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Quantifying Freshwater Sustainability Through Multiscale Mapping

PAGES 521, 524

The issue of freshwater availability and sustainability is gaining importance within U.S. federal and state governments. For example, a recent report by the U.S. National Science and Technology Council (NSTC) urges the federal government to take new steps to understand freshwater sustainability in the United States [*NSTC*, 2004]. Although the report refers to 'availability'—a concept that in the past has applied only to human needs and that implies that a resource may decline or be liquidated—the focus of the report is on 'sustainability' as commonly defined in the literature today. Sustainability requires that consumption will not cause a decline or liquidation of freshwater resources.

Today, the water needs of both the natural environment and human activity must be balanced. To attain this balance, freshwater sustainability must be quantified and then compared with the needs of humans and nature.

To quantify freshwater sustainability, this article proposes a new programmatic initiative of multiscale water resources mapping based on the framework of Earth systems that includes the biological, geological, and atmospheric systems.

A New Paradigm

A new paradigm is needed to quantify freshwater sustainability and fill this gap in knowledge, as requested in the 2004 NSTC report. Precipitation should be viewed as the gross amount of freshwater ultimately available for sustaining not only humans but also ecosystems.

To achieve this goal, the components of the water budget must be quantified at multiple temporal and spatial scales [*Liu and Taylor,* 2002]. The key components of that exercise are the recharge and discharge rates that are calculated using stream runoff data. The recharge rate quantifies the sustainable use of groundwater by humans, whereas the discharge rate quantifies the sustainable use of surface water by humans and at the same time provides the threshold value for meeting environmental needs.

In the process of quantifying and mapping these key components at multiple spatial and temporal scales, surface water must be linked to runoff formation characteristics, such as annual stream runoff rate, rather than to locations in a river where streamflow can be measured. In addition, groundwater must be linked to recharge or renewal rate rather than to storage.

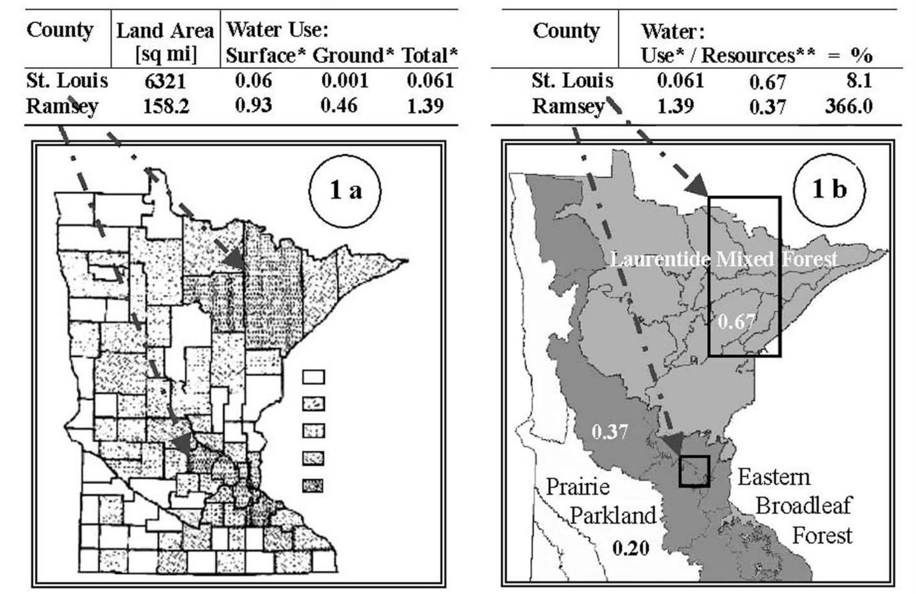
Ultimately, both the river's runoff formation characteristics and the recharge to the groundwater system are linked to ecosystems that sustain life in nature. Consequently, quantification of the discharge and recharge components is needed for ecological, hydrological, political, economic, or any other biological system at multiple spatial and temporal scales. This can be achieved by understanding the hydrologic cycle within the framework of Earth systems. In this regard, the focus for quantifying the recharge and discharge components should be on coupled biologic, geologic, and atmospheric systems, and the symmetry of their structural organization in ecohydrologic properties.

This new 'system paradigm' parameterizes and quantifies the relationships between the components of the 'hydrologic landscape': geology, the stream network system, relief, soils, vegetation, and climate. Given their geographical significance, the presentation of these relationships in a map format is essential.

A New Path to Quantifying Freshwater Systems

The system paradigm is important for structuring a scientific response to the challenge of freshwater sustainability and the requisite quantification of freshwater systems. The new paradigm also recognizes a different view of water circulation within the hydrologic cycle that includes the multiscale pattern recognition of river runoff from global to local, as well as hierarchical regionalization of a geologic reservoir [*Shmagin and Kanivetsky,* 2002]. Although measuring fresh-water sustainability could be challenging, its key indicator is the ratio of renewable water supply to water use by humans and the environment.

To illustrate the point, Figure 1 shows the water use by humans versus renewable water



County	Land Area [sq mi]	Water Use: Surface*	Ground*	Total*
St. Louis	6321	0.06	0.001	0.061
Ramsey	158.2	0.93	0.46	1.39

County	Water: Use*	/ Resources**	= %
St. Louis	0.061	0.67	8.1
Ramsey	1.39	0.37	366.0

Fig. 1. Renewable water resources and water use in Minnesota. (a) Water use by humans; (b) water resources versus water use by humans. [**Water use in cfs/sq. mi., **water resources in cfs/sq. mi.*]

BY R. KANIVETSKY AND B. SHMAGIN

resources for counties in Minnesota. Figure 1a shows the surface water, groundwater, and total water use, and Figure 1b shows sustainable water resources for ecoregions in Minnesota.

This figure illustrates how human water use may be sustainable in some counties (e.g., St. Louis County) but not others (e.g., Ramsey County). In St. Louis County, for example, water use by humans would be considered sustainable because it constitutes only a small fraction of the renewably-available supplies over the long term.

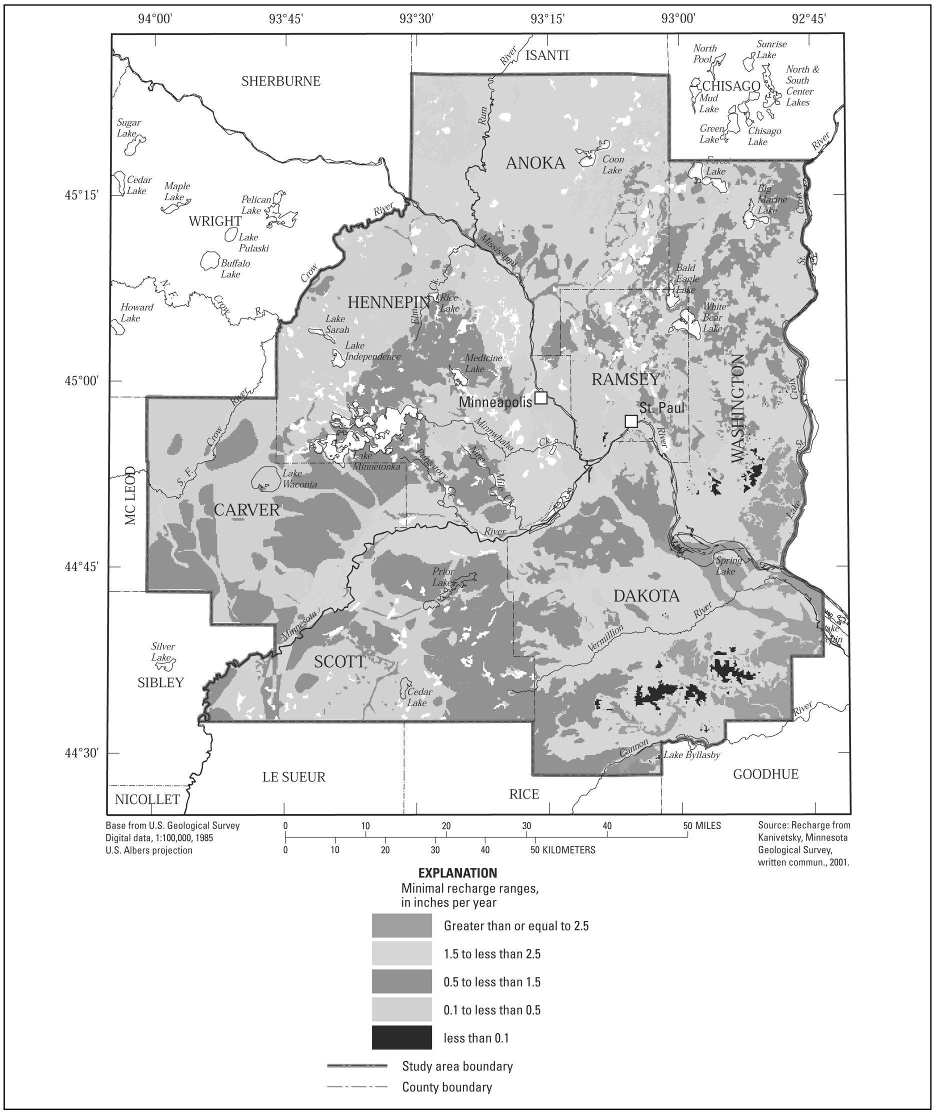
The quantification of environmental needs should be done by ecologists working together with hydrologists, and these needs also should be comparable to renewability. Thus, the renewability indicator, which can be quantified by multiscale recharge and discharge mapping, provides a measure for balancing water available for humans and nature. This path is the most commonsense way to measure the freshwater sustainability.

To quantify freshwater sustainability as illustrated in Figure 1, this article proposes the development of a new course of action: water resources mapping that focuses on renewability and sustainability. The path can be followed by establishing the relationships that bind hydrologic and hydrogeologic attributes to their climatic, biological, ecological, and geographical systems in a three-dimensional manner.

On the basis of such analysis, the structure of streamflow and its variability can be determined, and the areal pattern of the hydrospheric system, including the grouping pattern of stream runoff, can be recognized. The fundamental advantage of such analysis is that the hydrospheric system pattern can be recognized at many levels: planetary, global, national, regional, and basin [*Shmagin and Kanivetsky,* 2002]. Therefore, the runoff characteristics of the hydrosphere system can be determined for any territory, as well as for the entire Earth surface for two types of intercrossed systems overlayed on each other: systems of geospheres (i.e., hydrologic landscapes or ecoregions, representing the biological system) and systems of stream basins (i.e., watersheds, representing the hydrologic system). This approach allows for the quantification of the spatio-temporal structure of stream runoff.

The spatio-temporal structure that emerges from this approach can be used for regionalized quantification of recharge/discharge via stream runoff characteristics that are derived from their association with hydrologic landscape characteristics at multiple scales [*Shmagin and Kanivetsky,* 2002]. Thus, the discharge constant defines sustainable ecosystem water needs while the recharge constant defines sustainable groundwater supply needs. Some thresholds on both of these needs should be established. Furthermore, the recharge and discharge components are codependent and are quantified together, so that no contradiction of supply needs versus ecosystems needs can result.

The map for the Twin Cities metropolitan area in Minnesota (Figure 2) illustrates that new path where the quantification of groundwater systems is shown as an example. This figure shows the recharge/discharge distribution at a scale that is chiefly controlled by the geologic component of the hydrologic landscape.



Base from U.S. Geological Survey Digital data, 1:100,000, 1985
U.S. Albers projection

Source: Recharge from Kanivetsky, Minnesota Geological Survey, written commun., 2001.

Fig. 2. Minimal annual recharge/discharge rates for the Twin Cities metropolitan area.

Opportunities

The new path—towards multiscale freshwater resources mapping—provides a road map that may close the gap in scientific knowledge and dramatically improve quantification of the nation's water resources and their vulnerability to overuse. This road map could address human and environmental needs by defining and quantifying the regions and units of the hydrologic landscape, their runoff formation characteristics, and rates of recharge and discharge, and then comparing that information with the water needs of humans and nature at multiple scales.

Until that road map is followed, no progress can be made to address the challenge of freshwater sustainability. The nation's water resources are at risk, and it is time that federal and state governments, in partnership with the nation's universities, launch a sustained long-term programmatic initiative to quantify and map water sustainability information at national, regional, and local levels. The program could put the nation in the position finally to answer the fundamental question: Does the United States have enough water?

Previous national water availability assessments have focused solely on human activity and are thus inadequate. Today the necessity of also considering the water requirements of the natural environment is recognized. The new programmatic initiative would address both requirements as the road map is followed.

With current development in space-based measurement of hydrologic networks, it will be possible to monitor water resources remotely at the larger scales. Such information will not only greatly assist scientists and policymakers in developing a framework for the sustainable management of freshwater resources, but also will provide the foundation for national and state legislative agendas to adopt the institutional frameworks needed to solve tomorrow's water resources problems.

Furthermore, this program would address other critical scientific needs, such as studies of the water budgets of natural and human-affected systems, the coupling of hydrological and meteorological models, the fluxes of freshwater and pollutants into oceans and other hydrologic systems. This program would also help to address many other needs such as the maintenance of ecological services, the effects of climate change and urbanization on water resources, and the value of water that is not yet incorporated into sustainable development and management of natural resources.

Now is the time to make a genuine commitment to research on the sustainability of freshwater resources and to tackle the challenge of looming water crises across the United States and the world. To undertake the challenge, a water resources research portfolio must be initiated by federal and state governments and must include the long-term multiscale mapping of sustainable freshwater resources.

The first step would be to make a map for the entire United States that illustrates the national picture of freshwater sustainability and that could be compared to water use by humans and environmental water needs. Then, on the basis of that national map, maps would be created at the regional, state, and local levels in regions or states where freshwater resources are in jeopardy.

The long-term mapping program responds to the sustainability challenge by parameterizing Earth systems. Eventually, the scientific output of the mapping program should be integrated into the decisions people make every day in managing land and water resources, economies, and communities, because the concept of sustainability requires nothing less.

Acknowledgments

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Crater Glaciers on Active Volcanoes: Hydrological Anomalies

PAGES 521, 528

Mount St. Helens is an active volcano that hosts glacier ice within its crater. Although the common picture of volcano/glacier interactions is one of rapid meltwater generation when hot material is brought into contact with snow and ice [e.g., *Major and Newhall*, 1989], there have been practically no observable hydrological consequences of the ongoing episode of silicic lava dome emplacement at Mount St. Helens.

The glaciological consequences have nonetheless been dramatic: The crater glacier has been cut in half since the dome growth began in September 2004, and the resulting ice bodies have in succession been squeezed between the growing lava dome and the crater wall.

Although the data presented here are the first ever collected on silicic lava dome emplacement through glacier ice, the same process has surely occurred elsewhere. For example, *Gilbert et al.* [1996] inferred from geological and geophysical evidence that silicic lava domes have been emplaced beneath the caldera glacier of Sollipulli volcano, Chile. And *Tuffen et al.* [2001] described a dome-like rhyolite body that was evidently emplaced subglacially in Iceland and since exhumed.

Glaciers on active volcanoes are atypical in various ways. For crater glaciers, geothermal heat flow may be great enough that mass balance reflects primarily the trade-off between accumulation at the surface and melting at the bed [e.g., *Murav'yev and Salamatin*, 1990]. In such a circumstance, ice discharge from the crater is low, and ice cores may be valuable paleoclimatic indicators [*Shiraiwa et al.*, 1997].

Glaciers both in craters and on the flanks of a volcano may also be hydrologically unusual to the extent that basal meltwater is captured by fractured or permeable bedrock and clastic deposits rather than entering a channelized drainage system at the ice/rock interface. This article presents evidence for precisely such a hydrological anomaly at Mount St. Helens.

Photographic Record of Eruptive Effects on the Crater Glacier

The unnamed Mount St. Helens crater glacier grew from only a few discontinuous patches of perennial snow and ice in 1986 (at the end of the episode of lava dome growth that had begun in 1981) to a surface area of approximately one square kilometer and a thickness as much as ~150 meters by the time that the latest episode of lava dome growth began in September 2004. The rapid ice accumulation after 1986 occurred because the glacier sits in a north-facing, amphitheater-like basin (Figure 1a) and is fed by avalanches from the crater walls [*Schilling et al.*, 2004].

The first indication of lava dome growth that could be seen on the surface was the appearance in 2004 of a bulge in the crater glacier adjacent to the 1981–1986 lava dome. Within a few weeks, a new lava dome had pierced through the entire thickness of the glacier. The dome was extruded in a solid state, not as magma that solidified subaerially, and there was no evidence of rapid melting of the glacier.

As the eruption proceeded, the lava dome grew toward the south, surrounded by a 'bow

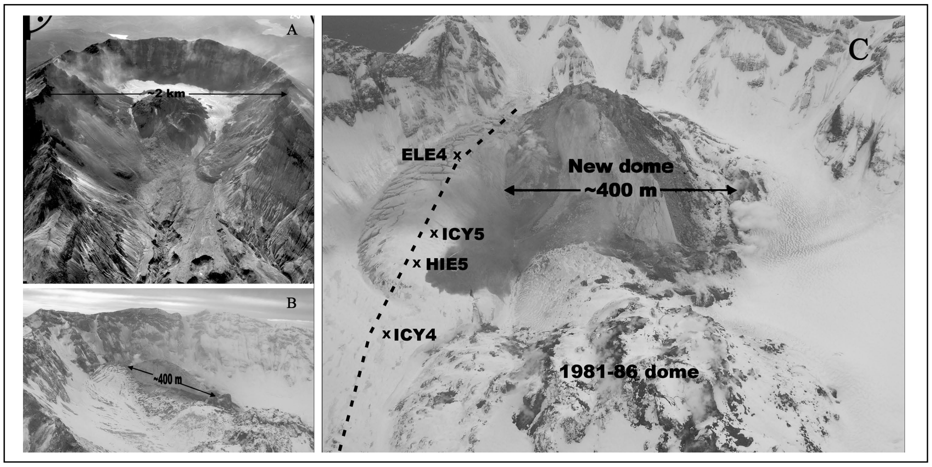

Fig. 1. (a) Mount St. Helens on 5 October 2000. View is to the south. The crater glacier is evident on the south side of the 1981–1986 lava dome and also wraps partly around the dome to both the east and west, but is obscured by rock-avalanche deposits. (b) New lava dome and compressed glacier ice as seen on 29 November 2004. View is toward the southwest. Photograph by D. Dzurisin, U.S. Geological Survey (USGS). (c) The east glacier and new lava dome as of 10 April 2005. View is toward the southeast. The dashed curve is approximately the line of section for the glacier bed and surface as shown in Figure 2b. Approximate locations of GPS stations are indicated by 'x'. Photograph by J. Major, USGS.

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