Trust Fund 2007 Work Program

Date of Report: May 30, 2007
Date of Next Status Report: December 31, 2007
Date of Work program Approval:
Project Completion Date: June 30, 2009

I. PROJECT TITLE: Water Resource Sustainability
Project Manager: John L. Nieber
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Location: University of Minnesota, St. Paul campus

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

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. PROJECT SUMMARY AND RESULTS: This research will address the key science question: how landscape heterogeneity controls spatial and temporal variability of stream runoff, recharge/discharge flux and vadose zone flux across spatial scales. To study this intimate relationship between these components of the terrestrial hydrologic system we propose a novel and improved regionalization model that integrates two parts: water balance characteristics quantification and hierarchical organization of landscape components. In this research we propose to build on previous research (Shmagin and Kanivetsky, 2002; Ruhl et al., 2002; Kanivetsky and Shmagin, 2005) by adding the vadose zone to existing hydrologic–hydrogeologic (surface water–ground water) regionalization. The hydrologic–hydrogeologic regionalization previously completed for Minnesota identifies hydrological units for stream runoff that are closely associated with ecological subdivisions, and hydrogeological units for ground water recharge/discharge that are closely associated with low-flow streamflow characteristics. By adding *vadose zone regionalization* the method will be *significantly improved* as we will make the regionalization of units more refined as well as the boundaries of units better defined.

The outcome of the regionalization procedure will be a set of water resource atlases that provide information on the spatial distribution of sustainable freshwater resource within Minnesota. Atlases will be produced for various scales; 1:3,000,000, 1:500,000, and 1:200,000 to 1:100,000. These atlases will be used in the development of a quantitative information system (QIS) intended for use in water resource planning. The QIS methodology will be tested by applying it to three Minnesota counties.

III. PROGRESS SUMMARY AS OF *(date)*: 250 word limit.

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: $ 0
Balance: $ 202,000

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

Result Status as of *(Insert Date of First Update Report)*:

Result Status as of *(Insert Date of Second Update Report)*:

Result Status as of *(Insert Date of Third Update Report)*:

Result Status as of *(Insert Date of Fourth Update Report)*:

Final Report Summary:

Result 2: Development materials for quantitative information system for freshwater sustainability,

Description: It is desirable to develop a 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:	$ 0
Balance:	$ 42,500

Deliverable	**Completion Date**	**Budget**	**Status**
1. GIS databases on CD	05/01/09	$42,500	
2.			
3.			

Completion Date:

Result Status as of *(Insert Date of First Update Report)*:

Result Status as of *(Insert Date of Second Update Report)*:

Result Status as of *(Insert Date of Third Update Report)*:

Result Status as of *(Insert Date of Fourth Update Report)*:

Final Report Summary:

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:	$ 0
	Balance:	$ 32,500

Deliverable	**Completion Date**	**Budget**	**Status**
1. Report detailing the test of the methodology	05/31/09	$32,500	
2.			
3.			

Completion Date:

Result Status as of *(Insert Date of First Update Report)*:

Result Status as of *(Insert Date of Second Update Report)*:

Result Status as of *(Insert Date of Third Update Report)*:

Result Status as of *(Insert Date of Fourth Update Report)*:

Final Report Summary:

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:	$ 0
	Balance:	$ 15,000

Deliverable	**Completion Date**	**Budget**	**Status**
1. Report detailing the comparison of our method with alternative methods	06/30/09	$15,000	
2.			
3.			

Completion Date:

Result Status as of *(Insert Date of First Update Report)*:

Result Status as of *(Insert Date of Second Update Report)*:

Result Status as of *(Insert Date of Third Update Report)*:

Result Status as of *(Insert Date of Fourth Update Report)*:

Final Report Summary:

V. TOTAL TRUST FUND PROJECT BUDGET:

Staff or Contract Services:

Dr. John L. Nieber, UofM, $12,180. 15%. Will be responsible for project management including tracking the progress of project task and deliverable milestones and tracking budgetary expenditures. He will also be primarily responsible for the research activities involving the characterization and parameterization of vadose zone processes and inclusion into recharge regionalization model.

Dr. Bruce N. Wilson, UofM, $12,180. 15%. He will work closely with Boris Shmagin on the statistical characterization of flow data. He will also examine alternative statistical analysis methods for the regionalization method, for instance, principal component analysis.

Dr. David Mulla, UofM, $12,180. 10%. Will take primary responsibility for parameterizing agroecoregions for inclusion into the recharge regionalization model. He will also examine the use of artificial neural networks methods for relating the hydrologic characteristics to hydrologic units.

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

Dr. Boris Shmagin, SDSU, $17,763. 13%. The developer of the original statistical analyses used to develop multi-scale maps, he will be primarily responsible to process acquired flow data for hydrologic characterization, and to develop the multi-scale regionalization.

Graduate Research Assistants(2), $82,824. 50%. Will assist with acquisition of data bases used for analyses. Both students will be studying at the Ph.D. level so they will be 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.

Undergrad Research Assistant, $8,877. The undergraduate research assistant will assist with routine data acquisition, and also prepare GIS maps and other summary charts and illustrations.

Fringe Benefits: Explanation for the fringe benefit charges.
32.8% of salary for Nieber, Wilson, Mulla, $11,985
13.4% of salary for Kanivetsky, $9,068
70% of salary for Graduate Research Assistants, $52,593
7.7% of salary for Undergrad Research Assistant, $684

Equipment:
Development: $ (improvement to land or building)
Restoration: $ (how many acres)
Acquisition, including easements: $ (how many acres, also who will hold the title to the land)

TOTAL TRUST FUND PROJECT BUDGET: $292,000

Explanation of Capital Expenditures Greater Than $3,500:

VI. OTHER FUNDS & PARTNERS:

A. Project Partners:

B. Other Funds Proposed to be Spent during the Project Period:

C. Past Spending:

D. Time:

VII. DISSEMINATION: The results of this project will be presented at scientific and professional society meetings, at other institutions (by invitation), at public forums within Minnesota (the PI has given three such presentations even before the project begins; one of these was at Cornell University, Ithaca, NY) and South Dakota, and in written form in scientific articles. A web site will be established to provide information on the research program.

VIII. REPORTING REQUIREMENTS:

Periodic work program progress reports will be submitted not later than December 31, 2007, June 30, 2008, December 31, 2008. A final work program report and associated products will be submitted between June 30 and August 1, 2009 as requested by the LCCMR

IX. RESEARCH PROJECTS: Research Addendum accompanies this workplan.

Water Resource Sustainability

Revised Peer Review Proposal to the LCCMR

May 31, 2007

Submitted by

John L. Nieber
Roman Kanivetsky
Bruce Wilson
David Mulla
University of Minnesota

and

Boris Shmagin
South Dakota State University

I. Abstract.

This research will address the key science question: how landscape heterogeneity controls spatial and temporal variability of stream runoff, recharge/discharge flux and vadose zone flux across the scales. To study this intimate relationship between these components of the terrestrial hydrologic system we propose ***a novel and improved regionalization model*** that integrates two parts: water balance characteristics quantification and hierarchical organization of landscape components. In this research we propose to build on previous research (Shmagin and Kanivetsky, 2002; Ruhl et al., 2002; Kanivetsky and Shmagin, 2005) by adding the ***vadose zone*** to existing hydrologic–hydrogeologic (surface water–ground water) regionalization. The hydrologic–hydrogeologic regionalization previously completed for Minnesota identifies hydrological units for stream runoff that are closely associated with ecological subdivisions, and hydrogeological units for ground water recharge/discharge that are closely associated with low-flow streamflow characteristics. By adding ***vadose zone regionalization*** the method will be ***significantly improved*** as we will make the regionalization of units more refined as well as the boundaries of units better defined.

The proposed research will test the following hypothesis: ***The flux for surface–vadose zone–ground water can be quantified using appropriate watershed characteristics (quantitative analysis) by subdividing landscapes into similarly functioning hierarchical structures (descriptive analysis) at multiple spatial scales.*** Our method of analysis, known as ***regionalization***, is based on the statistically significant differences in water balance characteristics distribution for hierarchical layers of flow fields for surface water–vadose zone–ground water systems. We will test the variants in generalization for each layer of flow fields that provides three-dimensional watershed characteristics.

II. Background and Hypothesis.

Current State of Knowledge

II 1. *Regionalization of hydrologic systems*

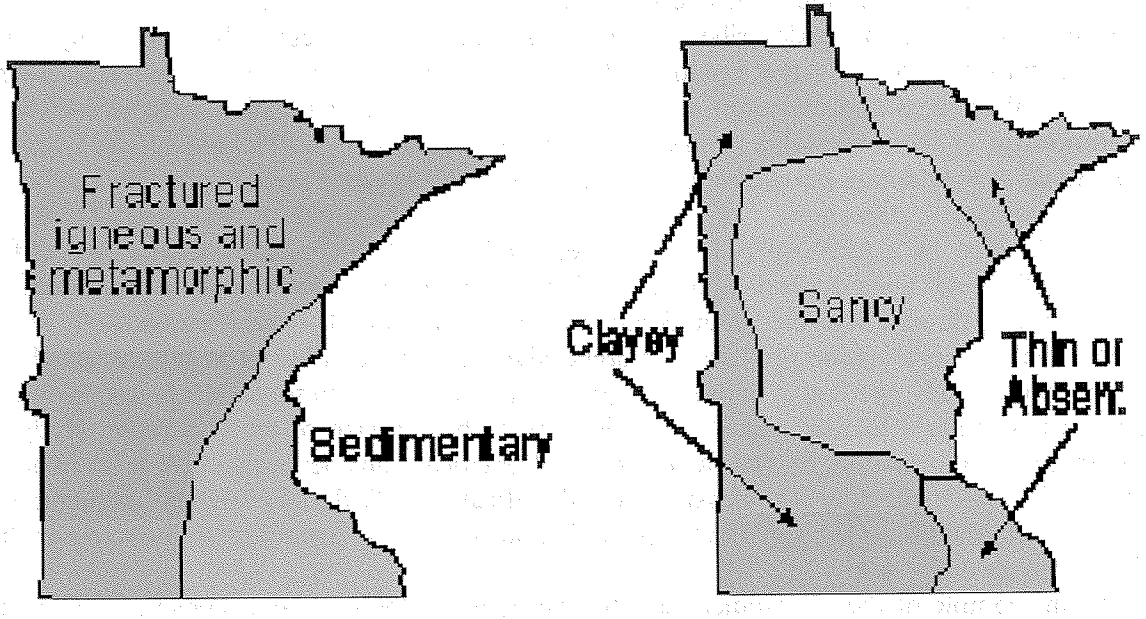
Regionalization (the division of the whole into parts) as a research method is widely used in many branches of natural sciences. While the method of regionalization has been applied off and on in hydrologic analysis over the years, most analyses in hydrology have been based on models or statistical methods. In recent years it has become increasingly apparent that regionalization is needed to adequately forecast the quantity and quality of water at multiple scales (Diekrüger, 1999). Regionalization is useful in developing water resource availability estimates for long-term regional development plans, as well as for evaluation of specific development projects such as new ethanol plants. Water availability for specific development projects must, however, still rely to some extent on pumping tests at specific locations. This proposed project will not provide data that substitutes for local pumping tests.

The fundamental concept of the regionalization method when applied to the hydrologic sciences is the systematization of the laws governing the spatial distribution and processes controlling hydrologic characteristics. The process of regionalization consists of: (1) the choice of characteristics by which land area is to be subdivided, and (2) the mapping of the boundaries of these characteristics (Pinneker, 1983). This is achieved by summarizing the regional data in hydrology, putting it in order, and mapping the hydrologically different land areas. That part of the Earth's landscape (surface and interior) which is distinguished by unity of characteristics of occurrence, or formation is described as an hydrological unit for regionalization. In hydrology the regionalization term is the isolation of land area units which differ from each other in hydrological features and characteristics. Put another way, regionalization in hydrology is the determination of hydrologically similar units (Diekrüger, 1999). As Pinneker (1983) states it, *multi-scale quantification must be regarded as the key principle of hydrological regionalization and is a guaranty of objectivity.*

The division of a territory (whole surface, continent, state/province, county, etc.) of the earth's surface into units depends upon the scale and the purpose for which the regionalization is being carried out, and also the methodology which the tasks of hydrological research require. Hydrological regionalization provides comprehensive knowledge of the hydrological laws for the territory under study and it also delivers the practical tools needed to forecast relevant hydrologic quantities. The scale of regionalization is determined by the size of territory under study, the availability of information, as well as by imposed practical considerations. The most important method in regionalization is classification/identification of the hierarchical structures of hydrological systems (Pinneker, 1983; Lin et al., 2006), because it reveals the hydrological laws of the territory under study.

As an example of the hierarchical structure of hydrogeologic systems consider the geologic map shown in Figure 1a for the area (territory) of Minnesota. Here it is seen that one part of the hierarchical structure is the bedrock geology associated with bedrock aquifers. For this, the territory is divided into two parts, the Precambrian basement rock in the west, northwest and northeast part, and the Paleozoic artesian basin in the southcentral and southeast. Information from the Quaternary geologic map shown in Figure 1b, shows that in some parts of the territory Quaternary sediments are absent, while in other areas they exist but with differences in surficial character (clay versus sand). Overlaying these maps leads to the hierarchical map shown in Figure 1c. There it is seen that the original division given in Figure 1a is further subdivided by considering some distinctive layers in the bedrock aquifers (not shown as a separate map) and the Quaternary deposits. The estimates of minimum ground water recharge are derived for each level of subdivision shown in Figure 2, derived by the proposed regionalization method as described by Shmagin and Kanivetsky (2002) and Kanivetsky and Shmagin (2005). Some details of the method for deriving these estimates are described in the next section. We also note that further subdivision than that shown in Figure 2 is possible and has been completed already (Ruhl et al., 2002) as will be shown in the next section.

To make sure the result of this mapping is clearly understood, let's consider the result shown in Figure 2. From the figure there appears to be a sharp distinction between recharge values as one crosses subdivisions. However, these subdivisions are not that sharply defined because the exact location of the dividing line depends partly on the number of gauging stations available for performing the subdivision, and it also depends on the quality of the geologic maps available. Also, it should be clear that an area defined by political boundaries (such as a county) can straddle a subdivision boundary. Water planners within that county should respect the differences that exist across that hydrologic subdivision boundary.



(a) (b)

Figure 1. Generalize geological maps for Minnesota. (a) Bedrock aquifer map. (b) Quaternary deposits

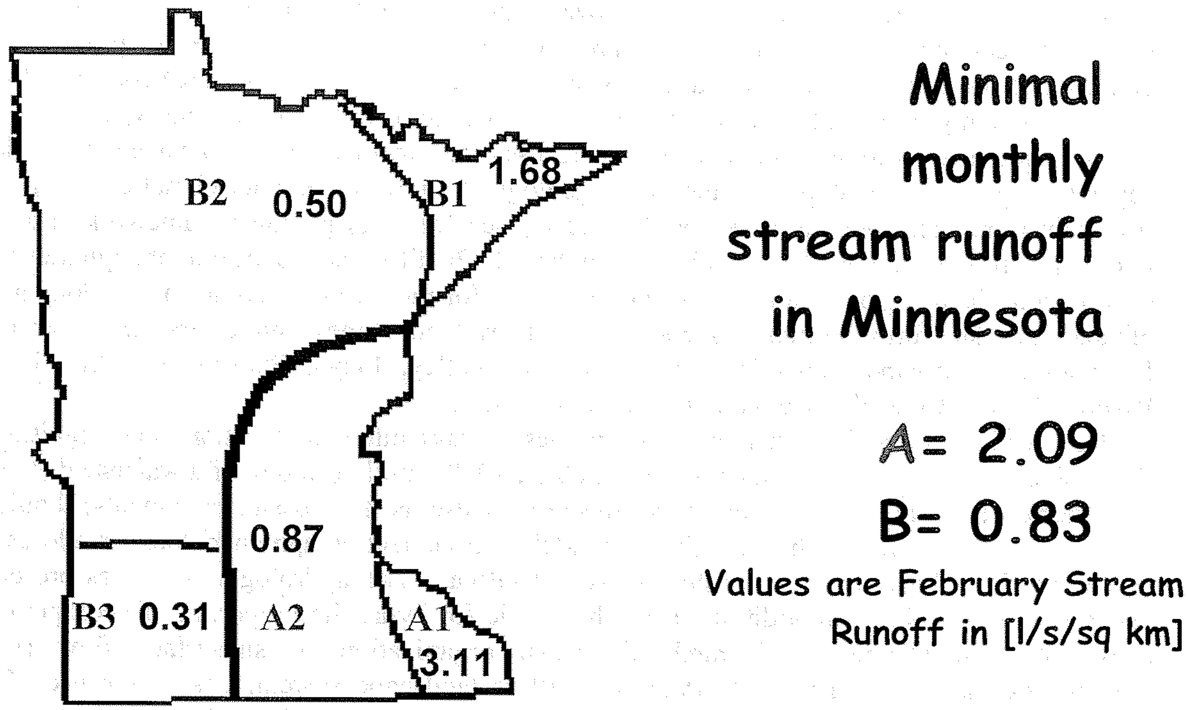


Figure 2. Regionalization of ground water systems in Minnesota (Shmagin and Kanivetsky, 2002; Kanivetsky and Shmagin, 2005). A- Artesian Basin; B – Precambrian Basement. The smaller subdivisions (A1, A2, B1, B2, B3) are based on the overlay of the Quaternary geology and other porous layer information.

With the basic idea of hierarchical subdivision described by example, we may now go on and present some of the more conceptual ideas behind the method, which are based on work by Pinneker (1983). He suggests an elegant and properly ordered classification of the regions for ground-water systems that is founded on scientific information of hierarchical hydrogeological systems from global to local levels. Each region corresponds to a defined ground-water system. From the largest to the smallest the regions are placed in the following taxonomic order: province, subprovince, region, area, and district. Thus the hydrological unit is a land area representing a ground water system. The result of distinguishing hydrogeological units in that manner is that the nomenclature of hydrogeological regions now becomes applicable for multi-scale regionalization at multiple scales, from global to local. Such nomenclature provides a much fuller characterization of a ground water system than traditional descriptions of aquifers and confining beds. It can be used for quantification of water balance characteristics at multi-scale levels and in addition, such nomenclature provides a linkage to the landscape perspective. Such synergistic ideas as those developed by Pinneker (1983) for hydrogeological systems will be implemented in our project for the entire terrestrial system, in this case for the State of Minnesota.

In contrast to scientific principles developed by Pinneker (1983) other researchers (e.g., Winter, 2001; Woolock et al., 2004; Vogel et al., 2005) do not use such scientific principles for regionalization described above and as a result their methods lack the scientific rigor and objectivity contained in the proposed approach. For example, Winter (2001) proposed the concept of hydrologic landscapes as a framework for objectively (author's word) conceptualizing the processes in ground water, surface water, and atmospheric water in different types of terrain. He defines the hydrologic landscape unit as land-surface form of upland adjacent to lowland separated by a steeper slope together with geologic framework and its climatic setting. His regionalization framework is based on 1) land-surface form; 2) geologic framework based on hydraulic properties; and 3) climatic setting based on difference between precipitation and evaporation. Such regionalization is based on metrics for measures of landforms, geology and a climate. For landform metrics his approach utilizes land slopes and offers six generalized Hydrologic Landscapes units including Mountain Valley, Playa, Plateau and High Plains, Riverine Valley, Coastal Terrain and Hummocky Terrain.

However, such a regionalization approach does not take into consideration the recognition of the similarity between land-surface forms (Strahler, 1958) and hydrology of a watershed (Freeze and Cherry, 1979), and that the watershed (this term is also used for basin, catchments) should be a unit for regionalization of hydrologic system. His regionalization approach does not address an important hierarchical interrelationship between landscape and hydrologic system as presented above (Pinneker, 1983). In addition, using the metric for hydraulic properties of geologic units does not acknowledge the hierarchical spatial organization of subsurface flow (local, intermediate, and regional) (Toth, 1963) as well as landscape system. Lastly, the use of the climate metrics is subjective, because data on evaporation are estimated and not measured. Besides, the metrics used for such regionalization requires an enormous amount of data.

This concept of hydrologic landscapes has been embraced by other researchers (Wolock et al., 2004 and Vogel et al., 2005). Wolock et al. (2004) regionalized 20 hydrologic-landscape regions in the United States using geographic information system (GIS) tools combined with principal components (land-surface form, geologic texture, and climate variables) and cluster analyses. These authors acknowledge that the regionalization is "objective in the sense that it is based on statistical methods applied to digital geospatial data". According to these authors, the method used to regionalize hydrologic-landscape units is very sensitive to the spatial scale and such regionalization does not provide a bridge for multi-scale organization and quantification of hierarchical structures of hydrologic system. Vogel et al. (2005), have done the regionalization using digital network of streamflow, climate and watershed boundary. Although these authors adapt the watershed-based methodology for regionalization of water balances their model does not address the hierarchical structures and spatio-temporal organization of the system. Therefore their approach does not account for hydrological regionalization across spatial scales and also is not readily transferable elsewhere. Many researchers (Kroll et al., 2004; Vogel et al., 2005) point to the need for better characterization of landscape components of watersheds. This could be achieved by adapting science principles for regionalization as described by Pinneker (1983) and recognition of hierarchical structures for landscape components expressed in various maps and classifications.

The distinction between regression methods and the generally accepted methods for regionalization in hydrology should be made clear. First, to reiterate what was stated earlier, the classical definition of hydrologic regionalization is the determination of hydrologically similar units (Diekrüger, 1999). So with the classical approach we seek to find landscape units that have similar hydrologic features. For example, a hydrologic unit in an area might have the following hydrologic features; humid climate, hardwood trees, mild slopes, sandy loam soil, fractured limestone, shale, limestone, sandstone, etc. The hydrologic response of this hydrologic unit, once established based on measurements at an appropriate scale, can be directly related to the hydrologic response of geometrically similar hydrologic units elsewhere. Geometric similarity does not require the same size of unit, but only similarity in characteristics. This similarity allows the scaling up or scaling down of hydrologic response based on the absolute size of the unit.

The typical approach using regression would base prediction of hydrologic response not on the similarity concept but based on the quantification of the various components of the hydrologic system. So for instance using the example hydrologic unit described above, the regression method would predict response based on the characteristics of layers present in the hydrologic unit, but does not distinguish between the possible sequences of layers. That is, the regression method would give the same response whether the shale layer is the third layer or the second layer. In short, the regression method does not require geometric similarity.

This regression approach is the basis for the method used by Lorentz and Delin (2006) and Delin et al. (2007). Their approach does not follow the classical approach for hydrologic regionalization (determination of hydrologically similar units). Their studies of recharge in Minnesota do not treat the entire hydrologic system of an area, but instead separate out the individual components of the systems examined. Through regression analysis it is hoped that the response of the systems can be predicted, but the response of a hydrologic unit is not simply the linear combination (regression) of its component parts, but a nonlinear response. Regression analysis really is not able to predict this nonlinear response, because the connectivity within the entire hydrologic system is not accounted for. Rather, it is necessary to look at the response of the hydrologic unit as a whole. This is becoming increasingly recognized and has resulted in the advocacy of the entire hydrologic system that is based on watershed-based methodology (Pinneker, 1980; Lin et al., 2006). This watershed-based approach is the only way to tackle the problem of multi-scales.

The regionalization map created by the Minnesota Department of Natural Resources (MN DNR) and used by other agencies (for instance, the Land Management Information Center and the Minnesota Pollution Control Agency) was compiled from pre-existing hydrogeological maps developed by Kanivetsky (1978, 1979). Those hydrogeologic maps pre-dated the application of the proposed regionalization method and therefore the MN DNR mapped units are not quantified by any hydrologic characteristics, and the boundaries of units are not defined by hydrologic characteristics, only hydrogeologic boundaries. Furthermore, the MN DNR maps do not reflect the connection between surface and ground waters and therefore cannot be used for a scientifically based multi-scale quantitative regionalization.

The Winona State University regionalization of the ground water system uses the term "ground water provinces" by using bedrock aquifers nomenclature in Minnesota from State hydrogeologic maps (Kanivetsky, 1978). This system did not require any further analysis other than using the hydrogeologic maps and therefore does not provide a basis for recharge estimation or ground water availability.

The alternative approaches that currently exist for defining regional hydrogeologic systems in Minnesota are listed in Table 1. These methods are presumably the basis for estimating the availability of ground water resources. Only the first method listed was developed based on the principles of regionalization as defined by Diekrüger et al. (1999), and it is the only method that emphasizes the estimation of ground water supply sustainability.

Table 1. Existing methods defining regional hydrogeologic systems for Minnesota.

Agency	Regionalization method	Units	Location
Minnesota Geological Survey	Watershed Characteristics	Ecohydrologic (see Figures 1, 2, 3 and Table 2)	(Shmagin and Kanivetsky, 2002; Ruhl et al., 2002; Kanivetsky and Shmagin, 2005)
Minnesota Department of Natural Resources (MN DNR)	Ground water provinces	Geographic Nomenclature	http://www.dnr.state.mn.us/groundwater/provinces/index.html
Land Management Information Center (LMIC)	Same	Same	http://www.lmic.state.mn.us/chouse/metadata/gwprovs.html
Minnesota Pollution Control Agency (MPCA)	Same	Same	http://www.geo.umn.edu/mgs/gwig/index.html
Winona State University	Ground water provinces	Aquifers Nomenclature	http://www.winona.edu/geology/2629.htm
USGS	No system for regionalization, but depiction of runoff and aquifer systems	Average annual runoff rate and nomenclature of aquifer systems and aquifers	http://capp.water.usgs.gov/gwa/ch_j/index.htm

II.2. *The watershed-based approach for regionalization of hydrologic systems.*

The methodology proposed for the regionalized quantification of freshwater sustainability is based on the watershed-based approach which is derived from ideas described by Pinneker (1980). A brief review of how the method has already been applied in Minnesota by members (e.g., Shmagin and Kanivetsky, 2002) of the research group will be presented. The presentation will be limited to the analysis of ground water recharge even though work has been completed for regionalization of surface water supplies as well using the same procedures.

The results for the large scale (1:3,000,000) estimation of regional ground water recharge were already shown in Figure 2. The details on how these were derived will be described first, and this will be followed by a description of how those results are scaled down to smaller regional units.

The analytical procedure for determination of the spatial distribution of freshwater sustainability consists of five stages as outlined in Table 2. The first three stages (I, II, III) are the primary drivers for the analysis. Stage I is analysis and processing of hydrological data and Stage II is the preparation of maps reflecting the physiographic framework. Stage III links the physiographic information to the streamflow results.

The objective for Stage I is the identification of characteristics for all stream runoff parameters (annual stream runoff rate, rate of minimal monthly stream runoff, coefficient of minimal ground-water contribution to stream runoff and bench –mark analogs) for the study area.

The results of Stage II are the variant for each map reflecting variations in ground water flow fields and other features of physiographic framework. The hydrologic units that are distinguished in this stage are defined based on the multiple layers of information, geological, atmospheric, biological (vegetative), soil, and anthropogenic (landuse). The concept of using these multiple layers in defining the hydrologic units originates from Krcho (1990).

Stage III is the development of the connection between the defined hydrologic unit characteristics and the quantified streamflow characteristics.

Stages IV and V are just follow-ups using the results from the three primary stages of the analysis procedure.

In Stage III the hydrologic parameters derived in Stage I are associated quantitatively, using statistical technique, with each variant of the hydrologic flow field maps derived in Stage II. The result of Stage III is pattern recognition for hierarchical hydrogeological subdivisions as well as for the physiographic framework.

In Stage IV a ground-water recharge map is compiled by combining the results of the stream runoff parameters (Stage I), the variation of each map (Stage II), and the principles of pattern recognition for hierarchical hydrogeological subdivision (Stage III). Stage V is not a part of the map compilation, but it is included in the flow chart to demonstrate that from the recharge maps the renewable ground water resources map, or safe yield map, can be compiled with quantification for any unit of physiographic, political, social or administrative divisions. The principles of compilation are the same for any scale, but the process of compilation proceeds from large-scale territory such as basin or region to a detailed scale.

It should be mentioned here, that there are in principle no general limitations in scale of compilation possible with the analytical methodology except that limited data can put a limit on the detail that is possible. The more detailed the map desired, the more detailed data will be required. Using only geological information for outlining the hydrologic units leads us to a map detail no better than 1:100 000 to 1:200 000. For example in Minnesota the analytical procedure was carried out from the state of Minnesota (scale 1: 5 000 000) to east - central Minnesota (scale 1:500 000) and finally to the TCMA (1:200 000). However, as will be mentioned in the next section, we propose that by adding other features, such as soil information, vadose zone information, and vegetative cover information we hypothesize that it will be possible to achieve confidence in even better detail than this.

With the general overall analytical procedure defined, the previous application to Minnesota will now be presented.

Streamflow records for gauged watersheds in the state that have long-term records (about 272 gaging stations) were examined to select those with a record that covered a similar time period. A total of 35 watersheds located throughout the state were found to have this common record for the period 1935 – 1986. The flow records were processed to quantify the temporal characteristics for interannual flows as well as the proportions of runoff by month and season. The analysis of the hydrologic data was a factor analysis, which is intended to maximize the variance of variables and while minimizing the cross-correlation between variables. The result of this analysis for interannual flows showed four distinct groups of watersheds, associated with the northeast, northwest, southeast, and southwest sections of the state. Presumably these differences are due to climatic, vegetative (affects hydrology because different vegetative types transpire different amounts of water during the year), as well as to geologic characteristics of the regions associated with each group. Three **benchmark watersheds** were selected from these groupings. Benchmark watersheds are those having the largest degree of variation of flow characteristics. The benchmark watersheds are used in the downscaling procedure that follows.

The factor analysis of the monthly flows led to the identification of nine groups of watersheds having distinct characteristics for temporal runoff. For instance, some were distinct in their spring runoff, other were different because of the fall-winter runoff, and others were different because of their runoff in mid-summer. Again, these distinct groups could be related to the watershed characteristics within the geographical areas associated with each distinct group.

Based on the results from the 35 watersheds, the number of watersheds used in the analysis was increased to 115. The common period of record for these watersheds was 1935 – 1981. These records were processed in the Stage I of the analytical procedure to determine the spatio-temporal distribution of stream runoff. The annual runoff and the minimum monthly flow for February for each watershed were used in the analysis.

Stage II was performed to subdivide the state into surface features representing ecological provinces, ecological districts, and geological hierarchy. The geological hierarchy is presented in Figures 1a and 1b, while the ecological hierarchy is presented in Figures 3a and 3b. Figure 3a shows the broad scale ecological provinces (after Nesser and Bailey, 1994), while Figure 3b shows the downscale classification of the ecological sections.

The analysis of annual runoff data showed distinct differences between watersheds located in the three ecological provinces. These annual runoff amounts are illustrated in Figure 3a, while the annual runoff amounts for the finer scale subdivision of districts are shown the Figure 3b. The differences seen in Figure 3 appear to reflect the effect of climate on streamflow, with higher values of flow in the northeastern part of the state, and lower values in the southwestern part. Analysis of the minimum monthly February flows for these same provinces indicated only a difference between the southwestern province and the other two provinces. This indicates that the minimum monthly February flow is affected by something other than climate only. This was assumed to be the geologic characteristics.

The statistical analysis of the minimum February flows for the set of watersheds yielded distinct characteristics for each of the geological hierarchical units presented in Figure 2. On the larger scale showing just two hydrogeological regions, the minimum monthly February flow for one is 0.83 l/sec/sq. km, and 2.09 l/sec/sq. km for the other. There is also a distinction within these two regions based on the geological characteristics that distinguish these geologic subregions.

The next step in the analysis is to go one more step down in scale. Take for example the spatial distribution of minimum ground water recharge within the East Central Minnesota region (ECM).