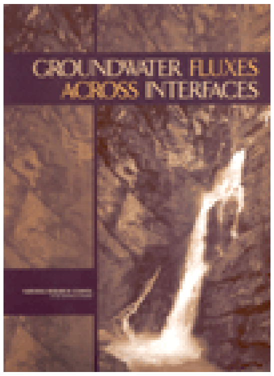
http://www.nap.edu/catalog/10891.html

We ship printed books within 1 business day; personal PDFs are available immediately.



Groundwater Fluxes Across Interfaces

Committee on Hydrologic Science, National Research Council

ISBN: 0-309-52847-X, 100 pages, 8 1/2 x 11, (2004)

This PDF is available from the National Academies Press at:
http://www.nap.edu/catalog/10891.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online for free
- Explore our innovative research tools – try the "Research Dashboard" now!
- Sign up to be notified when new books are published
- Purchase printed books and selected PDF files

Thank you for downloading this PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to feedback@nap.edu.

This book plus thousands more are available at http://www.nap.edu.

Copyright © National Academy of Sciences. All rights reserved.
Unless otherwise indicated, all materials in this PDF File are copyrighted by the National Academy of Sciences. Distribution, posting, or copying is strictly prohibited without written permission of the National Academies Press. Request reprint permission for this book.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

GROUNDWATER FLUXES ACROSS INTERFACES

Committee on Hydrologic Science

Water Science and Technology Board

Board on Atmospheric Sciences and Climate

Division on Earth Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, D.C. 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by the Army Research Office, National Aeronautics and Space Administration under Grant No. NAG5-8651, National Oceanic and Atmospheric Administration, National Science Foundation under Grant No. EAR-9986796, National Weather Service, U.S. Environmental Protection Agency under Grant No. X-2895301, and U.S. Geological Survey. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U. S. Government.

International Standard Book Number 0-309-09113-6 (Book)
International Standard Book Number 0-309-51962-4 (PDF)

Groundwater Fluxes Across Interfaces is available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu

Cover photograph: Savica springs and waterfalls, Triglav National Park, Slovenia, provided by Boštjan Burger (2003). http://www.burger.si/SlikaDneva/teme/wallpaper_slapovi.html.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON HYDROLOGIC SCIENCE[1]

ERIC F. WOOD, *Chair*, Princeton University, Princeton, New Jersey
MARY P. ANDERSON, University of Wisconsin, Madison
VICTOR R. BAKER, University of Arizona, Tucson
DARA ENTEKHABI, Massachusetts Institute of Technology, Cambridge
(through December 31, 2002)
NANCY B. GRIMM, Arizona State University, Tempe
GEORGE M. HORNBERGER, University of Virginia, Charlottesville
DENNIS P. LETTENMAIER, University of Washington, Seattle
WILLIAM K. NUTTLE, Consultant, Ottawa, Ontario, Canada
(through December 31, 2002)
KENNETH W. POTTER, University of Wisconsin, Madison
(through December 31, 2002)
JOHN O. ROADS, Scripps Institution of Oceanography, La Jolla, California
(through December 31, 2002)
JOHN L. WILSON, New Mexico Tech, Socorro, New Mexico

NRC Staff

WILLIAM S. LOGAN, Project Director, Water Science and Technology Board
ANITA A. HALL, Senior Project Assistant, Water Science and Technology Board

---

[1] The activities of the Committee on Hydrologic Science are overseen and supported by the NRC's Water Science and Technology Board and Board on Atmospheric Sciences and Climate (see Appendix D).

Preface

This report is a product of the Committee on Hydrologic Science (COHS), which was established in the NRC in late 1998. The committee exists for two separate but related purposes. These are:

(1) to advance hydrologic science through the identification of research and educational opportunities in hydrologic sciences, including data aspects, and

(2) to provide advice to U.S. government agencies and interagency efforts on program strategy with respect to hydrologic content and research priorities, and to advise on U.S. involvement in international programs such as the World Climate Research Program (WCRP) and the International Geosphere-Biosphere Program (IGBP).

In its relatively short history, the COHS has published three reports. The first was *Hydrologic Science Priorities for the U.S. Global Change Research Program: An Initial Assessment* (NRC, 1999). The second report, *Report of a Workshop on Predictability and Limits-to-Prediction in Hydrologic Systems* (NRC, 2002a), was based on a workshop on this topic held in September 2000 in Boulder, CO. The third report, *Review of USGCRP Plan for a New Science Initiative on the Global Water Cycle* (NRC, 2002b), was a fast-track review of a report commissioned by the USGCRP.

This report, like the *Predictability* report, was based on a workshop. This workshop, titled "Groundwater Fluxes Across Interfaces," was organized and convened by COHS members Mary P. Anderson and John L. Wilson, and was held in Egg Harbor, WI on May 12-14, 2002. The participants were asked to provide written material prior to meeting and to present brief prepared oral statements during the workshop. They were asked to examine and assess currently used and proposed new methods to estimate recharge and discharge rates to identify methods that hold the most promise for addressing three general issues related to groundwater fluxes. These were: diffuse vs. focused fluxes, climate feedback functions, and spatial and temporal scales. The participants were divided into three subgroups and as a starting point for discussion, were asked to consider the following issues and associated questions. Participants, however, were encouraged to redefine issues and develop new questions as the workshop progressed.

Subgroup on Diffuse and Focused Recharge/Discharge

- What is the relative importance of diffuse versus focused recharge/discharge in any specific hydrogeologic setting?

- Is fresh groundwater discharge a significant source of fresh water recycling to estuaries and the oceans?
- What is the role of landscape vegetation cover (including phreatophytes) on spatial and temporal groundwater recharge/discharge patterns?
- What are the landscape indicators and bio-indicators of groundwater recharge/-discharge?
- What are the effects of human activities on spatial and temporal groundwater recharge/discharge patterns?

Subgroup on Climate Feedback Functions

- Are fluxes to and from groundwater reservoirs important components of continental and global water balances?
- Do groundwater recharge and discharge processes provide feedback mechanisms that affect climate?
- How do spatial patterns of groundwater recharge/discharge change seasonally/-annually?
- What are the important time scales for groundwater reservoirs affecting continental and global water balances, and how are they controlled by fluxes and storage?
- What is the magnitude of the effect of fluctuations of sea level and levels of large lakes (e.g., the Great Lakes) on groundwater recharge/discharge?

Subgroup on Spatial and Temporal Scales

- How do estimates of groundwater recharge/discharge aggregate when averaged over different scales and what implications does this have for measurement scale?
- At the scale of a representative elementary volume, does groundwater recharge/discharge occur along preferential pathways? If so, when is it important to measure fluxes at this scale?
- How accurately can recharge/discharge patterns/rates be mapped over the contiguous U.S., and how does uncertainty in these patterns/rates vary with spatial and temporal scale and geographic location?

In addressing the three broad sets of issues outlined above, the group was also asked to consider the following questions:

1. What are the most promising techniques for measuring/estimating groundwater recharge? What are the most promising techniques for measuring/estimating groundwater discharge? What are the potential errors associated with applying these techniques at various spatial scales (i.e., is it possible to extrapolate point measurements of groundwater flux in order to obtain accurate estimates over broad geographical areas?)
2. What sorts of monitoring networks, instrumentation, and analyses are required to produce maps of seasonal recharge and discharge?
3. What scales of measurement and measurement techniques are most appropriate for assessing biogeochemical processes occurring within the groundwater-surface water interface and the effects of groundwater discharge on ecosystems?

The agenda for the workshop is in Appendix A. The hydrogeology of the Door Peninsula region of Wisconsin, based on a workshop presentation by Kenneth R. Bradbury of the Wisconsin Geological and Natural History Survey, is summarized in Appendix B.

Following the formal presentations, participants engaged in group discussions and group writing sessions. The written material provided by the participants formed the nexus of the first draft of this report. Some participants also contributed written materials at a later time.

We trust that this report will be useful to scientists and managers who work in groundwater, surface water, and land surface hydrology, as well as others interested in the cycling of water and its dissolved constituents.

Eric F. Wood, Chair
Committee on Hydrologic Science

Mary P. Anderson and John L. Wilson, co-chairs
Workshop on Groundwater Fluxes Across Interfaces

Acknowledgments

This report could not have been written without many days of writing and discussion on the part of the workshop participants. Those noted below contributed written materials prior to the workshop, helped in the synthesis of these materials, participated in the workshop discussions, and contributed written material to the report itself either at or following the workshop. We are grateful to all of these participants for their ideas, their time, their energy and their fortitude. We hope that they also derived benefit from what turned out to be a highly productive and stimulating experience.

Jean M. Bahr, University of Wisconsin, Madison
Kenneth R. Bradbury, Wisconsin Geological & Natural History Survey, Madison
Michael D. Dettinger, U. S. Geological Survey, San Diego
Christopher J. Duffy, Pennsylvania State University
Hendrik M. Haitjema, Indiana University
Stacy E. Howington, U.S. Army ERDC
Randall J. Hunt, U. S. Geological Survey, Middleton, WI
P. C. D. (Chris) Milly, U. S. Geological Survey, Princeton, NJ
Shlomo P. Neuman, University of Arizona, Tucson
Matthew Rodell, NASA Goddard, Greenbelt, MD
Guido D. Salvucci, Boston University
Bridget R. Scanlon, Texas Bureau of Economic Geology, Austin
John S. Selker, Oregon State University, Corvallis
Donald I. Siegel, Univ. of Syracuse, NY
Leslie Smith, Univ. of British Columbia, Vancouver, Canada
William W. Woessner, University of Montana, Missoula

Alan Flint, U. S. Geological Survey, Sacramento, kindly contributed material for Box 4-2. Additional insights into this topic were provided by the participants in Mary Anderson's graduate seminar at the University of Wisconsin-Madison held during the fall semester, 2002.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for

objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report:

Peter G. Cook, CSIRO Land and Water, Australia
Paul A. Ferre, University of Arizona
Efi Foufoula-Georgiou, University of Minnesota, Minneapolis
Glendon Gee, Pacific Northwest National Laboratory, Richland, Washington
F. Edwin Harvey, University of Nebraska-Lincoln
Mark Person, Indiana University
Mary W. Stoertz, Ohio University, Athens

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Lynn W. Gelhar, Massachusetts Institute of Technology. Appointed by the National Research Council, Dr. Gelhar was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

Atmospheric, surface and subsurface portions of the hydrologic system are three dynamically linked water reservoirs having distinctly different time and space scales. Many challenges remain in understanding and measuring the dynamic interchange among these reservoirs, especially for interchanges with the subsurface. Most subsurface storage of water is in the groundwater reservoir, with a small amount of water stored as soil moisture in the overlying unsaturated zone.

Fluxes to and from the groundwater zone are called, respectively, recharge and discharge. Natural groundwater recharge has several origins. The most important of these are the flux of water across the water table from precipitation that percolates through the unsaturated zone, and the influx of water from a bounding or overlying surface water body including rivers, lakes, wetlands and the ocean. Natural groundwater discharge is the efflux of water from the groundwater reservoir to surface water, or to the land surface itself where, for example, it may return to the atmosphere through evaporation and transpiration.

PROBLEM DEFINITION AND MOTIVATION

Much attention has been given to both the theory and measurement of groundwater fluxes to and from surface water bodies, yet there are still many difficulties in obtaining accurate estimates of the spatial and temporal distribution of these fluxes, including fluxes to and from rivers and streams, reservoirs and lakes, wetlands, and the ocean. Similarly, there are no standard procedures for measuring recharge to the groundwater system from precipitation.

The problems in measurement arise in part because of the diffuse nature and spatially large extent of most groundwater discharge and recharge areas. Challenges in addressing issues related to groundwater fluxes also arise because researchers are based in many different disciplines including soil science, hydrology, oceanography, geochemistry, geophysics, and wetland ecology.

Estimates of recharge/discharge fluxes are needed at many different scales and for many different purposes, including evaluating local risks of landslides, basin-scale sustainable use and management of groundwater resources, management of nuclear waste, and global budgets of water and greenhouse gasses for climate studies. Various scientific committees and federal agencies have identified groundwater fluxes at interfaces as a priority area for research. To respond to this need, the Committee on Hydrologic Science (COHS) convened a workshop on groundwater fluxes across interfaces in Egg Harbor, Wisconsin, in May 2002. Among other tasks, the participants were asked to assess the state of knowledge and science needs concerning three general issues related to groundwater fluxes: diffuse vs. focused recharge/discharge fluxes, climate feedback functions, and spatial and temporal scales. The outcome of the workshop formed the framework for this report.

STATEMENT OF TASK

The purpose of this report is to call attention to the importance of groundwater fluxes, to explore the potential of new technologies to measure or estimate these fluxes, and to identify research gaps and the potential for interdisciplinary collaboration. The report is not meant to be a comprehensive analysis of all issues related to groundwater fluxes but instead focuses on the following questions, drawn from a broader set of issues (see preface) that workshop participants were asked to consider:

1. Diffuse vs. focused recharge and discharge

- What is the relative importance of diffuse versus focused recharge/discharge in various hydrogeologic settings?
- Is fresh groundwater discharge a significant source of fresh water recycling to estuaries and the oceans?

2. Interactions of groundwater with climate

- Do groundwater recharge and discharge processes provide feedback mechanisms that affect climate?
- What are the important time scales for groundwater reservoirs affecting continental and global water balances, and how are they controlled by fluxes and storage?
- What is the magnitude of the effect of fluctuations of sea level and levels of large lakes (e.g., the Great Lakes) on groundwater recharge/discharge?

3. Spatial and temporal scales of recharge and discharge

- How do estimates of groundwater recharge/discharge aggregate when averaged over different scales and what implications does this have for measurement scale?
- How accurately can recharge/discharge patterns/rates be estimated at a regional or national scale, and how might uncertainty in these patterns/rates vary with spatial and temporal scale and geographic location?

FINDINGS AND RECOMMENDATIONS

Finding 1

Our ability to quantify spatial and temporal variability in recharge and discharge is inadequate and must be improved given the importance of groundwater in the hydrologic cycle, the contribution of groundwater to base flow in streams and inflow to lakes, and society's reliance upon groundwater for water supply. Moreover, the spatial distribution of recharge fluxes influences the vulnerability of aquifers to contamination and the discharge of groundwater into wetlands influences associated ecological and biogeochemical processes.

A key science question is how landscape heterogeneity controls spatial and temporal variability of recharge and discharge. Addressing this question will require consideration of the geology, biology and climate including variability in soils, topography and vegetation. There are no uniformly applicable methods for measuring and quantifying recharge/discharge fluxes in space and time, so our understanding of distribution and process is limited.

Recommendation 1-1

Experimental benchmark sites should be established with the goal of improving both measurement techniques and the understanding of the processes of groundwater recharge and discharge. These sites should include a wide range of geologic, climatic and landscape types and should be integrated with existing NSF, USDA/ARS and similar experimental watersheds. The proposed experimental benchmark sites program should also work cooperatively with field programs connected with large-scale hydroclimatic studies—for example, the WCRP Global Energy and Water Experiment (GEWEX) and with studies conducted under the NSF-supported CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science, Inc.) initiative.

Recommendation 1-2

A study/workshop should be initiated with the goal of developing scientific and implementation plans for such experimental benchmark sites, perhaps as part of CUAHSI. Such an activity would determine which sites would be most valuable to improving the science of groundwater discharge and research, the relevant science questions specific to particular sites, the range of measurement and modeling that would be undertaken and an evaluation of the historical data available for designing experiments.

Finding 2

The roles of groundwater storage, and recharge and discharge fluxes in the climate system are under-appreciated and poorly understood. Because groundwater is the largest reservoir of fresh water in the hydrologic cycle, characterization of the linkage between groundwater and climate is crucial.

Groundwater plays an important role in the carbon cycle and related subsurface biogeochemical processes, and therefore the variability and fluctuation in groundwater levels can influence climate. For example, the net accumulation (or depletion) of peat (and the sequestration or release of its stored carbon) depends on the depth to the water table, and whether peat is under aerobic or anaerobic conditions. Climate change may cause changes in the temporal and spatial distributions of groundwater recharge and discharge and, therefore, availability of the groundwater resource. Better understanding of the linkage between groundwater resources and paleoclimatic conditions would be helpful in understanding past climate and its variability and would supplement information provided by study of tree rings and ice cores.

Recommendation 2-1

Research should address the relationship between long-term fluctuations in groundwater levels in aquifers at a regional scale and climatic variability. Such efforts would include the preservation and study of historical data on groundwater levels, and related hydrologic data such as streamflow records and lake levels, in areas unaffected by direct human influence. These efforts should include a broad range of techniques including paleoclimatic research such as reconstruction of paleolake levels and isotope geochemistry of old groundwater to provide insights into climatic variables such as paleo-temperature.

Recommendation 2-2

Research is needed to allow for better representation of groundwater processes in climate models, including more realistic storage parameters, landscape partitioning into recharge and discharge areas, groundwater uptake by vegetation, and fluxes to wetlands, lakes and streams. Data from the benchmark sites discussed under Recommendation 1-1 above could be utilized to test the improved parameterizations.

Recommendation 2-3

A better understanding of the effects of human use of groundwater for water supply on climate is needed. This would require comprehensive tabulation of regional, continental and global groundwater withdrawals and the extent of the area of wetlands drained during the past century accompanied by evaluation of the effects of the withdrawals and drainage on climate

Finding 3

Groundwater measurements are needed across a range of temporal and spatial scales; measurements at one scale are often needed to address questions at another scale. For example, remote sensing techniques provide extensive, spatially complete data sets that hold promise for addressing many of the unresolved questions identified in this report. However, these data often provide information at large regional scales, like the information soon to be available from the NASA-supported micro-gravity mission GRACE (Gravity Recovery and Climate Experiment), and must be integrated with information generated at smaller scales. This will require an understanding on how groundwater processes scale spatially and temporally. But it is unclear how the variability measured at small scales will change as we move up in scale, and whether there are thresholds of continuity or uniformity that correlate with practical scales of measurements.

Recommendation 3-1

A broad and coherent strategy for the observation of groundwater recharge and discharge across scales is needed. This would involve the development of sensors that measure recharge and discharge at "point" scales, research to increase our understanding of the scaling of these measurements and underlying processes, the development of procedures for integrating measurements and observations across scales, and generation of mathematical tools to assimilate and synthesize observations at all scales into groundwater process models. Such a strategy could initially be tested on both the benchmark sites (Recommendation 1-1) and on aquifers of regional extent.

It is hoped that this report will lead to progress in understanding the spatial and temporal variability in diffuse and focused groundwater recharge and discharge, the interaction of groundwater with the climate system, and the spatial and temporal scales of recharge and discharge fluxes. Improved understanding is needed for sustainable utilization of groundwater resources, ecologically sound management of wetlands, lakes and watersheds, and to understand, predict and cope with the effects of potential climate change.

1
Introduction

Atmospheric, surface and subsurface portions of the hydrologic system (Figure 1-1) are three dynamically linked water reservoirs having distinctly different time and space scales. The challenge is in understanding and measuring the dynamic interchange among these reservoirs, especially for interchanges with the subsurface. Most subsurface storage of water is in the groundwater reservoir, with a small amount of storage as soil moisture in the overlying unsaturated zone (see Basic Concepts Related to Groundwater Recharge/Discharge). While soil moisture is directly connected to the atmosphere and is an important storage reservoir for the energy associated with water (latent heat), simply because of its ease of exchange with the atmosphere, groundwater is the far more important storage reservoir for the water mass itself.

Fluxes to and from groundwater are called, respectively, recharge and discharge. Natural groundwater recharge has several origins. The most important of these are the flux of water across the water table from precipitation that percolates through the unsaturated zone, and the influx of water from a bounding or overlying surface water bodies including rivers, lakes, wetlands and the ocean. Natural groundwater discharge is the efflux of water from the groundwater reservoir to surface water, or to the land surface itself where, for example, it may return to the atmosphere through evaporation and transpiration. Natural recharge and discharge zones develop in response to the regional climatic and local topographic, hydrogeologic and biospheric conditions. Important anthropogenic sources of recharge and discharge include agricultural irrigation and drainage, respectively, infiltration basins and recharge/injection and pumping (e.g., water supply) wells.

The various recharge and discharge fluxes can be measured or estimated at a wide range of temporal and spatial scales. Uncertainties in the measurement methods and the related understanding in the process, and disparities in measurement and modeling scales, prevent adequate closure of the transient water balance at the spatial and temporal scales of interest to scientists, engineers, and decision makers. For example, *in situ* point measurements are representative of the point value of a flux but are inadequate for mapping larger regions of interest to planners, while regional chemical tracers and modeling techniques can provide estimates representative of larger areas but these are difficult to relate to local conditions at water supply and aquifer remediation sites. The challenge to closing the groundwater balance, and to estimating groundwater fluxes to or from other water reservoirs, is to integrate flux measurement and estimation techniques at multiple scales, with multiple types of data. These estimates would make effective use of models to map recharge and discharge fluxes over a wide range of spatial and temporal scales.

Estimates of recharge/discharge fluxes are needed at many different spatial scales in water budget studies of natural hydrologic systems, and in studies of systems impacted by agriculture, water supply, or contamination. Estimation and understanding of recharge and discharge rates are of importance when evaluating

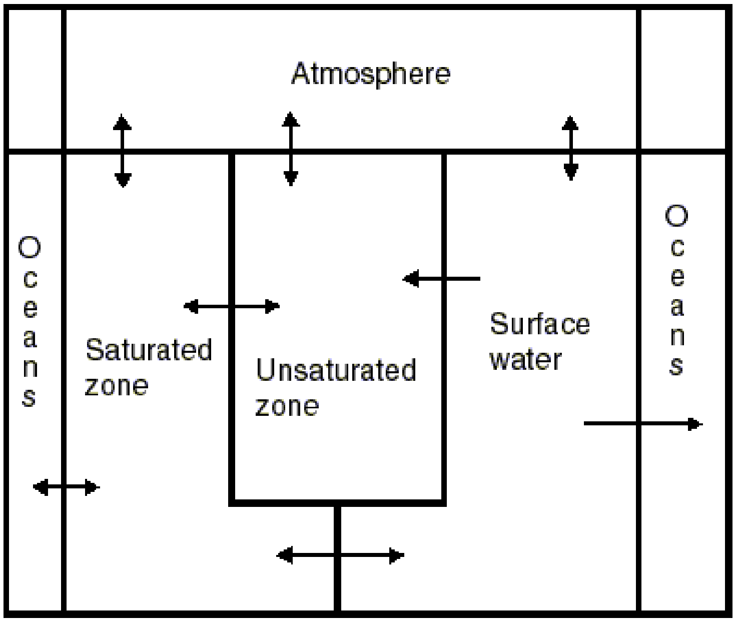


FIGURE 1-1 Global water reservoirs. Arrows show the interchange between reservoirs. The arrows connecting the saturated zone to the other reservoirs represent groundwater recharge and discharge and are the subject of this report. SOURCE: Guido Salvucci, Boston University, written communication, May 2002.

the effects of plans for sustainable use and management of groundwater resources since these rates, and how they respond to change dynamically affect surface water levels and ecosystems. At a regional scale, the amounts of total annual average groundwater recharge and discharge are important components of the water budget used for in decisions about basin management. At a smaller spatial scale information on groundwater fluxes is used in addressing local water supply issues and groundwater contamination problems. Groundwater discharge is a major component of surface water generation in headwater streams, and is responsible for stream baseflow. It plays a role in mass wasting (landslides) and in fluvial geomorphology (e.g., groundwater sapping). Groundwater fluxes affect the chemistry, biology, and ecology of the subsurface, in both the saturated and unsaturated zones, and in bounding surface waters. Basin scale biogeochemical cycles are influenced by recharge/discharge patterns and the physiology of vegetation is strongly linked to recharge/discharge zones. Discharge of groundwater to surface water bodies, including wetlands, carries nutrients important to biological communities. Recent work at the groundwater-stream interface (hyporheic zone) and at the groundwater/lake and wetland interfaces (hypolentic zone) has demonstrated that most of the chemical transformation during flow exchanged between surface water and groundwater occurs within a few inches of the interface between reservoirs. Improved measurements and estimates of groundwater fluxes and associated biogeochemical processes within these interfaces are needed. Of particular interest are processes involving pathogens and nutrients such as nitrogen. Thus, process understanding and accurate estimates of groundwater recharge and discharge play a role in groundwater sustainability, geomorphology, biogeochemistry and the health of ecosystems. Despite the importance to water and chemical cycles, to ecosystems, and to water reources management, there are no universally applicable methods or established networks to measure recharge and discharge rates, and only limited understanding of recharge and discharge processes.

Limited understanding and difficulties with measurements arise in part because of the distributed nature and spatially large extent of most groundwater recharge and discharge areas, as well as the many different environments where these fluxes occur, ranging from the ocean floor to mountain headwater streams. While there are instruments designed to make direct point measurements (see Table 1-1) of infiltration or recharge (e.g., infiltrometers, lysimeters) and discharge (e.g., seepage meters), in most cases these measurements methods have uncharacterized uncertainties, and it is not clear whether or how the measurements might be extrapolated to larger areas. Indirect methods of estimating fluxes (e.g., using head measurements and Darcy's law; analysis of water-level fluctuations, ground-based gravimetry, temperature profiles, electromagnetic methods, and isotopes and solutes dissolved in groundwater) also suffer from the similar limitations and from non-uniqueness (Table 1-2), as do integrated estimates of flux (e.g., baseflow estimates used to approximate groundwater discharge to rivers, water balance methods and model calibration to estimate recharge).

In summary, fluxes at groundwater interfaces interest hydrologists as well as researchers in related sciences (Figure 1-2). While both the theory and measurement of groundwater fluxes at interfaces has received some attention, there are still significant gaps in process understanding, and many difficulties in obtaining accurate estimates of the spatial and temporal distribution of these fluxes, including fluxes to and from rivers and streams, reservoirs and lakes, wetlands, and the ocean. Similarly, there are no standard procedures for measuring recharge to the groundwater system from precipitation or other sources.

Need for new work on these issues is widely recognized. Internationally, the World Water Council's World Water Vision initiative has singled out closer investigation of processes at hydrologic interfaces, including understanding surface-subsurface water interactions, as important to achieving its goal of developing a vision for water management in 2025 (Hartmann et al., 2000). The Hydrogeology Program Planning Group of the Integrated Ocean Drilling Program (IODP) is focusing attention on submarine fluxes occurring in the deep ocean basins as well as in coastal zones (Ge et al., 2003). The National Science Foundations LEXEN (Life in Extreme Environments) Program is sponsoring research focused on determining whether subsurface fluxes at the sea floor promote the growth of indigenous microbial communities (Johnson et al., 2003).

Nationally, NRC's Water Science and Technology Board recently identified mapping of groundwater recharge and discharge vulnerability as a priority area for research in environmental science (NRC, 2000). The Water Cycle initiative of the U.S. Global Climate Research Program (USGCRP) involves multiple federal agencies in coordinated research on the water cycle. The USGCRP Water Cycle Study Group (2001) has identified "quantifying fluxes between key hydrologic reservoirs" as one of three goals under their Science Question 2: "To what extent are variations in the global and regional water cycle predictable?" The newly formed Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) has proposed that the greatest challenges and most fertile opportunities to advance the science are found at primary hydrologic interfaces (www.cuahsi.org). Of the four interfaces they propose, one involves recharge (land surface – groundwater), and other recharge and discharge (surface water – groundwater). Finally, most of the federal agencies sponsoring the Committee on Hydrologic Science (COHS; see Preface) have identified groundwater fluxes at interfaces as an important priority area for research (Appendix C). Interest by agencies is widespread. The U.S. Army Corps of Engineers and the South Florida Water Management District are proposing artificial recharge by means of injection wells (so-called aquifer storage and recovery, ASR) engineering groundwater recharge and its recovery to help play an important role in the restoration of the Florida Everglades (NRC, 2002c), while the Department of Energy is concerned with the role of natural recharge in the performance of the proposed nuclear waste storage facility at Yucca Mountain, Nevada (Flint et al., 2002; Box 4-2). Brief summaries of agency interest in the topics of the workshop are in Appendix C.

TABLE 1-1 Methods for Estimating Recharge and Discharge

Hydrologic zone where actual measurement is made	Method	
	Arid and semi-arid climates	Humid climates
Surface water	Channel water budget	Channel water budget**
	Base flow discharge	Base flow discharge**
	Seepage meters	Seepage meters
	Heat tracers	Heat tracers
	Isotopic tracers	Isotopic tracers
	Solute mass balance	Solute mass balance
	Watershed Modeling	Watershed Modeling
Unsaturated zone (measurable discharge would mainly be upward exfiltration to vegetation)	Lysimeters*	Lysimeters*
	In situ sensors (Neutron probes, TDR, etc.)	In situ sensors (Neutron probes, TDR, etc.)
	Zero-flux plane*	Zero-flux plane*
	Darcy's Law	Darcy's Law
	Tracers [historical ^{36}Cl, ^{3}H, ^{2}H, ^{18}O), environmental (Cl)]	Tracers (applied)
	Numerical Modeling	Numerical Modeling
	Thermal analysis	
	Surface geophysics (DC, EM, radar)	Surface geophysics (DC, EM, radar)*
	Cross-hole geophysics (DC, EM, radar)	Cross-hole geophysics (DC, EM, radar)*
	Gravity geophysics	
Groundwater		Water-table fluctuations (observations wells, geophysics)
	Elastic compression measurements (e.g., GIS, InSAR)	
		Darcy's law
	Tracers [historical (CFCs, ^{3}H/^{3}He), environmental (Cl, ^{14}C)]	Tracers [historical (CFCs, ^{3}H/^{3}He)]
	Numerical modeling	Numerical modeling

Most methods can be used for estimating either recharge and discharge, although a given method may be better for one than the other. Methods appropriate only for recharge* and discharge** estimation are indicated by asterisks. SOURCE: Reprinted, with permission, from Scanlon et al. (2002). © 2002 by Springer-Verlag Heidelberg.

STATEMENT OF TASK

Fluxes to and from groundwater systems are critical to most aspects of hydrologic science, and therefore to its related sister sciences (Figure 1-2), but these fluxes are traditionally neglected or estimated by using simple and unverified assumptions (e.g., by assuming that recharge is equal to some fraction of precipitation). The purpose of this report is to call attention to the importance of groundwater fluxes, to explore the potential of new technologies to measure or estimate these fluxes, and to identify research gaps and the potential for interdisciplinary collaboration (Figure 1-2).

This report is an outgrowth of earlier recommendations of the Committee on Hydrologic Sciences (COHS), outlined in "Hydrologic Science Priorities for the U.S. Global Change Research Program" (NRC, 1999). It is intended to help develop the framework for assessing strategic directions in the hydrologic sci-

Table 1-2. Summary of methods for estimating recharge at Yucca Mountain, including strengths and limitations of each method.

Recharge Estimation Method	Scale	Model Parameters	Strengths	Limitations
Numerical model based on Darcy's law	Site scale.	Rock hydraulic properties; measured saturations and water potentials	Parameter-estimation methods in numerical model can provide quantitative measures of uncertainty.	Scarcity of site-specific hydraulic-conductivity data; measured saturations or water potentials may not reflect fracture-flow component.
Direct calculation of flux from Darcy's law	Deep Borehole scale.	Hydraulic conductivity and measured saturations or water potentials	Can obtain continuous profiles of flux along a borehole	Scarcity of site-specific hydraulic conductivity data; measured saturations or water potentials may not reflect fracture-flow component.
Neutron moisture monitoring	Shallow Borehole scale.	Change in water content below zone of evapotranspiration	In arid climates changes in water content with time can be converted directly to flux.	Each borehole represents only a point estimate; labor intensive due to need for long-term monitoring; may be insensitive to fracture flow and provide a minimum estimate of recharge.
Inverse models to match thermal profiles in boreholes	Borehole scale.	Measured temperature versus depth profiles	Flux estimate averaged over length of borehole; method sensitive to fracture flow as well as to matrix flow.	Must assume steady state; each monitored hole represents only a point estimate.
Modified Maxey-Eakin transfer method	Site or regional scale.	Average annual precipitation	Provides spatial distribution of recharge.	Method is empirical, developed for basin or watershed scale rather than point scale.
Chloride (Cl) mass balance	Point scale for pore waters, watershed scale for perched water, and basin scale for groundwater.	Cl deposition rate, measured Cl concentrations	Few parameters are needed; analyses are easy to make.	Not completely valid for fractured rock; mea-sured concentration may not be representative of fracture fluids, which can bypass matrix.
Natural atmospheric and global fallout radionuclides (C-14, Cl-36, tritium)		Measured isotopic concentrations or specific activities in subsurface waters	Detection of young waters using fallout tritium, ^{14}C or ^{36}Cl is well established in hydrologic community.	Not a direct measure of flux; bounding fluxes must be determined indirectly using numerical model.
Perched-water chemistry, including isotopes	Watershed scale.	Major-ion chemistry and isotopic data	Integrated signal	Uncertainty about origin and lateral extent of each perched-water body, and whether it is a relict of past climate.
Saturated-zone water chemistry, including isotopes	Basin and regional scales.	Major-ion chemistry and isotopic data	Integrated signal.	Sampling depths highly variable from well to well, rarely draw from uppermost saturated zone, and often tap more than one unit.
Watershed modeling	Point, watershed and regional scales.	Spatial/temporal distribution of precipitation, E-T, soil/bedrock properties.	Spatial and temporal distributions of recharge; provides tool for predicting effects of different climate scenarios.	Intensive data needs.

SOURCE: Reprinted, with permission, from Flint et al. (2002). © 2002 by Springer-Verlag Heidelberg.

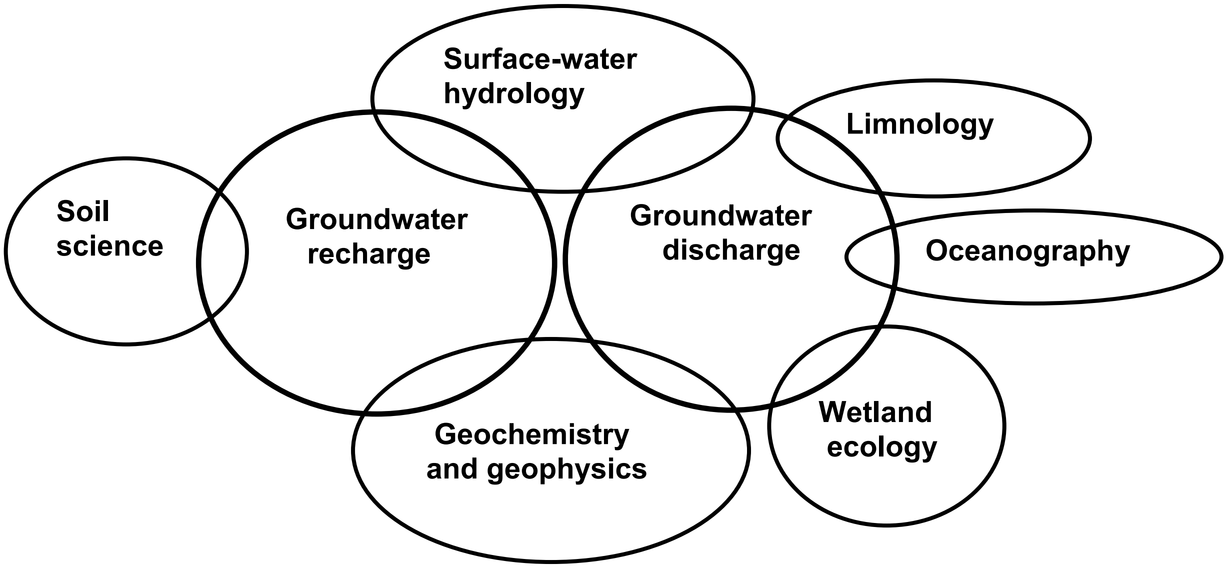


FIGURE 1-2 Disciplines involved in estimation of groundwater recharge and discharge.

ences. The report reflects deliberations at a COHS sponsored workshop held in May 2002 (preface; Appendices A, B). The discussions at the workshop focused on naturally occurring groundwater recharge and discharge. However, many of the concepts related to natural groundwater fluxes also apply to anthropogenic fluxes such as those associated with agriculture, municipal water supply, and aquifer contamination. The report is also not meant to be a comprehensive analysis of all issues related to groundwater fluxes but instead focuses on the following questions, drawn from a broader set of issues (see preface) that workshop participants were asked to consider:

1. **Diffuse vs. focused recharge and discharge**

- What is the relative importance of diffuse versus focused recharge/discharge in various hydrogeologic settings?
- Is fresh groundwater discharge a significant source of fresh water recycling to estuaries and the oceans?

2. **Interactions of Groundwater with Climate**

- Do groundwater recharge and discharge processes provide feedback mechanisms that affect climate?
- What are the important time scales for groundwater reservoirs affecting continental and global water balances, and how are they controlled by fluxes and storage?
- What is the magnitude of the effect of fluctuations of sea level and levels of large lakes (e.g., the Great Lakes) on groundwater recharge/discharge?

3. Spatial and temporal scales of recharge and discharge

- How do estimates of groundwater recharge/discharge aggregate when averaged over different scales and what implications does this have for measurement scale?
- How accurately can recharge/discharge patterns/rates be estimated at a regional or national scale, and how might uncertainty in these patterns/rates vary with spatial and temporal scale and geographic location?

BASIC CONCEPTS RELATED TO GROUNDWATER RECHARGE/DISCHARGE

The zone of ***subsurface water*** can be divided into the ***unsaturated zone*** above the water table and the ***saturated zone*** below the water table. The unsaturated zone includes the ***zone of soil moisture,*** which extends from the land surface down to the bottom of the root zone, and the ***vadose zone*** extending from the bottom of the root zone to the water table. The ***groundwater reservoir*** consists of the water in the saturated zone below the water table. The ***capillary fringe*** is located between the unsaturated and saturated zones and is the area where water is held under tension (as in the unsaturated zone) yet pore spaces are completely filled with water (as in the saturated zone). At the ***water table***, water is under atmospheric pressure; water pressure below the water table is greater than atmospheric pressure, while water pressure above the water table is generally less than atmospheric pressure.

Major sources of groundwater ***recharge*** include the downward flux of water across the water table, originating from precipitation, and the influx from a surface water body, while groundwater ***discharge*** is the efflux of water from the saturated zone. Precipitation ***infiltrates*** at the land surface and some fraction of this water ***percolates*** through the unsaturated zone and crosses the water table to become groundwater recharge. Additional water recharges the groundwater system from irrigated agricultural fields, from recharge wells constructed for various purposes, and from other engineering works. The groundwater reservoir may also be recharged from water in rivers, lakes, and wetlands (e.g., see Winter et al., 1998; Winter, 1999; Sophocleous, 2002). Water may also enter the groundwater reservoir from estuaries and the ocean, but this process is termed ***salt-water intrusion*** or *salt-water encroachment* and is not normally considered recharge. Groundwater in an unconfined aquifer may flow downward across a confining bed and enter an underlying confined aquifer. This is sometimes called ***deep recharge***. Recharge to confined aquifers sometimes occurs, at least in part, in response to pumping of the confined aquifer.

Groundwater discharges naturally to lakes, rivers, wetlands, estuaries and the ocean (Winter et al., 1998; Winter, 1999). Discharge also occurs at pumping wells, agricultural drains and other types of drainage structures. Groundwater may also leave the saturated zone by direct ***evaporation*** from shallow water tables, upward movement across the water table through ***evapotranspiration*** from plant roots in the unsaturated zone or from plants known as ***phreatophytes*** whose roots penetrate to the water table.

The interface between the groundwater zone and surface water in streams and rivers is a zone of active mixing and interchange between groundwater and surface water known as the ***hyporheic zone*** (e.g., see Jones and Mulholland, 2000). There is a similar mixing zone, the ***hypolentic zone,*** at the interface between the groundwater zone and lakes and wetlands. Another mixing zone occurs within the upper 500 meters of the oceanic crust (Johnson et al., 2003).

Fundamental to the analysis of recharge and discharge processes in any given hydrogeologic setting is the formulation of a ***conceptual model.*** This is a descriptive representation of a groundwater system that incorporates an understanding of the relevant geologic and hydrologic conditions and generally includes information about the water budget. Development of conceptual models is fundamental to the science of hydrogeology (e.g., Davis and DeWeist, 1966). Several major efforts have been made to organize the U.S. into regions of similar hydrogeologic characteristics. Recent attempts include the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey (Sun and Johnston, 1994) and a volume of papers on the hydrogeology of North America (Back et al., 1988). Recently, Winter (2001) introduced the concept of the ***Fundamental Hydrologic Landscape Unit (FHLU)*** to help guide the formulation of conceptual models. The FHLU is based on the concept that a single generic flow cell (Figure 1-3) forms a template for conceptualizing hydrologic landscapes (see Chapter 2). Conceptual models built upon the concept of the FHLU can be useful in identifying patterns of recharge and discharge in any given generic hydrogeologic setting, allowing hypotheses to be developed and tested independently of scale. The factors that influence the development of a conceptual model based on the FHLU concept include land surface form, geologic framework, and climatic setting, especially the net of annual precipitation minus evapotranspiration. The FHLU framework is used in this report to guide discussion.

OVERVIEW OF METHODS FOR ESTIMATING RECHARGE AND DISCHARGE

Scanlon et al. (2002) recently reviewed and summarized methods for estimating recharge (Table 1-1) and noted that these techniques are dependent on both spatial (Figure 1-4) and temporal (Figure 1-5) scales. They concluded that: "Recharge estimation is an iterative process that includes refinement of estimates as additional data are gathered. A wide variety of approaches should be applied in estimating recharge in order to reduce uncertainties and increase confidence in recharge estimates." Other review papers on recharge estimation are included in Scanlon and Cook (2002). Similar statements about methods and space/time scales can be made about the estimation of discharge, which uses many of the same methods for estimation (Table 1-1). Whether for recharge or discharge, the methods of estimation draw upon expertise resident in a variety of disciplines (Figure 1-2).

Estimates of recharge are dependent on the scale of measurement. Lysimeters, neutron probes, time-domain reflectometry (TDR) probes and (other) in situ sensors, and cross-borehole radar (Binley et al., 2001) offer "point" or "small-scale" data that can be used to estimate net infiltration. Translating estimates of infiltration into recharge is not straightforward, however, and the results after this transformation are not necessarily "point" estimates. Tracer studies, subsurface and in-stream thermal analyses, cross-borehole and surface DC, electromagnetic geophysics (e.g., Cook et al., 1992), gravity geophysics, and elastic compression measurements might be thought of as giving "mesoscale" estimates of recharge. The water-table fluctuation method (Healy and Cook, 2002), mass-balance calculations, measurements of thermocline alteration (heat tracer studies), and isotopic tracer analyses might be considered "basin-scale" or "macro-scale" measurements. Inferences based on inverse groundwater modeling in conjunction with measurements of the elevation of the potentiometric surface (Sanford, 2002) are related to the scale of the model and may range from mesoscale to basin-scale. Discharge estimates, sometimes using the same methods, are also dependent on measurement scale. The baseflow discharge method (Table 1-1) measures basin-scale groundwater discharge to streams, which is then used as a proxy for recharge estimates under the assumption that, under steady state conditions on the watershed scale, recharge equals discharge. Darcy's law is used to estimate point discharge rates by measuring hydraulic gradients in piezometers installed in a discharge area. Mini-piezometers are installed in river and lake beds to measure near shore gradients. According to Darcy's law, hydraulic gradient multiplied by hydraulic conductivity equals flux. The channel-water budget method can also be used to measure gains or losses of water from a stream by calculating the net gain or loss of water between two streamflow gaging stations, with the scale depending on the distance between the gages.

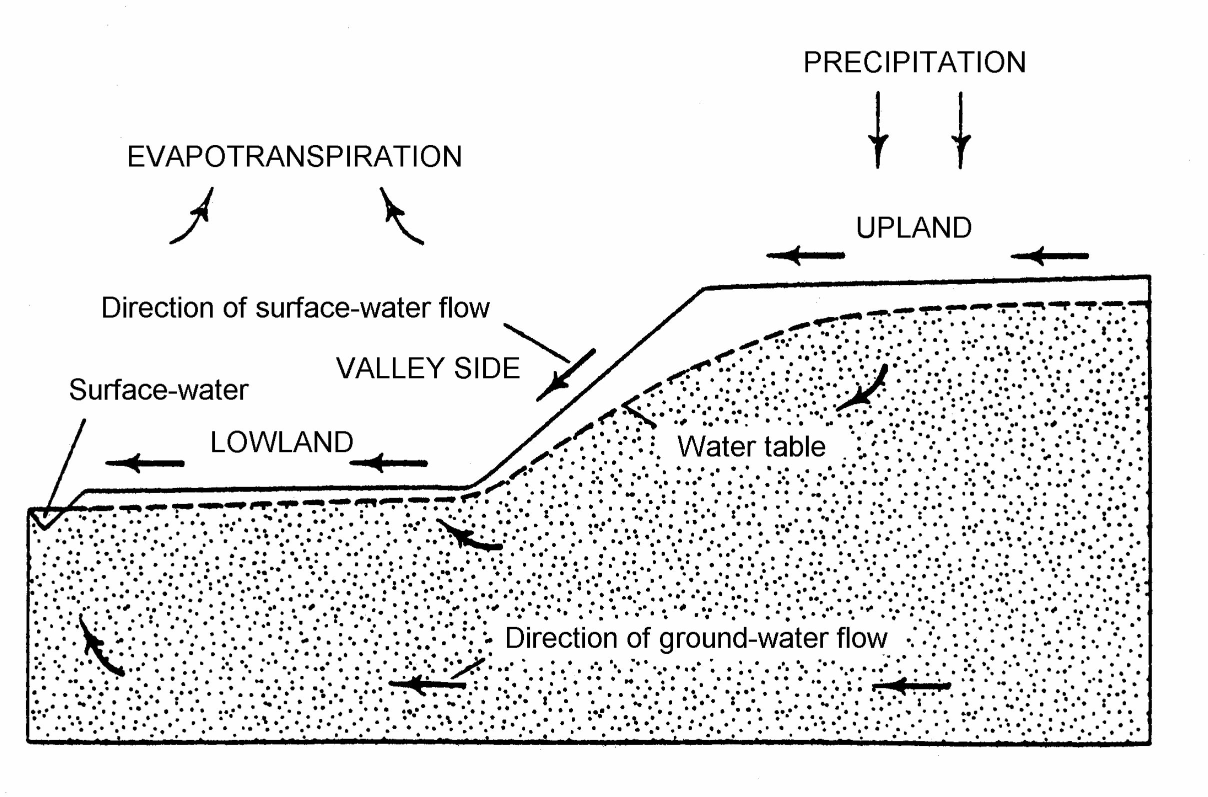


FIGURE 1-3 The Fundamental Hydrologic Landscape Unit (FHLU). SOURCE: Reprinted, with permission, from Winter (2001). © 2001 by American Water Resources Association.

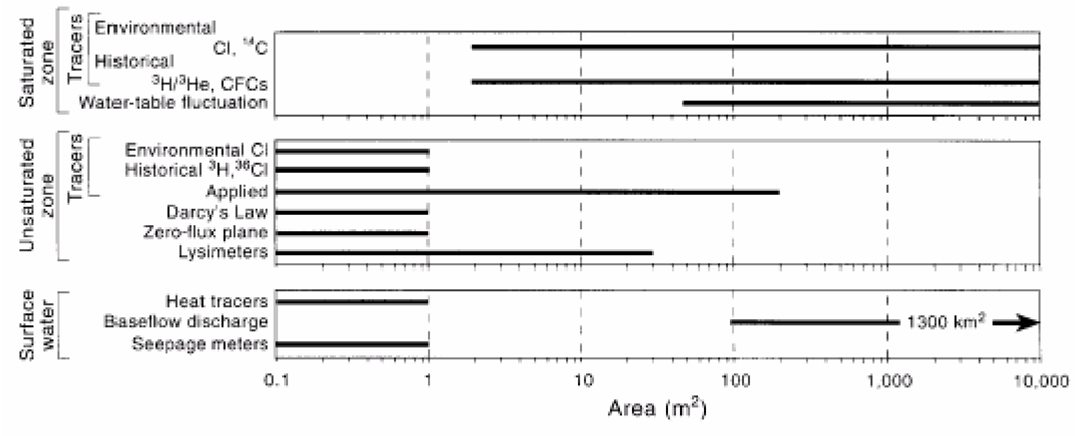


FIGURE 1-4 Spatial scales for recharge estimation. SOURCE: Reprinted, with permission, from Scanlon et al. (2002). © 2002 by Springer-Verlag Heidelberg.

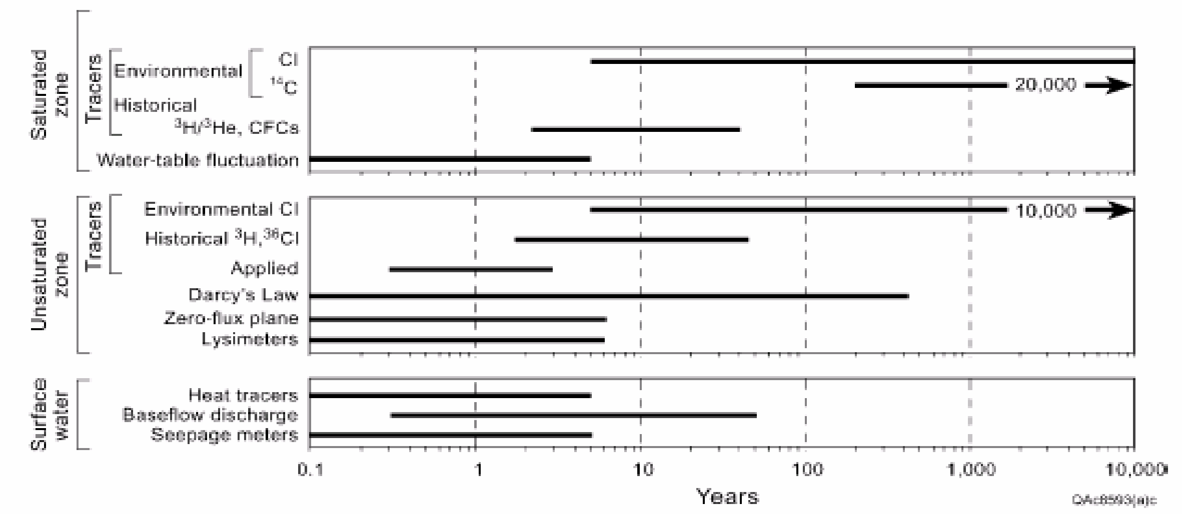


FIGURE 1-5 Temporal scales for recharge estimation. SOURCE: Reprinted, with permission, from Scanlon et al. (2002). © 2002 by Springer-Verlag Heidelberg.

Seepage meters, theoretically, can be used to make direct point measurements of either recharge or discharge of water between a surface water body and the groundwater system, but have been used more successfully to estimate discharge. Seepage meters for discharge estimation are designed to collect groundwater flux. The original design (Lee, 1977) was intended for use in lakes and estuaries and required manual collection of the water sample from which an estimation of flux was calculated based on the elapsed time. Newer designs (e.g., Taniguchi and Fukuo, 1993; Paulsen et al., 2001) allow for automated measurements. Mesoscale discharge can be estimated with the help of heat tracers by relying on the difference in temperature between groundwater and surface water (e.g., Lapham, 1989; Constantz et al., 1994; Hunt et al., 1996).

Solute mass balance techniques have been successfully used to estimate mesoscale or macroscale discharge to lakes and estuaries (e.g., Krabbenhoft and Webster. 1995; Burnett et al., 2002). Watershed models and numerical groundwater flow models are also helpful in estimating mesoscale or macroscale discharge.

Estimates of recharge and discharge are plagued by errors and uncertainties, especially biases. The errors depend on the scale, quantity, quality and type of data. Errors are often very large and are seldom quantified because available data are seldom adequate to give reliable assessments of the uncertainty in recharge/discharge estimates, and many of the measurement tools are not amenable to calibration. Furthermore, traditional hydrogeologic evaluations are deterministic, and lack assessments of error and uncertainty.

Estimates of recharge and discharge also suffer from non-uniqueness. For example, the base flow estimation method assumes steady flow, so that recharge balances discharge. But estimates of both recharge and discharge will be inaccurate if the flow is sufficiently transient, and the effects of storage changes are inappropriately assigned to one or the other, or missed entirely. Some of the methods (e.g., gravity, EM, and radar geophysical methods, elastic compression, water-table fluctuation, mass-balance calculations, inverse modeling) actually measure water in storage and use the water budget to estimate recharge or discharge indirectly. Moreover, these methods are sensitive to subsurface geological heterogeneity. The observed storage change may be due to reasons other than those assumed, making the recharge or discharge estimate non-unique, and dependent on assumptions. Many methods for recharge assume vertical infiltration, whereas lateral flow may likely be significant. Others suffer from poor space-time resolution of storm events. Flux estimates calculated using Darcy's law require an estimate of hydraulic conductivity, which can be difficult to measure accurately.

Hence, closing the water budget requires a reduction of uncertainty and non-uniqueness in the measurement of the relevant fluxes.

Flint et al. (2002) evaluated various methods to estimate net infiltration and recharge at Yucca Mountain, Nevada (Box 4-2). A summary of the methods, including general approach, scale of application, and strengths and limitations, is presented in Table 1-2 and illustrates some of the issues in estimating groundwater fluxes. The methods in the table produce estimates of flux that reflect different spatial and temporal scales; they have different data requirements, strengths and limitations; and have varying sensitivity to water flux in fractures, a major pathway through the unsaturated zone at Yucca Mountain. At this site, recharge varies spatially owing to variations in precipitation, surface microclimates, thickness of alluvial deposits, faults and fractures, and thickness and hydrologic properties of geologic strata in the unsaturated zone. Recharge also varies temporally due to weather and the climate variability.

SCOPE

The following three chapters examine processes and measurements of fluxes at groundwater interfaces, through the perspective provided by the three major themes of the workshop: diffuse vs. focused fluxes, interactions with climate, and spatial and temporal scales. Challenges in the understanding and estimation of fluxes are outlined within this context, and suggestions are made for future research. The themes are intertwined. For example, highly variable and focused recharge may limit our ability to upscale or downscale measurements, and changes in climate may change a temperate zone with diffuse recharge to an arid zone with focused recharge.

In Chapter 2, we also discuss the benefits that would be derived from the establishment of a network of experimental benchmark sites for recharge and discharge measurements. These sites would be integrated wherever possible with existing and planned experimental watersheds, such as those funded by the National Science Foundation (e.g., the Long Term Ecological Research [LTER] sites, or CUAHSI's proposed Hydrologic Observatories), or run by federal agencies (e.g., U.S. Department of Agriculture, the Forestry Service, and the U. S. Geological Survey), in order to leverage related hydrologic and ecological research.

2

Diffuse and Focused Recharge and Discharge

Depending on the hydrogeologic setting, recharge may occur fairly uniformly over the subsurface or may be focused by entering the subsurface through depressions such as sinkholes. Recharge can also be focused by unsaturated zone flow instabilities (e.g., gravity fingering); geologic features like fractures, faults, clastic dikes and karstic sinkholes; and manmade infrastructure including recharge wells and waste disposal facilities. While one mechanism typically dominates, sometimes diffused and focused recharge are both important, especially at regional scales (e.g., Izbicki et al., 2002). Similarly, discharge may be spread out over relatively large areas or may be focused into springs, including submerged springs discharging into rivers, wetlands, lakes, and the ocean. Naturally occurring discharge is also focused through transpiration by plants (e.g., Meyboom, 1966). Furthermore, discharge may be focused by pumping from wells or drainage systems. The distinction between diffuse and focused discharge can be difficult to determine since what may be termed diffuse discharge often occurs preferentially along curvilinear features such as rivers, shorelines, and slope breaks.

Recharge and discharge rates and locations can also vary greatly over time. Shallow flow systems are particularly responsive to seasonal changes, especially where the infiltration capacity of the soil and the hydraulic conductivity of the underlying rock or sediment are high (Winter, 2001). Focused recharge and discharge tends to be more episodic than diffuse flow. Recharge and discharge events in arid zones generally tend to be more episodic than in humid settings where recharge and discharge fluctuate in a relatively predictable way in response to seasonal changes in precipitation and evapotranspiration. Recharge and discharge fluxes also change temporally in response to climate change. These long-term temporal trends are discussed in Chapters 3 and 4.

Motivations for quantifying recharge and discharge fluxes arise from a variety of water resource and ecosystem management problems. The net balance between total recharge and discharge for a groundwater basin is the primary control on the amount of water stored in aquifers that are used for water supply. Thus, quantifying natural recharge and discharge fluxes is an essential step in evaluating the groundwater resource and provides a baseline assessment for managing/developing groundwater resources. Additionally, recharge is the primary mechanism by which contaminants enter the groundwater system. The spatial distribution of recharge fluxes and the travel time for movement of water from the land surface to the water table largely determine the vulnerability of aquifers to contamination including agricultural contaminants (e.g., Bohlke, 2002; Fogg et al., 1999) and are used to define zones of capture for pumping wells in wellhead protection programs (Reilly and Pollock, 1993). The distinction between focused and diffuse recharge mechanisms is particularly important to contaminant transport because these two end-member recharge regimes can lead to large differences in travel times, concentrations, and contaminant plume geometries.

A variety of aquatic ecosystems, including wetlands, lakes, and streams, are sustained by groundwater discharge. Distinct vegetation and aquatic communities are likely to be associated with focused and diffuse discharge (e.g., Rosenberry et al., 2000; Lodge et al., 1989). Biogeochemical processes that modify water quality during discharge (e.g., denitrification) are also likely to be affected differently by these two discharge modes. An understanding of both the physical and biochemical processes occurring at the interface between groundwater and river systems within the hyporheic zone and between groundwater and lakes and wetlands within the hypolentic zone is key to assessing and managing aquatic ecosystems.

Spatial and temporal variability in recharge and discharge fluxes has been studied in many different environments, from the prairie potholes (Winter and Rosenberry, 1995; van der Kamp and Hayashi, 1998) to coastal plains (Logan and Rudolph, 1997). However, there are no uniformly applicable methods for quantifying recharge/discharge fluxes in space and time. For example, measurement difficulties arise because focused recharge fluxes can vary widely over space and diffuse discharge fluxes may be of relatively low magnitudes. In most cases we estimate recharge and discharge indirectly, for example by measuring head or using baseflow estimates or tracers (Table 1-1). Such indirect estimates typically are affected by uncertainty in the estimates of other parameters used in the analysis (e.g., Winter, 1981).

Distribution of recharge/discharge fluxes may also be estimated by using mathematical models of the watershed in conjunction with field measurements to solve the inverse problem (e.g., Stoertz and Bradbury, 1989; Levine and Salvucci, 1999; Stone et al., 2001; Sanford, 2002; and Lin and Anderson, 2003). However, fluxes estimated in this way are also plagued by the uncertainty associated with estimating all the other parameters used in the model as well as uncertainty in the heads used to calibrate the model. When comparisons of different techniques to estimate recharge and discharge have been made, results from various techniques are often different (e.g., Flint et al., 2002; Burnett et al., 2002). Only when discharge is discretely focused and accessible to measurement, for example, springs that emerge at the land surface, is it possible to make relatively accurate direct measurement of a groundwater flux. Direct measurements of submerged springs can be made using seepage meters (Lee, 1977; Taniguchi and Fukuo, 1993; Paulsen et al., 2001) but these measurements can be logistically difficult to make and are often affected by measurement errors.

This chapter explores some of the research needs for understanding and characterizing the timing, spatial distribution, and rates of focused and diffuse recharge and discharge in major hydrogeologic settings. With an improved process-level understanding of controls on these fluxes, it may be possible to anticipate changes in the timing of recharge events and changes in the spatial patterns of recharge and discharge in response to climate variability, changes in land use, and water resource development. In particular, this chapter focuses on two questions discussed at the workshop that formed the basis of this report. The first is "How do the landscape setting and climate fundamentally control the nature of recharge and discharge in any given hydrogeologic setting?" The discussion of this question is woven throughout the chapter. The second question is "Is diffuse or focused fresh groundwater discharge a significant source of fresh water recycling to estuaries and the oceans?" This issue is discussed in the last section on coastal/estuarine systems, in Box 2-3, and also in Chapter 3 in the context of climate.

EXPERIMENTAL BENCHMARK SITES

In effect there are presently a large number of generally uncontrolled recharge and/or discharge experiments taking place each year, as hundreds of researchers, practitioners, and managers collect and analyze data, or build models of systems, in which groundwater recharge and discharge are quantified. In most of these studies, estimation of recharge/discharge fluxes is not the primary motivation for the study, and in many of them, inclusion of recharge/discharge is an afterthought, and few or no field measurements are made to quantify the fluxes or to verify guesses. There are few experimental sites at the scale proposed in this report (see discussion later in this section), and essentially no field campaigns, in which these processes were the focus of attention. Data and modeling results from other existing studies cannot be reliably synthesized, since recharge/discharge was not the focus and, in any event, the methods, scales, and uncertainties vary widely and may not even be documented. In summary, little is known about the spatial and temporal variability of these fluxes and little is known about the relative importance or magnitude of diffuse vs. focused fluxes. We do know that the relative importance of diffuse vs. focused flux and the variability of fluxes depend on the hydrogeologic setting.

One promising way to achieve consistency in addressing recharge and discharge issues would be to establish a network of experimental benchmark sites that sample a wide range of landscape and geohydrologic types, and climatic regimes, building on the concept of hydrogeologic conceptual models that is fundamental to hydrogeologic analysis. An example of a framework for organizing hydrogeologic conceptual models or generic hydrogeologic settings is the Fundamental Hydrologic Landscape Unit (FHLU) introduced by Winter (2001) (Figure 1-3). The proposed experimental sites would be selected to differentiate the relative importance of diffuse versus focused recharge and discharge processes at different scales and to test different methods of estimating recharge and discharge in disparate settings. Care would be taken to distinguish modern-day recharge rates from paleorecharge rates (see Chapter 3). Research at the experimental sites would facilitate the development and testing of new concepts and new tools for measurement of recharge and discharge fluxes.

Prior to and during startup of each experimental setting, generic modeling studies would be used to aid in selection of sites, design field instruments and instrumentation networks, and design experiments. Studies at each experimental site logically would lead to quality assured results that are transferable to similar settings elsewhere. Studies at the network of sites, using consistent science and technology, would permit synthesis. All data and information generated at these sites should be maintained at a centralized facility and made available to the scientific community.

Advances in technology including micro-instrumentation, access to online digital data bases, availability of remotely sensed data sets, high resolution tomography, hydrolithology, soil and other landscape data, improved computational tools, data telemetry from remote locations, automated sampling capabilities, and isotope and other novel geochemical tools, make beneficial detailed studies of recharge and discharge possible. With these advanced technologies incorporated into a network of benchmark sites, important science questions can be successfully addressed.

What size would be ideal for a benchmark site? The relevant scientific issues and methods of measurement change with scale (Chapter 4). Some experiments could be run at the "point" scale of, say, a meter or could be fixed on the hillslope scale of, perhaps, 10-100m, the scale used in many field studies of other hydrologic and geomorphic problems such as runoff generation and slope stability. However, many of the methods, questions, and issues demand a larger scale, perhaps that of a watershed, or even an entire river basin. Appropriate spatial scales also depend on the landscape, hydrogeology, and climate. Ideally each benchmark site would cover a spectrum of spatial scales, possibly using a nested design where the benchmark site itself is at the hillslope or watershed scale but smaller scale sites would be located within the benchmark site, while larger scale studies might also include more than one benchmark sites.

What is the appropriate temporal scale for studies at benchmark sites? New observations should be designed with a sufficient sampling frequency to address the relevant scientific issues and to test the measurement methods. Benchmark sites should be located where historical data such as that from streamgages and long-term monitor wells can be used to extend the record, and preferably where the record can be extended into the past even further using paleohydrological and paleoecological data.

While fixed benchmark sites would dramatically improve the scientific community's ability to address recharge and discharge issues, and to develop and test measurement methods, the sites would not have the geographic coverage necessary to answer all questions, or to work cooperatively with large scale hydroclimatologic field experiments and campaigns, such as the Hydrologic Atmospheric Pilot Experiment (NAPEX) or the more recent Global Energy and Water Cycle Experiment (GEWEX). While soil moisture issues were an important part of these experiments, groundwater recharge and discharge were effectively ignored and an important opportunity to improve understanding of these processes and the interconnection with other water reservoirs (Figure 1-1) was missed. The hydrogeologic community should develop the ability to lead and/or participate in such large-scale campaigns in order to take advantage of these opportunities in the future and thereby address the research questions that a fixed network of observatories cannot fully address. Further discussion of these opportunities (e.g., coupled aquifer-land surface-atmosphere models) may be found throughout Chapter 3.

A network of benchmark sites for groundwater recharge and discharge studies is an ambitious undertaking. A few hillslope scale sites might be readily achievable, but integrated watershed scale sites will require coordination by the hydrologic community. In particular, the community must leverage other opportunities such as existing federal experimental watershed programs, which have related long term databases, infrastructure support, and an interest in many of the same issues. A second opportunity lies with federally sponsored field sites like the system of Long Term Ecological Research Centers (www.lternet.edu) or the Consortium of Universities for the Advancement of Hydrologic Science's (CUAHSI) proposed network of hydrologic observatories (www.cuahsi.org). The benchmark sites would fit nicely into the proposed hierarchical structure and central management of the CUAHSI observatories.

The following sections illustrate how benchmark sites can be used to conduct research on recharge and discharge issues and methods by focusing attention on four generic hydrogeologic settings: karst, glaciated Midwest, mountain and valley, and coastal/estuarine. These settings represent four different types of landscapes and hydrogeologic conditions, and are used to suggest specific focal areas for research at each type of site. These four terrains represent a wide range of hydrogeologic conditions including some of the most problematic settings with respect to recharge and discharge but they are by no means a comprehensive representation of the types of settings found in the U.S. or elsewhere. The purpose is to illustrate the nature of the issues and questions that need to be addressed relative to groundwater fluxes and to show how the spatial and temporal variability and occurrence of diffuse vs. focused fluxes is dependent on the hydrogeologic setting. Important generic hydrogeologic settings that are not considered herein include alluvial valleys, permafrost regions, volcanic terrain (e.g., the Columbia River Plateau and the Hawaiian Islands), crystalline rock terrain (the Precambrian Shield), and unglaciated plains (i.e., the High Plains including the Ogallala Aquifer and the Sand Hills). For a more comprehensive description of the hydrogeologic settings found in North America, the reader is referred to Back et al. (1988). Similar expositions of the research needs relative to recharge and discharge could be written for each of these settings, and benchmark sites would ideally be located in many of them.

Karst

Karst is a general term for a wide range of landscape settings in which the underlying rocks have been modified by solutional processes. Rocks that are subject to dissolution include gypsum, rock salt, and carbonate rocks such as limestone and dolostone. Carbonate rocks are common in most karst settings, and the "classic" karst landscape contains such characteristic landforms as sinkholes, closed depressions, hummocky topography, caves, and springs. However, the continuum of karst landscapes ranges from minor, poorly developed karst features to major, integrated conduit networks. These environments are often extremely vulnerable to groundwater contamination and contain unique ecological niches, but understanding and quantifying recharge and discharge in karst environments poses significant scientific challenges (Appendix B).

Groundwater movement through karst systems is predominately along secondary features, such as fractures, conduits, or caves that are formed or enlarged by solution. Groundwater flow rates can be very rapid, and flow can be turbulent. Storage of groundwater in karst can be large or small depending on the nature of secondary void space (Figure 2-1). High-intensity precipitation events may move water through karst systems rapidly from recharge to discharge. Focused recharge to karst systems depends less on evapotranspiration and plant cover than in other hydrogeologic settings and occurs when the surface topography routes runoff to specific locations, such as sinkholes, exposed fractures, or closed basins. Thus, the structural, sedimentological, and geomorphic history of the rock, its mineralogical composition, and overlying soil thickness and composition all influence the extent to which focused recharge can occur. Many karst terrains contain springs, and groundwater discharge from conduit-flow karst springs can be very large and extremely variable.

Focused recharge and discharge can be fairly readily identified in many karst systems from geomorphic features such as sinkholes, stream networks, and vegetation patterns defining fracture traces (Sasowsky, 1999). Operationally, however, the three-dimensional distribution of conduits and fracture networks in karst systems can be very complicated, and discrete flowpaths are difficult to map. Often in karst terrains subsurface potentiometric divides do not coincide with surface topographic basins, making the computation of water and chemical balances very difficult. Discharges from springs, however, represent an integrated mix of water that has followed different flow paths. Potentially, a large amount of flow is captured by direct measurement of spring flow and under steady-state conditions recharge can be estimated indirectly from discharge measurements. For example, Plummer and others (1998) estimated the percentage of river water recharging the Floridan aquifer using chloride and isotopes.

Urbanization and agricultural practices have compromised karst systems throughout North America because of the ease with which water can be recharged in these settings and because of high yields to pumping wells. Dewatering has led to subsidence features (e.g., Wilson and Beck, 1992; Halliday, 1998) and major ecological stress and agricultural practices and urbanization has led to widespread contamination of karst aquifers by nutrients (USGS, 1999), solvents (Wolfe and Haugh, 2001), and other chemicals.

Remote sensing of vegetation and soil water content, geomorphological analysis, and field observation and mapping of focused recharge and discharge relative to fracture systems over the watershed would be a first step towards evaluating recharge and discharge in the karst setting. Numerous studies of karst hydrology in many climatic settings show that diffuse recharge and discharge is a very small component of a karst water budget (White, 1988).

A benchmark watershed to study karst recharge and discharge at a scale of ~100 km^2 might include the following field components:

1. development of long-term water balances for the watershed at several different spatial scales;
2. measurement of discharge and geochemical parameters at all major springs over a period of years;
3. measurement of travel times and residence times using environmental isotopes, geochemical parameters, temperature, and tracer tests;
4. installation of monitoring wells and meteorological stations; continuous measurement of water-level and geochemical changes in these wells;
5. detailed mapping of surface topography, soils, and individual karst features such as sinkholes, exposed fractures, and closed depressions; identification of vegetation to find possible correlations with discharge zones at seeps.

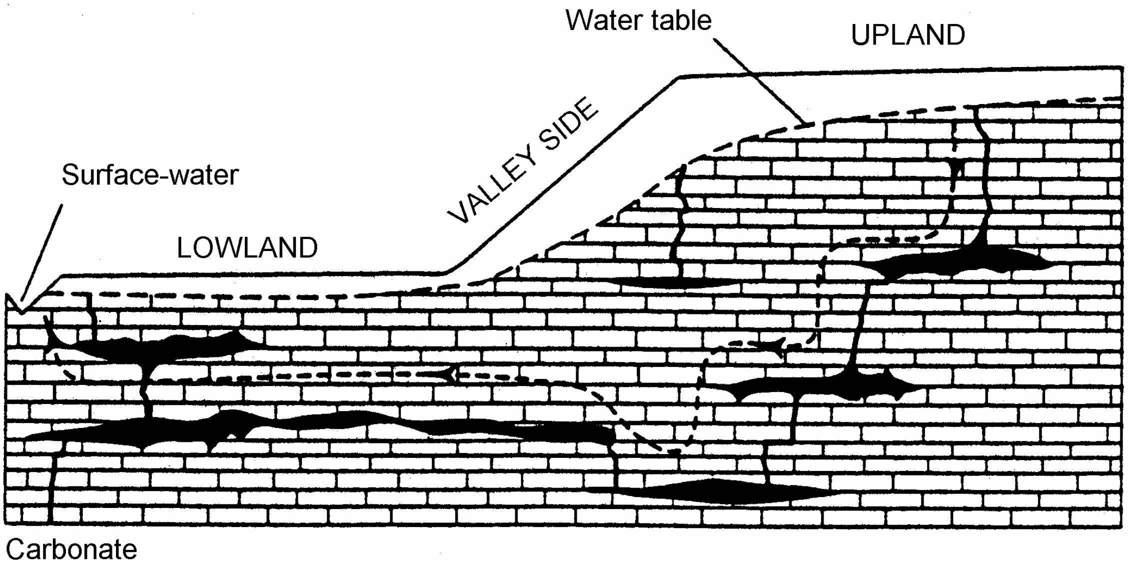


FIGURE 2-1 One type of karst Hydrogeologic Setting found in carbonate rock. The setting shown here is typical of well-developed karst with an integrated subsurface network but many other types of karst are found. SOURCE: Reprinted, with permission, from Winter (2001). © 2001 by American Water Resources Association.

Glaciated Midwest

Storage of groundwater in the glaciated Midwest can be large or small depending on whether the aquifer is confined or unconfined. High-intensity precipitation events commonly generate overland flow; in some instances the overland flow can converge on a topographic depression causing a type of focused recharge. Low-intensity rains provide diffuse groundwater recharge (Figure 2-2) provided the water is not intercepted by vegetation or used to replenish soil moisture. Antecedent soil moisture conditions and soil texture help determine whether rainfall results in overland flow (and associated focused recharge) or diffuse recharge. Generally, late fall rains and spring snowmelt events provide the majority of the annual recharge.

Focused recharge often occurs after extended periods of wetness such as snowmelt or a series of intense rains. The scale of focused recharge may be even smaller when considering the effects of macropores in the shallow soil column. Focused discharge areas are commonly characterized by springs or distinct hydrophytic (wetland) vegetation (e.g., Rosenberry et al. 2000). The presence of heterogeneities (i.e., zones of high or low hydraulic conductivity) can result in groundwater flow systems with complex three-dimensional distributions. In some cases distinct local and regional flow systems can develop (Toth, 1962).

The geochemistry of recharge water can be maintained along its entire flow path until it mixes with surface water at discharge points in both glacial outwash (Walker and Krabbenhoft 1998) and glaciated bedrock settings (Hunt and Steuer, 2000; Box 2-1). Vertical variation in geochemistry can be important where discharge is diffuse and redox conditions change (Box 2-2). While care is needed to characterize the spatial nature of recharge and discharge, temporal variability is less problematic in glacial sediments that have high hydraulic conductivity and storage. In these settings, a large amount of flow is captured by direct measurement of baseflow in streams and under steady state conditions an areally averaged recharge rate can be esti-

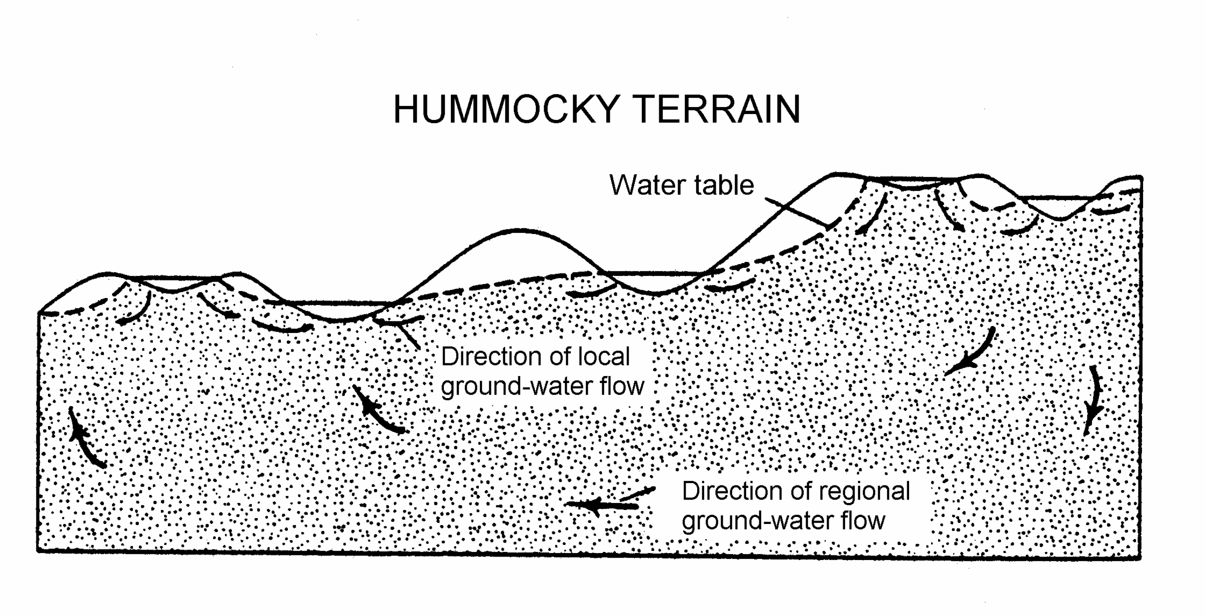


FIGURE 2-2 Glaciated Midwest (Hummocky) Hydrogeologic Setting. SOURCE: Reprinted, with permission, from Winter (2001). © 2001 by American Water Resources Association.

mated from discharge measurements. Glaciated areas can also have low conductivity sediments and/or confined units. In these settings the hydrologic system is flashier and less likely to be under steady-state conditions; thus, developing accurate estimates of recharge can be difficult.

Urbanization and agricultural practices have affected the magnitude and distribution of recharge. Both practices commonly involve draining and filling wetlands and modifications to the surface water system (e.g., channel straightening, impoundments, concrete lining). Urbanization may decrease both focused and diffuse groundwater recharge (e.g., Steuer and Hunt, 2001) by diverting recharge to stormwater conveyance systems. Moreover, interception by municipal wells can lower the amount of diffuse discharge (e.g., baseflow, and the groundwater component of wetland water budgets) and completely dry out focused discharge points such as springs (e.g., Bradbury et al., 1999). However, overall recharge often increases due to leaks from sources such water mains and sewers, which often contain water imported from other basins (Lerner, 2002). Agricultural practices common to the glaciated Midwest can reduce recharge rates by as much as ten times while practices under the USDA Conservation

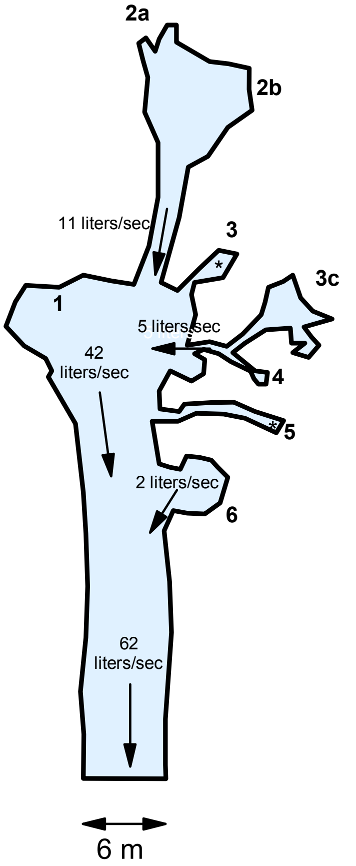
Reserve Program can significantly increase recharge rates (Steuer and Hunt, 2001). Agricultural pactices have led to contamination of many shallow midwestern aquifers by nutrients and pesticides (USGS, 1999).

Remote sensing of vegetation and the water content of soils, geomorphologic analysis, and field observation and mapping of diffuse and focused recharge and discharge over the watershed would be a first step towards evaluating recharge and discharge in the Glaciated Midwest. A benchmark watershed study to quantify recharge and discharge in the Glaciated Midwest at a scale of ~100 km^2 might include the following field components:

1. continuous measurement of groundwater fluxes at major discharge locations within the basin (streams/rivers/springs) over a period of years;

BOX 2-1
Horizontal Variation in Geochemistry of Focused Discharge into a Regional Spring Complex

One might assume that in areas of *focused* groundwater discharge relatively few samples would be needed to characterize water chemistry because focused discharge consists of an integrated, well mixed water volume channeled from a large collection area. However, this may not be true. Hunt and Steuer (2001) studied a regional spring discharge complex near an urbanizing fringe in south-central Wisconsin using numerical modeling and geochemical investigation (Figure 2-3). The spring had a discharge of about 3400 liters/minute (2 cubic feet per second), that drained an area of about 1000 hectares. Within the spring complex, large differences in spring water chemistry were noted even when vents were within 15 m of each other. Many constituents from carbon species to stable isotopes of water and strontium showed significant spatial variation within the spring complex. In the case of nitrate+nitrite, areas on one side of the spring were above drinking water standards and below them on the other. Particle tracking simulations demonstrated that the chemical variation was owing to distinct recharge areas that maintained their chemical signatures when discharged into the spring complex.



62 liters/sec = flow measured 4/6/2000
* = flow too low to measure

FIGURE 2-3 Map of spring complex with sampling locations. SOURCE: Reprinted, with permission, from Hunt et al. (2001). © 2001 by National Ground Water Association.

BOX 2-2
Vertical Variation in Geochemistry of Diffuse Discharge into a Wetland

In areas of *diffuse* groundwater discharge, vertical variation in water chemistry may be greater than horizontal variation. Hunt (1996) and Hunt et al. (1997) investigated a groundwater dominated wetland system in southwestern Wisconsin, in order to examine the type of sampling network needed to characterize the spatial and temporal patterns in the geochemical processes operating within the wetland. Four sites in the wetland complex were instrumented with typical water table wells and piezometers to capture relatively large scale trends, an array of suction lysimeters and mini-piezometers with 15 cm spacing for intermediate scale trends, and close interval membrane equilibrators with approximately 1.5 cm spacing for small scale trends. In this wetland, the large-scale instrumentation is insufficient to capture chemical variability, which can be substantial on the centimeter scale (Figure 2-4), and was generally larger than the horizontal variability. The vertical variability was also larger than the temporal variability over the growing season.

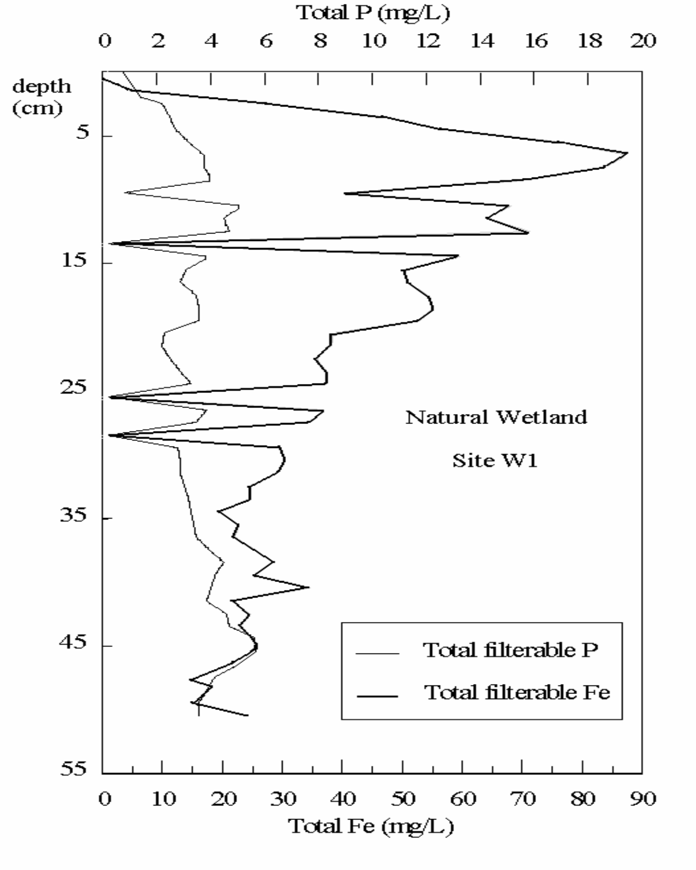


FIGURE 2-4 Chemical profile of total filterable phosphorus and iron within the wetland obtained using a close interval membrane equilibrator. Large changes in profile concentration were likely due to effects of plant roots. SOURCE: Reprinted, with permission, from Hunt et al. (1997). © 1997 by Kluwer Academic Publications.

2. stream hydrograph separation (using both physical and chemical methodologies) to discern baseflow, stormflow, and new and old water components;
3. identification of flowpaths using environmental isotopes, temperature, and tracer tests;
4. installation of monitoring wells and meteorological stations throughout the study watershed;
5. remote sensing with ground-truth of vegetation and moist soils to find possible correlations with discharge zones; and
6. synthesis of these data with coupled groundwater and surface water models that encompass the entire hydrologic system.

The models can be used to gain insight into processes and to identify data needs even when parameter uncertainty precludes accurate characterization and prediction. The models should be at the appropriate scale for the data collected. Thus, nested models would be used for simulating site-scale data and resulting parameters would be used directly or up-scaled for a larger scale model that includes the regional data (such as streamflow) (Chapter 4).

Finally, it should be noted that comprehensive data sets with large spatial and temporal coverage would be useful to assess scaling and the effects of heterogeneity at various scales.

Mountain and Valley

Mountain-dominated terrains constitute 20 percent of the earth's surface (Forster and Smith, 1988a). Mountainous terrain is found in several parts of the U.S.: the Western mountain ranges, the Basin and Range province, the Pacific Coastal Range/Central Valley of California, and the Appalachian region. The mountainous portions (uplands) are often rugged and are composed of exposed rock, or may have a weathered zone of a few tens of meters and be covered with vegetation, making direct measurements of groundwater recharge difficult (Forster and Smith, 1988a). The water table associated with the valley sides (sloping bedrock and alluvial fans) tends to be located in the bedrock or found near the base of thick alluvial deposits (Figure 2-5) making direct measurements costly (Forster and Smith, 1988a, b). Valley lowlands are covered by alluvial sediment. Sources of recharge to mountain and valley settings include diffuse direct infiltration of precipitation, including melting snowpack, to the mountain mass, valley slopes and lowlands. Discharge in these systems occurs locally as focused spring flow and seeps, and as diffuse inflow to streams and as focused discharge as water is transpired or lost to the atmosphere by direct soil evaporation in the riparian zone. Discharge measurements in these settings generally rely on standard stream gauging techniques and estimates of evapotranspiration.

In arid regions of the Western U.S., especially the Basin and Range province, closed basins surrounded by mountains may contain dried up lakes known as playas. In this setting focused recharge infiltrates the alluvium around the edge of the basin from streams that enter the basin from the surrounding mountains. Groundwater converges toward the playa where phreatophytes discharge groundwater.

In many mountain-valley groundwater system investigations and watershed models, water balance approaches are used to compute groundwater recharge or discharge rates by difference. Fluxes are then related to precipitation by developing a factor used to convert precipitation data to groundwater recharge (e.g., Maxey and Eakin, 1949). Discharge rates are measured when possible (e.g., changes in groundwater baseflow to streams) and estimated when the process is diffuse (e.g., evapotranspiration). For an example of the application of these methods see Lambert and Stolp (1999) for the Tooele Valley, Utah.

A benchmark watershed to study recharge and discharge in this hydrogeologic setting might include the following field components.

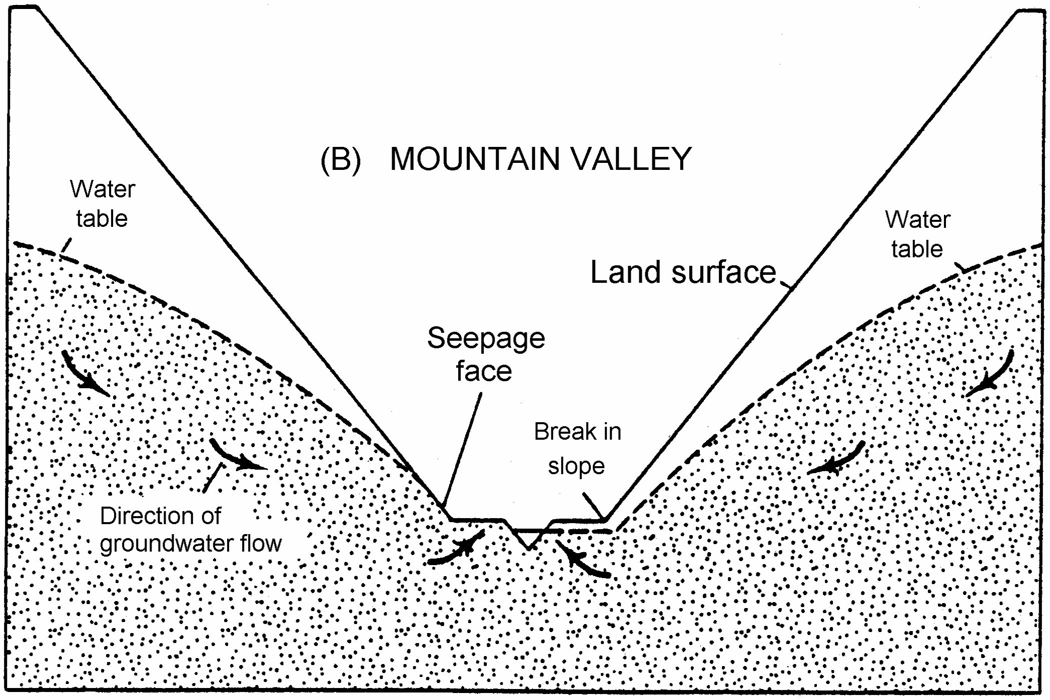


FIGURE 2-5 Mountain valley and playa hydrogeologic. SOURCE: Reprinted, with permission, from Winter (2001). © 2001 by American Water Resources Association.

1. Quantification of focused and diffuse recharge and discharge requires quantification of precipitation, snowpack storage, vegetation and runoff. Application of appropriate analytical techniques requires consideration of climatic data, distribution of soils, vegetation types and densities, and topographic setting. Mass and energy budget techniques need to be applied to define the fate of basin sources and sinks of water (Winter, 1981; Reiner et al., 2002).

2. Micrometeorological data such as net radiation, temperature, humidity, rainfall, snowpack, and wind data combined with soil moisture and soil heat flux information should be collected using remote recording meteorological stations strategically placed in the lowland, valley slope and upland portions of a study site. Land use and soil types, and vegetation types, densities and properties such as leaf area indexes, need to be spatially and temporally identified. Basin wide data collection over a number of annual cycles could be accomplished using a variety of remote sensing techniques, including airborne and satellite platforms supported by ground truth studies.

3. Quantifying the portion of basin recharge entering the bedrock mountain region would be based on the collection of hydrogeologic data sets at and immediately adjacent to the alluvial-bedrock contact within the primary recharge area. Nests of monitoring wells paralleling the mountain front and located along downgradient flowlines outfitted with continuous water level recorders could generate time dependent three-dimensional images of groundwater potential. Aquifer testing would provide estimates of hydraulic properties. Geophysical surveys would determine the depth of valley fill and its stratigraphy. In addition, the chemistry of the precipitation, stream flow (where present), and mountain mass (spring discharge) and alluvial groundwater at and downgradient of the mountain mass-alluvial fan interface would be obtained.

Physical and geochemical data would be used to compute flux rates from the mountain bedrock into the alluvial sediments. Analysis of isotopic signatures of snowpack might prove useful in determining the role of melting snowpack in recharging groundwater.

4. Focused recharge occurs as water from streams originating in the mountains flows across the adjacent alluvial fans. Recharge could be estimated from stream flow losses measured by performing standard seepage runs of these streams in conjunction with electrical resistance sensors (Blasch et al., 2002) to indicate streamflow timing. A research basin would include a number of continuous recording stream gauging stations to provide continuous information on seepage rates.

5. In the discharge areas, stream groundwater exchange in valley systems with rivers could be quantified using seepage runs and gauging stations. Riparian vegetation mapping, using airborne and satellite platforms, tied with climatic data and modeling would be used to estimate diffuse discharge.

Coastal/Estuarine

Coastal areas (Figure 2-6) are the terminus of groundwater flow systems; in some cases reflecting discharge from a local-scale flow system bordering the coast, and in other cases reflecting the distal end of a confined or unconfined regional flow system. Environments of interest include open coastlines, embayments where discharge may be focused, and estuaries at the mouths of rivers.

Freshwater seepage below the high tide line is called submarine groundwater discharge or SGD (e.g., Burnett et al., 2002; Taniguchi et al., 2002). Two factors greatly complicate the analysis of groundwater discharge in the immediate vicinity of the coastline: the position of the salt water interface influences the location of discharge sites, and tidal fluctuations cause reversals in the groundwater flow direction. Estuaries can pose an additional challenge if salt water moves in and out of the river channel during tidal cycles and with seasonal variations in river discharge.

A large body of literature exists on the behavior of the salt-water interface, especially the response of the interface to pumping from coastal wells. Most research has been on the landward movement of salt water in a coastal aquifer. Surprisingly less attention has been paid to the complementary case of freshwater discharge into the near-shore marine environment. In part this may reflect the difficulty of measuring direct discharge into the coastal zone (Burnett et al., 2001). The importance of SGD in the near-shore marine environment is primarily related to the delivery of nutrients such as nitrogen or phosphorous to the marine ecosystem. In areas with industrial development, SGD can be a significant pollutant vector in the coastal zone. The salt-water interface can be viewed as a hydraulic barrier to freshwater discharge. Where the freshwater flux is higher, it is able to displace the interface seaward and create a region within and beyond the intertidal zone where freshwater discharges through the seabed (Figure 2-7). It is unlikely that this process will be spatially uniform. Furthermore, tidally-driven and convective mixing processes within the upper few meters of the seabed cause this freshwater to co-mingle with the infiltrating saline water, so that observations of discharge at the seabed nearly always carry a significant seawater component (known as re-circulated sea water).

In an unconfined aquifer, the magnitude of the freshwater discharge generally decreases exponentially with distance offshore, and is likely to be limited to a distance offshore that roughly corresponds to a length two to three times the thickness of the unconfined aquifer (McBride and Pfannkuch, 1975). In settings with lower seaward groundwater fluxes, the freshwater discharge is likely to be predominantly occurring on the seepage face that forms during a falling tide. In a coastal setting where a confined aquifer extends offshore, it is possible for freshwater to migrate substantial distances beyond the coastline, perhaps several tens of kilometers or more. This freshwater may leave the system as either a diffuse upward leakage

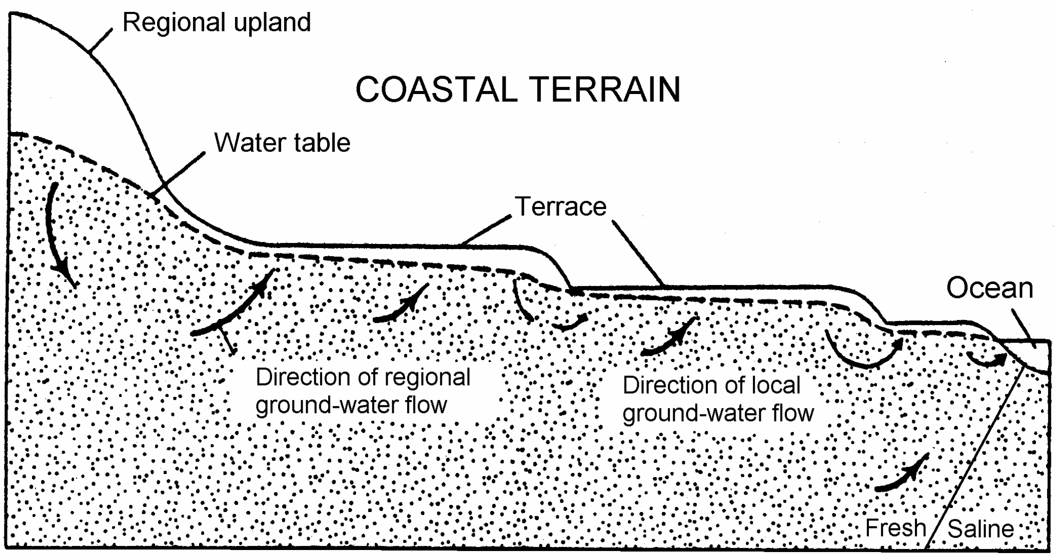


FIGURE 2-6 Coastal hydrogeologic setting. SOURCE: Reprinted, with permission, from Winter (2001). © 2001 by American Water Resources Association.

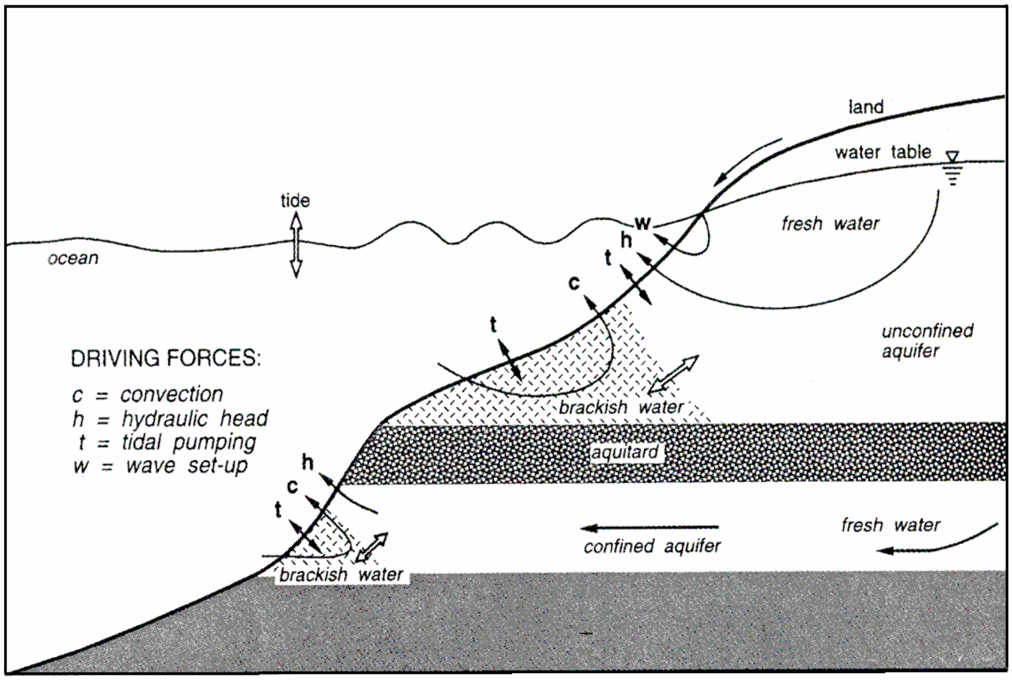


FIGURE 2-7 = Schematic depiction of processes associated with submarine groundwater discharge. Arrows indicate fluid movement. SOURCE: Modified from Taniguchi et al. (2002).

BOX 2-3
Measuring Submarine Groundwater Discharge

A team of researchers sponsored by the Scientific Committee on Oceanic Research, the Land-Ocean Interaction in the Coastal Zone Project, and the Intergovernmental Oceanographic Commission, has been carrying out experiments to compare different methods of estimating submarine groundwater discharge (SGD) in the near-shore marine environment. To date, measurements have been made at three sites; the Florida State University Marine Lab on Apalachee Bay in the northeastern Gulf of Mexico, in Cockburn Sound south of Perth, Australia, and in Long Island Sound, New York. The experiment in Florida (Figure 2-8) illustrates the approach of this interdisciplinary team of oceanographers and hydrogeologists (Burnett et al., 2002).

Three principal techniques have been compared to estimate the magnitude of submarine groundwater discharge: (1) direct measurement with manual and automated seepage meters, (2) isotopic techniques that use natural geochemical tracers to estimate the component of SGD present in the water column above the seabed, and (3) hydrogeologic modeling. Manual seepage meters to measure flow directly, and both heat-pulse and ultrasonic automated recording meters were placed on the seabed. The main tracers examined were radon and radium isotopes. A series of piezometers on the beach and in the offshore zone provided the key data for constructing a hydrogeologic model of the site.

The three types of seepage meters yielded similar estimates in side-by-side deployments. Automated meters provide the advantage of yielding a continuous record of the seepage that can be correlated to the tidal cycle (Figure 2-9). There was also reasonable consistency between the estimates of SGD derived by integrating the point estimates of SGD from the seepage meters across a zone extending 200 m offshore, with the estimates derived from geochemical tracers. Predictions of SGD using a density-dependent groundwater flow model yielded values for the offshore discharge that were approximately one order of magnitude smaller than these estimates. Work is continuing to understand this discrepancy. One possibility is that the hydrogeologic model did not account for transient processes that occur at the seabed, such as tidal pumping, the effects of which should be recorded by the other techniques.

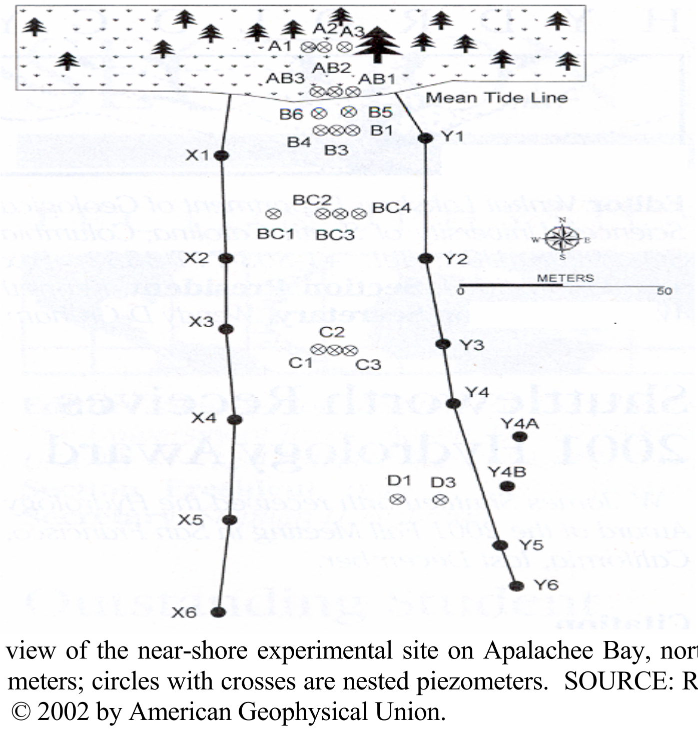


FIGURE 2-8. Schematic view of the near-shore experimental site on Apalachee Bay, northeastern Gulf of Mexico. Closed circles are seepage meters; circles with crosses are nested piezometers. SOURCE: Reprinted, with permission, from Burnett et al. (2002). © 2002 by American Geophysical Union.

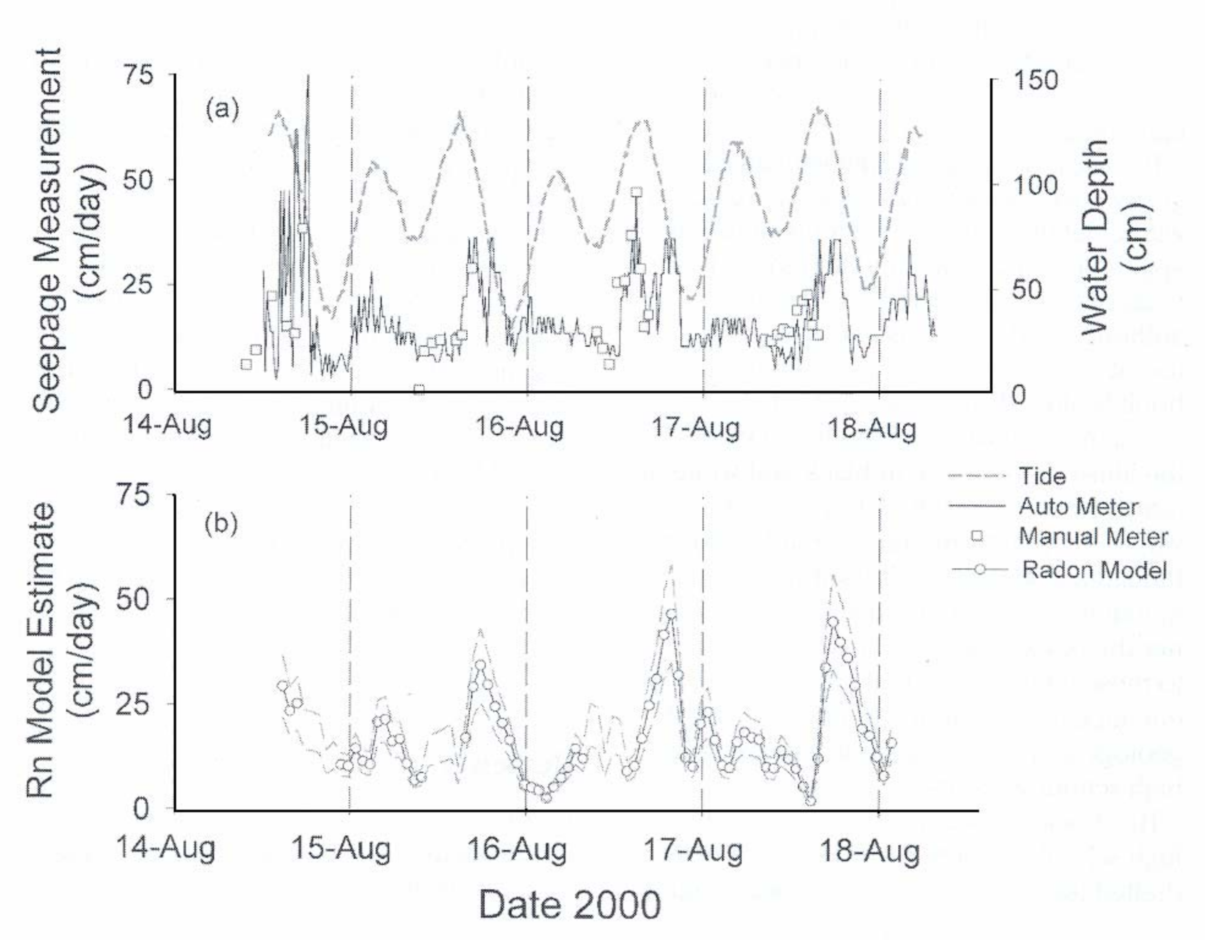


FIGURE 2-9. Records of (a) automated and manual seepage measurements at station Y4 (left-hand scale) and water depth (right-hand scale); and (b) seepage flux estimates based on modeling radon measurements. The gray dashed lines in (b) are 25% uncertainties of the estimates. SOURCE: Reprinted, with permission, from Burnett et al. (2002). © 2002 by American Geophysical Union.

across the confining bed, or as freshwater springs on the seabed where fractures or solution features focus discharge.

SGD occurs in a dynamic hydrologic environment. Driving forces originate both on land (e.g., fluid pressures beneath the sea bed that exceed the seafloor hydrostat, or a response to a local precipitation event in an unconfined system), and in the ocean (wave action, diurnal and spring / neap tides). Measurement techniques for SGD have been developed by both oceanographers and hydrogeologists. Oceanographers have emphasized the interpretation of various natural geochemical tracers as an indicator of the proportion of freshwater in the marine water column (Burnett et al., 2002). Examples of these tracers include methane, radon gas and radium isotopes. Tracer techniques provide a spatially averaged estimate of SGD. Hydro-geologists have used direct measurement techniques such as seepage meters placed on the seabed

(Taniguchi, 2002), or calibrated discharge using land-based groundwater flow models (Burnett et al., 2002). They have also inferred the magnitude of SGD using borehole temperature data (Taniguchi et al., 1998), pore pressure measurements (Davis et al., 1991; Schultheiss, 1990) or other techniques in conjunction with electrical conductivity (Harvey et al., 1997; Vanek and Lee, 1991) or temperature mapping (Henry et al., 1992). Where comparisons have been made among these various approaches or techniques, there has not always been uniform agreement among the estimates (see Box 2-3). Airborne thermal mapping has been successful in locating areas with enhanced SGD. Direct measurement of SGD is more problematic if the seafloor is rocky and bare of sediment, unless it occurs as focused discharge at a karst spring. At times or at sites with high surf, it is difficult if not impossible to seat any measurement devices on the seabed.

There is only limited understanding of the character of spatial and temporal variations of SGD, which creates difficulties in deciding upon sampling plans for direct measurement of SGD. It is possible that relatively small differences in the silt content of the seabed sediments may create substantial focusing of discharge below the low tide line. Other, still ill defined processes may also be involved. At Waquoit Bay on Cape Cod Massachusetts, measurements of seepage fluxes using a large array of seepage meters yielded a pattern of discharge that could not be explained with simple hydrologic models (Michael et al., 2003). There is a clear need for the accumulation of field observations in a number of different coastal settings, with differing geology, and differing magnitudes of the seaward movement of freshwater.

To a degree, benchmark sites to study discharge in this hydrogeologic setting already exist (Box 2-3). Several coastal LTER sites also exist – Florida Coastal Everglades, Georgia Coastal Ecosystems, Virginia Coast Reserves, and Plum Island Ecosystem. Research on small-scale flow systems has already been done at several of these sites.

3

Interactions of Groundwater with Climate

Water and energy are freely exchanged among the continents, the atmosphere, and the oceans, and these exchanges are, in many ways, the defining characteristics of climate. Groundwater is by far the largest unfrozen stock of fresh water (Maidment, 1993). In some cases, the physical processes of interaction between groundwater systems and climate are well understood qualitatively, but quantitative and practical consequences are unknown. In other cases, interactions may be speculative or yet undiscovered.

Climate and the hydrogeologic environment are the joint controls of groundwater recharge, discharge and storage. Amounts and pathways of aquifer recharge differ greatly from humid to arid climatic regions, with consequent influences on groundwater storage and discharge. Temporal changes in climate are reflected in groundwater fluxes, albeit with dampening of high-frequency variations

Not so obvious is that groundwater fluxes may have significant reciprocal impacts on climate and climate-related aspects of the Earth system. Groundwater fluxes are a component of the surface water balance, which is tightly coupled to atmospheric processes and, thus, to climate. Because groundwater is one of the major reservoirs in the hydrosphere, changes in its volume would also be reflected ultimately by changes in sea level.

Groundwater may also play an important, indirect role in determining climate by affecting atmospheric composition. Atmospheric concentrations of radiatively active gases such as carbon dioxide and methane are determined partially by exchanges with the continents. Such exchanges may be affected by water fluxes between the atmosphere and land and by biogeochemical processes near the land surface. The latter can be strongly influenced by soil moisture, which may be influenced by groundwater (e.g., high water tables), with consequences for soil aeration, microbiological activity, and greenhouse gas emissions. This is particularly true for northern peatlands. The location of the water table determines whether the peat is subjected to aerobic or anaerobic decomposition rates, which are substantially different, and the subsequent release of methane and carbon dioxide."

This chapter focuses on three topics: how climate affects groundwater fluxes, how groundwater fluxes affect climate, and how groundwater storage may have potential to indirectly affect the composition of the atmosphere, especially greenhouse gasses. Many kinds of studies within these areas could be done at the benchmark sites recommended in Chapter 2.

INFLUENCE OF CLIMATE ON GROUNDWATER

Groundwater recharge is determined to a large extent as an imbalance at the land surface between precipitation and evaporative demand; the latter depends primarily on the surface radiation balance and also on atmospheric temperature, humidity and windspeed. When precipitation exceeds evaporative demand by an amount sufficient to replenish soil-water storage, any further excess flows deeper into the ground, arriving at the water table as recharge. Groundwater systems, therefore, respond to temporal variations in climate. Because of the relatively slow response of many groundwater systems to changes in forcing (Townley, 1995; Haitjema, 1995), however, they tend to reflect much more the low-frequency "climate" signal than the high-frequency "weather" fluctuations (e.g., Box 3-1). This tendency contributes to the value of groundwater as a resource by imparting to it a high degree of temporal stability. It also can cause significant lags between climate changes and the resultant changes in groundwater characteristics.

Given the relatively long response times of groundwater systems, it is the climatic variations at longer time scales that most strongly influence changes in groundwater discharge. At shorter time scales, groundwater recharge will be affected by the short term variations of precipitation and evapotranspiration, and their relative magnitudes. Long term trends in the balance between precipitation and evapotranspiration (decades to centuries), caused by either long term variability or by anthropogenic global change, can be expected to cause fundamental changes in distributions of groundwater recharge (Vaccaro, 1992) and availability.

As an example of the impact of climate warming on recharge, the melting ice sheets may have contributed significantly on recharge to confined aquifer systems (e.g. Breemer et al., 2002). Geochemical evidence exists suggesting many confined aquifer systems of North America and Europe have experienced high recharge rates via sub-ice sheet recharge during the last glacial maximum (e.g., Siegel, 1991; Siegel and Mandle, 1994). Evidence for this paradigm comes from observations of isotopically light, low-salinity groundwater within the discharge area of the Williston Basin. Grasby et al. (2000) presents compelling evidence that the recharge beneath the Laurentide ice sheet reversed groundwater flow directions during the last glacial maximum. Since ice sheets were the dominant land cover of northern latitudes for the last 2 million years (Peltier, 1998), ice sheet topography may have controlled recharge to deep aquifer systems in Canada and northern North America.

In more recent times and at shorter time scales, climate variability and change also affect rates of groundwater recharge and discharge. For example, a rising water table may increase the near-surface soil moisture and streamflow, causing major changes in surface vegetation and ecosystems, in the extreme by creating or expanding wetlands and thereby affecting surface processes that influence recharge/discharge rates. Conversely, a decline in the water table may significantly reduce evapotranspiration and surface water discharges, also affecting vegetation and ecosystems. Changes in groundwater discharge may influence fluvial and estuarine habitats. Pumpage from developed aquifers also depend on evapotranspiration rates, growing season lengths, temperatures, and other climatic variations.

Groundwater hydrologists recognize these strong controls on groundwater recharge and discharge by climate. It is recognized, for example, that in arid regions much of the water being exploited today comes from aquifers that were recharged at higher rates during wetter or cooler conditions in the past (e.g., Zhu et al., 1998). Paleoclimate descriptions and data offer an important tool for providing long-term descriptors between climate variability and groundwater, especially as it affects lake levels. For example, Smith, A. et al. (2002) showed that about 5000 years ago, Elk Lake (Grant County, western Minnesota) dropped over 15 meters in response to the mid-Holocene warm period when the prairie-forest border shifted eastward from the Minnesota-North Dakota into Wisconsin. An extensive quantitative database exists for North America characterizing changes in climate during the Holocene and late Pleistocene using climatic

BOX 3-1
Amplification of Seasonal to Century Scale Oscillations in Closed Basins: The Role of Groundwater Fluxes in a Mountain-Front Setting

Mountain-front recharge and surface-groundwater interaction have a central role in closed-basin-lake response, forced by climate fluctuations at seasonal, interdecadal and century time scales. The hydrologically closed mountain and basin systems of the Great Basin Physiographic region of the western United States, and in particular the Great Salt Lake basin, in north-central Utah, creates an ideal environment to study the impact of climate variability on a terrestrial system where subsurface flow and discharge to mountain-front streams are forced by orographic precipitation and basin evaporation. Shun and Duffy (1999) hypothesized that the water cycle within topographically and hydrologically closed landforms of the Great Basin represent a multiscale averaging of the climate signal. They further hypothesized that dominant time scales of streamflow and lake level are determined by the space-time scales of storage within the system.

A conceptual model of the hydrogeology of the Wasatch-Front (Shun and Duffy, 1999) suggests that groundwater may play an important role in the interannual and decadal-scale dynamics of lake levels through stream-aquifer interaction and groundwater discharge. Deep groundwater upwells and discharges to the low end of streams before entering the Great Salt Lake (GSL). The ultimate source of this water is recharge at high elevations through the mountain block and mountain-front, and channel losses across the alluvial deposits adjacent to the mountain-front.

The GSL historical record is one of the longest measured climatic records in North America. The lake volume spectrum for the period 1847-1997 is shown in Figure 3-1. The labeled, filled circles on the graph at the edge of, or beyond, the noise spectrum, represent probable signals amid the noise. While the annual signal shows up strongly, lower-frequency (long period) interdecadal oscillations (i.e., the points labeled 11 and 14 years on Figure 3-1) are also prominent. The rivers along the Wasatch Front have the same spectral signature (not shown) as the low-frequency modes in the Great Salt Lake, suggesting that areal recharge and losing-gaining streams crossing the mountain-front contribute substantial amounts of ungaged flow to deep groundwater in the upper parts of alluvial fans that ultimately returns as baseflow (feedback) to the lower reaches of streams before entering the lake, or as underflow from fractured bedrock to basin sediments.

The relation of the time scale of runoff to altitude is further demonstrated with the "noise-removed" precipitation-temperature-runoff phase-plane plots at three elevations in the Wasatch Range (Figure 3-2). Note that at high elevation, monthly runoff is closely correlated with monthly precipitation and temperature, while at low elevation the dampening effect of upwelling groundwater smears this correlation. Research is necessary to explore what this behavior can tell us about unsaturated moisture flow, feedback and coupling of surface and groundwater at multiple elevations, and resonance–like effects that may arise from stochastic and periodic forcing in such systems.

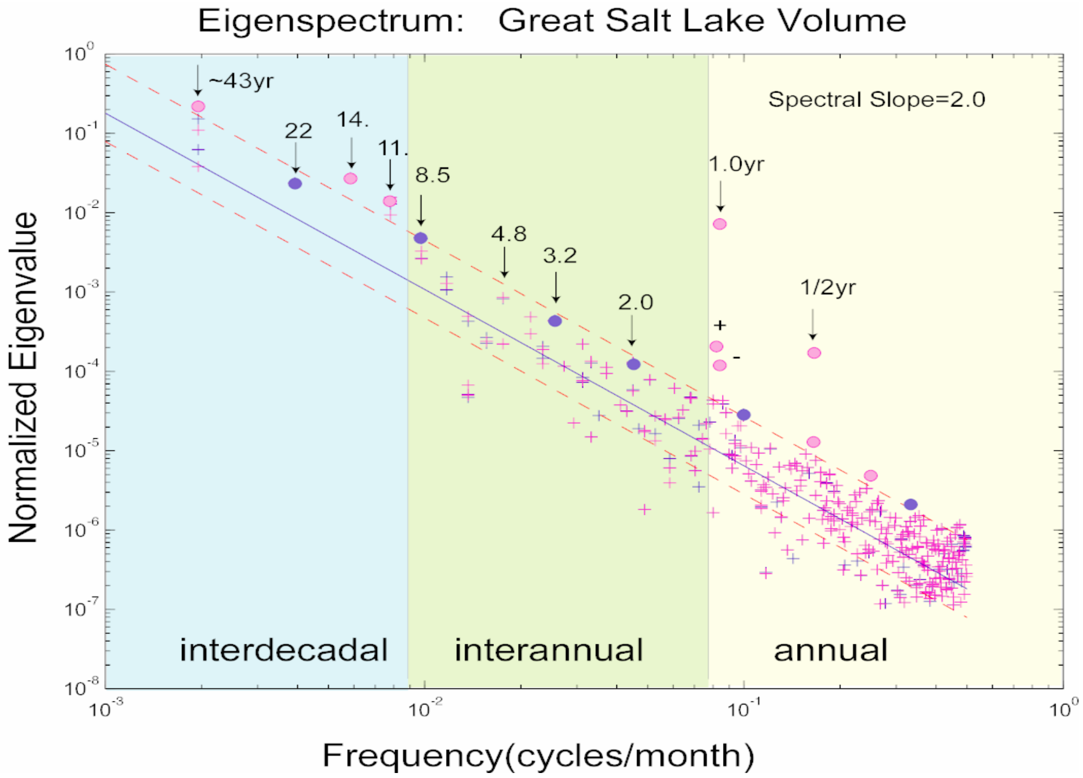


FIGURE 3-1 The spectrum for the historical record of the Great Salt Lake produced from bimonthly volume time series 1847-1997. The labeled, filled circles on the graph represent probable signals above or at the upper range of the noise envelope. Aside from the annual and semi-annual signals (indicating the obvious effect of yearly and seasonal changes in temperature and precipitation on runoff), interdecadal oscillations (i.e., the points labeled 11 and 14 years on Figure 3-1) are also prominent. This suggests that the groundwater basin may be amplifying these lower-frequency components of the climate signal. SOURCE: Reprinted, with permission, from Shun and Duffy (1999). © 1999 by American Geophysical Union.

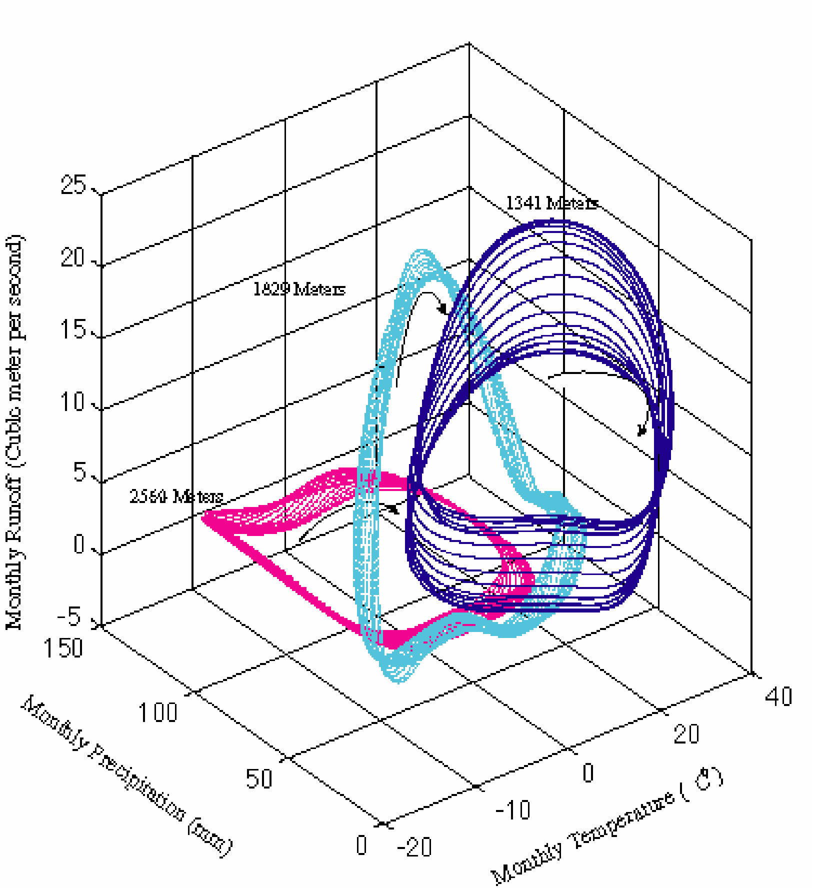


FIGURE 3-2 The 40yr "Noise-removed" precipitation-temperature-runoff (P_T_Q) phase-plane plot for three elevations along the Wasatch Front. These three variables represent the mountain-front water cycle, with each loop representing one year. At high elevation, oscillation is tightly bound (i.e., monthly runoff is closely correlated with monthly precipitation and temperature), reflecting the influence of seasonal conditions, while the low-elevation oscillation for P_T_Q is smeared out, representing the dampening effect of upwelling groundwater. This low-frequency contribution to runoff is derived from the climate but is amplified by the long-time scales of mountain-front recharge and valley discharge. SOURCE: Reprinted, with permission, from Shun and Duffy (1999). © 1999 by American Geophysical Union.

reconstructions based on lake-sediment cores. Quantitative reconstructions of paleoclimate have been developed using spatial and temporal changes in the assemblages of aquatic plant macrofossils, ostracodes, diatoms, pollen and chironomids, as well as sediment geochemistry and sediment facies information to infer changes in lake levels, paleo lake salinity, precipitation, and temperature (e.g. Bartlein and Whiltlock, 1993; Bernabo and Webb, 1977; Webb et al., 1998; Fritz et al., 2000). Filby et al. (2002) demonstrated paleoclimatic reconstructions based on pollen-transfer functions could reproduce mid-Holocene lake levels (four meters below modern) using a hydrologic model of groundwater-surface calibrated using a modern historical records of hydrologic stresses within the Shingobee watershed in Northern Minnesota.

For influence of climate variability on groundwater more recently, lake shore reconstruction through historical data bases can provide important information when linked to historical climate variability. For example, Donovan et al. (2002) used air photo analysis of lake shore lines across a glaciated watershed in Grant County, western Minnesota to document historical declines in lake and aquifer levels by over 5 m in response to drought conditions during the dust bowl (1923-1938). All but the deepest, lowest elevation lakes completely dried up during this time period.

With respect of the influence of potential effects of climate change on major aquifer systems, the above paleo and historical analyses can help in providing a setting for anticipated change, and for the modeling studies of anticipated change on groundwater systems. For example, Loaiciga et al. (2000) developed alternative scenarios of future temperature and rainfall in south-central Texas based upon projections from seven general circulation models (GCMs) of a doubling of carbon dioxide in the atmosphere. The scenarios of temperature and rainfall were used to calculate recharge of the aquifer, which occurs primarily through seepage of water from streams that cross the aquifer. The impacts of these scenarios on water levels and natural springflows were assessed for different rates of groundwater pumping. Most of the scenarios showed that water resource problems that already exist in the area would be exacerbated.

Rosenberg et al. (1999) analyzed the prospects for recharge rates of several regions of the Ogallala aquifer under climate change by analyzing climate predictions for 30 different scenarios of three GCMs, including four levels of temperature and three levels of CO_2 concentration. A hydrologic model, HUMUS, was coupled in daily time-steps to a vegetation-crop model to estimate irrigation needs and evapotranspiration.

Other studies include Bouraoui et al.'s (1999) simulations of reduced groundwater recharge near Grenoble, France, mostly due to increases in evaporation during the recharge season, and Vaccaro's (1992) study of the climate sensitivity of groundwater recharge for the Ellensburg basin of the Columbia Plateau in Washington. Another useful approach is to evaluate the response of a groundwater system to climatic conditions in the past through an analysis of paleowaters (e.g., Remenda et al., 1994). Despite these and a few other studies, the vulnerability of groundwater systems to climate changes and the implications for society and ecosystems remain poorly explored.

Climate variation and change will affect groundwater systems primarily by changing the rates and distributions of recharge of water to aquifers, the discharge of water from aquifers, and the removal of groundwater from aquifers by plants and human activities as near-surface water availability and energy inputs change. At long time scales, the salinity conditions and discharge at the freshwater/salt water interface of coastal aquifers may (or may not) be in equilibrium with modern ocean levels and conditions (Kohout, et al., 1977; Essaid, 1990; Voss and Andersson, 1993), and a better understanding these conditions and the underlying causes would enhance the understanding of climate-scale variability of coastal aquifers. Therefore, a better understanding of how groundwater recharge, discharge and demands vary with climatic fluctuations and change will be the first and most essential requirement for addressing the broader question of climate impacts on both the surface and subsurface hydrology.

For changes in the last century, preservation and analysis of groundwater level records in areas unaffected by direct human influences will be particularly useful. Streamflow records also contain information on spatially integrated, historical variations in groundwater discharge and these records should be fully exploited. Baseflow separation techniques can be combined with other data, such as that from chemical tracers, to provide increased confidence in physical interpretations. For information over a range of time scales, additional isotopic and geochemical studies of groundwater would be useful. The isotopic signature of water is a function of climatic factors such as temperature and humidity, and could inform investigations of natural climatic variations and of anthropogenic climate change (e.g., Shanley et al. 1998).

For regional to continental scales, satellite gravimetry (e.g., NASA's Gravity Recovery and Climate Experiment, or GRACE; see Box 4-1) shows promise for identifying changes in the water table by periodically measuring the Earth's gravity field (Wahr et al., 1998; Rodell and Famiglietti, 1999). Altimetric techniques, such as Interferometric Synthetic Aperture Radar (InSAR) (Amelung et al., 1999), laser and microwave altimetry, and global positioning systems (van Dam et al., 2001) permit measurement of vertical displacements of the land surface that can be directly indicative of subsurface pressure changes and/or changing groundwater loads. Altimetry may also prove useful for synoptic monitoring of surface-water levels that can be indicative of changes in either discharge or groundwater storage, depending on hydrogeologic framework.

Once recharge, discharge, and demand responses to climate variations can be projected with some level of confidence, any number of existing methods and models of groundwater resources and responses to change can be employed to assess the eventual vulnerabilities of groundwater systems (as parts of the natural world and human resource-supply systems) to long-term climate change.

INFLUENCE OF GROUNDWATER ON CLIMATE

Areas of groundwater discharge moisten and cool the atmosphere, with desert oases providing one example of this phenomenon. Similarly, persistent temporal anomalies in groundwater storage could condition local anomalies in climate, as climate is sensitive to water and energy balances (Yeh et al., 1984; Milly and Dunne, 1994). The partitioning of precipitation into runoff and evapotranspiration, and the partitioning of available radiation into sensible and latent heat fluxes (directly related to evapotranspiration) into the atmosphere establish boundary conditions that help drive both the atmospheric and oceanic circulations. The surface-water-balance partitioning is thus at the crux of these controls.

To the extent that groundwater systems influence evapotranspiration and runoff, they will influence climate. From a surface perspective, groundwater flow systems collect recharge from certain parts of the landscape, store it, and redistribute it to other parts of the landscape as discharge. These processes provide non-local and temporally stable sources of water for evapotranspiration and induce runoff of precipitation in groundwater-discharge areas. Thus, spatial and temporal characteristics of groundwater flow systems have the potential to alter the spatial and temporal patterns of water-balance partitioning (Salvucci and Entekhabi, 1995), and ultimately climate. For the same reasons, groundwater fluxes may influence sensitivities of water balance and climate to external forcing, such as land-cover change.

Influences on Climate Projections

The well-recognized and central importance of conditions very near the land surface for water-balance partitioning (Milly, 1994a,b) has perhaps obscured the potential importance of groundwater systems to affect atmospheric interactions. Most atmospheric models used for climate simulation have a one-dimensional representation of "soil moisture" that conceptually represents water in the plant root zone. Often, effects of groundwater must be parameterized in terms of, or "aliased" into, the "soil moisture" variable. While models may be tuned to account for some resulting biases, the confidence in the ability of the model to represent sensitivities to climatic variations must be questioned. A few investigators have recently incorporated the effects of landscape and lateral soil-water flow (i.e., interflow) on water balances (Famiglietti and Wood, 1994; Stieglitz et al., 1997; Koster et al., 2000). Continued progress may result from consideration of greater time and space scales, beginning perhaps with representation of the permanent water table within a landscape-based framework (Salvucci and Entekhabi, 1995; Winter, 2001).

In current weather-prediction and climate models, the partitioning of water and heat at all land surfaces is largely dependent on the availability of water in soil layers that extend down through the root zone (or slightly below). In the past decade, the weather-prediction community has learned that (short term) weather variations and predictions are sensitive to imposed or parameterized soil-moisture conditions (e.g., Atlas et al., 1993; Beljaars et al., 1996; Paegle et al., 1996). Climate models also are sensitive at both local and continental scales, to the parameterization and behavior of soil moisture (e.g., Charney, 1975; Xue and Shukla, 1993; Zeng and Neelin, 2000). Soil moisture, through its influence on the partitioning of heat and moisture fluxes at the land surface, provides potentially important feedbacks affecting continental precipitation and temperatures by modulating the Bowen ratio and (on climate time scales) vegetation land cover with its effects on albedo and roughness of land surface, which in turn modulate the forms and intensities of heat and momentum fluxes into the atmosphere on a variety of time scales.

The response time of many groundwater systems will greatly exceed that of some types of climate change (e.g., century-scale “greenhouse” global warming). Such systems will provide a stabilizing influence, continuing to deliver discharge that has already been “in the pipeline” for hundreds or thousands of years. These discharges are probably not large enough to be a major influence on global climate. However, groundwater influences at regional and, especially, local scales, where society interacts with groundwater systems, are more uncertain and variable, and therefore are an issue deserving careful evaluation, especially as our climate simulations telescope to increasingly small scales in the near future. Furthermore, given the nonlinear nature of hydrologic and Earth system processes, groundwater may alter the perceptible time scales of those processes (e.g., Duffy, 1996).

Influence of Changes in Groundwater Storage on Sea Level Rise

Sea-level rise during recent decades has been estimated to be 1.0-2.0 mm/y (IPCC, 2001), and the true value may be near the upper end of this range (Douglas and Peltier, 2002). Such a large rise is not fully explained by expansion due to ocean warming and glacier- and icecap-storage changes. Because groundwater is one of the major reservoirs in the hydrosphere, changes in its volume are likely to be reflected in the ocean volume. For example, a comprehensive tabulation of groundwater from the Mississippi River basin (Milly and Dunne, 2001), including much of the High Plains aquifer, suggests a contribution to sea-level rise on the order of 0.02 mm/y from groundwater-level changes in that basin. Groundwater mining thus could be a contributor to changes in ocean mass. Crude estimates of the global scope of mining (Gornitz, 2000) support this hypothesis, but leave a wide range of uncertainty. Extensive drainage of wetlands during the past century also may have contributed to sea-level rise, as may natural fluctuations in groundwater storage driven by climatic variability (P. C. D. Milly, USGS, written commun., 2003).

The following are needed in order to examine the consequences and importance of feedback mechanisms between groundwater and climate:

(1) Monitoring of groundwater-storage changes at large scales and over long observational periods as an indicator of climate and water cycle change on the largest scales. This can be done by detecting small changes in land-surface elevation (InSAR) and gravitational potential (Rodell and Famiglietti, 1999; 2001; 2002), properly validated with ground-based physical or geophysical measurements of groundwater level.

(2) Parameterizations of the groundwater function in global climate models for numerical experiments and climate projections. Key ingredients would include realistic storage parameters and landscape partitioning into recharge and discharge areas. The degree of availability of groundwater for evaporation and uptake by plant roots should also be represented in climate models. Ideally the "nonlocal" (from a surface perspective) distribution of recharge from one area to discharge in another would be included in some models. Development of such parameterizations and models requires regional to global scale maps of groundwater recharge and discharge areas, depths to water table, and estimates of evapotranspiration and groundwater discharge.

(3) Large-scale experimental watersheds with simultaneous surface and groundwater monitoring in varying climates and with varying aquifer characteristics, as described in chapter 2.

(4) Identification of areas that have undergone significant land cover/land use changes and analysis of resulting ground-water/surface-water/atmospheric water-balance changes. Comparisons should be made between responses by stand-alone surface water/groundwater models driven by prescribed climate variations and responses by coupled atmosphere/ surface water/groundwater models. A promising beginning to this - a coupled aquifer-land surface-atmosphere model to study aquifer-atmosphere interactions on decadal timescales—was documented by York et al. (2002) and Gutowski et al. (2002). In the watershed studied by York et al. (2002), during periods of persistent drought much of the evapotranspiration that occurred in regional discharge areas was apparently supported by groundwater.

(5) Comprehensive regional, continental, and global tabulations of groundwater withdrawals, in order to lead to improved estimates of the contribution of groundwater mining to sea level rise. Such research would also have intrinsic value to water-resource managers. Areas that have undergone significant alterations in water balance through groundwater pumping (e.g., for irrigation) should be identified and the changes in water balance and meteorological (e.g., precipitation) impacts assessed.

EFFECTS ON ATMOSPHERIC COMPOSITION

Atmospheric composition determines the atmospheric radiation balance, which determines climate. To the extent that groundwater systems affect atmospheric composition, they will also influence global climate. As humans change global cycling of water, energy, carbon and other chemicals, chemical fluxes at the groundwater interface will change; as humans change groundwater systems, they also may inadvertently change the global geochemical balances directly or indirectly (through the influence of groundwater change on vegetation, riverine, and coastal-ocean systems). Groundwater may influence atmospheric composition in two ways: (1) by modifying the "natural" atmospheric composition, and (2) by driving and modulating contemporary anthropogenic changes in atmospheric composition.

Of importance, then, are the generally long residence times in groundwater systems, which can range from decades to centuries and more. Changes in chemical composition of groundwater only start to show up in groundwater discharge after many years, and continue for many decades and centuries (Weissmann et al., 2002) after atmospheric inputs may have changed.

Exchange of radiatively active gases, such as carbon dioxide and methane, between the atmosphere and land is sensitive to water fluxes and to the "wetness" and thermal state of the land (which depends in many settings upon groundwater discharge) and is important in global geochemical balances (Crill et al., 1992; Moore and Roulet, 1993; Romanowicz et al., 1993; Siegel et al., 1995).

One of the major problems related to annual global carbon fluxes is an apparent deficit of ~2 gigatons (Gt) C/yr. in some budgets (e.g., Sundquist, 1993). Dissolved carbon in precipitation that recharges groundwater systems dissolves minerals by hydrolysis (Equation 1). In this process, the dissolved CO_2 is sequestered as dissolved inorganic carbon, the amount depending on the mineralogical composition, the ex-

TABLE 3-1 Estimation of Carbon Sequestration in Groundwater Per Meter Rise in Water Table

Area of Continents (m^2)	7.5E+13
Liters/m^3	1,000
Estimated HCO3 concentration (mgC/L)	37.3
Porosity (assumed)	0.2
Increase in water table (m)	1
Multiplying the above terms out	
Carbon sequestered as dissolved carbon (mg)	5.6E+17
Carbon sequestered as dissolved carbon (kg)	5.6E+11
Carbon sequestered as dissolved carbon (Gt) (1 Gt=10E+12 kg)	0.56
Percent of budget deficit	~30.

SOURCE: D. Siegel, Syracuse University, written communication, 2003.

tent to which the groundwater system is open or closed to soil CO_2 replenishment, reaction rates, and residence time.

Equation 1. Carbonate and silicate minerals +n CO_2 + H_2O = dissolved inorganic carbon (DIC) + base cations + silica + clay minerals.

A simple calculation (Table 3-1) shows that the amount of soil CO_2 that can be temporarily sequestered in ground water is very large. Assume that 1) the water table rises 1 meter over half of terrestrial earth, 2) the concentration of dissolved inorganic carbon is 37.3 mgC/L of ground water (the arithmetic average of data in White et al., 1963), and 3) the porosity of shallow unconsolidated aquifers is ~20 percent.

Multiplying the terms together produces ~30 percent of the carbon deficit per meter rise of the water table. Obviously, most of the terms in this crude estimate are unknown. More carbon would be sequestered in groundwater if the water table on average rises more, or if dissolved inorganic carbon concentrations were closer to equilibrium with carbonate minerals at typical open conditions. Groundwater at a typical soil P_{CO2} of 0.01 atmospheres, under open conditions and equilibrated with calcite, contains about four times as much dissolved carbon as is found in the same volume of soil gas (based on calculations made with the geochemical reaction model PHREEQC, http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/; D. Siegel, Syracuse University, written commun., 2003). Of course, if the average porosity were less, less carbon would be sequestered in ground water where the water table rises. In dry places where the water table drops because of the lack of recharge and evaporation, dissolved carbon can also be sequestered as precipitates in the soil zone.

The simple mass estimates above suggest that carbon sequestering in groundwater recharge may play an important role in the global cycling of carbon at a time scale important to climate change. It is possible that an assumption of steady-state with respect to carbon storage in ground water systems is not appropriate. Anthropogenically sequestering carbon in deep groundwater systems by injection is a major current topic of research (McPherson and Lichtner, 2003). However, little has been done with respect to evaluating how carbon is naturally sequestered and lost in shallow groundwater flow systems.

Research is needed to address the role of groundwater in (1) determining the "natural" atmospheric composition, and (2) driving and modulating contemporary anthropogenic changes in atmospheric composition. Global (or, at least, large scale) quantification of the historical and projected volumes of groundwater mined, changes in water table elevations, and estimates of water- and geochemical throughputs in groundwater systems will be building blocks for studies to address these issues.

4

Spatial and Temporal Scales of Recharge and Discharge

Our groundwater resources are highly vulnerable, as each new drought reminds us. Expected increases in groundwater extraction, increases in societal value of ecosystem function, and changes induced by global change (Chapter 3) indicate that forecasting potential variations in groundwater recharge and discharge will become ever more important.

However, in the context of forecasting recharge and discharge, what length of time is of interest? What area of land? Fluctuations in the Great Salt Lake (Box 3.1) and the Ogallala aquifer occur over time scales of decades, centuries, and even millennia. In contrast, major changes in flows and levels of hillside springs and shallow household wells may occur in days or weeks. Similarly, in terms of spatial scale, townships are concerned with recharge over square kilometers, and river basin planners over significant fractions of continents. We may suppose that the critical scales span weeks to centuries and from tenths of km to tens of thousands of km. How can measurements and estimates for one spatial scale and time period be scaled to different geographical areas and different time spans? Issues related to organization of measurements, observation networks, and modeling studies to address a host of scaling issues are the focus of this chapter.

NEXUS OF TECHNOLOGY AND NEED

Evaluations of groundwater fluxes often are based on observations at the scale needed for wetland delineation, seep and spring identification, recharge area identification for groundwater protection, or the identification of gaining and losing streams. Estimations of fluxes at larger scales are typically in the form of water budgets on a basin scale for river management. Now, the need to understand the effects of climate change has further expanded the range of scales of interest to continental (see Box 4-1) and global scales. However, published water-budget estimates at these scales (e.g., Oki, 1995; Dettinger and Diaz, 2000) rarely treat groundwater runoff separately from surface water runoff, nor do they separate discharge to the atmosphere (e.g., by phreatophytes) from surface-water discharge. Further, the need to assess anticipated changes in climate, land use/land cover, availability of groundwater resources, and trends in water quality begs for a predictive capability on many scales in both space and time.

Recent advances in technology provide both challenges and potential solutions to address these multi-scale needs. New data collection techniques have generated a plethora of data (much of it from remote sensing). Concurrent gains in computational power permit us to access and mine these very large data sets. Likewise, advances in simulation capability (e.g., resolution, processes modeled, and processor speed)

BOX 4-1
The Role of Climate Models and Satellite Data (GRACE) in Estimating/Mapping Changes in Groundwater Storage

Observing and modeling components of the terrestrial water budget at regional to continental scales is now feasible. Remote sensing of precipitation by satellite (Huffman and Bolvin, 2002) and radiation from geostationary satellite (e.g. Pinker and Laszlo, 1992) allows for remote sensing driven hydrologic modeling. As these models improve through large-scale validation, there is the potential for better understanding of the spatial and temporal variation of terrestrial water storage (soil moisture and groundwater). For the results from a 50-year run of the Variable Infiltration Capacity (VIC) macroscale model (Liang et al, 1994; Cherkauer et al., 2003) over the Mississippi River basin (Figure 4-1), forced with gridded precipitation, air temperature, and other derived forcings from NOAA Cooperative Observer stations (Maurer et al., 2002) shows the maximum range of model-predicted soil moisture over the 50-year period for each grid cell. Averaged over the Mississippi River basin, and weighted by mean annual precipitation, the range is 29.6 cm. The upper Mississippi River basin, the Red-Arkansas basin and the eastern side of the Rocky Mountain divide are areas of large interannual variation in water storage, and therefore expected large natural variability in groundwater levels and recharge.

As a comparison, early land surface modeling work (Manabe,1969) used a global average soil moisture capacity of 15 cm, a number that has been widely used in the climate community. The implication of the early climate models is a suppressed coupling between the terrestrial hydrosphere and the atmosphere, resulting in decreased predictions of evaporation.

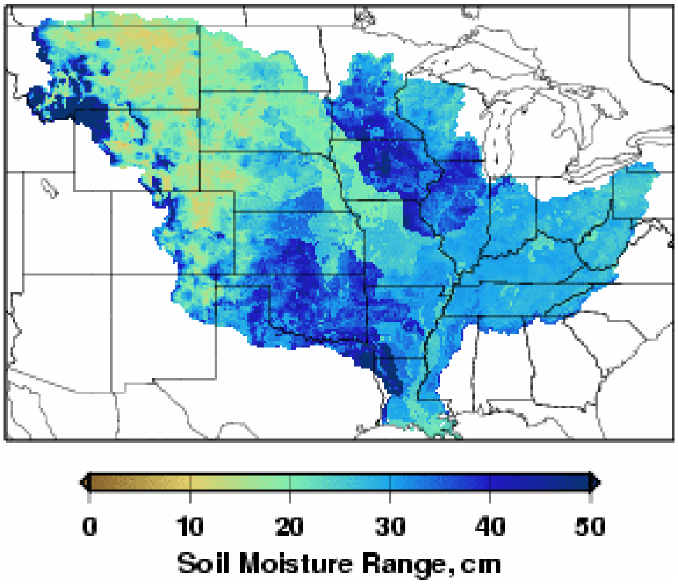


FIGURE 4-1. Range in simulated soil moisture content over the Mississippi River basin from the VIC model simulations, 1950-2000. SOURCE: Reprinted, with permission, from Maurer et al. (2002). © 2002 by American Meteorological Society.

An alternate approach to estimating evapotranspiration over large areas is to compute an atmospheric moisture balance:

$$\vec{\nabla} \cdot \int q\vec{v}\,\frac{dp}{g} + \frac{d}{dt}\int q\,\frac{dp}{g} = P - E$$

where the first term on the left-hand side is the divergence of the atmospheric moisture field (usually computed from a column-average effective moisture and corresponding wind field), and the second term is the change in atmospheric moisture storage over the domain. One limitation of this approach is that accurate estimates of the moisture flux convergence require spatial domains that are quite large, typically 10^6 km^2 or greater.

Ropelewski and Yarosh (1998) describe a moisture balance study of the central U.S. (the approximate domain of the Mississippi River basin). They used the atmospheric moisture balance equation with observed precipitation and convergence computed from radiosonde observations to solve for evapotranspiration. Figure 4-2 shows the accumulated departure from the mean for precipitation, computed evapotranspiration, and an inference of storage change that would have been required to satisfy the accumulated balance. The difference between the largest and smallest value of the normalized storage is an estimate of the minimum subsurface moisture storage capacity. This value is about 45 cm, or around 1.5 times the value estimated by the VIC model. Also, the period of analysis for the atmospheric budget (1973-1992) is less than half as long as that used in the surface modeling approach; the discrepancy would certainly be larger if the periods had been compatible.

Comparison of these two estimates raises several interesting questions:

1. Does the surface modeling approach, which ignores groundwater interactions, tend to bias the estimated moisture storage excursions downward? Restated, do groundwater-surface water interactions exert a significant influence on variations in subsurface storage, and hence evapotranspiration, over areas as large as the Mississippi River basin. If they do, how can they be estimated?

2. A second possibility that cannot be excluded, is that a significant part of the apparent subsurface storage "requirement" based on the atmospheric balance is attributable to "noise" in the atmospheric convergence estimate, which is effectively integrated in estimate of required storage (Gene Rasmussen, personal communication, 2002).

3. The new observing strategies, like the recently launched Gravity Recovery and Climate Experiment (GRACE) mission, and planned GRACE follow-on may provide some insights into issues addressed in 1 and 2, above. Given potential capabilities (at least with GRACE follow-on) to estimate total moisture variations (atmospheric plus surface and subsurface) to within a few cm over spatial scales as small as 100 km, can the contributions of the various moisture storage terms be deconvolved to sufficient accuracies so as to allow better understanding of continental scale subsurface moisture dynamics, and their relation to continental scale evapotranspiration? Figure 4-3 (from Rodell and Famiglietti, 2002) shows the mean annual cycles of monthly changes in terrestrial water storage and its components over Illinois. Their analysis indicates that these seasonal changes would be detectable if they occurred over regions greater that 500,000 sq. km.

The potential for understanding the seasonal and inter-annual variation in terrestrial water storage at continental scales has greatly increased with current modeling and remote sensing capabilities. The challenge to the hydrology community is to integrate into groundwater flux studies the results from macroscale hydrologic modeling, modeling and observations of moisture fluxes in the atmosphere, and terrestrial water storage observations to provide further insights into the spatial and temporal variability of recharge.

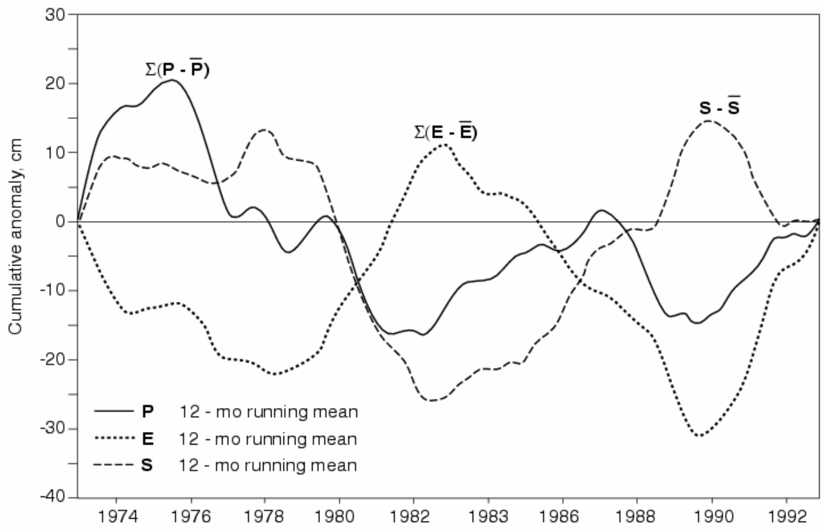


FIGURE 4-2 Accumulated departure from the mean for precipitation (observed), evapotranspiration (derived), and storage over the central U.S. SOURCE: Reprinted, with permission, from Ropelewski and Yarosh (1998). © 2002 by American Meteorological Society.

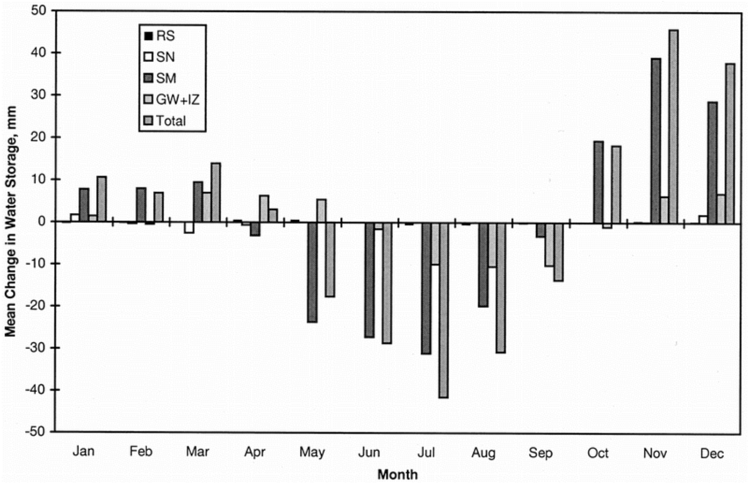


FIGURE 4-3 Mean annual cycles of monthly changes in terrestrial water storage and its components over Illinois. RS: reservoir water, SN: snow water, SM: soil moisture, GW: groundwater, IZ: intermediate zone storage. SOURCE: Reprinted, with permission from Rodell and Famiglietti (2002). © 2002 by Elsevier Science.

make it possible to test our understanding in new ways. Finally, the last ten years have brought forth a host of low-cost sensors that can collect data with unprecedented temporal resolution. These data provide a rich source of "ground truth" for the more spatially complete remotely sensed data. To take advantage of this nexus of need and technology we must use measurements made at many disparate spatial and time scales to address questions posed at another scale. Further, we must understand how our process descriptions vary with scale and that coupling of processes occurring at different scales. These scaling relationships are a function of geologic and climatic regimes, and precipitation intensity. Identifying these relationships will allow quantification of recharge and discharge at the local scale, where they affect urban planning and ecological function; prediction of and preparation for the effects of climate change; and most fundamentally, better understanding of recharge and discharge mechanisms.

One caveat is in order. Much of the new technology to address spatial scaling issues relates to near-surface measurements. Such measurements may provide ways to estimate net *infiltration*, by measuring surface evaporation and plant consumption, not by measuring net *recharge* directly. However, more accurate recharge estimates may be made not at or near the soil surface but deeper underground where flow is less coupled to other mass and energy transfer processes than is flow in the soil-plant-atmosphere system. At depth, the effects of evapotranspiration, and spatial and temporal fluctuations in infiltration are attenuated, rendering deeper subsurface flow more uniform and therefore easier to quantify (Figure 4-4). (Subsurface information that relates directly to fluid flow is typically limited to measurements taken in boreholes, which may be relatively far apart. Though such boreholes cannot provide information directly about lateral scale processes smaller than the distance between them, such detail is less important in the subsurface than it is in the near surface due to the slower and more uniform character of flow at depth.)

DEFINITION OF SCALING

Because the term "scaling" is not always clearly defined, there often is some confusion surrounding discussions of problems and issues.

> *The term "scaling", to many, is veiled in a nimbus of exciting mystery. At a basic level, part of the mystery simply comes from confusion of two connotations of the word – meaning either scale invariance (i.e., processes behaving similarly at small and large scales) and upscaling/downscaling (i.e., aggregating/-disaggregating data* (Blöschl, 2001).

In this report, we use the term "scaling" in the sense of aggregation and disaggregation of estimates and data. *Upscaling* refers to taking measurements made at a series of points or small scales and determining how to use them to estimate quantities or rates over a larger scale. In *downscaling*, measurements at a large scale are disaggregated to a finer scale using statistical methods.

A brief discussion of typical arid settings helps frame the challenge of the scale in recharge. In arid regions, recharge tends to occur at high elevations or along mountain fronts or focused along streams or swaths of irrigated land, whereas in humid regions, recharge is more diffuse over wider geographical areas; discharge tends to occur at springs, wetlands, and playas, and along the shorelines of oceans and estuaries, streams, and lakes. Except for focused spring discharge, these are neither points nor broad geographic areas. As an example, consider precipitation falling over basin floors in the playa landscape of the semiarid Southwest (Figure 2-5). Over vast areas of basin floor there is no net recharge. The geothermal gradient

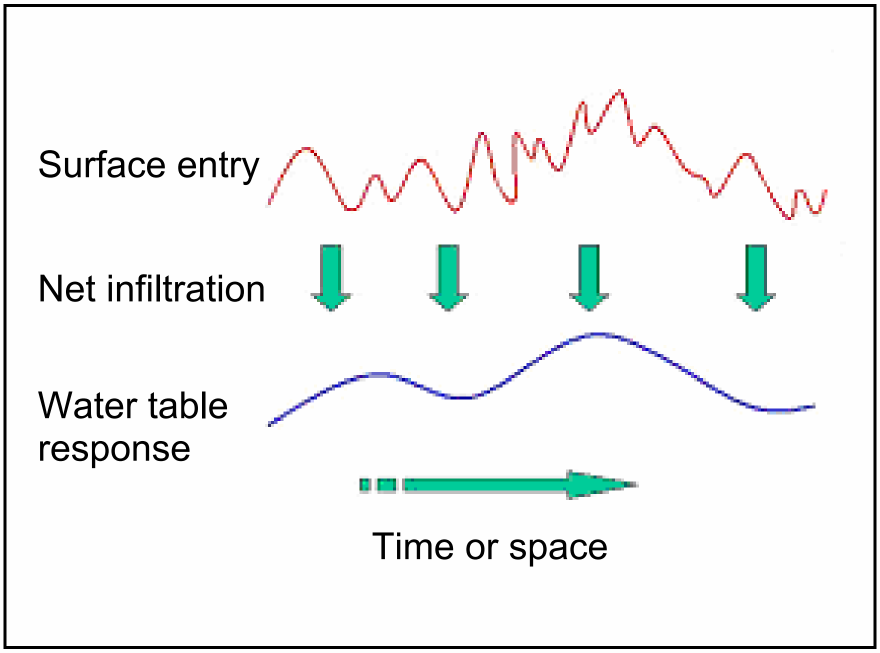
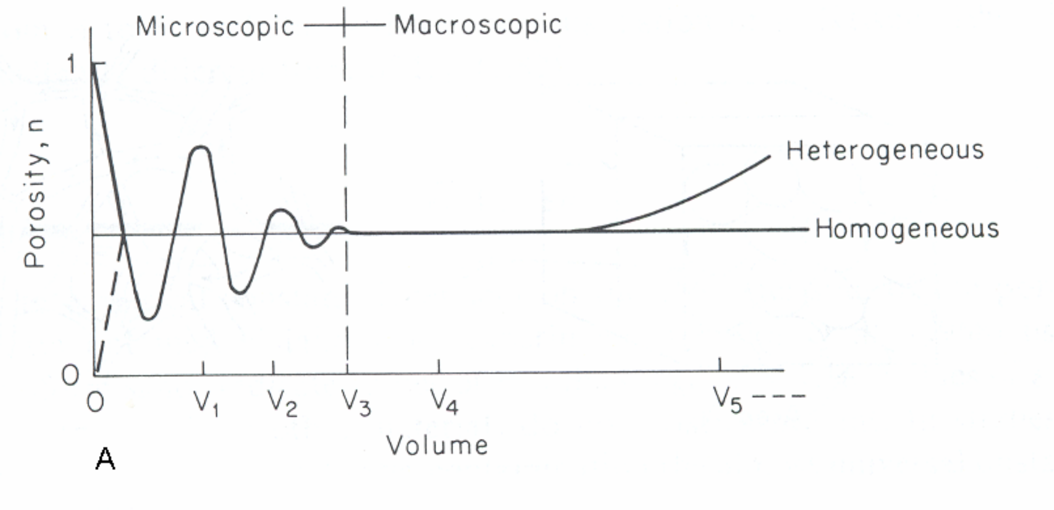


FIGURE 4-4 Schematic illustration of the smoothing of the recharge signal as water enters the subsurface as infiltration and some component of this arrives at the water table after percolating through the vadose zone. This smoothing simplifies measurement of the recharge flux at the water table, reducing the need for high resolution spatial and temporal monitoring.

drives water vapor upward, taking all the liquid water that reaches depth and returning it to the surface. During rainfall events that activate surface flow, small stream channels begin to collect and carry away surface runoff, and focus infiltration. Some streams are wide enough and flow long enough to allow recharge to the water table. So at the scale of a playa landscape (say 500 m), recharge occurs not at all or perhaps once a century, while at intermediate locations, relatively high rates of recharge occur episodically. Measurements taken in between stream channels would detect no recharge, while those in large stream channels would show that there is relatively high recharge.

It follows that the average recharge will depend on where the measurement is centered, over what period of time the measurements are made, and over what scale the average is computed (see Box 4-1, for example). In the example of the playa landscape, 99.9 percent of the basin floor might have no recharge whereas 0.1 percent of the area consisting of ephemeral stream channels that promote infiltration during 0.1percent of the time generate essentially all of the long-term regional recharge. As the averaging area increased from a point on the basin floor, segments of stream channel would be included along with a larger fraction of basin floor. When averaged together a ‘scale effect’ would be evident, at least with respect to when a meaningful average value could be defined. The same applies to the temporal scale of averaging. A graph of flux rate vs. spatial or temporal averaging scale might be drawn similar to the classic diagram of the representative elementary volume (REV) used to show the scaling behavior of hydrogeologic parameters such as porosity (Figure 4-5A) or the scaling of correlation length in heterogeneous porous media (Figure 4-5B). By examining the relative magnitude and variability of groundwater fluxes at increasing spatial and



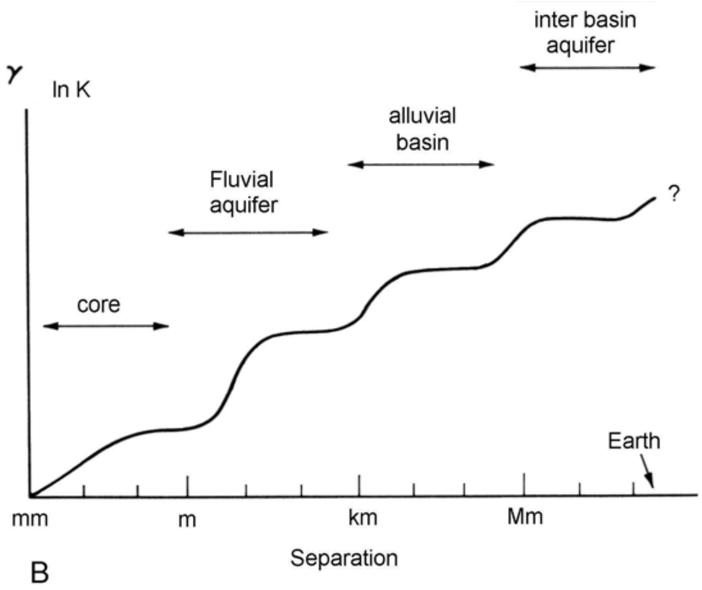


FIGURE 4-5 A) Scaling of porosity of a porous medium as it might be measured on samples of increasing volume (V-1, V2, V3…) taken at a random point within the system. A plateau starts at V3, known as the representative elementary volume. SOURCE: Reprinted, with permission, from Freeze and Cherry (1979). © 1979 by Prentice Hall. Adapted from Hubbert (1956) and Bear (1972). B) The semivariance (γ) of the natural log of hydraulic conductivity as a function of the correlation length in heterogeneous porous material. In this case there is a series of plateaus as one moves, for example, from a single sand bed to an interbedded sand-clay package to stacked packages to an entire basin. SOURCE: Reprinted, with permission, from Gelhar (1986). © 1986 by American Geophysical Union.

temporal scales, we may discover thresholds of continuity or uniformity that correlate with practical scales of measurement and/or application. For the example of the playa landscape, plateaus in scaling might occur at spatial scales related to the scale of the drainage network. Of course, for the scaling process to make sense knowledge of the underlying physical processes is needed; the averaging would not be simple statistical interpolation as is the case for many upscaling problems.

EXPECTED SCALING BEHAVIOR OF RECHARGE/DISCHARGE FLUXES

Understanding and measuring groundwater fluxes across interfaces along a continuum of temporal and spatial scales is important for determining water and solute budgets. For the purposes of this discussion we define increasing spatial scales as moving from smaller to larger areas of the landscape or volumes of material and increasing temporal scales as moving from short to longer time frames.

Scaling issues related to recharge and discharge have been the focus of studies in a variety of regions (e.g., Dyck et al. 2003; Desbarats et al. 2001; Delin et al. 2000; Lin and Anderson, 2003; Flint et al., 2002, see Box 4-2; Stoertz and Bradbury, 1989; Jorgensen et al., 1989; also see the review article by de Vries and Simmers, 2002). Many of these studies are, by their nature, specific to a place and do not necessarily address general processes. To our knowledge, no comprehensive studies of flux scaling exist. We can, however, make predictions about the expected scaling behavior of these processes. As we move from smaller to larger scales the *variability* of flux values will change (Figure 4-5A). These changes with scale are fundamentally related to the spatial and temporal heterogeneity of natural systems, and include both the physical properties of the system and the hydrodynamic parameters imposed by the larger environment. For example, for a small groundwater basin, recharge and discharge fluxes are controlled by the geology and topography (physical properties of hydraulic conductivity, porosity, surface drainage, etc.) and by the imposed stresses (climate, precipitation intensity, land cover, pumping, etc.). In general, at small spatial and temporal scales, we expect flux variability to be large, and to be highly correlated to small-scale variability in physical parameters. At larger scales we expect this variability to decrease as spatial and temporal changes are averaged.

The ease or difficulty of upscaling of point estimates depends on how variable the point estimates are. Variability itself is, of course, variable. That is, in some instances, recharge flux variations, even on a small scale, may be only mildly variable (e.g., Dyck et al., 2003) whereas in other instances it may vary over orders of magnitude from point to point (e.g., Cook and Kilty, 1992).

STRATEGY TO ADDRESS THE ISSUE OF SCALE

Below we sketch a framework or strategy to address the issue of scale as related to estimation of groundwater recharge and discharge. It is our belief that remote sensing will play an important role in the strategy. Although a case has been made for using various remote sensing tools in recharge and discharge studies (e.g., Cook and Kilty 1992; Salama et al. 1994; Meijerink 1996; Jackson 2002), and especially in scaling up from point measurements, there is much work to be done to develop the methods to a point where they are truly useful. Of critical importance is the interplay between remote sensing, land-based measurement and numerical modeling.

- <u>Conceptual Model</u>. The conceptual model is a basic tool for visualizing the hydrogeologic system where direct measurements of fluxes and other hydrologic processes may be lacking but similarity of form and process are evident (Figure 1-3). It provides a way of looking across multiple scales;

BOX 4-2
Recharge Mapping at Yucca Mountain, Nevada -- The Scale Effect

Flint et al. (2002) evaluated various methods to estimate net infiltration and recharge at Yucca Mountain. A summary of the methods, i.e. general approach, scale of application, and strengths and limitations, is was presented earlier in this report (Table 1-2). These methods produce estimates of flux that reflect different spatial and temporal scales; have different data requirements, strengths and limitations; and have varying sensitivity to water flux in fractures. Recharge varies spatially owing to variations in precipitation, surface microclimates, thickness of alluvial deposits, faults and fractures, and thickness and hydrologic properties of geologic strata in the unsaturated zone.

Two methods applied to measured data at different temporal and spatial scales may yield different fluxes, yet both could be correct. at the scale of measurement. For example, a water-balance model reflecting a conceptual model of shallow infiltration at Yucca Mountain was used to estimate the temporal and spatial variability of net infiltration (Figure 4-6a) for the upper boundary conditions of the unsaturated-zone flow model (Bodvarsson and Bandurraga, 1996) (Figure 4-6b). Although the average flux for both models are the same, this figure illustrates the differences between surface flux and flux at the water table due to the redistribution of percolating water that occurs in the unsaturated zone over varying spatial and temporal scales. Measurements of water content in shallow neutron-access boreholes used to calculate near-surface fluxes over the last 15 years may correctly represent average conditions over that period, yet be in apparent disagreement with fluxes estimated by applying the chloride mass-balance method to pore waters extracted from drill cores because the latter method may be representing fluxes that were in effect hundreds or even thousands of years ago. Recharge-estimation methods based on deeper measurements integrate, or average out, the excursions caused by local, near-surface processes.

The values in Figure 4-7 are results from the various methods used to estimate recharge at Yucca Mountain. The methods generally are arranged in order of the integrated depth or temporal scale that the method addresses.

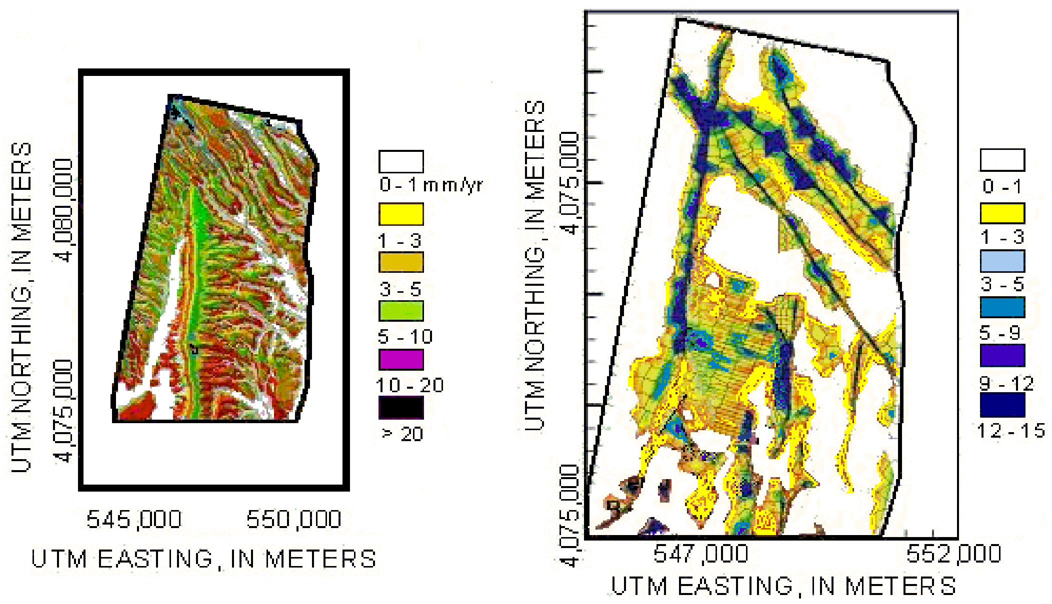


FIGURE 4-6 (a) Spatial distribution of shallow infiltration at Yucca Mountain using a water-balance model, compared with (b) percolation flux (recharge) at the saturated zone. SOURCE: Modified from Flint et al. (2002).

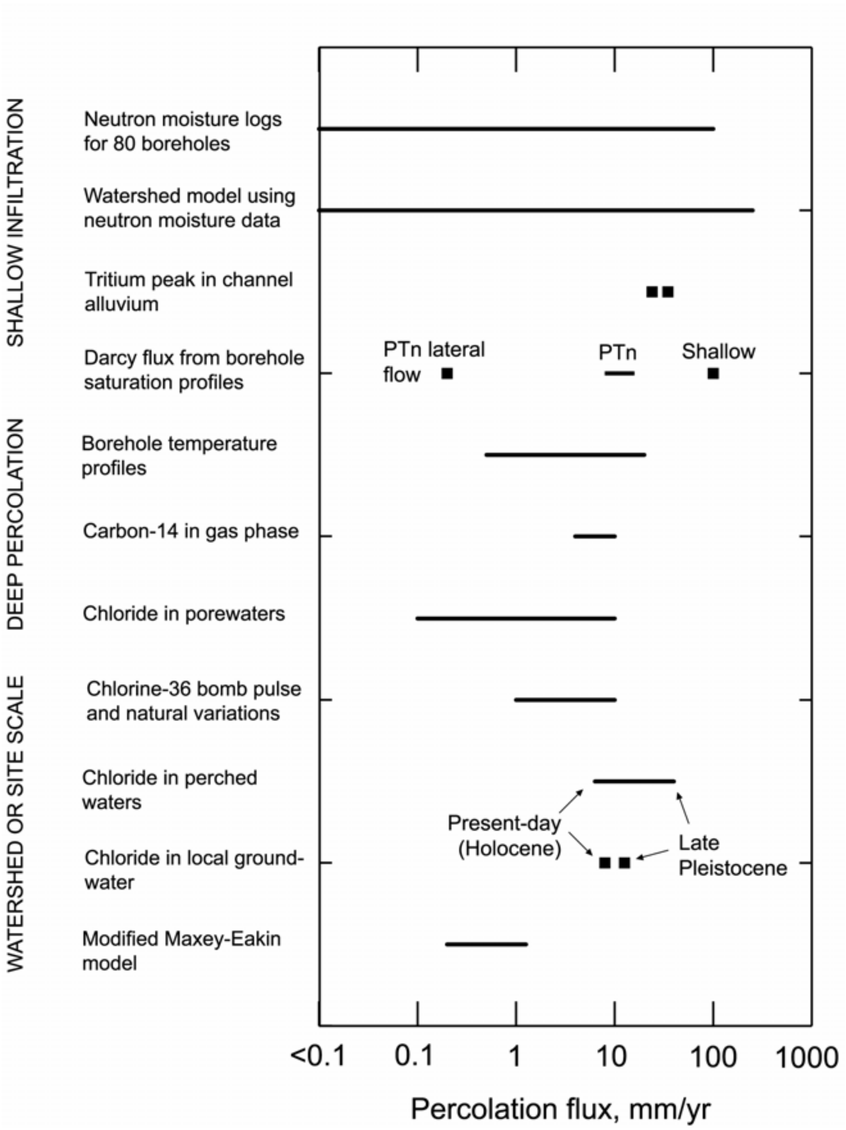


FIGURE 4-7 Comparison of percolation fluxes estimated by various methods. A bar represents the range of estimates using a given method in different topographic settings, whereas each point represents a single estimate. SOURCE: Modified from Flint et al. (2002).

Shallow point measurements address surface processes generally acting on a yearly to decadal scale, or reflect processes in a single topographic feature. Measurements made deeper in the mountain or integrating deep boreholes reflect an integration of time and space owing to unsaturated flow processes, stratigraphic influences, and differences in fracture/matrix interaction within the various hydrostratigraphic units. Some methods, such as those using perched-water chemistry, incorporate various percentages of water that may be thousands of years old. In summary, because recharge rates are variable in space and time, considerable differences in estimated flux values using different methods do not necessarily indicate that one of them is wrong. What is important is to match the appropriate method to the spatial and temporal scale of the problem. Regional or long-term average rates may require one method; local or recent rates, another.

a good conceptual model is essential to the design of new observing networks. The conceptual model also guides the interpretation of historical records (e.g., of streamflow and groundwater levels) and is a first step in evaluating the effect of climate forcing on recharge/discharge processes.

- Prototype and Lab-Scale Experiments. Benchtop experiments and new instrumentation packages will be an important step in creating new observing systems in field applications. Many of the fundamental processes that give rise to variability in space and time are manifest at small scales: e.g., crack-flow, unstable wetting, flow through random media packings. Given the intrinsically greater control and measurability of laboratory simulations, these experiments will be an integral component of gains in understanding of the underlying processes that give rise to scale-dependence in hydrologic processes.
- Field Experiments. The design of field experiments to capture the multiple spatial and temporal scales of recharge/discharge is fundamental to the scaling issue (Chapter 2). With the advent of low-cost sensor technology, meso-scale geophysical methods (mostly advances in interpretation), high-resolution elevation and remotely sensed land cover, and the computational capacity to digest this information, we now have the potential to enhance predictions from regional mean behavior to catchment, hillslope and plot scales. At the same time we must anticipate global climatic changes that will likely alter the patterns of these processes so critical to life. The challenge is to measure the nature, pattern and magnitude of fluxes with coordinated observations of the atmosphere, soil moisture regime, and groundwater-stream system.
- The Information System. Although we have vast data sets, and are poised to obtain even richer observational results, unless we can synthesize across these diverse sources of information we are fundamentally limited in our ability to compare observations at a range of scales. Efficient information management and the cataloging of compatible formats of hydroclimatic data that are collected at disparate spatial and temporal scales will be crucial for seeing the scale behavior in the data, and thereby identifying new constitutive relations, and validation of theories or process at multiple scales.
- Modeling. Finally, numerical modeling is fundamental to identification, estimation, simulation and prediction of recharge and discharge, and provides a fundamental tool to address coupling and scale interaction of such processes. Through model calibration the magnitude of average fluxes occurring at the watershed scale (>10,000 km^2) can be estimated reasonably well provided discharges are measured accurately. At local scales (i.e., the small to intermediate scale of 0.1 to 10 km^2), however, flux values as predicted by a model and measured in the field at pairs of proximal points (e.g., in a spring and 1 meter away from the spring) may be completely different and have large associated error. Since fluxes at local scales are those most relevant to ecosystems and to human habitation, there is great advantage to advancing our understanding to enable accurate predictions of fluxes at ever smaller dimensions. In addition to prediction of fluxes at various scales, models allow for testing hypotheses of scale interaction, for “what-if?” scenario investigations for water management and allocation. A third application of modeling to scaling issues is the problem of data assimilation (NRC, 2002a) and how the observing system will continuously update the model and model forecasts.

The issues of scale relative to recharge and discharge fluxes involve understanding the interdependence between variability in fluxes and the physical and chemical characteristics of a site. While both recharge and discharge occur as diffuse and focused fluxes, it is implicit that recharge and discharge processes must be studied independently. Furthermore, each process is expected to scale in distinct ways.

Up to the scale of perhaps 100 km^2, scaling studies can be done at the benchmark sites proposed in Chapter 2. Each experimental setting should be studied at nested scales with nested monitoring sites within the basin and measurement/sampling/monitoring stations on a range of scales across the basin. Methods of assessing uncertainty will be required for each of the issues as well as the development and verification of related scaling theories. The development, application, and evaluation of multiple assessment methods specific to each issue and the development, application and evaluation of conceptual and numerical models, and their comparison and independent validation are also required.

RELATION OF INFILTRATION TO GROUNDWATER RECHARGE

Most of the newly available technologies that may allow us to monitor variables at a variety of scales pertain to the near-surface environment (Smith, R. et al., 2002). Except at the scale of 100's of km via identifying changes in the water table through satellite gravimetry (Box 4-1), it is not possible to monitor groundwater recharge and discharge remotely. Since infiltration and recharge may vary in magnitude, timing, and distribution (e.g., Box 4-2), it is imperative for the scaling problem that we develop procedures that relate recharge and discharge to landscape features that we can observe directly with high spatial resolution. These relationships must be developed through tests of models with ground-based measurements that will yield estimates of infiltration (with associated uncertainties) coupled with the variety of methods that we have at our disposal to estimate recharge. The development of these relationships will itself involve attacking a scaling problem because the temporal and spatial variability regimes of infiltration and recharge are different (Figure 4-1). Ground-based measurements of infiltration will require elucidation of soil-plant-atmosphere controls on near-surface soil fluxes.

Estimation of recharge from infiltration can also be done by estimating evapotranspiration; recharge then is calculated as the difference between infiltration and evapotranspiration. Unfortunately, direct estimates of evapotranspiration are only possible at relatively small spatial scales – e.g., via flux towers using eddy correlation or Bowen ratio methods (Baldocchi et al., 2001), which typically have footprints of at most a few square km. Remote sensing using LIDAR can result in high-resolution images of water vapor that can be especially important in areas of high flux variability such as riparian zones (e.g., Cooper et al., 2000). Indirect methods, such as catchment water balance methods, are applicable to long (multi-year) time periods where subsurface storage changes can be averaged out, or alternatively require a modeling strategy to estimate subsurface storage change. Comparative studies of some of these methods have shown promise (e.g., Wilson et al., 2001). Hydrologic and/or macroscale land surface models typically produce estimates of evapotranspiration (and its space-time distribution) following calibration of model parameters to produce a match with observed streamflow. Given that they are forced with observed precipitation, they arguably can produce usable estimates of evapotranspiration provided that observed streamflow is matched reasonably well. Nonetheless, confidence is greater in their long-term average predictions than the time sequencing, due to difficulties in verifying that the dynamics of subsurface storage are properly represented.

With respect to the representation of subsurface storage, essentially all surface hydrology models (e.g., those intended for flood and drought forecasting) and land surface models (e.g., those intended to represent the role of the land surface in climate prediction models) represent the subsurface as one or more soil "slabs", with finest vertical resolution of depth typically a meter or two. Land surface models can be run in so-called "off-line" mode, that is, forced with observed precipitation and other surface atmospheric variables (e.g., downward radiation, wind, surface air temperature, vapor pressure deficit). Implemented in this way, they behave essentially like continuous watershed simulation models, although at much larger scales. As indicated above, if streamflow is simulated reasonably well, these models can offer insights into the dynamics of evapotranspiration, as well as changes in subsurface moisture content.

Many important sources of error and uncertainty affect the available estimates of infiltration rates. These include low space-time resolution of storm events; neglect of surface runoff; relatively or understanding of processes that control water uptake by plants from soils and fractures; poor definition of processes and properties that contribute toward the generation of focused infiltration and corresponding fast flow paths; and the transient nature of infiltration processes.

VARIATION OF FOCUSED AND DIFFUSE DISCHARGE WITH MEASUREMENT SCALE

Understanding and measuring groundwater *discharge* at various temporal and spatial scales is essential for completing any groundwater budget, and is a critical part of most groundwater flow models, yet most groundwater discharge measurements are highly uncertain. Moreover, the uncertainty is poorly characterized and probably most often underestimated. The main discharge points for groundwater (in addition to pumping wells) are springs and seeps, streams, lakes, wetlands, and oceans. Flow measurements in each of these environments present unique conceptual and measurement challenges. In addition, the common practice of estimating recharge using numerical flow models is subject to an implied scaling due to the inability of models to reproduce all surface-water features.

Springs and seeps- As point locations of groundwater discharge, springs are often attractive locations for flow measurements, yet the proportion of groundwater discharge that a particular point spring represents is usually unknown, and may be small. Seeps associated with wetlands can be complex, dynamic, and difficult to measure, but may exert a profound influence on the water balance of a basin. Can we develop ways to predict the relative proportion of diffuse to focused flow at different spatial and temporal scales?

Streams- Hydrogeologists commonly use low-flow, or baseflow, conditions in streams and rivers as a measure of basin-wide groundwater discharge, yet there is great uncertainty in such measurements (e.g., Halford and Meyer, 2000). We commonly describe the time series of low-flow measurements in a stream using flow-duration curves, but it is unclear what statistical measure derived from such curves (e.g., Q_{60}, Q_{80}, $Q_{7,10}$) appropriately represents groundwater discharge to the stream over various time scales. Our best low-flow measurements and statistics come from long-term USGS gaging stations with well-defined rating curves, yet such stations are usually only installed on major streams, and nationally the number of gaged sites is decreasing. Furthermore, even if we are convinced that a streamflow measurement under baseflow conditions represents groundwater discharge, how do we disaggregate the complex patterns of inflow, outflow, and interflow that occur higher in the watershed?

Groundwater flow models- Commonly-used finite-difference groundwater flow models (e.g., MODFLOW) include numerical methods for linking groundwater to surface water through head-dependant boundary conditions (such as the MODFLOW river, lake, drain, and streamflow routing packages). Due to model grid or mesh limitations such models must always ignore surface-water features smaller than a given size, and the usual rationalization for ignoring these features is that they are unimportant to the larger-scale problem. However, ignoring such small-scale features is likely to cause model-based recharge estimates to be smaller than field estimates. Continued effort into sub-gridscale parameterization schemes is essential and has proven to be a powerful avenue to address this issue intrinsic to spatially explicit modeling.

USE OF REMOTELY SENSED/MAPPED PARAMETERS AS SURROGATES FOR RECHARGE/DISCHARGE

Remote sensing and high-resolution digital elevation models will be fundamental to the extrapolation over landscape scales from points of estimation. The essential next step is for the highly variable features that control discharge and recharge (e.g., permeability distribution), to be associated with the remotely measured surrogate values. One example of this is the HOST (Hydrology of Soil Types) classification (Lilly et al., 1998), originally developed to predict river flows for ungaged catchments and later used within other models for predicting contaminant concentrations in runoff. HOST semi-quantitatively relates soil classification (e.g., loamy sand) to soil hydrologic characteristics, and thence to stream response to precipitation. Similarly, vegetation patterns (e.g., Rosenberry et al., 2000) have shown promise as surrogates for discharge.

5

Findings and Recommendations

This chapter summarizes the major findings related to the three primary themes of the workshop and recommends directions for future research.

Finding 1

Our ability to quantify spatial and temporal variability in recharge and discharge is inadequate and must be improved given the importance of groundwater in the hydrologic cycle, the contribution of groundwater to base flow in streams and inflow to lakes, and society's reliance upon groundwater for water supply. Moreover, the spatial distribution of recharge fluxes influences the vulnerability of aquifers to contamination and the discharge of groundwater into wetlands influences associated ecological and biogeochemical processes.

A key science question is how landscape heterogeneity controls spatial and temporal variability of recharge and discharge. Addressing this question will require consideration of geology, biology and climate including variability in soils, topography and vegetation. There are no uniformly applicable methods for measuring and quantifying recharge/discharge fluxes in space and time, so our understanding of distribution and process is limited (chapter 2).

Recommendation 1-1

Experimental benchmark sites should be established with the goal of improving both measurement techniques and the understanding of the processes of groundwater recharge and discharge. These sites should include a wide range of geologic, climatic and landscape types and should be integrated with existing NSF, USDA/ARS and similar experimental watersheds. The proposed experimental benchmark sites program should also work cooperatively with field programs connected with large-scale hydroclimatic studies—for example, the WCRP Global Energy and Water Experiment (GEWEX) and with studies conducted under the NSF-supported CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science, Inc.) initiative.

Recommendation 1-2

A study/workshop should be initiated with the goal of developing scientific and implementation plans for such experimental benchmark sites, perhaps as part of CUAHSI. Such an activity would determine which sites would be most valuable to improving the science of groundwater discharge and research, the relevant science questions specific to particular sites, the range of measurement and modeling that would be undertaken and an evaluation of the historical data available for designing experiments.

Finding 2

The roles of groundwater storage, and recharge and discharge fluxes in the climate system are under-appreciated and poorly understood. Because groundwater is the largest reservoir of fresh water in the hydrologic cycle, characterization of the linkage between groundwater and climate is crucial. Groundwater plays an important role in the carbon cycle and related subsurface biogeochemical processes, and therefore the variability and fluctuation in groundwater levels can influence climate. For example, the net accumulation (or depletion) of peat (and the sequestration or release of its stored carbon) depends on the depth to the water table, and whether peat is under aerobic or anaerobic conditions. Climate change may cause changes in the temporal and spatial distributions of groundwater recharge and discharge and, therefore, availability of the groundwater resource. Better understanding of the linkage between groundwater resources and paleoclimatic conditions would be helpful in understanding past climate and its variability and would supplement information derived from study of tree rings and ice cores.

Recommendation 2-1

Research should address the relationship between long-term fluctuations in groundwater levels in aquifers at a regional scale and climatic variability. Such efforts would include the preservation and study of historical data on groundwater levels, and related hydrologic data such as streamflow records and lake levels, in areas unaffected by direct human influence. These efforts should include a broad range of techniques including paleoclimatic research such as reconstruction of paleolake levels and isotope geochemistry of old groundwater to provide insights into climatic variables such as paleotemperature.

Recommendation 2-2

Research is needed to allow for better representation of groundwater processes in climate models, including more realistic storage parameters, landscape partitioning into recharge and discharge areas, groundwater uptake by vegetation, and fluxes to wetlands, lakes and streams. Data from the benchmark sites discussed under Recommendation 1-1 above could be utilized to test the improved parameterizations.

Recommendation 2-3

A better understanding of the effects of human use of groundwater for water supply on climate is needed. This would require comprehensive tabulation of regional, continental and global groundwater withdrawals and the extent of the area of wetlands drained during the past century accompanied by evaluation of the effects of the withdrawals and drainage on climate

Finding 3

Groundwater measurements are needed across a range of temporal and spatial scales; measurements at one scale are often needed to address questions at another scale. For example, remote sensing techniques provide extensive, spatially complete data sets that hold promise for addressing many of the unresolved questions identified in this report. However, these data often provide information at large regional scales, like the information soon to be available from the NASA-supported micro-gravity mission GRACE (Gravity Recovery and Climate Experiment), and must be integrated with information generated at smaller scales. This will require an understanding on how groundwater processes scale spatially and temporally. But it is unclear how the variability measured at small scales will change as we move up in scale, and whether there are thresholds of continuity or uniformity that correlate with practical scales of measurements.

Recommendation 3-1

A broad and coherent strategy for the observation of groundwater recharge and discharge across scales is needed. This would involve the development of sensors that measure recharge and discharge at "point" scales, research to increase our understanding of the scaling of these measurements and underlying processes, the development of procedures for integrating measurements and observations across scales, and generation of mathematical tools to assimilate and synthesize observations at all scales into groundwater process models. Such a strategy could be tested on both the benchmark sites (Recommendation 1-1) and on aquifers of regional extent.

It is hoped that this report will lead to progress in understanding the spatial and temporal variability in diffuse and focused groundwater recharge and discharge, the interaction of groundwater with the climate system, and the spatial and temporal scales of recharge and discharge fluxes. Improved understanding is needed for sustainable utilization of groundwater resources, ecologically sound management of wetlands, lakes and watersheds, and to understand, predict and cope with the effects of potential climate change.

References

Amelung, F., D. Galloway, J. Bell, H. Zebker, and R. Laczniak. 1999. Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation. Geology 27(6):483-486.

Atlas, R. N. Wolfson, and J. Terry. 1993. The effects of SST and soil moisture anomalies on GLA model simulations of the 1988 U.S. summer drought. Journal of Climate 6(11):2034-2048.

Back, W., J. S. Rosenshein, and P. R. Seaber (eds). 1988. Hydrogeology. The Geology of North America O-2: 524 p.

Baldocchi, D. D., E. Falge, L. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, Ch. Bernhofer, K. Davis, J. Fuentes, A. Goldstein, G. Katul, B. Law, X. Lee, Y. Malhi, T. Meyers, J. W. Munger, W. Oechel, K. Pilegaard, H. P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy. 2001. Fluxnet: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. Bulletin of the American Meteorological Society 82 11:2415-2434.

Bartlein, P., and C. Whiltlock. 1993. Paleoclimate interpretation of the Elk Lake pollen record. Pp. 275 to 293 in Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. J. P. Bradbury and W. E. Dean, eds. Geological Society of America Special Paper 276**.** Boulder, Colorado.

Bear, J. 1972. Dynamics of fluids in porous media. American Elsevier: New York, NY.

Beljaars, A. C. M., P. Viterbo, M. Miller, and A. K. Betts. 1996. The anomalous rainfall over the USA during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. Mon. Wea. Rev. 124:362-383.

Bernabo, J. C., and T. Webb, III. 1977. Changing patterns in the Holocene pollen record of northeastern North America: A mapped summary. Quaternary Research 8:64-96.

Binley, A., P. Winship, R. Middleton, M. Pokar, and J. West. 2001. High-resolution characterization of vadose zone dynamics using cross-borehole radar. Water Resources Research 37(11):2639-2652.

Blasch, K. W., T. P. A. Ferré, A. H. Christensen, and J. P. Hoffmann. 2002. A New Field Method to Determine Streamflow Timing Using Electrical Resistance Sensors. Vadose Zone Journal 1:289-299.

Blöschl, G. 2001. Scaling in hydrology. Hydrol. Process. 15: 709-711.

Bodvarsson G. S., and T. M. Bandurraga (eds). 1996. Development and Calibration of the Three-Dimensional Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada. Yucca Mountain

Project Milestone OBO2. Lawrence Berkeley National Laboratory Report LBNL-39315. Berkeley, Calf.

Böhlke, J. K. 2002. Groundwater recharge and agricultural contamination. Hydrogeology 10(1): 153-179.

Bouraoui, F., G. Vachaud, L. Z. X. Li, H. LeTreut, and T. Chen. 1999. Evaluation of the impact of climate changes on water storage and groundwater recharge at the watershed scale. Climate Dynamics 15:153–161.

Bradbury, K. R., S. K. Swanson, J. T. Krohelski, and A. K. Fritz. 1999. Hydrogeology of Dane County, Wisconsin. Wisconsin Geological and Natural History Survey Open-File Report 1999-04.

Breemer, C. W., P. U. Clark, and R. Haggerty. 2002. Modeling the subglacial hydrology of the late Pleistocene Lake Michigan Loge, Laurentide Ice Sheet. Geological Society of America Bulletin 114(6):665-674.

Burnett, W. C., J. Chanton, J. Christoff, E. Kontar, S. Krupa, M. Lambert, W. Moore, D. ORourke, R. Paulsen, C. Smith, L. Smith, and M. Taniguchi. 2002. Assessing methodologies for measuring groundwater discharge to the ocean. Eos 83(11):117, 122-123.

Burnett, W. C., M. Taniguchi, and J. Oberdorfer. 2001. Measurement and significance of the direct discharge of groundwater into the coastal zone. Jour. Sea Research 46:109-116.

Charney, J. G. 1975. Dynamics of deserts and droughts in the Sahel. Quart. J. R. Met. Soc. 101:193-202.

Cherkauer, K. A., L. C. Bowling, and D. P. Lettenmaier. 2003. Variable Infiltration Capacity (VIC) Cold Land Process Model Updates. Global and Planetary Change (in press).

Constantz, J., C. L. Thomas, and G. Zellweger. 1994. Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge. Water Resour. Res. 30:3253-3264.

Cook, P. G., and S. Kilty. 1992. A helicopter-borne electromagnetic survey to delineate groundwater recharge rates. Water Resources Research 28(11):2953-2961.

Cooper, D. I., W. E. Eichinger, J. Kao, L. Hipps, J. Reisner, S. Smith, S. M. Schaeffer, and D. G. Williams. 2000. Spatial and temporal properties of water vapor and latent energy flux over a riparian canopy. Agricultural and Forest Meteorology 105: 161-183.

Crill, P., K. Bartlett, and N. Roulet. 1992. Methane flux from boreal peatlands. Proceedings of the International workshop on Carbon Cycling in Boreal Peatlands and Climate Change. Suo 43: 173-182.

Davis, E. E., G. C. Horel, R. D. Macdonald, H. Villinger, R. H. Bennett, and H. Li. 1991. Pore pressures and permeabilities measured in marine sediments with a tethered probe. Journal of Geophysical Research 96:5975-5984.

Davis, S. N., and R. J. M. DeWiest. 1966. Hydrogeology. John Wiley & Sons: New York, NY.

Delin, G. N., R. W. Healy, M. K. Landon, and J. K. Bohlke. 2000. Effects of topography and soil properties on recharge at two sites in an agricultural field. Journal of the American Water Resources Association 36(6):1401-1416.

Dettinger, M. D., and H. F. Diaz. 2000. Global characteristics of stream flow seasonality and variability. Journal of Hydrometeorology 1(4):289–310.

Desbarats, A. J., M. J. Hinton, C. E. Logan, and D. R. Sharpe. 2001. Geostatistical mapping of leakance in a regional aquitard, Oak Ridges Moraine area, Ontario, Canada. Hydrogeology Journal 9(1):79-96.

de Vries, J. J., and I. Simmers. 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal 10:5–17.

Donovan, J. J., A. J. Smith, V. A. Panek, D. R. Engstrom, and E. Ito. 2002. Climate-driven hydrologic transients in lake sediment records: calibration of groundwater conditions using 20th Century drought. Quaternary Science Reviews 21:605-624.

Douglas, B. C., and W. R. Peltier. 2002. The puzzle of global sea-level rise. Physics Today 55:35-40.

Duffy, C. J. 1996. A two-state internal balance model for soil moisture and groundwater dynamics in complex terrain. Water Resources Research 32(8):2421-2434.

M. F. Dyck, R. G. Kachanoski, and E. de Jong. 2003 Long-term movement of a chloride tracer under transient, semi-arid conditions. Soil Sci. Soc Am J. 67: 471-477.

Essaid, H. I. 1990. A multilayered sharp interface model of coupled freshwater and saltwater flow in coastal systems: Model development and application. Water Resources Research 26(7):1431-1454.

Famiglietti, J. S., and E. F. Wood. 1994. Multi-Scale Modeling of Spatially-Variable Water and Energy Balance Processes. Water Resources Research 30(11):3061-3078.

Filby, S., S. Locke, M. Person, T. Winter, T., D. O. Rosenberry, J. Nieber, W. J. Gutowski, and E. Ito. 2002. Mid-Holocene Hydrologic Model of the Shingobee Watershed, Minnesota, Quaternary Research 58(3):246-254.

Flint, A. L., L. E. Flint, E. M. Kwicklis, J. Fabryka-Martin, and G. S. Bodvarsson. 2002. Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeology Journal 10(1):180-203.

Fogg, G. E., E. M. LaBolle, and G. S. Weissmann. 1999. Groundwater vulnerability assessment: Hydrogeologic perspective and example from Salinas Valley, California. In: D. L. Corwin, K. Loague and T. R. Ellsworth (eds.), Application of GIS, Remote Sensing, Geostatistical and Solute Transport Modeling. AGU Geophysical Monograph Series Vol. 108. AGU Press: Washington, DC.

Forster, C., and L. Smith. 1988a. Groundwater flow systems in mountainous terrain: 1. Numerical model technique. Water Resources Research 42(7):999-1010.

Forster, C., and L. Smith. 1988b. Groundwater flow systems in mountainous terrain: 2. Controlling factors. Water Resources Research 42(7):1011-1023.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall: Upper Saddle River, New Jersey.

Fritz, S. C., E. Ito, Z. Yu, K. Laird, and D. R. Engstrom. 2000. Hydrologic variation in the Northern Great Plains during the last two millennia. Quaternary Research 53:175-184.

Ge, S., B. Bekins, J. Bredehoeft, K. Brown, E. E. Davis, S. M. Gorelick, and others. 2003. Fluid flow in sub-sea floor processes and future ocean drilling. Eos 84(16).

Gelhar, L. W. 1986. Stochastic subsurface hydrology from theory to applications. Water Resources Res. 22:1355-1453.

Gornitz, V. 2000. Impoundment, groundwater mining, and other hydrologic transformations: impacts on global sea level rise. Pp. 97 to 119 in Sea Level Rise: History and Consequences. B. C. Douglas, M. S. Kearney, and S. P. Leatherman (eds.). Academic Press: New York.

Grasby, S., K. Osadetz, R. Betcher, and F. Render. 2000. Reversal of the regional-scale flow system of the Williston Basin in response to Pleistocene Glaciation. Geology 28(7):635-638.

Gutowski, W. J., C. J. Vörösmarty, M. Person, S. Ötles, B. Fekete, and J. A. York. 2002. Coupled land-atmosphere simulation program (CLASP): calibration and validation. J. Geophys. Res. 107 (D16):1-17.

Haitjema, H. M. 1995. Analytic Element Modeling of Groundwater Flow. Academic Press: New York.

Halford, J., and G. C. Meyer. 2000. Problems associated with estimating ground water discharge and recharge from stream-discharge records. Ground Water 38(3): 331-342.

Halliday, W. R. 1998. History and Status of the Moiliili Karst, Hawaii. Journal of Cave and Karst Studies 60:141-145.

Hartmann, H. C., T. C. Pagano, T. S. Hogue, S. Mahani, and S. Sorooshian. 2000. Town meeting revisits priorities in the hydrologic sciences. Eos, June 20, 2000, p. 283.

Harvey, F. E., D. R. Lee, D.L. Rudolph, and S. K. Frape. 1997. Locating Groundwater Discharge in Deep Lakes Using Electrical Conductivity Mapping. Water Resources Research 33(11): 2609-2616.

Healy, R. W., and P. G. Cook. 2002. Using groundwater levels to estimate recharge. Hydrogeology Journal 10(1):91-109.

Henry, P. J.-P. Foucher, X. Le Pichon, M. Sibuet, K. Kobayashi, P. Tarits, N. Chamot-Rooke, T. Furuta, and P. Schultheiss. 1992. Interpretation of temperature measurements from the Kaiko-Nankai cruise: Modeling of fluid flow in clam colonies. Earth and Planetary Science Letters 109:355-371.

Hubbert, M. K. 1956. Darcy's law and the field equations of the flow of underground fluids. Trans. Amer. Inst. Min. Met. Eng. 207:222-239.

Huffman, G., and D Bolvin. 2002. GPCP Version 2 combined precipitation data set documentation. Laboratory for Atmospheres, NASA Goddard Space Flight Center, Beltsville, MD.

Hunt, R. J. 1996. Do Created Wetlands Replace Wetlands that are Destroyed? USGS Fact Sheet FS-246-96, 4 p.

Hunt, R. J., and J. J. Steuer. 2001. Simulation of the Recharge Area for Frederick Springs, Dane County, Wisconsin. USGS Water-Resources Investigations Report 00-4172.

Hunt, R. J., J. J.Steuer, M. T. C. Mansor, and T. D. Bullen. 2001. Delineating a recharge area for a spring using numerical modeling, Monte Carlo techniques, and geochemical investigation. Ground Water 39(5):702-712.

Hunt, R. J., D. P. Krabbenhoft, and M. P. Anderson. 1997. Assessing hydrogeochemical heterogeneity in natural and constructed wetlands. Biogeochemistry 39(5):271-293.

Hunt, R. J., D. P. Krabbenhoft, and M. P. Anderson. 1996. Groundwater inflow measurements in wetland systems. Water Resources Research 32(3):495-508.

Intergovernmental Panel on Climate Change. 2001. Climate Change 2001: The Scientific Basis. World Meteorological Organization and United Nations Environment Programme. Online. Available at http://www.grida.no/climate/ipcc_tar/wg1/index.htm.

Izbicki, J. A., J. W. Borchers, D. A. Leighton, J. Kulongoski, L. Fields, D. L. Galloway, and R. L. Michel. 2002. Hydrogeology and Geochemistry of Aquifers Underlying the San Lorenzo and San Leandro Areas of the East Bay Plain, Alameda County, California. USGS Water Resources Investigations Report 02-4259. U.S. Geological Survey Sacramento, California.

Jackson, T. J. 2002. Remote sensing of soil moisture: implications for groundwater recharge. Hydrogeology Journal 10(1):40-51.

Johnson, H. P., and the LEXEN Scientific Party. 2003. Probing for life in the ocean crust with the LEXEN program. Eos 84(12).

Jones, J. B., and P. J. Mulholland. 2000. Streams and Ground Waters. Academic Press: San Diego.

Jorgensen, D. G., D. C. Signor, and J. I. Imes. 1989. Accounting for intracell flow in models with emphasis on water table recharge and stream-aquifer interactions: I. problems and concepts. Water Resources Research 25(4):669-676.

Kohout, F. A., J. C. Hathaway, D. W. Folger, M. H. Bothner, E. H. Walker, D. F. Delaney, M. H. Frimpter, E. G. A. Weed, and E. V. C. Rhodehamel. 1977. Fresh groundwater stored in aquifers under the continental shelf: implications from a deep test, Nantucket Island, Massachusetts. Water Resources Bulletin 13(2):373-386.

Koster, R. D., M. J. Suarez, A. Ducharne, M. Steiglitz, and P. Kumar. 2000. A catchment-based approach to modeling land surface processes in a general circulation model, 1. Model structure. J. Geophys. Res.105(D20): 24,809-24,822.

Krabbenhoft, D. P., and K. E. Webster. 1995. Transient hydrogeological controls on the chemistry of a seepage lake. Water Resources Research 31(9): 2295-2305.

Lee, D. R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnology and Oceanography 22-140-147.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A simple hydrologically based model of land and energy fluxes for general circulation models. Journal of Geophysical Research 99(D7): 14, 415-14.

Lambert, P. M., and B. J. Stolp. 1999. Hydrology and Simulation of the Ground-Water Flow System in the Tooele Valley, Utah. USGS WRIR 99-4014. 60 p.

Lapham, W. W. 1989. Use of Temperature Profiles Beneath Streams to Determine Rates of Vertical Ground-Water Flow and Vertical Hydraulic Conductivity. Water-Supply Paper 2337. 35 p.

Lerner, D. N. 2002. Identifying and quantifying urban recharge: a review. Hydrogeology Journal 10:143-152.

Levine, J. B., and G. D. Salvucci. 1999. Equilibrium analysis of groundwater-vadose zone interactions and the resulting spatial distribution of hydrologic fluxes across a Canadian prairie. Wat. Resour. Res. 35:1369-1383.

Lilly A., D. B. Boorman, J. M. Hollis. 1998. The development of a hydrological classification of UK soils and the inherent scale changes. Nutrient Cycling In Agroecosystems 50: 299-302.

Lin, Y-F., and M. P. Anderson. 2003. A Digital Procedure for Ground Water Recharge and Discharge Pattern Recognition and Rate Estimation. Ground Water 41(3):306-315.

Loaiciga, H. A., D. Maidment, and J. B. Valdes. 2000. Climate change impacts in a regional karst aquifer, Texas, USA. Journal of Hydrology 227:173-194.

Lodge, D. M., D. P. Krabbenhoft and R. G. Striegl. 1989. A positive relationship between groundwater velocity and submersed macrophyte biomass in Sparkling Lake, Wisconsin. Limnol. Oceanogr. 34: 235–239.

Logan, W. S., and D. L. Rudolph. 1997. Microdepression-focused recharge in coastal wetlands of the Rio de La Plata, Argentina. Journal of Hydrology 194: 221-238.

Maidment, D. R. 1993. Handbook of Hydrology. Mc-Graw Hill Book Co.:New York.

Maurer, E. P., A.W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. J. Climate. 15(22): 3237-3251.

Maxey, G. B., and T. E. Eakin. 1949. Ground water in the White River Valley, White Pine, Nye and Lincoln counties, Nevada. State of Nevada Office of the State Engineer. Water Resources Bulletin No. 8.

McBride, M. S., and H. O. Pfannkuch. 1975. The Distribution of Seepage within Lakebeds: Journal of Research of the U.S. Geological Survey 3(5): 505-512.

McPherson, B. J. O. L., and P. C. Lichtner. 2003. CO2 sequestration in deep aquifers. Pp. 1-8 in Proceedings: First National Conference on Carbon Sequestration. National Energy Technology Laboratory, May 14-17, 2001. U. S. Department of Energy: Washington, D. C.

Meijerink, A. M. J. 1996. Remote sensing applications to hydrology. Groundwater Hydrological Sciences Journal 41(4):549-561.

Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. J. Hydrol. 4:38-62.

Michael, H., J. Lubetsky, and C. Harvey. 2003. Characterizing submarine groundwater discharge: a seepage meter study in Waquoit Bay, Massachusetts. Geophysical Research Letters 30(6): 1297, doi:10.1029/2002GL016000.

Milly, P. C. D. 1994a. Climate, interseasonal storage of soil water, and the annual water balance. Adv. Water Resour. 17:19-24.

Milly, P. C. D. 1994b. Climate, soil water storage, and the average annual water balance. Water Resour. Res. 30:2143-2156.

Milly, P. C. D., and K. A. Dunne. 2001. Trends in evaporation and surface cooling in the Mississippi River basin. Geophysical Research Letters 28(7):1219-1222.

Milly, P. C. D., and K. A. Dunne. 1994. Sensitivity of the global water cycle to the water-holding capacity of the land. J. Clim. 7:506-526.

Mitchell, K. E., D. Lohmann, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B.A. Cosgrove, J. Sheffield, Q. Duan, L. Luo, R. W. Higgins, R. T. Pinker, J. D. Tarpley, D. P. Lettenmaier, C. Marshall, J. Entin, M. Pan, W. Shi, V. Koren, J. Meng, B. H. Ramsay, and A. A. Bailey. 2003. The Multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. Journal of Geophysical Research –Atmospheres, May 31, 2003.

Moore, T. B., and N. Roulet. 1993. Methane flux; water table relations in northern wetlands. Geophys. Res. Lett. 20: 587-590.

National Research Council (NRC). 1999. Hydrologic Science Priorities for the U.S. Global Change Research Program: An Initial Assessment. National Academy Press: Washington, D.C.

National Research Council (NRC) 2000. Grand Challenges in Environmental Sciences. National Academy Press: Washington, D.C.

National Research Council (NRC). 2002a. Report of a Workshop on Predictability & Limits-To-Prediction in Hydrologic Systems. National Academy Press: Washington, D.C.

National Research Council (NRC). 2002b. Review of USGCRP Plan for a New Science Initiative on the Global Water Cycle. National Academy Press: Washington, D.C.

National Research Council (NRC). 2002c. Regional Issues in Aquifer Storage and Recovery for Everglades Restoration: A Review of the ASR Regional Study Project Management Plan of the Comprehensive Everglades Restoration Plan. National Academy Press: Washington, D.C.

Oki, T., K. Musiake, H. Matsuyama, and K. Masuda. 1995. Global atmospheric water balances and runoff from large river basins. Hydro. Proc. 9:655-678.

Paegle, J., K. Mo, and J. Nogues-Paegle. 1996. Dependence of simulated precipitation on surface evaporation during the 1993 U.S. summer floods. Mon. Weather Review 124:345-361.

Paulsen, R. J., C. F. Smith, D. O'Rouke, and T. F. Wong. 2001. Development and evaluation of an ultrasonic ground water seepage meter. Ground Water 39(6):904-911.

Peltier, W. R. 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. Reviews of Geophysics 36(4):603-689.

Pinker, R. T., and I. Laszlo. 1992. Modeling of surface solar irradiance for satellite applications on a global scale. J. Appl. Meteor. 31: 194-211.

Plummer, L. N., E. Busenberg, J. B. McConnell, S. Drenkard, P. Schlosser, and R. L. Michel. 1998. Flow of river water into a karstic limestone aquifer: tracing the young fraction in groundwater mixtures in the Upper Floridan aquifer near Valdosta, Georgia. Applied Geochemistry 13:995-1015.

Reilly, T. E., and D. W. Pollock. 1993. Factors affecting areas contributing recharge to wells in shallow aquifers. U.S. Geological Survey Water-Supply Paper 2412.

Reiner, S. R., R. J. Laczniak, G. A. DeMeo, J. L. Smith, P. E. Elliott, W. E. Nylund, and C. J. Fridirch. 2002. Ground-water discharge determined from measurements of evapotranspiration, other available hydrologic components, and shallow water-level changes, Oasis Valley, Nye, County, Nevada. USGS WRIR 01-4239. 65 p.

Remenda, V. H., J. A. Cherry, and T. W. D. Edwards. 1994. Isotopic composition of old ground water from Lake Agassi: implications for late Pleistocene climate. Science 266:1975-1978.

Rodell, M., and J. S. Famiglietti. 1999. Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. Wat. Resour. Res. 35: 2705-2723.

Rodell, M., and J. S. Famiglietti. 2001. An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). Wat. Resour. Res. 37:1327-1340.

Rodell, M., and J. S. Famiglietti. 2002. The potential for satellite-based monitoring of groundwater storage changes using GRACE: the High Plains aquifer, central U.S. J. Hydrol. 263: 245-256.

Romanowicz, E., D. I. Siegel, and P. H.Glaser. 1993. Hydraulic reversals and episodic methane emissions during drought cycles in mires. Geology 21: 231-234.

Ropelewski, C. F., and E. S. Yarosh. 1998. The observed mean annual cycle of moisture budgets of the Central United States (1973-92). Journal of Climate 11(9): 2180-2190.

Rosenberg, N. J., D. J. Epstein, D. Wang, L. Vail, R. Srinivasan, and J. G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala Aquifer Region. Climatic Change 42:677-692.

Rosenberry, D. O., R. G. Striegl, and D.C. Hudson. 2000. Plants as indicators of focused ground water discharge to a Northern Minnesota Lake. Ground Water 38(2): 296-303.

Salama, R. B., I. Tapley, T. Ishii, and G. Hawkes. 1994. Identification of areas of recharge and discharge using Landsat-TM satellite imagery and aerial photography mapping techniques. J. Hydrol. 162:119–141.

Salvucci, G. D., and D. Entekhabi. 1995. Hillslope and climatic controls on hydrologic fluxes. Water Resources Research 31:1725-1739.

Sasowsky, I. D. 1999. Structural effects in carbonate aquifers. Pp. 38-42 in A. N. Palmer, M. V. Palmer, and I. D., Sasowsky, (eds). Karst Modeling. Proceedings of the symposium held February 24-27, Charlottesville, VA. Karst Waters Institute, Charles Town, WV.

Scanlon, B. R., R. W. Healy, and P. G. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal 19(1): 18-39.

Scanlon, B., and P.G. Cook (eds). 2002. Theme issue on groundwater recharge. Hydrogeology Journal 10(1) 237.

Schultheiss, P. J. 1990. Pore pressures in marine sediments: An overview of measurement techniques and some geological engineering applications. Marine Geophysical Researches 12:153-168.

Shanley, J. B., E. Pendall, C. Kendall, L. R. Stevens, R. L. Michel, P. J. Phillips, R. M. Forester, D. L. Naftz, B. Liu, L. Stern, B. B. Wolfe, C. P. Chamberlain, S. W. Leavitt, T. H. E. Heaton, B. Mayer, L. D. Cecil, W. B. Lyons, B. G. Katz, J. L. Betancourt, D. M. McKnight, J. D. Blum, T. W. D. Edwards, H. R. House, E. Ito, R. O. Aravena, and J. F. Whelan. 1998. Isotopes as Indicators of Environmental Change. Pp. 761-801 in Isotope Tracers in Catchment Hydrology. C. Kendall, J. J. McDonnell, eds. Elsevier: Amsterdam.

Shun, T., and C. J. Duffy. 1999. Low-frequency oscillations in precipitation, temperature, and runoff on a west facing mountain front: A hydrogeologic interpretation. Water Resources Research 35:191-201.

Siegel, D. I., A. Reeve, P. H. Glaser, and E. Romanowicz. 1995. Climate-driven flushing of pore water from humified peat: geochemical and ecological ramifications. Nature 374: 531-533.

Siegel, D. I. 1991. Evidence for dilution of deep, confined groundwater by vertical recharge of isotopically heavy Pleistocene water. Geology 19:433-436.

Siegel, D. I., and R. J. Mandle. 1984. Isotopic evidence for glacial meltwater recharge to the Cambrian-Ordovician Aquifer, north-central United States. Quaternary Research 22:328-335.

Smith, A. J., J. J. Donovan, E. Ito, D. R. Engstrom, and V. A. Panek. 2002. Climate-driven hydrologic transients in lake sediment records: multi-proxy record of mid-Holocene drought. Quaternary Science Reviews 21:625-646.

Smith, R., K. R. J. Smettem, P. Broadbridge, and D. A. Woolhiser. 2002. Infiltration Theory for Hydrologic Applications. American Geophysical Union Water Resources Monograph Series, Vol. 15, 210 p.

Stoertz, M. W., and K. R. Bradbury. 1989. Mapping recharge areas using a ground-water flow model--a case study. Ground Water 27(2):220-228.

Sophocleous, M. 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal 10(1):52-67.

Steuer, J. J., and Hunt, R. J. 2001. Use of a Watershed-Modeling Approach to Assess Hydrologic Effects of Urbanization, North Fork Pheasant Branch Basin near Middleton, Wisconsin. USGS Water-Resources Investigations Report 01-4113.

Stieglitz, M., D. Rind, J. Famiglietti, and C. Rosenzweig. 1997. An efficient approach to modeling the topographic control of surface hydrology for regional and global climate modeling. J. Climate 10:118-137.

Stoertz, M. W., and K. R. Bradbury. 1989. Mapping recharge areas using a ground-water model - a case study. Ground Water 27:220-228.

Stone, D. B., C. L. Moomaw, and A. Davis. 2001. Estimating recharge distribution by incorporating runoff from mountainous areas in the alluvial basin in the Great Basin region of the Southwestern United States. Ground Water 39(6):807-818.

Sun, R. J., and R. H. Johnston. 1994. Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978-1992. USGS Circular 1099. 126 p.

Sundquist, E.T. 1993. The global carbon dioxide budget. Science 259:934-941.

Taniguchi, M. 2002. Tidal effects on submarine groundwater discharge into the ocean. Geophysical Research Letters 29(12).

Taniguchi, M., and Fukuo, Y. 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. Ground Water 31:675-679.

Taniguchi, M., Y. Sakura, and T. Ishii. 1998. Estimations of saltwater-fresh water interfaces and groundwater discharge rates in coastal zones from borehole temperature data. Pg. 86-89 in the Proceedings of Japanese Association of Groundwater Hydrology Meeting, Tokyo.

Toth, J. 1962. A theory of groundwater motion in small drainage basins in central Alberta. Journal of Geophysical Research 67:4375-4387.

Townley, L. R. 1995. The response of aquifers to periodic forcing. Advances in Water Resources 18:125-146.

U. S. Geological Survey. 1999. The Quality of Our Nation's Waters: Nutrients and Pesticides. Circular 1225. USGS: Reston, VA.

U. S. Global Change Research Program Water Cycle Study Group. 2001. A Plan for a New Science Initiative on the Global Water Cycle. U.S. Climate Change Science Program/U.S. Global Change Research Program: Washington, D.C.

Vaccaro, J. J. 1992. Sensitivity of groundwater recharge estimates to climate variability and change, Columbia Plateau, Washington. Journal of Geophysical Research 97(D3):2821-2833.

Van Dam, T., J. Wahr, C. Milly, A. Shmakin, G. Blewitt, D. Lavallee, and K Larson. 2001. Crustal displacements due to continental water loading. Geophys. Res. Lett. 28(4):651-654.

van der Kamp, G., and M. Hayashi. 1998. The groundwater recharge function of small wetlands in the semi- arid Northern Prairies. Great Plains Research 8(1):39-56.

Vanek, V., and D. R. Lee. 1991. Mapping Submarine Groundwater Discharge Areas – an Example from Laholm Bay, Southwest Sweden. Limnol. Oceanogr. 36:1250-1262.

Voss, C. I., and J. Andersson. 1993. Regional flow in the Baltic Shield during Holocene Coastal Regression. Ground Water 31(6):989-1006.

Wahr, J., M. Molenaar, and F. Bryan. 1998. Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. Journal of Geophysical Research 103 (B12):30205-30229.

Walker, J. F., and D. P. Krabbenhoft. 1998. Groundwater and surface-water interactions in riparian and lake-dominated systems. Pp. 467-486 in Isotopic Tracers in Catchment Hydrology. J. J. McDonnell and C. Kendall, eds. Elsevier, Amsterdam, The Netherlands.

Webb, T., III, K. H. Anderson, P. J. Bartlein, and R. S. Webb. 1998. Late Quaternary climate change in eastern North America; a comparison of pollen-derived estimates with climate model results. T. Webb, III (editor). Late quaternary climates; data synthesis and model experiments. Quaternary Science Reviews 17 (6-7):587-606.

Weissmann, G. S., Zhang, Y., La Bolle, E. M., and Fogg, G. E. 2002. Dispersion of groundwater age in an alluvial aquifer system. Water Resources Research 38(10): 10.1029/2001WR000907.

White, D. E., J. D. Hem, and G. S. Waring. 1963. Chemical composition of subsurface Waters. U.S. Geological Survey Professional Paper 440-F.

White, W. B. 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press: Oxford.

Wilson, K. B., P. J. Hanson, P. J. Mulholland, D. D. Baldocchi, and S. D. Wullschleger. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agricultural and Forest Meteorology 106:153-168.

Wilson, W. L., and B. F. Beck. 1992. Hydrogeologic factors in affecting new sinkhole development in the Orlando Area, Florida. Ground Water 30:918-930.

Winter, T. C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37(2):335-349.

Winter, T. C. 1999. Relation of streams, lakes and wetlands to groundwater flow systems. Hydrogeology 7(1):28-45.

Winter, T. C. 1981. Uncertainties in estimation the water balance of lakes. Water Resources Bull. 17(1):82-115.

Winter, T. C., and D. O. Rosenberry. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979-1990. Wetlands 15(3):193-211.

Winter, T. C., J. W.Harvey, O. L. Franke, and W. M. Alley. 1998. Ground Water and Surface Water: A Single Resource. U.S. Geological Survey Circular 1139. USGS: Denver, CO.

Wolfe, W. J., and C. J. Haugh. 2001. Preliminary Conceptual Models of Chlorinated-Solvent Accumulation in Karst Aquifers. In Eve L. Kuniansky, editor, U.S. Geological Survey Karst Interest

Group Proceedings, St. Petersburg, Florida, February 13-16, 2001. U.S. Geological Survey Water-Resources Investigations Report 01-4011. USGS: Reston, VA.

Xue, Y., and J. Shukla. 1993. The influence of land surface properties on Sahel climate. Part I: desertification. J. Climate 6: 2232-2245.

Yeh, T-C., R. T. Wetherald, and S. Manabe. 1984. The effect of soil moisture on a short-term climate and hydrology change--A numerical experiment. Monthly Weather Review 112(3):474-490.

York, J. P., M. Person, W. J. Gutowski, and T. C. Winter. 2002. Putting aquifers into atmospheric simulation models: an example from the Mill Creek Watershed, northeastern Kansas. Advances in Water Resources 25(2): 221-238.

Zeng, N., and J. D. Neelin. 2000. The role of climate-vegetation interaction and interannual variability in shaping the African Savanna. J. Climate 13: 2665-2670.

Zhu, C., R. K. Waddell, Jr., I. Star, and M. Ostrander. 1998. Responses of groundwater in the Black Mesa Basin, northeastern Arizona to paleoclimatic changes during the late Pleistocene and Holocene. Geology 26(2):127-130.

Appendix A
Workshop Agenda

Sunday, May 12, 2002

6:00-9:30 PM	Reception and Poster Session.	

Monday, May 13, 2002

6:30-8:30	Breakfast	
8:30-9:30	Introductions/objectives (Anderson)	
9:30-11:30	Climate Issues	
	Facilitators:	Henk Haitjema, Indiana University Mike Dettinger, USGS, San Diego
	Panelists:	Guido Salvucci, Boston University Matt Rodell, NASA Goddard Chris Milly, USGS, Princeton
11:30-1:00	Lunch	
1:00-3:00	Diffuse vs. Focused Fluxes	
	Facilitators:	Bridget Scanlon, Texas Bureau of Economic Geology Don Siegel, Univ. of Syracuse
	Panelists:	Bill Woessner, Univ. of Montana Leslie Smith, Univ. British Columbia Randy Hunt, USGS

3:00-3:30	Break
3:30-5:30	Scaling Issues Facilitator: John Selker, Oregon State University Panelists: Ken Bradbury, WI Geological & Natural History Survey Chris Duffy, Penn State University Stacy Howington, U.S. Army ERDC
5:30-6:30	Break
6:30-8:00	Reception and dinner Special invited talk: "Hydrogeology of Door County" (Ken Bradbury) (See Appendix B)
8:00-9:00	COHS steering committee meets

Tuesday, May 14, 2002

6:30-8:30AM	Breakfast
8:30-9:30	Group discussion and writing assignments
9:30-11:00	Writing
11:00-noon	Discussion
Noon-1:00	Lunch
1:00-2:30	Group discussion. Design of a watershed scale experiment to measure spatial and temporal patterns in recharge and discharge (Wilson)
2:30-3:00	Group discussion and writing assignments
3:00-4:30	Writing
4:30-5:00	Turn in assignments and wrap up
5:00-6:00	Break
6:00-7:30	Reception and dinner
7:30	Introduction to CUAHSI (Wilson)

Appendix B
Groundwater Recharge and Discharge on Wisconsin's Door Peninsula

Based on a talk given at the workshop by Kenneth R. Bradbury
Wisconsin Geological and Natural History Survey

The workshop on "Groundwater fluxes across interfaces" was held in Egg Harbor, Wisconsin, which is situated on the Door Peninsula (Figure B-1). The hydrogeology of the Door Peninsula illustrates the complexity and importance of flow across interfaces - groundwater recharge and discharge processes. A rocky peninsula between Lake Michigan and Green Bay, the Door Peninsula is characterized by rugged rocky shorelines and sandy beaches. The scenery along with the mild climate, abundant natural resources, and a small-town feel have made the Door Peninsula one of the most popular tourist destinations in the midwestern United States. All residents of the county depend on groundwater, but groundwater quality problems have plagued the county for many years. Bacteria and nitrate exceed drinking water standards in about 30 percent of the private wells in the county, and private well owners often report turbid or muddy water in their wells during certain times of the year (Bradbury and Muldoon, 1992). Other groundwater contaminants include agricultural chemicals, pesticide residues from cherry and apple orchards, and petroleum and other non-aqueous phase liquids.

Much of the charm of the Door Peninsula, and its groundwater problems, are directly related to its unique geology – a combination of Paleozoic bedrock and Pleistocene modifications. Silurian-age dolomites form the backbone of the peninsula and dip gently eastward into the Michigan Basin (Figure B-2). In the Late Pleistocene, continental glaciers covered the area, and when they retreated they left behind a unique landscape. On the western side of the county the Silurian escarpment forms high cliffs along the Green Bay shoreline; only a few miles to the east the land meets Lake Michigan with sandy beaches and diverse wetlands. In between, in the uplands of the county, glaciers removed most of the soil, so that in most places the bedrock is less than two meters below the surface and in many places it is exposed at the land surface. The dolomite contains both near-horizontal and vertical fractures (Muldoon et al., 2001). These fractures are extensive, and the vertical fractures are easily visible from the air, particularly under alfalfa fields in dry weather. The combination of thin soils and fractured rock makes groundwater in the county extremely vulnerable to contamination.

Groundwater flow in the Door Peninsula is conceptually simple, with recharge occurring in the uplands along the crest of the peninsula, and discharge occurring in springs and seeps along the Green Bay and Lake Michigan shorelines. In detail, however, both the recharge and discharge processes are

FIGURE B-1 Location of the Door Peninsula in eastern Wisconsin, extending out into Lake Michigan. E.H. is Egg Harbor, the site of the workshop. SOURCE: Adapted from Kenneth R. Bradbury, Wisconsin Geological and Natural History Survey, written commun., 2002.

quite complex. Groundwater recharge is rapid, transient, and often focused in discrete depressions where open vertical fractures or solution features occur at the land surface. Most annual recharge occurs over a few weeks following spring rains and snowmelt; during this period groundwater levels often rise by tens of meters. Thermal and geochemical data collected during specific recharge events show that recharge water can move from the land surface to tens of meters below the water table in a matter of hours or days. Once in the aquifer, groundwater flow is generally horizontal along bedding-plane fractures that have been widened by solution (Rayne et al., 2001). Flow rates in this fractured dolomite can be extremely rapid – on the order of 10 km/yr. These rapid flow rates mean that local private and municipal water supply wells are extremely vulnerable to contamination from surface sources, and that contributing areas for local wells can be very large.

Groundwater not captured by wells in the Door Peninsula discharges to discrete shoreline springs, local wetlands, and as diffuse flow through offshore lake sediments. In general, springs occur where conductive horizontal or vertical factures intersect the shoreline. Locally, hydraulic gradients in the discharge zone can be high enough to create flowing wells, sand boils and measurable thermal anomalies,

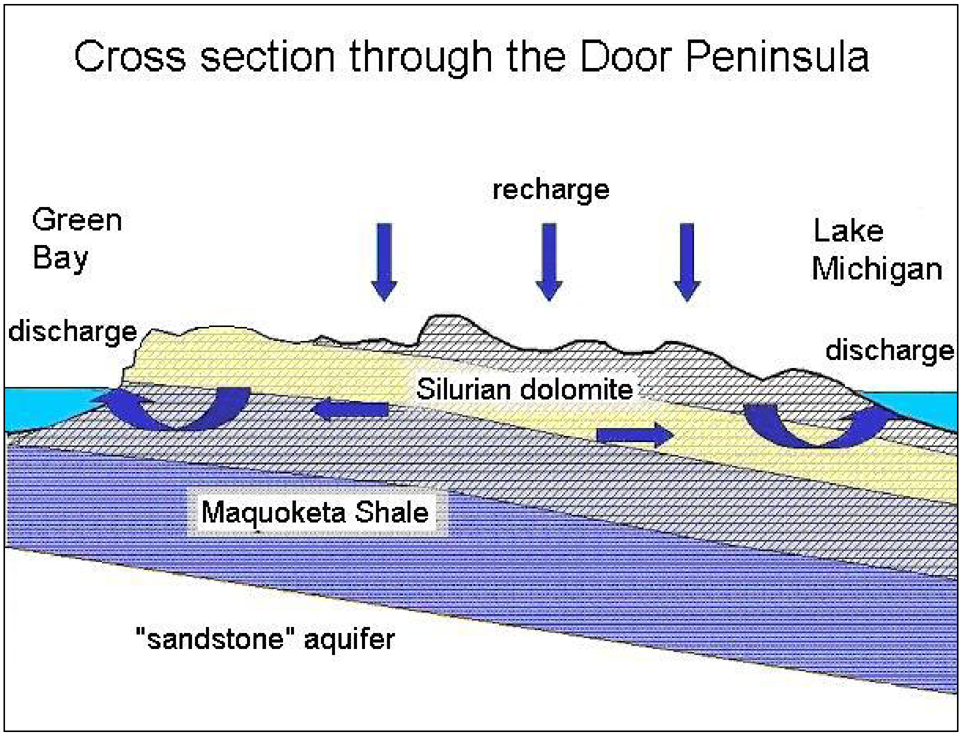


FIGURE B-2 West-to-east cross section of the Door Peninsula. SOURCE: Kenneth R. Bradbury, Wisconsin Geological and Natural History Survey, written commun., 2002.

but over large areas of the lakebed the upward groundwater discharge through lake sediments is slow and difficult to measure. In this environment, closing the water budget – balancing recharge processes with discharge processes - is extremely challenging, yet understanding recharge and discharge processes is essential for solving local groundwater contamination problems and for making wise land-use management decisions for the area.

Appendix C
Agency Interest in Groundwater Fluxes

The following are brief summaries of agency interest in the topics of the workshop.

Bureau of Reclamation (BuRec)

Due to its water management mission, BuRec is one of the federal leaders in artificial recharge of groundwater. Accurate conception and management of such projects, and of watershed management in general, requires an understanding of natural recharge and discharge rates and distribution in space and time as well. Other issues of interest include water quality and environmental benefits and impacts of underground storage and retrieval of water.

U.S. Department of Agriculture (USDA)

The USDA is intensely interested in soil moisture for agriculture, and the temporal and spatial distribution of soil moisture depends partially on rates of recharge and discharge. The Agricultural Research Service funds research on uncertainty estimates for groundwater recharge. The Natural Resources Conservation Service's Soil and Water Conservation Assistance program and Resource Conservation and Development program indirectly take recharge into account in their projects. And the Forest Service has long-standing research on understanding effects of forest and rangeland management and related human and natural disturbances on the quality and quantity of available water – including groundwater – in their watersheds.

U.S. Department of Defense (DOD)

The DOD's interest in groundwater fluxes arises from its responsibilities in several research areas and is not limited to a single geographic region or climate. Contaminants are frequently encountered in groundwater at Army, Navy, and Air Force facilities, where the distribution of infiltration in space and time, and fluxes of contaminants between groundwater and surface water bodies, are key questions. The Corps of Engineers' roles include permitting of wetland mitigation; discharge rates may be the key to whether a wetland type can be recreated in a given location. Flow rates beneath and through levees and earthen dams are of obvious interest to the Corps. Finally, there are direct military applications such as predicting soil saturation levels or stream depth and velocity for planning troop movements using estimates of the timing and volume of infiltration and runoff.

U.S. Department of Energy (DOE)

Groundwater fluxes are also of interest to the DOE, which recently laid out a blueprint for research in subsurface science in which they identified a need to characterize boundary conditions (i.e., fluxes at interfaces) that control contaminant transport and fate. Quantification of recharge rates is of intense interest at the DOE's Yucca Mountain Site for spent nuclear fuel (Flint et al., 2002), and at many other contaminated sites including the Hanford Site (Washington State), Idaho National Engineering and Environmental Laboratory, and the Savannah River Site (South Carolina).

U.S. Environmental Protection Agency (USEPA)

The Environmental Protection Agency oversees the remediation of a large number of contaminated sites. The rate of migration of dissolved contaminants in shallow soil and aquifers is a function of recharge rates. Likewise, discharge zones can either be areas of natural degradation of contaminants, or a pathway of contamination to surface water bodies. Groundwater vulnerability and the geometry of groundwater protection areas – both important topics to the USEPA – are functions of recharge rate and distribution among other factors. The USEPA and NSF's joint research initiatives on watersheds have also involved projects that measure recharge and discharge.

U.S. Geological Survey (USGS)

Quantifying groundwater recharge is a priority research area in the U.S. Geological Survey. In a summary article prepared by USGS researchers for the American Geological Institute (Reilly et al., 2000), recent advances in measuring flow between groundwater and surface water were highlighted (along with measuring land subsidence) as particularly important to sustainability of groundwater resources. Groundwater recharge rate estimation is one of the four priority topics for the Ground-Water Resources Program. And the National Research Program's project on "Role of Lakes in the Hydrologic System" has spent decades examining fluxes across the lake-groundwater interface.

National Air and Space Administration (NASA)

In general, NASA's interest in groundwater fluxes derives from: 1) the potential to measure – directly or indirectly – groundwater and its fluxes from satellite-borne remote sensing instruments; and 2) the perceived importance of groundwater as a component of the Earth system and its relationship to climate change. The Gravity Recovery and Climate Experiment (GRACE) aims to estimate changes in total terrestrial water storage with high precision. Use of laser altimetry measurements to deduce river stage, and from that baseflow (groundwater discharge) also shows promise. NASA is also interested in the consequences of climate change for life on Earth.

The following questions of interest to NASA all include a groundwater flux component: How is the global Earth system changing? How are global precipitation, evaporation, and the cycling of water changing? How are variations in local weather, precipitation, and water resources related to global climate variation? And how well can long-term climatic trends be assessed or predicted?

National Oceanic and Atmospheric Administration (NOAA)

Near-surface groundwater fluxes are critical to NOAA modeling needs. For example, the effect near-surface fluxes have on moisture content of the lower soil layers is not well understood. In current NOAA models, the moisture content in these lower zones contributes to long-term base flow in streams and rivers. Thus, any groundwater fluxes across the interface with these lower zones can impact base flow modeling. Including the groundwater surface-water interaction in these hydrologic models may have an impact on soil moisture simulations.

Second, the mechanisms for determining flow paths for near surface ground water need to be understood as the National Weather Service moves towards finer scale (distributed) hydrologic modeling. While the paths of overland flow on the surface are assumed to follow topographic slope, it is not clear if near-surface ground water can be modeled in this manner. Research needs to address the movement of near-surface soil moisture towards river channels. Finally, the effect of low frequency groundwater fluctuations on the climate needs to be evaluated. Under what conditions are the relationship between precipitation and groundwater out of phase? And does groundwater have a significant longer term feedback effect on the climate?

National Science Foundation (NSF)

NSF funds research in the hydrologic sciences (groundwater, surface water, and land surface hydrology), most of which comes through the Geosciences Directorate. In addition to the Hydrologic Science program run though the Division of Earth Sciences, NSF's Atmospheric Sciences Division funds research on Climate Variability and Predictability (CLIVAR). The two divisions are collaborating on a research initiative called Water and Energy: Atmospheric, Vegetative and Earth Interactions (WEAVE), which includes water and energy fluxes across interfaces. Further, NSF is sponsoring the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) (www.cuahsi.org), which has proposed a network of hydrologic observatories that could be used for research in groundwater fluxes at a fairly large scale.

Nuclear Regulatory Commission (NRC)

The NRC regulates civilian use of nuclear materials. As such, it is responsible for storage and disposal of nuclear materials and waste. Groundwater discharge rates and distribution in such areas are of obvious interest to the Commission. The NRC is also in charge of the license renewals of nuclear plants. These renewals require Environmental Impact Statements, which have sections on impacts on groundwater, water use, floodplains and wetlands.

REFERENCES

Flint, A. L., L. E. Flint, E. M. Kwicklis, J. Fabryka-Martin, and G. S. Bodvarsson. 2002. Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeology Journal 10(1):180-203.

Reilly, T. E., K. R. Prince, and J. W. LaBaugh. 2000. Solid earth: hydrogeology. Geotimes 45 (7): 23.

Appendix D
National Research Council Board Membership and Staff

WATER SCIENCE AND TECHNOLOGY BOARD

RICHARD G. LUTHY, *Chair,* Stanford University, Stanford, California
JOAN B. ROSE, *Vice Chair*, Michigan State University, East Lansing
RICHELLE M. ALLEN-KING, University at Buffalo (SUNY), Buffalo, New York
GREGORY B. BAECHER, University of Maryland, College Park
KENNETH R. BRADBURY, Wisconsin Geological and Natural History Survey, Madison
JAMES CROOK, Water Reuse Consultant, Norwell, Massachusetts
EFI FOUFOULA-GEORGIOU, University of Minnesota, Minneapolis
PETER GLEICK, Pacific Institute for Studies in Development, Environment, and Security, Oakland, California
JOHN LETEY, JR., University of California, Riverside
CHRISTINE L. MOE, Emory University, Atlanta, Georgia
ROBERT PERCIASEPE, National Audubon Society, Washington, DC
JERALD L. SCHNOOR, University of Iowa, Iowa City
LEONARD SHABMAN, Virginia Polytechnic Institute and State University, Blacksburg
R. RHODES TRUSSELL, Trussell Technologies, Inc., Pasadena, California
KARL K. TUREKIAN, Yale University, New Haven, Connecticut
HAME M. WATT, Independent Consultant, Washington, DC
JAMES L. WESCOAT, JR., University of Illinois at Urbana-Champaign

Staff

STEPHEN D. PARKER, Director
LAURA J. EHLERS, Senior Staff Officer
JEFFREY W. JACOBS, Senior Staff Officer
WILLIAM S. LOGAN, Senior Staff Officer
LAUREN E. ALEXANDER, Staff Officer
MARK C. GIBSON, Staff Officer

STEPHANIE E. JOHNSON, Staff Officer
M. JEANNE AQUILINO, Administrative Associate
ELLEN A. DE GUZMAN, Research Associate
PATRICIA JONES KERSHAW, Study/Research Associate
ANITA A. HALL, Administrative Assistant
JON Q. SANDERS, Senior Project Assistant
DOROTHY K. WEIR, Project Assistant

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ERIC J. BARRON (*Chair*), Pennsylvania State University, University Park
FREDERICK R. ANDERSON, Cadwalader, Wickersham & Taft, Washington, D.C.
RAYMOND J. BAN, The Weather Channel, Inc., Atlanta, Georgia
ROBERT C. BEARDSLEY, Woods Hole Oceanographic Institution, Massachusetts
ROSINA M. BIERBAUM, University of Michigan, Ann Arbor
RAFAEL L. BRAS, Massachusetts Institute of Technology, Cambridge
MARY ANNE CARROLL, University of Michigan, Ann Arbor
KERRY A. EMANUEL, Massachusetts Institute of Technology, Cambridge
CASSANDRA G. FESEN, Dartmouth College, Hanover, New Hampshire
MARGARET A. LEMONE, National Center for Atmospheric Research, Boulder, Colorado
JENNIFER A. LOGAN, Harvard University, Cambridge, Massachusetts
MARIO J. MOLINA, Massachusetts Institute of Technology, Cambridge
WILLIAM J. RANDEL, National Center for Atmospheric Research, Boulder, Colorado
ROBERT J. SERAFIN, National Center for Atmospheric Research, Boulder, Colorado
ROGER M. WAKIMOTO, University of California, Los Angeles
JOHN C. WYNGAARD, Pennsylvania State University, University Park

Ex Officio Members

ANTONIO J. BUSALACCHI, JR., University of Maryland, College Park
ERIC F. WOOD, Princeton University, New Jersey

Staff

CHRIS ELFRING, Director
SHELDON DROBOT, Program Officer
AMANDA STAUDT, Program Officer
JULIE DEMUTH, Research Associate
ELIZABETH A. GALINIS, Project Assistant
ROB GREENWAY, Project Assistant
DIANE GUSTAFSON, Administrative Associate
ROBIN MORRIS, Financial Officer

Appendix E
Biographical Sketches of Members of the Committee on Hydrologic Science

Eric F. Wood (chair) is a professor in the Department of Civil Engineering and Operations Research, Water Resources Program, at Princeton University. His areas of interest include hydroclimatology with an emphasis on land–atmosphere interaction, hydrologic impact of climate change, stochastic hydrology, hydrologic forecasting, and rainfall–runoff modeling. Dr. Wood is an associate editor for *Reviews in Geophysics, Applied Mathematics and Computation: Modeling the Environment*, and *Journal of Forecasting*. He is a member of the Climate Research Committee, and the Panel on Climate Change Feedbacks. He is a former member of the Water Science and Technology Board and BASC's GEWEX panel. Dr. Wood received an Sc.D. degree in civil engineering from Massachusetts Institute of Technology in 1974.

Mary P. Anderson is a professor in the Department of Geology and Geophysics at the University of Wisconsin, Madison. Her current research interests include the effects of potential global climate change on groundwater–lake systems and quantifying groundwater recharge. Dr. Anderson received a B.A. degree in geology from the State University of New York at Buffalo and a Ph.D. degree in hydrology from Stanford University. She is a co-author of two textbooks on groundwater modeling and is currently Editor in Chief of the journal *Ground Water*. She is a former member of the Water Science and Technology Board.

Victor R. Baker is regents professor and head of the Department of Hydrology and Water Resources at the University of Arizona. He is also professor of geosciences and professor of planetary sciences at the University of Arizona. His research interests include geomorphology, flood geomorphology, paleohydrology, Quaternary geology, natural hazards, geology of Mars and Venus, and philosophy of earth and planetary sciences. He has spent time as a geophysicist for U.S. Geological Survey and as an urban geologist. He has served on various committees and panels of the National Research Council, including the Panel on Alluvial Fan Flooding, the Panel on Global Surficial Geo-fluxes, and the Panel on Scientific Responsibility and Conduct of Research. He formerly chaired the U.S. National Committee for the International Union for Quaternary Research (INQUA) and served on the Global Change Committee Working Group on Solid Earth Processes. Dr. Baker was recently president of the Geological Society of America and president of the INQUA Commission on Global Continental Paleohydrology. He holds a B.S. from Rensselaer Polytechnic Institute (1967) and a Ph.D. from the University of Colorado (1971).

Dara Entekhabi is an associate professor in the Department of Civil and Environmental Engineering and the Department of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology. His research interests are in the basic understanding of coupled surface, subsurface, and atmospheric hydrologic systems that may form the bases for enhanced hydrologic predictability. Specifically, he conducts research in land-atmosphere interactions, remote sensing, physical hydrology, operational hydrology, hydrometeorology, groundwater-surface water interaction, and hillslope hydrology. He received his B.A. and M.A. degrees from Clark University. Dr. Entekhabi received his Ph.D. degree in civil engineering from the Massachusetts Institute of Technology.

Nancy B. Grimm is a professor in the Department of Biology at Arizona State University. She is also project director of the Central Arizona - Phoenix Long-Term Ecological Research (CAP LTER) project. Her research interests include biogeochemistry; stream ecosystem structure and function; urban ecosystem structure and function; nitrogen cycling in streams and cities; interactions between surface and groundwaters; terrestrial-aquatic linkages; disturbance and succession; and effects of global climate change and human activities on stream ecosystems. She is editor of Ecology Letters (2001-2004) and Ecosystems (1997-2003). She received her B.A. in Natural Science from Hampshire College (1978), and her M.S. and Ph.D. in Zoology from Arizona State University (1980, 1985).

George M. Hornberger (National Academy of Engineering) is the Ernest H. Ern Professor of Environmental Sciences at the University of Virginia. His current research interests include hydrogeochemical response of small catchments and transport of colloids in porous media. He is chair of the Water Cycle Study Group of the U.S. Global Change Research Program. Dr. Hornberger is a fellow of the American Geophysical Union and a member of the Geological Society of America. He has served on numerous NRC boards and committees, including chairing the Commission on Geosciences, Environment, and Resources. He served as editor of *Water Resources Research* from 1993 to 1997. He obtained his B.S. (1965) and M.S. (1967) degrees in civil engineering from Drexel University and his Ph.D. degree from Stanford University in hydrology in 1970.

Dennis P. Lettenmaier received his B.S. in Mechanical Engineering (summa cum laude) at the University of Washington in 1971, his M.S. in Civil, Mechanical, and Environmental Engineering at the George Washington University in 1973, and his Ph.D. at the University of Washington in 1975. He joined the University of Washington faculty in 1976. In addition to his service at the University of Washington, he spent a year as visiting scientist at the U.S. Geological Survey in Reston, VA (1985-86) and was the Program Manager of NASA's Land Surface Hydrology Program at NASA Headquarters in 1997-98. He is a member of the American Geophysical Union, the American Water Resources Association, the American Meteorological Society, and the American Society of Civil Engineers. He was a recipient of ASCE's Huber Research Prize in 1990, is a Fellow of the American Geophysical Union and American Meteorological Society, and is the author of over 100 journal articles. He is currently Chief Editor of the American Meteorological Society Journal of Hydrometeorology.

William K. Nuttle is an independent consultant in Ottawa, Ontario, Canada. Until recently, he was director of the Everglades Department, South Florida Water Management District, and was executive officer for the Florida Bay Science Program immediately prior to that. An expert in ecohydrology of wetlands and environmental science, he has coordinated extensive estuarine and wetlands research programs in South Florida. Currently, he is visiting scholar at the Southeast Environmental Research Center, Florida International University. Previously, he held positions with Memorial University of

Newfoundland and the University of Virginia. Dr. Nuttle has also consulted widely on topics generally related to coastal, wetland hydrology and the interface between research and environmental management. He is a current member of the Committee on Hydrologic Science. Dr. Nuttle received his M.S. degree and Ph.D. (1986) degree in civil engineering from the Massachusetts Institute of Technology and his BSCE degree from the University of Maryland.

Kenneth W. Potter is a professor of civil and environmental engineering at the University of Wisconsin, Madison. His teaching and research interests are in hydrology and water resources, including hydrologic modeling, estimation of hydrologic risk, estimation of hydrologic budgets, watershed monitoring and assessment, and hydrologic restoration. Dr. Potter is a past member of the Water Science and Technology Board and has served on many of its committees. He received his B.S. degree in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from Johns Hopkins University.

John O. Roads is Director of the Scripps Experimental Climate Prediction Center of the Scripps Institution of Oceanography at the University of California, San Diego. His research focuses on surface water and energy budgets, regional and global climate change, and medium- and long-range weather prediction using modeling and observation. He was a member of the NRC's Global Energy and Water Cycle Experiment (GEWEX) Panel from 1993 to 2000, and most recently chaired the panel. He is a member of the AGU Precipitation Committee. He has been named to advisory panels for the National Climate Data Center and the National Meteorological Center. He received a B.A. degree in physics in 1972 from the University of Colorado and a Ph.D. degree in meteorology in 1977 from the Massachusetts Institute of Technology, Cambridge.

John L. Wilson is professor of hydrology and chairman of the Department of Earth and Environmental Science at New Mexico Tech, Socorro. He studies fluid flow and transport in permeable media, using field and laboratory experiments and mathematical models. In the past this has included studies of the movement of water, nonaqueous phase liquids, dissolved chemicals, colloids, and bacteria through porous, fractured, and faulted media. He was the 1992 Darcy Lecturer for the Association of Groundwater Scientists and Engineers. He was elected a Fellow of the American Geophysical Union in 1994. He received the O.E. Meinzer Award from the Geological Society of America in 1996 and was elected Fellow of the Society in the same year. He received his B.S. degree from Georgia Institute of Technology and his M.S., C.E., and Ph.D. degree from Massachusetts Institute of Technology.