Journal of Contemporary

Water Research & Education

Issue 153
April 2014



Water Data

A Publication of the
Universities Council on Water Resources

JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION

Universities Council on Water Resources
Faner Hall, Room 4543 - Mail Code 4526
Southern Illinois University
1000 Faner Drive
Carbondale, IL 62901
Telephone: (618) 536-7571
www.ucowr.org

EDITOR

Christopher L. Lant
(618) 453-6020
Fax: (618) 453-2671
clant@siu.edu

ISSUE EDITORS

Melinda Laituri
Professor
Department of Ecosystem Science & Sustainability
Colorado State University, Fort Collins

Faith Sternlieb
Research Associate
Colorado Water Institute & Water Center
Colorado State University, Fort Collins

EDITORIAL STAFF

Justin Kozak
Southern Illinois University
Carbondale, Illinois 62901
jkozak@siu.edu

Tara Gracer
Southern Illinois University
Carbondale, Illinois 62901
tgracer@siu.edu

EDITORIAL BOARD

Mark Bricka
Mississippi State University

Melinda Laituri
Colorado State University

Faith Sternlieb
Colorado State University

Alexander G. Fernald
New Mexico State University

Timothy E. Link
University of Idaho

Laurel Saito
University of Nevada, Reno

ISSN 1936-7031

Subscription Information: The *Journal of Contemporary Water Research & Education* is published by the Universities Council on Water Resources. The annual subscription rate is $35 (domestic) and $80 (international). Prices per copy for past issues are $15 (domestic) and $30 (international). Members of UCOWR receive the *Journal of Contemporary Water Research & Education* as a part of their membership.

UCOWR is not responsible for the statements and opinions expressed by authors of articles in the *Journal of Contemporary Water Research & Education*.

Printed by the authority of the State of Illinois. April 2014. 700 copies. Order Number XXXXXXX.

Journal of Contemporary Water Research & Education

Issue No. 153 **April 2014**

Water Data

Introduction

Water Data Systems: Science, Practice, and Policy
Melinda Laituri and Faith Sternlieb.....1

Articles

Past, Present, and Future of Water Data Delivery from the U.S. Geological Survey
Robert M. Hirsch and Gary T. Fisher.....4

A Vision of Future Observations for Western U.S. Extreme Precipitation and Flooding
F.M.Ralph, M. Dettinger, A. White, D. Reynolds, D. Cayan, T. Schneider, R. Cifelli, K. Redmond, M. Anderson, F. Gherke, J. Jones, K. Mahone, L. Johnson, S. Gutman, V. Chandrasekar, A. Rost, J. Lundquist, N.Molotch, L. Brekke, R. Pulwarty, J. Horel, L. Schick, A. Edman, P. Mote, J. Abatzoglou, R. Pierce, and G. Wick.....16

WaDE: An Interoperable Data Exchange Network for Sharing Water Planning and Use Data
Sara G. Larsen and Dwane Young.....33

Landsat Thermal Infrared Imagery and Western Water Management
Anthony G. Willardson.....42

A Social-Ecological Framework to Integrate Multiple Objectives for Environmental Flows Management
David M. Martin, Dylan Harrison-Atlas, Nicholas A. Sutfin and N. LeRoy Poff.....49

Social Observation for Sustainability Science about Water
John B. Braden.....59

Challenges and Opportunities for Collecting and Sharing Data on Water Governance Institutions
Samuel Gallaher and Tanya Heikkila.....66

Determining the Dynamics of Agricultural Water Use: Cases from Asia and Africa
Lisa-Maria Rebelo, Robyn Johnston, Poolad Karimi, and Peter G. McCornick.....79

Conclusion

Water Data Resources
Melinda Laituri and Faith Sternlieb.....91

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 1-3, April 2014

Water Data Systems: Science, Practice, and Policy

Melinda Laituri and Faith Sternlieb

Colorado State University

Water agencies, governmental organizations, and non-governmental organizations accountable for water use, development, and conservation are dealing with ways to address changes in water data collection, maintenance, storage, visualization, and communication. As demand for water resources and variability of water availability increases, water data are essential to monitoring changes and finding solutions. Coupled with other data efforts to enhance "big data" and serve critical environmental issues, water data reveal the complex data-scape that demands streamlined data standards across scientific communities where data processing systems are fragmented due to multiple sources and methodologies, limited data sharing, and incomplete data coverage. With a better understanding of some of the discrepancies in the science, practice, and policy of water data systems, we need to consider and implement innovative ways to foster stronger water data sharing arrangements. This special issue on Water Data explores the science, practice, and policy of water data systems, provides examples in which data integration has been successful or ineffective, and explores the technological frontier of water data systems.

What are Water Data?

"Water data" is a diverse set of information that address the physical, environmental, ecological, social, economic, cultural, and political parameters of water use, availability, and accessibility. These data can be divided into general categories that include:

- Water availability: This includes metrics of precipitation, temperature, surface and still water amounts and flow, snow and ice, groundwater, and soil moisture (Willardson, this issue).
- Water use: Use refers to human consumptive uses (i.e., per capita), use by sector (i.e., agriculture, industry), environmental use (i.e., evapotranspiration rates), and ecosystem services (Rebelo et al., this issue; Martin et al., this issue).
- Water quality: Quality parameters for both surface and groundwater essential for the regulatory process.
- Water extremes: Hazard and disaster data that include drought and flood monitoring, storm watches and reports, and weather data (Ralph et al. this issue).
- Water indicators: Usually linked to some aspect of human or environmental health, indicators integrate other data to provide a metric for water poverty, sustainability, and human well-being (Sternlieb and Laituri 2010).

These catagories are not all inclusive and do not capture all the human dimensions of water data that impact the delivery and sharing of data as well as the infrastructure for data systems.

While the water sector is data-rich, the extent, accessibility, and availability of water data is unevenly distributed across the globe. These challenges make it difficult to compare results from water data studies across global regions and river basins in addition to the difficulty decision-makers have in managing water resources in data scarce places. Water data are a complex mix of a multitude of data formats that include spreadsheets, satellite images, geospatial databases, and photographs. Other data types include measures of climate change from climatological models, hydrological modeling outputs at local, regional, and global

scales, and processed remote sensing data or satellite images (i.e. metrics of evapotranspiration, change detection studies on water flows and flux).

Global datasets of water supply and water-related resource issues are generally better than local and regional water data. Federal agencies such as the United States Geological Survey house comprehensive datasets on national water resources regarding stream flow, groundwater supplies, precipitation, water quality, and lakes and reservoirs (National Water Information System, http://waterdata.usgs.gov/usa/nwis/rt). Many thematic global datasets are also available online and are useful for developing world users, such as those provided by academic institutions (e.g, Center for International Earth Science Information Network of Columbia University). Many of these datasets are available via the Internet; however, understanding how to download the data or process and analyze the data is not as clear, despite efforts to create help sheets, useful tips, and frequently asked questions. Additionally, water data are not easily scale-able; assumptions cannot necessarily be made from data analyses at the global scale to those at a local scale.

Due to the complexity and challenges associated with water data, determining ways to construct integrated datasets are needed. Increasingly, computing capabilities allow us to examine large amounts of data. Forecasting, predicting, and modeling water availability across spatial scales is essential for future water planning. Integration of existing data can be improved by coordinating ongoing data collection activities, enhancing interoperability, and ensuring consistency.

Data Integration

Due to the multi- and inter-disciplinary challenges of water resources management, there is a need for greater integration of water data. Characteristics of data integration include the ability to cross spatial scales from local to regional to global, utilization of common data formats to ensure interoperability between datasets, and establishing linkages between science and applications. Results of data integration create shared information for dissemination and training products, new assessment tools to meet collective needs, and decision support systems for analysis and forecasting. Integrated datasets create cross-sectoral links to improve water stewardship that is inclusive of human and ecological needs.

Methods to integrate data are challenging. The need for integrated data that address myriad aspects of water resources is paramount. Comprehensive water data increasingly include satellite imagery and remotely-sensed data to create time series and capture local and regional scale products. Complementing such activity is the need to establish terrestrial networks for the validation of remotely-sensed data.

Water data are essential for planning, policy, and prediction. Decision-making is dependent upon water data that can provide real time information about weather patterns, consumption needs for agriculture on an annual basis, assessing competing uses for scarce water resources, hydrologic modeling after disastrous fire events, and infrastructure needs for water conveyance and storage structures.

Issue Overview

The papers selected for this special issue address the key issues associated with water data across the science, policy, and data management arenas. The authors that are represented in these papers come from diverse organizations representing both governmental and nongovernmental agencies from national and global perspectives, including the Western Governor's Association, the U.S. Geological Survey, the International Water Management Insitute and a broad geographic range of academic institutions. The first article in this issue, "Past, Present, and Future of Water Data Delivery from the U.S. Geological Survey", by Robert M. Hirsch and Gary T. Fisher, presents an overview of the water databases managed by the U.S. Geological Survey. Tracing the changes in water data availability from pre-internet to the present, this paper documents the delivery of real-time information of water parameters, the development of web-based mapping applications, and the creation of mobile applications of current hydrologic conditions.

This is followed by Ralph et al. "A Vision of Future Observations for Western U.S. Extreme Precipitation and Flooding" that provides a vision for tracking, predicting, and managing the impacts of major storms across the U.S. west. A description is provided of a comprehensive monitoring network for rain,

snow, snowmelt, flood, and hydrometeorological parameters that includes terrestrial and oceanic stations to create integrated datasets for scientific analysis and decision support assessments.

The third paper in this issue, "WaDE: An Interoperable Data Exchange Network for Sharing Water Planning and Use Data", by Sara G. Larsen and Dwane Young, discusses the development of the Water Data Exchange (WaDE) to enhance water planning. The article emphasizes the "nuts and bolts" of data exchange through proposing a governance structure, common formats, database development, and data delivery for U.S. western states. This approach may provide a template for future projects across the globe to develop mechanisms for getting water data in the hands of water planners more effectively.

Satellite imagery has become an essential source of derived water data. Willardson's "Landsat Themal Infrared Imagery and Western Water Management" describes the important contributions of Landsat imagery to measuring and monitoring water uses in the U.S. west. Situating his topic within the complex context of U.S. western water law, he describes multiple applications of thermal infrared sensor to water management. Such data collection techniques have significant implications for cost-savings for data collection and scientific progress in new analysis techniques.

The fifth paper in this issue, "Integrated Water Data and the Quest for Holistic Environmental Flows Management", by David M. Martin, Dylan Harrison-Atlas, Nicholas A. Sutfin, and N. LeRoy Poff, situates the need for socio-ecological water data within the framework of environmental flows. Science, data integration, and policy all intersect in an approach to provide a holistic framework for freshwater system management. Socio-ecological water data assimilation is recommended to develop a systematic approach to fill knowledge gaps and inform decision makers on complex water planning.

John Braden's article, "Social Observation for Sustainability Science about Water", sets a provocative tone by challenging the research community to consider how to collect data that support sustainability science defined as the interactions between human and natural systems. Braden provides two examples regarding water quality and environmental attitudes and behaviors that demonstrate the challenges of coupled human-nature research and the need for comprehensive data.

The article is followed by Gallaher and Heikkila's paper entitled, "Challenges and Opportunities for Collecting and Sharing Data on Water Governance Institutions." This paper examines 33 water governance organizations' websites for publically available datasets specifically focusing on outcome information of institutional mandates, objectives, and goals. Their findings reveal the on-going problem of publically available data on water governance institutions, yet another data integration issue.

The last paper in this collection is "Determining the Dynamics of Agricultural Water Use: Cases from Asia and Africa", by Lisa-Maria Rebelo, Robyn Johnston, Poolad Karimi and Peter G. McCornick. While the other papers focused on the United States in general and the U.S. west specifically, this paper addresses international water data needs with a specific emphasis on regional watersheds in developing countries. The need for comprehensive data at the regional and local scale cannot be overstated for holistic water planning for agricultural water management.

The suite of papers address critical issues of water data and the problems associated with comprehensive, integrated datasets for water planning and management. The explosive trajectory of technology sets the stage for an interesting future for data collection, development, and dissemination. Challenges associated with the need for holistic datasets at the local and regional scale for developing countries, however, remains a critical issue. Metrics for sustainable water management, developing integrated datasets, and understanding outcomes of institutional water governance are all arenas for further exploration. Next steps for water data include the development of a program for collaboration between existing projects and activities to facilitate a community of practice, to share best practices and lessons learned, and to raise awareness of the multitude of water-related activities that are being undertaken to create appropriate water data.

References

Sternlieb, F. and M. Laituri. 2010. Water, Sanitation, and Hygiene (WASH) Indicators: Measuring hydrophilanthropic quality. *Journal of Contemporary Water Research & Education* 145(1): 51-60.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 4-15, April 2014

Past, Present, and Future of Water Data Delivery from the U.S. Geological Survey

Robert M. Hirsch and Gary T. Fisher

U.S. Geological Survey, Reston, VA

Abstract: We present an overview of national water databases managed by the U.S. Geological Survey, including surface-water, groundwater, water-quality, and water-use data. These are readily accessible to users through web interfaces and data services. Multiple perspectives of data are provided, including search and retrieval of real-time data and historical data, on-demand current conditions and alert services, data compilations, spatial representations, analytical products, and availability of data across multiple agencies.

Keywords: *Water data, data applications, real-time data*

Hydrologic data are central to the mission of water programs at the U.S. Geological Survey (USGS) as reflected in the recently released Water Science Strategy – Observing, Understanding, Predicting, and Delivering Water Science to the Nation (Evenson et al. 2013). We collect a wide range of hydrologic data, assure the quality of those data, and make them freely available in national databases. The most institutionally significant of those databases is the National Water Information System (NWIS), which began as a core USGS capability in the 1980s and has been maintained and improved to meet ongoing requirements. NWIS included a blending of several previous database systems, and was ultimately the successor to the USGS Water Data Storage and Retrieval System (WATSTORE). Data from NWIS are available to the public through a web interface (http://waterdata.usgs.gov) and through data services (http://waterservices.usgs.gov). Instructions and tutorials are provided through an online help system (http://help.waterdata.usgs.gov/). In this paper, we describe the objectives of these and other USGS water data systems, the size and variety of holdings, the level of usage, and the variety of data delivery mechanisms that these USGS systems employ.

The USGS water data systems follow a set of key principles:

- The data stored and delivered meet USGS quality-assurance standards. These are mostly data collected by USGS, but some are collected by others and quality-assured through very specific agreements and protocols.
- Access to the data is the same regardless of the geographic location of a data collection site or the data user. The key principle is that users should not need to learn multiple data delivery mechanisms as they shift their geographical focus. The system needs to serve users operating at all scales from local to regional to national.
- As much as possible, the system delivers all types of water resources data using the same methods and definition of terms. The data cover open channel flow, groundwater, water levels, water chemistry, water use, and other water-related data. There are major differences between different types of hydrologic monitoring environments (for example: rivers, lakes, and wells), however, so the system needs to be organized in a way that recognizes any intrinsic differences. There is just one data dictionary and set of definitions of sites and variables.
- The system integrates the most current information (in some cases minutes old) with historical information (dating back a century or even more). This enables users to put current information into a historical context.

- The system delivers data in many different product forms. These include graphical, tabular, and text presentations that are equally useful on web browsers and for export to applications. The system supports automatic data delivery and provides data on request. Through this wide range of products, we aim to make the information available to individuals who range from casual users curious about the environment or about recreational opportunities, to highly specialized users who will ingest the data into scientific analyses or water-management models.
- The database contains only the data and not interpretive products or analyses based on the data. Methods of analysis are always evolving as our understanding of hydrology and development of analytical tools improves, and users should be able to control the analysis they conduct. The data themselves are fundamental and do not change over time.
- In addition to a well-designed graphical user interface (including help and tutorial information accessible from all pages), the system has clearly defined and documented Application Programming Interfaces or data services, that conform to international standards where available, from which models and other value-added products can be based.

Application of these principles over 125 years has provided some basic "lessons learned" that may be valuable to other organizations considering similar water-data acquisition and management programs:

- Apply quality assurance practices consistently and without compromise.
- Use standard, well-documented techniques and methods for data collection, processing, and management.
- Make sure that the long-term integrity and availability of data are accepted as mission critical.
- Do not shortcut metadata; these are essential to categorize, qualify, and search data.
- Develop technical and joint-funding partnerships with other organizations with mutual interests for high-quality and robust water-resources data to assure the sustainability of data collection programs and long-term data availability.

Table 1. Number of sites by data type provided in the USGS NWIS public database as of January 27, 2014.

Data Type	Number of Sites
All monitoring sites	1,570,000
Real-time data	*14,520
Streamflow	9,578
Lake level	455
Groundwater level	1,559
Water quality data	1,730
Precipitation data	2,703
Tide level data	115
Daily values data	*34,509
Surface water	26,217
Groundwater	6,550
Water quality	11,264
Streamflow measurements data	56,740
Groundwater level measurements data	852,335
Water quality samples data	393,370
Peak discharges (floods) data	28,363

*Some sites have multiple data types

The amount of data stored in the system is significant and always growing. Table 1 lists some of the major data types in the system and the number of sites where collected. Table 2 lists the number of data values or records they represent. An important data type in hydrology is daily values. These data represent either one representative measurement per day or the average of many observations per day. These datasets typically span many years or decades and are of great value in determining long-term statistics and trends in hydrologic conditions. Table 3 lists the major types of daily values and the number of observations of each type.

The multi-purpose nature of the data delivery system is a crucial characteristic. By design, it provides products that benefit many different types of users who have diverse needs and have diverse levels of knowledge. The data are very well suited to national and regional scales of analysis, and in some cases, local scales as well.

Table 2. Number of data values provided in the USGS NWIS public database as of January 27, 2014.

Data Type	Number of Data Values
Instantaneous values	3,710 million
Daily values	534 million
Streamflow measurements	3.6 million
Groundwater level measurements	9.0 million
Water quality samples	5.3 million
Water quality analyses	100 million
Peak discharges (floods)	0.74 million

Table 3. Number of daily values in the USGS NWIS public database by major data type as of January 27, 2014.

Data Type	Number of Daily Values
Discharge	219 million
Stage (water level in surface water)	36 million
Water level in wells	23 million
pH of water	3.4 million
Water temperature	22 million
Specific cunductance of water	9.8 million
Other daily values	42 million

Example uses include:

- Active water management (hourly to monthly time scales)
- Water planning (short and long term)
- Emergency management
- Establishing initial conditions for water forecasting models
- Risk assessment (flood and low-flow frequency)
- Water quality assessment and regulation
- Water-based recreation
- Scientific research on water quantity and quality

We can characterize current levels of usage of the system in several ways. During 2013, there were over 300 million pages accessed through users' web browsers and the equivalent of an additional 190 million page views through data services. Data services provide for direct computer-to-computer delivery of the data product. For users who will use the data as input to some application (for analysis or operations), the advent of these data services has been a vast improvement over downloading through a web browser and then having to manipulate the output to make it suitable for input to user applications. The growth in the use of USGS hydrologic data is clearly in the area of data services although browser use continues at an average of 25 million data views per month.

Figure 1 summarizes the history of system use. Major events such as widespread flooding or drought explain some of the temporal variability. Growth over time depends on general user awareness, but growth has also coincided with the release of new features.

The Fundamental Time Step

For more than a century, from 1888 through the 1990s, the primary product of much of USGS water data collection was the daily value of a hydrologic variable of interest. The most common of these was daily mean discharge, but it also included daily mean values parameters such as temperature, specific conductance, or water level in wells. This approach was driven by practical limitations of records processing and print publishing. Before the 1960s, manual and graphical records provided limited time resolution and processing was particularly labor intensive. Daily computations were at about the limit of commonly available technology. Later, digital recording and computing technologies provided a capability to collect and process data at a finer time step. A single printed report page, however, can only accommodate a table of one year of daily values of discharge for a given streamgage. The printed page was still the primary means by which we delivered data. In its earliest years, USGS released data in Water-Supply Papers and other publications. Water-year compilations began in 1911, and until 1976, USGS released data by hydrologic regions in periodic Water-Supply Papers. From 1961 to 2005, USGS produced state-based annual Water Data Reports, and in 2006 converted those fully to an electronic-only national Water Data Report, still with a focus on daily data for a water year. In 2014, the national Water Data Report will be replaced with a similar on-demand, site-by-site, web-based report.

With the advent of digital data recorders and computers, changes were coming fast in the availability of hydrologic data. It was possible to collect, process, store, and distribute data faster than ever before. Hydrologic data processing now

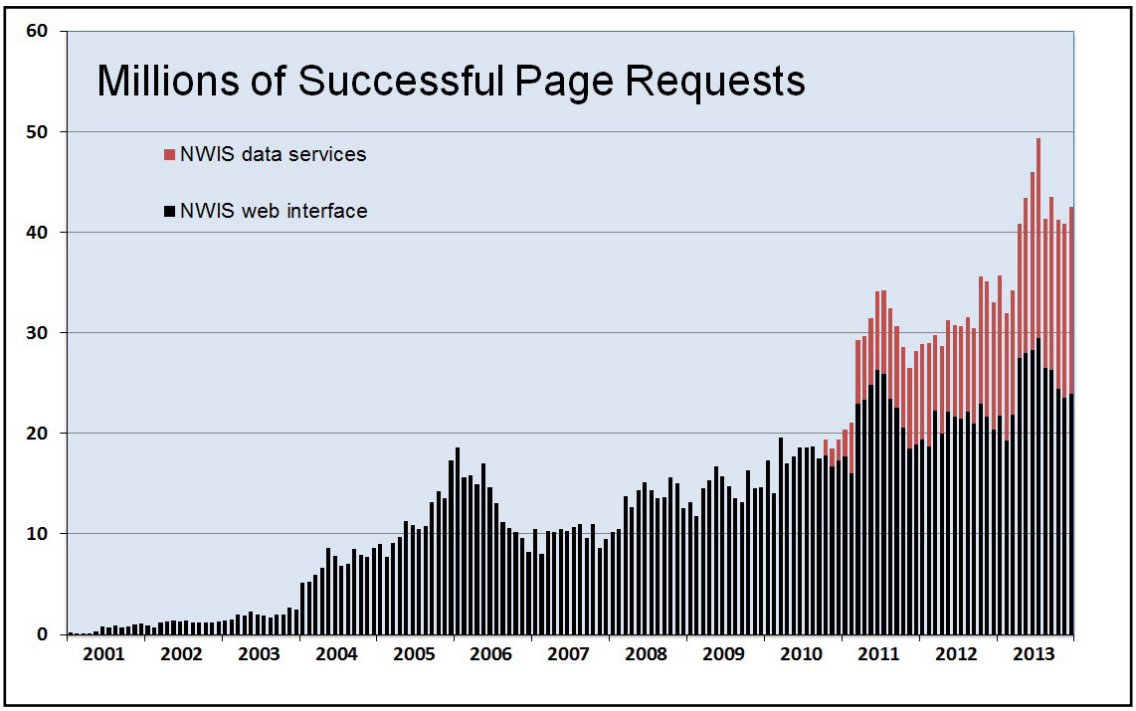


Figure 1. Millions of NWIS web interface and data services page views by month.

provided the same daily data products as printed reports, but in the form of computer files of tabular data. The sensor data used to create the daily data product were actually collected at a much shorter time step (most commonly 15-minute intervals) as "instantaneous values," but these were only used within the individual USGS office in the process of creating the daily values product. Because data storage was still very expensive, few of the early instantaneous values were stored in databases. Hydrographers saw them only as "raw material" for the daily computations and not as a standalone data product. Furthermore, there was no process to track the details of final data editing and adjustment, so even if a hydrographer reprocesses the data, the computed daily averages may not agree with the final published daily value.

With ongoing reductions in the cost of data storage and data transmission, USGS re-examined its data delivery paradigm in the late 1990's and began a transition towards making the finer time-step data (instantaneous values) a primary product. Especially important in lower order streams, instantaneous values data are crucial to understanding the dynamics of changing water levels, flows, concentrations, and fluxes (or loads). Better understanding will ultimately lead to better models and tools that will enhance the interpretation of the large body of historical data.

In the case of streamflow data, these finer time-step data have a great deal of utility. They are crucial to the process of streamflow modeling and streamflow prediction. Determining how the watershed responds to rainfall input can be severely limited if the data can only be presented as a step function of daily values rather than as a nearly continuous time series. Shorter time-step data are also important for determining the transport of sediment and chemicals downstream. Current practice is to estimate transport using a relationship between instantaneous sediment or chemistry measurements and daily mean discharge. For example, methods described in Cohn and others (1992) and Hirsch and others (2010) use the full record of daily mean discharge to estimate a record of daily mean fluxes. We know that when there is a large variation in discharge during the course of a day, these relationships are seriously limited in their ability to predict flux. Sub-daily information is also critical for flood hazard mitigation because the time history of inflows to a river or reservoir is required to determine the effectiveness of a design. Flood-control systems must work to limit the size of the peak water levels or flows, which cannot be determined based on daily averages.

The USGS provides fully qualified instantaneous values online from October 1, 2007 onwards, and in some cases prior to 2007 because of the need for this data at a finer time step. On January 27, 2014, there were more than 3.7 billion values available for 14,517 sites and 160 parameters. We believe that these shorter time interval data will be of great value to the hydrologic science community.

Real-Time Data

The best-known USGS hydrologic data product, the streamflow record, was only an historical product for about 80 years. That is to say, the numbers became available to the science and water management community a few months to a year or more after the fact. They were quite useful for scientific studies and provided important data for water planning and for hazard and resource assessments, but they were of no help to timely water management, water operations, or hazard warnings. Gradually, various systems became available in USGS streamgages that provided direct transmission of the data in near-real time to forecasting and operations activities of the National Weather Service, the Bureau of Reclamation, the Army Corps of Engineers, water and power utilities, and other agencies. Early systems used landline telephone (starting in 1921) and radio technologies (starting in 1931). They were diverse and complex systems, typically uniquely designed for use by a particular partner agency, and not available to the public or scientific community.

In 1976, USGS began to experiment with the use of Geostationary Operational Environmental Satellite (GOES) to transmit data from field stations. The use of this technology has grown rapidly and continues to grow to the present day. For streamflow, the number of real-time sites has grown from 120 in 1978, to 1000 in 1982, 5100 in 1999, and 9600 in 2014. The system transmits not only streamflow data, but also groundwater levels, many sensor-derived chemical and physical variables related to river conditions, and atmospheric conditions at USGS water-monitoring locations. Table 4 shows a partial list of the major data types that USGS delivered in real time on one particular day. Data sites are distributed across the nation and are in every state, although the density of sites in any given state will vary due to the hydrologic regime and requirements of partner agencies.

Table 4. Real-time parameters transmitted on January 27, 2014. List includes the top 11 parameters and 5 other selected variables for which interest is growing. Some sites transmit more than one similar parameter so count may be more than the number of sites.

Variable Being Transmitted	Count
Gage height (water level in stream)	10,084
Discharge	8,262
Precipitation	2,829
Water temperature	2,373
Groundwater level	1,950
Specific conductance	1,082
Dissolved oxygen	594
Lake or reservoir elevation	503
pH	496
Turbidity	452
Stream velocity	395
Nitrate plus nitrite	49
Suspended sediment	45
Chlorophyll	42
Sodium absorption ratio	10
Blue green algae	18

The investment in real-time data delivery has had a number of outcomes that the USGS did not anticipate. One of those outcomes is the expansion of the community of users of USGS hydrologic data. Availability of these new data has led many ordinary citizens, business owners, farmers, and local government officials to become users of the data, and in many cases frequent users. Making a decision about moving people and property out of flood-prone areas is an example of a decision informed by these real-time data. For recreation, people are keenly interested in knowing if the river is near its ideal flow for the activity that they plan. Flows that are too high or too low can make for an unrewarding or unsafe water sports experience. Water recreation enthusiasts have become major consumers of USGS streamflow data. Real-time data are also very helpful to the scientific research community because they help to monitor current field conditions to help determine optimal times to travel to the site to collect critical scientific data.

Frequently, USGS program managers are asked if the addition of real-time capability makes data collection less expensive because of reduced labor costs. The simple answer is no. The counterpoint, however, is that it does significantly improve the usefulness, accuracy, and completeness of the dataset. We described some of the added utility of the data above. Accuracy is improved because the hydrographers who make flow measurements to keep an accurate calibration for the streamgage (the rating curve) can target particular ranges of water level that need additional measurements and the real-time data can help them determine when those conditions exist. This information triggers their travel to the site to make an additional measurement. Also, without real-time data, if any kind of system failure happened at a streamgage (e.g., loss of power, damage to sensors, damage to data storage systems, or even total destruction of the streamgage) the problems would be unknown to the USGS staff until the time of the next field visit, which might be as much as 6 weeks away. Now, when serious problems occur at a streamgage, the real-time data help to identify problems quickly and can trigger a visit to the streamgage to rectify the situation within a few days or less. Estimates of missing data values are more reliable if the gaps are short than if the gaps are long.

Perhaps most surprising is the increase in the availability of real-time groundwater level data (about 1600 sites nationwide). In general, groundwater levels in wells fluctuate much more slowly than do water levels in rivers, and having just one observation per day may be sufficient for most scientific or water management purposes. Nevertheless, providing real-time groundwater data actually has a number of benefits. For example, during drought periods, water managers and public officials need to know water levels in aquifers throughout their area in order to assess drought severity. Without real-time data, it becomes a very slow and costly process to visit every well in a regional groundwater-monitoring network. Groups such as a governor's drought task force may require weekly updates from a network of groundwater wells. We can now provide a summary in a matter of minutes using data that are no more than a few hours old. This contrasts with summaries that used to take several days and multiple people to compile using data that were already a few days old. Also, real-time data are just as important for operating groundwater sites as any other sites, if not more so. Because groundwater conditions in general change slowly and instrumentation is relatively stable, routine visits are much less frequent than for streamgages. The ability to retrieve and review data through telemetry can lead to fewer routine visits, but more importantly it can reveal problems that otherwise might not be detected for several months. There is also a public information benefit with the provision of real-time groundwater data. Groundwater is largely unobservable directly and is poorly understood by the public. The availability of real-time groundwater data on the web enables the public and public officials to view the heretofore "invisible" water resource beneath their feet and to understand how it changes in response to precipitation events and to pumping, particularly during dry periods when groundwater is especially important. We believe that access to real-time groundwater data has the potential to improve the public's understanding of this important, but poorly understood, resource.

With the real-time capability in place and a new challenge of how to make so much data tractable to USGS stakeholders, systems such as WaterWatch were conceived as a means to summarize current water conditions in a nationally consistent and useful way. The WaterWatch system (http://waterwatch.usgs.gov) provides national or state map depictions of the status of streamflow (Figure 2). The color-coding of each site's status depends on the percentile level of the current streamflow from the historical distribution of streamflow for that day of the year. For example, a dark brown dot on the map represents a streamgage for which the most recent estimated streamflow is lower than the 10th percentile on the historic flow distribution for that day (but not the flow of record, depicted by a red dot). This map makes it possible, at a glance, to determine where flows are very high, or normal, or in extreme low flow condition. Animations of previous maps, available at the WaterWatch web site, can be highly informative about the spatial and temporal coherence of hydrologic anomalies and the way that they spread, shrink, and persist for long periods on the landscape. Users can select an individual state to see it in more detail and then

explore each individual streamgage represented, learning their name and current condition, or "clicking through" to gain access to both the historic and recent data about the site.

USGS also provides GroundwaterWatch, (http://groundwaterwatch.usgs.gov) which tracks water levels in wells, and WaterQualityWatch, (http://waterwatch.usgs.gov/wqwatch) which tracks water quality as measured by stream water-quality sensors nationwide. WaterQualityWatch includes the most common parameters of temperature, specific conductivity, pH, dissolved oxygen, turbidity, and nitrate. GroundwaterWater and WaterQualityWatch provide fewer sites than WaterWatch (see tables 1 and 4 to compare relative data population), but each product provides a useful status review of current conditions across the nation.

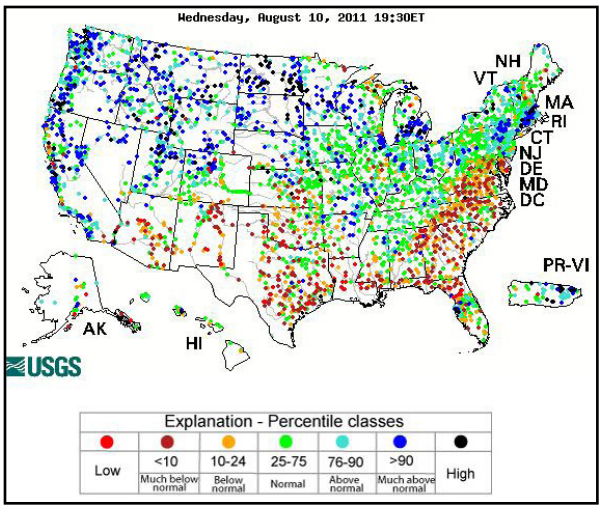


Figure 2. USGS WaterWatch map for August 10, 2011, showing much above normal conditions in the West and upper Missouri River basin, moderate to high flow conditions in the Midwest and New England area, and low flow conditions from the Southwest through the South and into the Middle Atlantic states.

Data Discovery Using NWIS Mapping Applications

For scientists engaged in hydrologic research within a watershed, state, or region, a common challenge is to find sites that offer a rich data record that may be useful for the research they are conducting. The NWIS web interface allows searching of the public database for sites that meet criteria, and visualization of the results using its mapping functions. For example, a researcher may be interested in finding all stream sites in the five water resources regions that make up much of the eastern United States (New England, Middle Atlantic, Great Lakes, South Atlantic, and Ohio) that have at least 1200 water quality samples.

Figure 3 shows the results returned by a search. Information about each site on the map is available by selecting it with the mouse cursor on the map or from the list on the left. In either case, "clicking through" will give the user direct access to the available data. For input to other software or for future data retrieval, an option is available to export the results to a file. Access to the user interface starts at http://waterdata.usgs.gov. Data discovery capabilities such as these are of great value to the research community because they can quickly identify the datasets that have significant potential for use in research on a given topic. Sorting through the 1.57 million sites in the NWIS public database to find the sites with the type and amount of data needed for a given study is a daunting task, but these tools help to make it much easier.

A spatial database that may be useful to some researchers is GAGES-II (Geospatial Attributes of Gages for Evaluating Streamflow; Falcone 2011). This was an update to the original GAGES database (Falcone 2010). It includes the attributes of the watersheds upstream of each of 9,322 streamgages that the USGS has monitored with at least 20 complete years of discharge record since 1950, and/or were active in water year 2009. The dataset documents important variables such as drainage area, mean basin altitude, geologic and soil characteristics, population density, population change, types of agricultural activities, rates of fertilizer application, extent of man-made water storage, climatic variables, and many other relevant hydrologic variables. One use of the database is for locating sites with the desired characteristics for a planned study. It quantifies a variety of possible explanatory variables in regional or national hydrologic studies, and is available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.



Figure 3. Screenshot of NWIS mapping application that show results of a search for sites meeting criteria.

Access to USGS Water Data in Conjunction with Other Sources of Water Data

All of the discussion above has related simply to USGS datasets and access to them. Of course, there are many other sources of water data available. At a national scale, there is the Environmental Protection Agency's (EPA) STORET system for water quality data, which aggregates regional, state, and local data using the Environmental Exchange Network (http://www.exchangenetwork.net/). Other state agencies, federal water agencies, river basin commissions, regional agencies, local water utilities, volunteer groups, and university researchers maintain additional regional and local datasets. About a decade ago, the USGS began forming a variety of partnerships that have led to some very successful approaches to discover and access data from multiple sources. The two most significant of these are the Hydrologic Information System (HIS) that has been created and is maintained by the Consortium of Universities for the Advancement of Hydrologic Sciences Incorporated (CUAHSI), and the Water Quality Portal, which is a cooperative service sponsored by the USGS, EPA, and the National Water Quality Monitoring Council. Both of these efforts are the result of work across the water community in developing common standards for time series and discrete water-quality data, respectively.

HIS is a system for finding and retrieving relevant data from a wide variety of data sources; particularly the USGS, several other federal agencies, and many universities (see http://wdc.cuahsi.org/). It uses a data service format known as WaterML. The USGS has been an active participant in the development of



Figure 4. USGS WaterAlert subscription form showing user-selectable settings.

WaterML, making sure that the HIS would have full and accurate capabilities to find and deliver a wide range of USGS water data to HIS users. Associated with the HIS is HydroDesktop (http://his.cuahsi.org/hydrodesktop.html) that not only finds and downloads data via the HIS, but also structures it in such a way that it can be seen in map and graphical form, and entered easily into a variety of data analysis and modeling systems. WaterML Version 2 is being developed within a joint working group of the World Meteorological Organization and Open Geospatial Consortium, and will provide a consistent international standard (http://www.opengeospatial.org/projects/groups/waterml2.0swg).

The Water Quality Portal (http://www.waterqualitydata.us) is a system for discovery and retrieval of water quality data from NWIS and the EPA STORET system. Searching includes location parameters, site parameters, or sampling parameters; and can return data files to users in several forms: comma-separated values, tab-separated values, workspaces in the statistical language "R", as spreadsheets, or KMLs (for site information only). Using the Portal avoids users having to learn two different search and retrieval protocols, and there is a cross-reference for the differences in categories and codes between NWIS and STORET.

An additional source of interagency data is the Reservoir Sedimentation Database (http://ida.water.usgs.gov/ressed/), which includes nationwide data from the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the USDA Natural Resources Conservation Service, and the USGS.

Linking Data Services Directly to Analysis Software

An innovative approach to data access is the incorporation of retrieval from data services directly into the body of analysis or modeling code. One example is an R statistical package for retrieval, analysis, and anomaly calculation of daily streamflow data (Ryberg and Vecchia, 2012, http://pubs.usgs.gov/of/2012/1168). Another

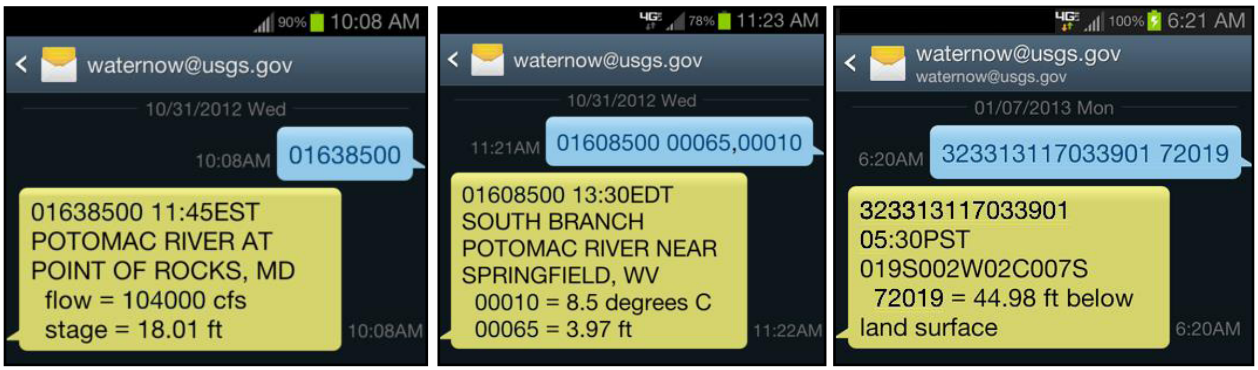


Figure 5. Examples of WaterNow queries using text messages for a standard streamgage, multiple parameters, and a parameter at a well.

is Exploration and Graphics for River Trends (EGRET), which is available at https://github.com/USGS-R/EGRET/wiki. The EGRET package and the associated dataRetrieval package facilitates a variety of statistical methods of exploring trends in surface-water quality and trends in streamflow. These software packages contain the necessary code to download data from USGS data services, check for certain types of errors, and organize the information into data structures that are appropriate to the analyses being made by the particular package. Data retrieval and data analysis should be a single integrated process. In the future, we expect that integrated data retrieval and application systems will be an important part of the USGS water data delivery system.

New Systems Designed for Mobile Devices and for Push Notification of Hydrologic Data

USGS provides several data delivery products that make current hydrologic conditions data more readily available for timely decisions. For field researchers, that could make the difference between getting and missing a critical sample or measurement for target conditions.

In 2010, USGS released WaterAlert (http://water.usgs.gov/wateralert) to provide frequent users of current data with an email or text-message notification when conditions cross a threshold that they set, such as when river stage or discharge goes above a particular level. Its flexible design allows for any up-or-down threshold of interest and supports multiple data parameters. It provides a map to locate sites of interest; a subscription form to customize user preferences; and, where available, information to help select thresholds, such as a link to National Weather Service flood stages. Figure 4 shows the subscription form with the user-selectable settings. As of January 21, 2014, there were 55,060 WaterAlert site-parameter-threshold subscriptions from 40,330 users.

In early 2013, USGS released WaterNow (http://water.usgs.gov/waternow) to provide users with a readily available and fast tool to obtain up-to-date data. The service works on any device that supports email or text messaging, either online or mobile. For a streamflow site, send an email or text message to WaterNow@usgs.gov with a USGS station number in the subject or body and within a few minutes, you will receive a response with the most recent values of stage and streamflow. For other site types, by including just a USGS station number, WaterNow will return a list of available parameters for that site. The service supports any real-time surface-water, groundwater, water-quality, or atmospheric parameters available from USGS. Figure 5 shows several examples of text-message queries.

Later in 2013, USGS released a mobile-friendly version of the NWIS web interface (http://m.waterdata.usgs.gov) that delivers frequently accessed current conditions data. It includes an easy-to-use map browser and automatic-location functions that are particularly suited to smart phones (Figure 6).

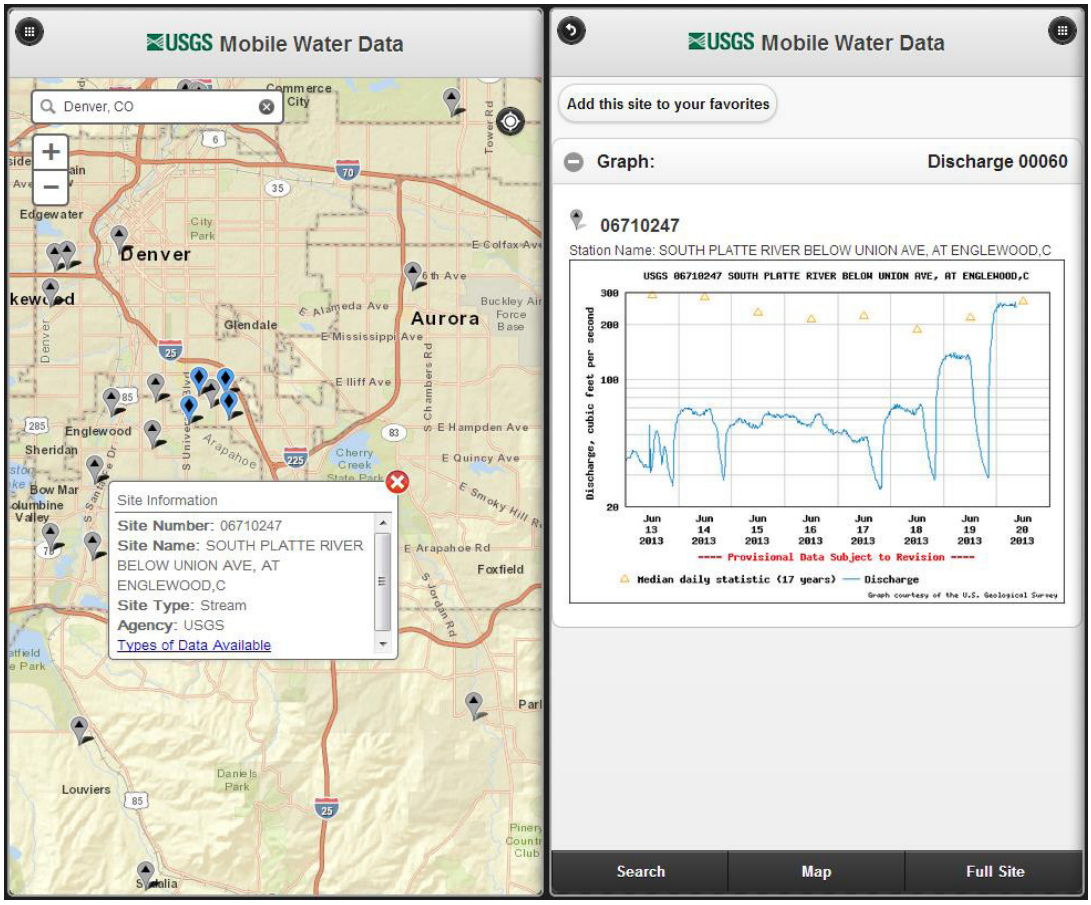


Figure 6. Screenshots of the USGS Mobile Water Data showing map browser used to locate sites and example of hydrograph returned.

Summary

USGS endeavors to make its water data readily accessible to users. Technological developments over the last few decades have enabled a transition from paper reports to online reports and from daily data to instantaneous data. Targeted data compilations and analytical tools add value to the data and enhance information overall. For up-to-the-minute use, data are available on demand through the NWIS web interface, NWIS data services, WaterAlert, WaterNow, and USGS Mobile Water Data. The USGS Water Data Discovery page at http://water.usgs.gov/data includes updated information for these and other USGS water data products. The USGS motto is "Science for a Changing World." In the realm of water data access we continue to focus both on change that happens hour to hour and day to day, but also the change that happens over time frames of decades to centuries. USGS water delivery mechanisms continue to evolve and improve in step with new information technologies. An increasing emphasis on national and international data standards and web services allows USGS to integrate our data with others more readily and to share software components across the research and water management communities. Distributing water data with applications on new mobile platforms brings value to new and nontraditional consumers of hydrologic information.

Author Bio and Contact Information

Robert M. Hirsch is a Research Hydrologist with the USGS in Reston, VA. His research focuses on the description and understanding of long-term variability and change in surface-water quality and streamflow. Bob served as USGS Chief Hydrologist from 1994-2008 before returning to research. He can be contacted at rhirsch@usgs.gov.

Gary T. Fisher is a retired Hydrologist and resides in Baltimore, MD. He managed Special Projects from 2007-2013 for the USGS Office of Water Information, including an NWIS User Group and the development of new data delivery applications. As a USGS Scientist Emeritus, he continues to develop and promote applications of USGS water data. He can be contacted at gtfisher@usgs.gov.

References

Cohn, T., D.L. Caulder, E.J. Gilroy, L.D. Zynjuk, and R.M. Summers. 1992. The validity of a simple statistical model for estimating fluvial constituent loads: An empirical study involving nutrient loads entering Chesapeake Bay. *Water Resources Research* 28(9): 2353-2364.

Evenson, E.J., R.C. Orndorff, C.D. Blome, J.K. Böhlke, P.K. Hershberger, V.E. Langenheim, G.J. McCabe, S.E. Morlock, H.W. Reeves, J.P. Verdin, H.S. Weyers, and T.M. Wood. 2013. *U.S. Geological Survey Water Science Strategy—Observing, Understanding, Predicting, and Delivering Water Science to the Nation*. U.S. Geological Survey Circular 1383–G, 49.

Falcone, J.A. 2011. *GAGES–II: Geospatial Attributes of Gages for Evaluating Streamflow.* U.S. Geological Survey. Available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Falcone, J.A., D.M. Carlisle, D.M. Wolock, and M.R. Meador. 2010. GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States. *Ecology* 91(2): 621.

Hirsch, R.M, D.L. Moyer, and S.A. Archfield. 2010. Weighted Regressions on Time, Discharge, and Season (WRTDS), with an application to Chesapeake Bay river inputs. *Journal of the American Water Resources Association* 46(5): 857-880.

Ryberg, K.R. and A.V. Vecchia. 2012. *waterData—An R Package for Retrieval, Analysis, and Anomaly Calculation of Daily Hydrologic Time Series Data*, *version 1.0.* U.S. Geological Survey Open-File Report 2012–1168, 8.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 16-32, April 2014

A Vision for Future Observations for Western U.S. Extreme Precipitation and Flooding

F.M. Ralph[1], M. Dettinger[2], A. White[3], D. Reynolds[4], D. Cayan[2], T. Schneider[5], R. Cifelli[3], K. Redmond[6], M. Anderson[7], F. Gherke[7], J. Jones[7], K. Mahoney[4], L. Johnson[8], S. Gutman[9], V. Chandrasekar[10], J. Lundquist[11], N. Molotch[12], L. Brekke[13], R. Pulwarty[14], J. Horel[15], L. Schick[16], A. Edman[17], P.Mote[18], J. Abatzoglou[19], R. Pierce[20], G. Wick[3]

[1]Univ. of California, San Diego/Scripps Inst. of Oceanography/Center for Western Weather & Water Extremes, La Jolla, CA

[2]U.S. Geological Survey, Scripps Institution of Oceanography, La Jolla, California

[3]NOAA/Earth System Research Laboratory/Physical Sciences Division, Boulder, Colorado

[4]Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado

[5]NOAA/NWS/Office of Hydrologic Development, Boulder, Colorado

[6]NOAA/Western Region Climate Center, Reno Nevada

[7]California Department of Water Resources, Sacramento, California

[8]Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado

[9]NOAA/Earth System Research Laboratory/Global Systems Division, Boulder, Colorado

[10]Colorado State University, Department of Electrical and Computer Engineering, Fort Collins, Colorado

[11]University of Washington/Dept. of Civil and Environmental Engineering, Seattle, Washington

[12]University of Colorado at Boulder, Geography Department, Boulder, Colorado

[13]U.S. Bureau of Reclamation, Technical Services Center, Denver, Colorado

[14]NOAA/OAR/Climate Program Office, Physical Sciences Division, Boulder, Colorado

[15]University of Utah, Department of Meteorology, Salt Lake City, Utah

[16]U.S. Army Corps of Engineers, Seattle, Washington

[17]NOAA/NWS Western Region Headquarters, Salt Lake City, Utah

[18]Oregon State University, Oregon Climate Change Research Institute, Corvallis, Oregon

[19]University of Idaho, Department of Geography, Moscow, Idaho

[20]NOAA/NWS/San Diego Weather Forecast Office, San Diego, California

Abstract: Recent and historical events illustrate the vulnerabilities of the U.S. west to extremes in precipitation that result from a range of meteorological phenomena. This vision provides an approach to mitigating impacts of such weather and water extremes that is tailored to the unique meteorological conditions and user needs of the Western U.S. in the 21st Century. It includes observations for tracking, predicting, and managing the occurrence and impacts of major storms and is informed by a range of user-requirements, workshops, scientific advances, and technological demonstrations. The vision recommends innovations and enhancements to existing monitoring networks for rain, snow, snowmelt, flood, and their hydrometeorological precursor conditions, including radars to monitor winds aloft and precipitation, soil moisture sensors, stream gages, and SNOTEL enhancements, as well as entirely new observational tools. Key limitations include monitoring the fuel for heavy precipitation, storms over the eastern Pacific, precipitation distributions, and snow and soil moisture conditions. This article presents motivation and context, and describes key components, an implementation strategy, and expected benefits. This document supports a Resolution of the Western States Water Council for addressing extreme events.

Keywords: *Extreme events, observations, hydrometeorology*

The California Department of Water Resources, Western States Water Council (WSWC), and the Western Governors' Association (WGA) are currently collaborating to develop and, ultimately, implement a plan for a new generation of monitoring, forecasting, and decision support tools that will address ever-present, but growing, needs to better prepare for, and accommodate, extreme precipitation and flooding events across the Western United States. This effort is informed by a range of user-requirements workshops, scientific advances, and technological demonstrations over the last several years. Key elements of a vision for these improvements were prepared (at the WSWC's request) by the authors, and have been presented to the WSWC, which has approved a formal Resolution stating its official "position." The Resolution (the full resolution is available from WSWC and is reproduced in NOAA 2012a,b) states that recent advances in weather forecasting research, such as that of NOAA's Hydrometeorological Testbed program on West Coast atmospheric rivers (Ralph et al. 2005, 2013a), demonstrate the potential for improving extreme event forecasting at operational time scales. Benefits of advanced flood warning can be as much as a third of all residential damages, based largely on the ability to remove valuables from risk areas (Day et al. 1969). Additionally, as forecasts of extreme precipitation and runoff become accurate enough, they could enable forecast-informed reservoir operations that could yield increased water storage using existing flood control structures–offsetting some need for new storage facilities. This, of course, would require careful and comprehensive demonstration prior to implementation. Based on these advances and their potential benefits, the Council supports development of an improved observing system for Western extreme precipitation events to aid in monitoring, prediction, and climate trend analysis associated with extreme weather events and urges the federal government to support and place a priority on research related to extreme events, including research on better understanding of hydroclimate processes, paleoflood analysis, design of monitoring and change detection networks, and probabilistic outlooks for climate extremes.

The purpose here is to describe this vision of next generation observations that could aid in monitoring, prediction, and climate understanding associated with extreme weather events that affect either water supply or flooding in the semi-arid Western U.S. A primary motivation for such an advance is the stark fact that, during a 17-year period studied by Pielke et al. (2002), the Western States of WA, OR, CA, ID, NV, UT, AZ, MT, WY, CO, NM, ND, SD, NE, KS, OK, and TX experienced $24.7 billion in flood damages, an average of $1.5 billion annually. California, Washington, and Oregon alone accounted for $10.6 billion (46 percent) of this regional total (Downton and Pielke (2005) describes the accuracy of these loss data). In this context, there is a growing recognition that more needs to be done to provide: (1) necessary flood protection while ensuring adequate water supply in an environment characterized by extreme events, (2) improved warning lead times with quantified forecast uncertainties out to several days lead time that enable more confident actions by emergency preparedness officials, (3) the best possible observational and forecasting basis for addressing risks from aging flood control infrastructure (e.g., the Howard Hanson Dam crisis (White et al. 2012)) and aging levees in many settings (Florsheim and Dettinger 2007), and (4) better information for management actions to protect endangered species, such as salmon, aided by potential benefits to water supplies. At the extreme, the goal is to avoid, or reduce the impacts of, a "Katrina-of-the-West" scenario in which an extreme event disrupts or overwhelms existing operations or aging infrastructures catastrophically. Studies such as the ARkStorm scenario in California have identified this as a significant risk, with projected damages exceeding $500 billion (Porter et al. 2011). These challenges are only enhanced by the growing recognition of risks associated with the effects of climate change on the water cycle and atmospheric processes, which may include declining overall snowpack, shortening snow seasons with resulting extensions of interior flood seasons earlier into spring, possible expansion of the flood season on west coast to earlier in the fall or later into spring, increasing flood risk with warmer, and possibly more intense, storms, and increasing intensity, duration, or extent of drought.

The envisioned improvements would help reduce potential impacts of climate change by providing better information for developing adaptation strategies such as forecast-informed reservoir operations that can enable greater water supply while maintaining maximum flood control using existing structures

(Figure 1). Thus, responses to extreme events increasingly need to be weighed against the potential impacts of those responses on later water supplies, on fragile ecosystems and ecosystem services, on local to regional economies, and on positioning for accommodating subsequent floods and extremes and ultimately long-term climate changes.

At its core, the ability to meet many of these demands is restricted by two technical limitations: the short lead times over which current forecasts are accurate enough to support hard decision-making, and the fact that at least one key aspect of the extreme events in question–the transport of the water vapor that fuels the extremes–is woefully under-monitored. It used to be adequate to provide a few hours of lead time. Today, however, community leaders not only have to be prepared from a safety standpoint, but they need to be able to minimize the costs of taking preparedness actions (e.g. by shifting work schedules so that preparatory work can be done on regular time versus overtime). Increasingly, community leaders need lead times out to 7, 10, even 14 days. One crucial step necessary to provide these needed lead-time improvements is a better ability to track and predict the basic fuel of the extreme events being forecasted (i.e. the intense episodes of water-vapor transport into and through the region, whether by winter storm, upslope storms or summer monsoon). The good news is that new technologies, not available as recently as 5 to 10 years ago, are now available to improve our tracking and forecasts of these transports. Appropriate uses of these new technologies need to be conceptualized and integrated with existing observational networks to improve the value of the latter and to get the most informational improvements from the former. This paper represents our vision of new technologies to address the many and varied challenges listed above.

This requires innovative solutions that, in turn, will require a strong enterprise of monitoring, observation, modeling, science, and demonstrations. Solutions will depend upon better understanding, tracking, and prediction of the causes of extreme events, and how they might change in the future. Solutions will also depend on innovative engineering efforts to develop capabilities that can cost-effectively fill gaps in observations, forecasts, and related services that support vibrant economies, healthy ecosystems, and reliable water and living resources.

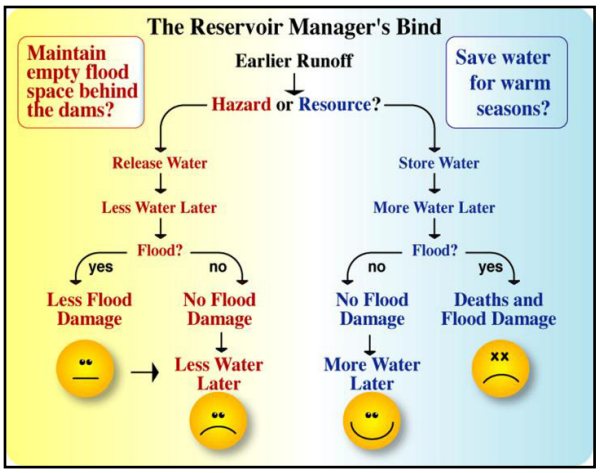


Figure 1. Schematic illustration of possible outcomes associated with early spring runoff depending upon whether the decision is made to release water to preserve flood control space for use in a potential late season flooding storm or to store water in expectation of summertime water-supply demands.

Extreme precipitation and flooding in Colorado's Front Range and in New Mexico in September 2013, catastrophic flooding in Spring 2011 on the upper Missouri River, major damage to a key flood control dam above Seattle in January 2009, the tragic loss of at least 36 lives in a major landslide in Washington State in March 2014 (immediately following a record-breaking drought in the region), and historic flooding events in California (e.g., 1969, 1986, 1997, 2005) illustrate the vulnerabilities of the west to extremes in precipitation. They also point to the urgency to explore and implement 21st Century capabilities.

The Context

Lessons learned from recent projects and requirements assessments

The main drivers for a future observing network are needs related to real-time monitoring, predictions (from minutes to days for flooding, and to seasons for water supply), research, and climate trend analysis. The network vision described here is informed by a broad set of recent user needs and requirements, documents, and demonstration studies (Table 1).

This paper takes advantage of a series of significant recent advances in observing system technology, research findings, experience gained by testing prototype observing systems in NOAA's

Table 1. Key reports, papers, and other sources used to inform the development of this Vision.

Source	Description and References
NRC reports	Flooding in Complex Terrain; Network of Networks; GPM Satellite system
Needs assessments	Reclamation and USACE (2011), USBR Science & Technology Program (2011), Climate change and water resources management- federal perspective (Brekke et al. 2009), USWRP Workshop (Ralph et al. 2005)
IWRSS	USACE, USGS, NOAA formal agreement and coordination; National Water Center
NOAA/HMT	10-year effort on extreme precipitation causes and predictions (Ralph et al. 2005; 2013a)
Atmospheric river research	Understanding of the joint roles of atmospheric rivers in extreme events and water supplies in the west (Dettinger et al. 2011)
ARkStorm	USGS-led emergency preparedness exercise in California focused on atmospheric rivers
NOAA/RISA	Regional Integrated Science and Assessment (RISA) studies on climate change
State Climatologists	Regional expertise and deep experience in states' needs for climate information
Unmanned Aircraft	NOAA UAS Program observing system gap analysis for atmospheric rivers over Pacific
NOAA Radars	Cross-NOAA Radar planning team reports
NOAA Science Plans	NOAA held interagency workshops on water cycle and climate science that produced detailed recommendations for future science directions nationally (NOAA 2012a, 2012b)

HMT (Ralph et al. 2003; White et al. 2012, 2013), the National Integrated Drought Information System (NIDIS), and the North American Monsoon Experiment (NAME; Higgins et al. 2006), as well as advances in numerical weather prediction, hydrologic forecasting, and real-time communications. Interagency needs assessments have also been produced that relate to these issues, including a report focused on extreme precipitation forecasting (Ralph et al. 2005), and more recently, a major report on dealing with issues related to quantifying extreme event probabilities (Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management; Olsen et al. 2010, http://www.cwi.colostate.edu/publications/is/109.pdf).

One broad conclusion of observing system research has been that monitoring of the atmospheric column, and not just the surface meteorology, and monitoring the atmosphere over the Pacific (where key weather features take shape before moving ashore) are vital to understanding and predicting precipitation intensity and form (rain/snow) in the western states (e.g., Ralph et al. 2013b).

Another vital requirement is that data from key elements of this network, especially those that provide observations aloft or offshore, need to be assimilated into numerical weather prediction models to reap maximum rewards. Existing models either already are able to assimilate key observations (e.g., wind profiler, GPS-met, and dropsonde data), or methods to assimilate other data can be developed. An example of a key recent finding (Doyle et al. 2014) is that a relatively small filament of water vapor in an atmospheric river over the Eastern Atlantic was critical to the development of strong European storms, and thus would be key to monitor offshore. Many direct uses of these same data exist even without this data assimilation, but maximum benefits will accrue from the combination of both the direct uses and model assimilation, as highlighted by forecast process evaluations (e.g., Morss and Ralph 2007) and emergency response experiences in the region (e.g., Ralph et al. 2003; White et al. 2012). A new tool, developed to monitor and predict the timing and intensity of landfalling atmospheric rivers (ARs) combines observations from an atmospheric river observatory (ARO; White et al. 2013) and a high-resolution numerical model (Neiman et al. 2009). These several findings are at the root of the vision presented here.

This vision was developed by a team of experts from federal, state, and local agencies, the academic community in hydrometeorology, hydrology, and climate, and representatives of some of the western

water-related systems that require information on extreme precipitation, flooding, and water supply. Lessons learned from the recent flood control crisis in Washington State, where the flood protection from Howard Hanson Dam above Seattle was seriously compromised by seepage that developed after a record AR storm in January 2009, are incorporated (White et al. 2012). Similarly, experience from an emergency preparedness scenario named ARkStorm (Dettinger et al. 2012) that explored the potential impacts of a devastating series of atmospheric rivers hitting California, also informed this report. The ARkStorm exercise concluded that over $500 billion in economic impacts could occur from a single major storm sequence in California through damages, business disruption, and other dimensions, and that significant loss of life could occur (Porter et al. 2011). Historical flood damages provide much the same perspective.

This vision was developed within, and recognizing, the context of the following several recent and current efforts to enhance observing capacities and networks related to extreme precipitation events in the West.

Enhanced Flood Response and Emergency Preparedness (EFREP; led by California Department of Water Resources, NOAA and Scripps Institution of Oceanography; White et al. 2013, Ralph et al. 2013a): Development and deployment of statewide monitoring, modeling, and decision-support programs drawing from, and making operational, key findings from HMT-West, for better detection, monitoring, and prediction of ARs and their impacts. Key components are a "picket fence" of four coastal atmospheric river observatories, a statewide soil-moisture network, snow-level radars, and land-based monitoring of vertically integrated water vapor (IWV), with associated decision support capabilities. Out of a total of four "tiers" (i.e., levels of complexity, investment and protection), the ongoing implementation covers key elements of tiers 1 and 2 for California (93 field sites in all), and will be complete in 2015. A brochure from California Department of Water Resources is available online at: http://www.esrl.noaa.gov/psd/atmrivers/projects/pdf/Advanced%20Monitoring%20Network%20FloodER%20Prgrm.pdf. The lessons there apply directly to Washington and Oregon. The top two tiers, 3 and 4, are broader in scope and cost, with benefits stretching across much of the Western U.S., and are included in this white paper. Tier 3 focuses on vulnerable subregions or watersheds, while Tier 4 is offshore.

Deployment of a NEXRAD on the Washington Coast (led by NOAA/NWS): The Next-Generation Radar (NEXRAD) network consists of over 150 radars across the U.S. and territories. Recently a major gap in NEXRAD radar coverage off of the Washington coast has been identified and filled through installation of a NEXRAD radar on the Washington coast that became operational in 2011.

Addition of dual-polarimetric capability to NEXRAD (led by NOAA): Starting in 2011, NEXRAD radars have been upgraded to include dual polarization capability. Dual polarization offers several advantages compared to current single-polarization radar systems, providing additional information about the size, shape, and orientation of precipitation particles. This information can be used to more accurately identify the type of precipitation (e.g., hail vs. rain), correct for signal loss (attenuation) in heavy precipitation, and more easily identify and remove non-meteorological radar echoes. Dual polarization phase measurements allow for rainfall estimation that is much less affected by problems related to absolute calibration of the radar system, to signal attenuation effects, and to partial beam blocking.

Enhancements of the SNOTEL high altitude network (led by NRCS): This includes the addition of soil moisture at a number of SNOTEL sites, as well as selected other instrument upgrades.

Enhancement of the Climate Reference Network (USCRN) to include soil and humidity measurements (led by NOAA): Supported by the National Integrated Drought Information System (NIDIS), by September 2011, all 114 CRN locations had soil probes and associated data loggers and relative humidity instruments installed.

Deployment of Regional Climate Reference Network Pilot Network (USRCRN; led by NOAA): The USRCRN vision consists of about 430 new stations nationally that meet siting and instrumentation standards of CRN. (These sites do not include soil moisture or relative humidity sensors.) A pilot project was installed between

2009 to 2011 involving several dozen sites in the southwestern states in support of NIDIS. Expansion beyond the Southwest has been suspended. See http:www.ncdc.noaa.gov/crn/usrcrn/.

The Winter Storm Reconnaissance (WSR) Program (led by NOAA/NWS): Using NOAA's G-IV and military C-130s, for several years (ending in 2013) an annual monitoring effort was conducted for several weeks over the Pacific Ocean to improve forecasts across the US. However, analyses of the 2011 WSR observations showed minimal impact on forecasts across the U.S. (Hamill et al. 2013). This result contributed to the cancellation of the program in 2014, but also pointed out the potential that alternative sampling and assimilation strategies could have greater impact.

CalWater atmospheric river research flights with the NOAA G-IV aircraft (led by NOAA and Scripps): Following the cancellation of WSR 2014, and in response to planning for a major scientific field campaign off the West Coast in 2015 and potentially additional years ("CalWater" http://www.esrl.noaa.gov/psd/calwater/), the NOAA G-IV was deployed in February 2014 over the northeast Pacific Ocean to observe atmospheric rivers. New flight strategies were invented and demonstrated to measure atmospheric rivers, including their strength, position and presence of mesoscale frontal waves key to landfall predictions (Ralph et al. 2011). Twelve flights were completed, using 190 dropsondes over 3 weeks. It is envisioned that this demonstration could be expanded in future winters to include forecast improvement goals and validation strategies. Unlike the WSR, these flights would focus on atmospheric rivers, and their impacts on precipitation on the U.S. West Coast. The recent results of Doyle et al. (2014) showing model sensitivity to details within an atmospheric rivers suggest a promising avenue of study.

Testing of Unmanned Aircraft Systems (UAS) for offshore weather data collection: (led by NOAA, in close partnership with NASA). The "Winter Storms and Pacific Atmospheric Rivers" (WISPAR) experiment was conducted in early 2011 over the eastern Pacific Ocean. The ability of the unmanned NASA Global Hawk aircraft to carry a NOAA dropsonde system that directly measured atmospheric profiles in atmospheric rivers over the ocean was demonstrated. Flights were up to 25 hours long, and were coordinated with NOAA's G-IV reconnaissance aircraft, which also sampled an AR near Hawaii. The CalWater experiment has proposed using this aircraft to measure ARs over three to four winter seasons.

Water Management Context

Monitoring and observing systems covering all phases of the hydrologic cycle are fundamental to water management. The monitoring infrastructure historically used to support water management has been facing an array of challenges: inadequate federal funding to maintain and modernize basic networks such as USGS streamgages, USDA SNOTEL sites, or NWS cooperative observer weather stations; increased demands for better spatial coverage of observations; and needed upgrades to incorporate improvements in technologies. Emerging challenges such as climate change adaptation place additional demands on observational networks, requiring targeted monitoring to improve process understanding as well as to track expected impacts.

Water management in the West is particularly focused on managing for extremes –floods and droughts. The California Department of Water Resource's experience with the EFREP project led the California Department of Water Resources to recommend to the Western States Water Council that it support expansion of the observing system being developed for California into other states. The observing system vision provides a framework for modernizing existing networks as well as for improving understanding, monitoring, and forecasting of the extreme events that dominate operational water management. Preliminary research associated with scoping the observing system and improving understanding of extreme precipitation has also revealed some unanticipated findings. For example, since atmospheric rivers were determined to play such a dominant role in West Coast total annual precipitation, improving the ability to identify sub-seasonal to seasonal conditions favorable for atmospheric rivers could possibly inform drought prediction at these timescales. Serendipitous discoveries such as this illustrate the value of focused research to improve observations.

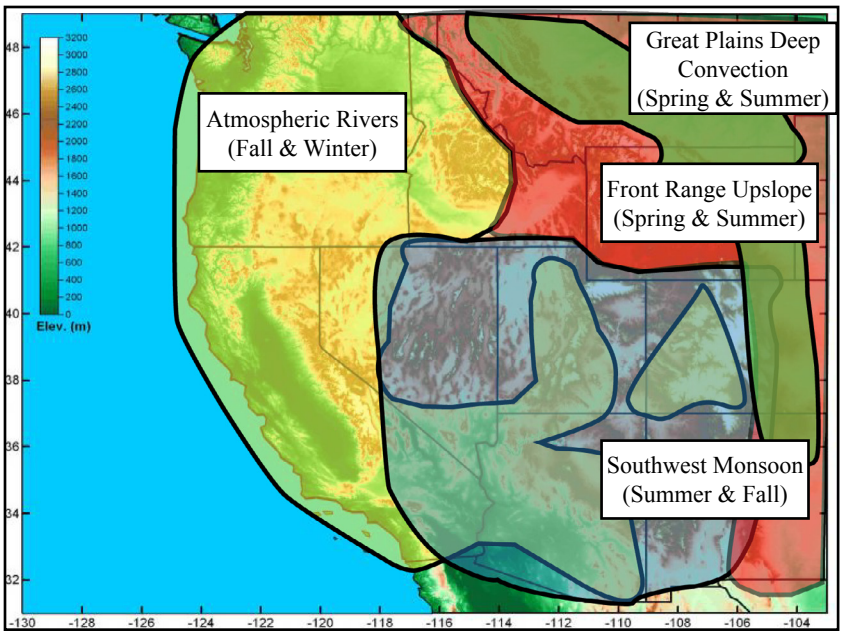


Figure 2. Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation and flooding and contribute to water supply in the Western U.S. This has been developed with input from experts on these phenomena who contributed directly to this document.

Meterological Context

Extreme precipitation is the primary cause of flooding and landslides in the region, and when these events occur in winter they can substantially increase snowpack and thus water supply. Another major cause of extreme runoff and flooding in some regions is snow melt in the spring and summer, which can be triggered by unusually warm and sunny conditions and warm, heavy rainfall.

The meteorological phenomena responsible for extreme precipitation varies across the region, as illustrated in Figure 2. Four primary precipitation-causing phenomena are highlighted here:

- Atmospheric rivers (cool-season storms that come ashore from the Pacific)
- Southwest monsoon (involving summer thunderstorms and remnant tropical storms)
- Great Plains convective storms, i.e., thunderstorms (in spring and summer)
- Upslope storms along the "front range" of the Rocky Mountains (spring and summer)

Although there is some overlap in the seasonality of these phenomena, they are relatively distinct, with hydrometeorologically significant ARs occurring primarily from October through March, spring upslope storms occurring from April to June (can also occur in late summer), the southwest monsoon being almost exclusively in July-October, and Great Plains deep convection from April to August.

The availability of COOP daily precipitation data from thousands of sites in the region, going back 30 years or more, helps to clarify the geographic domains for each of these phenomena. For each COOP site, the 10 historical days with the largest daily precipitation totals were identified (i.e., the top 10 out of roughly 10,000 dates or more days in a site's period of record). The season that had the largest number of these "top-10" extreme precipitation events at each COOP site was then plotted on a map (Figure 3a). While the seasonal and geographic boundaries can blur or overlap to a degree (as in Colorado), the overall patterns are clear enough to illustrate the regionally and seasonally varying causes of extreme precipitation across the West. Peak-streamflow dates (Figure 3b) help to corroborate these patterns. Recent studies of inland penetration of ARs (Rutz and Steenburg 2012; Neiman et al. 2013a; Rutz et al. 2014) has confirmed that such events can have impacts far inland (Figure 3a).

Challenges Associated with the Regional Geography

The geography of the west severely complicates both the monitoring and prediction of these extreme events, including weather and climate time scales, for several reasons. Many storms originate over the Pacific Ocean where there are major limitations in weather observations. For example, severely

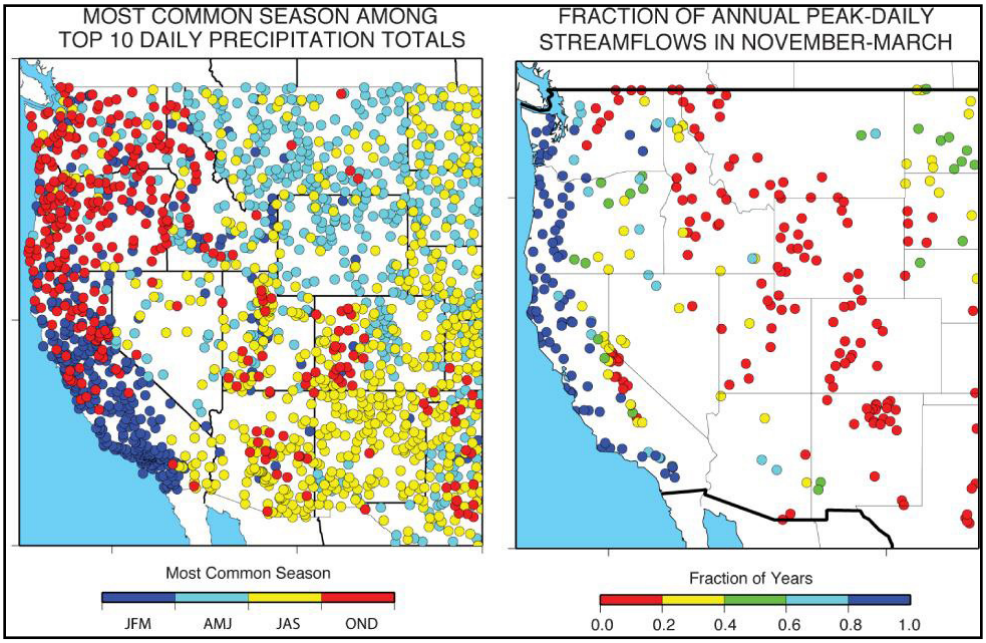


Figure 3. (a) Seasonality of extreme precipitation events across the Western U.S. based on daily precipitation totals from thousands of COOP observations (dots) covering at least 30 years each. The color of each site corresponds to the season of the year when more of the top-10 daily precipitation events occurred than any other season. (b) Seasonality of annual peak daily stream flows highlighting the geographic distributions of AR-, snowmelt, and monsoon dominated regions.

limited measurements of vertical profiles of winds, temperature and moisture in ARs and the larger-scale weather systems within which they are embedded. These limitations contribute to errors in the predicted position of land-fall of ARs of roughly 500 km at 5-days lead time (Wick et al. 2013). The presence of large, complex mountains creates large differences in weather conditions over short distances, making monitoring and forecasting much more challenging. Large areas of the mountainous west are uniquely vulnerable to future increases in flooding during extreme events because over half of the largest (historical) daily precipitation totals occurred when daily mean temperatures were between -3 and 0ºC, meaning that a warming of 3ºC would greatly exacerbate flooding (Bales et al. 2006). Much of the weather-observing infrastructure in place today is simply too sparse, outdated (e.g., most vertical profiling today depends on infrequent in-situ balloon measurements when higher observation frequencies are needed), or is not deployed in an optimal manner for western U.S. applications. For example, quantitative precipitation estimates (QPE) by NEXRAD scanning radars are hamstrung by their siting and scanning strategies, which often miss shallow rain or misinterpret virga aloft as rainfall at the surface, or use inappropriate drop-size distributions (Matrosov et al. 2014).

Selected Requirements

Based on the many user needs and requirements analyses noted earlier, as well as the broad experience of the coauthors of this paper, a list of key requirements is provided in Table 2. From a climate perspective, many of these requirements correspond with the information needs outlined in the Bureau of Reclamation's Science and Technology Program's climate change and variability priority area, specifically addressing the following needs (USBR 2011, section 5.A.2) on time scales of days to years:

- Improved use of existing-quality weather, climate, and hydrologic predictions in the development of operations outlooks (e.g., improved use of forecast uncertainty through novel methods or tool development);
- Development of superior-quality weather and climate and predictions relative to current information products from Reclamation's forecast providers;

Table 2. Key information requirements to support decision making related to extreme events in the water cycle.

Accurate Quantitative Precipitation Estimates (QPE) in complex terrain
Accurate Quantitative Precipitation Forecasts (QPF) for extreme events
Accurate hydrometeorological forcings for the next generation flood-forecasting and streamflow models, including soil moisture conditions, snow pack, existing stream flow, base flow, precipitation inputs, temperature, evapotranspiration, etc.
Atmospheric river landfall position, strength, orientation, timing and duration
Nowcasts and short-term QPF in urban areas for water, stormwater and sewage management
6-h forecasts of the end of heavy rain over key watersheds for reservoir operations
1-5 day guidance/forecasts of the location and intensity of extreme events to support future forecast-informed reservoir operations to optimize flood control and water supply
Better situational awareness to allow enough lead time with quantified forecast uncertainty to enable preemptive actions by emergency preparedness officials out to 10 days where feasible
Seasonal guidance of the potential for both flood risk and water supply that can enable decision makers to select optimal policy options
Accurate QPE and QPF for fire risk management and fire fighting
Short term (minutes to hours) forecasts of rain rates that initiate debris flows over burn scars and other lanslides
Increase in the use of GIS to pinpoint areas of concern to help local forecasters track events

- Enhanced communication of un-certainties and risks associated with weather and climate predictions in the development of Reclamation's operations outlook.

These requirements also reflect some of the goals and recommendations identified in NOAA's Water Cycle Science Challenge Interagency Workshop Report (NOAA 2012a):

- Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate prediction.
- Improve representations, understanding and forecasting of hydrometeorological forcings to rival those of other non-water-cycle variables in the weather-climate system.
- Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors.
- Explicitly characterize key uncertainties in climate and hydrologic models.

The Vision

Overview

This section outlines a strategy that would lead to a fully functional modern monitoring system optimized for the West (plausibly over a roughly six-year period). It would largely utilize existing organizations with the suitable expertise, infrastructure, and missions to perform the implementation, and then to carry on long-term operation, maintenance, and ongoing improvements. While many details remain to be worked out, in principle, capabilities (i.e., knowledge, skills, tools) currently exist to execute this strategy if adequate funding becomes available. The vision is an expert opinion on what can be done to address these major societal challenges based on existing and emerging technologies and techniques.

The observational tools and related efforts are based on several key inputs: 1) a set of requirements (often overlapping or complementary to one another) associated with detecting the phenomena that cause extreme precipitation as well as predicting them hours to days beforehand and monitoring signatures of climate change; 2) progress in atmospheric and hydrologic numerical modeling, and need for high resolution observations and predictions of key hydrometeorological conditions that drive them; 3) several years of testing and prototyping of new tools and methods in HMT and other experimental settings and campaigns, such as CalWater and the Yosemite High-Altitude Hydroclimate Network, that have provided many lessons about what works, does not work, and how

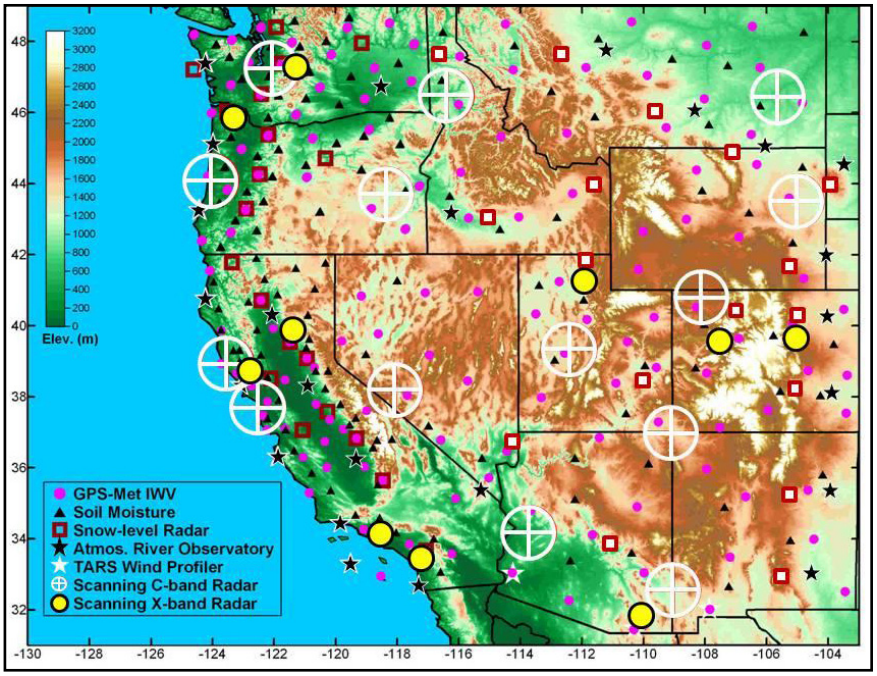


Figure 4. Schematic network of new sensors (land-based) to improve monitoring, prediction, and climate trend detection for hydrometeorological conditions that create extreme precipitation and flooding.

much effort is involved; and 4) the emergence of new observational technologies, information systems, real-time and reliable communication from remote sites, and better understanding of the storms themselves.

The vision consists of:

- A broad land-based network (Figure 4) customized to monitor conditions in the extreme precipitation regimes identified in Figure 2, with observations focused on water vapor content and its transport, QPE, snow level, soil moisture, and dust and rain-on-snow effects. A key strategy is monitoring conditions aloft, below roughly 3 km altitude. This is the layer most difficult to observe using satellite or scanning radars, and yet is where some of the most important meteorological conditions, in terms of extreme precipitation, reside. It is where most of the water vapor and clouds are concentrated, where airflows interact with terrain, and where the atmospheric "boundary layer" conditions set the stage for heavy precipitation.
- Enhancements to the mostly already existing observing network in the mountains (Figure 5), focused on snowmelt preconditioning, including snow density and albedo observations.
- Offshore monitoring, with an emphasis on AR conditions (including frontal waves influencing AR durations and intensities at landfall) and assimilation of data into weather models from the critical upwind region over the eastern Pacific from which most western storms approach. States and communities need time to prepare, to minimize the impact of preparations and recovery from major storms in any ways they can. Offshore monitoring can provide lead time before storms and flooding. This need not be a perfect forecast but a heads up that a big storm is coming with key characteristics of the storm (e.g., cold, wet, windy, once in 10 year event, or a normal winter storm).

The land-based network (Figures 4 and 5) described here would ideally include (see details online):

- 100 new low-mid altitude soil moisture observing sites
- 125 existing high-altitude sites with new snow-related data
- 100 new GPS-met observing sites
- 25 snow-level radars
- 25 wind profiling/ARO sites
- 14 C-band scanning radars
- 10 X-band scanning radars or mini CASA networks

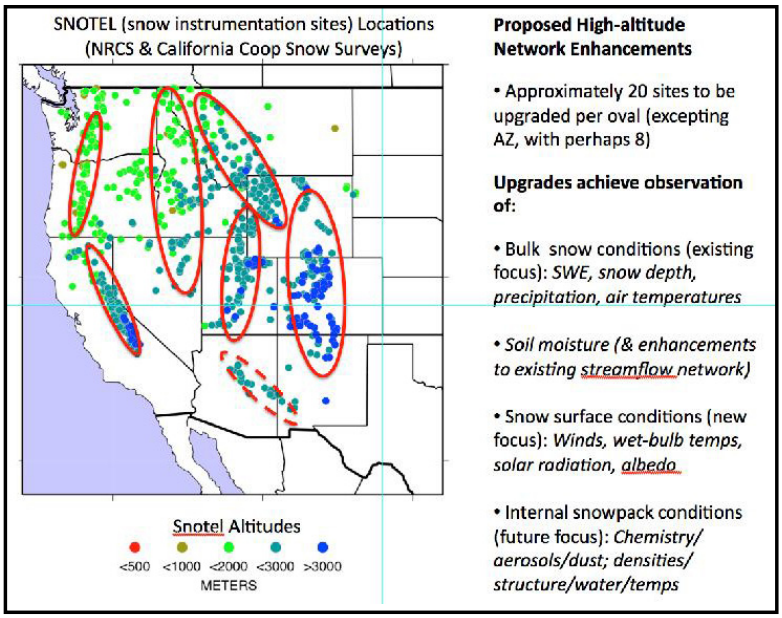


Figure 5. Existing SNOTEL sites color coded to their altitude range. Red ovals highlight regions where a subset of the existing SNOTEL sites would have additional sensors emplaced to support better spring snow melt monitoring and prediction, or where new sites would be needed to broaden the altitude range of coverage.

Overarching Gap: Monitoring Water Vapor Transport – The Fuel for Precipitation

An overarching gap in observations associated with extreme precipitation events is monitoring of water vapor transport (i.e., the "fuel" for the precipitation). Existing observations typically do not measure winds and water vapor aloft except in a handful of locations twice per day using balloon soundings, and yet these are the key variables that determine the water vapor transports that fuels precipitation. A major component of the observing system that is proposed here is based on filling this gap, and designed in many settings on the specific characteristics of ARs that are most important to severe storms and that have now been well documented, including their width, depth, snow level, water vapor transport and orientation. It has recently been shown that 75 percent of the variance in storm-total rainfall at the coast in ARs is explained by variance in storm-total upslope water vapor transport, and that more than 60 percent of the variance in storm-total streamflow was explained by this flux (Ralph et al. 2013b). In addition, it has been shown that the direction of the low-altitude wind in ARs has a major controlling effect on exactly which watersheds will receive the greatest rainfall in a given event (Ralph et al. 2003; Neiman et al. 2011). The orientation of the winds in the AR creates rain shadows that can shelter some regions from the heaviest rainfall. In the case, where the "dividing streamline" crossed the Santa Cruz Mountains, Ralph et al. (2003) showed that it separated flood-producing rain to its west from weak rain to its east that did not create flooding. Recently, studies of the inland penetration of ARs to the Sierras and the intermountain west have highlighted the role of ARs in focusing water vapor transport into these regions (Rutz and Steenburgh 2012; Rutz et al. 2014) and the role of the Sierra Barrier Jet in modulating this (Hughes et al. 2012; Neiman et al. 2013b).

Based on a decade of development at NOAA and in HMT, a method has been invented that deploys a wind profiling radar, GPS met receiver, snow-level radar, and surface data to monitor AR conditions aloft on an hourly basis. This is called an atmospheric river observatory (ARO; White et al. 2013). Because an average AR is about 400 km wide, the optimal horizontal spacing of AROs is 200 km. Four atmospheric river observatories (AROs) are now being deployed along the California coast as part of its EFREP program and the technique was part of NOAA's rapid response to the Howard Hanson Dam crisis (White et al. 2012). Three additional sites along the Oregon and Washington coasts are slated for future deployment supporting multiple applications including wind energy. Ideally, ARO data are shown in combination with output from a high-resolution numerical weather prediction model tailored to the AR phenomenon.

The present vision involves completing a west coast array of AROs to observe water vapor transport from over the Pacific Ocean in ARs, along with a few more AROs farther inland to monitor water vapor transports through preferred pathways into the intermountain west. Similar instrumental arrays (called TARS) already exist along the border with Mexico, to support drug interdiction efforts by providing wind profile information aloft for operation of tethered balloons carrying surveillance radars to detect low-flying aircraft. The present plan would develop tools to take advantage of this border array to help monitor water vapor influx into the Southwest from the South, especially as part of the summer monsoon, which derives its moisture through transport from either Mexico or the Gulf of Mexico. The plan also applies this technology along a line roughly 100 km east of the Front Range of the Rockies to monitor water vapor influxes from the Great Plains towards the Rockies in upslope storms (such as the record flooding of September 2013 along the Colorado Front Range), and would be coupled with snow-level radars in the foothills to monitor, in real time, the fraction of vulnerable watersheds that would be exposed to rain versus snow. This fraction, a critical factor determining the mix of flooding versus snowpack water storage from any given storm, could be a key issue in spring 2014 from Montana and Wyoming to Colorado, where snowpack is greater than 150 percent and people are bracing for spring floods. Because water vapor transport from north to south across the Canadian border tends to be very weak (due to the prevalence of dry cold continental air there), no such array is proposed for that area.

Phenomenological and Regional Requirements and Relevant Observations

This section summarizes specific observational enhancements addressing gaps related to the phenomena primarily responsible for extreme precipitation and streamflow.

Broad Area Coverage Components: (addressing all four meteorological phenomena that cause extreme precipitation, plus spring and summer rapid snowmelt). These represent low-cost sensors that would benefit most of the Western U.S: soil moisture, GPS met for IWV, "bulk" snow measurements (depth, SWE, precipitation), air-snow interface (snow albedo, wind, dew point temperature, solar radiation), snowpack internal conditions (e.g., chemistry of dust, snow densities), and additional stream gages.

Atmospheric River-focused Components. Another element of the network emphasizes horizontal water vapor transport in ARs, along with snow level monitoring and enhanced QPE through gap-filling scanning radars over major urban areas. The design also requires offshore monitoring to extend the range of predictions out to several days. Sensors include atmospheric river observatories (ARO) in the AR-impacted regions, snow level radars, scanning polarimetric radars over major cities (e.g., Seattle, Bay Area, Vegas), and offshore monitoring, including frontal waves that affect ARs (coastal scanning radars C-band, aircraft, buoy-mounted wind profilers, all taking advantage of satellites).

Monsoon-Focused Components. As indicated in Figure 2, the southwestern U.S., including Arizona, Nevada, Utah, Colorado, and New Mexico, are impacted by the precipitation associated with the North American Monsoon (NAM). In particular, parts of southern Arizona and New Mexico receive over 50 percent of their annual precipitation during the NAM season (Douglas et al. 1993; Adams and Comrie 1997). The key gaps for monsoon monitoring include both water vapor transport from Mexico or the Gulf of Mexico, plus scanning radars to fill very large gaps in current radar coverage. Sensors include ARO-like installations, but focused on Monsoon-related water vapor transport and taking advantage of the existing TARS profiler network, and gap-filling scanning radars with polarimetric capability over major urban areas.

Great Plains Convection Components. The Great Plains have one of the best existing radar networks for monitoring broad area storms (although gaps for monitoring tornadoes and severe thunderstorms remain). The present vision emphasizes water vapor distribution and transport, as well as soil moisture and recommends gap filling polarimetric radars in flood-prone, front-range watersheds and an enhanced lightning network.

Front Range Upslope Storms. Upslope storms primarily occur along the east slopes of the Rocky Mountains, extending from Montana to New

Mexico (Figure 2). These storms usually consist of a 200 to 300 km wide area of easterly or northeasterly winds north of a cold front and surface low pressure system. The passage of the cold front is often complicated by local terrain, and uncertainties regarding the specific location of the low pressure center development typically confounds forecasts. The monitoring system thus emphasizes monitoring these features and the conditions that modulate them, with a network of 449 MHz wind profilers 100 km east of the foothills to monitor cold fronts and upslope winds, plus another array of 915 MHz wind profilers 10 km east of the base of the foothills to monitor both barrier jet winds and snow level (449 HMz profilers are more expensive, but can see much higher into the atmosphere than 915 MHz systems), and snow level radars at the base of the foothills as an alternative to the wind profilers.

Snow Melt. As shown in Figure 3b, spring melt creates most of the highest flows on many rivers, especially in the intermountain region. Thus special emphasis is given here to snowmelt conditions. Most of the proposed actions for this purpose require new sensors at high altitudes, but could also include sensors at altitudes where cold storms deposit snow that can contribute to flooding in somewhat rare events. The most effective approach would leverage the existing SNOTEL network, which already targets regions of significant snowpack, and has infrastructure that could facilitate deployment of new tools. Some of this is already happening within the NRCS, and with California's EFREP, in terms of adding soil moisture measurements to some sites. Figure 5 highlights the locations where system enhancements are recommended, and lists the key sensors that would be used. Future remote sensing capabilities, such as JPL's Airborne Snow Observatory (ASO) provide additional opportunities to monitor snow water equivalent and albedo (Painter et al. 2013).

Some Excluded Elements

While additional NEXRAD systems have potential uses here the NEXRAD network is optimized more for Great Plains convection and detection of tornadoes and hail. For example, the NEXRADs do not scan at elevation angles below 0.5 degrees above the horizon. In the west, where radars are commonly positioned in areas of high terrain to reduce blockage, the ability of the radar to observe at or below the horizon is critical for accurate QPE. Moreover, the NEXRAD network is already far more dense in the Great Plains than over the mountainous part of the west and individual new NEXRAD radars are prohibitively expensive relative to the scope of this vision.

Also, although new satellite techniques (i.e., new sensors or next generation satellites) hold potential to support the objectives of this white paper, their costs are beyond the scope of what is being considered here for regional applications. Nonetheless, the proposed network will integrate with existing and future radar and satellite observations, e.g., by using existing satellite sensors and NEXRAD data in new ways. For example, a) passive microwave and GPS occultation satellite observations are crucial over the ocean for AR monitoring; however, the passive microwave method does not work over land. A land-based, GPS-met land-based network is proposed here specifically to help fill this gap. Also, no satellite methods currently monitor AR winds and water vapor transports aloft over the oceans or land, so airborne reconnaissance is proposed here to fill this gap. Finally, some key satellite footprints or spatial resolutions are simply too coarse to resolve conditions associated with the especially complex terrain of the west.

Additional Actions Related to Achieving the Objectives of this Vision. Performance measurements should be developed that focus specifically on extreme precipitation events, and others that represent snow-level and soil moisture forecast performance. Create a scale for assessing the strength of ARs offshore (e.g., compare water vapor transport in an AR to the average flow of the Mississippi River; as in "this AR transports in one day an amount of water as vapor similar to what 7 to 15 Mississippi Rivers transport in one day as liquid). Create a simple scale for communicating and comparing magnitudes of extreme precipitation and stream flow over land (e.g., a 3-day precipitation scaling; Ralph and Dettinger 2012). Develop predictive modeling and decision support tools and systems to optimize use of the data. Use new GIS-based tools for information management, display and dissemination. Ensure that data from key elements of this network, especially those that provide observations aloft or offshore, are assimilated into operational weather prediction

models. Note that models either are already able to assimilate many of the observations (e.g., wind profiler, GPS-met and dropsondes data) proposed here when and if they are made, and that methods to assimilate other data types could be developed. Sustaining the western observing network requires a stronger collaboration across agencies.

Transition to Operations

This new observational network would be established in the midst of significant new capabilities in the nation's water resources science and services, which would facilitate the operational transition and increase the operational impacts of these new information streams. This section discusses this operational framework as well as related existing infrastructure and alternative strategies.

The Integrated Water Resources Science and Services (IWRSS). IWRSS is a new multi-agency framework to meet the nation's growing water resource challenges. In May 2011, the National Oceanic and Atmospheric Administration, the US Army Corps of Engineers, and the US Geological Survey signed a memorandum of understanding establishing IWRSS. Through IWRSS, these agencies will engage in collaborative science and develop services and tools to support integrated and adaptive water resources management. IWRSS consortium members will operate within a common operating picture, employing shared modeling and information services frameworks, allowing their individual decision support systems to work in concert towards meeting the water challenges faced by our Nation. IWRSS considers a broad range of time scales – from historical "analyses of record" through forecasts and projections spanning weather and climate. A key element of the IWRSS strategy is a series of regional watershed demonstrations (or pilots), including one recently identified in the region, i.e., California's Russian River. More information on IWRSS is available at: http://www.nohrsc.noaa.gov/~cline/IWRSS/IWRSS_ROADMAP_v1.0.pdf.

The National Water Center (NWC). NWC is housed in a new NOAA facility constructed in Tuscaloosa, Alabama and will serve as a focal point for IWRSS developments and NOAA's water resource information services. The NWC will provide capabilities to integrate the new observations discussed herein, through assimilation into the IWRSS forcing data engine and operational modeling framework, and by integrating them into a data model that supports both NWS operations, as well as those of the IWRSS consortium. The NWC then becomes a vehicle for widespread dissemination and application to operational centers and stakeholders and customers of water resource information.

NCEP/WFOs. The IWRSS/NWC will complement and enhance the NWS's long-established framework for disseminating weather and water information, forecasts and warnings. The NOAA National Centers for Environmental Prediction (NCEP) provide 24x7x365 large scale modeling forecasts and guidance. This information supports a network of 122 Weather Forecast Offices (WFOs) and 13 River Forecast Centers (RFCs), that serve as focal points of local expertise and knowledge, as well as for engagement with local communities and stakeholders. These data will feed into WFOs, supporting their role in issuance of local watches and warnings.

NCEP leads NOAA's assimilation of observations into operational numerical models, including wind profiler and dropsondes data from aircraft. NOAA's Global Systems Division innovates on assimilating observations from many sources in high resolution models. The existing capabilities in these arenas will be utilized, including use of current assimilation methods and development of new ones.

Additional operational strategies. Outside of the relatively traditional approaches outlined above, many observing networks have been developed, deployed and operated under a diverse array of strategies that differ from the large federal approach, and they had large impact on a diverse array of information users using alternative strategies. These include State Departments of Transportation, individual water system operators, agricultural services and many others. Transitioning of new observations, such as those identified in this vision, into "operations" could very well take place in this alternative manner. The emergence of Testbeds linking weather research to forecasting operations over the last 10 to 15 years has illustrated many possibilities in this regard (Ralph et al. 2013a). Regional Centers, local agencies, state agencies, universities and other groups represent a versatile

pool of knowhow that can support the transfer of information from this network, or sub-elements of it, into targeted applications, and can develop new methods in a highly adaptable manner.

Comments on Implementation

Laying out a specific set of strategies for implementation is beyond the scope of this report; however, some comments on broad strategies are feasible. The costs to operate, maintain and optimize the network can be reduced considerably by deploying automated monitoring systems and methods for monitoring performance, diagnosing faults, emphasizing reliability during critical meteorological conditions, training local "hosts" who can perform less technical tasks (e.g., restarting a computer), depending upon existing sensor network communications and quality control tools (such as MADIS - http://madis.noaa.gov/ and MESOWEST - http://mesowest.utah.edu/index.html), maintaining a small, technical and engineering staff that can be on call to perform repairs, and using methods developed partly in HMT for maintaining regional networks in a cost-effective manner. The envisioned network is also structured to also take advantage of existing, underutilized networks, such as the TARS profiler network along the southern border with Mexico, pre-existing GPS sensors currently deployed for seismic monitoring, and extensive existing SNOTEL and streamgage networks, and provides resources to ensure key stream gauges are supported long-term. Experiences gained in various projects, e.g., California's EFREP network (White et al. 2013) and NOAA's aircraft reconnaissance experience, provide a basis for a rough order of magnitude cost estimate in the range of $200 million, spread over several years, followed by an O&M "tail" of roughly $30 million per year.

Anticipated Outcomes

Based on past experience with major new observational infrastructure (e.g., NEXRAD, satellites, EFREP, and HMT-West), the time frame for implementation is roughly 5 to 10 years. During this time the methods and tools to use the new data would also be enhanced, and benefits would begin to accrue. This is not a "quick fix." It is a thorough, scientifically based, interagency-requirements-driven strategy to modernize the region's observational infrastructure for dealing with the extremes of too much, or too little water. This 21st century observing system for the West will meet many of the 21st Century needs for solid, real-time information based on up-to-date science, to support decisions affecting millions of people, innumerable businesses and the environment of the west.

Benefits will include:

- Mitigating risks of greater than $100 billion Katrina-like disasters on the U.S. West coast (see NRC reports from before Katrina and ARkStorm activities since then);
- Reducing flood risks and damages through development of modern decision support tools that allow for pre-storm releases from flood control reservoirs that are refilled by the storm, thereby also enhancing water supply for the summer;
- Enabling forecast-informed reservoir operations for combined benefits of improved flood control and enhanced water supplies, possibly offsetting some requirements for new reservoir space being considered in the west, resulting in billions of dollars in savings;
- Improving drought monitoring and associated benefits in support of NIDIS;
- Improving capacity for early detection of climate change impacts on water supply and flooding in the west to inform adaptation and mitigation strategies optimized for regional impacts and needs;
- Tighter collaborations across federal, state, and local agencies to assure effective implementation into existing water information and management systems;
- Strengthening of science and technology job sectors in the region.

From a policy perspective, it is perhaps most notable that improved water-year-type forecasts in California alone have estimated values that could exceed $100 million in a single year (Simpson et al. 2004). In terms of flood risks, enhanced preparedness for flooding events that mitigates loss of life and property for flooding–the phenomena that is responsible for the greatest impacts as defined through Presidential disaster declarations (e.g., average flood losses in the region are $1.5 billion

per year)–is a primary strategy for controlling and reducing those risks. With improved monitoring, forecasts and longer lead times, community leaders will be better able to prepare for extreme events, not only from a safety standpoint, but to minimize the costs of taking preparedness actions (e.g., by shifting work schedules so that preparatory work can be done on regular time versus overtime).

This vision describes an approach to dealing with extreme events in a way that is tailored to the unique meteorological conditions and user needs of the Western U.S.

Acknowledgments

This article reflects views of the authors only; nothing herein is intended to express a policy or position of the California Department of Water Resources, NOAA, USGS, or other agencies.

References

Adams, D.K. and A.C. Comrie. 1997. The North American Monsoon. *Bulletin of the American Meteorological Society* 78: 2197–2213.

Bales, R., N. Molotch, T. Painter, M. Dettinger, R. Rice, and J. Dozier. 2006,.Mountain hydrology of the western US. *Water Resources Research* 42: W08432, 13.

Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White. 2009. Climate change and water resources management-A federal perspective: U.S. Geological Survey Circular 1331, 65.

Day, H.J., G.Bugliarello, P.H.P. Ho, and V.T. Houghton 1969. Evaluation of benefits of a flood warning system. *Water Resources Research* 5(5): 937–946.

Dettinger, M.D., F.M. Ralph, T. Das, P.J. Neiman, and D. Cayan. 2011. Atmospheric rivers, floods, and the water resources of California. *Water* 3: 455-478.

Dettinger, M.D., and other authors. 2012. Design and quantification of an extreme winter storm scenario for emergency preparedness and planning exercises in California. *Natural Hazards* 60: 1085-1111.

Douglas, M.W., R. Maddox, K. Howard, and S. Reyes. 1993. The Mexican monsoon. *Journal of Climate* 6: 1665–1667.

Doyle, J.D., C. Amerault, C.A. Reynolds, and P.A. Reinecke. 2014. Initial condition sensitivity and predictability of a severe extratropical cyclone using a moist adjoint. *Monthly Weather Review* 142: 320–342.

Downton, M.W. and R.A. Pielke. 2005. How accurate are disaster loss data? The case of U.S. flood damage. *Natural Hazards* 35(2): 211-228.

Hamill, T.M., F. Yang, C. Cardinali, and S. J. Majumdar. 2013. Impact of targeted winter storm reconnaissance dropwindsonde data on Midlatitude numerical weather predictions. *Monthly Weather Review* 141: 2058-2065.

Higgins, W.D. and coauthors. 2006. The NAME 2004 field campaign and modeling strategy. *Bulletin of the American Meteorological Society* 87(1): 79-94.

Hughes, M., P.J. Neiman, E. Sukovich and F.M. Ralph. 2012. Representation of the Sierra Barrier Jet in 11 years of a high-resolution dynamical reanalysis downscaling compared with long-term wind profiler observations. *Journal of Geophysical Resources: Atmospheres (1984-2012)* 117(D18).

IWRSS Roadmap: http://www.nohrsc.noaa.gov/~cline/IWRSS/IWRSS_ROADMAP_v1.0.pdf.

Matrosov, S.Y., F.M. Ralph, P.J. Neiman, and A.B. White. 2014. Quantitative assessment of operational weather radar rainfall estimates over California's Northern Sonoma County using HMT-West data. *Journal of Hydrometeorology* 15: 393–410.

Morss, R.E. and F. M. Ralph. 2007. Use of information by National Weather Service Forecasters and emergency managers during the CALJET and PACJET-2001. *Weather and Forecasting* 22: 539-555.

Neiman, P.J., A.B. White, F.M. Ralph, D.J. Gottas, and S.I. Gutman. 2009. A water vapor flux tool for precipitation forecasting. *Proceeding of the ICE. Water Management* 162(2): 83-94.

Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick. 2011. Flooding in western Washington: The connection to atmospheric rivers. *Journal of Hydrometeorology* 12: 1337-1358.

Neiman, P.J., F.M., Ralph, B.J. Moore, M. Hughes, K.M. Mahoney, J.M. Cordeira, and M.D. Dettinger 2013a. The landfall and inland penetration of a flood-producing atmospheric river in Arizona. Part 1: Observed synoptic-scale, orographic and hydrometeorological characteristics. *Journal of Hydrometeorology* 14: 460-484.

Neiman, P.J., M. Hughes, B.J. Moore, F.M. Ralph and E.M. Sukovich. 2013b. Sierra barrier jets, atmospheric rivers and precipitation characteristics in Northern California: A composite perspective based on a network of wind profilers. *Monthly Weather Review* 141: 4211-4233.

NOAA. 2012a. *Understanding the Water Cycle* Interagency final report, 60 pp. (http://www.esrl.

noaa.gov/psd/events/2011/pdf/waterCycle-report-reformat.final.pdf).

NOAA. 2012b: *Toward Understanding and Predicting Regional Climate Variations and Change.* Interagency final report, 32 pp. (http://www.climateneeds.umd.edu/pdf/NOAA Workshop-Toward Understanding and Predicting Regional.pdf).

Olsen, J.R., J. Kiang, and R. Waskom (eds.). 2010. *Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management. Colorado Water Institute Information Series No. 109*. www.cwi.colostate.edu.

Painter T.H., J. Boardman, J.S. Deems, F. Gehrke, C. Heneghan, B. McGurk, F. Seidel, A. Trangsrud, and K. Andreadis. 2013. The NASA/JPL airborne snow observatory: Imaging spectrometer and LIDAR for coincident retrieval of snow albedo and snow water equivalent. *Proceedings of the Davos Atmosphere and Cryosphere Assembly* DACA-13, Davos, Switzerland.

Pielke, Jr., R.A., M.W. Downton, and J.Z. Barnard Miller. 2002. *Flood Damage in the United States, 1926-2000: A Reanalysis of National Weather Service Estimates*. Boulder, Colorado: UCAR.

Porter, K., and coauthors. 2011. *Overview of the ARkStorm Scenario*. U.S. Geological Survey Open-File Report 2010-1312, 183 p. and appendixes.

Ralph, F.M., P.J. Neiman, D.E. Kingsmill, P.O.G. Persson, A.B. White, E.T. Strem, E.D. Andrews, and R.C. Antweiler. 2003. The impact of a prominent rain shadow on flooding in California's Santa Cruz mountains: A CALJET case study and sensitivity to the ENSO cycle. *Journal of Hydrometeorology* 4: 1243-1264.

Ralph, F.M., and other authors. 2005. Improving short-term (0-48 hour) cool-season quantitative precipitation forecasting: Recommendations from a USWRP Workshop. *Bulletin of the American Meteorological Society* 86: 1619-1632.

Ralph, F.M., P.J. Neiman, G.N. Kiladis, K. Weickman, and D.W. Reynolds. 2011. A multi-scale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave. *Monthly Weather Review* 139: 1169-1189.

Ralph, F.M. and M.D. Dettinger. 2012. Historical and national perspectives on extreme West Coast precipitation associated with atmospheric rivers during December 2010. *Bulletin of the American Meteorological Society* 93: 783-790.

Ralph, F.M., and other authors. 2013a. The emergence of weather-focused testbeds linking research and forecasting operations. *Bulletin of the American Meteorological Society* 94: 1187-1210.

Ralph, F.M., T. Coleman, P.J. Neiman, R. Zamora, and M.D. Dettinger. 2013b. Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal northern California. *Journal of Hydrometeorology* 14: 443-459.

Reclamation-USACE (Bureau of Reclamation and U.S. Army Corps of Engineers). 2011. *Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information* U.S. Army Corps of Engineers Civil Works Technical Series CWTS-10-02, 160.

Rutz, J.J. and W.J. Steenburgh. 2012. Quantifying the role of atmospheric rivers in the interior western United States. *Atmospheric Science Letters* 13: 257–261.

Rutz, J.J., W.J. Steenburgh, and F.M. Ralph. 2014. Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Monthly Weather Review* 142: 905-921.

Simpson, J.J., M.D. Dettinger, F. Gehrke, T.J. McIntire, and G.L. Hufford. 2004. Hydrologic scales, cloud variability, remote sensing, and models: Implications for forecasting snowmelt and streamflow. *Weather Forecasting* 19: 251-276.

U.S. Bureau of Reclamation (USBR). 2011. *FY 2011 Science and Technology Program*, Research and Development Office, Denver, Colorado. www.usbr.gov/research/docs/S&T_2011_research_abstracts.pdf.

White, A.B., and other authors. 2012. NOAA's rapid response to the Howard A. Hanson Dam flood risk management crisis. *Bulletin of the American Meteorological Society* 93: 189-207.

White, A.B. and coauthors. 2013. A 21st century California observing network for monitoring extreme weather events. *Journal of Atmospheric and Oceanic Technology* 30: 1585-1603.

Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill. 2013. Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Weather Forecasting* 28: 1337-1352.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 33-41, April 2014

WaDE: An Interoperable Data Exchange Network for Sharing Water Planning and Use Data

Sara G. Larsen[1] and Dwane Young[2]

[1]*Western States Water Council, Murray, UT*
[2]*Office of Water, U.S. Environmental Protection Agency, Washington, D.C.*

Abstract: The Water Data Exchange (WaDE) is a project initiated by the member states of the Western States Water Council (WSWC), in cooperation with the Western Governors' Association (WGA), to assist state water agencies when answering local, regional, and national water availability questions. WaDE provides requested information more easily, sustainably, and cost-effectively, by streamlining the publication of water planning, use, and allocation data for access by planners, policy makers, and the public.

This paper presents the background of the WaDE project, how it was envisioned to function, the types of data it will provide, and why access to the information is important for water managers. The goals of WaDE include the establishment of a governance structure, documentation of the current state agency capabilities and methodologies, and the design of a common data format that targets water data products and/or water-quantity information. Many of these foundational products have been developed, such as governance workgroups, databases, web services code, and a prototype mapping application for centralized access. A major milestone, still underway, is the distribution and deployment of the databases and web services code within member states' information technology environments. Lastly, WaDE seeks to encourage the publication of other agency datasets using web services and standardized data formats.

Keywords: *Water use, availability, planning, data exchange*

The Western States Water Council (WSWC) is an organization created in 1965 by state governors consisting of appointees of the governors from the eighteen western states (North Dakota to Texas and westward). Since its inception, the WSWC has striven to accomplish its chartered purposes, which include facilitating effective cooperation among western states on the conservation, development, and management of water resources. A lack of water data was identified as a significant hurdle to states interested in collaborating on regional water issues as early as 2006 in the WGA's "Water Needs and Strategies for a Sustainable Future" publication (WGA 2006, 8):

> There is a need for more and better water information, specifically data on water use, efficiencies, and water availability, to facilitate decision-making. While there exists a substantial amount of data on streamflows, much of which is now available on a real-time basis, there is less data and less reliable information related to water quality and ground water and rural water supplies.

As the idea of sharing and publishing water data gained increasing support, it was adopted as a formal priority by the Governors in the "Next Steps" report, a follow-up publication issued in 2008 (WGA 2008, 3):

> State and federal water resource agencies should work together to provide universal access to the water-related data collected by all state, local, and federal agencies, as well as tools and models that better enable the synthesis, visualization, and evaluation of water-related data, including that to be shared with local governments.

Similarly, Western States Federal Agency Support Team (WestFAST), a collaborative body of twelve federal agencies with water management responsibilities in the west, created to support the

WSWC, adopted the objective above as a work plan item as well (WestFAST 2012).

Coincident with these publications was a national shift in the view of water as an integral component of national security in light of energy-water nexus concerns, food security, prolonged drought, and climate change. In 2011, as part of a study on water and energy nexus impacts related to energy transmission planning, the Department of Energy (DOE) and its suite of National Laboratories, led primarily by Sandia National Laboratory, looked to assess current and future water availability in the west (Tidwell et al. 2014). Specifically, using as much state agency generated data as possible, Sandia's "Energy and Water in the Texas and Western Interconnects" study proposed a methodology for evaluating common and alternative water source and supply types. They proposed to estimate the quantity of these that may be available for future energy production on a broad scale using large watersheds, calculate the associated costs of development, and project the increase in demand for water over a 30 year timescale. The results would be shown as mapped "metrics" that would identify areas where new water sources were sufficient to meet future demand, and also areas where scarcity or shortage might occur. To create the water availability metrics, the Sandia research team assembled disparate water data from the states concerning water supply, legal and institutional water availability, water uses, and projected demand. Gathering the data and aggregating them into a comparable dataset was a difficult task and the study allowed for only one "snap-shot" in time of water availability, but the results were incorporated into the long-range energy transmission models utilized by the Western Electric Coordinating Council and the Electric Reliability Council of Texas as a new constraining variable—a water-energy nexus model parameter that had never been explicitly defined in prior model runs.

Realizing the Sandia study would likely need to be repeated, the WSWC proposed to work with its member states to establish a data exchange framework that could provide the updated information necessary to repeat the study, and thereby support the DOE's water-related national security efforts. The project would also allow the WSWC, WestFAST, and the states to work toward the completion of their stated goal of sharing information with each other and the public. As the Water Data Exchange (WaDE) project got underway, however, it became apparent that the scope of shared data could be expanded to support more than just the water availability figures needed by Sandia. To allow for the publication of the most common state agency datasets, the scope of WaDE was revised to include physical water supply summaries (basin inflows, outflows, natural system uses, etc.), water use summaries by beneficial use category, legal/institutional and regulatory constraints, water allocation information (owners, legal status, beneficial use, priority date, etc.), diversions (locations, volumes or flow rates), consumptive uses, return flows, and any other targeted data that could be made public and also be updated by the state agency on some frequency, as well as accompanying metadata regarding methods used to generate the information.

The DOE and the member states themselves are not the only potential beneficiaries of the WaDE project. Many federal agencies use state agency-supplied data in their day-to-day reports, models and analyses as well.

In a report to congress in 2011, the Federal Interagency Panel on Climate Change and Water Data and Information stated:

> There is a need to modernize hydroclimatic data networks and climate-relevant data collection, data management, mapping, modeling, and information dissemination (FIPCCWDI 2011, *v*).

Their findings identified a wide range of water planning data, such as streamflow and groundwater monitoring networks, reservoir and lake storage, consumptive use, and withdrawal data, as either in need of additional support or inadequate for making long-term decisions about water availability in the U.S., especially with regard to additional stress brought about by a changing climate. The U.S. Geological Survey has also identified these categories of data as an essential part of completing their National Water Census – a program mandated by the Secure Water Act of 2009 – and as a significant data gap (Alley et al. 2013).

WaDE enables the states to support and provide some of the necessary pieces of critical planning such as water withdrawal and use and water allocation information that allow for a more complete national picture of water availability.

The Environmental Protection Agency (EPA) has more recently been reviewing the relationship between water quality and quantity. The WaDE project will make water quantity information more directly available to the EPA and state agencies that are co-regulators of the Clean Water Act, encouraging a tighter integration between what have historically been two very distinct regulatory groups. WaDE will also allow for better decision-making by agencies or groups pursuing an integrated water resource management strategy by facilitating access to published cross-sectoral, water-related data. As an example, a state agency may wish to publish their estimates of physical water supply within a specified basin. This encapsulates the inflows and outflows from the basin, natural system uses, and human withdrawals of water from the reach; however, water supply estimates may not reflect the water that is available for appropriation within that basin. A state agency may wish to also publish what they deem available for appropriation, which would take into account the regulatory, institutional, and legal considerations that are present within the basin. Regulatory considerations include environmental constraints such as minimum instream flow requirements and special management areas. The agency may also wish to elaborate on the different types and relative proportions of different water uses within the basin. These sets of data, which span natural and human uses of water, and include physical, institutional, environmental and legal considerations, will be published and updated via WaDE and will allow integrated water resource management modelers access to the best available information for their modeling efforts.

Finally, one of the primary goals for the WSWC member states and the WGA is to encourage other curators of water data, including the many federal agencies that have water related efforts in the West, to provide easier access. Publication of federal agency data and incorporation of their "dataflows" into a centralized location such as WaDE would facilitate the day-to-day tasks of state and academic researchers and hydrologists. A number of outreach visits were conducted during the initial phase of the WaDE project to encourage federal agencies to begin to share their data using web services and standardized data schemas. A full implementation of the WaDE project will increase the availability of water quantity-related information from state, federal, and other governmental agency partners.

Governance

The Water Information and Data Subcommittee (Subcommittee) was formed under the direction of the Water Resources Committee of the WSWC. The Subcommittee is comprised of representatives from the states and federal agencies. The Water Resources Committee approved a proposal sponsored by the Subcommittee to begin building the framework that would eventually become the WaDE project. They also agreed to create four workgroups under the direction of the Subcommittee. These four workgroups continue to lay the groundwork for the development of the data exchange and function as its primary governance bodies:

1. State Capabilities Assessment Workgroup: Evaluates the current capabilities of the western states with regard to water allocation, supply and demand data, as well as their current methods of publishing data and their respective IT environments.
2. Methods Workgroup: Documents existing methods and science for estimating targeted water planning data, such as water availability and consumptive use and related definitions.
3. Data Exchange Template (Schema Development) Workgroup: Identifies and defines the data elements necessary for exchanging targeted water data. Using the data elements as a guide, the group refines the data exchange schema (a standard format proposed for the data using eXtensible Markup Language (XML)) that reflects the relationships of the data.
4. Data Exchange Methodology Workgroup: Reviews the existing field of data exchange technologies, evaluates existing state, federal, and academic data exchange collaborations, and makes recommendations for technological approaches.

The activities of the four workgroups and the coordination and reporting for the WaDE project in general are coordinated by the WSWC.

Outreach, Participation, and Data Schema Review

Site visits to 15 of the 18 member western states were conducted to explain the WaDE project to state agency staff, garner support, and to define and refine the data schema originally developed by the Data Exchange Template Workgroup. Several federal agencies, including the Natural Resource Conservation Service, the Bureau of Reclamation, and the U.S. Geological Survey, were also visited to discuss the adoption of a common format for publishing data controlled by their respective offices, which would greatly improve state agency access and facilitate their water planning processes. The site visits resulted in broad support of the project and several adjustments to the proposed data schema, such that it would provide a better "fit" for more state agency data. These included semantic changes to accommodate what the states defined as "available water," as well as determining a hierarchy among data elements or relationships utilized by the states within the databases that house their information. Some information that had not been deemed relevant was re-introduced into the schema, while some data elements originally thought to be important were removed.

Categories of Data

There are two categories of data targeted for publication by the WaDE project. Both require a different solution for the implementation in the exchange. Phase 1 of the WaDE project targets the first category of data, termed "derived" or "value added" data. These can be described as data that are not direct measurements, but rather reflect interpretations, evaluations, models, or decisions based on other datasets. Examples include water availability summaries or metrics (e.g., an evaluation of the actual or relative volume of water that may be available for a given timeframe within a watershed or other delineation), water use summaries (including a breakdown by beneficial use category or sector), water appropriations (including water rights/permit owners, legal status, priority dates, volumes or flow rates for a given timeframe), regulatory information, and general water planning data. "Derived" data products are usually generated from other datasets, such as a streamgage time series, reservoir storage stage, or meteorological data, to arrive at a conclusion. An important piece of information that must be captured for "derived" data is the methodology used by the agency to arrive at their final calculation so that others can understand the context of that estimate. WaDE workgroup members determined that this category of data would benefit the states more directly and immediately, and gave it priority over Phase 2.

Phase 2 of the WaDE project involves the incorporation of a second category of data, termed "measured" data, i.e. a dataset containing measurements of some parameter taken over a period of time. Although some measurements may still be derived from other measured values, they can be quantified as a specific measurement at a specific time, which can be evaluated along with other measurements over that same time period. Examples of data that fit within this category include streamgage data, groundwater level, snow depth, reservoir elevation, and precipitation data. Recommendations from WaDE workgroup members concerning "measured" data are based on recent work conducted by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUASHI). CUASHI has established a framework for hydrologic measurement data called Water Mark-up Language, widely known as WaterML, to transfer hydrologic measurement and sensor data using a common format (Open Geospatial Consortium 2007). Recognizing that much of the state and federal data that would be shared within the WaDE framework would be of this category, workgroup members recommended that the WSWC's state and federal partners be encouraged to adopt the WaterML 2.0 schema – the most recent Open Geospatial Consortium approved version – in preparation for Phase 2.

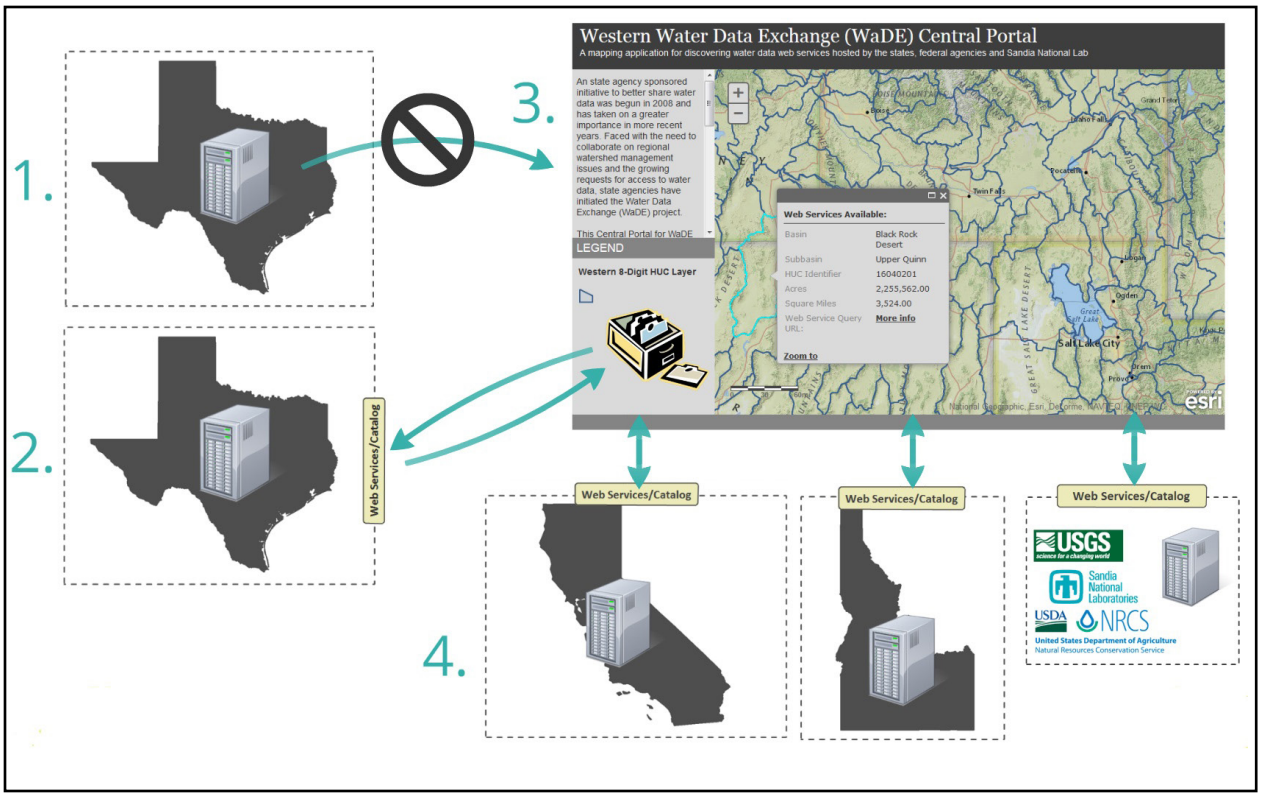


Figure 1. Conceptual Framework of the Water Data Exchange (WaDE).

System Design

WaDE employs an innovative, distributed database framework, wherein partners control and maintain their datasets locally (ensuring that published data are the best available), while making them discoverable via a centralized web mapping application using web service requests. When a client requests a set of data, they are transferred using platform-independent XML, which can be directly incorporated into models and modeling software. It provides a state-to-state, state-to-fed, fed-to-state data exchange that is entirely open and accessible to the public. The design of the system is such that data flows in either an automated, computer-to-computer fashion or as requested. Data owners or partners control what data are shared and oversee quality control of published estimates. Participants benefit by being able to access other agency data, while having their own published in a common format via web service using a centralized data portal, which facilitates data discovery.

Figure 1 is a conceptual diagram of the WaDE system architecture. Partners that supply data to the WaDE interface will include state and federal partners, as well as organizations that house significant datasets dealing with water planning or management. The data exchange design has some key components:

1. Each state operates a "node" on the exchange network infrastructure that is based on their in-house databases. Databases are *not* transferred away from any state agency; instead, nodes respond in the same manner when queried with a web browser address of the same format. This arrangement allows the WaDE retrieval system to query all relevant nodes at once without having to build a custom interface for each. Nodes also manage security and access to the data. Node databases and software need not be identical as long as the responses are similar.
2. Each state maintains both a core set of defined web services as well as a "catalog" of the data housed within the node. The use of a catalog allows other partners to be able to discover data without having to search through entire datasets. Once a

user has narrowed in on the data that they want via the catalog, it can be used as a gateway to retrieve what is available on a particular node.

3. The WaDE Central Portal with a corresponding centralized catalog has the ability to consume the summary information available in partner catalogs, display that information on a searchable map interface, compile a user's request for specific data, request the data from the respective nodes, and return a report or dataset to the user. The portal is a key piece in demonstrating the value of the data flow. The central catalog would allow the portal to perform quickly, for ease-of-use by the client.
4. As more partners deploy the WaDE database and enable their web services, the value of the information shared and the ability to perform a more regional analysis also grows. As Phase 2 begins, federal partners also begin to share their datasets using web services that can be accessed from the WaDE Central Portal.

Based on feedback gathered during outreach visits and reviews within the workgroups, the WSWC has developed a preliminary draft schema and defined services that their state partners will implement as they plug into the WaDE framework (WaDE schema version 0.2). As the components are deployed by each partner agency, suggested changes to the schema will be documented and evaluated by the workgroups for incorporation into the next official schema version.

Types of Services

After a careful evaluation of many options and approaches for sharing data, WSWC and its workgroups made the recommendation to use a combination of Representational State Transfer (REST) and Simple Object Access Protocol (SOAP) web services for the exchange of information between partners (WSWC 2012). The majority of the web services will be shared using REST, with some SOAP services as needed to gather information about participating nodes and to retrieve information about data available at each node. Both the SOAP and the REST services offered by WaDE are modeled after and adhere to the specifications for services used by the Environmental Protection Agency's (EPA) National Environmental Information Exchange Network (NEIEN) program (NEIEN 2010, 2012).

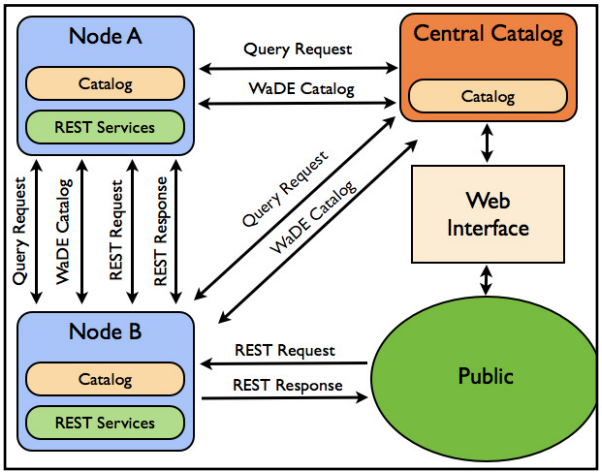


Figure 2. WaDE Web Service Types between Nodes.

Figure 2 provides examples of transactions between nodes, the public, and the central catalog that would require either REST or SOAP.

Publishing and Discovery via the Central Portal

Easy access and discovery of water-related datasets is of paramount importance. A major step of the WaDE project was to build a prototype web-mapping application to access the results from the Sandia study and other sample data gathered from state agencies. The prototype used REST-based URL requests to query databases residing at an emulated node. The queries were returned to the user by super-imposing web browser stylesheets over the returned raw XML data for human readability. This Central Portal demonstration was created to show how the different components that comprise the WaDE system function together to provide the user with an easy-to-navigate and responsive dashboard-like interface.

Figure 3 is a screenshot of the prototype application, showing some of the Sandia results and the sample state-hosted data side-by-side. The WSWC anticipates continued refinement and customization of the interface as more and more states are brought into the data exchange.

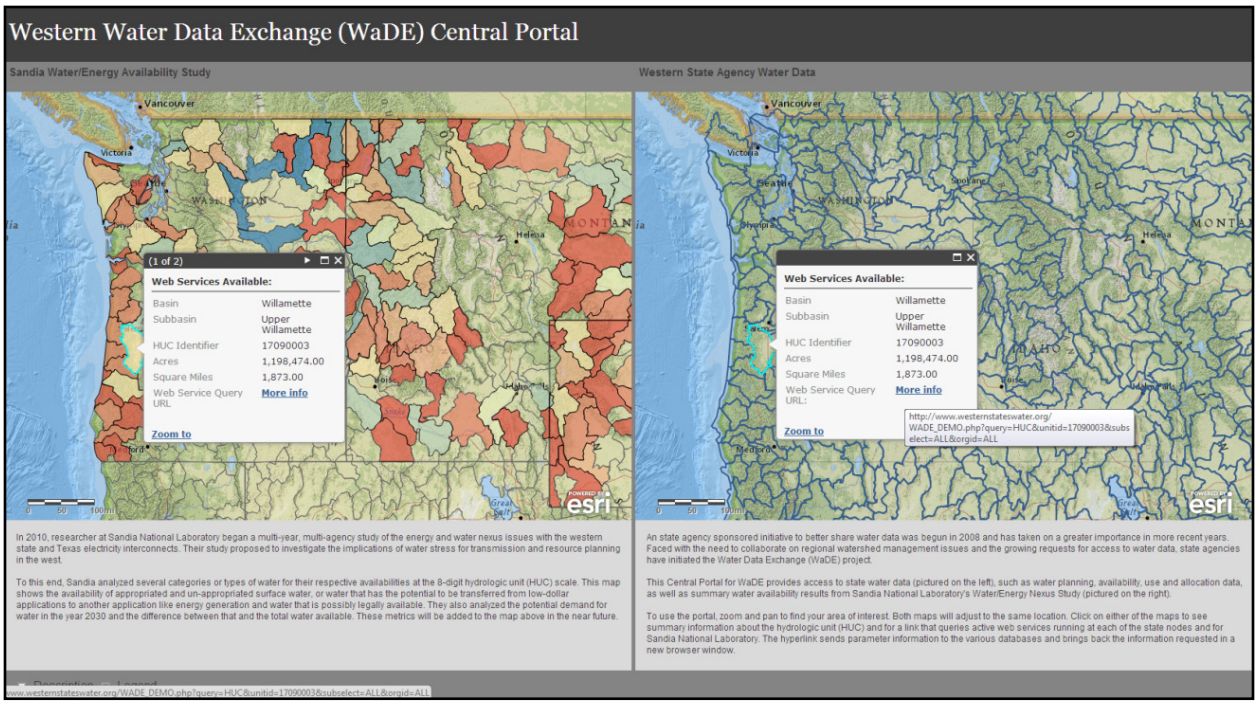


Figure 3. Prototype WaDE Central Portal Application.

Potential Data Challenges

One of the greatest challenges to a full implementation of WaDE was identified during both the outreach visits and the work conducted by the State Capabilities Assessment Workgroup. The primary hurdle for WaDE is the lack of consistent sets of summary-level water planning data targeted by the schema that are generated on a complete spatial (statewide) and temporal (seasonal/annual) scale and interval. A goal of the Sandia study was to generate a Westwide snapshot of water availability based on a uniform hydrologic basin scale and the best available state data. When the Sandia team began to contact the state water agencies for the necessary information,they found a wide variety of outputs and methods, most of which only covered certain portions of the state or that were generated for different timeframes. This led to the use of water "metrics" that utilize state-generated data when available, but defaulted to a streamgage/streamflow analysis of water availability when it was not. However, physical presence of water flowing in a stream in the watershed is not necessarily an indicator of water availability. There are many other considerations for permitting, including the institutional and legal limitations, the public interest, and environmental considerations such as instream flow requirements and endangered species habitat.

Another limitation is simply that some states define the term "water availability" differently. Most of the states use the term water availability when referring to a series of tasks performed during the permitting process, which is usually ad hoc and site-specific.

There are also spatial and temporal differences between state water planning programs. Most of the states that summarize their water supply, availability, or water use data optimize the process by using their own planning program delineations that have been used by the agency since their early basin analyses. The state may use hydrologic unit codes (HUCs), counties, regional planning areas, or some combination of these for summarizing information depending on how the planning program has evolved over the years. Most of the states use a variation of a hydrologic basin with an additional customization of administrative or jurisdictional boundaries. The states that use more refined watershed delineations have the ability to aggregate their data to a larger scale, but the reverse is not always the case. The states also use

differing timeframes for summarizing their data – some on a monthly basis, some use a calendar year, and others use the traditional "water year."

Each state has a specific methodology for estimating their important figures such as physical supply, legal availability, and water use data. They also have their own models for capturing water permitting/rights data. Some states use the drought of record to decide whether water can be appropriated, others use statistical analyses. Some use sophisticated decision support tools to support their appropriations while others generate hydrologic models to review applications on a case-by-case basis. This is one of the reasons why the WaDE portal, at the current time, allows for data discovery using custom delineations used by the states, but does not apply any internal shading or coloring. It is also one of the reasons why each estimate is closely accompanied by metadata that describe the method from which the value was derived. Given these differences in approach, a primary concern for the development of the WaDE portal is to impose a strong end-use agreement or disclaimer that informs incoming clients that different states (or potentially even regions within a state) are using different methods to create estimated values. It is the intention of the WaDE program to portray the data and methods that the states currently have, while also pointing the state agencies in a direction that will help to create a more uniform and spatially complete picture of water availability and use in the west in the future. Discussions among the various workgroups and amongst WSWC members regarding the adoption of a common Westwide water availability metric and methodology are ongoing. Until that time, WaDE will serve as a template for state agencies when they are evaluating their programs or considering new data products.

Conclusion

Whether addressing population growth, national security, drought, climate change, or meeting our growing energy needs, questions surrounding water availability in the west will increase and become more important in the coming years. WaDE allows its partners to share and publish important water planning and use data and methods to their customers easily, and in a common, defined format that minimizes the difficulties and costs of data collection. WaDE will also dovetail with other ongoing national water efforts, such as the U.S. Geological Survey's National Water Census, positioning the states to proactively provide water use estimates and other necessary data. Other potential customers of the data exchange range from large organizations such as the Government Accountability Office, with their recent water-energy nexus work, and the Department of Energy, to research institutions, non-governmental organizations, the EPA, water district managers, and even farmers, journalists, and politicians concerned about ongoing drought. The accomplishment of Phase 1 of the WaDE project will be a major step toward improved access to "derived" data products like water availability and use summaries, while Phase 2 will provide greater access and discoverability to "measured" hydrologic measurement data. Finally, the tangible step of sharing water data and methodologies between state agencies signals a paradigm shift toward more cooperative and collaborative regional watershed and water resource management.

Acknowledgements

The authors wish to express their thanks to the members of the Western States Water Council and the Western Federal Agency Support Team, as well as our WaDE workgroups for their continued support. We would also like to thank Vince Tidwell and his team at Sandia National Laboratory for their collaboration on this project.

Author Bio and Contact Information

Sara G. Larsen is the Water Data Exchange (WaDE) Program Manager for the Western States Water Council (WSWC). Prior to WSWC, Sara developed hydraulic/hydrologic models and GIS analyses at Los Alamos National Laboratory for the Energy and Infrastructure Analysis Group. She has also assisted with project plans and land-use mapping applications within Utah's Division of Water Resources. Her research interests lie at the intersection of water and energy, urban water systems, hydroinformatics, data sharing, mapping applications and Western water. She has a degree in geography and GIS, and a MS in water resources civil engineering from the University of Utah. She can be contacted at Western States Water Council, 5296 South Commerce Drive, Suite 202, Murray, Utah 84107; phone: 801-685-2555; e-mail: saralarsen@wswc.utah.gov.

Dwane Young is the senior data advisor in the Assessment and Watershed Protection Division in EPA's Office of Wetlands, Oceans, and Watersheds in the Office of Water. He recently served as the WestFAST Federal Liaison Officer to the Western States Water Council. Dwayne also led the initial development of the Water Quality Exchange (WQX) for the EPA, and has extensive experience with assisting partners in sharing water quality data. Dwane has a degree in Fisheries and Wildlife Management from Utah State University. He has spent the last thirteen years working on environmental data management systems. He can be contacted at U.S. EPA Office of Water, Assessment Watershed Protection Division, U.S. EPA (4503F), Ariel Rios Building, 1200 Pennsylvania Ave NW, Washington, DC 20460; phone: 202-566-1214; e-mail: young.dwane@epa.gov.

References

Alley, W.M., E.J. Evenson et al. 2013. *Progress Toward Establishing a National Assessment of Water* Availability and Use: U.S. Geological Survey Circular 1384, 34.

Federal Interagency Panel on Climate Change and Water Data and Information. 2011. *Report to Congress – Strengthening the Scientific Understanding of Climate Change Impacts on Freshwater Resources of the United States*, 49.

National Environmental Information Exchange Network (NEIEN). 2010. *Data Exchange Design Rules and Conventions (EDRC) for the Exchange Network*. Available at http://www.exchangenetwork.net/exchange-design-rules-and-conventions-edrcs/.

National Environmental Information Exchange Network (NEIEN). 2012. *Exchange Network REST Guidance: Optimize Your REST Services and Simplify Their Usability*. Available at http://www.exchangenetwork.net/news/en-governance-releases-rest-guidance/.

Open Geospatial Consortium (OGC). 2007. *CUAHSI WaterML*. Available at http://portal.opengeospatial.org/files/?artifact_id=21743.

Tidwell, V., et al. 2014. *Mapping Water Availability and Cost in the Western United States*. Available at http://energy.sandia.gov/?page_id=1741.

Western States Water Council (WSWC). 2012. *WaDE Flow Configuration Document*. Available at http://www.westernstateswater.org/wp-content/uploads/2012/11/WADE_FCD_v02.pdf.

Western Governors' Association (WGA). 2006. *Water Needs and Strategies for a Sustainable Future*. Available at http://www.westgov.org/reports/doc_download/83-water-needs-and-strategies-for-a-sustainable-future.

Western Governors' Association (WGA). 2008. *Water Needs and Strategies for a Sustainable Future: Next Steps*. Available at http://www.westgov.org/wswc/water%20needs%20&%20strategies-6%2708%20final.pdf.

Western States Federal Agency Support Team (WestFAST). 2012. *WestFAST Agencies: 2012 Work Plan*. Available at http://www.westgov.org/wswc/westfast/workplan/westfast_2012_workplan.pdf.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 42-48, April 2014

Landsat Thermal Infrared Imagery and Western Water Management

Anthony G. Willardson

Western States Water Council

Abstract: The Western States Water Council strongly supported the use of thermal infrared sensor (TIRS) data from Landsat 8 (Western States Water Council 2010). TIRS is increasingly important in monitoring consumptive water uses, particularly agricultural uses. Landsat is the only operational satellite system with a spatial resolution (30m) fine enough to map water use field-by-field. TIRS data applications include:

- Administering state water rights
- Planning for present and future water needs
- Implementing interstate compacts, court decrees, and negotiated tribal settlements
- Mapping evapotranspiration and consumptive surface and groundwater use
- Protecting endangered species and estimating water use by invasive species
- Monitoring food supply security
- Forecasting commodity market fluctuations

TIRS is essential to quantify beneficial consumptive use, evaluate water rights transfer requests, monitor interstate water compacts, negotiate tribal water right settlements and interstate agreements, and review water right "calls." The Landsat data archive tracks temporal changes in water uses over decades. A permanent operational land observation program with TIRS is essential.

Keywords: *Remote sensing, thermal imaging, water law and conservation*

Since 2005, the Western State Water Council (WSWC) has provided longstanding bipartisan support for maintaining data continuity and integrity with Landsat thermal-infrared (TIR) and reflected-light imagery (see www.idwr.idaho.gov/GeographicInfo/Landsat/WSN.htm). WSWC has been an active advocate for TIR imaging as an increasingly essential tool for water resource monitoring, planning, and management applications in the western United States. Landsat is the only operational satellite system providing thermal data at a spatial resolution (30m) fine enough to map consumptive water-resources use at the level of agricultural fields. Landsat 8's multispectral measurements – both thermal and reflective – provide the accuracy and quality consistent with previous Landsat missions that are important to western water managers and administrators. The availability of archived data over decades is also critical for water management and administration of western water law.

Western Water Law

Western water law is designed to provide certainty with respect to water use priorities in an arid region with an uncertain climate where the water supply depends on precipitation that varies greatly both temporally and spatially. The recent droughts across much of the West and Midwest are evidence of this uncertainty. Water rights are property rights, the use of which are primarily regulated and administered by western States under principles consistent with the legal Doctrine of Prior Appropriation – water is a public resource allocated or appropriated by the State for private use. With few exceptions, the Prior Appropriation Doctrine governs surface water use, while rights to the use of groundwater are more diverse.

Two of the best known tenants of Prior Appropriation are the "first in time, first in right" and "use it or lose it" principles. The first

use of water for a beneficial purpose is granted priority, and any unused water returns to the public domain. It is also important, however, to recognize principles that require "reasonable beneficial use" and "prohibit waste." The Prior Appropriation Doctrine generally requires that water be diverted or withdrawn from a public water body (river, stream, lake, or groundwater aquifer) and put to a use that, by custom, statute, and sometimes constitutional definition, is considered reasonable and beneficial, both with respect to the quantity of water used and the use to which the water is put. Water rights define domestic, municipal and industrial, agricultural, stock water, mining, and other off-stream consumptive water uses. In many cases they also recognized instream non-consumptive uses for recreation, fish and wildlife, hydropower, and other purposes.

Water rights are ordered and administered by priority date, or the date on which the use was first recognized. Uses with a senior priority date are allowed to exercise their right to the use of water first, before any junior or subsequent use or user. All uses are limited, however, to a decreed or customary amount considered reasonable and beneficial; any more is considered waste. If any portion of a senior user's water right is not put to beneficial use in a timely manner, that unused portion is available for use by other more junior users. The intent is to maximize beneficial use and discourage idle speculation. Therefore, any water returning to a waterbody, through surface runoff or deep percolation to an aquifer from an irrigated field, or discharged from a municipal wastewater treatment plant or other source, may be reused by junior users or becomes waters of the State subject to subsequent allocation and reuse. The measure and limit of a water right is the amount consumptively used beneficially.

Roughly 80 percent of the water diverted or withdrawn from western waterbodies is put to agricultural use, primarily irrigation of fields and pastures (Hutson et al. 2005). Much of that water eventually returns to the hydrologic cycle. Only those amounts lost through plant evapotranspiration, stockwatering, or otherwise actually consumed are exclusively used and unavailable for further appropriation.

Measuring and monitoring consumptive water use can be a daunting task limited by available data and information, assumptions, and the accuracy of engineering calculations. Agricultural withdrawals and consumptive uses may or may not be carefully regulated, depending on the demand. Often, agricultural water rights are calculated based on a "water duty," specified in acre-feet per acre, an amount of water that is generally considered adequate to irrigate a particular crop over a season, that may be diverted. For example, a water duty of three acre-feet would be the amount of water diverted over an irrigation season sufficient to cover one acre of land three feet deep. In the past, water duties have been determined largely by custom, but increasingly better information is available on diverse cropping needs, agricultural yield statistics, and irrigation best management practices.

Compared to agricultural water use, measuring municipal and industrial water use can be relatively straight-forward because the amount of water delivered to a home or factory is often metered and, after use, largely discharged as wastewater (treated or untreated) at the other end of a pipe.

Thermal Infrared Imagery and Water Management Applications

The availability of Landsat's thermal infrared satellite imagery has led to the development of various techniques that can accurately measure the energy exchanged through the evapotranspiration (ET) process to calculate consumptive crop water use (adjusting for background ET, temperature, precipitation, wind, and other variables). Such remote sensing measurements have been compared favorably with lysimeter measurements (Allen et al. 2005). Typical applications include: (1) mapping irrigated lands as well as crop type; (2) measuring and monitoring consumptive irrigation uses; (3) mapping and determining the extent of surface and groundwater use; (4) allocating and administering rights to the use of water; (5) approving water rights transfers; and (6) consideration of water right "calls," where senior users request junior uses be curtailed to ensure they have sufficient water to exercise their prior rights.

Western water managers and water right administrators are also increasingly using various Landsat-data-driven mapping tools to monitor and manage water rights, both spatially and temporally (seasonal and inter-annual). This allows state and federal agencies to track beneficial consumptive use, administer negotiated tribal agreements and monitor interstate compacts, determine use for agriculture and urban needs, estimate water-use by invasive species, monitor food supply sustainability and security, and provide information to help forecast and moderate commodity market fluctuations. These uses and other applications are expanding (see Table 1; Kustas and Anderson 2012).

None of these applications would be possible without Landsat 7 and 8 as they are presently configured with TIRS. Using different platforms on separate satellites to record multispectral and thermal imagery would degrade the quality of ET calculations when wetting events occur, during periods of rapid vegetation growth, senescence and stress onset, and when crops are harvested or killed by frost, disease, or pests. These situations are all precisely the types of localized conditions that Landsat is uniquely well-suited to monitor.

Some of the state agencies using Landsat data as an element of their water monitoring, planning, and management programs and water rights administration processes include the California Department of Water Resources, Idaho Department of Water Resources, Nevada Department of Water Resources, Colorado Division of Water Resources, New Mexico Office of the State Engineer, Wyoming Office of the State Engineer, Montana Department of Natural Resources and Conservation, and Nebraska Department of Natural Resources, as well as the North Platte Decree Committee and a growing number of other water conservation and irrigation districts (Allen et al. n.d.). There are data also used extensively by federal agencies, including USDA's Agricultural Research Service and Natural Resources Conservation Service, the Bureau of Reclamation, and the U.S. Department of Justice (Miller et al. 2011).

The WSWC strongly supports the establishment of an operational land observation program that maintains the current spatial resolution (30m) essential for land and water management on scales used to build the 40-year global archive of Landsat data. Image procurement every eight days provided by two satellites is critical, and four satellites, one passing every four days would be ideal. This means that multiple future Landsat missions need to be considered, planned, and built simultaneously, and launched expeditiously. There is a need to accelerate policy and funding decisions in order to ensure there are no future data gaps. Landsat 8 has a five-year design life, but its TIRS instrument only has a three-year design life. Any delay while evaluating new technological option puts TIRS data continuity at risk (Environment News Service 2013).

The WSWC worked hard over several years to secure a place for the TIR sensor onto the Landsat Data Continuity Mission (LDCM), which was successfully launched on February 11, 2013. LDCM operational responsibility has been transferred from NASA to the U.S. Geological Survey (USGS), and the satellite is now known as Landsat 8.

The U.S. Department of Interior and NASA partnership that led to the success of LDCM is expected to continue. The President's FY2014 budget request includes USGS funding for Landsat 8 operations as well as NASA funding to explore appropriate next steps forward with future satellites that will provide a permanent operational federal land imaging program. Any uncertainty regarding future funding and Landsat TIR data availability will be an obstacle to building and expanding operational water resources planning, monitoring, and management programs that have begun to flourish with the use of TIR imagery, which is available online free. Further innovations in the use of TIRS data are also expected.

In December 2012, the WSWC and Western Governors' Association completed a report on the use of water rights transfers to meet present and future water supply needs (Iseman et al. 2012). In particular, it addressed transfers from agriculture to other uses, while at the same time highlighting mechanisms available to minimize the impact on small, rural agricultural communities and economies, as well as the environment and ecological systems dependent on current patterns of use. The use of TIRS data to accurately measure consumptive use and evaluate the impacts of specific transfer proposals provides a sound scientific basis for related water management decisions. The USGS archive of Landsat and TIRS data provides an invaluable means to identify

historical consumptive water use patterns, determine how much water diverted under existing rights has actually been used, and quantify the amount available for transfer. Market forces are driving the value of water upwards and also provide a strong incentive for conservation and more efficient use of limited western water supplies.

Ensuring that quality TIRS data remains available as part of future Landsat missions will further facilitate innovative water resources monitoring, planning, and management.

The Economic Value of Landsat Data

Landsat imagery in general and TIRS data in particular provide the nation and the world with continuous, consistent monitoring of critically important natural resources and water use information. There are thousands of users and hundreds of applications of Landsat data in the United States, with strong use internationally as well. An unprecedented archive of four decades of Landsat data provides a record of changes in land cover and water uses over time. Landsat has made and continues to make critical "contributions to U.S. economic, environmental, and national security interests" (Marburger 2005). The dollar value of Landsat imagery can be difficult to estimate as it is primarily used by academic and non-commercial entities and government agencies. The Department of Interior recently requested that the Landsat Advisory Group of the National Geospatial Advisory Committee provide advice to the Department "concerning the economic benefits of Landsat data." A white paper prepared by the Advisory Group provided estimates of the economic value of ten uses of Landsat data. It also summarized recent estimates of the economic value of Landsat data from two large-scale surveys, which showed the annual economic value of Landsat data exceeds the cost of building, launching, and managing Landsat satellites and sensors (NGAC 2012a,b).

The use of Landsat data is growing given the opportunities for cost savings and innovative ways of providing decision support. The Landsat Advisory Group looked at several proven uses of Landsat technology and compared them to the costs of using other alternative technologies, methods, and data. It found these alternatives to be significantly more expensive than funding an operational Landsat program. Many Landsat data applications are associated with the U.S. government and save significant amounts of federal money compared to other methods of accomplishing the same objective. Productivity savings also benefit non-governmental science applications where scarce academic research dollars cannot be wasted on inefficient measurement technologies. The estimated annual Landsat data efficiency savings are conservative and substantial. Ten Landsat applications, highlighted in Table 1, produce estimated savings of $180 million to over $266 million per year for federal and state government agencies.

Notably, the WSWC estimated savings from the use of Landsat TIRS data to measure consumptive agricultural groundwater use from wells. Center-pivot irrigated fields are easily identified as crop circles (Figure 1), and proved to be a relatively easily quantifiable application. A more comprehensive estimate of the value of Landsat TIRS data, however, would require monitoring other agricultural and outdoor water uses, such as furrow irrigated fields, golf courses, public parks, and other areas supplied with surface and ground water.

The WSWC and Idaho Department of Water Resources (IDWR) collaborated in estimating only the value of using Landsat's thermal infrared imagery to measure and monitor consumptive water use by agricultural irrigation wells. However, TIRS data is also used by the State of Idaho in hydrologic modeling, water planning, water use comparisons when cropland is converted to urban uses, monitoring aquifer depletion, administering water rights (legal findings of fact, ensuring compliance with administrative orders, court decrees, and interstate compacts, as well as water right buy-back programs), endangered species protection, invasive species monitoring, and Indian water rights settlements (see www.idwr.idaho.gov/GeographicInfo/METRIC/et.htm).

IDWR and the University of Idaho have partnered to pioneer TIRS data uses, and have been recognized with an award from the Harvard Kennedy School of Government. The award recognized IDWR's use of TIRS data

Table 1. Estimated productivity from ten uses of Landsat imagery.

Landsat Application	Estimated Annual Efficiency Savings
Monitoring consumptive outdoor water usage	$20-73 million
U.S. government mapping	over $100 million
Forest health monitoring	$12 million
National agricultural commodities mapping	over $4 million
Flood mitigation mapping	over $4.5 million
Forest fragmentation detection	over $5 million
Forest change detection	over $5 million
World agricultural supply and demand estimates	over $3-5 million
Support for fire management	$28-30 million
Coastal change analysis program	$1.5 million

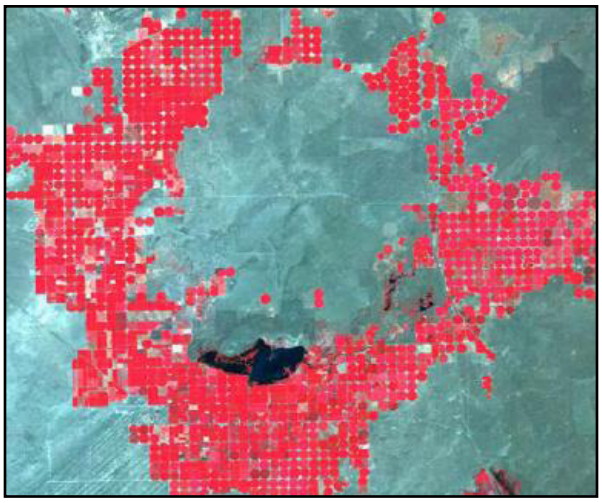


Figure 1. Landsat TIRS imagery showing easily identifiable crop circles from center-pivot irrigated fields.

in adjudicating, measuring, and monitoring consumptive irrigation use by wells on the Snake River Plain Aquifer (see www.ash.harvard.edu/Home/News-Events/Press-Releases/Mapping-Evapotranspiration-Wins-Innovations-Award).

IDWR previously used a power consumption coefficient measurement method to estimate groundwater extraction and use at an annual cost of about $500,000 for some 5,000 Snake Plain wells or about $100 per well. IDWR began using Landsat TIRS data through a process called METRIC (Mapping EvapoTranspiration with high Resolution and Internalized Calibration) to measure actual crop evapotranspiration on a field-by-field base. IDWR's annual costs dropped to approximately $53,500 per year for the same 5,000 wells or less than $11 per well. These two measurement options were also compared with requiring installation of flow meters on every well at an estimated capital cost of several hundred to thousands of dollars per well.

Given IDWR's cost experience and extrapolating the use of the power consumption coefficient method (or installing flow meters) on unmetered irrigation wells in the 17 western waters states, the potential annual cost savings were estimated to range from nearly $20 million to over $73 million annually (again for measuring agricultural groundwater well extraction alone). These figures represent a conservative estimate using unpublished IDWR cost figures (Morse 2012) and west-wide unmetered irrigation well numbers from USDA's 2002 Census of Agriculture (USDA 2002).

Conclusion

The water resources of the United States are a $200 billion per year economic engine that supports hundreds of thousands of jobs. In the West, water is in short supply, often requiring reductions in consumptive uses. Water and water rights are increasingly valuable commodities being bought and sold. Remotely sensed TIRS imagery collected by Landsat satellites is essential for determining past and present water use and evapotranspiration at scales (30m) that reveal patterns of land use and water consumption to inform future decision-making. Evapotranspiration maps derived from Landsat TIRS imagery are used operationally by water managers to monitor and manage myriad water uses. Landsat is the only operational satellite system that combines thermal data with multispectral data at the spatial resolution (30m) needed to administer water use and water rights at the level of the individual agricultural fields.

As water becomes an increasingly valuable commodity, the use of which will be subject to greater public scrutiny, the innovative use of Landsat TIRS data to measure and monitor consumptive water use will help further revolutionize water management and state water rights administration, leading to greater efficiency and better planning and decision-making. It is therefore essential that the nation maintain this capability and expeditiously move to establish a permanent operational land observation program, including the accelerated development and launch of a Landsat 9 satellite with TIRS capabilities.

Acknowledgements

The help of Anthony (Tony) Morse, retired, formerly with the Idaho Department of Water Resources, is gratefully acknowledged in preparing the cost estimates and comparisons for monitoring groundwater wells in the Snake Plain Aquifer and identifying other IDWR uses. He can be reached at tmorsell@yahoo.com.

Biographical Information

Anthony G. Willardson was named Executive Director of the Western States Water Council (WSWC) in July 2009. Formerly the Deputy Director, he has been with the Council since 1979. The Council is affiliated with the Western Governors' Association (WGA). Its members are appointed by the governors of eighteen states. He holds a BA in political science from Brigham Young University, and a MS in public administration from the University of Utah and is a member of the National Honor Society for Public Affairs and Administration (Pi Alpha Alpha). He oversees publication of a weekly newsletter, Western States Water, which he edited for many years. He is the author of numerous articles and reports covering a wide range of water resource issues, including water project financing and cost sharing, groundwater management and recharge, water conservation, drought, and interregional water transfers. He is also one of the principal authors of the WGA's 2006 Report, *Water Needs and Strategies for a Sustainable Future* and 2008 *Next Steps Report*, as well as a 2010 *Progress Report*. He actively contributed to the WGA/WSWC's December 2012 *Water Transfers in the West* report. He can be reached at Western States Water Council, 5296 S. Commerce Drive, Suite 202, Murray, Utah 84123, phone: (801) 685-2555, e-mail: twillardson@wswc.utah.gov. For additional information see: http://www.westernstatewater.org.

References

Allen, R.G., M. Tasumi, and A. Morse. 2005. *Satellite-Based Evapotranspiration by METRIC and Landsat for Western States Water Management*. U.S. Bureau of Reclamation Evapotranspiration Workshop, February 8-10, 2005, Ft. Collins, Colorado.

Allen, R., R. Trezza, B. Kramber, T. Morse, J. Hendrickx, A. Irmak, J. Huntington, C. Robison, C. Kelly, J Kjaersgaard, J. Greth, M. Tasumi, and T. Martin. n.d. *ET Investigations Involving METRIC/Landsat Applications for Water Management*. Available at: http://www.idwr.idaho.gov/GeographicInfo/METRIC/pdfs/MetricOtherStates.pdf.

Environment News Service. 2013. *Uncertain Funding Jeopardizes U.S. Land Imaging Satellites*. posted August 8, 2013, 12:24 pm.

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin. 2004. *Estimated Use of Water in the United States in 2000*. U.S. Geological Survey Circular 1268, Reston, Virginia. Revised February 2005.

Iseman, T., C. Brown, N. Bracken, and T. Willardson. 2012. *Water Transfers in the West: Projects, Trends, and Leading Practices in Voluntary Water Trading.* A report from the Western Governors' Association and the Western States Water Council, December.

Kustas, B. and M. Anderson. 2012. A new way to map drought and water use worldwide, *Agricultural Research Magazine*, 60(2): 4-7.

Marburger III, J. 2005. *Landsat Data Continuity Strategy Adjustment*. Executive Office of the President, Office of Science and Technology Policy, December 23, 2005.

Miller, H.M., N.R. Sexton, L. Koontz, J. Loomis, S.R. Koontz, and C. Hermans. 2011. *The Users, Uses, and Value of Landsat and Other Moderate-Resolution Satellite Imagery in the United States*. Executive report: U.S. Geological Survey Open-File Report 2011-1031, 43.

Morse, A. 2012. *Comparison of Ground Water Monitoring Costs as a Reason to Maintain the Thermal Band on the Landsat Data Continuity Mission: A Quick Look*. Internal report to the Idaho Department of Water Resources, Boise, Idaho. Updated May 25, 2012.

National Geospatial Advisory Committee (NGAC). 2012. *Statement on Landsat Data Use and Charges*. NGAC Landsat Advisory Group. Adopted September 18, 2012. Available at: http://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-cost-recovery-paper-FINAL.pdf.

National Geospatial Advisory Committee (NGAC). 2012. *The Value Proposition for Ten Landsat Applications*. NGAC Landsat Advisory Group. Adopted September 18, 2012. Available at: http://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-economic-value-paper-FINAL.pdf.

U.S. Department of Agriculture (USDA). 2002. *Census of Agriculture*. National Agricultural Statistics Service. Available at: http://www.agcensus.usda.gov/Publications/2002/FRIS/tables/fris03_14.pdf.

Western States Water Council (WSWC). 2010. *Position of the Western States Water Council regarding NASA's Applied Science Research Program*. Position #356. Revised and readopted on October 3, 2013.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 49-58, April 2014

A Social-Ecological Framework to Integrate Multiple Objectives for Environmental Flows Management

David M. Martin, Dylan Harrison-Atlas , Nicholas A. Sutfin, and N. LeRoy Poff

Colorado State University, Fort Collins, CO

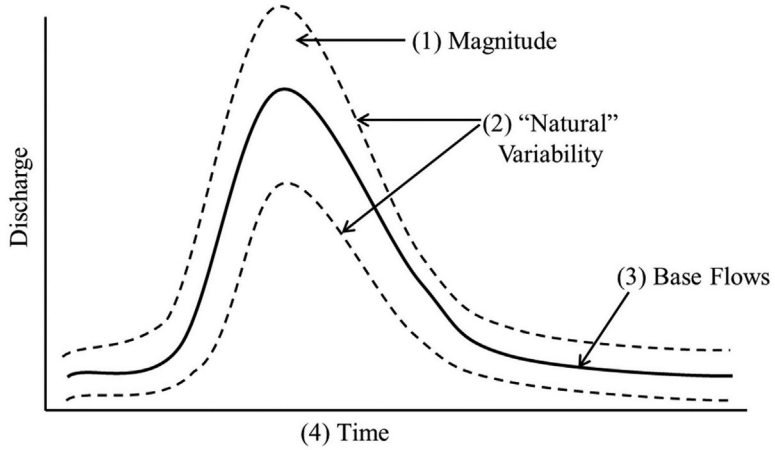
Abstract: "Environmental flows" is a research discipline that emphasizes freshwater allocation in rivers to sustain desired ecological conditions and human well-being. The basis for environmental flow requirements has traditionally relied on hydrological and ecological data. Contemporary methods focus on detailed hydro-ecological relationships within river ecosystems; however, there is currently no structured approach to systematically incorporate socially relevant data into the environmental flows discipline. To address this limitation we developed a flexible framework that applies a social-ecological systems approach to account for multiple flow-related objectives that reflect both biophysical sustainability and societal preferences. First, we conceptualize the freshwater social-ecological system as a hierarchy of human and environmental domains. Then, we recommend stepwise procedures to assess flow-related vulnerabilities of important system attributes, address their feedbacks, and translate these assessments to a common classification for comparative analyses that guide holistic flow management decisions.

Keywords: *Environmental flows, social-ecological systems, river management*

Unique management challenges over freshwater have been developing throughout the world over the last century (Postel 2000; Postel and Richter 2003). Appropriation of freshwater from rivers to meet human needs and socio-economic development is made difficult by withdrawals for competing demands (Gleick 1998; Poff et al. 2003; Vörösmarty et al. 2010) and from external climate drivers (Bates et al. 2008; Beniston 2003). Additional pressures are put on the availability of freshwater resources for non-consumptive uses like recreation and environmental conservation. Recent legal recognition of the "beneficial use" of non-consumptive needs for instream flows in U.S. state statutes (Mathews 2006) is an important step towards legitimizing the preservation and restoration of healthy, functioning river ecosystems (Baron et al. 2002).

"Environmental flows" is a science-based discipline that emphasizes the beneficial use of instream flows in rivers. The discipline has developed out of growing knowledge that the ecology of the river is coupled with natural patterns of streamflow variability; this is formalized in Poff et al. (1997) as the natural flow regime paradigm. Research on environmental flows typically begins by using daily stream gauge data to derive and compare flow regimes in river hydrographs, which are graphical depictions of fluctuating river discharges per unit of time (Figure 1). Hydrographs are fundamental for establishing flow-ecology relationships (Poff et al. 2010), which define how ecological variables change in response to deviations in flow from natural, baseline conditions. These relationships require two basic steps. First, the statistical derivation of flow metrics (Richter et al. 1996; Olden and Poff 2003) explain important disturbance characteristics of the flow regime such as magnitude, frequency, seasonal timing, duration, and rate of change. Second, flow metrics are used to model hypothesized effects on the biophysical components of a river system (Arthington et al. 2006; Poff et al. 2010).

The natural flow regime provides a range of flow characteristics that facilitate conditions responsible for maintaining ecological structure and function of rivers and streams (Poff et al. 1997). Natural disturbances and human impoundments like dams and diversions cause alterations to the flow regime,



(1) Large and peak floods allow access to floodplains at the right time for spawning fish, vegetation recruitment, flushing sediment
(2) Overall flow variation maintains habitat (channel and floodplain)
(3) Base flows provide adequate wetted habitat
(4) Timing used as cues for organismal life history characteristics

Figure 1. Example of a river hydrograph, typical flow regime characteristics, and examples of their hypothesized effects.

which impair the distribution and abundance of aquatic organisms, water quality, and the ecological integrity (i.e. unimpaired condition) of the river ecosystem. Several mechanisms that underlie these impairments include (Bunn and Arthington 2002):

1. Undesirable modifications to river biophysical habitat and processes;
2. Loss of life history cues for aquatic organism survival and recruitment;
3. Loss of longitudinal and lateral connectivity upstream, downstream, and across the river and its floodplain;
4. Encouraging exotic species proliferation.

An Environmental Flow Requirement (EFR) (Tharme 2003) is a flow regime that targets desired ecological conditions through statistical deviations between a river's un-altered and altered flow regime. Flow-ecology relationships are typically used to prescribe EFRs and can be visualized as statistically derived trade-offs between percent flow alteration and ecological condition.

The methods for establishing EFRs were traditionally driven by hydrologic and biophysical data requirements for small-scale river flow management. The earliest holistic methods embodied an ecosystem-based management approach but lacked a social component (Poff and Matthews 2013). Contemporary holistic methods extend management considerations to societal and ecological objectives. Although the holistic methods advocate multiple freshwater needs, they lack structured approaches to assimilate and screen different types of data.

This paper extends the current practice from holistic environmental flows management to include an understanding of societal objectives expressed through socio-economic data. We frame this discussion by beginning with a historical assessment of hydrological and biophysical considerations for flow management. Next, we review several contemporary and holistic methods that integrate socio-economic data to assess how flow alterations affect societal objectives. We end by presenting a conceptual framework that systematically assimilates relevant data from societal and ecological objectives to support holistic environmental flows management.

Traditional Criteria for Environmental Flows: Hydrologic and Biophysical Data

Hundreds of methods for assessing environmental flows have been developed to address river ecosystem condition (Tharme 2003).

Table 1. Selected reference list of environmental flow methods and relevant data by class. Information in this table is a sub-set of methods and is provided to illustrate the breadth of the existing knowledge base and data requirements.

Class	Example Methods	Relevant Data	Metrics	Source
Hydrologic	Tennant Method	Percentage of mean annual flow (MAF) for two six month seasonal periods	Recommended % of MAF	Tennant 1976
	Range of Variability	Multiple years of daily flow records (e.g. stream gauge, groundwater wells)	32 statistically-derived hydrologic metrics	Richter et al. 1996, 1997
	"Percent of Flow" approaches	Observed or modeled "unaltered" daily flows	% deviation above and below "natural" flow regime	Richter et al. 2012
Hydraulic Rating	Wetted Perimeter Method	Cross-section width of the stream bed and banks in contact with water for various discharges;	Relationship between discharge and wetted perimeter	Gippel and Stewardson 1998
	R-2 Cross Method	Hydraulic parameters for mean depth, percent of bankfull wetted perimeter, and average water velocity	Plots of wetted perimeter vs. discharge	Nehring 1979
Biophysical Habitat	Instream Flow Incremental Methodology	Species data: preferred hydraulic habitat attributes by life history stage; channel geometry; modeled flow-hydraulic attribute relationships (PHABSIM)	Weighted Usable Area (WUA) versus discharge function	Stalnaker et al. 1995; Milhous 1998
	Physical Habitat Simulation Model (PHABSIM)	Cross-section data: depth, velocity, substrate, cover, WUA	Habitat suitability indices	Milhous and Waddle 2012
	Biological Response Modeling	Flow associations for macroinvertebrate taxa; flow parameters associated with community structure	Lotic invertebrate Index for Flow Evaluation	Extence et al. 1999
Holistic	Building Block Methodology	Discharge data; cross-section data; hydraulic characteristics; fish and macroinvertebrate data; riparian vegetation surveys	Monthly flows that describe regime types to meet modeled ecological conditions	King and Louw 1998
	Riparian vegetation-flow response guilds	Hydrologic characteristics for stream classes; functional response traits of riparian plant species; empirical flow response guild relationships	Predictions for riparian trait occurrence; vegetation-flow response guilds	Merritt et al. 2010

Most methods involve a simplified assessment of the river ecosystem and the development of flow-ecology relationships for biotic and abiotic conditions. The methods fall into four general classes: hydrologic, hydraulic rating, habitat simulation, and holistic methods (Acreman and Dunbar 2004; Tharme 2003). Each class of methods has a common conceptual basis for their approach but often differ in their data requirements or in their selection of flow regime metrics to model flow-ecology relationships (Table 1). Hydraulic rating methods, for example, typically assume a strong importance on geomorphology and physical habitat characteristics like river depth, velocity, and sediment substrate. All classes of environmental flows methods require hydrological flow data that are typically provided by stream gauges.

Hydrologic methods represent the simplest of the four classes and typically define acceptable minimum base flow discharge requirements on the basis of a proportional flow volume. More sophisticated hydrologic methods incorporate additional criteria representing biological, hydraulic, or other desired endpoints tied to specific characteristics of the flow regime. Hydraulic rating methods assess relationships between discharge

data and hydraulic variables (e.g., instream wetted width, depth) that are used to quantify thresholds for critical instream habitat (Acreman and Dunbar 2004). This may include a specific magnitude and duration of flow required to mobilize instream sediment and scour the channel bed. More complex habitat simulation or physical habitat methods extend this idea to model how changes in discharge affect physical conditions that influence the habitat suitability for target organisms (Booker 2003).

Traditional holistic methods have embodied the perspective of ecosystem-based management, emphasizing large-scale linkages between riverine, riparian, and wetland environments (Acreman and Dunbar 2004). The earliest attempts to incorporate holistic methods established multiple EFRs that specified the timing of acceptable river flows needed to simultaneously achieve multiple environmental objectives like channel maintenance, habitat maintenance and fish spawning and migration (King and Louw 1998). Despite their focus on ecosystem-based management, most of the holistic methods do not include formal frameworks to incorporate socio-economic data that capture societal perspectives on desired ecological endpoints.

Contemporary Social Contexts and Relevant Data

Environmental flows assessments have extended beyond the traditional hydro-ecological research domain into broader river management methods that integrate both ecosystem maintenance and societal objectives like water supply and recreation. At its core, integration of societal objectives requires linking socio-economic conditions with flow variables. In practice, this entails understanding how alterations to a river's hydrograph affect the ecosystem services or benefits supplied to society. For example, recreational visitor days for fishing or whitewater boating are potentially impacted by streamflow alterations (see e.g., Daubert and Young 1981). Socio-economic data like these can be used to derive relationships that describe how social benefits are related to important flow regime characteristics (Sanderson et al. 2012). To date there are limited efforts to actively incorporate societal objectives into EFRs, despite the fact that such incorporation is critical for successful implementation of environmental flow targets (Pahl-Wostl et al. 2013; Poff et al. 2010). We review several common methods for their approaches to integrate socio-economic data requirements into the environmental flows discipline.

The Ecologically Sustainable Water Management framework attempts to design and implement a water management program that establishes EFRs in an open dialogue among stakeholders (Richter et al. 2003). This framework is developed to a large extent using a priori information on the impacts that dams place on river ecology. Ecologically Sustainable Water Management attempts to rehabilitate flow regimes as storage release decisions that use the historical range of variability approach to EFRs (Richter et al. 1997).

The Downstream Response to Imposed Flow Transformation is considered a holistic method that was established for water development projects in South Africa (King et al. 2003). Downstream Response to Imposed Flow Transformation's decision support framework generates multiple scenarios that each describe alternative river ecosystem conditions with varying ecological and socio-economic condition estimates (Brown and Joubert 2003). This information can be used by decision makers for future watershed planning purposes. Downstream Response to Imposed Flow Transformation's sociological module allows for the assimilation of socio-economic data like fish catch, vegetable harvest, and drinking water volume. The resulting relationships are explained as varying degrees of human health risk that correspond to alternative flow scenarios (King et al. 2003). The framework relies on a priori communication with subsistence users of the river ecosystem.

The Ecological Limits of Hydrologic Alteration framework supports large-scale watershed management by classifying hydrologically similar rivers as the basis for developing regional flow-ecology relationships (Poff et al. 2010). The Ecological Limits of Hydrologic Alteration process occurs in two phases: i) a series of science-based steps that specify a regional hydrologic foundation, classification of river types using hydrologic or geomorphic data, and derivation of flow-ecology relationships with biological data; and ii) a social step that integrates societal management needs with EFRs to improve river management policy

decisions. Current applications of this framework (Kendy et al. 2012) emphasize the importance of Ecological Limits of Hydrologic Alteration's social process but offer limited guidance for taking steps to accommodate societal objectives.

A Social-Ecological Systems Approach to Flow Management

The contemporary methods for environmental flows management lack a structured approach to integrate ecological and socio-economic data. Such a framework is needed to support multi-objective flow management. To address this limitation, we envision a screening process that accommodates multiple flow-ecology relationships and socially derived flow-related relationships. Our approach is through the research lens of social-ecological systems (SES), a discipline that conceives of managed systems as an aggregation of linked social (e.g., institutions, property rights, behavior) and ecological (e.g., environmental resources) sub-systems (Berkes and Folke 1998). SES research integrates important information from these sub-systems by establishing relationships between ecological and social conditions.

First, we define the freshwater SES as a hierarchy of environmental and human organizational domains. The domains interact through feedbacks to influence overall system behavior, which we define as the ability to achieve a balance between desired societal and ecological objectives. Our characterization of a freshwater SES is based on human institutions for resource management (e.g., ethical and legislative rules, behavior) and adapted from the hierarchical decision systems approaches of Ciriacy-Wantrup (1967) and Ciriacy-Wantrup and Bishop (1975).

Our hierarchical representation of the freshwater SES (Figure 2) includes, at its foundation, the ecosystem, which provides goods and services that facilitate human endeavors at higher levels (Daily 1997). Distinct operational and community domains within the second level of the hierarchy operate through direct interaction (i.e., monitoring and use) with freshwater ecosystems. Operational entities may include irrigation districts, water conservancy districts, academic institutions, dam operators, or water rights holders. The community refers to public elements such as water consumers and other beneficiaries reliant on flow-related sustenance and recreation (i.e., ecosystem services). The institutional domain consists of members who regulate the operation and use of water resources (e.g., Bureau of Reclamation, U.S. Army Corps of Engineers) and conduct appropriate assessments of the freshwater ecosystem (e.g., Environmental Impact Statements). The policy domain of the hierarchy may grant or restrict rights and change the regulating responsibilities of the institutional domain like state soil and water conservation boards, the Environmental Protection Agency, or the use of Threatened and Endangered Species Act designations.

To understand how a freshwater SES functions, identification of system boundaries is followed by an assessment of system performance indicators we term "attributes." System boundaries are defined for each management context. For watershed-based management, the system may be defined at multiple scales depending on the management objectives. For example, Beechie et al. (2010) partition a catchment into watershed and reach scales for defining distinct ecological outcomes. Attributes of a freshwater SES serve as comprehensive, measurable, and manageable proxies for management objectives. We select socially desirable attributes on the basis that they are amenable to flow management decisions.

We developed a framework that extends a SES approach to integrate many types of data into the environmental flows discipline (Figure 2). Our goal with the framework is to provide a systematic account of relevant water data from relevant domains of a freshwater SES and to use the data to assist in integrative environmental flows studies and decision-making.

The framework consists of six steps:

1. Identify the target scenario and define objectives;
2. Determine relevant domains of the freshwater SES;
3. Identify target social-ecological attributes from relevant SES domains;
4. Assess flow-related vulnerabilities of the attributes through expert opinion and/or data analysis;

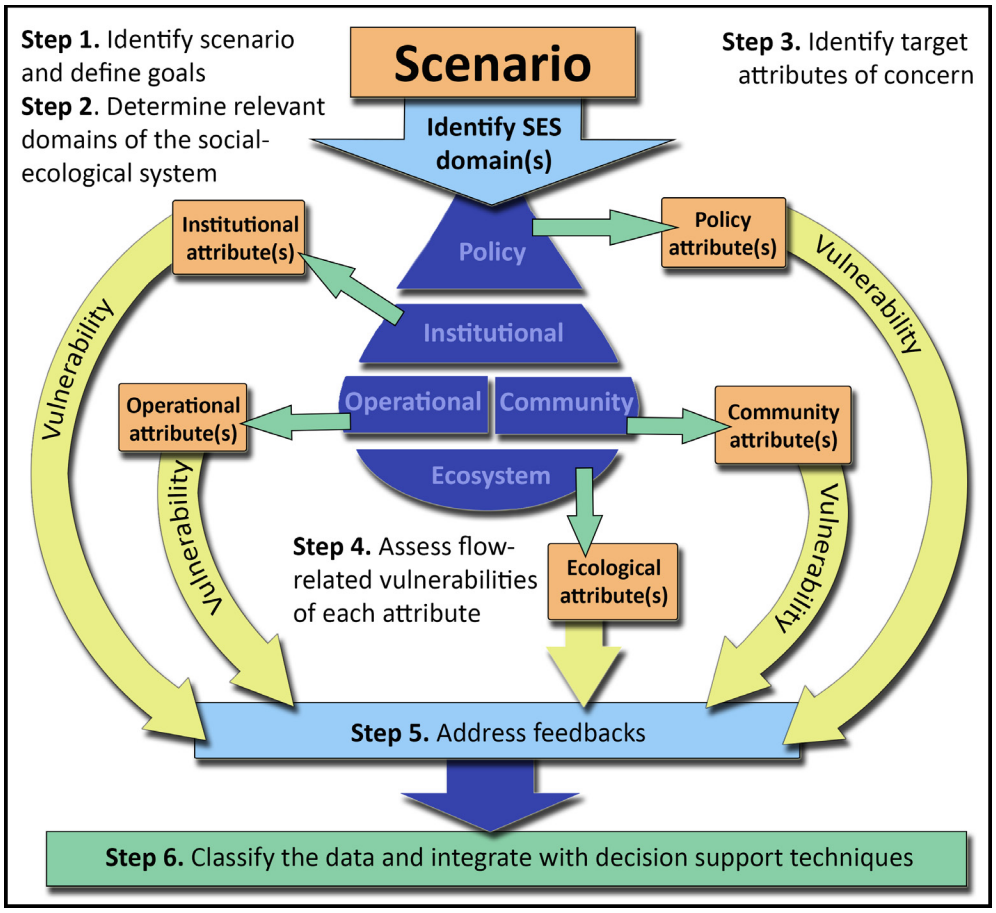


Figure 2. Hierarchical representation of a social-ecological systems approach to flow management.

5. Address feedbacks among system attributes;
6. Classify the data and integrate using decision support techniques.

Steps 1 through 3 in Figure 2 are the data assimilation phase and may be achieved with various stakeholder activities that include but are not limited to: i) focus group meetings to enhance an understanding of the problem and how flow-related data may be effectively used in its analysis; ii) formulate several future climate or management (e.g., water supply) scenarios that may impact the seasonal magnitude and timing of flows; iii) use existing data or perform limited empirical modeling of system components to understand relevant flow-response conditions with respect to the problem scenario(s).

Table 2 provides a growing knowledge base on the different kinds of relevant water data that may be useful for future holistic approaches to environmental flows management. We provide data from the current environmental flows literature that can be used as reference information for identifying SES domains and attributes to develop flow-related relationships. We anticipate this field of research to grow and incorporate flow needs for a multitude of management objectives.

We consider vulnerability in Step 4 as a function of a flow alteration scenario. We measure vulnerability for each attribute by quantifying flow-related condition estimates. In other words, we construct a relationship between the flow regime and the attribute's condition and use that information to assess the effect of a flow alteration scenario. Expert opinion and/or empirical analysis (e.g., results from aforementioned methods Ecologically Sustainable Water Management, Downstream Response to Imposed Flow Transformation, Ecological Limits of Hydrologic Alteration) may be used to derive condition estimates of the attributes for a scenario. Likewise, empirical results of some attributes may be

Table 2. Selected reference data for SES analysis of environmental flows. Each attribute is a manageable performance indicator that corresponds to a domain within the SES from Figure 2.

SES Domain	Social-Ecological Attributes	Relevant Data	Source
Ecosystem	Hydrological Physical Habitat/Hydraulic Biological	Flow regimes estimates and metrics that correspond to biophysical indices (see Table 1)	
Community	Cultural Services -Indigenous harvest species	Catch per unit effort	Finn and Jackson (2011)
	Ecosystem Services -Recreational fishing	Preference survey estimates of willingness to pay for optimal flow ranges	Daubert and Young (1981)
	-Recreational whitewater	Estimated visitor days for optimal flow ranges	Sanderson et al. (2012)
Operational	City Water Quality Standards	Instream nutrient loading exceedence functions	N/A (attribute is a suggestion)
	Agricultural	Percent change of water storage capacity based on instream ecological and policy needs	Grantham et al. (2013)
Institutional	Water Rights	Instream flow availability based on fulfillment of senior water allocations	N/A (attribute is a suggestion)
	Threatened and Endangered Species	Instream flow requirements based on federal regulations	Sanderson et al. (2012)

used alongside alternative data sources that pertain to other relevant attributes. We stress, however, that results of disparate methods must be translated into common values (e.g., "Low," "Medium," "High") in order to enable the simultaneous comparison and evaluation of all attributes. To illustrate, flow-related ecological and socio-economic data modeling may be used with expert opinion to decompose a vulnerability estimate into exposure, sensitivity, and resilience criteria values (Turner et al. 2003) (Table 3).

Step 6 of our framework recommends that attribute condition values are integrated under a management decision context. An example decision context can begin by asking: What attributes are worth managing? In this example, the step is designed to prioritize the attributes based on comparing their vulnerabilities under alternative flow scenarios (Table 3). This step of the framework is similar to the Downstream Response to Imposed Flow Transformation Method's current focus (King and Brown 2006) and we assert that quantitative methods from decision analysis (Howard 1988) are better suited for integration. Decision analysis combines methods from systems theory and decision theory, allows for the assessment of scenarios that have multiple sources and types of attribute data, and addresses feedbacks (Step 5) if strong links can be made among them. We make these recommendations based on challenges from the academic literature to establish a common classification framework to facilitate SES research (Ostrom 2009) and to blend evolved methods from decision theory with contemporary integrative research methods like scenario planning and resilience theory (Polasky et al. 2011).

The Quest for Holistic Flow Management

The challenge to sustain freshwater ecosystem conditions while satisfying consumptive and non-consumptive uses lies at the complex interface of ecological science and social science. Lasting

Table 3. Example evaluation matrix for scenario planning on a single, hypothetical scenario ("A"). The definitions for vulnerability criteria are uniquely tied to each attribute and intentionally not defined here. Attributes are stakeholder defined and defined in specific metrics and units. Estimates of attribute condition (based on unit data) are translated into a common ordinal scale of criteria values, which are uniquely defined for each attribute. Management priority depends on the decision context. In this example scenario, stakeholders want to know which attributes will be most vulnerable ("1") or least vulnerable ("4").

Flow Scenario "A"

Attribute	Expert/Empirical Data		Vulnerability Criteria			Management Priority
	Metrics	Units	Exposure Value	Sensitivity Value	Resilience Value	
Native Fish	Discharge (% alteration); wetted perimeter	Seasonal fish abundance	Low	Moderate	Good	4
Recreational Whitewater	Discharge (% alteration)	Seasonal usable days	High	Very Low	Fair	3
City Water Quality	Discharge (% alteration); nutrient loading	Parts per million	High	High	Fair	2
Agriculture	Discharge (% alteration); storage capacity	Square kilometers	Medium	Very High	Poor	1

solutions will require blending ecological theory with social science methods in an open dialogue with collaborations among ecologists, biologists, geomorphologists, economists, watershed planners, and other, non-technical stakeholders. This paper reviews traditional approaches for making EFRs and highlights the need for a systematic approach to account for and integrate societal objectives for holistic environmental flows management. Our framework operationalizes the multi-objective integration needed for sustainable river management.

Acknowledgments

We thank two anonymous referees for their helpful comments on the manuscript. This research is based upon work supported by National Science Foundation IGERT Grant No. DGE-0966346 "I-WATER: Integrated Water, Atmosphere, Ecosystems Education and Research Program" at Colorado State University.

Author Bios and Contact Information

David M. Martin is a doctoral student in the department of biology and in the graduate degree program of ecology at Colorado State University. He can be contacted at 1878 Campus Delivery, Colorado State University, Fort Collins, CO 80523; e-mail David.Minor.Martin@colostate.edu.

Dylan Harrison-Atlas is a doctoral candidate in the graduate degree program in ecology at Colorado State University. He can be contacted via e-mail at dha@rams.colostate.edu.

Nicholas A. Sutfin is a doctoral student in the department of geosciences at Colorado State University. He can be contacted at nick.sutfin@colostate.edu.

N. LeRoy Poff is a Professor of Biology and the Director of the graduate degree program in ecology at Colorado State University. He can be contacted at poff@lamar.colostate.edu.

References

Acreman, M. and M.J. Dunbar. 2004. Defining environmental river flow requirements–a review. *Hydrology and Earth System Sciences* 8: 861-876.

Arthington, A.H., S. Bunn, N.L. Poff, and R.J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16: 1311-1318.

Baron, J.S., N.L. Poff, P.L. Angermeier, C.N. Dahm, P.H. Gleick, N.G. Hairston, R.B. Jackson, C.A. Johnston, B.D. Richter and A.D. Steinman. 2002. Meeting ecological and societal needs for freshwater. *Ecological Applications* 12: 1247-1260.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof, editors. 2008. Climate change and water. Technical

Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 200.

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, and M.M. Pollock. 2010. Process-based principles for restoring river ecosystems. *BioScience* 60: 209-222.

Beniston, M. 2003. Climate change in mountain regions: a review of possible impacts. *Climate Change* 59: 5-31.

Berkes, F. and C. Folke. 1998. Linking social and ecological systems for resilience and sustainability. Pages 1-25 in Fikret Berkes and Carl Folke (Ed.) *Linking Social and Ecological Systems: Management Practices and Social Mechanisms*. University Press, Cambridge, Massachusetts: 476.

Booker, D.J. 2003. Hydraulic modeling of fish habitat in urban rivers during high flows. *Hydrologic Processes* 17: 577-599.

Brown, C.A. and A. Joubert. 2003. Using multicriteria analysis to develop environmental flow scenarios for rivers targeted for water resource management. *Water SA* 29: 365-374.

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30: 492-507.

Ciriacy-Wantrup, S.V. 1967. Water policy and economic optimizing: some conceptual problems in water research. *The American Economic Review* 57: 179-189.

Ciriacy-Wantrup, S.V. and R.C. Bishop. 1975. "Common property" as a concept in natural resources policy. *Natural Resources Journal* 15: 713-728.

Daily, G (Ed.). 1997. *Nature's Services: Societal Dependence On Natural Ecosystems*. Island Press, Washington D.C., 412.

Daubert, J.T. and R.A. Young. 1981. Recreational demands for maintaining instream flows: a contingent valuation approach. *American Journal of Agricultural Economics* 63: 666-676.

Extence, C.A., D.M. Balbi, and R.P. Chadd. 1999. River flow indexing using British benthic macroinvertebrates: a framework for setting hydroecological objectives. *Regulated Rivers: Research and Management* 15: 543-574.

Finn, M. and S. Jackson. 2011. Protecting indigenous values in water management: a challenge to conventional environmental flow assessments. *Ecosystems* 14: 1232-1248.

Gippel, C.J. and M.J. Stewardson. 1998. Use of wetted perimeter in defining minimum environmental flows. *Regulated Rivers: Research and Management* 14: 53-67.

Gleick, P.H. 1998. Water in crisis: paths to sustainable water use. *Ecological Applications* 8: 571-579.

Grantham, T.E., M. Mezzatesta, D.A. Newburn, and A.M. Merenlender. 2013. Evaluating tradeoffs between environmental flow protections and agricultural water security. *River Research and Applications*.

Howard, R.A. 1988. Decision analysis: practice and promise. *Management Science* 34: 679-695.

Kendy, E., C. Apse, and K. Blann. 2012. A practical guide to environmental flows for policy and planning, with nine case studies from the United States. *The Nature Conservancy*, 74.

King, J. and C. Brown. 2006. Environmental flows: striking the balance between development and resource protection. *Ecology and Society* 11(2): 26.

King, J. and D. Louw. 1998. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. *Aquatic Ecosystem Health and Management* 1: 109-124.

King, J., C. Brown and H. Sabet. 2003. A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* 19: 619-639.

Mathews, Ruth. 2006. Instream flow protection and restoration: setting a new compass point. *Environmental Law* 36: 1311-1329.

Merritt, D.M., M.L. Scott, N.L. Poff, G.T. Auble, and D.A. Lytle. 2010. Theory, methods, and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. *Freshwater Biology* 55: 206-225.

Milhous, R.T. 1998. Application of the principles of IFIM to the analysis of environmental flow needs for substrate maintenance in the Trinity River, northern California. Pages 50-52 in S. Blazkova, C. Stalnaker, and O. Novicky (Ed.) *Hydroecological Modelling: Research, practice, legislation, and decision-making. Praha*, Czech Republic: T.G. Masaryk Water Research Institute.

Milhous, R.T. and T.J. Waddle. 2012. Physical Habitat Simulation (PHABSIM) Software for Windows (v.1.5.1). Fort Collins, Colorado: USGS Fort Collins Science Center.

Nehring, R.B. 1979. *Evaluation of Instream Flow Methods and Determination of Water Quantity Needs for Streams in the State of Colorado: Fort Collins, CO, Division of Wildlife*, 144.

Olden, J.D. and N.L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing

streamflow regimes. *River Research and Applications* 19: 101-121.

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325: 419-422.

Pahl-Wostl, C., A. Arthington, J. Bogardi, S. E. Bunn, H. Hoff, L. Lebel, E. Nikitina, M. Palmer, N. L. Poff, K. Richards, M. Schluter, R. Schulze, A. St-Hilaire, R. Tharme, K. Tockner, and D. Tsegai. 2013. Environmental flows and water governance: managing sustainable water uses. *Current Opinion in Environmental Sustainability,* 5.

Poff, N.L. and J.H. Matthews. 2013. Environmental flows in the Antrhopocene: past progress and future prospects. *Current Opinion in Environmental Sustainability,* 5.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. *BioScience* 47: 769-784.

Poff, N.L., J.D. Allan, M.A. Palmer, D.D. Hart, B.D. Richter, A.H. Arthington, K.H. Rogers, J.L. Meyer, and J.A. Stanford. 2003. River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment* 1: 298-306.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* 55: 147-170.

Polasky, S., S.R. Carpenter, C. Folke and B. Keeler. 2011. Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology and Evolution* 6: 398-404.

Postel, S.L. 2000. Entering an era of water scarcity: the challenges ahead. *Ecological Applications* 10: 941-948.

Postel, S.L. and B. Richter. 2003. *Rivers for Life: Managing Water for People and Nature*. Island Press, Washington, D.C.

Richter, B.D., M.M. Davis, C. Apse, and C. Konrad. 2012. A presumptive standard for environmental flow protection. *River Research and Applications* 28: 1312-1321.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* 10: 1163-1174.

Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37: 231-249.

Richter, B.D., R. Mathews, D.L. Harrison and R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13: 206-224.

Sanderson, J., B. Bledsoe, N.L. Poff, T. Wilding, and N. Fey. 2012. Y*ampa-White Basin Roundtable Watershed Flow Evaluation Tool Study*. Prepared by CDM Smith for The Nature Conservancy.

Stalnaker, C., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The Instream Flow Incremental Methodology: A Primer for IFIM. Technical Report 29, National Biological Service, U.S. Department of the Interior, 44.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries* 1: 6-10.

Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19: 397-441.

Turner, B.L., R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperson, A. Luers, M.L. Martello, C. Polsky, A. Pulsipher and A. Schiller. 2003. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Science* 100: 8074-8079.

Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C. Reidy Liermann, and P.M. Davies. 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555-561.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 59-65, April 2014

Social Observation for Sustainability Science about Water

John B. Braden

University of Illinois, Urbana, IL, USA

Abstract: I advance the following argument: (1) Coupled observation of humans and nature at large scale is important to many fundamental questions of sustainability. (2) Current programs observing natural and social systems are inadequate to address fundamental questions of sustainability at coarse scale. (3) Water is an attractive medium around which to design an observation program, and water researchers agree on many characteristics of water-related data needed to advance sustainability science. (4) A program of coupled observation around water will need to be (a) realistic about attainable scope, (b) design data collection scientifically to be representative at useful scale(s) and of both humans and the hydrosphere, (c) leverage existing data collection programs, (d) explore new ways of protecting privacy while enhancing spatial resolution of data and (e) include data on social institutions as well as individuals.

Keywords: *Sustainability science, water data, human-nature interactions, survey research*

Sustainability science is an important new intellectual frontier studying interactions between humans and natural systems (Clark 2007; Kates et al. 2001; Schnoor 2010). These interactions are interesting on their own and critical to harmonizing economic and social development with resource availability and environmental quality. This new field challenges the scientific community to collect data that "encompass[es] different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests) and multiple failures (systemic faults)" (Martens 2006, 36). I argue in this paper that research at the interface of humans and nature is not adequately supported by existing data collection programs and new programs explicitly designed for coupled research are needed.

As a resource essential to humans but distributed unevenly and unpredictably in nature, water is a compelling medium for the study of human-nature couplings. Braden et al. (2010) call for collecting data on water and humans "across time and space that enable evidence on perceptions, attitudes, social institutions, situation-behavior relationships, and decision-making to be linked comprehensively to measurements of the natural environment."

Due to the complexity of human-nature interactions, most sustainability science has been conducted at small scale through localized observation and analysis. However, many important questions require research at large geographic scales where the effects of climate, terrain, preferences, culture, legal and regulatory systems, information sources, and other spatially and temporally variable factors can be examined. Examples include: (1) how attitudes, preferences and environmental quality interact to influence the evolution of regulatory institutions and (2) how culture and environmental conditions interact to influence human response to information about the environment.

Illustrating Flaws in Current Water Observation Programs

Current data collection programs provide little support for coupled research at large geographic scales. Two examples developed by Braden et al. (2014) illustrate the problem. The examples

investigate whether measured water quality affects environmental attitudes and behavior. The specific behaviors involve recreational choices and household water conservation efforts.

In principle, the findings of studies linking environmental conditions to perceptions, attitudes and behaviors could be important for designing information programs about water that better inform water users. To be useful, however, the data must be representative of the populations and resources of interest with sufficient precision to capture the hypothesized relationships. It will become apparent that existing data sets do not readily meet these standards.

Data Sources

In the U.S., considerable variation in local institutions and cultures as well as in environmental conditions is available through observation at national scale. The U.S. Environmental Protection Agency's (EPA) National Aquatic Resource Surveys (http://water.epa.gov/type/watersheds/monitoring/aquaticsurvey_index.cfm0, Feb. 13, 2013) of streams and rivers, lakes and reservoirs, coastal waters, and wetlands comprise the leading effort to characterize water quality conditions at national scale. They provide point observations on dozens of water quality metrics using sampling frames designed to be statistically representative at national and ecoregional scales. For example, the 2004 to 2005 Wadeable Stream Assessment (WSA) collected data on more than 100 water quality indicators at 2,042 locations nationwide and is representative of water quality conditions at the ecoregional scale (Omernik 1987). These observations are collected in limited time periods and may be influenced by anomalous hydrologic or climatic conditions. They are intended primarily for characterizing trends over time.

To examine behavioral and attitudinal responses to the water quality measurements reported in the WSA, two surveys offer the best available human data at national scale. One of them is the decadal environmental module of the General Social Survey (GSS) (http://www.norc.org/Research?Topics?Pages?environment.aspx, Feb 13, 2013) which is sponsored by the National Science Foundation. The GSS collects demographic, attitudinal, behavioral, and social involvement data through extensive personal interviews. The 2010 GSS sample of 2,044 households is statistically representative of the national demographic profile with some oversampling of minority ethnicities. The second relevant source of social data is the U.S. Forest Service's National Survey on Recreation and the Environment (NSRE) (http://warnell.forestry.uga.edu/nrrt/nsre/clemsc907.html, Feb. 13, 2013). The 2009 round of NSRE provides detailed recreation information as well as demographic data for a nationally representative sample of 103,770 households. The observations were collected by random digit dialing telephone survey administered on a rolling basis from 2005 to 2009.

To protect the privacy of GSS and NSRE respondents, individually-identifiable data are not released. Only data aggregated to census tract (GSS), zip code (NSRE), and county (both GSS and NSRE) scales are available to researchers. Multiple observations within a polygon are averaged, losing information present in the original data. Precise locations and thus, the proximity to specific point observations of water quality, are lost.

People may experience water resources in many different contexts: as drinking water, local geographic features, recreational destinations, and so on. Some resources are experienced near their residences and some further away, so there is ambiguity about the natural environments with which individuals most closely associate and from which they form impressions of water quality. The available social surveys are not conducted with tight couplings of humans and the natural environment in mind and do not collect information that might help identify these associations. Assumptions must therefore be made about the water resources that weigh most heavily in people's impressions of water quality conditions. Based on David (1971), Braden et al. (2014) assume people relate most closely to the condition of surface waters near their homes. Furthermore, since the landscape is laced with more streams than rivers or lakes, people are more likely to reside close to a stream. They therefore assume that nearby stream conditions are most influential and that stream data collected within each respondent's zip code, census tract, or county are broadly representative

of the conditions experienced by respondents, although the WSA, in contrast, does not claim to be representative at scales finer than ecoregions. Based on these assumptions, Braden et al. (2014) geospatially match the social and water quality information. The spatial matching process reveals that WSA and GSS observations were collected in only 4 of the same census tracts and 129 of the same counties; WSA and NSRE observations are collocated in 888 zip codes and 849 counties.

To assemble samples large enough for statistical analysis, Braden et al. (2014) use county-level data for the WSA-GSS match and zip code-level data for the WSA-NSRE match. The resulting samples exclude majorities of the information in the full samples of each individual survey. The WSA-GSS match is further diminished by missing data-only 97 of the matched observations contain all of the requisite information. An immediate concern is whether the matched samples continue to be representative of the nationally-representative samples from which they were drawn. Braden et al. (2014) use Welch's T-test to compare the means of the raw samples to those of the matched sub-samples for 56 variables of particular interest. The tests reveal statistically significant differences for all but 12 variables. Thus, the matched samples are almost certainly unrepresentative of the underlying populations and findings derived from the matched samples are probably not generalizable.

Water Quality, Attitudes, and Water Conservation

Two attitude questions and one behavioral question in the GSS are analyzed by Braden et al. (2014):

1. Is pollution of America's rivers, lakes, and streams?
   a. not dangerous at all for the environment,
   b. not very dangerous,
   c. somewhat dangerous,
   d. very dangerous,
   e. extremely dangerous for environment?
2. How willing would you be to pay much higher taxes in order to protect the environment?
   a. Not at all willing,
   b. Not very willing,
   c. Neither willing nor unwilling,
   d. Fairly willing,
   e. Very willing.

The water conservation question is:

3. How often do you choose to save or re-use water for environmental reasons?
   a. Never,
   b. Sometimes,
   c. Often,
   d. Always.

Braden et al. (2014) separately test three types of water quality indicators for influence on the responses to these questions. A measure of biotic richness is provided by the EPT (Ephemeroptera, Plecoptera and Trichpetra) index (Lenat 1988). Two measures of physical quality are turbidity, measuring light deflection due to particulate matter suspended in water, and the Rapid Habitat Assessment Index, which provides a visually-based overall assessment of stream health (Barbour et al. 1999). Finally, three common chemical measures of water quality are NO_3, phosphorus, and dissolved oxygen.

Braden et al. (2014) separately include each of these three classes of indicators in econometric models of attitudes and efforts to conserve water as described above. Data limitations force them to use the county-level matched GSS-WSA data. They include ecoregional identifiers of the observations to test the possibility of regional differences in the relationships. While several demographic variables (e.g., for attitudes: income, political views, and membership in an environmental group; for water conservation: age, sex, and membership in an environmental group) influence perceptions of pollution danger and conservation behaviors robustly across water quality indicators, not a single one of the water quality indicators themselves significantly affects the perception of danger or conservation efforts. These findings suggest that common water quality measurements collected at nearby streams have little meaning to people as they consider personal water use. Perhaps they pay more attention to indicators other than those considered, or to water bodies other than those where sampling took place, or they may simply be unaware of conditions. In the case of domestic water conservation, it is also quite possible that households decouple their usage of treated water, often drawn from subsurface sources or reservoirs, from the quality of nearby streams. However, another plausible explanation is that data

reduced to county scale in order to support statistical analysis are simply too aggregated and too few to identify relationships that do exist.

Braden et al. (2014) find a significant overall effect, but few regionally-specific effects, from inclusion of the ecoregional identifiers. This result provides evidence of regional differences in water attitudes and behaviors and cautions against generalizing from localized studies.

Water Quality and Recreation

Braden et al. (2014) use WSA and NSRE data matched at zip code scale to study the effects of measured water quality on water-based recreation activities. Zip code scale allows relatively close proximity between people and the locations at which water quality is measured, although the relevance of proximity is questionable as noted above. In addition, some water-based recreation categories defined in NSRE–boating, swimming, fishing, and other waterside activities–are probably pursued more commonly in lakes, reservoirs or coastal waters than in wadeable streams. The conditions of those other surface water resources are assessed by EPA separately from the WSA, and new assessments were underway and not yet available at the time of Braden et al. (2014)'s study. It remains to be determined how researchers might simultaneously use data from multiple assessment programs to identify the most pertinent indicators of water conditions.

Using the matched sample, Braden et al. (2014) find significant relationships between demographic and attitudinal variables and participation in the water-based categories defined in the NSRE: boating, swimming, fishing, and other waterside activities. Almost all of the relationships remain stable across different measures of water quality. However, the water quality indicators themselves are almost always insignificant; the only exception is EPT's positive effect on frequency of swimming. Irrespective of the particular indicator, it is the water quality in wadeable streams nearest survey respondents' homes that most influences their decisions about boating, swimming, and fishing activities seems particularly suspect since some of those activities may be better undertaken at larger water bodies or at locations farther away, but there is little basis in the scientific literature for making alternative assumptions about those geospatial relationships.

These case studies illustrate several limitations of existing data sets for exploring interactions between humans and water resources. First, the aggregation of household data to protect privacy, and to match data spatially when precise locations are not available, sacrifices a great deal of the information available in the full samples. Second, the spatial matching process further reduces the useable data and produces subsamples that are unrepresentative of the full sample and, by extension, the population of interest. Third, the matching process requires linking people to the natural environments (e.g., water bodies near or far) that most influence them, but the information sources provide no basis for mapping those relationships. The obvious solution to these problems is a data collection program designed from the outset to be jointly representative of human and natural systems and to position humans explicitly in relationship to the environmental conditions they actually experience.

Disciplinary Data Aspirations

What would a coordinated program of data collection around water look like? Input on this question was provided in 2011 by a multi-disciplinary convenience sample of water scientists and professionals surveyed by Braden et al. (Forthcoming). Participation in the online survey was invited at a variety of professional conferences and through listserves[1]. Two-hundred and sixteen usable responses were collected over a period of several weeks. Most worked in academic positions, although government, nonprofit, and for-profit organizations also were represented.

The survey asked respondents about their discipline, current work on water resources and the types of data, if any, they use in their work. Disciplines were subsequently clustered into two large groups: (1) natural scientists and engineers and (2) social scientists. The survey also asked respondents to propose research questions they would like to examine. Two types of questions were invited: scientific questions were described as addressing fundamental mechanisms or relationships while policy questions were described as focusing on specific objectives or outcomes. Some respondents suggested questions of both

types. Members of the research team independently conducted content analysis to ascertain the types of data (natural system, human system, or both) required by the stated questions, then reached consensus where their initial assessments differed. The respondents characterized their data needs in terms of frequency of collection (one-time to more-than-decadal), scale (individuals to nations), types of human (attitudes to community conditions) and/or natural system (climate, water, biotic, etc. conditions). Here, we briefly summarize Braden et al. (Forthcoming)'s findings about data aspirations.

Concerning science questions, social scientists emphasize household-level data while natural scientists and engineers prioritize community-level and climate data. For policy questions, surprisingly, natural scientists and engineers among the respondents were more likely than social scientists to emphasize the need for data on attitudes, preferences, group composition and community conditions as well as climate, water quantity and quality and geophysical and biotic conditions while social scientists are more likely to want panel data. Comparing the characteristics of data needed for coupled questions versus questions that were judged to require social data alone, only two differences are apparent: questions requiring only social data are more likely to need attitudinal information while coupled questions are more likely to require panel data. Overall, Braden et al. (Forthcoming) report remarkable interest in social data relevant to water-oriented research questions, even among natural scientists and engineers, and a high degree of agreement in the characteristics of the desired data.

A Coupled Observation Program

Coordinating data collection across scientific domains raises a number of research questions at the outset. First, no such program can encompass all conceivable issues linking people and the environment. It will be essential to narrow the scope of the questions that the endeavor aims to address, then to select variables to measure and record that provide maximal leverage toward the desired scientific program. In a report culminating several years of study to characterize a novel program to observe, measure, and understand coupled interactions between people and the water environment, Dozier et al. (2009) provide a starting point for research on water. Their vision is captured in the following passage (Dozier et al. 2009, 6):

> Transcending the disciplinarily fragmented and place-specific understanding of water that currently exists requires a coordinated and systematic research investment. The objective of the WATERS Network is not to transform all researchers into generalists, but rather to capitalize on the differing perspectives of different research fields. These perspectives can shift our research paradigm from one in which each interacting discipline is treated as a branch with its own knowledge and approaches to a more complete understanding of the coupled human and natural system… by comparing results in different water environments and enabl[ing] advancement through larger-scale, integrated, analyzed data sets that are useful to everyone.

Their ambitious agenda may exceed what is immediately possible.

Second, it will be important to determine the physical scales at which resolution is sought so that data collection can be designed to be representative at the selected scales. Ecoregions were selected for representation in the EPA's National Aquatic Resource Surveys. Along similar lines, for water resources, Hutchinson et al. (2010) propose "Human Influenced Water Environmental Classes" for clustering similar human, hydrographic and ecological features at sub-national scale. In addition to physical and climatic features, they include land cover, population density and human water use among the variables used to define clusters. This methodology warrants further development.

Third, within the desired spatial scale(s), a key issue is to design an observation program that is at once representative of both humans and the water environment. Representation of humans is generally conceived in terms of age, ethnicity, education, and economic profiles. What it means to represent water resources is less clear. The EPA's Aquatic Resource Surveys have wrestled with this issue at least for surface waters and may provide

a starting point for a program that aims at a more comprehensive representation of the hydrosphere.

Fourth, due to fiscal challenges facing the federal government, a new large-scale data collection program comparable to the National Science Foundation-sponsored Earthscope (http://www.earthscope.org/, May 31, 2013) and the Longterm Ecological Research Network (http://www.lternet.edu/, May 31, 2013) is probably out of the question for the near future. To the extent possible, such a program will need to leverage existing data collection efforts of the EPA, U.S. Geological Survey, National Oceanic and Atmospheric Administration, U.S. Department of Agriculture and other mission agencies, in addition to core support from a sponsor of basic research.

Fifth, the program should strive for data protocols that allow more precise spatial identification of human data without violating privacy (Krumm 2009). And, finally, depending on the scientific objectives, it should collect social data not only about individuals, but also formal and informal social institutions such as political jurisdictions, legal regimes, advocacy organizations, and social networks (Braden et al. 2009). These institutions are separable from individuals and extremely important interfaces between water in nature and water in use.

The idea that social and natural systems are co-determined is a central tenet of sustainability science and obviously at work in most water challenges. Current data collection programs in the U.S. do not support generalizable insights about important ingredients of human interactions with water. Coordinating the collection of human and environmental data will be an important step forward in sustainability science and toward strengthening the underpinnings of water management.

Acknowledgements

The research reflected here has been supported, in part, by awards CBET-0838607, CBET-0827497, and EAR 1038813 WSC of the National Science Foundation and USDA/National Institute for Food and Agriculture project ILLU-470-316 of the Illinois Agricultural Experiment Station. The author alone is responsible for all aspects of the analysis, interpretation, and conclusions.

Author Bio and Contact Information

John B. Braden is a Professor Emeritus of environmental economics in the Department of Agricultural and Consumer Economics at the University of Illinois. He can be reached at jbb@illinois.edu.

Notes

1. Invitations to the online survey were distributed through conferences (C) and electronic communities (E) of: Agricultural & Applied Economics Association (C), American Political Science Association Section on Science, Technology & Environmental Policy (E), Association of American Geographers (C), Association of Environmental & Resource Economists (E), Association of Environmental Engineering & Science Professors (C&E), Consortium of Universities for the Advancement of the Hydrologic Sciences (E), International Association for Society & Natural Resources (C), Land & Resource Economics Network (E), Society for Conservation Biology (E), Universities Council on Water Resources (E). Participants in an October 2011 workshop on a National Survey on the Water Environment, sponsored by the National Science Foundation, Johnson Foundation, and USDA/NIFA, also responded. Twenty nine percent of 216 survey respondents were referred to the survey by colleagues.

References

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. *Rapid Bioassessment Protocols For Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish - Second Edition. EPA 841-B-99-002.* U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Braden. J.B., D.G. Brown, J. Dozier, P. Gober, D.R. Maidment, S.L. Schneider, P.W. Schultz, J.S. Shortle, S.K. Swallow, and C.M. Werner. 2009. Social science in a water observing system. *Water Resources Research* 45: W11301.

Braden, J.B., S. Hughes, S. Schneider, P.W. Schultz, J.S. Shortle, and C. Werner. 2010. *Coupling human system data with natural system data: laying a foundation for sustainability science*. Paper submitted to Social, Behavioral and Economic Sciences Division, National Science Foundation, Arlington, Virginia.

Braden, J.B., M.C. Jolejole-Foreman, and D.W. Schneider. 2014. Humans and the water

environment: the need for coordinated data collection. *Water* 6: 1-16.

Braden, J.B., D.G. Brown, D. Maidment, and S. Marquart-Pyatt. Forthcoming. Populating the water world: exploring data aspirations of water experts. *Society and Natural Resources*.

Clark, W.C. 2007. Sustainability science: a room of its own. *Proceedings of the National Academy of Sciences* 104: 1737-1738.

David, E.L. 1971. Public perceptions of water quality. *Water Resources Research* 7: 453-457.

Dozier J., J.B. Braden, R.P. Hooper, B.S. Minsker, J.L. Schnoor, R.C. Bales, M.H. Conklin, L.A. Derry, T. Harmon, A. Michalak, J.R. Mihelcic, J. Myers, S.L. Schneider, D. Tarboton, J.M. VanBriesen, and P.R. Wilcock. 2009. *Living in the Water Environment: The WATERS Network Science Plan*. National Science Foundation, Arlington, Virginia.

Hutchinson, K.J., D.A. Haynes, and J.L. Schnoor. 2010. Human-impacted water resources: domain stratification and mapping to determine hydrologically similar units. *Environmental Science and Technology* 44: 7890-7896.

Kates, R.W., W.C. Clark, R. Corell, J.M. Hall, C.C. Jaeger, I. Lowe, J.J. McCarthy, H.-J. Schellnhuber, B. Bolin, N.M. Dickson, S. Faucheux, G.C. Gallopin, A. Gruebler, B. Huntley, J. Jager, N.S. Jodha, R.E. Kasperson, A. Mabogunje, P. Matson, H. Mooney, B. Moore III, T. O'Riordan, and U. Svedin. 2001. Sustainability science. *Science* 292(5517): 641–642.

Krumm, J. 1999. A survey of computational location privacy. *Personal and Ubiquitous Computing* 13: 391-399.

Lenat, D.R. 1988. Water quality assessment using a qualitative collection method for benthic macroinvertebrates. *Journal of the North American Benthological Society* 7: 222-233.

Martens, P. 2006. Sustainability: Science or fiction? *Sustainability: Science, Practice, & Policy* 2: 36-41.

Omernik, J. 1987. Ecoregions of the coterminous United States. *Annals of the Association of American Geographers* 77: 118-125.

Schnoor J. 2010. *Water sustainability in a changing world*. Clarke Prize Lecture, National Water Research Institute, Fountain Valley, California.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 66-78, April 2014

Challenges and Opportunities for Collecting and Sharing Data on Water Governance Institutions

Samuel Gallaher and Tanya Heikkila

University of Colorado, Denver, CO

Abstract: This article explores the usability and availability of data needed for investigating the interplay between institutional arrangements (i.e. rules, regulations, policy, compacts, laws) and water resource outcomes. It examines a sample of 33 water governance and water research organizations' websites for publicly available datasets containing linked information on institutions and water resource conditions or outcomes. While scholars and decision-makers alike have identified institutional arrangements as an important aspect of improving water governance, their calls for enhancing publicly available institutional data remain unanswered. Within our sample of websites, few datasets link institutions and water resource conditions or outcomes and those that do limit the institutional data to jurisdictional boundaries. More in-depth and diverse institutional data are required to understand which governance tools and structures do and do not work in varying contexts. This will require funding of strategically located, place-based data collection efforts, more transparent and replicable data collection instruments, and coding and storage of institutional data for enhanced data integration.

Keywords: *Institutional arrangements, water governance, public datasets*

Water resource governance concerns in the U.S. and internationally are widespread and persistent. Governance concerns commonly focus on whether and how the organizational and institutional arrangements address the challenges of supplying, storing, treating, maintaining, protecting, and sharing water for growing populations and competing demands (Blomquist et al. 2004a; Steele and Regan 1955). In order for water managers, policymakers, and scholars to understand which governance arrangements are successful, they must be able to systemmatically diagnose and study "the black box of institutional processes and effects" (Blomquist et al. 2004a, 927). Doing so requires in-depth and contextually rich data that describe the structure of governance organizations and institutions (i.e. rules, policies, and regulations) across space and time (Blomquist et al. 2004a; Meinzen-Dick 2007). It also requires the ability to link institutional data to data and evidence on "outcomes" related to water, such as water quantity, quality, usage patterns, and ecological conditions.

Conducting systemmatic and rigorous research on water governance institutions and linking institutional data to outcomes has proven challenging (Braden et al. 2009; National Research Council 2001; National Research Council 2009; National Reserach Council 2001; Braden et al. 2014). This challenge is related to the complexity of water governance institutions. Water is governed by an array of policies, plans, rights, agreements, and mandates across multiple jurisdictional scales. Moreover, water governance is typically fragmented around sectoral or functional domains such as water allocation, water quality, endangered species protection, storage and distribution systems, and hydropower production. These complexities make it difficult to measure, prioritize, and standardize data on water governance institutions and to connect such data to outcomes.

In this paper, we examine the challenges and limitations of collecting and providing data on water governance institutions, with a focus on the U.S. First, we provide an overview of the literature

and research that points to the importance of institutional arrangements in studying water systems and their outcomes. Second, we show the need for more water-related institutional data and some of the challenges that scholars have identified in collecting data on water governance institutions. Then, through an assessment of data from a sample of public and academic water governance organizations and publications, we discuss the current status of water governance institutional data. The analysis focusses on water institutions linked to water management outcomes. We then offer conclusions and recommendations for expanding and enhancing these data sources.

Importance of Water Governance Institutions

Water governance, or our collective decisions and choices about the use and management of water, emerges through institutions. Broadly speaking, institutions are the formal or informal rules that structure human interactions and shape understanding about "what actions (or states of the world) are required, prohibited, or permitted" (Ostrom 2007, 36). In this paper, we focus on formal institutions such as laws, agreements, regulations, and policies. Informal institutions are often thought of as norms or societal expectations. Some examples of formal water institutions in the U.S. include federal and state regulations on water quality, state water rights regimes, instream flow laws, water lease agreements between irrigators and municipalities, and an international treaty on hydropower development.

Defining institutions as formal or informal "rules" suggests that institutions are not the same as organizations. However, institutions may establish organizations and organizations frequently create, implement, or administer institutions. In the water sector, these organizations may be public, quasi-public, private, or non-governmental. Examples can include irrigation associations, local water utilities, state water agencies, river basin commissions, and task forces. Multiple organizations may also work together, as in the case of a watershed collaborative, to create or implement water institutions. Such organizations therefore are important in how we observe and understand water institutions and governance.

Understanding and analyzing water institutions can be essential to improving water resource management and allocation. In the U.S., maintaining adequate, safe, and reliable water supplies for diverse needs has been a major concern of governments, farmers, industry, and environmental organizations. For many years, water research and analysis focused on the engineering and technical solutions to these concerns. In the 1950s and 1960s some scholars began to call for more attention to the role of institutions in water resource management; this was significant since much of the research at the time emphasized the need for large-scale water diversion and storage projects (Ciriacy-Wantrup 1967; V. Ostrom 1953, 473). As the political feasibility of developing large water projects in the U.S. started to wane by the 1970s (Bromley et al. 1974), awareness of the need to evaluate and understand water institutions began to grow among practitioners and scholars. As Gleick (2003) has argued, institutions provide "soft path" solutions (as opposed to the "hard path" of large scale infrastructure) for managing for improving water resource management.

A growing body of research has begun to collect and analyze data on institutions to understand water systems and their performance. An exhaustive review of these studies is beyond the scope of this paper. However, a few examples help illustrate the breadth and depth of this literature across different domains and contexts. Some investigations have compared and evaluated how the design of institutions influence social and political outcomes related to water. For instance, Schlager and Heikkila (2011) found the design of water allocation rules in interstate compacts shapes disputes over water resources. Other studies have explored how the design of water markets affect water use efficiency and environmental performance (Garrick and Aylward 2012; Garrick et al. 2011). Others have looked at how institutions such as water pricing or conservation incentives influence water consumption (Campbell et al. 1999; Nauges and Whittington 2010). Another example of institutional research related to water has explored how the rules governing decision-making, such as allowances for public participation and dialogue among diverse water sectors, have influenced the success of collaborative water management processes (Kallis et al. 2009; Leach and Sabatier 2005; Weber et al. 2005).

In recent years, the interest in understanding the impacts of different types of institutions has been reiterated in global water governance discussions (Conca 2006; Pahl-wostl et al. 2008; Wagener et al. 2010; Wiek and Larson 2012). Scholars and decision-makers alike acknowledge that today's global water governance challenges will be met by better management and understanding of the human element, namely the institutional arrangements, in the water system (Blomquist et al. 2004a; Goulet 2005; Jury and Vaux 2005; National Research Council 2009).

The Need for and Difficulties Acquiring Data on Water Institutions

Despite the growing attention to water institutions in the scholarly and practitioner communities, research describing the relationship "between human behavior and institutional performance" is still considered inadequate (Berger et al. 2001; Braden et al. 2009, 5; Scholz and Stiftel 2005; Ostrom et al. 2007). Jury and Vaux (2005) found that issues related to organizational and institutional arrangements and water management have been "largely neglected in recent decades" (15717) and that research related to institutions surrounding water resources has been negligible over the past twenty years. Blomquist and colleagues (2004a) describe a need to better understand "what institutional features work well under different settings or how certain rule arrangements are shaped by particular environments" (Blomquist et al. 2004a, 930). In response to such calls, the National Research Council has made research on institutions and resource use a priority for over a decade (Braden et al. 2009). Additionally, scholars have begun to call for greater integration of social and natural sciences to grasp the interrelationship between water and society over space and time and to understand, predict, and effectively utilize the water environment (Braden et al. 2009).

One potential reason for the inadequacy of institutional data is that the collection and analysis of institutional data is fraught with difficulties. Our experience in studies of water policies in Colorado (Gallaher et al. 2013), and our experience with collecting data on the design of institutions governing interstate water agreements (see Schlager and Heikkila 2011; Heikkila et al. 2011), on large-scale watershed restoration programs (Heikkila and Gerlak 2005; Gerlak and Heikkila 2006), and on conjunctive water management programs in the West (Blomquist et al. 2004b) suggests that in-depth data collection takes significant time and resources. In part, this is because institutions can change slowly, are often influenced by their societal and geographic context, and their impacts are not immediately obvious. Data collection that can capture both geographic and temporal variation in institutions and in physical water processes therefore may be needed to achieve meaningful analysis of institutional outcomes or performance.

At the same time, data on institutions often must be collected from multiple sources and sub-divided and organized in a way that is meaningful to the questions at hand. For instance, in studying and comparing how different interstate water compacts perform, Schlager and Heikkila (2011) collected data from formal laws, compact commission reports, meeting minutes, interviews, and news sources. These data sources were then "coded" in order to draw out the different types of sub-rules and institutions embodied within the compacts and the commissions that administer the compacts. The data collected included different types of water allocation rules found within a compact, the funding mechanisms for compact administration, the rules governing the compact commission, the mechanisms for monitoring and compliance with compact agreements, and changes to the compacts and their outcomes over time. Finally these data were linked with data on related water conflicts that emerged in the basins over the course of the agreement, data on state water laws and state water administration, and streamflow data. Because efforts like these take time and amass a large quantity of information, they require significant resources; the aforementioned example was funded by the National Science Foundation and required a team of research assistants and three years of data collection to complete.

Furthermore, answering new research questions with existing datasets can be a challenge. For example, while analyzing policy issues and tools in Colorado (Gallaher et al. 2013) we attempted to glean indicators of major versus minor policy change using data previously collected on

Colorado water laws. This task was untenable as the dataset described each policy, not its context or any related conflicts or events. Indeed, as other water researchers have shown, to answer new questions with existing datasets typically requires new and "append-able" information (Benjamin et al. 1994; Wolf 1998). Related to this issue, Bakker (2012) argues there is a mismatch between academic research output and the needs of policy-makers and practitioners, which limits integration of different types of data.

Even when assuming a perfect world of "adequate" data, it is difficult to assess the effects of institutions on water outcomes because of the interactions between different types of institutions with the contextual settings in which they play out (Bakker 2012, 915). As a result, one institutional arrangement may work in one place or time, but not in the next (Meinzen-Dick 2007). Moreover, because water resources are complex social-ecological systems, it can be extremely difficult to determine the effects of a particular institution of interest in the face of confounding environmental and social factors (Lubell et al. 2013).

How we deal with and move beyond these data limitations is of critical importance if we are to meet the imperative to study and analyze water institutions. In the following section we offer an assessment of the current state of publicly available data on water institutions before offering recommendations on how to move forward.

Exploring the Availability of Data on Water Institutions

As mentioned above, U.S. water governance is an amalgamation of overlapping institutional arrangements which include laws, policies, rules, and regulations from multiple levels of government. To analyze publically available data on water institutions in the U.S., we reviewed a sample of websites from government, academic, and research organizations and academic publications of water institution researchers. State, sub-state, and municipal website data was collected through a stratified random selection of states: we randomly selected one state from six different regions of the U.S. Within each state we included the state's water governing departments,

Table 1. Organizations sampled for water institution data.

Federal
U.S. Geological Survey: USGS Water Use Data for the Nation
Regional
Delaware River Basin
The Council of Great Lakes Governors
State
Colorado Water Conservation Board
Colorado's Decision Support System
Florida Department of Environmental Protection
New York Department of Environmental Conservation
New York State Department of Health
New York State GIS Clearinghouse
Ohio Department of Natural Resources: Division of Soil and Water Resources
Ohio Environmnetal Protection Agency
Oregon Water Resources Department
Texas Commission of Water Quality
Texas Natural Resource Information System
Texas Water Development Board
Sub-State Organization
Colorado Basin Roundtable
Northwest Florida Water Mangement District
City
Austin Water
Austin Watershed Protection Department
City of Columbus
City of Tallahassee
Denver City
Denver Water
New York City Environmental Protection
New York City Waterboard
Portland Water Bureau
Portland Water District
Water Research Institutes
Columbia Water Center
Institute for Water and Watersheds
Pacific Institute
Academic
Bren School of Environmental Science & Management: California Water Records
ETH Zurich Center for Comparative and INternational Studies
ICPSR: Inter-university Consortium for Political and Social Research

the state capital's municipal water managing department, and any sub-state water governance organizations. We also purposefully sampled the websites of two multi-state regional water governance organizations and the U.S. Geological Survey (USGS). Finally, we included academic and research sources for water data. The academic and research organizations were selected because of their prominence and expertise in the water field, while the research consortium was reviewed because it provides datasets from researchers who may study institutions related to water.

Although our primary focus was on U.S. data, in exploring research institutes, we found references to notable datasets at the international scale, which we discuss further below. Since the population of organizations that might collect or provide data on water institutions is unknown, our purposive sampling approach was meant to provide sufficient variation in geography, organizational type, and jurisdictional scale to draw initial insights on the type of data that are available. Table 1 provides the individual organizations included in the study.

Data were collected through a search of each organization's website for reports and datasets in June, 2013. If an internal search engine was available, then key word Boolean phrases such as ["water" AND "data" or "water" AND "database"] or simply ["water"] were used to identify potential water related information that was not found during the initial review of the website. Each resulting internal webpage or online dataset was evaluated for three attributes: 1) the availability and type of water institution data (e.g. jurisdictional boundaries, polices, rules, by-laws); 2) if data on water resource conditions or water related outcomes were available (e.g. conflicts, water quality, drought, flood, water levels); and 3) if water institution and outcome data were linked in the same dataset. To be considered "linked," the water institution and outcome data needed to be explicitly in the same dataset or model. For example, a Geographic Information Systems (GIS) tool containing both layers of water districts and water quality test outcomes was considered linked. On the other hand, data on the same webpage that includes a list of regulations and a number of separate reports related to water quality was not considered linked.

Table 2. Summary of sampled websites where data on water institutions and outcomes are linked.

Online Datasets with Linked Institutional and Outcome Data		
Organization Type	Only Jurisdictional Linkages	Beyond Jurisdictional Linkages
Federal (n=1)	1	0
Multi-State (n=2)	0	0
State (n=12)	8	3
Sub-state (n=2)	1	0
City (n=10)	2	0
Water Research (n=3)	1	1
Academic Databases (n=3)	3	0
Total (n=33)	**16**	**4**

Finally, using Google Scholar and key searches, we reviewed academic publications to scan for datasets used by water institution researchers. Boolean phrases, such as ["water" AND "institutions" AND "dataset"] and ["water" AND "policy" AND "dataset"], were used to limit the Google Scholar search results. The results were added to our current set of academic manuscripts and are discussed in the text of the results and conclusion sections.

Summary results of available data on water-related institutions and outcomes are shown in Table 2. The table provides the count of organizations from the sample that had institutional information linked to water resource outcome data. The institutional data is split between jurisdictional information (i.e. county, state, and water district information) and other information (i.e. water policy tools, compacts, and voting rules).

Within our sample, public online datasets that link institutions and outcome data are limited, both in terms of usability and breadth. The website reviews found public water governance organizations often provide rich information regarding the institutions, such as descriptions of events leading up to a new policy or the regulations guiding a program or data collection effort, but this information typically is embedded in the text of the website or

separate PDF documents. For example, the New York Department of Environmental Conservation provides in-depth information through a series of webpages on the agency's involvement in the New York City watershed, the physical water sources and boundaries of the New York City watershed, and related programs and regulations pertaining to the watershed. The information is neither ready for analysis nor is it linked to water quality, use, levels, or in most cases, events before or after the institution was begun.

The most common methodology for linking institutions to outcomes is geospatial referencing. Federal, state, and municipal governments have used geospatial referencing to link jurisdictional boundaries and individual water rights information to water outcome data. The water outcome data include water level and flow for lakes, streams, rivers, and reservoirs, water quality, and water monitoring sites. Though these datasets are often comprehensive for a state or specific region within the state, the files must be collected separately and sometimes from various sites. For example, the Oregon Water Resource Department GIS files only include water rights, rule, and jurisdiction boundary areas, and water gauge station locations; the outcome data such as water quality and contamination sites for the state are found at Oregon Department of Environmental Quality. The Institute for Water and Watersheds includes GIS data with the greatest breadth and variety of institutional and physical boundaries (country boundaries, river basins, and treaties) as well as outcome data, which include project counts, discharge, runoff, and water stress levels. The second most commonly found institution-and-outcome-linked datasets were Microsoft Excel based datasets that included water contamination, flow, or level alongside county, water district, or individual water rights.

The largest water-related dataset found is housed at the USGS, links to which were found at multiple state and municipal organization websites. The USGS Water Data for the Nation includes historical data for surface water (e.g. flows and levels in streams and lakes), groundwater (e.g. well water levels), water quality (e.g. chemical data from water sources), and water use information. The USGS water datasets are searchable by state, county, or hydrologic unit.

The majority of information posted on academic and water research group websites were publications rather than datasets. The Columbia Water Center provides a large searchable database of water-related research, but no raw datasets. Likewise, the Pacific Institute's website offers a wide range of online water-related programs to aid decision making and reports, but lacks data for others to analyze. The websites of the Institute for Water and Watersheds, the Bren School of Environmental Science & Management, and ETH Zurich CIS each provide at least one dataset with linked institution and outcome data. The Institute for Water and Watersheds' website provides two time-series databases in addition to the spatial GIS files. One of the time-series databases is a searchable database of 6,400 international water events (ranging from military action to political statements, to peaceful unification of states) between 1948 and 2008. The other database is an event-oriented database with basin and regulatory action, as well as drought and water quality indices from 1990 to 2004 for the state of Oregon (Institute for Water and Watersheds). The ETH Zurich CIS website provides data related to international river basin events with location, time, and indicators of whether events were conflictive or cooperative. The "events" covered in the Institute for Water and Watersheds databases and the ETH Zurich CIS may be related to particular types of institutions, such as a water agreement, but not all events are necessarily associated with an institution. The Bren School's dataset focuses on a particular type of institution, water markets at the state level, which focuses on the market transactions that were drawn from monthly reports of a water trade journal, the Water Strategist, from 1987 to 2010.

Based on our review of data available on the 33 organizations' websites and the reviewed academic manuscripts, we found a stronger representation of data on "outcomes" or physical properties (e.g. flows, quality) relative to institutional data. The most descriptive institution-related information provided by public agencies was embedded in reports and webpages rather than downloadable datasets. Datasets that linked institutions and outcomes were mostly focused on outcome measures and high level institutional divisions (e.g. state, county, or water district boundaries). While these data do provide potential for spatial analysis

or review of outcomes over time, in their current state they are largely inadequate to investigate research questions related to outcomes pre- and post-institutional change or to compare different institutional arrangements to one another. To perform these more nuanced analyses, institutional data would need to be added by the user. Indeed, we found that scholars studying water and institutions are not necessarily using the publicly available data from agencies or research institutes. Through Google searches for publications focused on water institutions and outcomes, the datasets typically employed by researchers are custom-built to match their research agenda (e.g. see Bardhan, n.d.; Benjamin et al. 1994; Blomquist et al. 2001; Heikkila 2004; Lubell et al. 2002).

The variety of data found in academic and quasi-academic websites and publications extends beyond the more functional datasets found at government websites and includes more historical information. For example, in addition to jurisdictional and rule boundaries, datasets also include rule or policy changes (Gallaher et al. 2013), treaties and conflicts (Bernauer et al. 2012; Institute for Water and Watersheds, n.d.), or water right transactions over time (Brewer et al. 2008). The scale of work from these academic and quasi-academic organizations is also more diverse than the government's website data. They include international river basin agreements (Wolf 2002), water transfers in the west (Brewer et al. 2008), multi-state basins (Blomquist et al. 2004b), and state-level water policies (Gallaher et al. 2013). While these academic datasets provide more time and space variance than the government-provided datasets, all the data we sampled are limited in the same fundamental way: the data are only fit to answer the questions of the organization or researcher.

Conclusions and Recomendations

The lack of publicly available data on water governance institutions is a perpetual challenge. The problem with throwing up our hands in the face of limited funding or continuing with the current pace of piecemeal data collection efforts is that such inaction could impede improvements in water governance. As other scholars have argued, the "current uncoordinated data collection programs in the U.S. are unlikely to support generalizable insights about fundamental human-nature relationships that vary at large-scale" (Braden et al. 2014, 12). A starting point to improve coordinated data collection and use is to make data accessible. Water agencies, institutes, and scholars using data that link institutions and water resource conditions or outcomes should strive to make more data publicly available.

Next, data are often not user-friendly or transferable between databases. Institutional data sets are complex and unique and there is not a currently accepted set of attributes to identify various institutions, water resources, or outcome information. The geospatial reference data we found provide some guidance to improve data usability. The spatial reference points and the available software for layering geospatial files make independently created datasets easily combined. Indeed, a powerful feature of geospatial analysis is the ability to combine multiple layers from independent users. If water researchers are to follow other crowd-sourced data endeavors, an agreed upon set of reference points, institutional and descriptive typologies, and data formats needs to be determined. Standards like these would make data more easily merged or appended. Making institutional data more user-friendly also requires transparency about how data are collected, including how concepts are operationalized and measured. In other words, researchers need to share data collection instruments such as coding forms and surveys. This will allow for enhanced replication of data collection efforts over time and across different locations.

Funding is also needed to support long-term data collection to diagnose and unpack the complexity of institutions. This includes support for studies on 1) changes to institutions over time (e.g. the evolution of a states regulatory programs); 2) how institutions connect across scales (e.g., relationships of state laws to interstate agreements) and connect across sectors (e.g., the connections between non-point source policies and point source policies through water quality trading programs); 3) how similar types of institutions function in different locations (e.g., cross-state comparisons of the design of instream flow institutions); and 4) how these institutions relate to the availability and

quality of water resources and the impacts on other systems (e.g. how instream flow programs affect the protection of species). Improving data collection and access to contextual social and political data, such as the networks of actors involved in water governance or the political preferences of water users, can also enhance the analysis and understanding of water institutions and governance.

Given that funding is always a limitation, water researchers may need to prioritize place-based studies of both systems that are in stress and those that appear to be working successfully, or similar types of institutional arrangements that allow for comparisons across locations. Researchers, policymakers, and managers need to understand more directly the other's needs and questions if we want to improve the design of institutions. Researchers often "follow the data," but sometimes the important and interesting questions cannot be answered with what is available. Engaged scholarship from the research angle and forward thinking by public agencies to "go beyond compliance" with regulations and think about systems and long-term planning can also help promote a more robust data collection agenda.

As our analyses show, some agencies and researchers are already carrying out some of these recommendations. But more data are needed and these efforts can be better coordinated to make the data applicable to diverse sets of research questions. Federal and state research institutes and think-tanks can provide an important middle ground to facilitate these discussions. Funders, such as the National Science Foundation, and other large federal agencies and foundations can play a critical role in encouraging research that promotes inter-disciplinary efforts and data integration.

Some of these suggestions add effort and cost to how we carry out research or manage data in public agencies. Indeed, adding tags to datasets or creating community standards for sharing and disseminating data collection instruments for others to freely use is a collective challenge. If we wish to continue the efforts underway to understand institutions and their impact on water governance, however, researchers and decision makers alike need a wider variety of data over space, time, and contexts. If a national agenda for water-related research follows the suggestions above, a rich clearinghouse of information will develop.

Author Bio and Contact Information

Samuel Gallaher is a Ph.D. student at the University of Colorado, Denver. He can be reached at samuel.gallaher@ucdenver.edu.

Tanya Heikkila is an Associate Professor at the University of Colorado, Denver. She can be reached at tanya.heikkila@ucdenver.edu.

References

Bakker, K. 2012. Water Security: Research Challenges and Opportunities. *Science* 337: 914-915.

Bardhan, P. n.d. *Water Community: An Empirical Analysis of Cooperation on Irrigation in South India*, University of California at Berkeley.

Benjamin, P., F.L. Wai, E. Ostrom, and G. Shivakoti. 1994. Institutions, Incentives, and Irrigation in Nepal. *Workshop on Political Theory and Policy Analysis*, Indiana University.

Berger, J., E. Ostrom, R.B. Norgaard, D. Policansky, and B. Goldstein (Eds.) 2001. *Protecting the Commons: A Framework for Resource Management in the Americas*. Island Press, Washington D.C., 328.

Bernauer, T., T. Böhmelt, H. Buhaug, N.P. Gleditsch, T. Tribaldos, E.B. Weibust, and G. Wischnath. 2012. Water-Related Intrastate Conflict and Cooperation (WARICC): A New Event Dataset. *International Interactions* 38(4): 529-545.

Blomquist, W., T. Heikkila, and E. Schlager. 2001. Institutions and Conjunctive Water Management Among Three Western States. *Natural Resources Journal* 41(3): 653-683.

Blomquist, W., T. Heikkila, and E. Schlager. 2004a. Building the agenda for institutional research in water resource management. *Journal of the American Water Association* 40(4): 925-936.

Blomquist, W., E. Schlager, and T. Heikkila. 2004b. *Common Waters, Diverging Streams: Linking Institutions and Water Management in Arizona, California, and Colorado*. Resources for the Future, Washington, D.C.

Braden, J.B., D.G. Brown, J. Dozier, P. Gober, S.M. Hughes, D.R. Maidment, and S.L. Schneider. 2009. Social science in a water observing system. *Water Resources Research* 45(11): W11301.

Braden, J.B., M.C. Jolejole-Foreman, and D.W. Schneider. 2014. Humans and the Water Environment: The need for coordinated data collection. *Water* 6(1): 1-16.

Brewer, J., R. Glennon, A. Ker, and G. Libecap. 2008. Water markets in the west: prices, trading and contractual form. *Economic Inquiry* 46: 91-112.

Bromley, D.W., R.W. Butcher, and S. C. Smith. 1974. Policy and research implications of the National Water Commission's recommendations. *Land Economics* 50(1): 15-34.

Campbell, H.E., E.H. Larson, R.M. Johnson, and M.J. Waits. 1999. *Some best bets in residential water conservation: Results of multivariate regression analysis, City of Phoenix, 1990-1996.* Final Report to the Arizona Department of Water Resources, Arizona, USA. Available at: http://www.asu.edu/copp/mprrison/bestbets.pdf on 29th August 2006.

Ciriacy-Wantrup, S.V. 1967. Water policy and economic optimizing: Some conceptual problems in water research. *The Economic Review* 57(2): 179-189.

Conca, K. 2006. *Governing Water: Contentious Transnational Politics and Global Institution Building*. MIT Press, Cambridge, Massachusetts.

Gallaher, S., T. Heikkila, W. Patterson, V. Frank, and C. Weible. 2013. Adapting water policy tools to new issues: Lessons from Colorado's experience over time. *Water Policy* 15(1): 43.

Garrick, D., C. Lane-Miller, and A.L. McCoy. 2011. Institutional innovations to govern environmental water in the western U.S.: Lessons for Australia's Murray–Darling Basin. *Economic Papers* 30: 167-184.

Garrick, D. and B. Aylward. 2012. Transaction costs and institutional performance in market-based environmental water allocation. *Land Economics* 88(3): 536-560.

Gerlak, A.K. and T. Heikkila. 2006. Comparing collaborative mechanisms in large-scale ecosystem governance. *Natural Resources Journal* 46: 657-707.

Gleick, P.H. 2003. Global freshwater resources: Soft-path solutions for the 21st Century, *Science* 302: 1524-1528.

Goulet, D. 2005. Global governance, dam conflicts, and participation. *Human Rights Quarterly* 27(3): 881-907.

Heikkila, T. 2004. Institutional boundaries and common-pool resource management: A comparative analysis of water management programs in California. *Journal of Policy Analysis and Management* 23(1): 97-117.

Heikkila, T. and A.K. Gerlak. 2005. The formation of large-scale collaborative resource management institutions: Clarifying the roles of stakeholders, science, and institutions. *Policy Studies Journal* 33(4): 583-612.

Heikkila, T., E. Schlager, and M.W. Davis. 2011. The role of cross-scale institutional linkages in common pool resource management: Assessing interstate river compacts. *Policy Studies Journal* 39(1): 121-145.

Institute for Water and Watersheds. (n.d) The Transboundary Freshwater Dispute Database (TFDD). Accessed via http://www.transboundarywaters.orst.edu/database/index.html.

Jury, W. A. and H. Vaux. 2005. The role of science in solving the world's emerging water problems. *Proceedings of the National Academy of Sciences* 102(44): 15715-20.

Kallis, G., M. Kiparsky, and R. Norgaard. 2009. Collaborative governance and adaptive management: Lessons from California's CALFED Water Program. *Environmental Science & Policy* 12(6): 631-643.

Leach, W.D., and P.A. Sabatier. 2005. Are Trust and Social Capital the Keys to Success? Watershed Partnerships in California and Washington. Pages 233-258 in P. A. Sabatier W. Focht, M. Lubell, Z. Trachtenberg, A. Vedlitz , and M. Matlock (Eds.), *Swimming Upstream: Collaborative Approaches to Watershed Management*. MIT Press, Cambridge, Massachusetts, 328.

Lubell, M., A. Gerlak, and T. Heikkila. 2013. Calfed and Collaborative Watershed Management: Success Despite Failure? Pages 65-75 in J. F. Warner, A. van Buuren, and J. Edelenbos (Eds.) *Making Space for the River.* IWA Press, New York, 218.

Lubell, M., M. Schneider, J.T. Scholz, and M. Mete. 2002. Watershed partnerships and the emergence of collective action institutions. *American Journal of Political Science* 46(1): 148-163.

Meinzen-Dick, R. 2007. Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences* 104(39): 15200-5.

National Research Council. 2001. *Grand Challenges in Environmental Sciences*. National Academies Press, Washington, D.C., 106.

National Research Council. 2009. *Letter Report Assessing the WATERS Network Science Plan* (p. 12). Washington, D.C.: The National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=12707.

Nauges, C. and D. Whittington. 2010. Estimation of water demand in developing countries: An overview. *The World Bank Research Observer* 25(2): 263-294.

Ostrom, V. 1953. State administration of natural resources in the West. *The American Political Science Review* 47(2): 478-493.

Ostrom, E. 2007. Institutional Rational Choice: An Assessment of the Institutional Analysis and Development Framework. In P. A. Sabatier (Ed.), *Theories of the Policy Process* (2nd ed., pp. 21–64). Westview Press, Boulder, Colorado.

Ostrom, E., M.A. Janssen, and J.M. Anderies. 2007. Going beyond panaceas. *Proceding from the National Academy of Sciences* 104:15176-15178.

Pahl-wostl, C., E. Mostert, and D. Tàbara. 2008. The growing importance of social learning in water resources management and sustainability science. *Ecology and Society* 13(1): 24.

Scholz, J.T. and B. Stiftel (eds.) 2005. *Adaptive Governance and Water Conflict: New Institutions for Collaborative Planning*. Resources for the Future: Washington, D.C.

Schlager, E. and T. Heikkila. 2011. Left high and dry?: Climate change, Common Pool Resource theory and the adaptability of western water compacts. *Public Administration Review* 71(3): 461-470.

Steele, H.A. and M.M. Regan. 1955. Organization and administrative arrangements for an effective water policy. *Journal of Farm Economics* 37(5): 886-896.

Wagener, T., M. Sivapalan, P.A. Troch, B.L. McGlynn, C.J. Harman, H.V. Gupta, P. Kumar, P.S.C. Rao, B.B. Nandita, and J.S. Wilson. 2010. The future of hydrology: An evolving science for a changing world. *Water Resources Research* 46(5): W05301.

Weber, E.P., N.P. Lovrich, and M. Gaffney. 2005. Collaboration, enforcement, and endangered species: a framework for assessing collaborative problem-solving capacity. *Society and Natural Resources* 18(8): 677-698.

Wiek, A. and K.L. Larson. 2012. Water, people, and sustainability—A systems framework for analyzing and assessing water governance regimes. *Water Resources Management* 26(11): 3153-3171.

Wolf, A.T. 1998. Conflict and cooperation along international waterways. *Water Policy* 1(2): 251-265.

Wolf, A.T. 2002. *Atlas of International Freshwater Agreements*. United Nations Publications. ISBN: 92 807 2232 8.

Appendix 1. Data availability from a sample of water agencies.

Level	Agency/Group	Institutional Data	Outcome Data	Institutional Data Linked to Outcome Data
Federal	USGS: USGS Water Use Data for the Nation	State Boundaries	Water use in various categories, surface water, groundwater, and water quality data overtime over time for each state	Information categorized by state
Regional	Delaware River Basin	PDF-format of regulations	Water quality reports, contaminant data by site or sample,	No
Regional	The Council of Great Lakes Governors	No	Physical data, links to other state's modeling tools	No
State	Colorado Water Conservation Board	Model - water rights, operating rules, projects over time; GIS data - hazard plan status, NFIP participation, jurisdiction boundaries, watershed restoration project locations; General data - lists and descriptions of legislation, statutes, rules, policies, guidelines, CWCB rule and regulation processes	Model - flow, capacity; GIS - NFIP savings per policy, savings per community	Model can be setup to include various institutional arrangements to estimate outcomes; GIS shows spatial association;
State	Colorado's Decision Support System	GIS: water rights, division, district and county boundaries; irrigated lands; General data: water-rights information for structures such as ditches, reservoirs, and wells	General data: historical daily (cfs) or monthly (acre-feet) diversion data	General data: historical flows or levels linked to structures
State	New York State Department of Health	No	Annual water quality reports	No
State	NYSGIS Clearinghouse	Water boundary data, designated use,	Yes	GIS map shows spatial association
State	Oregon Water Resources Department	Information on specific water rights. GIS data includes Water rights by type/use, and point of diversion; Rule Boundaries; Political Boundaries (Administrative Basins, Water Districts); Water Availability (priority WABS, Water availability basins); active and inactive stream gauge locations.	Hydrographic data set; historical stream flow datasets	GIS map tool displays multiple jurisdictional and rule boundaries, water right by type and use, water monitoring stations, and waterways.
State	New York Department of Environmental Conservation	Individual documents on guidelines and regulations	Water quality reports	No
State	Texas Natural Resource Information System	State boundaries, county boundaries, city boundaries, federal parks, state parks, and landmark boundaries (airports, universities, wildlife refuges, and military bases).	No	No

State	Texas Water Development Board	Yes - rules, regulations, policies, plans, etc.	Yes - flood, drought, levels, flows, contamination, etc.	No
State	Florida Department of Environmental Protection	PDF/website information on policies, regulations, programs, etc. Set of reports describing issues and programs. 52 GIS data layers with multiple institutional boundaries, physical water locations, and physical outcome data	Yes - water flows, contaminations; quality reports for surface, ground, drinking water	Through GIS. Multiple types of institutional data (jurisdiction, program boundaries, protection boundaries) and outcome data. Other datasets include outcome data with some jurisdictional connections
State	Ohio Department of Natural Resources: Division of Soil and Water Resources	Regulations and programs in report form; GIS maps of jurisdictional divisions	Water quality for surface and ground; well levels; visual maps for multiple outcomes	Jurisdictional links through GIS.
State	Ohio Environmental Protection Agency	Rules, policies, guidelines, programs, use designations in report format; GIS maps with boundaries and use designations;	Water quality (surface and ground) data sets available and GIS maps of some outcome data	Jurisdictional links through GIS and excel files.
sub-State region	Colorado Basin Roundtable	Yes - tax zones, counties, parcel divides, land ownership	No	No
sub-State region	Northwest Florida Water Management District	Yes - tax zones, counties, parcel divides, land ownership	Yes - water quality	GIS spatial association. Jurisdictional
City	Denver City	FEMA flood insurance rate map panel index and flood zone Divisions; Metropolitan Districts; Survey relinquished easements. Zoning for aquaculture; Zoning for general manufacturing of food		
City	Denver Water	Water policy, rules, regulations	Quality and use data over time	No
City	New York City Environmental Protection	Separate documents and reports for rules, regulations, MOUs	Separate reports for various water quality, usage, flows, levels for different sites and sources	No
City	New York City Waterboard	Separate documents for governing documents and policies	Financial statements	No
City	Portland Water Bureau	Yes - regulations	Some - link to EPA site for water sample results	Some- e.g. Information collection rule (1996) and link to water sample outcomes at EPA website
City	Portland Water District	No	Budgets and water quality reports	No
City	Austin Water	PDF-format policy and planning documents	Flood data	No
City	Austin Watershed Protection Department	PDF-format regulation and policy	Flood data	No
City	City of Tallahassee	PDF and webpage policies and programs	PDF format of measurement outcomes	No
City	City of Columbus	PDF database of rules/policies, discussion of watershed partnership	PDF reports	No

Appendix 2. Data Availability from Sample of Research Institutes and Academic Sources.

Level	Agency/Group	Institutional Data	Outcome Data	Institutional Data Linked to Outcome Data
Water Research Institutes	Columbia Water Center	No	Delaware River Stream flow monthly data	No
Water Research Institutes	Pacific Institute	No	No	No
Water Research Institutes	Institute for Water and Watersheds	Multiple datasets: basins, country boundaries, treaties, tenders, irrigation; regulatory action	Multiple datasets: project count, discharges, runoff, water stress level; collaboration level; drought index, news events, use index, water quality index	Multiple datasets: GIS spatial association; basins and events; regulator action, basins and events, drought, use, and water quality
Academic Database	ICPSR	County data collected	Perceptions and technology of user	Yes
Academic	Bren School of Environmental Science & Management: California Water Transfer Records	Information by state	Transaction amount, price	Yes
Academic	ETH Zurich CIS	Country identification	Water event: time, location, intensity, and if its conflictive or cooperative event	Yes

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 79-90, April 2014

Determining the Dynamics of Agricultural Water Use: Cases from Asia and Africa

Lisa-Maria Rebelo[1], Robyn Johnston[2], Poolad Karimi[2], Peter G. McCornick[2]

[1]*International Water Management Institute, Vientiane, Lao P.D.R.*
[2]*International Water Management Institute, Colombo, Sri Lanka*

Abstract: Across Africa and Asia water resources are being affected by a complex mixture of social, economic, and environmental factors. These include climate change and population growth, food prices, oil prices, financial disruptions, and political fluctuations. The need to produce more food will have one of the largest impacts on water and will continue to re-shape the patterns of agricultural water use in major food-growing regions.

With this increasing demand on water for agriculture, from large-scale irrigation to intensification of rainfed systems, it is becoming increasingly important to ensure that water resources decision-making has access to information that captures the spectrum of water uses, across seasons, and over time. Furthermore, the major sectors that place demands on water and otherwise affect the resource need water-related information to inform their decisions. In this paper we consider two cases where the range of agricultural water management uses have been examined. We examine the methodologies and approaches used, the utility of this information to decision-making in the water and agricultural sectors, and the limitations of the information gathered.

Keywords: *Agriculture, water, data*

Agriculture is the largest consumer of water in Africa and Asia and plays an essential role in economic development and poverty reduction in these regions. Growth in the agricultural sector is critical to achieving the Millennium Development Goals related to poverty and hunger eradication. While these, in their present form, aim to reduce the proportion of people who suffer from hunger by 50 percent between 1990 and 2015, the proportion of people in the developing world who went hungry from 2005 to 2007 remained stable at 16 percent despite significant reductions in extreme poverty (MDG Report 2011). Projections show that feeding a world population of 9.1 billion people in 2050 will require raising 2007 levels of food production by around 70 percent; production in sub-Saharan Africa and parts of South and East Asia would need to double (Rockström et al. 2010). In order to achieve this, new strategies aimed at sustainably increasing agricultural production and ensuring the effective use of land and water resources are necessary. Future increases in food production will need to occur largely on existing agricultural land; 80 percent of the growth in crop production in developing countries is expected to come from higher yields and increased cropping intensity, with the remainder coming from land expansion (FAO 2009). Allowing for relatively ambitious reductions in inefficiencies will necessitate large increases in water use. It is estimated that annual agricultural water use will need to increase from approximately 7,100 km^3 globally to between 8,500 and 11,000 km^3 in order to meet food requirements in 2050 (de Fraiture et al. 2010).

As water scarcity is increasing in many regions, along with salinization and pollution of rivers and water bodies and degradation of water-related ecosystems, mobilizing the water resources needed to increase food production will require informed decisions within the water sector and in related sectors in order to balance



	Greater Mekong Subregion	Nile Basin
Population	275 million	238 million
Area	2.6 million km^2	3.1 million km^2
Countries	Cambodia, Vietnam, Lao P.D.R., Thailand, Mynamar, China	Tanzania, Kenya, Rwanda, Burundi, Uganada, Democratic Republic of Congo, Ethiopia, Sudan, South Sudan, Eritrea, Egypt
Major Crops	Rice, maize, cassava	Cassava, maize, wheat
Annual Rainfall	700-5000 mm/yr	0-2060 mm/yr

Figure 1. Overview of the study locations (Source: Johnston et al. 2010; Nile Basin Initiative 2012).

water use and requirements among sectors (FAO 2011). Climate change is likely to complicate these efforts; the Intergovernmental Panel on Climate Change has highlighted the increased vulnerability of freshwater resources under climate change scenarios that result in greater climatic and hydrological variability (Field et al. 2012). Effective management of water across sectors requires information on how much water is available and how much is being used and depleted for various purposes, as well as an understanding of how this will change under future scenarios. As a result, achieving water security for regions, nations, and individuals is increasingly identified as one of the greatest development challenges confronting the world today (USAID 2013).

To showcase lessons learned in providing the information needed for effective water decision-making, we consider two cases, the Greater Mekong Subregion and the Nile Basin, where the range of agricultural water management uses have been studied at the regional scale as an input to planning and policy formulation (Figure 1). The overall objective of this paper is to demonstrate the potential tools and methods that can be used to assess agricultural water use at the national to regional scale. The two case studies have been selected because agriculture is the biggest consumer of water in each and is critical to poverty reduction. Informed decisions are essential in each location in order to balance water use requirements among sectors, as well as to ensure effective management of the resource under climate change scenarios and future increases in food production. Analysis of these two regions allows us to examine the methodologies and approaches used to assess agricultural water use, the utility of this information to decision-making in the water and agricultural sectors, and the limitations of the information gathered.

The Greater Mekong Subregion

Rapid economic growth and increasing populations in the Greater Mekong Subregion (GMS) are resulting in increasing demand for food. To keep pace with growing populations and dietary changes, food production in the GMS will need to increase by an estimated 25 percent over the next 15 years. In order to achieve this, decisions need to be made regarding the management of water resources in the region, that balance the requirements of different sectors. The three major interlinked water related sectors in the GMS are hydropower, agriculture and fisheries. Management responses need to take into account the interactions and trade-offs between these sectors in order to offset potential conflicts and to capitalize on synergies (Johnston et al. 2010).

Agriculture is currently the greatest consumer of water in all GMS countries, accounting for 68 percent of all withdrawals in the People's Republic

of China and in Vietnam, to over 90 percent in Cambodia, Lao P.D.R., Myanmar and Thailand (Johnston et al. 2010). As the availability of renewable freshwater is high in most countries, rainfed systems dominate and the proportion of irrigated land is low in comparison to other regions. Upgrading these systems has the potential to increase resilience to future increases in climatic variability, and promises large social, economic and environmental paybacks in terms of reducing poverty and boosting economic development. A study, commissioned by the Swedish International Development Cooperation Agency (Sida), and undertaken by the International Water Management Institute investigated opportunities for improving production in rainfed agriculture in the GMS through small-scale water management interventions (Johnston et al. 2012). The study analyzed the agro-ecosystems and current patterns of production in the GMS, the impacts of climate on production (using current and projected future climate data), the suitability of crops under different conditions, and the current versus potential yield. Suitable agricultural water management interventions for different contexts were also assessed, as was the current and potential use of groundwater in agriculture in the region.

Data Availability and Constraints

Data for the agro-climate analysis were derived from the global Climate Research Unit (CRU) of the University of East Anglia, which provided gridded, monthly rainfall and potential evapotranspiration data at 0.50 for the period 1901 to 2009 (Mitchell and Jones 2005). In addition, detailed analysis of variability in key climate parameters relating to crop growth were analyzed for two locations (Ubon Ratchathani in Thailand, and Luang Prabang in Lao P.D.R.) using pan evaporation data measured from 1962 to 2004 and rainfall time series recorded at the two stations from 1953 to 2004. Potential climate change in the GMS was characterized using daily rainfall and temperature time series produced by the regional climate model, Providing Regional Climates for Impacts Studies (PRECIS), and forced by the global climate model, European Centre Hamburg Model, version 4 (ECHAM4), under the SRES scenarios A2 and B2 over the period 1960 to 2049.

As this was a regional analysis, agricultural statistics were compiled at national to provincial level. National crop production and yield trend data were derived from published national statistics compiled by FAO available through the FAOSTAT database (faostat.fao.org), which includes data from 1960 to the present. To examine spatial patterns of production, crop statistics at provincial level were compiled from data published by national statistical agencies and FAO Regional Data Exchange System (FAORAP) (www.faorap-apcas.org). Availability of data varied between countries; reliable time series data at provincial level could be sourced at the time of the study only for Cambodia (MAFF 2009) and Vietnam (VN GSO 2011).

Bioclimatic suitability of crops was assessed using data from the FAO EcoCrop database (ecocrop.fao.org). Due to the constraints of the basin-scale study, suitability was assessed based only on bioclimatic variables without considering factors such as soil requirements, pests and diseases; or the specific requirements of different varieties.

Information on current agricultural water management practices, and particularly irrigation, was derived from a range of sources including official estimates of irrigation coverage reported in FAO's AQUASTAT database, national and global land cover mapping (e.g. European Space Agency (ESA) GlobCover), crop production statistics reported by season, and published studies. Estimates of irrigated area are inconsistent and generally unreliable for all GMS countries. This is due to a number of factors. The region's dominant crop is paddy rice, which is grown under varying degrees of water management that range from fully rainfed to fully irrigated depending on location and season. The distinction between irrigated and rainfed cropping in lowland systems is blurred. Growing paddy rice requires water management to maintain inundated conditions even if the water used mainly comes from rainfall or from the recession of seasonal floods. On average, more than half of crop water requirements for irrigated crops in GMS come from rainfall (Johnston et al. 2012). Crop production statistics do not distinguish whether the crop is irrigated and dry season figures include a large component of rainfed production.

For example, more than half of Cambodia's reported dry-season rice crop is actually recession rice watered primarily from receding floodwaters (Nesbitt 2003), while in the Mekong Delta, cultivation of two irrigated dry-season crops per year has progressively replaced traditional wet-season rice, but both crops receive a significant amount of rainfall. Statistics on the area equipped for irrigation do not accurately reflect the actual extent of irrigation, since, in many areas, only a small proportion of the land equipped for irrigation receives water during the dry season. Even in the wet season, poor maintenance and design mean that many systems are not fully functional (see for example Thuon and Bastakoti 2010; McCartney et al. 2013). Areas of informal, farmer-managed pump irrigation are rarely recorded in official statistics, though evidence suggests that they are an increasingly important component of irrigated production.

Our study focused on compiling comprehensive and consistent data across the GMS, which was available only at province to national level. Government agricultural statistics are compiled at finer resolution, but are usually aggregated to district or province level before publication. The FAORAP website (http://www.faorap-apcas.org/) provides details of the systems for reporting sub-national agricultural statistics in each country. Data on crop statistics and water resources at district to village level are sometimes available through government departments in internal reports, usually in local languages, but coverage is patchy and often restricted to specific research studies. Data are used mostly within government agencies for statistical reporting and planning, and analysis and verification vary significantly between countries. There are initiatives in several countries to make data on development-related issues more available in the public domain – see for example Open Development Cambodia (http://www.opendevelopmentcambodia.net/) and Myanmar Information Management Unit (www.themimu.info).

Discussion

The quality and availability of data significantly limited analysis of the effectiveness of and constraints to rainfed agriculture in the GMS. The first issue is the poor quality of information on irrigation. To determine the extent to which access to water is limiting productivity, better information is needed on two different aspects: on the location and extent of irrigation infrastructure (including small-scale, farmer-managed infrastructure, and groundwater systems); and the degree to which irrigation is actually used in different seasons. The first is a relatively simple, though evolving, inventory; the second is more difficult, since it varies both seasonally and spatially. Crop statistics, as currently reported, are not adequate to define irrigation use. Approaches using multi-temporal satellite measurements of greening and evapotranspiration are increasingly being used to map and monitor irrigation (see for example Conrad et al. 2007; Gumma et al. 2010).

Secondly, we found that crop statistics reported at national or even province level are not sufficiently spatially disaggregated to reflect the impacts of weather extremes, which tend to be highly localized. For example, the severe regional drought of 1998 was not reflected by a national-level drop in yield or total production (except in Myanmar); neither was the drought of 2004 in Thailand, despite estimates that it affected two Mha of crops (Bank of Thailand 2005). Collation of crop production data at district to village level would provide a more robust basis for assessing yield patterns and trends.

Because of the paucity of data on farming practices (such as use of fertilizers, improved varieties, mechanization etc.), it is not possible to disaggregate the impacts of water management on yield from those of other management factors. These data tend to be collected only sporadically and for specific studies. The Cambodian Commune Database (available at http://db.ncdd.gov.kh/cdbonline) provides an interesting example of what could be done in this area. This database compiles information collected at village level for a wide range of socio-economic and agricultural indicators, including areas irrigated from different sources, use of chemical fertilizers and pesticides, and ownership of pumps and tractors. This is potentially a very valuable resource for understanding trends in agricultural practices. In practice, however, data are not regularly collected for all fields, and there are inconsistencies in data between years, making trend analysis impossible at this stage.

The Nile Basin

Poverty, food insecurity, and water scarcity are widespread across the Nile Basin, which covers approximately 10 percent of the African continent and is home to about 20 percent of the population. Rapidly increasing populations coupled with existing high levels of food insecurity mean that increasing agricultural production is an urgent imperative for the region (Johnston 2012). The poorer countries in the basin have a greater dependence on agriculture, with contribution to Gross Domestic Product ranging from 17 percent in Egypt to 55 percent in Ethiopia (World Bank 2008). In contrast to Asia, where agricultural expenditure as a percentage of agricultural Gross Domestic Product ranges from 8.5 to 11 percent over the past ten years, in Africa this figure is only five percent (Fan et al. 2008). While the importance of increasing government spending for agriculture has been recognized by African leaders, it is critical to identify the high potential investments that can contribute to increased production and achievement of target growth rates in agricultural Gross Domestic Product.

The identification of suitable water management interventions that will improve access to water, particularly for the poor, and yet sustain the resource, requires an understanding of water availability and use in the basin. A study commissioned by the Challenge Program on Water and Food was undertaken by the International Water Management Institute in the Nile Basin to identify high potential investments that could reduce poverty yet also reverse trends in land and water degradation (Molden et al. 2009). A key component of this focused on the assessment of water availability across the region, and the water productivity of existing agricultural systems, in order to determine how much water is being used, and where there are opportunities to increase agricultural productivity. An initial assessment of the availability of water for agriculture in the basin was carried out using traditional data sources such as hydrological records, climate data and agricultural statistics (Johnston 2012). A water accounting framework based on remotely sensed data was also applied to understand water use patterns and the benefits derived from these uses in the basin (Karimi et al. 2013). Crop water productivity was assessed for the agricultural systems based on the ratio of benefits (i.e. yield) to the amount of water required to produce them, which provides an understanding of the spatial distribution of the effectiveness of water use (Karimi et al. 2012a).

Data availability and constraints

Climate data used in the study were derived from the Climate Research Unit (CRU) (Mitchell and Jones 2005). As in the GMS, these were supplemented by observational data compiled and analysed in this case by Sutcliffe and Parks (1999). Hydrological data were drawn from two sources: a major compilation of data for the Nile by Sutcliffe and Parks (1999), updated by Sutcliffe (2009); and a water account for 23 sub-basins of the Nile developed by Kirby et al. (2010) using the ds552.1 dataset of Dai and Trenberth (2003).

The extent, type, and location of agricultural production was assessed using a combination of national agricultural statistics and land cover maps derived from remote sensing data (European Space Agency Globcover 2009), and an earlier dataset based on AVHRR imagery from 1992-3 (International Water Management Institute 2006). Crop statistics are available for all Nile countries at the national level in FAOSTAT, but disaggregated statistics at the state or province level are patchy, available only for certain crops and for some years. Ethiopia and Sudan publish annual statistics for major crops at sub-national levels based on field surveys. Such data are not available or accessible however, for other countries of the basin. The International Water Management Institute's analysis was based on a combination of published national statistics, unpublished statistics compiled by FA0 (2010), and a study by Bastiaanssen and Perry (2009) for the Nile Basin Initiative. As in the GMS, and despite a very different setting, estimates of irrigated area in the Nile Basin vary widely, ranging from 4.9 to 6.4 million ha, due at least in part to confusion in reporting areas of single versus double cropping. Estimates of areas of rainfed agriculture are even more variable since much of the rainfed agriculture is small-scale subsistence production in mixed crop-livestock systems.

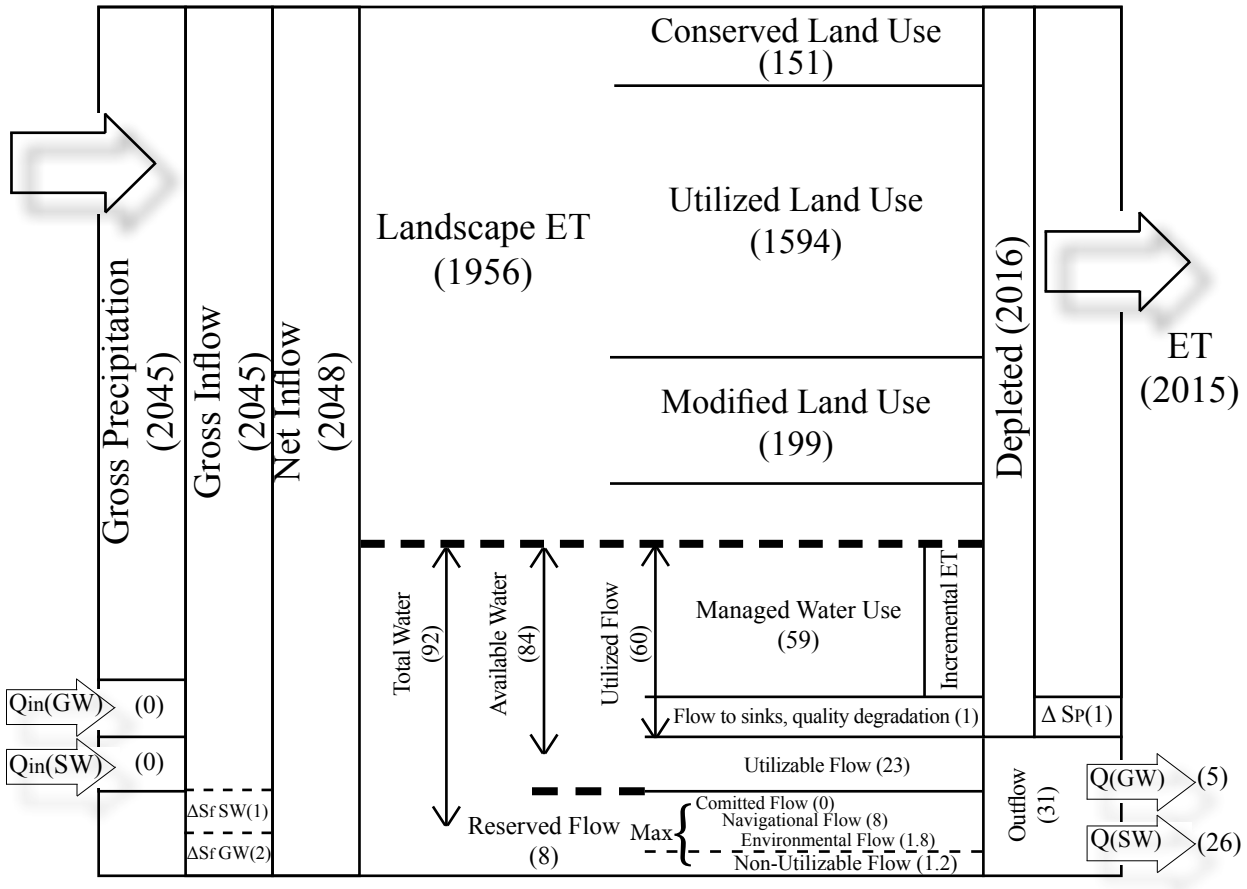


Figure 2. Water account for the Nile Basin, based on remotely sensed data (based on Karimi et al. 2013).

A water accounting framework was developed by Karimi et al. (2013) to understand how water is used in the Nile Basin and to identify opportunities for improvement (Figure 2). The water accounting analysis was based exclusively on remote sensing data. Core input datasets included precipitation derived from 10-day RFE product at 1 km spatial resolution, land cover (European Space Agency GlobCover 2009), and actual evapotranspiration (split into E and T) also at a spatial resolution of 1 km, calculated using ETLook (Bastiaansen et al. 2012). All datasets are publicly available, except for the maps of evapotranspiration, which are a propriety dataset produced by the company WaterWatch (www.waterwatch.nl), and were only available for a single year due to cost restrictions. The accounting method was used to estimate overall water stocks of the basin, water consumption by different land use classes including rainfed and irrigated agriculture, the basin outflow, as well as water and land productivity. The framework separates green water and blue water (Falkenmark and Rockström 2006) and also divides overall water consumption to managed and unmanaged processes. Managed processes refer to water consumptions that are due to human interventions such as agriculture, domestic and industrial use, and evaporation from man-made reservoirs. Unmanaged processes refer to water consumption through evapotranspiration of natural vegetation and evaporation from lakes and natural water bodies. Such information can play a key role in understanding water flows in a basin. For example, results of the study suggest that in the Nile Basin only four percent of total rainfall ends up in the blue water system (which includes water in rivers, lakes, and aquifers) with the remainder (96 percent) consumed through green processes (i.e. evaporation and transpiration from retained rainfall in soil profiles).

Maps of actual evapotranspiration derived from remotely sensed data were used to assess consumptive water use across the basin. This

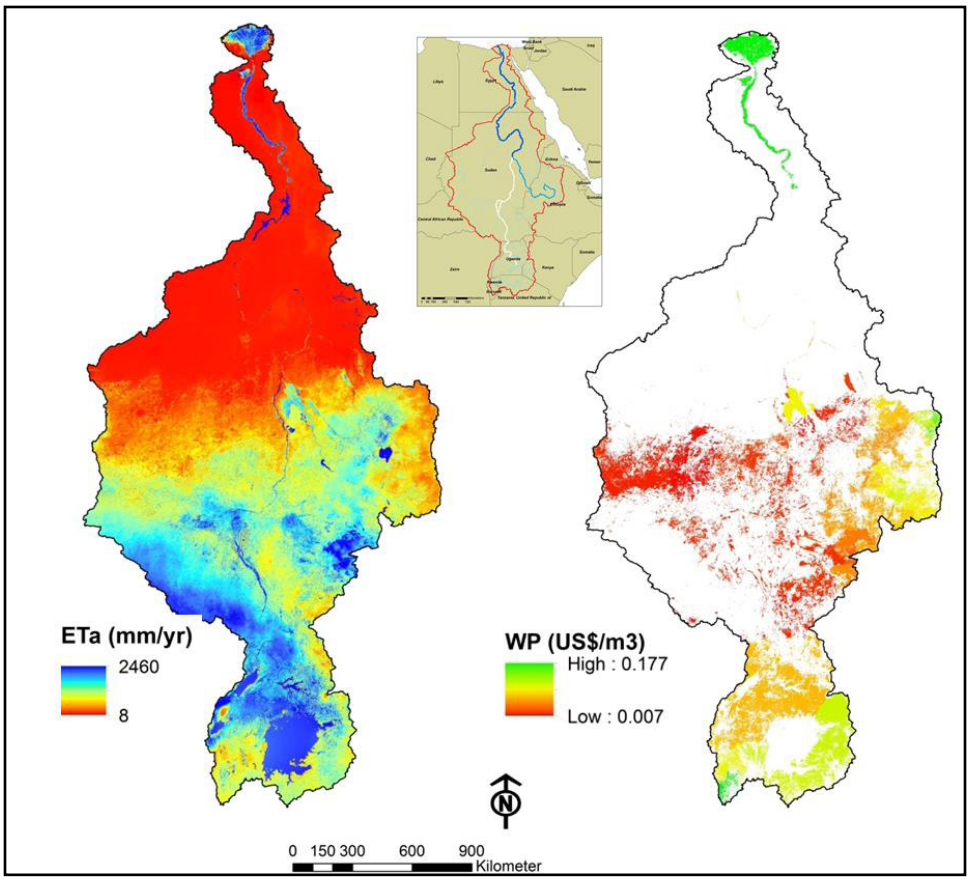


Figure 3. Actual evapotranspiration and derived crop water productivity for the Nile Basin (from Karimi et al. 2012b).

was combined with the Standardized Gross Value of Production (SGVP), derived from national production statistics, in order to estimate crop water productivity across the basin (Figure 3). Using a standardized index such as the SGVP overcomes data constraints that typically occur when working at the transboundary level. Different pricing systems and local market fluctuations can complicate efforts to estimate the total value of agricultural goods and services in large transboundary basins such as the Nile (Karimi et al. 2012b). For this study, wheat was chosen as the base crop, with prices of other crops pegged to the international standard wheat price allowing for comparison of the economic value of the different crops regardless of the country or location (Molden et al. 1998).

Discussion

Since the Nile is effectively a closed basin with less than two percent of total annual precipitation reaching the sea, accurate accounting of water availability and use is an important priority. However, it is surprisingly difficult to get a clear picture of the volume and distribution of flows in the basin. For example, estimates for flow entering the sea through the Delta vary between 4 and 28 km^3 (see Johnston 2012). This is due in part to extreme spatial and temporal variability in flows but is exacerbated by lack of data, despite a relatively well-developed and long established hydrological monitoring network. Availability of flow monitoring data has declined, rather than increased since the 1960s; and data for major stations in Egypt have not been released into the public domain since the 1990s.

Estimates of water use are similarly constrained. Irrigation accounts for the largest fraction of water use in all Nile Basin countries, but estimates of irrigated area and irrigation water use vary widely, which compromises planning for water allocation. For example, recent studies put demand within Egypt between 42 and 66 km^3 annually (Awulachew et al. 2012 and FAO 2010,

respectively). In planning terms, the difference is highly significant. Given that Egypt's nominal total allocation (for all uses including irrigation) under the Nile Agreement is 55.5 bcm, the lower estimate indicates that Egypt has room to increase current levels of irrigation. The higher estimates suggest that Egypt is already overusing its allocation by 10 bcm (20 percent), and is dependent on "excess" flows to Aswan that may not be guaranteed in the longer term, resulting in vulnerability to any increase in upstream withdrawals (Johnston 2012). Karimi et al. (2012a) used satellite estimates of ET and land use in combination with census data on crop production and market prices of crops to map crop water productivity in the Nile basin. They were able to distinguish significant differences in water productivity across the basin by comparing crop yield and other production statistics with water use (mapped as evapotranspiration). The method provides useful information on spatial variation of productivity of water use in agriculture. Nonetheless, the spatial resolution of the resulting map depends on the scale at which production statistics are reported and collected. In the Nile Basin, production statistics are available at province and state level at best. Hence, the results are too coarse for any decision on focused interventions. The effectiveness and accuracy of these analyses would be considerably increased if agricultural statistics could be disaggregated to a finer level, particularly in Sudan and Ethiopia, where conditions for rainfed agriculture vary significantly within a single state. In the absence of detailed information on crop types, all the agricultural crops were aggregated. As a result, the effect of crop choice on overall water productivity could not be assessed. Information on climate and land use is very sparse in many areas of the Nile Basin and, as a result, many studies rely on remotely sensed data. Multi-temporal evapotranspiration datasets, such as those produced from MODIS (modis.gsfc.nasa.gov), enable consistent estimates of crop water use and (within the constraints of low spatial resolution) can be used to map irrigated areas. Products from sensors such as MODIS are publicly available, and those derived from combinations of different datasets are becoming more accessible to non-specialist users through initiatives such as the Famine Early Warning Systems Network (www.fews.net). Importantly, these databases are acquired through replicable methods and are politically neutral, a significant fact in the highly political transboundary context of the Nile. Validation of these data (and model outputs derived from them) against actual field conditions is, however, an ongoing and important challenge.

In the light of Egypt's dependence on the Nile, and the prospect of conflict between basin countries over water, perhaps the most pressing question facing planners in the basin is the extent to which upstream development will impinge on supplies to Egypt. The International Water Management Institute's study concluded that uncertainties in current estimates of both irrigation demand and available flows are so high that it is not possible to determine the stage at which demand will outstrip supply in Egypt. That such a critical question cannot be resolved underlines the urgent need to improve water-related information for the basin, and, equally importantly, sharing of that information among countries. The Nile Basin Initiative (www.nbi.org) is attempting to address these deficiencies by promoting open exchange of information through institutional dialogues and a shared information system (http://nileis.nilebasin.org/). Progress is limited by the lack of available data in some countries, but also by the difficult politics of transboundary water management in the Nile Basin (see Abawari 2011; Paisley and Henshaw 2013).

Conclusions

Two cases have been presented in this paper where the range of agricultural water management uses has been examined. The methodologies and approaches used have been discussed, and the availability and constraints of available data determined. In the GMS, the quality and availability of data significantly limited analysis of the effectiveness of, and constraints to, rainfed agriculture. In particular, the poor quality of information on irrigation and the lack of detailed or spatially disaggregated crop statistics proved a major hindrance. In the Nile, the integrity of the hydrological monitoring network and the availability of reliable records of river flows were a major constraint, along with the lack of accurate data on irrigation extent and water use.

Crop statistics were also required at a higher level of disaggregation.

As in the Nile and GMS, agriculture is the largest consumer of water in many countries across Africa and Asia. Future increases in food production to meet the needs of expanding populations in these regions will necessitate large increases in water use. Mobilizing the water resources needed and identifying appropriate management decisions will require an understanding of how much water is available. Detailed, reliable, and regular water accounts in agricultural basins are needed to ensure proper monitoring and management of water resources. In both of the case studies presented here, the quality and availability of data has limited the analysis and hindered the identification of appropriate interventions to increase the productivity of the agricultural systems.

Access to hydrological data is still a challenge in many parts of the world. Investing in data collection is critical at the national level, and the UN has emphasized that the decline of hydrological networks needs to be stopped and reversed so that decision-making can be based on solid empirical evidence (UN Water 2013). With the increasing demand on water for agriculture to meet global food needs, it is becoming increasingly important to ensure that water resources decision-making has access to information that captures the spectrum of water uses across seasons and over time. The lack of such information will directly affect the identification of successful and sustainable investments and limit the formulation of informed policies that are viable in the long term as well as the immediate future.

In recent years, the increasing availability of Earth observation data has resulted in a move away from conventional, ground-based measures and ways of augmenting data availability with approaches developed that increasingly rely on the use of remote sensing data. Remotely sensed data are an attractive alternative to in situ methods. Satellites provide spatial information with a high temporal frequency over wide areas, and are publicly (although not always freely) available. Hence, they provide the opportunity for building time series databases on various hydrological parameters such as precipitation, evapotranspiration, snow cover, and soil moisture at different spatial and temporal scales. The replicable, publicly available nature of the data is particularly important in regions where there is potential for conflict over water resources. In addition, significant progress has been made over the past few years in data assimilation capabilities allowing for the integration of remote sensing data products along with ground-based observations into land surface and hydrological models, metrics and accounting frameworks.

The water accounting framework described by Karimi et al. (2013) offers an alternative approach to assessing water use in a basin where almost all of the input data can typically be derived from satellite measurements. The framework provides a link between water consumption and land use. Hence, it allows evaluation of the impact of future interventions, which involve land use change, on water flows in river basins. The WA+ separates blue and green water flows. This has an important implication for water allocations and also for identifying effective water-saving strategies. The example described by Karimi et al. (2012b) is based on analysis for a single year, but the real benefits of such accounting practices will come with multiple-year analysis. Multiple-year analysis would allow planners to define the baseline status of water resources in the basin, assess performance of the current basin water management regime in an average year, identify future issues and opportunities for water resources development, and evaluate the impact of proposed large-scale interventions in water and land management, such as increasing areas under irrigation. Flow measurements data, if they exist, can be used to verify the results of water accounting analysis at both basin and sub-basin levels. Ideally water accounting should be done at sub-basin level and with a monthly temporal scale. This would allow the users to better understand local conditions, and spatial and temporal variations of water availability and water use patterns.

In addition to the above, it is important to stress the need for better information other than that on water, especially from the agricultural sector. Effective management of water requires information on how much is available, how this is being used, the impact of other sectors on water, and an understanding of how this will change under future scenarios. Informed decision making in the water

and related sectors, especially agriculture, requires access to relevant information that captures this. Other than the information that could be drawn from remotely-sensed sources, the studies reviewed here relied on global data sets that are usually aggregated from national reports, especially for data related to agricultural production. The rigor and completeness of such information varies considerably. Furthermore, the availability of relevant comprehensive data sets that are disaggregated at the sub-national levels was generally quite limited in the countries in both of these important basins.

Acknowledgements

This work was undertaken as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security, which is a strategic partnership of CGIAR and Future Earth, and as part of the CGIAR Research Program on Water, Land and Ecosystems which is led by the International Water Management Institute, a member of the CGIAR Consortium. CGIAR is a global research partnership for a food secure future. The views expressed in this document cannot be taken to reflect the official opinions of CGIAR or Future Earth.

Author Bios and Contact Information

Lisa-Maria Rebelo is a Senior Researcher with the International Water Management Institute in Vientiane, Lao P.D.R. Her research focuses on the provision of spatial information for land and water management, and in particular on the application of remote sensing tools to better understand the influence of various agricultural water management practices on wetlands and other agro-ecosystems, and the interactions between basin scale hydrological and ecological functioning.

Robyn Johnston is a Senior Researcher with the International Water Management Institute in Colombo, Sri Lanka. Her research on water resources planning and management focuses on the integration of scientific, economic and social information. Before joining IWMI in 2009, she worked with the Mekong River Commission in Southeast Asia and with the Murray Darling Basin Commission in Australia. She can be contacted at r.johnston@cgiar.org .

Poolad Karimi is a Post-Doctoral scientist with the International Water Management Institute in Colombo, Sri Lanka. His current research focuses on river basin water accounting. He has also worked on issues related to agricultural water management and productivity of water use in agriculture in different regions in Africa and Asia. He can be contacted at P.Karimi@cgiar.org.

Peter G. McCornick, Deputy Director General-Research, International Water Management Institute, Colombo, Sri Lanka. He directs IWMI's research for development program. He can be contacted a P.McCornick@cgiar.org.

References

Abawari, Y.M. 2011. *Conflict and Cooperation among the Nile Basin Countries with Special Emphasis on the Nile Basin Initiative (NBI)*. International Institute of Social Studies, The Hague.

Awulachew, S., D. Bekele, S. Solomon, F. Hagos, T. Erkossa, and D. Peden. 2012. Water management intervention analysis in the Nile Basin. In Awulachew, Seleshi Bekele; Smakhtin, Vladimir; Molden, David; Peden D. (Eds.). *The Nile River Basin: Water, agriculture, governance and livelihoods.* Abingdon, UK: Routledge-Earthscan, 292-311.

Bank of Thailand. 2005. *The Inflation Report - January 2005*. Bangkok, Thailand: Bank of Thailand. http://www.bot.or.th/English/MonetaryPolicy/Inflation/Download/Doc_LibInflation%20Report/5.1.1full_eng.pdf (accessed on January 23, 2011).

Bastiaanssen, W. and C. Perry. 2009. Agricultural water use and water productivity in the large scale irrigation schemes of the Nile Basin. *Report for the Efficient Water Use in Agriculture Project*, Nile Basin Initiative.

Bastiaanssen, W.G.M., M.J.M. Cheema, W.W. Immerzeel, I. Miltenburg, and H. Pelgrum. 2012. The surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model. *Water Resources Research* 48(11).

Conrad, C., S. Dech, M. Hafeez, J. Lamers, C. Martius, and G. Strunz. 2007. Mapping and assessing water use in a Central Asian irrigation system by utilizing MODIS remote sensing products. *Irrigation and Drainage Systems* 21(3-4): 197-218.

Dai, A. and K.E. Trenberth. 2003. New Estimates of Continental Discharge and Oceanic Freshwater Transport. *Proceedings of the Symposium on Observing and Understanding the Variability of Water in Weather and Climate*, 83rd Annual AMS Meeting, American Meteorological Society. Long Beach, California, 18.

de Fraiture, C. and D. Wichelns. 2010. Satisfying future water demands for agriculture, *Agricultural Water Management* 97(4): 502-511.

European Space Agency Globcover Project 2009. Available online at http://due.esrin.esa.int/globcover/.

Falkenmark, M., and J. Rockström. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management, *Jounral of Water Resource Planning and Management* 132(3): 129-133.

Fan, S., M. Johnson, A. Saurkar, and T. Makombe. 2008. *Investing in African Agriculture to Halve Poverty By 2015*, IFPRI Discussion Paper 751. Washington, D.C. International Food Policy Research Institute (IFPRI).

Food and Agriculture Organization of the United Nations. 2009. Global Agriculture Towards 2050, High-Level Expert Forum, *How to feed the World 2050 Information Brief*, Rome, Italy.

Food and Agriculture Organization of the United Nations. 2010. *Areas of Rainfed and Irrigated Cropping in the Nile Basin*.Unpublished data.

Food and Agriculture Organization of the United Nations. 2011. The State of the World's Land and Water Resources for Food and Agriculture, Managing Systems at Risk. *Food and Agriculture Organization of the United Nations Report*, Earthscan, Rome, Italy

Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley. (Eds.). 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, Cambridge, U.K.., 582.

Gumma, M.K., A. Nelson, P.S. Thenkabail, and A.N. Singh. 2010. Mapping rice areas of South Asia using MODIS multitemporal data. *Journal of Applied Remote Sensing* 22(12): 053547-053547-26.

International Water Management Institute. 2006. *USGS Landuse/Landcover: Nile river basin*. Colombo, Sri Lanka: Center of Remote Sensing and Geographic Information System, International Water Management Institute.

Johnston, R. 2012. Availability of water for agriculture in the Nile Basin. In Awulachew, S.B., V. Smakhtin, D. Molden, and D. Peden (Eds.). *The Nile River Basin: Water, agriculture, governance and livelihoods*. Abingdon, UK: Routledge - Earthscan, 61-83.

Johnston, R., C.T. Hoanh, G. Lacombe, R. Lefroy, P. Pavelic, and C. Fry. 2012. Managing water in rainfed agriculture in the Greater Mekong Subregion. *Final Report Prepared by IWMI for Swedish International Development Cooperation Agency (Sida)*. Colombo, Sri Lanka: International Water Management Institute (IWMI); Stockholm, Sweden: Swedish International Development Cooperation Agency (Sida), 100.

Johnston, R., C.T. Hoanh, G. Lacombe, A. Noble, V. Smakhtin, D. Suhardiman, S.P. Kam, and P.S. Choo. 2010. *Rethinking Agriculture in the Greater Mekong Subregion: How to sustainably meet food needs, enhance ecosystem services and cope with climate change*. [Summary report]. Colombo, Sri Lanka, International Water Management Institute (IWMI), 24.

Karimi, P., D. Molden, W.G.M. Bastiaanssen, and X. Cai. 2012a. Water accounting to assess use and productivity of water: Evolution of a concept and new frontiers. In Godfrey, J.M. and K. Chalmers (Eds.). *Water Accounting: International Approaches to Policy and Decision-Making*. Edward Elgar Publishing, U.K.: 76-88.

Karimi, P., D. Molden, A. Notenbaert, D. Peden. 2012b. Nile basin farming systems and productivity. *In The Nile river basin; water, agriculture, governance and livelihoods*. Edited by Awulachew, et al.. Routledge, U.K., 133-153.

Karimi, P., W.G.M. Bastiaanssen, and D. Molden, 2013. Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements. *Hydrology Earth System Science* 17: 2459-2472.

Kirby, M., J. Eastham, and M. Mainuddin. 2010. Water-use accounts in CPWF basins: Simple water-use accounting of the Nile Basin. CPWF Working Paper: Basin Focal Project series, BFP03. Colombo, Sri Lanka: *The CGIAR Challenge Program on Water and Food*, 29.

MAFF. 2009. *Agricultural Statistics*. Available online at Ministry of Agriculture, Forestry and Fisheries, Cambodia. Available at: http://www.maff.gov.kh/.

McCartney, M., P. Pavelic, G. Lacombe, K. Latt, A.K. Zan, K. Thein, S. Douangsavanh, S. Balasubramanya, R. Ameer, A. Myint, C. Cho, R. Johnston, and T. Sotoukee. 2013. *Water Resource Assessment of the Dry Zone of Myanmar*. Report to Livelihoods and Food Security Trust Fund / UNOPS for Component 1.

MDG Report 2011. T*he Millenium Development Goals Report 2011*. Available at http://www.un.org/millenniumgoals/reports.shtml, Accessed August 5th 2013.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25: 693-712.

Molden, D., R. Sakthivadivel, C.J. Perry, C. de Fraiture, and W.H. Kloezen.1998. Indicators for comparing performance of irrigated agricultural systems. *Research Report 20*. Colombo, Sri Lanka: International Water Management Institute.

Molden, D., S.B. Awulachew, K. Conniff, L.M. Rebelo, Y. Mohamed, D. Peden, J. Kinyangi, P. van Breugel, A. Mukherji, A. Cascao, A. Notenbaert, S.S. Demise, M.A. Neguid, and G. el Naggar. 2009. Nile Basin Focal Project. *Synthesis Report*. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF).

Nesbitt, H. 2003. *Water used for agriculture in the Lower Mekong Basin*. MRC BDP Research Report. Mekong River Commission, Phnom Penh, 33.

Nile Basin Initiative. 2012. *State of the River Nile Basin*. Available at http://nileis.nilebasin.org.

Paisley, R.K. and T.W. Henshaw. 2013. *Transboundary Governance of the Nile River Basin: Past, Present and Future.* Environmental Development (online). DOI: 10.1016/j.envdev.2013.05.003.

Rockström, J., L. Karlberg, S. Wani, J. Barron, N. Hatibu, T. Oweis, A. Bruggeman, J. Farahani, and Z. Qiang. 2010. Managing water in rainfed agriculture – the need for a paradigm shift. *Agricultural Water Management* 97: 543-550.

Sutcliffe, J.V. and V.P. Parks. 1999. *The Hydrology of the Nile*. IAHS special publication 5. Wallingford: International Association of Hydrological Sciences.

Sutcliffe, J.V. 2009. The hydrology of the Nile Basin. In Dumont, H.J. (Ed.), *The Nile: Origin, Environments, Limnology, and Human Use*. Springer, 334.

Thuon, T. and R.C. Bastakoti. 2010. Localizing Development and Irrigation Management System in Cambodia. In *Water governance in Practice: Evidence from local studies in the Mekong Region.* R.C. Bastakoti, P. Floch, K. Manorom, X. Lu, and B.T. Singh (Eds.). Selangor, Malaysia: Strategic Information and Research Development Centre (SIRD).

U.N.Water. 2013. *A Post-2015 Global Goal on Water: Recommendations from UN-Water.* Report of the UN-Water Working Group on SDGs. Geneva Switzerland.

U.S.AID. 2013. USAID Water and Development Strategy 2013-2018. Available at: http://www.usaid.gov/documents/1865/usaid-water-and-development-strategy-2013-2018.

VN GSO (General Statistical Office of Vietnam). 2011. *Agricultural Statistics for Vietnam. Data Translated and Provided by Soils and Fertilizers Research Institute (SFRI)*, *Vietnam*. Available at http://www.gso.gov.vn/.

World Bank. 2008. *World Development Report 2008: Agriculture for development*. Washington D.C., USA.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 91-92, April 2014

Water Data Resources

Melinda Laituri and Faith Sternlieb

Colorado State University

There exist numerous, web-based water portals that provide links to a variety of water data. We have developed a list of those sites highlighted by the papers in this special issue. Accessing and using water data is a metric of success. Further research needs to be conducted to determine what audiences are using these data and how "user-friendly" such sites are. This represents just a slice of the global water "data landscape." Appendix 1 of Gallaher and Heikkila's paper provides a table of a sample of water agencies examined in the U.S. that provide city, local, and regional state data.

Global Data: Climate, Agriculture, and Water

- Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/data). For example, a historical monthly precipitation dataset for global land regions from 1900 to 1998.
- The PRECIS Regional Climate Modelling System (http://www.metoffice.gov.uk/precis/).Developed by the Met Office Hadley Centre, this is a regional climate modeling system to generate climate change projections.
- European Centre Hamburg Model, ECAHM 6 (http://www.mpimet.mpg.de/en/science/models/echam.html). Developed at the Max Planck Institute for Meteorolggy, ECHAM is an atmospheric general circulation model.
- Food and Agricultural Organization of the United Nations – FAOSTAT (http://faostat.fao.org/). Provides national data on crop production and crop yield trends (and other statistical data on hunger and malnutrition) that includes 245 countries and 35 regional areas from 1961 to present.
- Regional Data Exchange System (RDES) on Food and Agricultural Statistics in Asia and the Pacific (http://www.faorap-apcas.org/). Launched in 2001 and funded by FAO and the Government of Japan, it provides reports and statistical information at the provincial level on crop statistics and country profiles on 16 Asian and Pacific countries.
- Food and Agricultural Organization of the United Nations (FAO) EcoCrop (http://ecocrop.fao.org/ecocrop/srv/en/home). Since 1991, the Land and Water Development Division of FAO created EcoCrop to identify plant species for specific environments to inform land use planning.
- Food and Agricultural Organization of the United Nations (FAO) AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm). A global water information system developed by FAO's Land and Water Division. The program collects, analyzes, and disseminates information on water resources, water uses, and agricultural water management focusing on Africa, Asia, Latin America, and the Caribbean.
- European Space Agency – GlobCover (http://due.esrin.esa.int/globcover/). Beginning in 2005, the GlobCover Portal provides global composites and land cover maps for 2005, 2006, and 2009.

United States Water Data

- U.S. Geological Survey Water Data for the Nation - NWIS (http://waterdata.usgs.gov/nwis). Access to water resources data in all 50 states and territories that include surface water, groundwater, water quality, and water use.

- U.S. Geological Survey National Water Census (http://water.usgs.gov/watercensus/0). Develops new water accounting tools and assesses water availability at regional and national scales.
- U.S. Geological Survey Water Quality Assessment Program (http://water.usgs.gov/nawqa/).NAWQA provides information on water quality conditions, regional and national assessments as well as monitoring of hydrological characteristics. Land use and other landscape features are possible.
- U.S. Geological Survey Reservoir Sedimentation Database (http://ida.water.usgs.gov/ressed/). Provides access to sedimentation survey data for selected reservoirs in the US.
- U.S. Geological Survey WaterAlert (http://maps.waterdata.usgs.gov/mapper/wateralert/). A mobile app service that sends e-mail or text messages when certain parameters measured by USGS realtime data collection stations exceed user-defined thresholds.
- U.S. Geological Survey WaterNow (https://water.usgs.gov/waternow/). Check current conditions at for water data at gaging stations on your cell phone.
- Water Quality Portal (http://www.waterqualitydata.us/). Consortium between the USGS, EPA and the National Water Quality Monitoring Council to provide water quality data.
- U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (http://www.epa.gov/emap2/). Data collected from 1990 to 2006 monitored and assessed the status and trends of national ecological resources.
- U.S. Environmental Protection Agency National Aquatic Resource Surveys (http://water.epa.gov/type/watersheds/monitoring/aquaticsurvey_index.cfm). Data on US streams, rivers, lakes, resevoirs, coastal waters, and wetlands to characterize water quality conditions.
- Consortium of Universities for the Advancement of Hydrologic Science – CUAHSI (http://wdc.cuahsi.org/). Provides data services and data to the hydrologic science community and supports the Hydrological Information System (HIS) accessed via the HydroDesktop (http://hydrodesktop.codeplex.com/). CUAHSI provides access to over 100 agencies and their water data.
- National River Restoration Science Synthesis (http://library.ucr.edu/wrca/restoration/nrrss.html). Provides a catalog of river restoration projects.
- U.S. Geological Survey LandSat 8 - LandSat Data Continuity Mission (http://www.nasa.gov/mission_pages/landsat/main/index.html). LandSat provides the longest unbroken data stream of the Earth's surface, as seen from space, to track land cover changes since 1972.
- NASA Thermal-Infrared Sensor (TIRS) , LandSat 8 (http://www.nasa.gov/mission_pages/landsat/main/LDCM_TIRS_intro.html). State water managers use thermal energy bands to track land use and water consumption for agriculture.
- Water Data Exchange (WaDE) (http://www.westernstateswater.org/wade/). U.S. Western states will adopt a data exchange protocol to sustainably manage water resources to address consumptive use of water for agricultural crops.
- Water Mark-Up Language (http://www.opengeospatial.org/projects/groups/waterml2.0swg). An Open Geospatial Consortium encoding standard for the representation of in-situ hydrological observation data.



Water Systems, Science, and Society Under Global Change
2014 UCOWR / NIWR / CUAHSI Conference

June 18-20, 2014

Conference Theme

Global changes in climate, population, land use, biodiversity, and infrastructure continue to pose enormous challenges to our ability to effectively manage our water resources. UCOWR, CUAHSI, and NIWR invite you and your colleagues to join leading water managers, educators, researchers, and other professionals from across the country to the first joint conference of these national organizations to address some of the most compelling and important challenges facing our profession. This conference is unique because it is both a scientific conference and an exploration of how universities organize themselves to meet societal goals concerning water resources. A central theme to be addressed will be: **How does university water research contribute to solving societal challenges?**

Tufts University



The 42nd Annual Universities Council on Water Resources Conference will be held on the campus of Tufts University–a significant change in format from previous years. Tufts University became an institutional member of UCOWR in 2011 and its lead delegate, Dr. Richard Vogel, has been an active member serving on the Board of Directors and as the 2014 Conference Chair. UCOWR, NIWR, and CUASHI are enthusiastic about the unique opportunities made possible by having the conference on a university campus.

Conference Sponsors

Universities Council On Water Resources

NIWR The National Institutes for Water Resources

CUAHSI universities allied for water research

Current Plenary Sessions

Green, Blue, & Gray Water
- Argen Hoekstra, University of Twente, Netherlands

University Contributions to Water Resource Management
- Dennis Lettermaier, University of Washington
- Robert Hirsch, U.S. Geological Survey

Water Data Services
- Richard Hooper, CUAHSI
- Alva Couch, CUAHSI Water Data Center

Does Integrated Water Resources Management Work?
- Jay Lund, University of California, Davis
- Dan Sheer, Hydrologics, Inc.
- Daene McKinney, University of Texas, Austin

The World's Water Challenges
- Upmanu Lall, Columbia University
- Annette Huber-Lee, Tufts University

Conference Co-Sponsors

USDA

Bank of America

NSF



The Ivanhoe Foundation

Pennsylvania WRRC Pennsylvania Water Resources Research Center

Tufts University

Water Data

Issue Editors
Melinda Laituri and Faith Sternlieb

Introduction

Water Data Systems: Science, Practice, and Policy
Melinda Laituri and Faith Sternlieb.....1

Articles

Past, Present, and Future of Water Data Delivery from the U.S. Geological Survey
Robert M. Hirsch and Gary T. Fisher.....4

A Vision of Future Observations for Western U.S. Extreme Precipitation and Flooding
F.M.Ralph, M. Dettinger, A. White, D. Reynolds, D. Cayan, T. Schneider, R. Cifelli, K. Redmond, M. Anderson, F. Gherke, J. Jones, K. Mahone, L. Johnson, S. Gutman, V. Chandrasekar, A. Rost, J. Lundquist, N.Molotch, L. Brekke, R. Pulwarty, J. Horel, L. Schick, A. Edman, P. Mote, J. Abatzoglou, R. Pierce, and G. Wick.....16

WaDE: An Interoperable Data Exchange Network for Sharing Water Planning and Use Data
Sara G. Larsen and Dwane Young.....33

Landsat Thermal Infrared Imagery and Western Water Management
Anthony G. Willardson.....42

A Social-Ecological Framework to Integrate Multiple Objectives for Environmental Flows Management
David M. Martin, Dylan Harrison-Atlas, Nicholas A. Sutfin, and N. LeRoy Poff.....49

Social Observation for Sustainability Science About Water
John B. Braden.....59

Challenges and Opportunities for Collecting and Sharing Data on Water Governance Institutions
Samuel Gallaher and Tanya Heikkila.....66

Determining the Dynamics of Agricultural Water Use: Cases from Asia and Africa
L. M. Rebelo, R. Johnston, P. Karimi, and P. McCornick.....79

Conclusion

Water Data Resources
Melinda Laituri and Faith Sternlieb.....91



2014 UCOWR / NIWR / CUAHSI
Annual Conference
Water Systems, Science, and Society
Under Global Change
Boston, Massachusetts
June 18-20, 2014

Universities Council on Water Resources
Faner Hall, Room 4543 - Mail Code 4526
1000 Faner Drive
Southern Illinois University
Carbondale, IL 62901
www.ucowr.org