Regionalization of landscape characteristics to map hydrologic variables

H. M. Peterson, J. L. Nieber, R. Kanivetsky and B. Shmagin

ABSTRACT

By integrating groundwater, surface water and vadose zone systems, the terrestrial hydrologic system can be used to spatially map water balance characteristics spanning local to global scales, even when long-term stream gauge data are unavailable. The Watershed Characteristics Approach (WCA) is a hydrologic estimation model developed using a system-based approach focused on the regionalization of landscape characteristics to define unique hierarchical hydrogeological units (HHUs) and establish their link to hydrologic characteristics. Although the WCA can be used to map any hydrologic variable, its validity is demonstrated by summarizing results generated by applying the methodology to quantify the renewable groundwater flux at a spatial scale lacking long-term stream gauge monitoring data. Landscape components for 97 East-Central Minnesota (ECM) watersheds were summarized and used to identify which unique combinations of characteristics statistically influenced mean annual minimum groundwater recharge. These resulting combinations of landscape characteristics defined each HHU; as additional characteristics were applied, units were refined to create a hierarchical organization. Results were mapped to spatially represent the renewable groundwater flux for ECM, demonstrating how hydrologic regionalization can address knowledge gaps in multi-scale processes and aid in quantifying water balance components, an essential key to sustainable water resources management.

Key words | regionalization, renewable flux, sustainable recharge

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ABBREVIATIONS

AWC available water capacity
ECM East-Central Minnesota
GIS geographic information system
HHU hierarchical hydrogeological unit
PAB Paleozoic artesian basin
PB Precambrian basement
USGS United States Geological Survey
WCA Watershed Characteristics Approach

INTRODUCTION

Watershed Characteristics Approach (WCA)

Estimating renewable groundwater flux at various scales is crucial for water resources sustainability management, protection and enhancement of ecosystem health, and water budget research of natural and human impacted ecosystems. Although much attention has been given to quantifying recharge/discharge fluxes at local and immediate scales (De Vries & Simmers 2002; Scanlon *et al.* 2002; Cherkauer 2004; Dripps & Bradbury 2010), there is a need for the ability to spatially depict fluxes across multiple scales, from global to local, for aiding future water planning and sustainable management decision-making (NRC 2004; NSTC 2007). This paper demonstrates how critical water management issues can be addressed using a system-based approach integrating groundwater, surface water and vadose zone systems, to spatially map hydrologic variables and address multi-scale processes, even when long-term streamflow data are unavailable.

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The WCA is a hydrologic estimation model developed by using a system-based approach focused on regionalization of landscape characteristics to define unique hierarchical hydrogeological units (HHUs) with statistically significant hydrologic variables. It is based on the regionalization approach described by Pinneker (1983), which requires that parameters for dividing a given territory be defined and then boundaries of these parameters be mapped. To do so, the WCA couples Krcho's (2001) system model of geospheres with Freeze & Cherry's (1979) conceptual watershed model for water balance components; thereby enabling it to depict hydrologic variables spatially and temporally making it applicable for addressing hydrologic processes at multiple scales. The idea that details of hydrologic processes or heterogeneity within watersheds need not be examined, but rather instead characterized by the hydrologic behavior of the watershed system, can be viewed compatible with the Representative Elementary Watershed approach introduced and outlined by Reggiani & Rientjes (2005) and the new hydrologic vision described by McDonnell *et al.* (2007).

Watersheds are self-organizing systems, whose characteristics are a result of adaptive, ecological, geomorphic or landforming processes; therefore, they may establish patterns which upon examination can lead to simplification of descriptions used in analysis and predictions (Sivapalan 2005). Hence, the methodology is referred to as the 'WCA', indicating that all variables of landscape components are associated with water balance characteristics, using the watershed as a quantification unit (Kudelin & Fideli 1970).

Spatial variation of regional recharge

Recharge is generally the most difficult component of the groundwater system to quantify (Bredehoeft 2007). Rising water demands and increased scarcity for humans and nature makes the need for improved regional recharge estimates critical for transitioning to sustainable water resources management (Barlow *et al.* 2002). Regional recharge estimation methodologies must apply interdisciplinary approaches to facilitate creation of the spatial connectivity within the hydrologic system, specifically to extrapolate data from gauged to ungauged watersheds (Wagener *et al.* 2009).

Many hydrologic models ignore spatial and temporal variations in recharge rates because of limited available critical parameter measurements or the method is not adequate to accurately evaluate the variations at the scales of interest (Hyndman *et al.* 2007). There are, however, several methods for estimating the spatial distribution of recharge across a landscape. Physically based methods apply, to various degrees of complexity, equations that quantitatively describe various processes involved in the land surface and shallow unsaturated zone water balance. In some cases, water balance models are coupled to a physically based groundwater flow model that interacts with the land surface water balance processes, thereby connecting the simulated net recharge to the simulated discharge to surface water bodies. For instance, Batelaan & De Smedt (2007) coupled their WetSpass model, which provides recharge estimates on a rather refined grid scale (50 m × 50 m), with a MODFLOW model for the regional groundwater system to estimate the spatial distribution of recharge and then correlate those recharge estimates to local landscape characteristics.

To characterize each component of the terrestrial landscape, specifically the hydrogeology (Kroll *et al.* 2004), there needs to be a grasp on the connectivity within the entire hydrologic system. Therefore, the WCA incorporates terrestrial mapping to quantify hydrologic variables at multiple scales. We hypothesize that the WCA may be applied to estimate and spatially depict any hydrologic variable, and demonstrate in the following application that the methodology does work using mean annual minimum recharge to represent the renewable flux of the groundwater system across East-Central Minnesota (ECM), a scale lacking long-term stream gauge monitoring data.

Regional recharge mapping using the WCA is based on the idea of regionalization of the entire terrestrial hydrologic system in a hierarchical organization (Pinneker 1983), as well as on valid and reliable hydrologic characteristics (e.g. stream discharge) to represent groundwater recharge (Kanivetsky & Shmagin 2005). Classical hydrologic regionalization is the determination of hydrologically similar units (Diekrüger *et al.* 1999); which the WCA defines by identifying specific sets of unique landscape characteristics. The hydrologic response of this unit is based on measurements at an appropriate scale, which can be directly related to the hydrologic response of characteristically similar hydrologic units elsewhere. This concept is becoming increasingly recognized and has resulted in advocacy for examining the entire hydrologic system through a watershed-based methodology (Pinneker 1983; Reed *et al.* 2006; McDonnell *et al.* 2007).

METHODOLOGY

System model for watershed water balance

System science focuses on inter-relationships between components of a whole, examining complexity and integration to identify patterns of interaction (Haigh 1985). Earth can be viewed as an open, self-organizing and complex system of geospheres including the atmosphere, hydrosphere, pedosphere, lithosphere, biosphere, and anthroposphere; each geosphere is influenced by adjacent spheres (Khain 2010). The WCA is based on the idea that the landscape is composed of different layers, each representing a fundamental landscape component defined by the concept of geospheres (Poliakov *et al.* 1988; Krcho 1995, 2001). At a given point on Earth's surface, a combination of these layers (i.e. geospheres) yields unique features to which hydrologic response is hypothesized to be sensitive. The hydrologic response is, therefore, a result of the interaction of the various geospheres, or landscape characteristics.

Using this idea of geospheres, any terrestrial land area, regardless of size, can be subdivided into hierarchical units based on differences in combinations of hydrologic and landscape characteristics (Krcho 2001; Shmagin & Kanivetsky 2006). The composite landscape characteristics within a particular hierarchical unit are related to the spatially defined landscape data layers associated with that unit. For example, variations of characteristic combinations can be visualized by imagining a vertical profile into Earth's surface capturing the sequence of landscape characteristics extracted as layers (i.e. topography, soil type, Quaternary thickness, bedrock material). Water balance variables can then be related to the composite landscape characteristics (i.e. series of layers identified within the hypothetical profile) derived from maps and other spatial data, to establish the regional set of statistically significant HHUs. By identifying similar units having unique landscape characteristics, the flow and transport domains are assumed to be more similar within a unit than between units, allowing simpler mathematical treatment of hydrologic processes (Santra *et al.* 2011).

Based on this model of geospheres, the WCA uses a multi-level system structure for landscapes to capture multi-scale process variations. Using the boundaries of a given watershed to represent a subsystem, the landscape can be analyzed from a vast global scale to a more localized regional scale (i.e. county) to quantify hydrologic characteristics and classify hydrologic units.

Quantification of watershed hydrologic characteristics

The watershed as a part of Earth's landscape can be studied as a unit with three-dimensional boundaries to characterize the freshwater system. It is assumed that the groundwater divide coincides with the surface topographic divide used to delineate the watershed drainage area (Tóth 1963). By recognizing that the watershed is a unit of the hydrologic system and combining it with the hydrosphere structure, the land surface can be represented by a set of watersheds. Watersheds are thus 'nested'; larger watersheds encompass many smaller watersheds.

In the demonstrated application, to avoid inconsistencies due to annual seasonal variability of discharge, the rate of mean minimum monthly streamflow is used as a conservative proxy for the minimum groundwater recharge rate, or stable baseflow (Kanivetsky & Shmagin 2005). It is assumed that groundwater recharge is just discharge measured in the river (Bredehoeft 2007) at the watershed outlet. This is taken from actual measurements, and not from using methods such as hydrograph separation which may overestimate recharge due to bank storage (Halford & Mayer 2000; Scanlon *et al.* 2002) or unaccounted surface storage resulting from recent rainfall events. Streamflow records indicate that historically, Minnesota monthly streamflow has been at its minimum during February, when, because of subfreezing temperatures, it typically consists of baseflow with little or no surface runoff (Ruhl *et al.* 2002). Winter is also the time when water losses due to riparian and phreatic vegetation, which can significantly reduce stream recharge, will be absent. In other climatic regions where freezing temperatures are not a factor, one would need to work out the surrogate measure for minimum recharge. In the case where perennial streams are lacking, such as in semi-arid or arid climates, an alternative proxy could be considered.

The WCA uses the watershed area as a quantification unit; a module of minimum recharge as a unit of watershed area (expressed as $L\,s^{-1}\,km^{-2}$; which is converted to $cm\,yr^{-1}$ by multiplying by 3.16) is computed so that each watershed could be compared and related (Zektser 2002). Because of this uniformity, mean minimum flow values are comparable between spatial areas regardless of size and results can be mapped as hydrological units in a hierarchical organization. Recharge values are assumed to be equal to watershed discharge values, which are considered to be constant and uniform for each defined HHU, but may vary between individual units. This distinction is important because organizing knowledge based on hydrologic units rather than on aquifers acknowledges unity of the surface and groundwater system, enabling an integrative, systems viewpoint of the terrestrial hydrologic system (Alley & Leake 2004; Falkenmark 2008).

Although consistent long-term data are unavailable, ECM has an extensive historic gauging station network (Figure 1). It encompasses approximately 45,000 km^2 and includes the St. Paul and Minneapolis (Twin Cities) Metropolitan Area, which has received increased attention due to concern over potential hydrologic impacts associated with increased urban development northwest toward the city of St. Cloud and east into Wisconsin (Ruhl *et al.* 2002; Delin *et al.* 2007; Lorenz & Delin 2007).

Watersheds of interest for the WCA are those with actual recorded stream runoff measurements. Ninety-seven gauging stations representing small scale watersheds in ECM were selected based on availability of low–flow characteristics data described by the United States Geological Survey (USGS) (Lindskov 1977; Kanivetsky 1979b). Available one-time, low-flow discharge observations collected between years 1940 and 1976 were recorded for each of these 97 watersheds (Figure 1).

The period of hydrologic monitoring record available for large scale watersheds is typically much longer and complete than those records accessible for small scale watersheds. To address this limitation, benchmark watersheds were used to

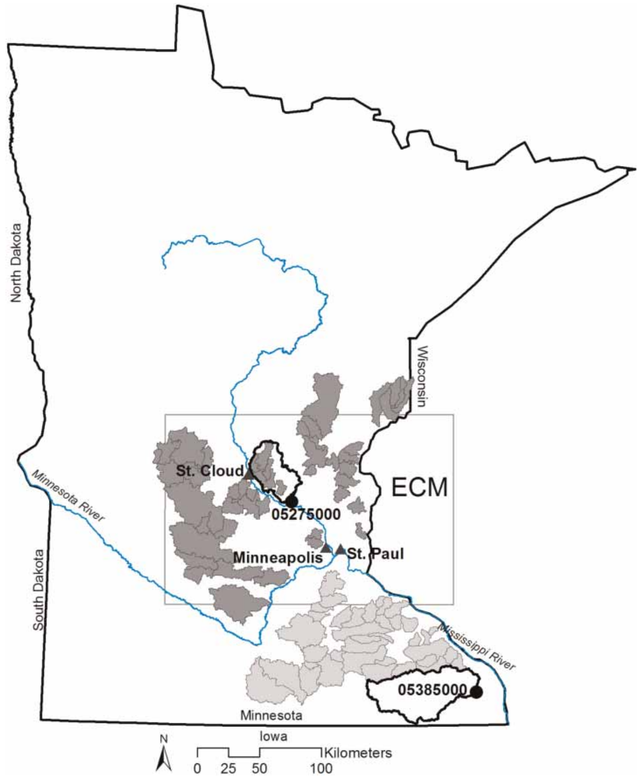

Figure 1 | ECM study area is depicted with the two benchmark watersheds, projected to illustrate the distribution of the 97 analyzed watersheds and shaded gray to reflect the corresponding, designated benchmark watershed.

extrapolate data from partial or one-time observations recorded at small scale watersheds (Figure 1). These benchmark watersheds have relatively long-term annual mean streamflow records, which based on their strong hydrologic signature determined through factor analysis results from previous statewide analyses, can be used to represent the hydrologic characteristics of smaller watersheds having short-term records within the same territory (Shmagin & Kanivetsky 2002; Peterson *et al.* 2011). For this analysis, two benchmark watersheds were selected to represent the ECM area because they are located within or adjacent to the area, each comprises a diversity of landscape characteristics representative of the study area (e.g. varying Quaternary thickness, bedrock material, topography, soil type), and had USGS daily observations for overlapping consecutive years of 1940 through 1983. They included Elk River near Big Lake (USGS gauge #05275000) and the Root River near Houston (USGS gauge #05385000). Mean annual minimum monthly (February) recharge for the period of 1955 through

1978 was calculated for each benchmark watershed. This period was selected because watersheds had recovered from the drought conditions of the Dust Bowl period, but had not yet experienced significant hydrologic influence from recent anthropogenic landscape changes (Peterson *et al.* 2011). Additional time intervals were estimated, including 1955 through 2008 and 1978 through 2008; however, in this analysis 1955 through 1978 provided the lowest, most conservative mean annual minimum monthly recharge estimates, which establishes a reference for comparing the hydrologic effects of future anthropogenic changes.

Each watershed analyzed was assigned to a corresponding benchmark based on proximity to the benchmark watershed, shared dominant landscape characteristics, and regime results of the statewide streamflow regionalization (Peterson *et al.* 2011). Mean annual minimum monthly runoff values for the 97 analyzed watersheds were estimated by determining the linear proportion between the discharge of the specific corresponding benchmark watershed and the regional watershed's observed discharge value.

The extrapolation was completed by first recording the low-flow observations collected between 1955 and 1978 for each of the analyzed watersheds listed in Lindskov (1977). These flow rates were converted to a yield (d_i) based on the drainage area for each corresponding watershed ($_i$). The flow rate and yield for the assigned benchmark watershed (b_i) was recorded for the corresponding sample date. The mean annual February (minimum) streamflow (recharge) for the time interval of 1955 through 1978 was calculated for both of the benchmark watersheds (m_i). The ratio of the benchmark watershed's low flow observation to the mean minimum recharge could then be calculated as $b_i/m_i = p_i$. Each analyzed watershed's yield could then be divided by this calculated benchmark ratio to get the estimated mean minimum groundwater recharge $d_i/p_i = f_i$ for that specific analyzed watershed. These values defined by f_i are the recharge rates used throughout the regionalization analysis to be presented.

Tables 1 and 2 summarize the delineated drainage areas and calculated mean annual minimum groundwater recharge rates for all analyzed watersheds, categorized by their assigned benchmark watershed. Gray scale coding in Figure 1 clusters the watersheds based on this benchmark assignment.

Table 1 | Analysis watersheds corresponding to benchmark watershed #05275000-Elk River near Big Lake, MN

USGS stream gauge	Mean minimum groundwater recharge[a] (L s^{-1} km^{-2})	Ratio to benchmark watershed (p_i)	Drainage area[b] (km^2)	Final HHU[c]
05270110	1.93	0.96	139	Bl
05270130	0.68	0.89	68	Bl
05270150	0.36	2.93	333	Bl
05270180	0.98	0.90	630	Bl
05270210	0.29	0.96	226	Bl
05270230	0.30	3.99	1,114	Bh
05270250	0.04	0.91	76	Bh
05270280	0.07	0.88	179	Bh
05270350	0.85	0.88	1,658	Bh
05270455	1.01	0.88	113	Kl
05272300	0.69	3.91	144	Bl
05272600	0.74	0.66	77	Bl
05273000	0.09	0.66	202	Kh
05273498	0.30	0.23	446	Kl
05273600	0.42	1.04	135	Bh
05273990	0.09	0.66	87	Bl
05274000	0.34	0.84	299	Bl
05274300	0.29	0.80	97	Bl
05274380	1.58	0.66	608	Bl
05274480	3.11	2.36	83	Bl
05275970	0.50	1.00	392	Bl
05277050	0.14	0.94	127	Bh
05278100	0.63	1.23	1,925	Kl
05278150	0.03	1.27	218	Kh
05278590	0.10	1.10	1,192	Kh
05278830	0.03	0.94	588	Bh
05278835	0.12	1.13	247	Bh
05278950	0.04	1.10	1,062	Bh
05284810	1.19	0.88	77	AQ1
05284950	0.25	0.87	381	AQ3t
05284970	0.66	0.87	113	AQ1
05288700	1.95	1.00	82	AQ1
05288900	0.23	4.46	105	AQ3t
05326400	0.35	1.03	1,046	AQ3t
05329900	0.15	0.96	332	AQ3t
05335110	0.33	0.95	180	A4
05335130	0.25	0.95	118	A4

(*continued*)

Table 1 | continued

USGS stream gauge	Mean minimum groundwater recharge[a] (L s^{-1} km^{-2})	Ratio to benchmark watershed (p_i)	Drainage area[b] (km^2)	Final HHU[c]
05335151	0.50	0.95	473	A4
05335170	1.25	0.91	238	A4
05335755	0.54	1.01	200	Bh
05335890	0.66	1.01	73	A4
05335900	1.07	0.95	292	A4
05337500	0.49	0.91	1,149	Bh
05337530	0.03	1.01	83	Bh
05337600	0.27	1.01	163	Bh
05337700	0.97	1.01	194	Bh
05339490	0.34	1.06	140	AQ3t
05339720	0.46	0.88	144	AQ3t
05339750	0.42	0.88	176	AQ3sl
05339800	0.24	0.88	135	AQ1
05339950	1.23	0.88	139	AQ1
05340110	0.04	0.80	69	AQ3sl
05340130	2.84	0.80	135	AQ1
05340170	3.60	0.90	182	AQ2
05341540	1.44	1.11	77	AQ3sh

[a]Extrapolated using benchmark watershed for the time interval of 1955–1978.
[b]Watersheds were delineated from USGS stream gauge stations.
[c]Hierarchical hydrogeological unit corresponds to Table 3.

Table 2 | Analysis watersheds corresponding to benchmark watershed #05385000-Root River near Houston, MN

USGS stream gauge	Mean minimum groundwater recharge[a] (L s^{-1} km^{-2})	Ratio to benchmark watershed (p_i)	Drainage area[b] (km^2)	Final HHU[c]
05320020	0.12	0.96	198	AQ3t
05320040	0.05	0.96	128	AQ3t
05320060	0.57	0.97	62	AQ3sh
05320070	0.26	0.96	460	AQ3t
05320330	0.01	1.37	790	AQ3t
05320480	0.10	1.37	885	AQ3t
05345000	1.23	2.07	328	AQ3t
05352010	0.23	0.85	863	AQ3t

(*continued*)

Table 2 | continued

USGS stream gauge	Mean minimum groundwater recharge[a] (L s^{-1} km^{-2})	Ratio to benchmark watershed (p_i)	Drainage area[b] (km^2)	Final HHU[c]
05352810	0.06	0.77	108	AQ3t
05352850	0.66	0.95	529	AQ3sl
05352900	0.24	1.36	104	AQ3sl
05353600	0.06	0.63	283	AQ3sl
05354600	0.14	1.44	109	AQ3t
05355020	0.04	0.75	106	AQ3t
05355040	0.44	1.44	218	AQ3sl
05355080	0.96	1.44	204	A1
05355140	1.32	1.44	220	A1
05355215	1.82	0.83	188	A1
05355260	1.64	0.82	59	A2
05355280	4.31	0.82	119	A3
05355350	2.08	1.81	187	A3
05372800	2.46	0.76	401	AQ3sh
05372930	2.64	1.38	203	A
05372990	0.75	0.76	99	A
05373100	0.17	0.82	74	AQ3sl
05373130	0.72	1.27	151	A
05373150	1.20	1.37	527	AQ3sh
05373200	0.30	0.83	197	AQ3t
05373290	1.07	0.83	547	AQ3sh
05373400	1.66	0.99	76	A1
05373850	1.70	1.43	452	AQ3sh
05373950	2.08	0.83	140	AQ3sh
05373995	1.10	1.62	119	A2
05374420	0.92	1.81	85	A2
05374480	0.98	1.55	164	A2
05374520	1.67	1.81	70	A3
05375000	0.28	1.55	43	A3
05376200	2.76	1.55	138	A1
05376500	3.18	0.80	203	A1
05377510	3.05	0.61	830	A1
05378240	2.57	0.83	123	A2
05378400	2.42	1.64	129	A3

[a]Extrapolated using benchmark watershed for the time interval of 1955–1978.
[b]Watersheds were delineated from USGS stream gauge stations.
[c]Hierarchical hydrogeological unit corresponds to Table 3.

System characterization through geographic information system (GIS) integration

The advantage of representing data within a GIS is the ability to view and analyze information assimilated from various sources in a geospatial context to identify relationships (Strassberg *et al.* 2007). Physically based models using GIS are powerful tools for addressing the complexity of hydrological processes and basin-wide characteristics (De Smedt & Batelaan 2003).

Geographic coordinates for the 97 gauging stations selected from Lindskov (1977) were georeferenced in ArcGIS®. Using Arc Hydro (Maidment 2002), a GIS mapping plug-in software for water resources, along with NHDPlus data (http://nhd.usgs.gov/index.html), an integrated suite of application-ready geospatial data sets available through the USGS and the US Environmental Protection Agency, watershed boundaries were delineated for each gauging station using raster analysis with a seamless, 30 m resolution digital elevation model compiled from the USGS National Map Server (http://nationalmap.gov/viewer.html).

Landscape characteristics in raster and shapefile format were added into the GIS to complete the watershed characterization based on these watershed boundaries. Data layers superimposed for the analysis included three 1:500,000 scale statewide hydrogeological maps representing the bedrock material (Kanivetsky 1978; http://www.lmic.state.mn.us/chouse/), Quaternary sediment (Kanivetsky 1979a), and depth to bedrock (R. Lively, Minnesota Geological Survey, unpublished data 2007). National Resources Conservation Service statewide soil data at a scale of 1:250,000 from the US General Soil Map (STATSGO2) Database (http://soildatamart.nrcs.usda.gov/) were also formatted and analyzed. Mapping the spatial relationship of the watershed boundaries with respect to the various landscape characteristics derived from these digital data layers enables the geospheres within the hydrologic system to be defined and incorporated into the analysis.

Development of hierarchical hydrogeological units

Each watershed's characteristics were summarized in matrix format (e.g. an analysis spreadsheet), with each row dedicated to a specific watershed. The first column of the matrix includes the watershed's corresponding hydrologic variable (i.e. mean annual minimum recharge) and subsequent columns represent series of landscape characteristics extracted from the GIS overlay. This matrix was then used to find a link between the hydrologic variable and landscape components; resulting in the discrimination and delineation of HHUs.

Qualitative landscape characteristics were summarized based on the fraction of each watershed comprised by each specific characteristic, completed by overlaying landscape characteristic GIS data layers. Fuzzy rule-based classification (Makropoulos & Butler 2004; Li *et al.* 2011; Santra *et al.* 2011), an efficient tool to classify domains having multiple parameters and parameter range while providing expert knowledge-based inferences about the system, was used to assign characteristic codes to each watershed based on the predominant characteristic found within the boundaries of the watershed. For instance, when evaluating Quaternary sediments, the fraction of each watershed falling into units Q1 (predominantly gravel with sand), Q2 (predominantly sand with gravel), or Q3 (till) was indicated in the analysis matrix with each unit listed as a separate column. In a fourth column, the watershed was then coded to represent whichever unit comprised the largest fraction of the watershed. Therefore, if 53% of a watershed was Q2, the watershed would be coded to reflect this predominant characteristic. This coding process was completed for each qualitative landscape characteristic. In the case where a quantitative characteristic was summarized, such as available water capacity (AWC), the characteristic was coded based on a defined range of values with a noticeable shift in the hydrologic variable (i.e. minimum recharge). This shift was identified by plotting the recharge data in numerical order to observe whether any breaks in the rates exist. Since the system of landscape characteristics varies geographically, depending on the spatial scale and location of a given study area, the qualitative and quantitative landscape characteristic categories summarized will vary, therefore, resulting in unique sets of HHUs.

Statistical analyses

Using a set of watersheds with the same coded series of landscape characteristics, the mean minimum groundwater recharge was calculated at each revised hierarchical level.

Upper and lower quartiles were calculated to provide a range of minimum recharge values within the characteristics to show the uncertainty distribution attributed primarily to the fuzzy classification scheme. Following the hierarchical procedures defined by Pinneker (1983), regionalization begins with the most general landscape features at the Province hierarchical level, and as more specific characteristics are overlaid in combination with that previous general feature, HHUs are refined at subsequent levels to the most refined level possible with currently available data, District (Figure 2).

At each hierarchical level, non-parametric Mann–Whitney *U* tests and Kruskal–Wallis analysis of variance (ANOVA) by ranks were used to distinguish which unique set of overlaid landscape characteristics significantly influenced the corresponding mean minimum groundwater recharge. Based on the statistical results performed at each hierarchical level, characteristics exhibiting a significant statistical difference with a probability-value less than or equal to 0.05 (i.e. $p \leq 0.05$) in mean minimum recharge values were used to establish the regionalization of HHUs. Both tests evaluate whether the minimum recharge rates were taken from the same population; Mann–Whitney is used when there are two characteristic groups, while Kruskal–Wallis is used when there are at least three characteristic groups (StatSoft 2012). Ability to detect differences between groups with small data sets is critical for the WCA since the number of gauged watersheds exhibiting the unique sets of characteristics at each hierarchical level becomes limiting.

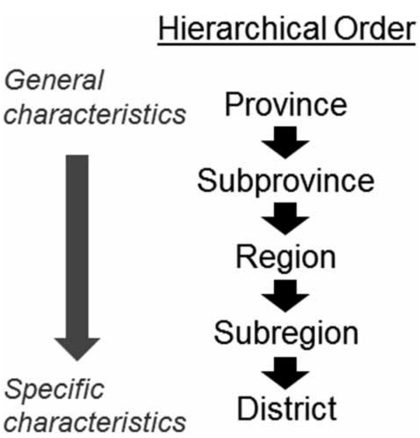

Figure 2 | Hierarchical order used in the hydrogeological regionalization.

RESULTS

Hierarchical hydrogeological units

Table 3 outlines the final statistically significant HHU regionalization results for ECM, including the combinations of landscape characteristics at each hierarchical level with their corresponding calculated mean minimum recharge rates. Tables 1 and 2 list the corresponding HHU symbol for each watershed so that it is clear which were used for each non-parametric analyses. For example, watershed #05339750 labeled HHU AQ3sl (Table 1), was also used for the Paleozoic artesian basin (PAB), AQ, AQ3, and AQ3 s calculations used to construct Table 3. This delineation of characteristics resulted in the most detailed regionalization possible at the current scale with statistically significant differences between minimum recharge values for each refined HHU. To illustrate the division of watersheds into the refined HHUs at each hierarchical level, the number of watersheds analyzed is included in parenthesis adjacent to the HHU symbol within Table 3.

Province level

Landscape characteristics used to define Province and Subprovince hierarchical levels were based on previous analyses using the WCA in a statewide regionalization (Shmagin & Kanivetsky 2002). The Province level HHUs are the most general, defined based on hydrogeologic boundaries of the PAB and Precambrian crystalline basement (PB). The Paleozoic rocks form an artesian system consisting of beds of sandstone, shale, and limestone while the Precambrian basement is composed of more ancient rocks acting as confining layers. Therefore, mean minimum recharge results at the Province level depicted in Table 3 are supported by the underlying hydrogeology, estimating higher mean minimum recharge values for HHU PAB ($p = 0.02$). A box plot illustrating the data spread between PB and PAB is included as Figure 3(a).

Subprovince level

At the Subprovince level, each Province HHU was further subdivided based on the number of groundwater flow field

Table 3 | Mean minimum groundwater recharge rates for hierarchical hydrogeological units defined for ECM

Province	Mean minimum recharge (L s^{-1} km^{-2})	Subprovince	Mean minimum recharge (L s^{-1} km^{-2})	Region[c]	Mean minimum recharge (L s^{-1} km^{-2})	Subregion	Mean minimum recharge (L s^{-1} km^{-2})	District	Mean minimum recharge (L s^{-1} km^{-2})
PB – Precambrian basement (33)[a]	0.55 (0.10–0.69)[b]	K (6) Three groundwater flow field layers: Quaternary sediments, Cretaceous deposits and Precambrian basement	0.36 (0.09–0.63)			Kl (3) – Low AWC <0.13	0.65 (0.30–1.01)		
						Kh (3) – High AWC >0.13	0.07 (0.03–0.10)		
		B (27) Two groundwater flow field layers: Quaternary sediments and Precambrian basement	0.59 (0.12–0.74)			Bl (13) – Low AWC <0.15	0.89 (0.34–0.98)		
						Bh (14) – High AWC >0.15	0.31 (0.04–0.49)		
PAB – Paleozoic artesian basin (64)	1.09 (0.25–1.67)	A (26) One groundwater flow field layer: Quaternary sediments, <21 m thick, Paleozoic artesian aquifers	1.57 (0.75–2.42)	A1 – (7) St Peter aquifer	2.11 (1.32–3.05)				
				A2 – (5) Prairie du Chien Jordan aquifer	1.44 (0.98–1.64)				
				A3 (5) – Franconia-Ironton-Galesville aquifer	2.15 (1.67–2.42)				
				A4 (6) – Keweenawan Volcanic Rocks aquifer	0.67 (0.33–1.07)				
		AQ (38) Two groundwater flow field layers: Quaternary sediments, >21 m thick, Paleozoic artesian aquifers	1.17 (0.35–1.85)	AQ1 (6) Gravel and Quaternary sediment	1.35 (0.66–1.95)				
				AQ2 (1) Sand and gravel Quaternary sediment	3.60	AQ3 (14) – Quaternary sediment thickness >40 m	0.89 (0.24–1.44)	AQ3sl (7) – >9% slope	0.29 (0.06–0.44)
				AQ3 (31) Till Quaternary sediment	0.54 (0.12–0.66)			AQ3sh (7) – <9% slope	
						AQ3t (17) – Quaternary sediment thickness >40 m	0.25 (0.10–0.30)		

[a](#) refers to the number of watersheds included in the analysis.

[b]Range of the upper and lower quartile.

[c]Watersheds included in analysis at Region level may not equal those in Subregion level due to a combination of predominant characteristics not identified within the boundaries of ECM.

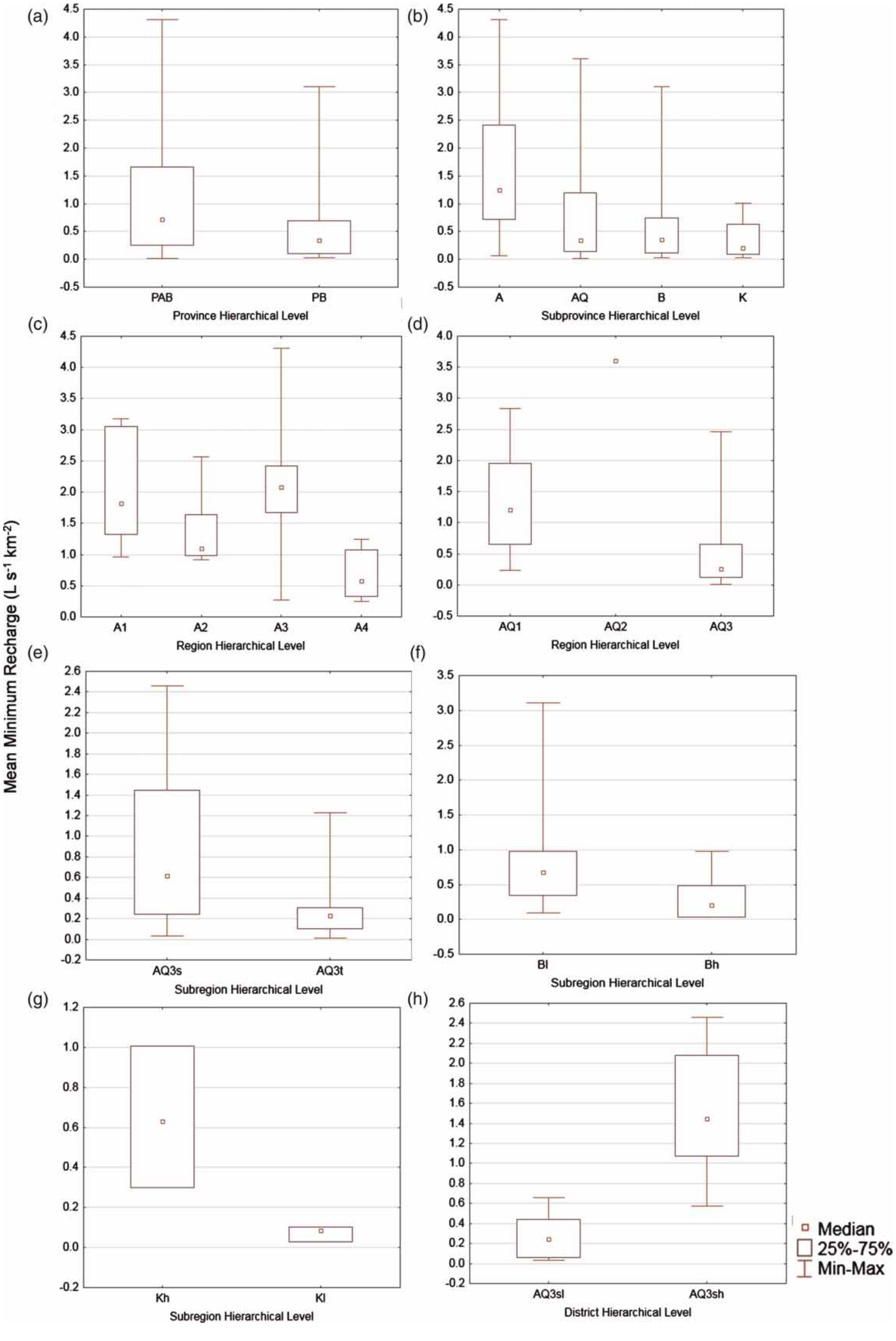

Figure 3 | Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge results within the hydrogeological units that comprise the Province (a), Subprovince (b), Region (c) and (d), Subregion (e), (f), and (g), and District (h) hierarchical levels summarized in Table 3.

layers ($p = 0.00$). The PB HHU was subdivided to isolate units with two or three flow field layers. Most of the PB HHU contains two flow field layers (B); however, the western border contains a third layer, consisting of Cretaceous shale deposits (K), which underlies the Quaternary sediments. These Cretaceous deposits cause the K HHU to have a significantly lower mean minimum recharge compared to the areas without the deposits.

The PAB HHU was refined into two units based on one or two groundwater flow field layers. Areas of PAB with shallow (<21 meters) or exposed bedrock (A) were separated from those with thicker layers (AQ) of Quaternary sediments. As expected, HHU A resulted in a higher mean minimum recharge rate due to the shallowness of the system (Figure 3(b)).

Region level

Refining HHUs after the Subprovince level became less straightforward as each HHU began to have varying underlying controlling factors. Results did not identify any discriminating bedrock or Quaternary characteristics for the K and B HHUs at the Region level, suggesting their recharge was homogeneous throughout; however, A and AQ HHUs were further subdivided.

It was hypothesized that the underlying bedrock aquifer influenced the recharge rate for HHU A. The four aquifers located within ECM include the St. Peter (A1), Prairie du Chien Jordan (A2), Franconia-Ironton-Galesville (A3), and lastly, the Keweenawan Volcanic Rocks (A4). The calculated mean minimum recharge rates for each HHU varied but corresponded to the aquifer material. Those composed of sandstone (A1 and A3) had the highest recharge rates while the Keweenawan (A4) had the lowest rate ($p = 0.03$; Figure 3(c)). Due to the limited number of gauged watersheds comprising each HHU at the Region level, the Subprovince A HHUs could not be further refined to yield statistically significant results. This was verified by applying additional characteristics, such as AWC ($p = 0.10$) or slope ($p = 0.86$), within each bedrock aquifer.

Thirty-one of the 38 AQ watersheds were comprised predominantly of till (i.e. AQ3 watersheds) making it statistically possible to further refine the AQ3 HHUs into Subregion and District levels, whereas HHUs AQ1 (i.e. gravel and sand) and AQ2 (i.e. sand and gravel) could not be further refined due to their small number of corresponding watersheds. The presence of till sediment reduced the recharge rates in comparison to the gravel and sand Quaternary sediment (Figure 3(d)).

Subregion level

At this hierarchical level, the number of watersheds apportioned into each unit became the limiting factor in computing statistical significance. HHU AQ3 was refined by Quaternary sediment thickness. All of the units developed from the AQ Subprovince were previously defined by having a thickness >21 m; because of the till Quaternary sediment that the AQ3 HHUs have at the Region level, this thickness could be further divided. When sediments are present >40 m in thickness (AQ3t), till acts as a confining unit further impeding groundwater recharge. Areas with sediments <40 m in thickness (AQ3 s) have a significantly higher minimum recharge rate (Figure 3(e)). The AQ3 Subregions were the only HHUs that could be further refined to the District level due to the limitation in available watershed data.

Results indicated Subprovince HHUs K and B could be further refined based on the AWC of the soil overlaying the geologic unit ($p = 0.01$). Soil with a higher AWC can retain more infiltrating water than a soil with a lower capacity; water that is not retained by the soil goes to deep percolation and groundwater recharge. This can lead to more precipitation being held by the soil and made available for plant water extraction instead of deep drainage (Sophocleous 2004). This is reflected in Subregion K and B HHUs because the lower the AWC, the higher the mean minimum recharge rates (Figures 3(f) and 3(g)). The combination of Cretaceous deposits and high AWC produced the lowest recharge rates, with a mean minimum recharge of 0.07 $L\ s^{-1}\ km^{-2}$. Due to the limited number of watersheds corresponding to HHUs Kl and Kh, refinement into the District level was not statistically possible.

District level

HHU AQ3 s represents landscape areas having moderate Quaternary thickness overlaying till. These units are located primarily along the eastern boundary of ECM where there are deep valleys creating a higher mean average watershed slope. Karst geology is often found in these areas of higher slope within ECM, which may be contributing to the statistically significant higher mean minimum groundwater recharge compared to the areas with a slope <9% (Table 3; Figure 3(h)). In addition, as the slope of an area increases, the thickness of the soil layer or overburden tends to decrease, reducing the total volume of water that can potentially be retained within the profile, which may contribute to more recharge and surface runoff.

Results did not identify any further discriminating soil characteristics for the Bl or Bh HHUs for the District level, suggesting recharge was homogeneous within these units at this analysis scale.

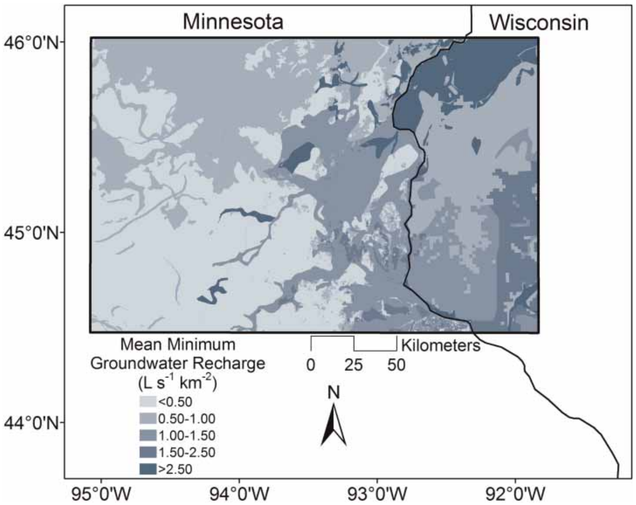

Figure 5 | Map of mean minimum groundwater recharge rates for ECM expressed as L s^{-1} km^{-2} (convert unit to cm yr^{-1} by using 3.16 as multiplier).

DISCUSSION

Regional minimum recharge map

Boundaries of the most refined HHUs were extracted in GIS (Figure 4) and corresponding calculated mean minimum recharge rates for each HHU were digitally linked to create a map of mean minimum groundwater recharge rates based on the ECM regionalization results (Figure 5). These mean minimum recharge rates represent the renewable groundwater flux through the system. Depicting the values spatially across the study territory creates a map of renewable groundwater recharge rates for areas where long-term monitoring data are otherwise unavailable.

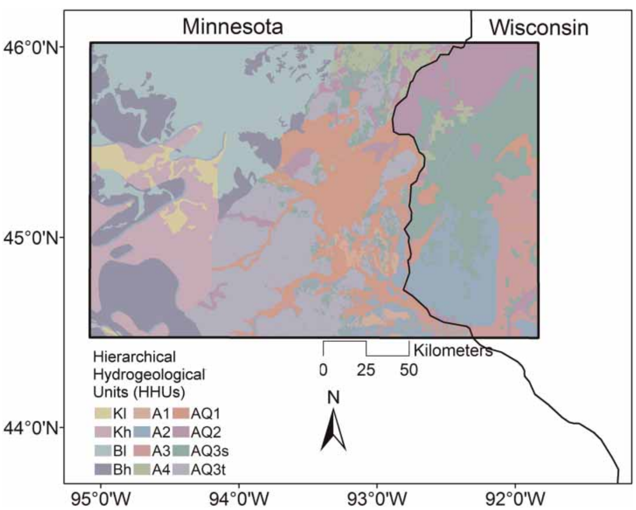

Figure 4 | Map depicting spatial location of hierarchical hydrogeological units (HHUs) refined to the Subregion level within ECM.

Alternative HHU composition

A question arises regarding whether the set of landscape characteristics that produce the HHUs are unique, or if instead an alternative set of characteristics might also work. This question gets at the issue of repeatability of the WCA method. A general principle of the WCA is subdivision of a territory into landscape units at a scale that appears to be generally homogeneous with respect to a particular set of landscape characteristics at that scale. One would expect, for example, that bedrock landscape characteristics will be homogeneous at a larger scale than, for instance, soil characteristics.

As an example of an alternative starting point, we tried initiating the hierarchy with soil order. The dominant soil orders within ECM are Mollisols (44 watersheds), Alfisols (40 watersheds), Inceptisols (seven watersheds), and Entisols (six watersheds). This produced statistically significant ($p = 0.05$) HHUs at the Province level. However, further refinement with statistically significant results was determined to be limited. The watersheds classified as Mollisols could be further refined based on the groundwater flow field layers ($p = 0.04$) and Quaternary thickness ($p = 0.00$), but subdividing by any additional characteristics, such as the AWC ($p = 0.14$), the statistical results were no longer significant. Statistically significant Kruskal–Wallis results stopped after further dividing the watersheds dominated by Alfisols by Quaternary thickness ($p = 0.00$). HHUs produced by trying to further subdivide Quaternary thickness patterns based on groundwater flow layers ($p = 0.44$) or AWC ($p = 0.37$) were not statistically significant.

Additional landscape characteristics examined without producing statistically significant HHUs for ECM, which may do so at refined spatial scales, included average altitude, drainage density (perennial, intermittent, and total), and drainable porosity. Although visual interpretation of landscape characteristic maps was used at the ECM scale to discriminate hydrogeological unit similarity, statistical methods such as principal component analysis could also be used to identify such similarity (Wolock *et al.* 2004).

Validation, extension, and limitations of the WCA method

The validity of groundwater recharge estimates from stream gauge data is difficult to confirm (Halford & Mayer 2000); however, unlike other regional recharge estimation models which require evapotranspiration (Faust *et al.* 2006) and surface runoff measurements, accuracy of the WCA depends primarily on correct selection of benchmark watershed runoff characteristics and use of high resolution landscape characteristic maps. The effectiveness of the analysis is dictated by a thorough benchmarking of the hydrologic variable.

To provide some test of the validity of the method, two USGS gauges (#05286000 and #05374000) with available long-term data located adjacent to both of the ECM benchmark watersheds were modeled. Low-flow data were estimated using the same extrapolation technique used for the ECM analyzed watersheds, as if consistent long-term data were unavailable. Following the extrapolation discussed in the methodology, and assuming there were only 'partial-record' samples available, a mean minimum recharge value was estimated for the two modeled watersheds. A date of observed low flow was chosen to base the extrapolation, and the estimated mean minimum recharge rates were compared using the two benchmarks. Both of the results produced conservative estimates within 14% of the actual observed minimum recharge (Table 4).

A comparison of the WCA results was also made by using an alternative approach to estimate recharge. The alternative estimate was calculated from baseflow recessions derived for USGS gauges #05286000 and #05374000 using the Web-based Hydrograph Analysis Tool (Lim *et al.* 2005; https://engineering.purdue.edu/~what/). The baseflow separation estimates were found to be higher than the estimate from the WCA (Table 4), which is expected since the WCA estimate is for the minimum flow, or what is referred to as the stable baseflow (Lee *et al.* 2006), while the baseflow separation estimate would include flows resulting from the effects of bank storage, interflow components such as tile drainage and hillslope drainage, and discharge from wetlands, ponds, and lakes.

Although this specific application of the WCA focuses on the use of minimum recharge, it is hypothesized that the methodology can be applied to other hydrologic variable quantities, such as peak flow or mean annual flow. In the present analysis, we have proposed the use of the mean minimum flow to discriminate watersheds into distinct HHUs based on landscape characteristics. The question is then raised whether the HHUs derived from mean

Table 4 | Benchmark watershed validation comparison

USGS stream gauge	Benchmark gauge	Low-flow observation date	Actual mean minimum groundwater recharge (L s^{-1} km^{-2})	Estimated mean minimum groundwater recharge[a] (L s^{-1} km^{-2})	Modeled mean annual baseflow[b] (L s^{-1} km^{-2})	Drainage area[c] (km^2)
05286000	05275000	9/27/1967	1.75	1.71	2.99	4,017
05374000	05385000	5/22/1968	2.53	2.19	2.31	2,969

[a]Extrapolated using benchmark watershed for the time interval of 1955–1978.
[b]Modeled using WHAT: Web-based Hydrograph Analysis Tool (Lim *et al.* 2005)
[c]Watersheds were delineated from USGS stream gauge stations.

minimum flow will also produce distinctly different values for other hydrologic variables. This question will need to be tested by future research efforts.

Theoretically, there are no general limitations with the analytical methodology regarding the possible scale of compilation, except as demonstrated using ECM; the availability of data can put a limit on the achievable detail. The more refined the map desired, the more detailed data and watersheds required. With the ever increasing availability of hydrological geospatial data (e.g. Consortium of Universities for the Advancement of Hydrologic Science, Incorporated), it appears that future results may be feasible at refined scales.

Application to sustainability

When estimating the sustainable groundwater flux, conservative estimates are imperative to ensure that there are not detrimental impacts on the environment (Loáiciga 2006). This provides a preliminary standard for water resources management. In this application, mean minimum recharge rates were calculated, which could be used in future research to identify changes due to more recent non-stationary trends in water balance input components including precipitation, potential evapotranspiration, surface infiltration, and artificial recharge. This demonstrated application of the WCA illustrates how minimum groundwater recharge rates could be spatially depicted to map sustainable groundwater flux at a scale where long-term stream gauge monitoring is unavailable (Figure 5). The key indicator of sustainable water use is the ratio of the renewable capacity of the hydrologic system to the water use by humans and the environment (Kanivetsky & Shmagin 2005). Maintaining groundwater extraction within these estimated recharge rates will reduce the risk of depleting the storage (Peterson *et al.* 2013) and thereby detrimentally affecting flows in streams and levels in lakes and wetlands (Alley 2007).

It has become increasingly apparent that in order to link water balance characteristics with the landscape, there is a need to look into hydrologic similarity of land areas with commonality in landscape components (Reed *et al.* 2006). This new conceptual vision, rooted in scarcity, is dictated by shifting water resources management strategies from supply management to demand management; with the idea of decreasing water demand by increasing efficiency per parcel of land (Scanlon *et al.* 2007). Because of this shift in the water management paradigm: 'it is urgent that the '*L*' (land) be incorporated in strategic planning of water for livelihoods and sustainability, since evidence clearly shows that the freshwater legacy of the past is definitely inadequate to enable us to face the challenges ahead of us' (Falkenmark & Rockström 2006).

CONCLUSIONS

This demonstrated process of refining landscape characteristics into refined hierarchical levels reflects each HHUs set of similar hydrologic properties with respect to minimum recharge. The WCA uses this unit similarity to allow for scaling and translation of hydrologic response from one geospatial location to another. Through this characterization of the groundwater system, the three-dimensional structure of the watershed is recognized and boundaries for the specific units of regionalization are quantified; which is essential for the multi-scale mapping of regional recharge or any other hydrologic variable.

Using the WCA to map ECM, it was determined that unique combinations of hydrogeologic, topographic, and vadose zone characteristics control the minimum groundwater recharge. Sustainable groundwater recharge was highest in areas dominated by Paleozoic artesian aquifers composed of sandstone materials overlain with a thin layer of Quaternary sediments and lowest where Cretaceous deposits were dominant and overlain by soils with a high AWC.

The WCA enables quantitative water management decisions to occur in areas with limited data availability by defining the hydrologic controlling characteristics within the watersheds of a study area and then mapping those characteristics to spatially depict corresponding recharge rates. Comparing these mapped recharge rates to actual water use would provide an indicator of groundwater sustainability, which could be used in water resources management to reduce the risk of freshwater resource over-extraction. By generating geospatial data for water balance characteristics, the WCA is an important management tool for integrating land and water resources to address the growing challenge of increased demand and scarcity of water.

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REFERENCES

Alley, W. M. 2007 Another water budget myth: the significance of recoverable ground water in storage. *Groundwater* **45** (3), 251.

Alley, W. M. & Leake, S. 2004 The journey from safe yield to sustainability. *Groundwater* **42** (1), 12–16.

Barlow, P. M. *et al.* 2002 *Concepts for National Assessment of Water Availability and Use*. USGS Circular 1223, Reston, VA.

Batelaan, O. & De Smedt, R. 2007 GIS-based recharge estimation by coupling surface–subsurface water balances. *J. Hydrol.* **337** (3–4), 337–355.

Bredehoeft, J. 2007 It is the discharge. *Groundwater* **45** (5), 523.

Cherkauer, D. S. 2004 Quantifying ground water recharge at multiple scales using PRMS and GIS. *Groundwater* **42** (1), 97–110.

Delin, G. N., Healy, R. W., Lorenz, D. L. & Nimmo, J. R. 2007 Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA. *J. Hydrol.* **334** (1–2), 231–249.

De Smedt, F. & Batelaan, O. 2003 Investigation of the human impact on regional groundwater systems. In: *Ecosystems and Sustainable Development* (E. Tiezzi, C. A. Brebbia & J. L. Uso, eds). WIT Press, Southampton, UK, pp. 1145–1153.

De Vries, J. J. & Simmers, I. 2002 Groundwater recharge: an overview of processes and challenges. *Hydrogeol. J.* **10** (1), 5–17.

Diekrüger, B., Kirkby, M. J. & Schröder, U. (eds) 1999 Preface. In: *Regionalization in Hydrology*. IAHS Publication no. 254, IAHS Press, Wallingford, UK, p. v.

Dripps, W. R. & Bradbury, K. R. 2010 The spatial and temporal variability of groundwater recharge in a forested basin in northern Wisconsin. *Hydrol. Process.* **24** (4), 383–392.

Falkenmark, M. 2008 Water and sustainability: a reappraisal. *Environment* **50** (2), 4–17.

Falkenmark, M. & Rockström, J. 2006 The new blue and green water paradigm: breaking new ground for water resources planning and management. *J. Water Res. Pol. Manage.* **132** (2), 129–132.

Faust, A. E., Ferré, T. P. A., Schaap, M. G. & Hinnell, A. C. 2006 Can basin-scale recharge be estimated reasonably with water-balance models? *Vadose Zone J.* **5**, 850–855.

Freeze, R. A. & Cherry, J. A. 1979 *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ, USA.

Haigh, M. J. 1985 Geography and general system theory, geosophical homologies and current practice. *Geoforum* **16** (2), 191–203.

Halford, K. J. & Mayer, G. C. 2000 Problems associated with estimating ground water discharge and recharge from stream-discharge records. *Groundwater* **38**, 331–342.

Hyndman, D. W., Kendall, A. D. & Welty, N. R. H. 2007 Evaluating Temporal and Spatial Variations in Recharge and Streamflow Using the Integrated Landscape Hydrology Model (ILHM). Subsurface Hydrology: Data Integration for Properties and Processes. AGU Monograph Series 171, Washington, DC, pp. 121–142.

Kanivetsky, R. 1978 *Hydrogeologic Map of Minnesota, Bedrock Hydrogeology*. Minnesota Geological Survey State Map Series S-2, scale 1:500,000, St. Paul, Minnesota, USA.

Kanivetsky, R. 1979a *Hydrogeologic Map of Minnesota, Quaternary Hydrogeology*. Minnesota Geological State Map Series S-3, scale 1:500,000, St. Paul, Minnesota, USA.

Kanivetsky, R. 1979b *Regional Approach to Estimating Groundwater Resources of Minnesota*. Report of Investigations 22, University of Minnesota, St. Paul, Minnesota, USA.

Kanivetsky, R. & Shmagin, B. 2005 Quantifying freshwater sustainability through multiscale mapping. *Eos Trans. AGU.* **86** (50), 521–524.

Khain, V. E. 2010 Constructing a truly global model of Earth's dynamics: basic principles. *Russian Geol. Geophys.* **51**, 587–591.

Krcho, J. 1995 Landscape as a spatially organized system and the georelief as a subsystem of landscape – the influence of georelief on spatial differentiation of landscape processes. In: *Gabčíkovo Part of the Hydroelectric Power Project – Environmental Impact Review*. Comenius University, Bratislava, Slovakia, pp. 323–351.

Krcho, J. 2001 *Modeling of Georelief and its Geometrical Structure using DTM: Positional and Numerical Accuracy*. Q111 Publishers, Bratislava, Slovakia.

Kroll, C., Luz, J., Allen, B. & Vogel, R. M. 2004 Developing a watershed characteristics database to improve low streamflow prediction. *J. Hydrol. Eng.* **9**, 116–125.

Kudelin, B. I. & Fideli, I. F. 1970 Contribution to the problem of the hydrogeological zonation of the USSR. In: *5th Scientific Account of the Geological Faculty of Moscow State University*, Moscow, 16–19 March 1970, pp. 270–272.

Lee, C. H., Chen, W. P. & Lee, R. H. 2006 Estimation of groundwater recharge using water balance coupled with base-flow-record estimation and stable-base-flow analysis. *Environ. Geol.* **51**, 73–82.

Li, P., Chen, B. & Husain, T. 2011 IRFAM: integrated rule-based fuzzy adaptive resonance theory mapping system for watershed modeling. *J. Hydrol. Eng.* **16** (1), 21–32.

Lim, K. J., Engel, B. A., Tang, Z., Choi, J., Kim, K. S., Muthukrishnan, S. & Tripathy, D. 2005 Automated web GIS based hydrograph analysis tool, WHAT. *J. Am. Water Resour. Assoc.* **41** (6), 1407–1416.

Lindskov, K. L. 1977 *Low–flow Characteristics of Minnesota Streams*. USGS Open–File Report 77–48.

Loáiciga, H. A. 2006 Comment on "The persistence of the water budget myth and its relationship to sustainability" by J. F. Devlin and M. Sophocleous, Hydrogeology Journal 13:549–554. *Hydrogeol. J.* **14**, 1383–1385.

Lorenz, D. W. & Delin, G. N. 2007 Regional estimation of groundwater recharge in Minnesota using a multiple regression model. *Groundwater* **45** (2), 196–208.

Maidment, D. (ed.) 2002 *Arc Hydro GIS for Water Resources*. ESRI Press, Redlands, California, USA.

Makropoulos, C. K. & Butler, D. 2004 Spatial decisions under uncertainty: fuzzy inference in urban water management. *J. Hydroinform*. **6**, 3–18.

McDonnell, J., Sivapalan, M., Vache, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M. L., Selker, J. & Weiler, M. 2007 Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology. *Water Resour. Res.* **43**, W07301.

National Research Council (NRC) 2004 *Groundwater Fluxes across Interfaces*. The National Academy Press, Washington, DC, USA.

National Science and Technology Council (NSTC) 2007 A Strategy for Federal Science and Technology to Support Water Availability and Quality in the United States. Report of the Subcommittee on Water Availability and Quality of the Committee on Environment and Natural Resources, Washington, DC, USA.

Peterson, H. M., Nieber, J. L. & Kanivetsky, R. 2011 Hydrologic regionalization to assess anthropogenic changes. *J. Hydrol.* **408** (3–4), 212–225.

Peterson, H. M., Nieber, J. L., Kanivetsky, R. & Shmagin, B. 2013 Water resources sustainability indicator: application of the watershed characteristics approach. *Water Resour. Manage.* **27** (5), 1221–1234.

Pinneker, E. V. 1983 *General Hydrogeology*. Translated by D.E. Howard & J.C. Harvey, Cambridge University Press, Cambridge, MA, USA.

Poliakov, A. S., Sokolov, V. N. & Shmagin, B. A. 1988 *Probabilistic Models for B. I. Vernadsky's Geospheres (in Russian)*. Moscow University Geology Bulletin, Vestnik Moskovskogo Universiteta. Seriya 4 pp. 30–41.

Reed, P. M., Brooks, R. P., Davis, K. J., DeWalle, D. R., Dressler, K. A., Duffy, C. J., Lin, H., Miller, D. A., Najjar, R. G., Salvage, K. M., Wagener, T. & Yarnal, B. 2006 Bridging river basin scales and processes to assess human climate impacts and the terrestrial hydrologic system. *Water Resour. Res.* **42** (7), W07418.

Reggiani, P. & Rientjes, T. H. M. 2005 Flux parameterization in the Representative Elementary Watershed (REW) Approach: application to a natural basin. *Water Resour. Res.* **41** (4), W04013.

Ruhl, J. F., Kanivetsky, R. & Shmagin, B. 2002 Estimates of recharge to unconfined aquifers and leakage to confining aquifers in the seven-county metropolitan area of Minneapolis-St. Paul, Minnesota, United States. Water Resources Investigations Report 02-4092, USGS, Reston, Virginia, USA.

Santra, P., Das, B. S. & Chakravarty, D. 2011 Delineation of hydrologically similar units in a watershed based on fuzzy classification of soil hydraulic properties. *Hydrol. Process.* **25**, 64–79.

Scanlon, B. R., Healy, R. W. & Cook, P. G. 2002 Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeol. J.* **10** (1), 18–39.

Scanlon, B. R., Jolly, I., Sophocleous, M. & Zhang, L. 2007 Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resour. Res.* **43**, W03437.

Shmagin, B. A. & Kanivetsky, R. 2002 System analysis to estimate subsurface flow: from global level to the State of Minnesota. *Environ. Geol.* **42** (2–3), 259–269.

Shmagin, B. & Kanivetsky, R. 2006 Regional hydrology: tools vs. ideas. In: *Coastal Hydrology and Processes: Proceedings of the AIH 25th Anniversary Meeting & International Conference on "Challenges in Coastal Hydrology and Water Quality"* (V. P. Singh & Y. J. Xu, eds). Water Resources Publications, LLC., Highlands Ranch, Colorado, USA, pp. 183–196.

Sivapalan, M. 2005 Pattern, processes and function: elements of a unified theory of hydrology at the catchment scale. In: *Encyclopedia of Hydrological Sciences* (M. Anderson, ed.). John Wiley, London, pp. 193–219.

Sophocleous, M. 2004 Groundwater Recharge. In: *Encyclopedia of Life Support Systems (EOLSS) – Groundwater* (L. Silveira, S. Wohnlich & E. J. Usunoff, eds). UNESCO, Eolss Publishers, Oxford, UK.

StatSoft, Inc. 2012 *Electronic Statistics Textbook*. StatSoft, Tulsa, OK: Available at: http://www.statsoft.com/textbook/.

Strassberg, G., Maidment, D. R. & Jones, N. L. 2007 A geographic data model for representing ground water systems. *Groundwater* **45** (4), 515–518.

Tóth, J. 1963 A theoretical analysis of groundwater flow in small drainage basins. *J. Geophys. Res.* **68** (16), 4795–4812.

Wagener, T., Reed, P., van Werkhoven, K., Tang, Y. & Zhang, Z. 2009 Advances in the identification and evaluation of complex environmental systems models. *J. Hydroinform*. **11**, 266–281.

Wolock, D. M., Winter, T. C. & McMahon, G. 2004 Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *J. Environ. Manage.* **34**(Supplement 1), s71–s88.

Zektser, I. S. 2002 Principles of regional assessment and mapping of natural groundwater resources. *Environ. Geol.* **42**, 270–274.

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