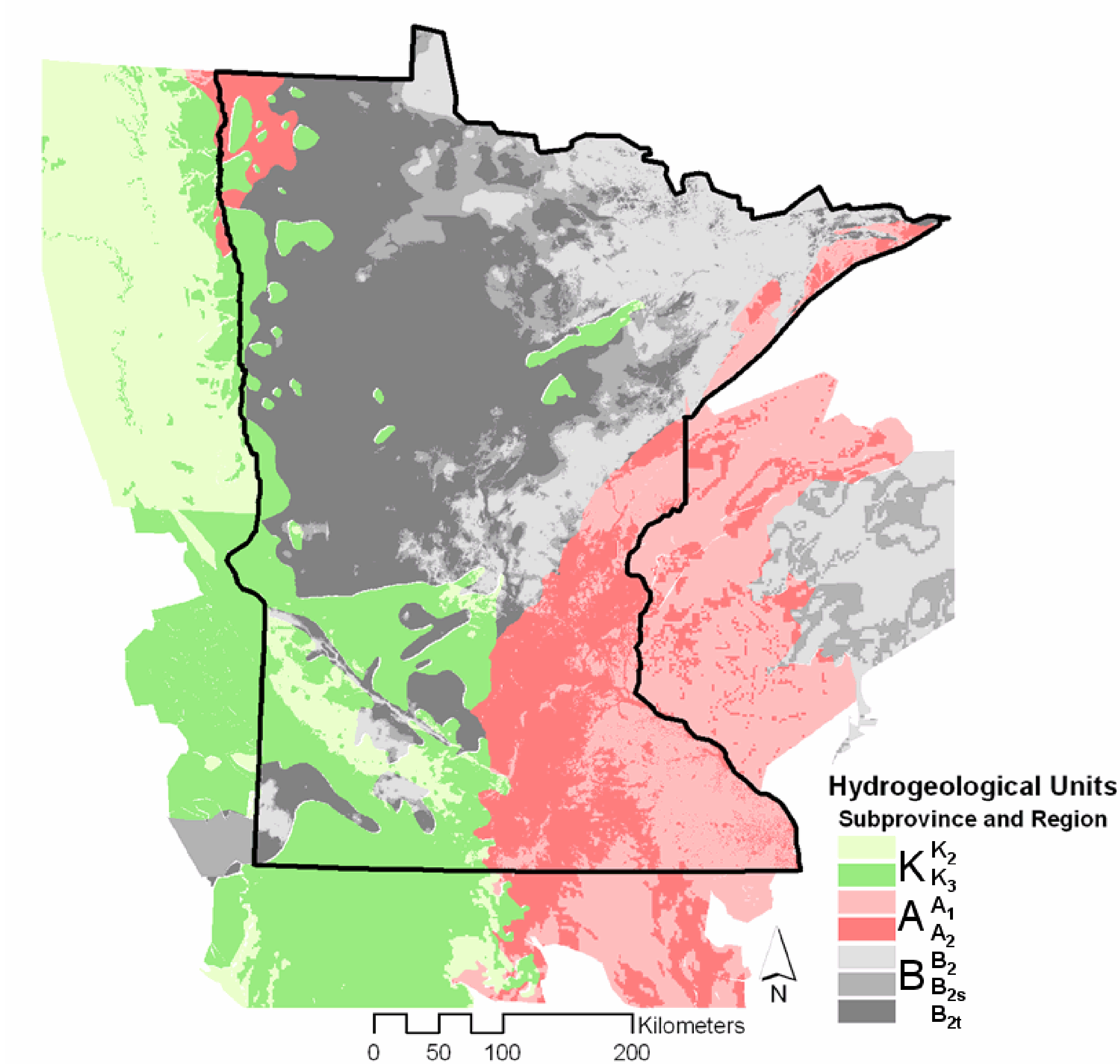



Figure 9. Final state-wide atlas created by overlaying hydrogeologic boundaries with Quaternary thickness.

**Region scale.**

We conducted analysis for three regional locations, the East Central Minnesota (ECM) region, the South East region (Karst), and the South Central (SC) region. The method for developing the atlases of mean minimum annual groundwater recharge for each of these regions will now be presented.

For the region scale a total of 176 gauging stations were used to analyze the minimal monthly stream runoff.. These locations were selected based on data summarized in

Lindskov [1977], which contains an extensive summary of low-flow characteristic data for Minnesota streams prior to the period of anthropogenic influences. GIS procedures were used to delineate the catchment boundaries (watershed) corresponding to each gauging station.

Various combinations of landscape characteristics were derived for these watersheds by the overlaying the spatial distribution of individual landscape characteristics onto each of the watersheds. One could then determine the fraction of a given watershed that is composed of a given characteristic. These characteristics are then entered into a table that has the watershed identifier along with the fraction of watershed composed of a given characteristics.

The next step is to derive the estimates of mean minimum February flow to be used in the analysis. For larger watersheds, such as those used at the state level scale the periods of record are much longer and complete than those records for the regional scale analysis. It is unfortunate that this is the case, but this is the reality of hydrologic monitoring at the present time.

To address this problem we use the idea of benchmark watersheds. These are defined as watersheds having relatively long-term records that exist in a given region and can presumably be used to represent the hydrologic characteristics of smaller watersheds within the same region that have short-term records.

From the 129 watersheds analyzed for the state scale analysis we selected four_ benchmark watersheds, these being the Elk River near Big Lake (5275000), the Yellow Medicine River near Granite Falls (5313500), the Root River near Lanesboro (5384000) and the Root River near Houston, MN (5385000). The records used were those from 1955 to 1976. The Root River data near Lanesboro was used as a benchmark for some of the ECM watersheds, while the Root River data near Houston was used as a benchmark watershed for some of the Karst and the SC watersheds. _The procedure for deriving the mean minimum February flow for a watershed from the regional scale using the benchmark watersheds is now explained briefly.

Average long-term characteristics of minimal monthly (February) discharge for the period of 1958-1976 were recorded for each of these watersheds were calculated for these benchmark watersheds. Each watershed was assigned to a corresponding benchmark based on proximity to the benchmark and the results of a state-wide streamflow regionalization. The February monthly runoff values for the 176 regional watersheds were obtained by determining the linear proportion between the discharge of the specific corresponding benchmark watershed and the regional watershed's observed February discharge value.

The available data for a given regional scale watershed is selected for analysis. Using an example, let us say that a given watershed in the ECM has but one year of flow data available, and that those data exist within the period of record of the Elk River watershed. The minimum February flow (in $L \cdot s^{-1} \cdot km^{-2}$) for the Elk River for the year corresponding to that one year of record for the ECM watershed is identified, and that flow is then divided into the flow that occurred for the ECM watershed for the same date in February. This ratio is then multiplied by the mean minimum February flow for Elk River to obtain the estimate of the mean minimum February flow for the ECM watershed. This procedure is then applied to all of the watersheds, and the resulting estimated mean minimum February flows are then entered into the tables along with the derived watershed characteristics.

These calculated minimal monthly discharge values represent the sustainable groundwater recharge rate for each regional watershed. The watershed characteristics approach uses these values together with the corresponding watershed's landscape characteristics to determine the hydrologic drivers.

A matrix table like the one created for the state-wide analysis was also created for the regional scale using the 176 watersheds. A detailed, simplified, step-by-step description is given in Appendix A of this attachment. This matrix table was used to conduct the non-parametric statistical analysis, specifically the Kruskal-Wallis analysis of variance (ANOVA). Using this analysis, it was determined whether minimal monthly streamflow (February yield) was statistically different between catchment groups having different watershed characteristics.

Based on the results of the ANOVA, characteristics exhibiting a significant statistical difference ($p \leq 0.05$) were used to establish the final HHUs. A statistically significant difference in minimum February flows between various groups of watersheds each containing a specific landscape characteristic (such as watersheds with a Quaternary thickness <100 ft or >100 ft) means that the specific HHU characteristic does play a role in determining the flows. If the difference is not significant, than one can conclude that the HHUs behave similarly and therefore cannot be separated, or distinguished, by way of the value of the recharge. These characteristics, specifically bedrock material, Quaternary sediment, and depth to bedrock, represented the primary hydrologic drivers. A list of all evaluated characteristics is included in Attachment 1. Some of these characteristics may have been statistically significant at one hierarchical level but could not be further subdivided into additional units; therefore, they were not included in the final regionalization.

With the combination of these characteristics HHUs at a subprovince, region, subregion, district, and subdistrict hierarchical level within the regional atlas were established. At each level moving from subprovince down to subdistrict, recharge values were refined. For example, at the subprovince level, three HHUs are identified within boundaries of the ECM (Figure 10) based on the hydrogeologic boundaries of K, B and A. However, at the region hierarchical level, these units are further refined into an additional HHU created by applying Quaternary thickness to subprovince HHU denoted by symbol A (Figure 11). The means test showed that the recharge values for these two units are significantly different and therefore A was subdivided into two distinct units with respect to their recharge characteristics. Further subdivisions continue to develop by refining the bedrock features, the type of Quaternary material, and the thickness of the Quaternary material.

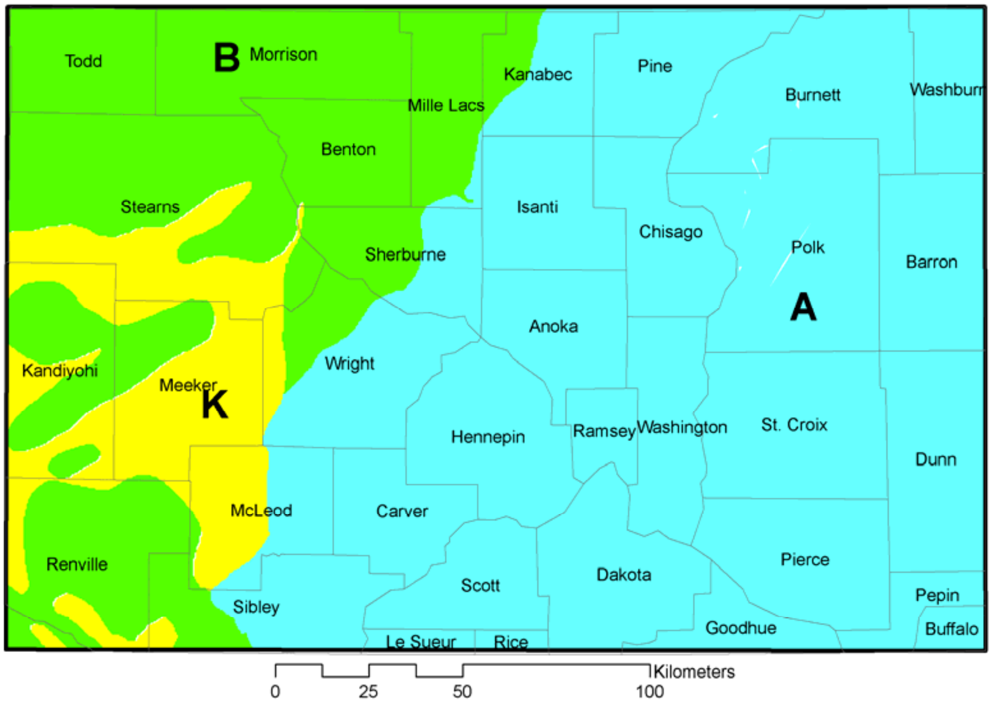



Figure 10. Subprovince hierarchical units boundaries for the ECM.

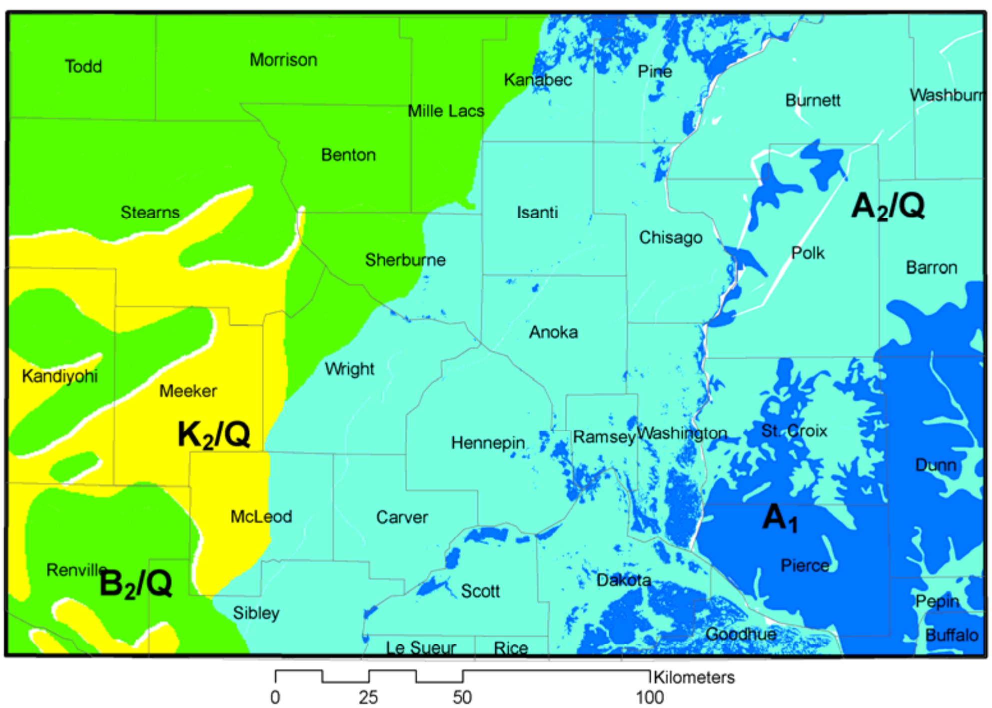



Figure 11. Region hierarchical unit boundaries for the ECM.

Basic descriptive statistics were conducted to compute the mean minimum annual recharge values along with upper and lower quartiles for each HHU. We note that the quartiles were computed only when sufficient watershed data was available to represent a given HHU at the corresponding scale. As the level of analysis decreases in scale, that is, as the number of HHUs increases, the number of watersheds available for a given HHU decreases, and eventually only one or two watersheds are available to estimate the recharge associated with each HHU. At that level, especially when there is only one watershed for an HHU the assignment of the recharge rate is made by expert judgment. Some background information on the approach to derive expert judgment estimates of recharge is provided in Appendix B of this attachment.

Atlases for spatial distribution of mean minimum annual recharge are presented for each of the regions (East Central Minnesota, South East Minnesota, South Central Minnesota) in Attachment 1. Also given is the table that summarizes the details of the estimated recharges for each level of HHU.

**County scale.**

Our objective was to derive atlases of minimum annual groundwater recharge for the counties of Olmsted, Pope and Lac Le Parle. There is not sufficient watershed gauging station data at the county scale to allow for the same type of statistical analysis possible at the statewide and region scales. Therefore, for the present condition it is necessary to extrapolate/interpolate the recharge results derived from the state scale analysis and from the region scale analyses to the county scale. This is done by transferring the estimates of minimum groundwater recharge for the individual HHUs derived from the state scale and the region scale to those same units where they occur at the county scale. The resulting county scale atlases are presented in Attachment 1 for the counties of Olmsted, Lac Qui Parle and Pope. Also given in the attachment are the maps of the HHUs for each county and the associated tables for the HHUs in each county.

It is hoped that in future efforts by federal, state and county agencies, that streamflow records will be collected at the smaller scale and that these data will be used along with the analyses derived for the larger scale (like that derived in this project) to provide estimates of recharge at county level and even at higher resolutions. Evidence that such will be possible is suggested in the article by Eng and Milly (2007).

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**Appendix A**.

## Step-By-Step Regional Procedure Documentation

A matrix of watershed characteristics is generated with watersheds listed as the rows and characteristics as the columns. The first characteristics included are the watershed area and yield.

Qualitative characteristics are listed as a percentage (decimal) of the watershed containing the specific attribute, each listed as an independent matrix column (**Figure** Figure A.1 and Figure A.2).

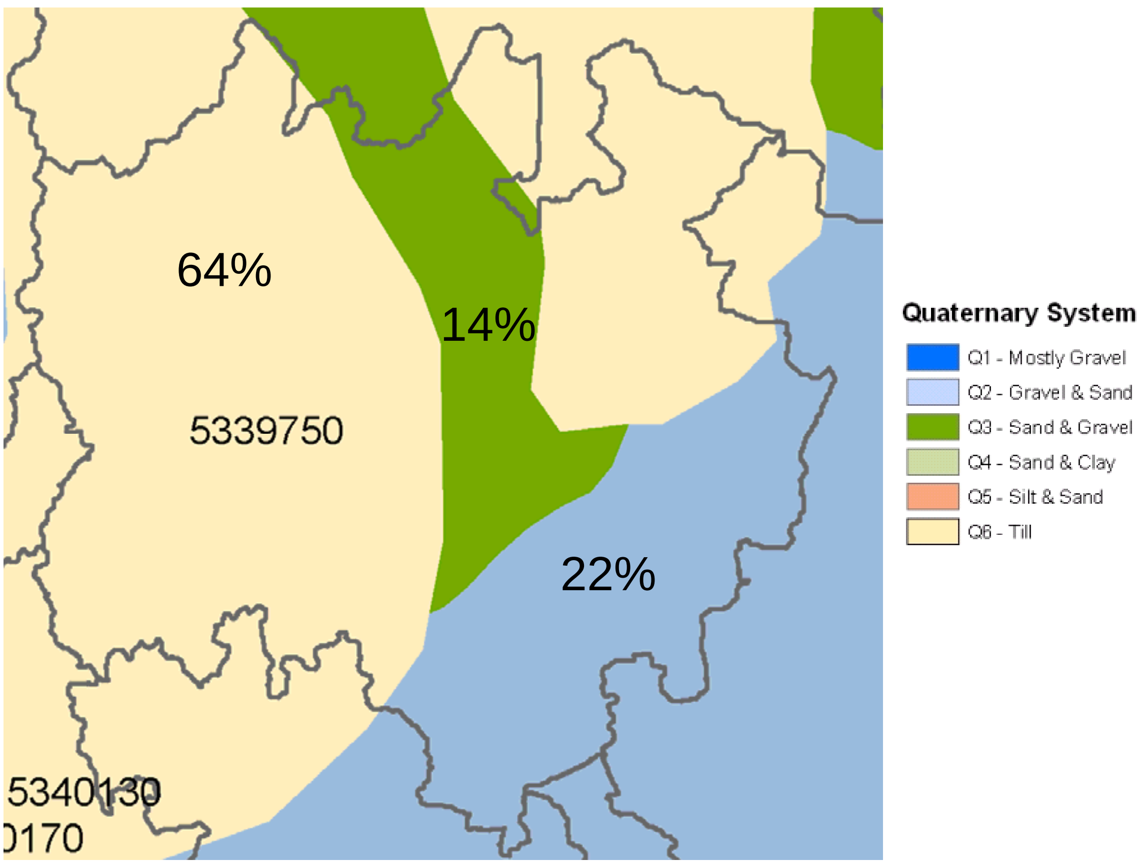



Figure A.1. Percentage of watershed #5339750 which falls within each type of quaternary sediment.

| | | | | Quaternary Sediment Material | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Name | Area (km2) | FebY (L/s/km$^2$) | Quat Thickness (Ft) | Q1 | Q2 | Q3 | Q6 | Q7 | Q8 | Quat Code |
| 5339750 | 175.8 | 0.60 | 129.62 | 0.00 | 0.22 | 0.14 | 0.64 | 0.00 | 0.00 | 6 |
| 5339800 | 134.8 | 0.19 | 192.70 | 0.00 | 0.59 | 0.00 | 0.41 | 0.00 | 0.00 | 2 |
| 5339950 | 138.8 | 0.80 | 180.31 | 0.00 | 1.01 | 0.00 | 0.00 | 0.00 | 0.00 | 2 |
| 5340110 | 69.0 | 0.04 | 97.97 | 0.00 | 0.40 | 0.18 | 0.42 | 0.00 | 0.00 | 6 |
| 5340130 | 134.8 | 2.84 | 114.50 | 0.00 | 0.43 | 0.23 | 0.35 | 0.00 | 0.00 | 2 |
| 5340170 | 181.7 | 3.86 | 141.75 | 0.00 | 0.35 | 0.40 | 0.26 | 0.00 | 0.00 | 2 |
| 5341540 | 77.5 | 1.49 | 115.03 | 0.00 | 0.10 | 0.00 | 0.90 | 0.00 | 0.00 | 6 |
| 5345000 | 328.3 | 1.74 | 143.20 | 0.00 | 0.43 | 0.00 | 0.57 | 0.00 | 0.00 | 6 |
| 5352010 | 863.2 | 0.71 | 185.83 | 0.00 | 0.00 | 0.05 | 0.95 | 0.00 | 0.00 | 6 |
| 5352810 | 108.1 | 0.06 | 137.30 | 0.00 | 0.09 | 0.05 | 0.85 | 0.00 | 0.00 | 6 |
| 5352850 | 528.6 | 1.13 | 130.50 | 0.00 | 0.07 | 0.22 | 0.70 | 0.00 | 0.00 | 6 |
| 5352900 | 104.4 | 0.52 | 126.39 | 0.00 | 0.07 | 0.00 | 0.93 | 0.00 | 0.00 | 6 |

Figure A.2. Example of matrix development using quantitative and qualitative characteristics.

Compiling the data into a matrix enables statistical analyses to be conducted on the entire dataset to get a preliminary understanding of connections. For example, a factor analysis (varimax normalized) was completed on the regional watersheds to see if any characteristics are linked directly to February yield throughout the dataset. Unfortunately, the results shown below do not indicate that solely one characteristic is controlling the yield (Figure A.3). Therefore, it will be necessary to continue the analysis to uncover the relationships.

| Variable | Factor Loadings (Varimax normalized) (FullRegionalData_Revised.sta)<br>Extraction: Principal components<br>(Marked loadings are >.700000)<br>Factor 1 | Factor 2 | Factor 3 | Factor 4 |
|---|---|---|---|---|
| FebY (l/s/km2) | -0.495789 | 0.467276 | 0.108654 | 0.424980 |
| Area (km2) | 0.608301 | 0.002356 | 0.051363 | 0.163292 |
| Quat Thickness (Ft) | 0.694142 | -0.329705 | 0.131974 | -0.254688 |
| Perennial Drainage Density (km/km$^2$) | 0.065646 | -0.145551 | -0.132125 | 0.908187 |
| Intermittent Drainage Density (km/km$^2$) | 0.051849 | 0.915910 | 0.025722 | -0.314510 |
| Total Drainage Density (km/km$^2$) | 0.086949 | 0.935427 | -0.032578 | 0.073427 |
| Average Slope | -0.457696 | 0.649316 | -0.043096 | -0.024292 |
| Average Altitude (ft) | 0.744477 | 0.207379 | -0.017656 | -0.224613 |
| Available Water Capacity | 0.104778 | 0.197694 | -0.885955 | 0.012524 |
| Total Porosity | -0.340475 | -0.253962 | -0.726397 | 0.150010 |
| CO | 0.644855 | -0.064328 | 0.040097 | 0.099291 |
| Expl.Var | 2.418700 | 2.634494 | 1.367386 | 1.284810 |
| Prp.Totl | 0.219882 | 0.239499 | 0.124308 | 0.116801 |

Figure A.3. Results of factor analysis for regional study; no preliminary connection to February yield was determined.

Next, non-parametric statistical analyses (specifically, Kruskal-Wallis ANOVA by ranks) were conducted. To use the Kruskal-Wallis test, characteristics must be assigned a "Code". This code is based on the predominant characteristic within the watershed. Based on the data summarized in Figure A.2 for watershed 5339750, 64% of the watershed is listed as Q6-till so this watershed would be coded "6" for quaternary sediments (Figure A.2). The Kruskal-Wallis test evaluates whether there is a statistical difference between mean values within each "Code". A p-value less than 0.05, was considered significant (Figure A.4).

| Depend.:<br>FebY (l/s/km2) | Kruskal-Wallis ANOVA by Ranks; FebY (l/s/km2) (BQ.sta)<br>Independent (grouping) variable: CQt<br>Kruskal-Wallis test: H ( 1, N= 38) =6.000000 p =.0143<br>Code | Valid N | Sum of Ranks |
|---|---|---|---|
| 1 | 1 | 26 | 585.0000 |
| 2 | 2 | 12 | 156.0000 |

Figure A.4. Result output for Kruskal-Wallis ANOVA by Ranks test; result indicates a significant difference ($p<0.05$) between quaternary thickness in the $B_2$/Q Region.

This approach can be time consuming and involves trial and error to evaluate which characteristic combinations can refine units and remain statistically significant. Once it is determined if there is a significant difference in each characteristic, then descriptive statistics are calculated to determine the mean for each characteristic, as well as the lower and upper quartiles (Figure A.5). Providing the quartile range summarizes the variation within each unit.

| Variable | All Groups Descriptive Statistics (BQ.sta) | | | | |
|---|---|---|---|---|---|
| | **Valid N** | Mean | Lower Quartile | Upper Quartile | Std.Dev. |
| **FebY (l/s/km2)** | 38 | 0.454580 | 0.036574 | 0.621334 | 0.650835 |

Figure A.5. Descriptive statistics for $B_2$/Q Region; summary of mean and lower and upper quartiles.

## Appendix B.

### Description of Expert Judgment for Assigning Recharge Rates to Units

The quantification of recharge values for hierarchical hydrogeologic units (HHUs) using the statistical quantification method becomes problematic when the number of gauging stations representing a unit becomes too small to draw statistical inferences. This problem occurs when the size of the HHUs reach a lower limit because gauging station data are generally available only for larger watersheds.

To partially overcome this limitation for estimating of recharge rates for small HHUs a procedure using expert judgment was employed. The procedure is based on the interpretation of the dominant character of flow fields using landscape descriptors (in the immediate case, bedrock and quaternary geology) for the area of interest and uses inferences about those flow field characteristics for the (larger) spatial scales where sufficient data was available to draw statistically significant results. In that way the estimates are essentially derived as extrapolations from the larger scale to the smaller scale, and therefore can be derived by any analyst familiar with the steps in the statistical data analysis and the regionalization procedure. This part of the assigning the flow to the HHU is rather objective.

There is however a significant amount of subjectivity in the interpretation of the physical setting for any given HHU, and this subjectivity comes from having extensive experience in understanding the workings of the hydrogeologic systems of interest. Thus the final interpretation and assigning of the recharge rates to HHUs that have insufficient data requires significant background knowledge from the field of hydrogeology and familiarity with the region (e.g., Kanivetsky, 1979).

As an example let's consider an HHU, call it HHU-small that is dominated by carbonate bedrock (fractured media) for which we want to derive an estimate of the minimum annual recharge. Within the same region and at a larger scale let us say that an HHU, call it HHU-large, exists that contains both the same carbonate bedrock feature, but also sandstone feature as well. Let us also say that HHU-large is large enough such that enough flow data was available to derive a statistically significant estimate of recharge for the unit, and let us say that the mean value for the estimate is 2.5 $l/s/km^2$ and the range (lower and upper 25% values) is 1.25 $l/s/km^2$ to 3.5 $l/s/km^2$. Since HHU-large contains both carbonate and sandstone units, the lower value of the range presumably is for measured flows associated with sandstone dominated features and the upper value is for measured flows dominated by the carbonate features. Thus since HHU-small is dominated by carbonate features the expert judgment would be that the recharge rate would be from the upper part of the range, or 3.5 $l/s/km^2$.

# Attachment 3

# Result 2. Freshwater Sustainability Database – for use in a Quantitative Information System (QIS)

## Purpose

The *Freshwater Sustainability* database is designed to quantify sustainability for a desired area of interest by comparing permitted water use to available groundwater recharge volumes by way of a MS Access database (db) queries or manipulation in MS Excel. The db is intended to allow querying of spatially referenced data without the need of a GIS. Areas of interest are queried by using references to the different areal extents (county, major and minor watershed) that are associated with each row of sustainability data.

## Methodology

The db was created using ArcGIS 9.2 and MS Access 2003. Fundamentally, it is formed by the intersection of three geospatial layers for Minnesota (MN): bedrock-quaternary (BQ) spatial unit polygons, DNR permitted-use points, and Section level public land survey polygons. As such, the db is composed of three tables:

1. *Recharge_units_12_09*: consists of groundwater recharge rates for each BQ spatial unit in Minnesota. The data were generated from dissolution of BQ polygons at three different spatial resolutions (State-wide, Southern MN "zone" and county [Lac Qui Parle, Olmsted and Pope]) to produce a master list of 80 unique BQ units.
2. *Sections_final*: stores all MN Sections and the dominant BQ spatial unit for each as well as the associated county, and major- and minor watersheds. The data were generated by intersecting publically available MN Section polygons with BQ, county, and watershed polygons.
3. *DNR_wateruse_permits_new*: consists of volume and location data for surface- and groundwater use permits issued in Minnesota from 1988 through 2007. The data were generated by taking the permit point data available from the MN-DNR

http://www.dnr.state.mn.us/waters/watermgmt_section/appropriations/wateruse.html) and intersecting it with the MN Section polygons.

Tables 1 through 3 for provide descriptions of table columns.

Table 1. Column descriptions for *Recharge_units_12_09* db table

| | |
|---|---|
| ID | Subdistrict code that uniquely identifies BQ Subdistrict unit and links *Recharge_units_12_09* table to *Sections_final* table |
| zone_subdist | Combination of BQ resolution "zone" and Subdistrict |
| subprovince | BQ Subprovince (non-unique) |
| Region | BQ Region (non-unique) |
| subregion | BQ Subregion (non-unique) |
| District | BQ District (non-unique) |
| subdistrict | BQ Subdistrict (unique) |
| Yield | Recharge rate of BQ unit (L/s/km$^2$); this value is converted to inches/year for query calculations |
| Shape_Area | Total area of BQ unit in Minnesota (m$^2$) |

Table 2. Column descriptions for *Sections_final* db table

| **Column Name** | **Column Description** |
|---|---|
| Objectid | Unique identifier for each section row |
| Area | Area of the section (m$^2$) |
| Town | Township number |
| Rdir | Range direction |
| Rang | Range number |
| Sect | Section number |
| Cty_name | County name where geographic center of section is located |
| Cty_fips | County FIPS code |
| Majorws | Major watershed number |
| Majwsname | Major watershed where geographic center of section is located |
| Minorws5 | Minor watershed number |
| Minwsname | Minor watershed where geographic center of section is located |
| Subdist_code | Code linking the section with the BQ spatial data |

Table 3. Column descriptions for *DNR_wateruse_permits_new* db table

| **Column Name** | **Column Description** |
|---|---|
| PERMIT | Permit code |
| INST | Installation (note: the combination of PERMIT and INST that creates a unique permit ID) |
| PERMITTEE | Name of permit holder |
| USE_CODE | ID associated with designated use |
| USENAME | Designated use name |
| CATEGORY | Designated use category |
| PERMIT_VOL | Maximum permitted volume (Mgallons/year) |
| PERMIT_GPM | Maximum permitted volume (gallons/minute) |
| PERMIT_ACR | Permit acres |
| STATUS | Status code (1, 2, or 99) |
| RES_CODE | ID associated with permit resource |
| RES_NAME | Permit resource name (surface water body or aquifer name) |
| PWI_ID | Public Waters Inventory ID |
| WELL_NUM | Well number |
| WELL_DEPTH | Well depth (feet) |
| COUNTY_ID | ID associated with permit county |
| COUNTY | Permit county |
| WATERSHED | Watershed code ID |
| TWP | Township |
| RNG | Range |
| SECTION_ | Section |
| TWPRNGSEC1 | Section code consisting of township+range+section; used to link this table to *Sections_final* table |
| SUB_SECT | Sub-section |
| XUTM | X-coordinates for permit location (UTM NAD1983 Region 15) |
| YUTM | Y-coordinates for permit location (UTM NAD1983 Region 15) |
| ACCURACY | Estimated accuracy of reported use volumes |
| USE_2007 | Reported volume by year (Mgallons/year) |
| USE_2006 | |
| USE_2005 | |
| USE_2004 | |
| USE_2003 | |
| USE_2002 | |
| USE_2001 | |
| USE_2000 | |
| USE_1999 | |
| USE_1998 | |
| USE_1997 | |
| USE_1996 | |
| USE_1995 | |
| USE_1994 | |
| USE_1993 | |
| USE_1992 | |
| USE_1991 | |
| USE_1990 | |
| USE_1989 | |
| USE_1988 | |

Recharge rates for *Recharge_units_12_09* were determined by deriving BQ units defined at three different resolutions (i.e., “zones”); listed from lowest to highest they are State-wide, Southern MN, and County. High resolution County level BQ units have been defined for Lac Qui Parle, Olmsted and Pope Counties. All three resolution sets of polygons were merged together in ArcGIS with the highest resolution polygon taking precedence at any given point. This resulted in a mosaic-like BQ polygon map with significantly varying resolution state wide (See Figure 1).

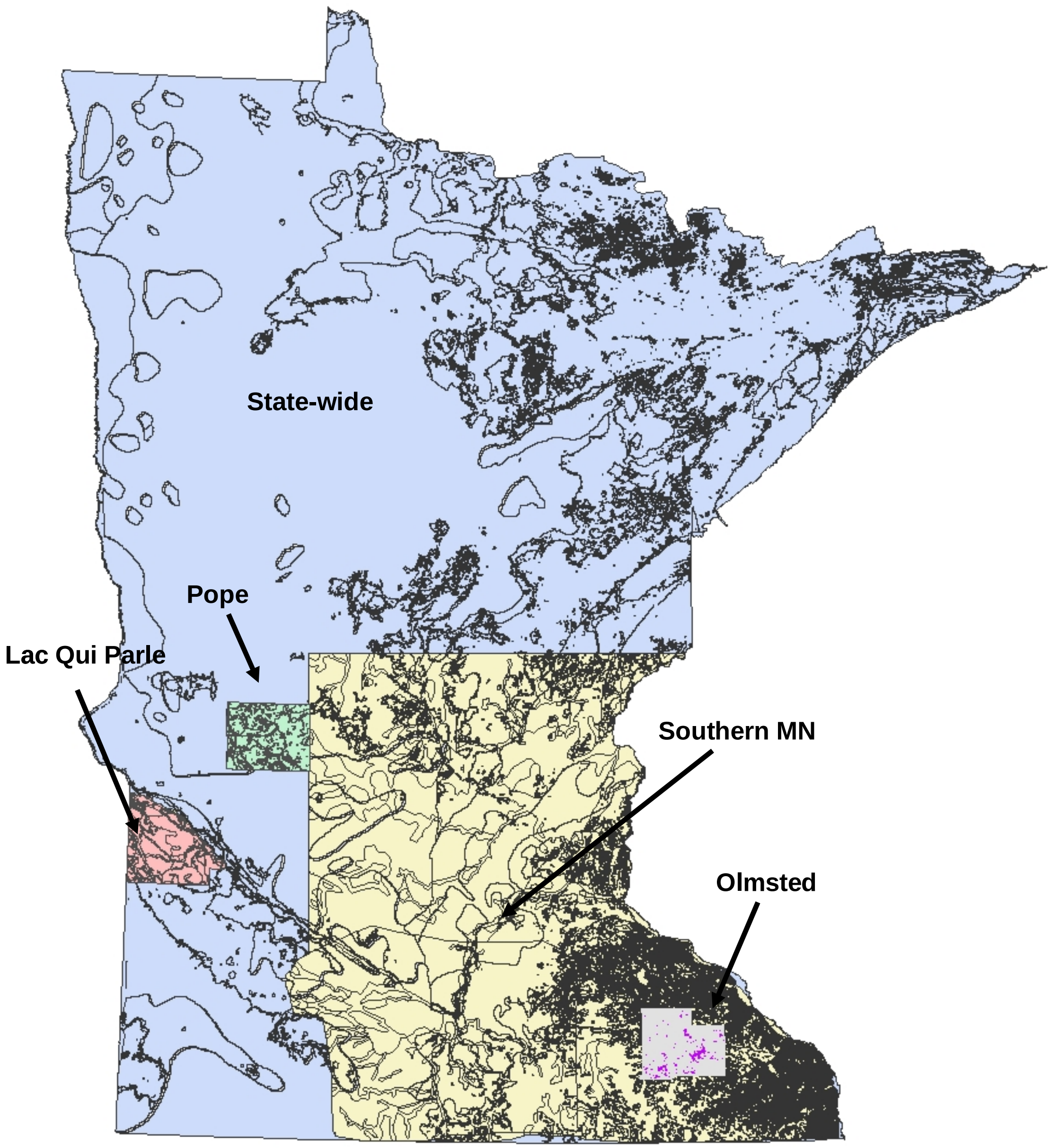



Figure 1. Resulting map from merging bedrock-quaternary unit polygons of different scales.

Each section was intersected by one or more BQ units. The dominant BQ Subdistrict for a given section was determined as that with the highest areal proportion in the section.

Water use was quantified by intersecting the BQ-Section map with MN-DNR water permit points. The annual permits are a mix of ground- and surface withdrawals with groundwater comprising the vast majority of permitted volumes. Currently, annual water use data is available from 1988 to 2007.

# Attachment 4

**Result 3. Assessment of water resources sustainability with the constructed database**

The freshwater sustainability database (db) is meant to be browsed or queried using MS Access 2003 or higher. Sustainability calculations are performed by db queries which are required to pull together the necessary data from the three db tables. Sections are used as the elementary units of analysis in the db; that is, for purposes of calculating sustainability, an area of interest is defined as a set of Sections. County and watershed are coded for each section allowing querying by these areal boundaries.

Three queries are included with the db to provide examples of how it can be used to evaluate sustainability for an area of interest: *All_Sections*, *County_sustainability* and *Majwatershed_sustainability*. These queries can be modified and expanded upon by anyone with intermediate knowledge of MS Access. The queries require entering a county or watershed name exactly as they appear in the *Sections_final* table (although they are not case-sensitive). Consequently it may be necessary to browse the db table first to see how a particular county or watershed is spelled and formatted.

Output from the queries are nearly identical in that they all group results by BQ Subdistrict (i.e., BQ Subdistrict recharge – permitted use = sustainability). *All_sections* queries data for all sections in MN. *County_sustainability* and *Majwatershed_sustainability* query data for all sections in a user-defined county or watershed, respectively. Maximum permitted and 2007 reported use volumes were arbitrarily selected for the queries as they provided the most conservative and most recently reported use scenarios, respectively. Query results can be easily exported into MS Excel for further analysis and manipulation by copy/pasting (see Table 1 for description of query results).

Table 1. Column descriptions for db query results

| Column Name | Column Description |
|---|---|
| County[1] | County that was inputted into the query |
| Watershed[2] | Watershed that was inputted into the query |
| Subprovince | Bedrock-quaternary Subprovince associated with dominant Subdistrict |
| Region | Bedrock-quaternary Region associated with dominant Subdistrict |
| Subregion | Bedrock-quaternary Subregion associated with dominant Subdistrict |
| District | Bedrock-quaternary District associated with dominant Subdistrict |
| Subdistrict[3] | Dominant bedrock-quaternary Subdistrict within section as determined by highest areal percentage |
| Yield | Recharge rate (inches/year) associated with the dominant Subdistrict |
| TotArea | Total area (square miles) for sections associated with the dominant Subdistrict |
| Recharge_totvol | Total recharge (Mgallons/year) for sections associated with the dominant Subdistrict |
| Permit_totvol | Maximum permitted volume (Mgallons/year) for permits in sections associated with the dominant Subdistrict |
| Permit_2007vol | 2007permitted volume (Mgallons/year) for permits in sections associated with the dominant Subdistrict |
| Recharge_TotPermit_Diff | Difference (Mgallons/year) between Total recharge and Max permitted volume (Recharge_totvol - Permit_totvol) |
| Recharge_2007Permit_Diff | Difference (Mgallons/year) between Total recharge and 2007 permitted volume (Recharge_totvol - Permit_2007vol) |

[1] Column present in County_sustainability query only
[2] Column present in MajWatershed_sustainability query only
[3] All query results are aggregated by Subdistrict

The queries mentioned above were applied to three counties where high resolution BQ data was available as well as three major watersheds that intersected the counties to illustrate how the db can be used.

(1) Open db, click *Queries* on the left navigator pan, and double-click *County_sustainability* (See Figure 1)

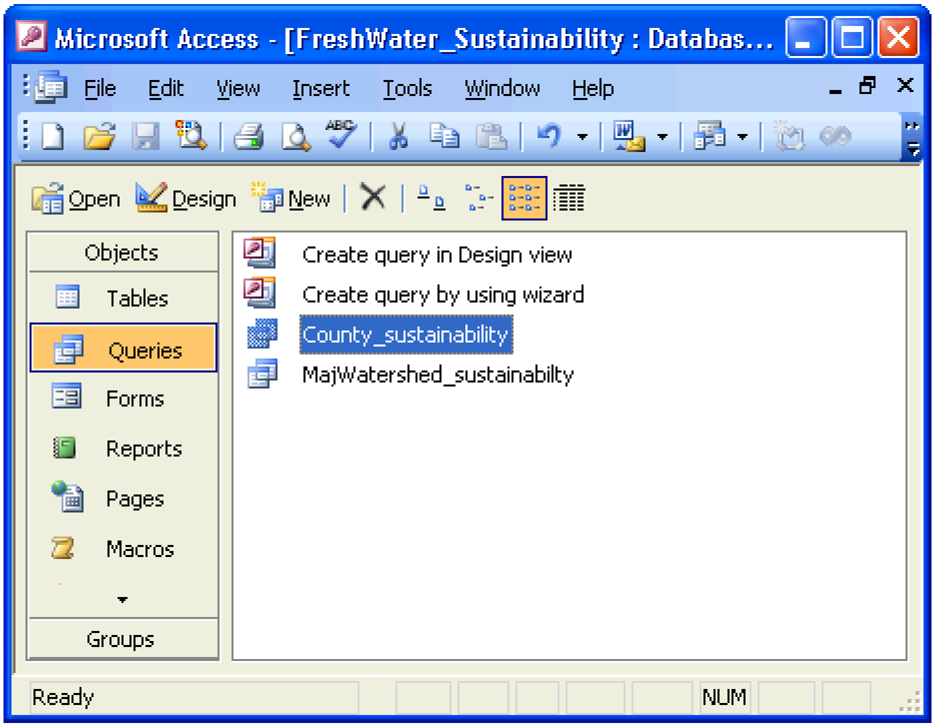



Figure 1. Opening db and selecting an example query.

(2) Enter name of county—Olmsted, in this example (Figure 2) – and click OK

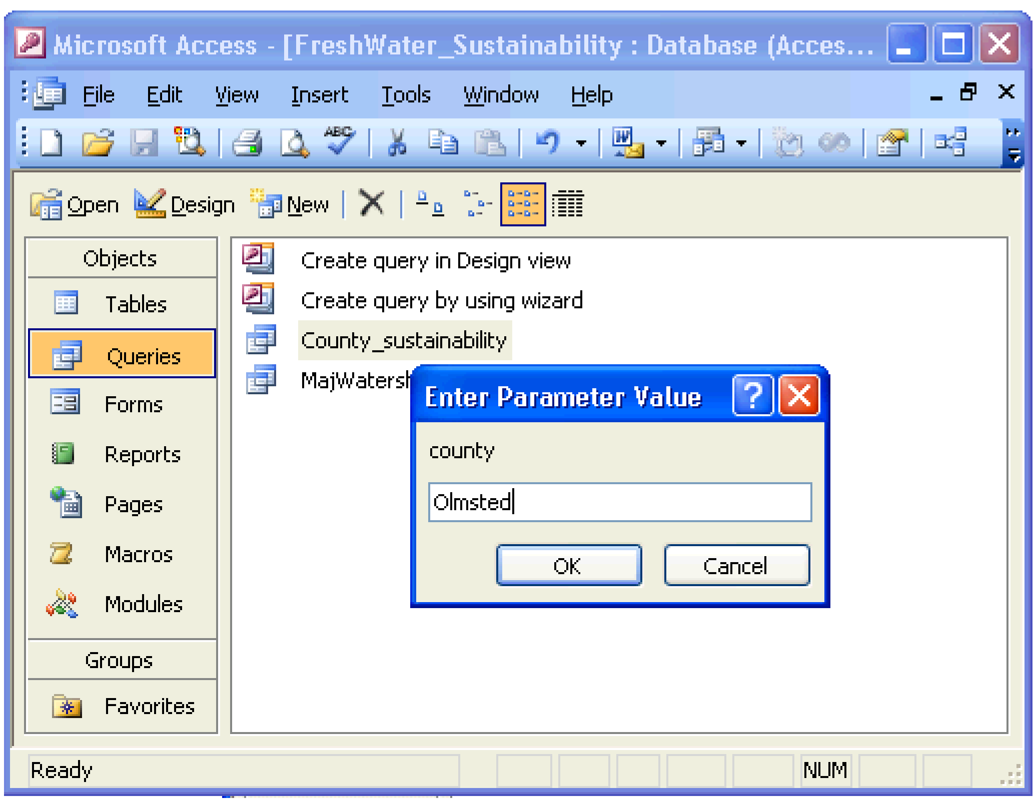



Figure 2. Entering County value for query argument

The resulting query-table (See Table 2) shows the distribution of the dominant Subdistricts for all the sections within Olmsted county as well as annual recharge, max permitted volume and 2007 volume used as well as the differences between annual recharge and max and 2007 volumes. Note: the sum totals comprising the last row of the table were added using MS Excel.

Table 2. Results of sustainability query for Olmsted county

| sub-province | region | subregion | district | Subdistrict | yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | A_1 | A_1^1 | A_1^1 | A_1^1 | 2.4 | 220.3 | 11484.1 | 15931.7 | 860 | -4447.6 | 10624.1 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^1/Q2 | 2.15 | 1 | 46.3 | 0 | 0 | 46.3 | 46.3 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^1/Q6 | 1.33 | 96.3 | 2782.1 | 20416.4 | 705.8 | -17634.3 | 2076.3 |
| A | A_1 | A_1^2 | A_1^2 | A_1^2 | 3.38 | 49.4 | 3628.9 | 20286 | 740.8 | -16657.1 | 2888.1 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^2/Q2 | 2.6 | 4 | 228.5 | 0 | 0 | 228.5 | 228.5 |
| A | A_2/Q | A_2/Q3 | A_2/Q3 | A_2^2/Q3 | 2.4 | 3 | 155 | 0 | 0 | 155 | 155 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^2/Q6 | 1.77 | 28.7 | 1105.4 | 15000 | 416.5 | -13894.6 | 688.9 |
| A | A_1 | A_1^3 | A_1^3 | A_1^3 | 2.07 | 89 | 4002.2 | 27200.9 | 1354.8 | -23198.7 | 2647.4 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^3/Q2 | 2.5 | 6 | 323.5 | 10193.3 | 360 | -9869.8 | -36.5 |
| A | A_2/Q | A_2/Q3 | A_2/Q3 | A_2^3/Q3 | 2.3 | 7.9 | 395.7 | 36865 | 10123 | -36469.3 | -9727.5 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^3/Q6 | 1.6 | 44.6 | 1549.6 | 21184 | 4378.7 | -19634.4 | -2829.1 |
| A | A_1 | A_1 | A_1 | A_1c1 | 0.1 | 53.5 | 116.3 | 20146 | 1104.1 | -20029.7 | -987.8 |
| A | A_2/Q | A_2/Q | A_2/Q | A_2c1/Q6 | 0.1 | 26.7 | 58.1 | 4.8 | 0.6 | 53.3 | 57.5 |
| A | A | A | A | Q2/A_2c1 | 0.3 | 2 | 13.1 | 0 | 0 | 13.1 | 13.1 |
| A | A | A | A | Q6/A_2^1 | 0.3 | 5 | 32.4 | 0 | 0 | 32.4 | 32.4 |
| A | A | A | A | Q6/A_2^2 | 0.2 | 11.9 | 51.6 | 100 | 46.2 | -48.4 | 5.4 |
| A | A | A | A | Q6/A_2^3 | 0.8 | 1 | 16.8 | 0 | 0 | 16.8 | 16.8 |
| A | A | A | A | Q6/A_2c1 | 0.1 | 4 | 8.7 | 0 | 0 | 8.7 | 8.7 |
| | | | | | SUM | 654.3 | 25998.3 | 187328.1 | 20091 | -161329.8 | 5907.6 |

The following examples further illustrate use of the included queries with Zumbro Watershed, Lac Qui Parle County, Lac Qui Parle Watershed, Pope County, and Chippewa Watershed, respectively.

## Table 3. Results of sustainability query for Zumbro Watershed

| sub-province | region | subregion | district | subdistrict | Yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | A_1 | A_1^1 | A_1^1 | A_1^1 | 3 | 194.8 | 10154.8 | 15928.3 | 813.1 | -5773.5 | 9341.7 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^1/Q2 | 2.69 | 20.7 | 967.9 | 131.4 | 27.7 | 836.5 | 940.2 |
| A | A_2/Q | A_2/Q3 | A_2/Q3 | A_2^1/Q3 | 2.44 | 24 | 1016.7 | 0 | 0 | 1016.7 | 1016.7 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^1/Q6 | 1.66 | 49.5 | 1430.7 | 20373.4 | 705.8 | -18943 | 724.9 |
| A | A_1 | A_1^2 | A_1^2 | A_1^2 | 4.22 | 88.1 | 6472.1 | 20496 | 775.2 | -14024 | 5696.9 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^2/Q2 | 3.25 | 10 | 564.3 | 0 | 0 | 564.3 | 564.3 |
| A | A_2/Q | A_2/Q3 | A_2/Q3 | A_2^2/Q3 | 3 | 3 | 155 | 0 | 0 | 155 | 155 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^2/Q6 | 2.21 | 24.7 | 951.5 | 15000 | 416.5 | -14049 | 535 |
| A | A_1 | A_1^3 | A_1^3 | A_1^3 | 2.59 | 255.6 | 11495.2 | 28140.1 | 1616.3 | -16645 | 9878.9 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^3/Q2 | 3.12 | 24.8 | 1346.8 | 10235.7 | 384.9 | -8888.9 | 961.9 |
| A | A_2/Q | A_2/Q3 | A_2/Q3 | A_2^3/Q3 | 2.88 | 9.9 | 495.5 | 36865 | 10123.2 | -36370 | -9627.7 |
| A | A_2/Q | A_2/Q6 | A_2/Q6 | A_2^3/Q6 | 2 | 40.6 | 1410.4 | 21184 | 4378.7 | -19774 | -2968.3 |
| A | A_1 | A_1^4 | A_1^4 | A_1^4 | 2.06 | 35.6 | 1275.8 | 0 | 0 | 1275.8 | 1275.8 |
| A | A_2/Q | A_2/Q1 | A_2/Q1 | A_2^4/Q1 | 1.44 | 2 | 49.6 | 0 | 0 | 49.6 | 49.6 |
| A | A_2/Q | A_2/Q2 | A_2/Q2 | A_2^4/Q2 | 1.12 | 12.8 | 250.8 | 0 | 0 | 250.8 | 250.8 |
| A | A_1 | A_1 | A_1 | A_1c1 | 0.12 | 24.7 | 53.7 | 20100 | 1090.3 | -20046 | -1036.6 |
| A | A_2/Q | A_2/Q | A_2/Q | A_2c1/Q6 | 0.12 | 16.8 | 36.6 | 4.8 | 0.6 | 31.8 | 36 |
| A | A_2/Q | A_2/Q6 | A_2/Q_s6 | A_2^1/Q_s6 | 1.66 | 131.3 | 3793.2 | 183 | 76.5 | 3610.2 | 3716.7 |
| A | A_2/Q | A_2/Q6 | A_2/Q_s6 | A_2^2/Q_s6 | 2.21 | 40.7 | 1566.2 | 695.5 | 266.7 | 870.7 | 1299.5 |
| A | A_2/Q | A_2/Q6 | A_2/Q_s6 | A_2^3/Q_s6 | 2 | 45.7 | 1586.8 | 14.6 | 6.9 | 1572.2 | 1579.9 |
| A | A_2/Q | A_2/Q6 | A_2/Q_s6 | A_2^4/Q_s6 | 0.38 | 4 | 25.8 | 0 | 0 | 25.8 | 25.8 |
| A | A_2/Q | A_2/Q6 | A_2/Q_t6 | A_2^1/Q_t6 | 0.48 | 283.6 | 2340.7 | 1175.8 | 300.6 | 1164.9 | 2040.1 |
| A | A_2/Q | A_2/Q6 | A_2/Q_t6 | A_2^2/Q_t6 | 0.29 | 35.6 | 177.8 | 0 | 0 | 177.8 | 177.8 |
| A | A_2/Q | A_2/Q6 | A_2/Q_t6 | A_2^3/Q_t6 | 1.06 | 4 | 74.5 | 0 | 0 | 74.5 | 74.5 |
| A | A_2/Q | A_2/Q6 | A_2/Q_t6 | A_2^4/Q_t6 | 0.15 | 12.8 | 33.5 | 0 | 0 | 33.5 | 33.5 |
| A | A | A | A | Q2/A_2c1 | 0.38 | 2 | 13.1 | 0 | 0 | 13.1 | 13.1 |
| A | A | A | A | Q6/A_2^1 | 0.38 | 2 | 13 | 0 | 0 | 13 | 13 |
| A | A | A | A | Q6/A_2^2 | 0.25 | 11.9 | 51.6 | 100 | 46.2 | -48.4 | 5.4 |
| A | A | A | A | Q6/A_2^3 | 1 | 1 | 16.8 | 0 | 0 | 16.8 | 16.8 |
| A | A | A | A | Q6/A_2c1 | 0.12 | 4 | 8.7 | 0 | 0 | 8.7 | 8.7 |
| A | A_2 | A_2 | A_2 | A_2 | 1.49 | 4 | 103.5 | 43 | 22.4 | 60.5 | 81.1 |
| | | | | | SUM | 1420.2 | 47932.6 | 190670.6 | 21051.6 | -142738 | 26881 |

## Table 4. Results of sustainability query for Lac Qui Parle County

| sub-province | region | subregion | district | subdistrict | yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007_Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q10 | 0.55 | 43.3 | 414.1 | 2598 | 689.3 | -2184 | -275.2 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q3 | 1.06 | 79.8 | 1472.8 | 381.7 | 84.1 | 1091.1 | 1388.7 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q6 | 0.6 | 104.3 | 1087.2 | 10 | 4.9 | 1077.2 | 1082.3 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q10 | 0.35 | 92.9 | 564.9 | 921.3 | 346.3 | -356.4 | 218.6 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q3 | 0.75 | 188.5 | 2456.9 | 494.3 | 155.3 | 1962.6 | 2301.6 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q6 | 0.41 | 258.7 | 1854.6 | 549.3 | 166.1 | 1305.3 | 1688.5 |
| Water | Water | Water | Water | Water | 0 | 9.8 | 0 | 0 | 0 | 0 | 0 |
| B | B_1 | B_1 | B_1 | B_1 | 4.62 | 3.9 | 317.3 | 46.8 | 16 | 270.5 | 301.3 |
| B | B_2s | B_2s | B_2s | B_2s | 2.05 | 1 | 34.4 | 0 | 0 | 34.4 | 34.4 |
| | | | | | SUM | 782.2 | 8202.2 | 5001.4 | 1462 | 3200.8 | 6740.2 |

## Table 5. Results of sustainability query for Lac Qui Parle Watershed

| sub-province | Region | subregion | district | subdistrict | Yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q10 | 0.55 | 18.1 | 172.8 | 2548 | 689.3 | -2375 | -516.5 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q3 | 1.06 | 48.1 | 888.7 | 381.7 | 84.1 | 507 | 804.6 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q6 | 0.6 | 81.4 | 848.5 | 10 | 4.9 | 838.5 | 843.6 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q10 | 0.35 | 62.9 | 382.7 | 869.3 | 322 | -486.6 | 60.7 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q3 | 0.75 | 101.1 | 1317.2 | 92.3 | 45.3 | 1224.9 | 1271.9 |
| K | K_2/Q | K_2/Q | K_2/Q | K_2/Q6 | 0.41 | 197.4 | 1414.8 | 549.3 | 166.1 | 865.5 | 1248.7 |
| K | K_2 | K_2 | K_2 | K_2 | 0.15 | 96.9 | 252.7 | 490 | 171.9 | -237.3 | 80.8 |
| K | K_3 | K_3 | K_3 | K_3 | 0.45 | 155.2 | 1213.7 | 1760 | 375.5 | -546.3 | 838.2 |
| | | | | | SUM | 761.1 | 6491.1 | 6700.6 | 1859.1 | -209.5 | 4632 |

## Table 6. Results of sustainability query for Pope County

| sub-province | region | subregion | district | subdistrict | yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q3 | 0.85 | 261.2 | 4822.4 | 23874.2 | 10475 | -19051.8 | -5652.8 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q6 | 0.48 | 427.2 | 4454.2 | 2734 | 1254.3 | 1720.2 | 3199.9 |
| Water | Water | Water | Water | Water | 0 | 28.8 | 0 | 74.2 | 48.8 | -74.2 | -48.8 |
| | | | | | SUM | 717.2 | 9276.6 | 26682.4 | 11778 | -17405.8 | -2501.7 |

## Table 7. Results of sustainability query for Chippewa Watershed

| Sub-province | region | subregion | district | subdistrict | Yield | TotArea | Rchrg_totvol | Permit_totvol | Permit_2007vol | Rchrg_TotPermit_Diff | Rchrg_2007Permit_Diff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| K | K_3/Q | K_3/Q | K_3/Q | K_3/Q3 | 0.75 | 2.9 | 38.4 | 0 | 0 | 38.4 | 38.4 |
| K | K_3/Q | K_3/Q | K_3/Q | K_3/Q6 | 0.41 | 4.9 | 35.1 | 0 | 0 | 35.1 | 35.1 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q3 | 1.06 | 196.4 | 3627 | 15379.4 | 6603.3 | -11752 | -2976.3 |
| B | B_2/Q | B_2/Q | B_2/Q | B_2/Q6 | 0.6 | 389.2 | 4058.7 | 1945.5 | 875.5 | 2113.2 | 3183.2 |
| B | B_2/Q | B_2/Q | B_2/Q_s | B_2/Q_s3 | 1.06 | 1 | 18.6 | 0 | 0 | 18.6 | 18.6 |
| B | B_2/Q | B_2/Q | B_2/Q_s | B_2/Q_s6 | 0.6 | 1 | 10.5 | 0 | 0 | 10.5 | 10.5 |
| B | B_2/Q | B_2/Q | B_2/Q_t | B_2/Q_t3 | 0.62 | 31.4 | 341.6 | 115 | 77 | 226.6 | 264.6 |
| B | B_2/Q | B_2/Q | B_2/Q_t | B_2/Q_t6 | 0.14 | 10 | 23.9 | 0 | 0 | 23.9 | 23.9 |
| Water | Water | Water | Water | Water | 0 | 28.8 | 0 | 74.2 | 48.8 | -74.2 | -48.8 |
| B | B_1 | B_1 | B_1 | B_1 | 4.62 | 7.9 | 635.7 | 327 | 33.6 | 308.7 | 602.1 |
| B | B_2s | B_2s | B_2s | B_2s | 2.05 | 7.9 | 281.9 | 0 | 0 | 281.9 | 281.9 |
| B | B_2t | B_2t | B_2t | B_2t | 1.06 | 493.1 | 9104.8 | 8724.2 | 2976.4 | 380.6 | 6128.4 |
| K | K_2 | K_2 | K_2 | K_2 | 0.15 | 7 | 18.2 | 128 | 19.9 | -109.8 | -1.7 |
| K | K_3 | K_3 | K_3 | K_3 | 0.45 | 886.2 | 6930.3 | 10932.1 | 2187.4 | -4002 | 4742.9 |
| | | | | | SUM | 2067.7 | 25124.7 | 37625.4 | 12821.9 | -12501 | 12302.8 |

# Attachment 5

**Result 4. Estimate of mean minimum annual groundwater recharge and comparison to the RRR method**

The results derived from the watershed characteristics (WC) method are used here to estimate the mean minimum groundwater recharge for three selected watersheds in Olmsted County, and those estimates are then compared to the estimated mean annual groundwater recharge derived from the regional regression recharge (RRR) method developed by the USGS (Lorenz and Delin, 2007).

The watersheds considered for analysis are the South Fork of the Zumbro River on Belt Line near Rochester (5372800; 155 sq. miles), Bear Creek at Rochester (5372930; 78 sq. miles), and the South Fork of the Zumbro River at Rochester (5372995; 303 sq. miles).

To implement the results from the WC method the Hierarchical Hydrogeologic Units (HHUs) for the watersheds were outlined on each of the watersheds using GIS with the bedrock and the quaternary overlay data. These units are shown in Attachment 1 for the Olmsted County map. The estimated mean minimum recharge flux into each of the HHUs is given in the tables for Olmsted County, and the corresponding tables for the Karst Region in Attachment 1. Here we used the tables derived for Olmsted County.

The summary of the analysis is presented in Table 1. The predicted mean minimum recharge is determined by taking the area weighted average of the HHU fluxes. Table 1 presents the summary for each watershed of the percentage of area that each HHU comprises in each watershed, and also presents the estimated recharge rate for each of the HHUs (see the Olmsted County table in Attachment 1). The area weighted average recharge is derived from these figures. The totaled results give the recharge rate in inches/year for each watershed, and in addition the predicted mean minimum February flow is presented in cubic feet per second.

For the three watersheds, the mean minimum annual recharge rate are 1.6 inches/year, 2.1 inches/year, and 1.3 inches/year for watersheds 5372930, 5372930 and 5372995, respectively.

The mean annual recharge rate for these watersheds using the RRR method is essentially the same for all of the watersheds because they are nested and therefore exist in the same area of the state. According to the chart given by Lorenz and Delin (2007) the recharge rate for the watershed ranges between 10 and 20 cm/year or 3.9 to 7.9 in/year.

The estimates of mean annual recharge given by the RRR method are higher than those estimated by the WC method because in the current application of the WC method the quantity estimated is the mean minimum annual groundwater recharge. Since most of the runoff generated in the southeast part of Minnesota is from groundwater, the estimate of groundwater recharge by the RRR method is closer to the mean annual flow for streams in the region. As such, the RRR estimate for that region should be similar to the regionalized estimates of mean annual flow provided within the scope of our project.

For the region surrounding Olmsted County the estimate of mean annual flow is about 5 l/s/sq. km, or about 6.5 in/year.

The types of results shown in Table 1 are currently being replicated for other selected watersheds within several locations around the state. The selected watersheds are ones that have some record of streamflow measurement but were not included in the original set of data used to derive the estimates of recharge for HHUs. The reason for doing this analysis is to provide a measure of the predictive accuracy of the watershed characterization method for ungauged watersheds. Since this work is currently being done it is not available for this report, but will be reported in manuscripts being prepared for publication.

## Table 1. Calculation of the mean minimum recharge rate for three watersheds in Olmsted County

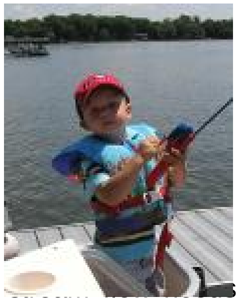
| Watershed | Watershed Area (sq.mi) | HHU | HHU Area (m^2) | HHU Area % | HHU flux (l/s/sqkm) | recharge (l/s/sqkm) | recharge (in/yr) | predicted minimum flow (cfs) |
|---|---|---|---|---|---|---|---|---|
| 5372800 | 154.6 | A2/Q2 | 79761 | 0.02 | 1.85 | 0.0004 | 0.0005 | |
| | | A1/Q3 | 30576279 | 7.62 | 1.95 | 0.1487 | 0.1858 | |
| | | A2/Q3 | 33674829 | 8.40 | 1.8 | 0.1511 | 0.1889 | |
| | | A1/Q6 | 316957714 | 79.03 | 1.15 | 0.9089 | 1.1361 | |
| | | A2/Q6 | 19433101 | 4.85 | 1.62 | 0.0785 | 0.0981 | |
| | | **Totals** | **400721684** | | | **1.2876** | **1.6095** | **18.3** |
| 5372930 | 78.1 | A2/Q2 | 2210546 | 1.09 | 1.85 | 0.0202 | 0.0252 | |
| | | A1/Q3 | 80569484 | 39.78 | 1.95 | 0.7758 | 0.9697 | |
| | | A2/Q3 | 40560680 | 20.03 | 1.8 | 0.3605 | 0.4506 | |
| | | A1/Q6 | 50964180 | 25.17 | 1.15 | 0.2894 | 0.3617 | |
| | | A2/Q6 | 28065008 | 13.86 | 1.62 | 0.2245 | 0.2806 | |
| | | **Totals** | **202369898** | | | **1.6704** | **2.0880** | **12.0** |
| 5372995 | 303 | A2/Q2 | 18831029 | 1.93 | 1.85 | 0.0358 | 0.0447 | |
| | | A3/Q2 | 1652119 | 0.17 | 3.4 | 0.0058 | 0.0072 | |
| | | A1/Q3 | 165070519 | 16.94 | 1.95 | 0.3304 | 0.4130 | |
| | | A2/Q3 | 146942994 | 15.08 | 1.8 | 0.2715 | 0.3393 | |
| | | A3/Q3 | 57621 | 0.01 | 3.2 | 0.0002 | 0.0002 | |
| | | A1/Q6 | 543503002 | 55.78 | 1.15 | 0.6415 | 0.8019 | |
| | | A2/Q6 | 97239005 | 9.98 | 1.62 | 0.1617 | 0.2021 | |
| | | A3/Q6 | 283696 | 0.03 | 0.85 | 0.0002 | 0.0003 | |
| | | **Totals** | **788026318** | | | **1.0751** | **1.3438** | **30.1** |

# Attachment 6

# *Water Resources Sustainability*

## Why is Water Resources Sustainability a Concern in Minnesota?

Water resources sustainability is the key to Minnesota's economy, healthy ecosystem functioning and well-being of its citizens. Yet, presently, the State is managing water resources unsustainably. This unsustainable management of water resources is a concern for the State, educators, businesses and general public and must be transformed toward sustainable management. It is exhibited by stream flow depletion and lake desiccation;



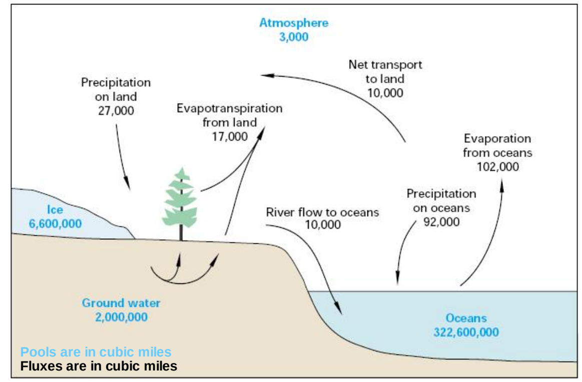
falling water levels of ground water systems; loss and degradation of wetlands, water bodies and associated wildlife habitats; contamination of surface and ground waters; competition for in- [illegible] for recreation, navigation, waste assimilation and aquatic habitat; land use changes; etc. As our water resources become depleted and degraded, so is the natural resource base that sustains the economy (Nelson, 1998). Water resources include ground water, rivers, lakes, wetlands, etc. The label of Minnesota as water rich does not fit as well as once thought. In areas of the State, the demands on renewable water resources are a special concern for water supply management (VanBuren and Wells, 2007). In portions of Minnesota, there has been a decline, depletion or pollution of surface and ground water resources. To address this concern, the LCCMR funded a Water Resources Sustainability project to the University of Minnesota.

## Addressing the Issue

The challenge of meeting human development needs while protecting natural ecosystems and water resources for future generations, confronts this and all generations to come. The Minnesota Legislature has established the legal and institutional framework to ensure that water supplies meet human and environmental needs for present and future generations. *Minnesota Statutes*, section 103G.265, assigns the Department of Natural Resources (DNR) the task of managing water resources to meet long-range needs for a variety of economic, social and ecological purposes. Although the DNR (2005) stated the needs for sustainable water use, it does not have a quantitative base to compare a growing demand with the supply of the natural hydrologic system. It is becoming clear that traditional approaches dealing with only one part of the hydrologic system (i.e. ground or surface water) are not able to address the water resources sustainability issue. This project will develop a new approach and tool to quantify the renewable water resources supply at multiple scales and demonstrate it at the State, regional, and county levels. Once the limit of the hydrologic system as a renewable (i.e. sustainable) water resource is determined, the State will be able to move toward sustainable water use by developing a framework for managing water resources based on comparison of human and environmental needs with the quantitative tool developed in this project.

## Review of the Hydrologic Cycle

The hydrologic cycle provides the basis of water resources sustainability. The hydrologic cycle is the continuous movement of water on, above, and below the surface of the earth, generally with a "*minimal*" overall fluctuation of water (near equilibrium state). **Water resources sustainability is ensuring that this overall fluctuation of water within the hydrologic cycle remains near equilibrium**. The hydrologic cycle explains why the depletion of ground water affects surface water. Surface and ground water systems are linked components of the hydrologic continuum and it is imperative to characterize them together to address the complex issue of water resources sustainability. For example, if water will be withdrawn from the ground water system at a rate that will deplete that system, less water will be discharged back into the surrounding rivers/streams, lowering water levels and




From: Ground water and surface water: a single resource / by Thomas C. Winter et al., 1998. (U.S. Geological Survey circular: 1139)

potentially affecting stream flow or drying up wetlands and water bodies. To understand water resources sustainability, it is necessary to grasp the relationship within the hydrologic cycle between the atmosphere, hydrosphere, lithosphere, pedosphere, biosphere and anthroposphere.

## The New Paradigm for Quantification

Researchers at the University of Minnesota are quantifying freshwater sustainability by addressing the key scientific question: How does landscape heterogeneity control spatial and temporal variability of stream runoff, ground water flux (recharge/discharge) and vadose zone flux, across spatial scales. The principle water balance characteristic used for integrating surface water, ground water and vadose zone fluxes is stream runoff. This new paradigm parameterizes and quantifies the relationships between landscape components and water balance characteristics. The method will not only quantify the water balance characteristics, but will provide a practical mapping tool. The key indicator in freshwater sustainability is the ratio of renewable water supply to water use by humans and the environment (Kanivetsky and Shmagin, 2005). Sustainable water use by humans and the environment ***should not cause a decline or depletion*** of freshwater resources.

## Explanation of Water Resources Sustainability Terms:

**Discharge:** Any water that exits the ground water system (Jyrkama and Sykes, 2006).

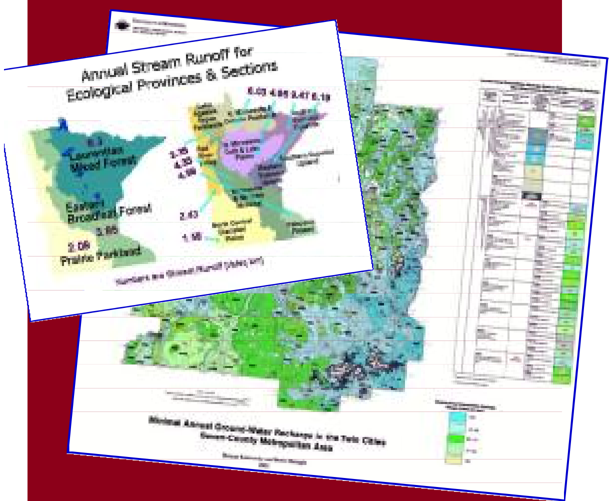
**Hydrologic unit:** A parcel of land surface defined and quantified by association of hydro-climate characteristics (stream run-off, ground water levels, precipitation, air temperature, etc.) with landscape components (climate, soil, vegetation, topography and geology) (Kanivetsky and Shmagin, 2005).

**Recharge:** Any water that is added as an input to the ground water system (Jyrkama and Sykes, 2006).

**Spatio-temporal:** Relationship of space and time together.

**Vadose Zone:** The portion of Earth between the land surface and the zone of saturation, extending from the top of the ground surface to the water table.

**Watershed:** Area of land drained by a single stream or river (catchment area).




For more information on water resources sustainability in Minnesota, and to learn about current research projects, please visit:

https://wiki.umn.edu/twiki/bin/view/Water_Sustainability/WebHome

A complete list of references included in this publication can also be found on the website.

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# WATER RESOURCES SUSTAINABILITY
## *Minnesota Project*

*Genuine "sustainability" requires that consumption **will not cause a decline** or depletion of freshwater.*

*The Legislative and Citizens Commission on Minnesota Resources (LCCMR) has provided the University of Minnesota with funding to quantify sustainable supplies of surface and ground water by integrating surface water, vadose zone, and ground water systems into defined hydrologic units.* *The purpose of this publication is to provide a general overview of water resources sustainability.*

# Attachment 7

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ORIGINAL ARTICLE

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# Estimation of groundwater recharge using water balance coupled with base-flow-record estimation and stable-base-flow analysis

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**Abstract** In this paper, the long-term mean annual groundwater recharge of Taiwan is estimated with the help of a water-balance approach coupled with the base-flow-record estimation and stable-base-flow analysis. Long-term mean annual groundwater recharge was derived by determining the product of estimated long-term mean annual runoff (the difference between precipitation and evapotranspiration) and the base-flow index (BFI). The BFI was calculated from daily streamflow data obtained from streamflow gauging stations in Taiwan. Mapping was achieved by using geographic information systems (GIS) and geostatistics. The presented approach does not require complex hydrogeologic modeling or detailed knowledge of soil characteristics, vegetation cover, or land-use practices. Contours of the resulting long-term mean annual *P*, BFI, runoff, groundwater recharge, and recharge rates fields are well matched with the topographical distribution of Taiwan, which extends from mountain range toward the alluvial plains of the island. The total groundwater recharge of Taiwan obtained by the employed method is about 18 billion tons per year.

**Keywords** Groundwater recharge · Water balance · Base-flow-record estimation · Stable-base-flow analysis · Base-flow index

## Introduction

Estimating groundwater recharge is an important issue in hydrogeologic studies. In most cases, recharge is estimated by multiplying the magnitude of water-level fluctuations in wells by the specific yield of the aquifer material or by applying the water budget model or using the water-balance method. While other parts of the water-balance equation, such as precipitation and runoff, are relatively easy to measure, recharge remains an elusive process to quantify. This is especially so because it depends not only on precipitation but also on meteorological conditions, as well as on soil type, soil–moisture status, vegetation cover and condition, slope, cultivation practices, and most of all, on evapotranspiration, which is a function of the previously noted factors.

Currently, standard techniques of estimating regional recharge most often involve (1) applying a water-balance model, where the moisture content of the soil is tracked through time (Finch 1998; Simmons and Meyer 2000; Chen et al. 2005), or (2) parameter-value adjustment of groundwater flow models (Lee et al. 2000; Jyrkama et al. 2002; McDonald and Harbaugh 2003). Application of the first approach, while generally less intensive computationally, requires knowledge of the vegetation and soil types within the study area, in addition to a number of basic meteorological variables such as air temperature and precipitation. The second approach is more taxing of computer resources because a potentially complex groundwater flow model may have to be run repeatedly in search of a multidimensional parameter-value optimum.

With the purpose of inspecting recharge, estimating the groundwater component of streamflow has been a research focus for more than a century. Following the work of Boussinesq (1877), numerous studies (Bevans 1986; Moore 1992; Rutledge 1992; Rutledge and Daniel 1994; Mau and Winter 1997; Chen and Lee 2003) have investigated the recession of streamflow, particularly baseflow, and have estimated the contribution of groundwater to streamflow. In some cases, the value of baseflow is assumed to be equal to groundwater recharge. The primary purpose of most researches is to determine the groundwater component of streamflow. Nevertheless, only a handful of researchers, including Meyboom (1961), Rorabaugh (1964), and Rutledge (1992), have focused on groundwater recharge through analyzing the streamflow data. Rutledge (2005) further summarizes constraints involved with the application of the Rorabaugh model for estimating groundwater recharge. Mau and Winter (1997) have provided the instantaneous recharge method and the constant recharge method of hydrograph analysis to estimate recharge.

Although several methods have been used to estimate the groundwater discharge and recharge from streamflow records, the most commonly used are the techniques of baseflow separation. These methods aim at estimating a continuous or daily record of baseflow under the streamflow hydrograph. In other words, it requires an extended period of recording efforts in estimating the long-term groundwater discharge, as well as the exercise of a variety of manual methods (Horton 1933; Barnes 1939; Olmsted and Hely 1962; Dzhamalov 1973; Zektser 1977) or a rapid analysis and that introduces some elements of subjectivity in the research for the base-flow-record estimation (Rutledge 1992; Mau and Winter 1997). One study employed a water-balance approach and digital filter method to estimate base recharge to groundwater in Nebraska (Szilagyi et al. 2003).

To increase the speed of analysis and reduce the subjectivity inherent in manual analysis, Rutledge (1993) proposes several computer programs: RECESS, RORA, and PART, and newer versions have been proposed (Rutledge 1998, 2000). The research of this paper is accomplished using an automated analysis procedure by the programs described above.

To prevent overestimation caused by rainstorm events, several studies (Rutledge 1993, 1998, 2000; Zektser 2002; Chen and Lee 2003) indicate that the baseflow in the dry season should be chosen to be the average value of the year. For this purpose, the stable-base-flow analysis is developed in this study to obtain a more reliable result.

Based on our previous research (Chen and Lee 2003), the proposed approach in this paper offers an estimate of total recharge for regions where groundwater evaporation is negligible, i.e., for areas where the water table is not so close to the surface that the vegetation can use it through its root system. The approach combines the water-balance model, base-flow-record estimation, and stable-base-flow analysis. It is computationally simple, requires minimal optimization, and does not need information on vegetation and soil types. The technique is mainly a collection of existing methods which, to the best knowledge of the authors, have not yet been combined in a similar fashion for recharge estimation. It is expected to be most practical for regional-scale studies where the long-term mean annual value of the spatially variable recharge is of interest. The approach was applied using data from Taiwan to demonstrate the utility of the technique.

## Methodology

The water balance of a geographic region can, in general, be written as

$$P = \mathrm{ET} + q_\mathrm{s} + q_\mathrm{b} + q_\mathrm{N} + \Delta S, \tag{1}$$

where $P$ is the precipitation ($\mathrm{LT}^{-1}$); ET is the evapotranspiration ($\mathrm{LT}^{-1}$); $q_\mathrm{s}$ is the surface runoff ($\mathrm{LT}^{-1}$); $q_\mathrm{b}$ is the groundwater contribution to runoff ($\mathrm{LT}^{-1}$), which is the definition of baseflow; $q_\mathrm{N}$ is the net flux ($\mathrm{LT}^{-1}$) of any water entering or leaving the region other than precipitation (e.g., water diversions, groundwater flux across the basin boundaries, and irrigation); and $\Delta S$ is the change in stored water ($\mathrm{LT}^{-1}$) within the area. Generally, evapotranspiration is by far the largest loss term in Eq. 1, amounting to 70% of precipitation (including evaporation from open water surfaces) on a global basis (Brutsaert 1982). Long-term ET measurements are practically nonexistent, and the available ET estimation methods may differ by as much as 10–20% on an annual basis (Vorosmarty et al. 1998). In light of these uncertainties, the general assumption that $\Delta S$ is negligible in most cases on a long-term basis may be well justified. For our purposes, this assumption is employed, acknowledging that for some watersheds where hydraulic heads have changed significantly in the past, it may lead to biased recharge estimates. It is further assumed that $q_\mathrm{N}$ in Eq. 1 can be neglected as well, at least on a regional scale.

With regard to the stated assumptions, Eq. 1 simplifies to

$$P - E = q_\mathrm{s} + q_\mathrm{b} \tag{2}$$

which states that the difference between precipitation and ET emerges as surface runoff and baseflow. If the change in the stored water volume is negligible, as was assumed, then on a long-term basis, baseflow must represent a lower bound to groundwater recharge within a given watershed. By quantifying $q_b$, one obtains an estimate of recharge, provided that the portion of the areal ET originating from the groundwater is negligible when compared to the total ET of the watershed.

Flow as completely groundwater discharge (while the surface runoff is negligible) can be based on the antecedent recession. Linsley et al. (1982) proposed the empirical relation that

$$N = A^{0.2}. \quad (3)$$

This relation gives the time base of surface runoff ($N$ [$d$]) as a function of the drainage area ($A$) upstream from a streamflow-gauging station, in square miles. The time base of surface runoff is the number of days after a peak in the hydrograph of streamflow while the component of flow attributed to surface runoff (including the bulk of interflow) is considered negligible. A part of the streamflow hydrograph may thus be considered completely groundwater discharge, if it is preceded by a period of recession equal to or greater than $N$.

Various techniques have been used to estimate a record of groundwater discharge under the streamflow hydrograph. The base-flow-record estimation employed here is a form of streamflow partitioning. Rutledge (1992) developed this method first based on the antecedent streamflow recession. The principles of this method are as follows: (1) Daily data of streamflow are required. (2) Linear interpolation is used to estimate groundwater discharge during the period of surface runoff.

Figure 1 shows a flow diagram of the steps analyzed by the method of base-flow-record estimation. The requirement of the antecedent recession is met for the day in question if, for the part of the daily mean streamflow record that includes all days that precede the day in question by $N$ days or less, the streamflow on each of these days is greater than or equal to the streamflow on the day that follows where $N$ is the time base of surface runoff.

Steps of the base-flow-record estimation are as follows (see Fig. 1). First, a one-dimensional array of the daily mean streamflow data is filled. This array is searched for days that fit the requirement of the antecedent recession. On each of these days, groundwater discharge is designated equal to streamflow, as long as it is not followed by a daily decline of more than 0.1 log cycle. According to Barnes (1939), a daily decline more than 0.1 log cycle could indicate interflow (stormflow) or surface flow. The array is searched again, and it is determined by linear interpolation of the groundwater discharge on remaining days. For some streamflow records, this interpolation can cause the calculated groundwater discharge to exceed streamflow for a few days on the record. The last step of the procedure is to correct this error.

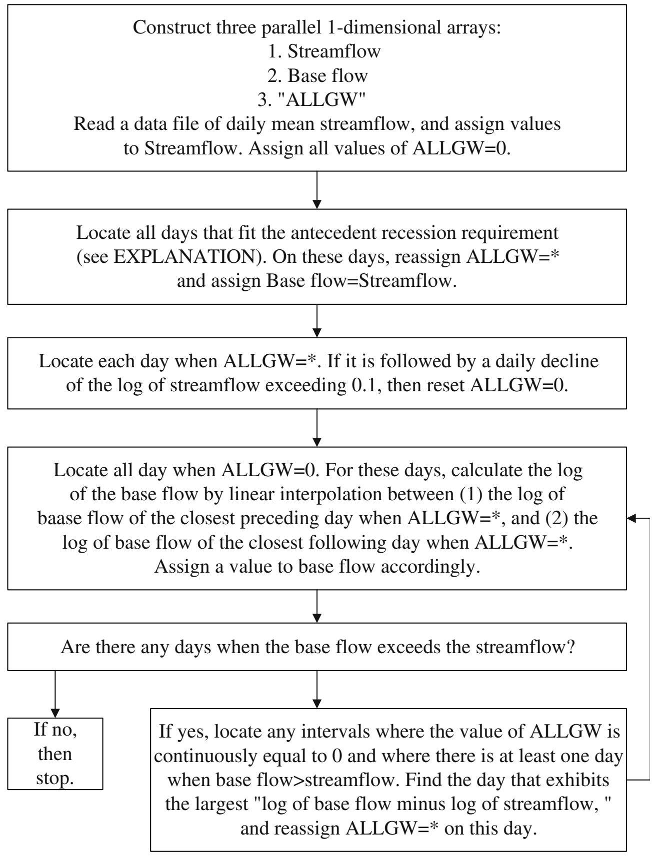


**Fig. 1** Flow diagram showing the procedure of streamflow partitioning [baseflow is considered to be groundwater discharge. Referenced from Rutledge (1993)]

To prevent overestimation caused by rainstorm events, Rutledge (1993, 1998, 2000) suggests that the wintertime recession data are chosen to represent the behavior of the recession characteristic. Zektser (2002) indicates that the lowest two monthly baseflows should be chosen to be the average value of the year in some cases. For this purpose, an alternative method, the stable-base-flow analysis, is developed in this study to obtain a more reliable result.

The diagram of the stable-base-flow analysis according to our previous study is shown in Fig. 2 (Chen and Lee 2003). The procedure of the stable-base-flow analysis is as follows:

1. Obtain monthly baseflow from the base-flow-record estimation.
2. Obtain long-term mean monthly baseflow.
3. Perform data processing by sorting and accumulating the long-term mean monthly baseflow, and then a new series of long-term mean monthly accumulated baseflows is obtained.
4. Choose the most stable (near-linear) segment and obtain the slope of the stable baseflow. To avoid

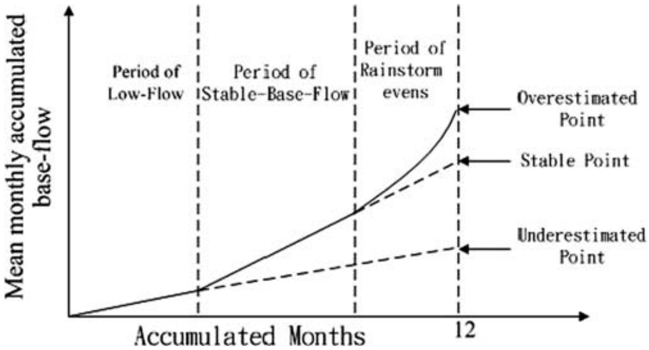


**Fig. 2** The diagram of the stable-base-flow analysis

overestimating the results, the largest several monthly values (minimally adjusted requirements for each gauging station) will not be chosen.

5. Use linear interpolation on the remaining months, and finally the mean annual baseflow is obtained.

Baseflow ($Q_b$) is obtained by employed the base-flow-record estimation and the stable-base-flow analysis. As a consequence, the drainage area value of the gauging station is used for the calculation of $N$, and Eq. 2 is employed through the introduction of the dimensionless base-flow index (BFI), which is the ratio of baseflow and total stream runoff ($Q = Q_b + Q_s$) over time:

$$\mathrm{BFI} = \frac{Q_b}{Q_b + Q_s}. \tag{4}$$

Inserting Eq. 4 into Eq. 2 yields

$$\mathrm{BFI} \times (P - ET) = \mathrm{BFI} \times q = q_b \approx R, \tag{5}$$

where $R$ ($LT^{-1}$) is the yet unknown groundwater recharge, and $q = Q/A_d$, with $A_d$ denoting the contributing drainage area. Note that the base-flow-record estimation and the stable-base-flow analysis are only used to calculate BFI, but neither $q$ nor $q_b$ were used in Eq. 5 because they require the extent of the contributing drainage area, $A_d$, whereas BFI does not. When the two

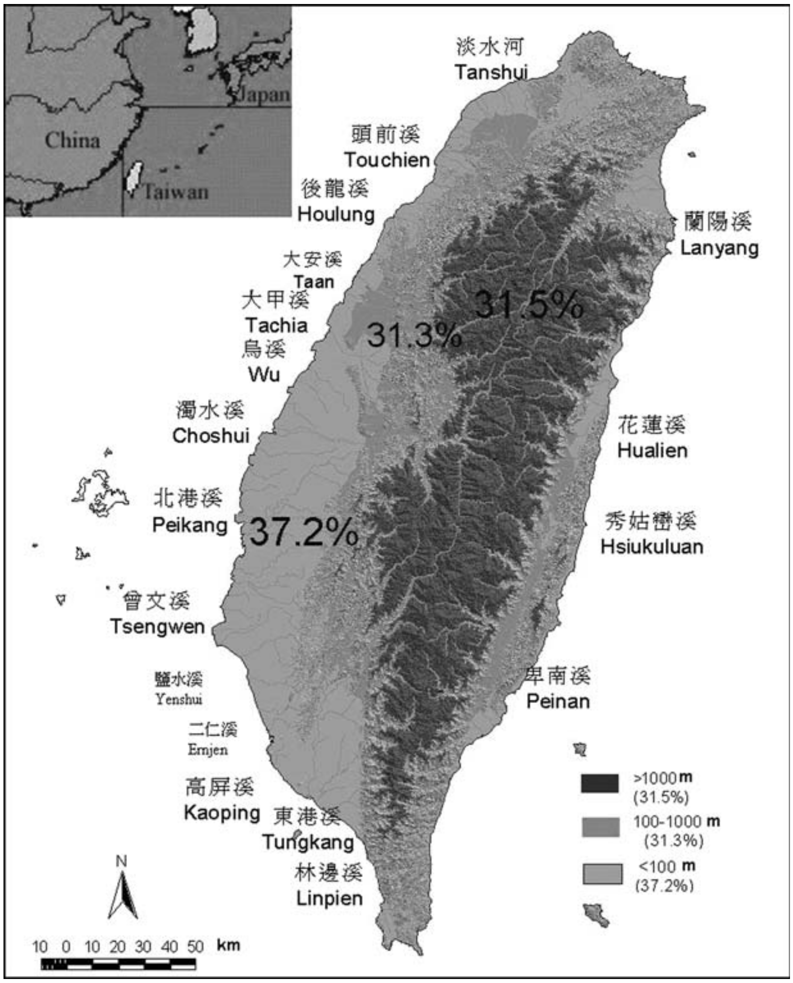


**Fig. 3** Topography of Taiwan

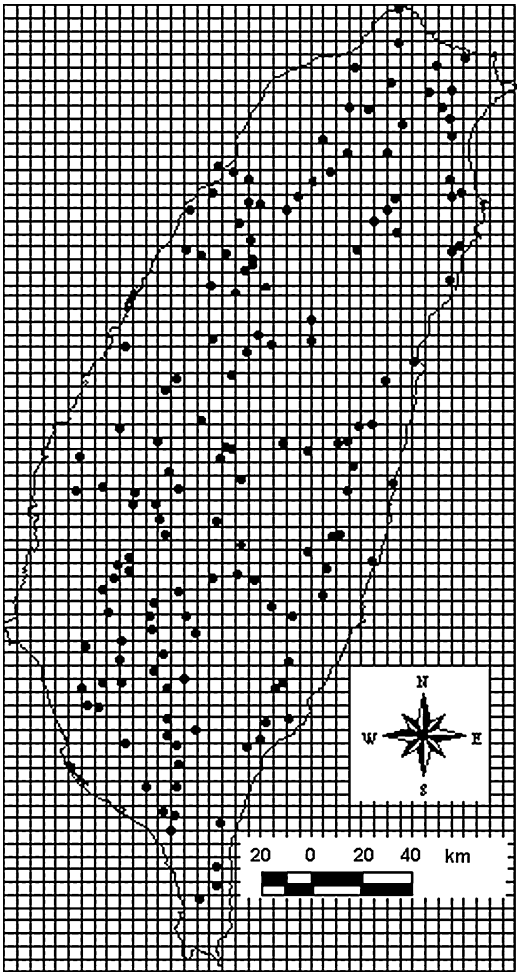


**Fig. 4** Distribution of the climatic stations in Taiwan with long-term daily precipitation records

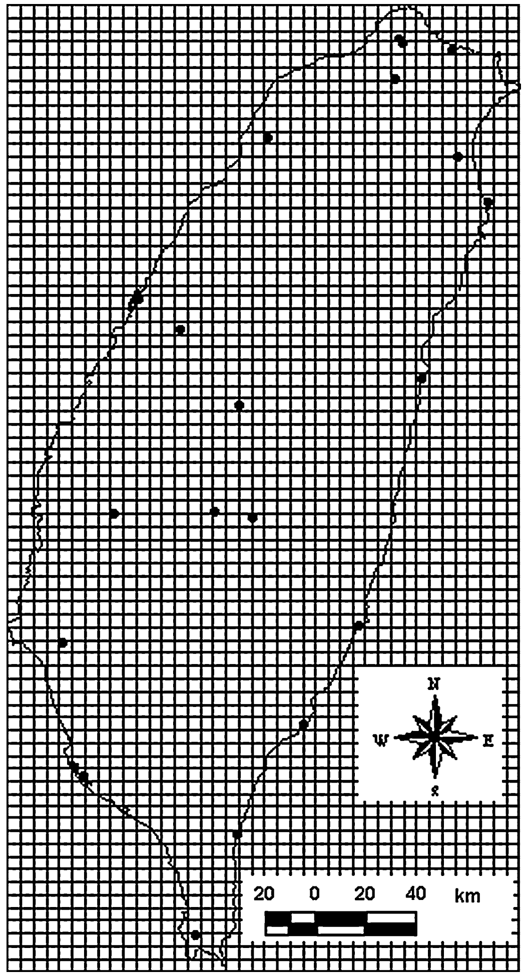


**Fig. 5** Distribution of the climatic stations in Taiwan with long-term daily evapotranspiration records

contributing areas for surface runoff and groundwater are known to be fairly close, then $q$ can be used in Eq. 5, eliminating the need for the $P$ and ET measurements.

## Results and discussion

The island of Taiwan is in the Western Pacific between Japan and the Philippines off the southeast coast of China, from which it is separated by the Taiwan Strait. With a total area of about 36,179 km$^2$, Taiwan is 394 km long and 144 km wide at its widest point.

High mountains over 1,000 m constitute about 31% of the island's land area; hills and terraces between 100 and 1,000 m above sea level make up 31%; and alluvial plains below 100 m in elevation, where most communities, farming activities, and industries are concentrated, account for the remaining 38%. Taiwan's most prominent geographic feature is its 270-km central mountain range, which has more than 200 peaks over 3,000 m high. Foothills from the central mountain range lead to tablelands and coastal plains in the west and south. The eastern shoreline is relatively steep, and mountains over 1,000 m high dominate the island in the north. The topography of Taiwan is shown in Fig. 3.

Taiwan is between the world's largest continent (Asia) and largest ocean (the Pacific). The Tropic of Cancer (23.5° N) running across its middle section divides the island into two climates, the tropical monsoon climate in the south and subtropical monsoon climate in the north. High temperature and humidity, massive rainfall, and tropical cyclones in summer characterize the climate of Taiwan. The latitude and topography, ocean currents, and monsoons are the main contributing factors. According to Köppen's climate classification, the four climate types in Taiwan are a monsoon and trade-wind coastal climate (Am) in the south, mild, humid climate (Cfa) in the north, wet–dry tropical climate (Cwa) in the west, and temperate rainy climate with dry winter (Cw) in mountain areas.

Figures 4 and 5 show the distribution of the climatic stations with long-term daily precipitation and evapotranspiration values used respectively in the study. From the long-term mean annual values of the point measurements of *P* and ET, surfaces were generated using universal kriging with a linear drift. Contours of the resulting long-term mean annual *P* and ET fields are shown in Figs. 6 and 7, respectively.

The main stream of the northward-moving Kuroshio Current passes up the eastern coast of Taiwan, thus bringing in warm and moist air. Summer and winter monsoons also bring intermittent rainfall to Taiwan's hills and central mountains. As a result, more than 2,300 mm of rain fall every year. The northeastern corner is the rainiest place in Taiwan, receiving 4,000–5,000 mm of rain per year. The coast of the western plain of the island is the driest spot, with less than 1,000 mm per year. Some characteristics of Taiwan's rainfall are as follows. (1) Spatial distribution of rain: More rain falls in the mountains than in the plains, on the east coast than the west coast, and at the windward side of hills than the leeward (sheltered) side. (2) Seasonal distribution of rain: The north has rain all year round while the south is rainy in summer and dry in winter. In winter, when the northeastern monsoon system is active, the north is constantly visited by drizzle while the south remains dry. However, in summer when the southwestern monsoon comes in force, afternoon thunderstorms and typhoons carry heavy rain to central and southern Taiwan. This intensive and concentrated summer rainfall, which constitutes up to 80% of annual precipitation, often causes flooding and landslides. (3) Variability of rainfall: As northern Taiwan has more rainy days than the south, the variability of rainfall increases as we move toward the south.

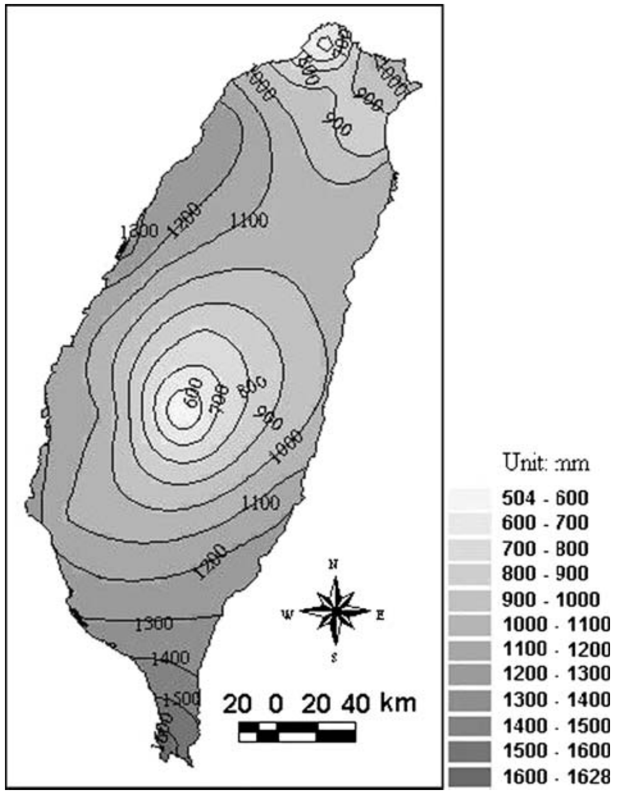


**Fig. 7** Long-term mean annual evapotranspiration (mm) in Taiwan. The contour interval is 100 mm

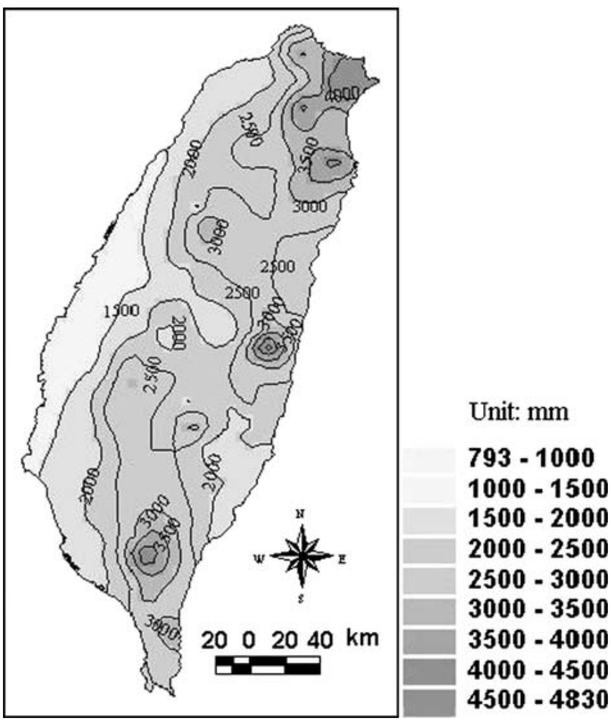


**Fig. 6** Long-term mean annual precipitation (mm) in Taiwan. The contour interval is 50 mm

The evaporative behavior is mainly related to sunshine in Taiwan. The number of hours of sunshine has an inverse relationship with the degree of cloudiness. That is, the accumulation of clouds shortens the daylight. Less sunshine is seen in the mountains than on the plains, and less on the east coast than the west. While rainy days prevent the northeastern corner from getting much sunshine, the western and southern areas of Taiwan enjoy more hours of sunshine a year.

The spatial distribution (Fig. 8) of long-term mean annual runoff is obtained by subtracting the ET map values from those of the precipitation map, in accordance with Eq. 5. Runoff is about 0–1,000 mm in the western area, and above 3,000 mm in the northeastern corner. This significant difference in runoff is mostly due to the general distribution in annual precipitation and

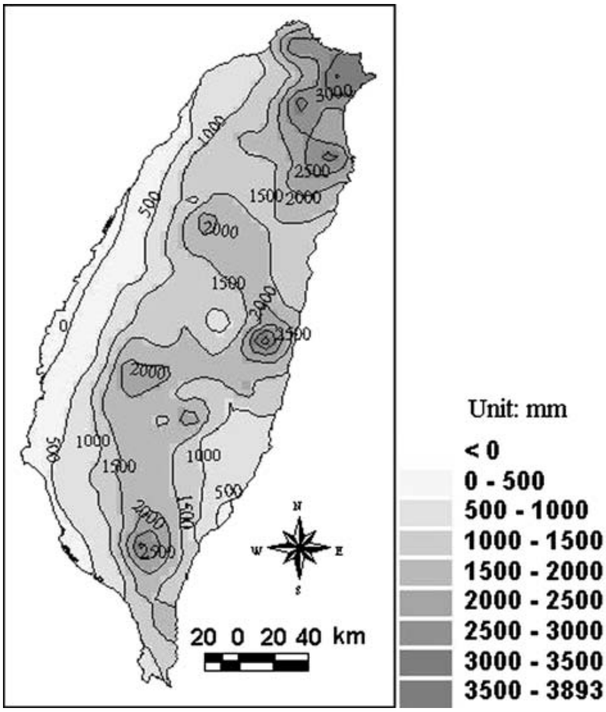


**Fig. 8** Estimated long-term mean annual runoff (mm) in Taiwan, estimated as the difference between precipitation and evaportranspiration. The contour interval is 500 mm

the aridity of the environment around the island. The degree of aridity can expressed as the ratio of ET and precipitation (Fig. 9). The closer the value to unity (i.e., 100%), the more arid the environment. Note the extremely high aridity value of the western edge of Taiwan. A long-term mean runoff ratio of 55.5% for Taiwan can be obtained by dividing the spatial mean (1,304 mm/year) of the runoff values of Fig. 8 by the long-term mean precipitation (2,348 mm/year, from Fig. 6) of the island.

There are 129 rivers in Taiwan, most of which flow toward the east or west. Because of the major watershed, the drainage area of western Taiwan is larger than that in the east. Taiwan's rivers have the following characteristics: (1) They are fast flowing due to their short length and steep grade. Even Taiwan's longest river, the Choshui River, is only 186 km long but its degree of steepness of slope is 1/55. (2) They have a limited water flow in dry seasons, and they even became wildbachs unsuitable for sailing. (3) Their peak flow is enormous; a catchment area of 2,000–3,000 $km^2$ often receives peak flows of up to 10,000 $m^3/s$.

According to the watershed division of the Water Resource Agency, Ministry of Economic Affairs, Taiwan, can be divided into 61 catchments in total. The first step is to collect and establish a complete daily streamflow database, and the streamflow gauging stations collected in this paper, total 191. The distribution of the daily streamflow gauging stations used in this study is shown in Fig. 10.

The daily streamflow of each gauging station is used to calculate BFI by employing the base-flow-record estimation and the stable-base-flow analysis. To avoid overestimating results due to rainstorm events which mostly occur in the typhoon season, the largest three monthly values (minimally adjusted requirements for each gauging station) will not be chosen when the stable-base-flow analysis is employed. From the long-term mean annual values of the estimations of BFI, surfaces were generated using ordinary kriging where no apparent spatial drift in the values could be detected. The contour of the resulting long-term mean annual BFI field is shown in Fig. 11.

Finally, the spatial distribution of the naturally occurring long-term mean annual groundwater recharge (Fig. 12) is obtained by multiplying the runoff map values (Fig. 8) with those of the BFI map (Fig. 11). The highest rates (> 1,000 mm/year) occur in the northeastern part and the central-eastern part of Taiwan, primarily due to more abundant precipitation and a less severe aridity index. High mountain areas (over 1,000 m) express a rate of 800–2,000 mm/year annually, the areas of hills and terraces (between 100

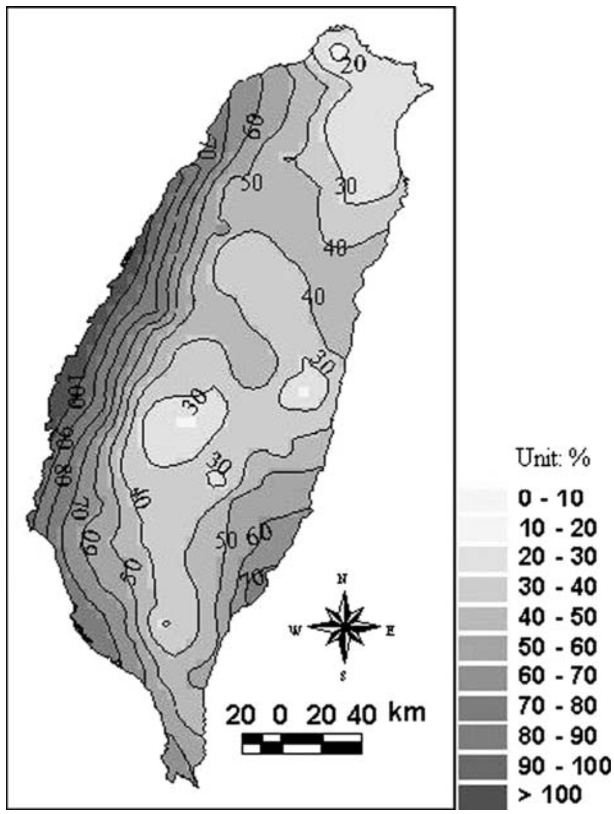


**Fig. 9** Aridity (%) of the environment in Taiwan. The closer the value to 100%, the more arid the environment becomes

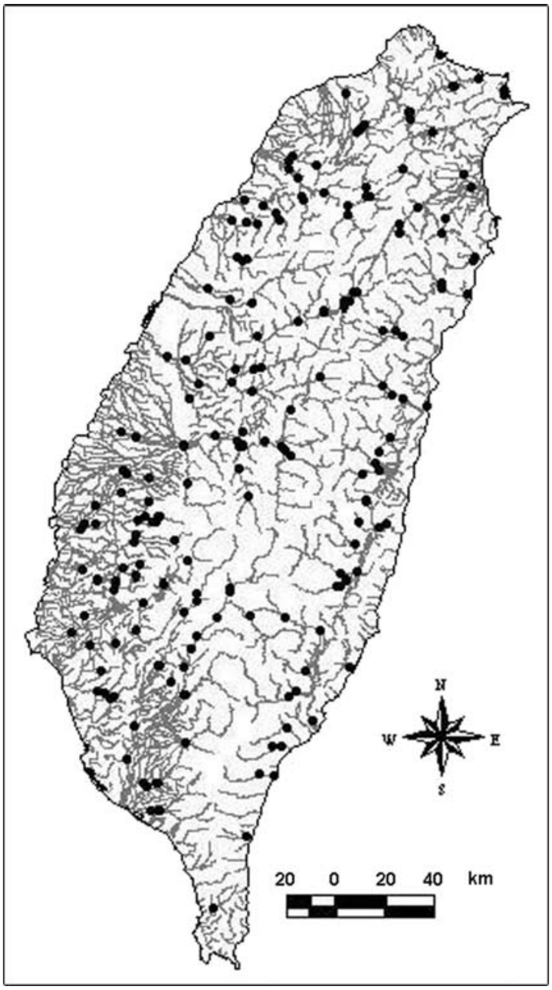


Fig. 10 Distribution of the gauging stations in Taiwan, used in the study

and 1,000 m above sea level) express a rate of 200–600 mm/year annually, and the areas of alluvial plains (below 100 m in elevation) receive an annual groundwater recharge of 0–200 mm. Note that the mean annual groundwater recharge is below 0 mm at the western edge of Taiwan, which is the most serious land subsidence area in Taiwan. The total groundwater recharge of Taiwan is obtained by multiplying the long-term mean annual groundwater recharge map values by the area of each grid. The total groundwater recharge of Taiwan is about 18 billion tons per year. The value compares well with the long-term mean groundwater recharge provided by the Water Resource Agency (2003). They obtained a long-term mean annual groundwater recharge of 17.3 billion tons for Taiwan.

The central mountain range of Taiwan has long been considered the main recharge area for groundwater due to the region's highly permeable gravelly/sandy aquifers. The high recharge rates are reflected in the high values of the BFI map (Fig. 11) and in the increased recharge rates in Fig. 12 when compared to the areas of hills, terraces, and alluvial plains. Because aridity increases and precipitation decreases from the mountain range toward its alluvial plains, groundwater recharge decreases as well. Note that at the western edge of Taiwan below 0% of the long-term mean annual precipitation recharges the groundwater (Fig. 13), while this recharge is larger than 20% of the annual precipitation in the mountain range of the island. This mainly due to greater precipitation and a less arid climate in the mountain range of Taiwan.

## Conclusions

Naturally occurring long-term mean annual groundwater recharge on a regional scale can be estimated using a water-balance approach coupled with an automated baseflow separation technique and a procedure of adjustment. The water balance uses meteorological and discharge measurements. Geostatistics are used to generate surfaces of variables from point measurements. An objective automated baseflow separation technique (the base-flow-record estimation) and a procedure of adjustment (the stable-base-flow analysis) are applied to estimate the BFI. Finally, geographic information

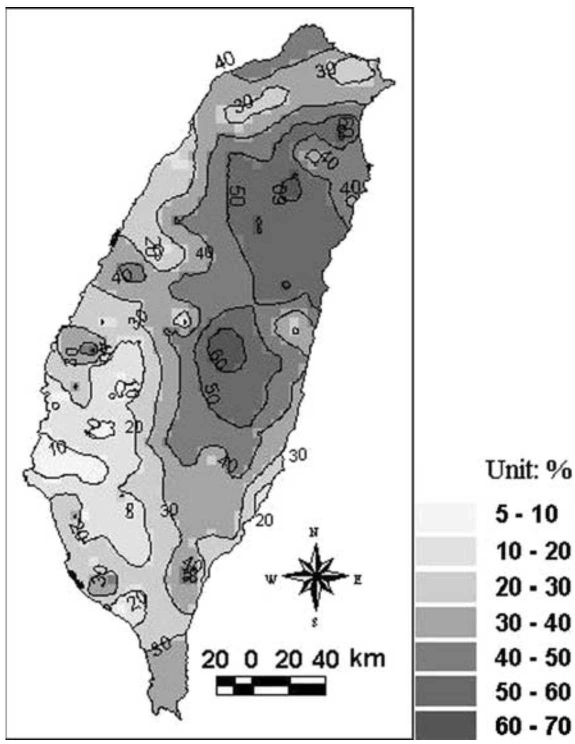


Fig. 11 Estimated long-term mean annual baseflow index, BFI (%) in Taiwan

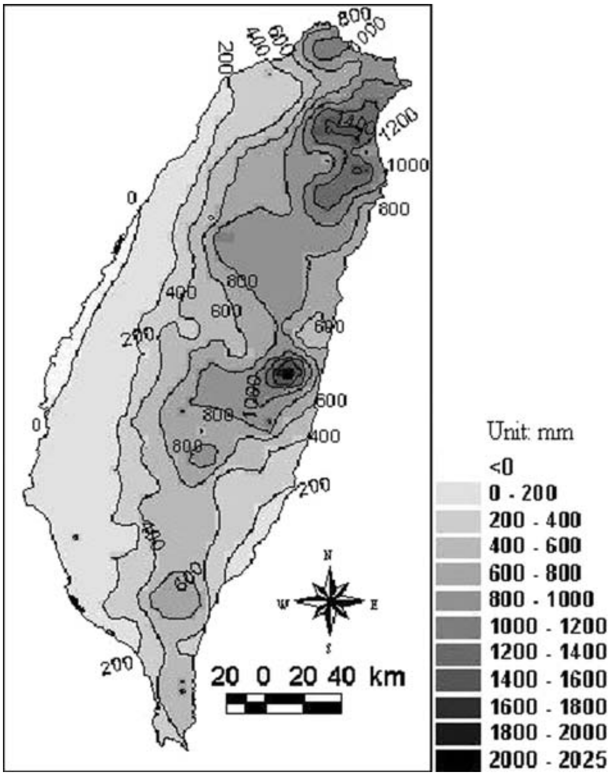


**Fig. 12** Estimated long-term mean annual groundwater recharge (mm) in Taiwan. The contour interval is 200 mm

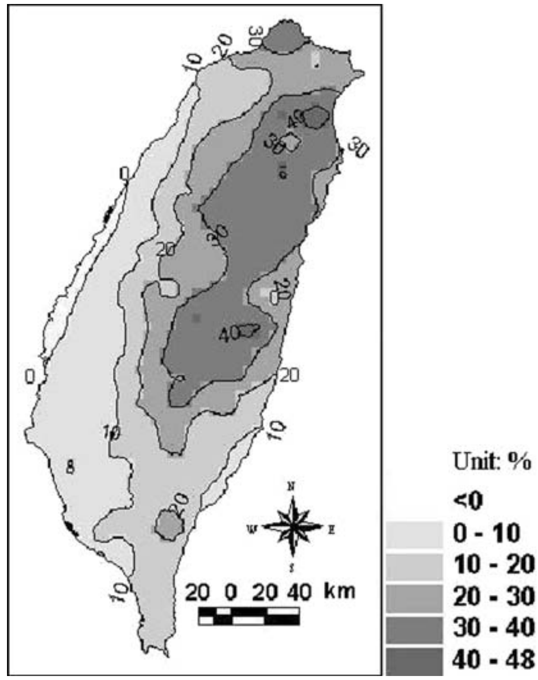


**Fig. 13** Estimated long-term mean annual groundwater recharge as a percentage of long-term mean annual precipitation in Taiwan

system (GIS) is used to manipulate the maps of the different variables in the water balance.

Contours of the resulting long-term mean annual *P*, BFI, runoff, groundwater recharge, and recharge rates fields are well matched with the topographical distribution of Taiwan, which spans from the mountain range toward the alluvial plains of the island. Note that the mean annual groundwater recharge is below 0 mm at the western edge of Taiwan, which is the most serious land subsidence area due to overdrawing groundwater in Taiwan. The total groundwater recharge of Taiwan is about 18 billion tons per year as obtained by the employed method. The value compares well with long-term mean groundwater recharge estimates from related research.

The techniques used are easy to implement, widely available and do not require complex hydrogeologic modeling or detailed knowledge of soil characteristics, vegetation cover, or land-use practices. The technique can also provide input to complex groundwater flow models or validate their recharge estimates obtained through parameter optimization.

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# Principles of regional assessment and mapping of natural groundwater resources

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**Abstract** The modern state of scientific investigations for regional assessment and mapping of the natural groundwater resources is characterized. The main methods for regional assessment of the natural groundwater resources (river hydrograph separation by genetic recharge species for a long-term period, hydrodynamic methods, methods for perennial water-balance assessment for water recharge or discharge areas), their advantages and limitations are discussed. It is noted that the use of these methods for regional assessment of natural groundwater resources and groundwater runoff is based on analyzing and processing available hydrological and hydrogeological information and does not demand special expensive drilling and pumping tests. It is suggested to assess specific groundwater discharge modules, characterizing groundwater flow in 1 l/s per 1 $km^2$, the coefficient of groundwater discharge, characterizing groundwater recharge by infiltration in percent from the precipitation volume, and the coefficient of river recharge by groundwater, indicating the contribution of groundwater in the total river runoff, as the main quantitative characteristics of natural groundwater resources. The above-mentioned methods and quantitative characteristics of natural groundwater resources were used for compiling different scale maps of groundwater discharge for separate large regions, countries, central and eastern Europe, as well as the map of hydrogeological conditions and groundwater discharge of the world.

**Keywords** Investigations · Regional assessment · Mapping methods

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## Introduction

This paper is dedicated to the memory of my great friend and prominent scientist Valery Mironenko. Valery Mironenko did not study spontaneously problems of regional assessment of groundwater resources alone. However, being a man of encyclopedic knowledge and an outstanding many-sided researcher, he was very interested in many problems of modern hydrogeological science. In our private conversations we discussed some methodological approaches for assessing and mapping groundwater resources, and debated about advantages and disadvantages of some scientific approaches and methods.

In recent decades there have been many investigations of regional assessments of natural groundwater resources and flow. This has happened for two main reasons. First, there is the necessity and ever-increasing need for determining groundwater use perspectives in different regions, which must be considered in regional schemes and projects for the complex use and protection of groundwater resources. Second is the development of techniques for regional assessment of groundwater flow which will make it possible to objectively and economically assess natural groundwater resources by analyzing and handling the available hydrological and hydrogeological materials without undertaking special expensive and labor-consuming explorations.

## Methodology

Natural resources are defined as rechargeable groundwater flow, characterizing the amount of recharge by infiltration of atmospheric precipitation, inflow from rivers and leakage from adjacent aquifers. Natural groundwater resources occur and are continuously renewed in the process of a total hydrological cycle. Making a regional assessment, we can equate the average long-term value of groundwater recharge with the deduction of the evaporation from the groundwater level to the groundwater discharge value. Hence, main quantitative groundwater discharge characteristics can serve as indicator for natural groundwater resources in the territory being studied. In other words, natural resources characterize the natural productivity (groundwater discharge) of main aquifers in the intensive water-change zone. In practice, natural groundwater


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resources indicate the higher level for possible use of constantly rechargeable groundwater on withdrawals with the indefinite exploitation (but for coastal withdrawals, functioning mainly due to river discharge). Generally, natural groundwater resources are expressed by following quantitative characteristics of groundwater discharge: modules and coefficients of groundwater flow and coefficients of river recharge with groundwater.

A module of groundwater flow is defined as groundwater flow discharge from a unit of catchment area, given in liters per second per 1 $km^2$. The coefficient of groundwater flow is the ratio of groundwater flow to atmospheric precipitation. It demonstrates (usually on a percentage basis) which part of atmospheric precipitation recharges the groundwater. The coefficient of river recharge with groundwater is the ratio of groundwater flow being drained by the river to total river runoff, and it characterizes a portion of groundwater in the river runoff. This shows (usually on a percentage basis) which part of the total river runoff is formed by the groundwater.

Given quantitative characteristics (modules, coefficient of groundwater flow and river recharge with groundwater) make it possible not only to show natural groundwater resources, but also to consider them as important water-balance characteristics, allowing us to compare different components of total water balance and total water resources for different regions.

To cite one example: on the average 600 mm of atmospheric precipitation falls yearly in the area of Moscow. A mean annual module of total river runoff for a multiyear period is about 6 l/s per 1 $km^2$ (equivalent to a layer about 190 mm/year). The groundwater flow module, calculated by the method of genetic stream hydrograph separation for a multiyear period, is about 2 l/s per 1 $km^2$, which is equivalent to a layer of 63 mm/year. Thus, it is clearly seen that the groundwater flow coefficient (ratio of groundwater recharge 63 mm/year to precipitation 600 mm/year) is about 10% in the area of Moscow. Therefore, one tenth of atmospheric precipitation contributes to groundwater recharge. The groundwater portion in total river runoff or, in other words, the relationship between groundwater resources (groundwater flow) and total water resources (river runoff), is 30% on the average.

Regional assessments are aimed to determine natural groundwater resources in large territories, for example, river basins or artesian basins or parts thereof, and to calculate relative quantitative characteristics (modules and coefficients of groundwater discharge) as well as total natural groundwater resources. At present, the main and most widely used methods for regionally assessing groundwater resources are:

1. genetic stream hydrograph separation for a multiyear period;
2. hydrodynamic method for calculating groundwater discharge (modeling included);
3. computation of changes in the river low-water runoff between two stations;
4. calculating a long-term water balance of groundwater recharge or discharge areas (Table 1).

Having no way of considering in detail methods for regionally assessing groundwater flow and groundwater natural resources and, as extensive literature is devoted to them (see below), the principal aspects of the two most commonly used methods will be given, namely, the method of stream hydrograph separation and the hydrodynamic method for calculating groundwater flow discharge.

The method for stream hydrograph separation according to genetic types of recharge used to estimate flow, is based on the commonly held assumption that groundwater flow for a zone with intensive water exchange in areas with a constant river system is formed mainly because of the draining impact of the river. Singling out groundwater components in a total river runoff allows for assessing the amount of regional groundwater flow.

**Table 1**
The main methods for regional assessments of natural groundwater resources

| Methods | Advantages | Disadvantages |
|---|---|---|
| River hydrograph separation | Possibility of obtaining average long-term groundwater flow characteristics<br>Possibility of evaluating groundwater flow variability | Need for long-term observations of a river runoff under disturbed conditions<br>Applicable only to the upper hydrodynamic zone where groundwater discharges into rivers |
| Computation of changes in the river low-water runoff between two hydrometric stations | Possibility of obtaining both average long-term and annual and seasonal groundwater flow characteristics | Difference in the river flow between two section lines should exceed the total error in the river flow measurement. |
| Hydrodynamic method of computing a specific groundwater flow (analytical approach or modeling) | Possibility of evaluating groundwater discharge in individual aquifers | Need for good aquifer parameters, difficulty in averaging them<br>Impossibility to evaluate long-term groundwater flow variability |
| Method for determining a long-term water balance in groundwater recharge or discharge areas | Possibility of evaluating a discharge of deep aquifers not drained by rivers | Need for determining the main water-balance components by independent methods<br>Estimated groundwater flow value should exceed the error in determining main water-balance components |
| Computation of infiltration values using groundwater level regime data | Possibility of evaluating groundwater discharge of individual aquifers | Difficulties in areal extension of groundwater recharge values computed for a point (well)<br>Need for numerous observation wells |

At present, there are many scientifically proven methods and technical procedures for genetic hydrograph separation. In this case, most authors proceed from the fact that base-flow water level is formed only due to the groundwater flow (excluding rivers with prevailing lacustrine or swamp recharge). The main difference of the available techniques concerns hydrograph separation during floods and high water. The approaches used here can be conditionally subdivided into three groups:

1. not considering the effect of coastal regulation during a flood, e.g., not considering possible decrease or increase in groundwater discharge during floods;
2. reducing the effect of coastal regulation to insignificant lowering of the river recharge with groundwater;
3. increasing groundwater discharge into the river as a result of augmentation of groundwater recharge.

The experience in genetic hydrograph separation speaks for a necessity to consider concrete hydrogeological conditions of interaction between surface and groundwater, that is, a degree of their hydraulic connection. Some methods for separation of the common river runoff hydrographs characterizing river basin peculiarities are given in the hydrogeological literature (Linsley and others 1962; Chow 1964; Freeze and Cherry 1979).

To obtain reliable data on river recharge with groundwater, it is necessary to jointly consider the surface and groundwater regime of runoff within a catchment area, and prove the character and degree of their interaction. The processes of coastal control during floods cause a considerable decrease or increase of river recharge with groundwater, which should be considered under hydrograph separation.

Russian specialists have developed a complex hydrologic-hydrogeologic method for hydrograph separation which was successfully used for regional assessment of groundwater discharge in the USSR territories and countries of central and eastern Europe (Kudelin 1960; Anonymous 1965; Lebedeva 1972; Dzhamalov 1973; Zektser 1977; Anonymous 1982, 1983; Vsevolozhsky 1983; Zektser 1986). The main feature of this method is to consider the character and degree of interconnection between groundwater and surface water in the river basin, which is determined as a result of careful study of the available geologic-hydrogeological data. In difficult cases, a reconnaissance or special investigation of the river valley is carried out. A typical scheme of draining for different parts of the river basin is made based on literature and field data. Drained aquifers and their lithological composition, and also levels of groundwater and river water for different seasons are given in these schemes. The different character of hydraulic connection between a river and aquifers, depending on the relationship between levels of groundwater and river water, determines different schemes for hydrograph separation.

The simplest way to assess groundwater flow drained by the river is to calculate low-water runoff changes for a multiyear period at the river site between two gauging stations.

A hydrodynamic method for assessing groundwater discharge is based on studying hydrogeological parameters of the main aquifers. Here, maps of the level surface and transmissivity are compiled for every aquifer. Total groundwater discharge is determined by the main Darcy dependence for flow paths singled out. This traditional method, being very simple, gives the possibility of obtaining a reliable enough value of groundwater flow for each aquifer. Here, special attention should be paid to the reliability and accuracy of the initial hydrogeological parameters (transmissivity and permeability), compiled on the basis of hydrodynamic maps. Flow discharge is calculated by flow paths, taking into account all the main parameters. Initial hydrodynamic parameters are not averaged for large territories, but are used and given in detail for calculated sites and flow paths.

Under complex hydrogeological conditions, with enough available data characterizing regional conditions of groundwater filtration, different methods of modeling are applicable for groundwater flow assessment. Methods for assessing the interconnection between aquifers of an artesian basin should be considered the most suitable for this kind of calculations. Under a known areal distribution of head and transmissivity, this allows the gathering of horizontal and vertical components for groundwater flow at every point of calculations (Ogilvi and Semendyaeva 1972; Dzhamalov 1973; Zektser and others 1984).

Groundwater flow within a water catchment described by the models of total river runoff formation is of great practical value (Kutchment and others 1983; Khublaryan and others 1990). There are approaches proposing a complex consideration and solution of differential equations for moisture transport, groundwater filtration, and water flow above the river bed (San Venant equation).

The main methods for regional assessment of groundwater flow, their advantages and disadvantages are given in Table 1. Thus, for instance, a widely used method, primarily in the territories of sufficient humidity, for determining groundwater flow by genetic stream hydrograph separation along with important advantages (the possibility of obtaining mean perennial data to characterize groundwater flow variability for a long-term period), is essentially restricted. It is most important to use data for an undisturbed river runoff regime, the assumption of coincidence between water catchment areas for surface water and groundwater (which is impossible for areas of intensive karst and fissured rocks distribution), and to use data for a long-term observation. Each of the methods mentioned has both advantages and disadvantages. This is why the right choice will depend on concrete geologic-hydrogeological and hydrologic conditions of investigated regions, and also on the aims and scale (details) of the investigations made. The given methods are not competing; they supplement each other very well. This is why the most reliable result is obtained using a combination of different methods to assess regional groundwater flow (Zektser and Dzhamalov 1988; Zektser 2000).

It must be noted that there are enough methodological problems of regional evaluation of groundwater natural resources to be solved. Thus, the researcher gets the value of groundwater discharge of all drainage zone using the method of river hydrograph separation, but the way of evaluating the recharge of every aquifer of this zone is not clear yet. The problem of this method applicable to river basins with very disturbed river flow is not enough developed. While using the hydrodynamic method of calculation of ground flow rate, the problem of hydrogeological parameters averaging also is not enough developed. There are several other methodological problems to be examined.

## Results

It should be noted that the first studies for regional assessment and mapping of natural groundwater resources and groundwater flow were made in the former USSR territory at the beginning of the 1960s under the initiative and guidance of Professor B.I. Kudelin. This work resulted in compiling and editing in 1964 of the "Maps of groundwater flow of the USSR area" at a scale of 1:5,000,000, and a monograph entitled "Groundwater flow of the USSR area" in 1966, which is actually a detailed explanation note to this map. Later, in the early 1970s, the maps of groundwater flow in the USSR at a scale of 1:2,500,000 were compiled by a large group of hydrogeologists and hydrologists. At the same time, many years of work went into assessing and mapping groundwater flow in central and eastern Europe. This work was carried out in accordance with the UNESCO International Hydrological Program and resulted in compiling and editing "The international map of groundwater flow in central and eastern Europe" at a scale of 1:1,500,000, and a monograph entitled "Groundwater flow in central and eastern Europe" in 1983. Here, values of groundwater flow for large regions have been obtained, the main regularities of groundwater flow formation, depending on physical geographical and geologic-hydrogeological conditions, have been revealed, and time and space peculiarities of changes for specific values and coefficients characterizing groundwater flow have been defined. Considering the positive experience of international cooperation in the field of regional assessment and mapping of groundwater resources in the period from 1987 to 1992, in accordance with UNESCO's Project for the International Hydrological Program, investigations have been made for regional assessment and mapping of groundwater flow of the whole world. A large group of scientists from many countries (former USSR, USA, France, Australia, India, Brazil, Argentina, Thailand, etc.) participated in this work. As a result of their joint effort, the "The world map of hydrogeological conditions and groundwater flow", at a scale of 1:10,000,000, was compiled, then edited and published by an international group of experts in the USA in 1999 (Anonymous 1999). Among other works on the problem under consideration, studies made in different years for the regional assessment and mapping of groundwater flow and groundwater resources of the Russian Nechernozemie, Moscow and Baltic artesian basins, eastern Siberia, Cis-Caucasus and other regions of the former USSR territory should be noted. The "Map of groundwater flow in California" at a scale of 1:2,000,000, published in 1991 and jointly compiled by Russian and American specialists, should also be noted.

One most important point should be noted. Regional quantitative characteristics of the main aquifers (groundwater modules and coefficients of the river recharge with groundwater), characterizing their natural productivity and groundwater recharge in natural conditions, are given in these maps. These maps contain quantitative information on groundwater and its resources, which makes them different from other hydrogeological maps. Besides natural conditions, factors (mainly geologic-hydrogeologic) causing groundwater resources formation are given in the maps of groundwater flow.

Maps of groundwater flow are widely used in practice (hydrologic-hydrogeologic and water-management works), allowing practical problems for the complex use and protection of water resources to be solved on a quantitative basis. Such problems incorporate determining fresh groundwater natural resources for characterizing water supply of separate areas, determining and predicting changes of groundwater component for the river runoff, assessing the amount of groundwater recharge when characterizing its safe yield, quantitative assessment of groundwater flow as an element of water balance for the territories, etc.

## Tasks for further investigations

Main tasks for further investigation are:

1. to improve the available and to develop new methods for assessing groundwater resources, accounting for natural measures;
2. to develop and put into practice nature-protecting criteria, determining the acceptable impact of groundwater withdrawal on other components of the environment, and also the acceptable effect of anthropogenic activities on groundwater resources and quality;
3. to perfect the available methods and to develop new methods for predicting changes in groundwater resources and quality under intensive anthropogenic activities and possible climate changes;
4. to substantiate the principles of conducting groundwater monitoring under different natural climatic and anthropogenic conditions as a component of the general monitoring of water resources and the environment;
5. to assess the function of groundwater discharge in the water-salt balance of large regions, including separate seas and large lakes.

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# Attachment A

**Attachment A: Budget Detail for 2007 Projects**

**Project Title: Water Resource Sustainability**

**Project Manager Name: John L. Nieber**

**Trust Fund Appropriation: $** *292,000*

**1) See list of non-eligible expenses, do not include any of these items in your budget sheet**

**2) Remove any budget item lines not applicable**

| **2007 Trust Fund Budget** | **Result 1 Budget:** | **Amount Spent** *(06/30/09)* | **Balance** *(06/30/09)* | **Result 2 Budget:** | **Amount Spent** *(06/30/09)* | **Balance** *(06/30/09)* | **Result 3 Budget:** | **Amount Spent** *(06/30/09)* | **Balance** *(06/30/09)* | **Result 4 Budget** | **Amount Spent (06/30/09)** | **Balance** *(06/30/09)* | **TOTAL BUDGET** | **TOTAL BALANCE** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Development of hierarchical hydrologic units and estimation of associated ground water recharge* | | | *Development of materials for quantitative information system for freshwater sustainability* | | | *County level test of the sustainable supply estimation methodology.* | | | *Compare recharge estimates from alternative methodologies* | | | | |
| **BUDGET ITEM** | | | | | | 0 | | | 0 | | | | 0 | 0 |
| **PERSONNEL: wages and benefits** | 169,600 | 169,600 | 0 | 42,500 | 42,500 | 0 | 24,100 | 24,100 | 0 | 15,000 | 15,000 | 0 | 251,200 | 0 |
| **Contracts** | | | 0 | | | 0 | | | 0 | 0 | | 0 | 0 | 0 |
| **Professional/technical: Boris Shmagin; hydrological/statistical analysis** | 30,000 | 30,000 | 0 | 0 | | 0 | 8,000 | 8,000 | 0 | 0 | | 0 | 38,000 | 0 |
| **Travel outside Minnesota; Brookings, SD** | 1,200 | 1,200 | 0 | 0 | | 0 | 400 | 400 | 0 | 0 | | 0 | 1,600 | 0 |
| **Travel outside Minnesota; San Francisco** | 1,200 | 1,200 | 0 | 0 | | 0 | 0 | | 0 | 0 | | 0 | 1,200 | 0 |
| **Other** *(Describe the activity and cost) be specific* | | | 0 | | | 0 | 0 | | 0 | 0 | | 0 | 0 | 0 |
| **COLUMN TOTAL** | **$202,000** | **$202,000** | **$0** | **$42,500** | **$42,500** | **$0** | **$32,500** | **$32,500** | **$0** | **$15,000** | **$15,000** | **$0** | **$292,000** | **$0** |