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AWRA AT 50: WATER RESOURCES IN THE U.S., 1964-2014

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PROGRESS IN DATA COLLECTION AND DISSEMINATION IN WATER RESOURCES – 1974-2014

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INTRODUCTION

In the 50 years since the founding of the American Water Resources Association (AWRA), there has been tremendous and likely unforeseen progress in water-resources data collection and dissemination. Langford and Doyel (1974) (henceforth L&D) described progress during the decade following the founding of AWRA, and focused their description around seven topics. L&D described the changes as being "more philosophical than technical," and noted the importance to the water-resources community of the more than 30 Federal Acts or Amendments enacted in the decade.

The purpose of this article is to provide an update to L&D by reviewing L&D's predictions of anticipated changes in water resources data collection and dissemination, providing an overview of some of the drivers of change in the water-resources community in the last 40 years, identifying some key advances in water-resources data collection and dissemination since 1974, and outlining some important near-term challenges. The overview is necessarily incomplete, but represents one perspective based on years of collaboration throughout the water-resources community.

REVIEW OF LANGFORD AND DOYEL'S PREDICTIONS

L&D outlined seven topics as indicators of change during 1964-1974. These topics were (1) knowledge of the data base, (2) data dissemination, (3) coordination of data collection, (4) data collection methods, (5) the water-data user community, (6) interpretation of water data, and (7) the role of States in water data collection and dissemination. At some level, each of these topics remains an issue today, although perhaps in a manner somewhat different from that in 1974.

Building on these seven topics, L&D outlined four "major changes that we can see for the future."

• ***Recognition of, and improved communication with, a new, expanded user community coupled with the development of new information products that will meet their needs.*** It is unlikely that L&D foresaw the development of the Internet, wireless technology, miniaturization of computing, or even the development of satellite communications, but these developments have combined to help connect water data to a much broader water-data user community than existed in 1974. Water-data users now have expanded beyond the traditional engineering design community to include those who rely on real-time data for operational decisions; those who conduct research on an array of multi-disciplinary activities and depend on readily available water data of all types; and citizens and nongovernmental organizations (NGOs) that plan recreational activities, "adopt" water bodies, or advocate for particular decisions, policies, and regulations.

• ***Agreement on data acquisition methodologies that will permit various data to be utilized and evaluated in conjunction with each other, no matter what the source of those data may be.*** L&D articulated an important concept – the use of data from all sources to provide a broader perspective than possible using data from one or selected sources. This certainly is an issue of resources, but also was recognition by L&D of the (correctly) anticipated increased role of States in water-data collection (see below).

The water-data community recognizes the general need for consistent methodologies, both in data acquisition and in data interoperability – a topic which was less of an issue in 1974. Progress has been made in development of standards for data acquisition. As was the case in 1974, there remain a number of organizations that publish standards for water data collection and/or laboratory methods, including the International Standards Organization, ASTM International, and the World Meteorological Organization WMO), as well as numerous Federal agencies – primarily the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (USEPA). To some extent, however, the water-data community has begun to recognize that the harmonization of all water-data collection methods will not be possible. In addition to the number of organizations producing standards, new sensors, new uses for existing sensors, and new analytical methods continue to be developed, further complicating the development and maintenance of a single set of standards for water-data collection. Nevertheless, there remains a need, as L&D said, for greater agreement on some set of fundamental data acquisition methodologies to permit greater utilization of all data.

• ***The utilization of the indexing technique to assure availability of data and the voluntary participation of the data organizations in such an effort. This is in contrast to a central-data-bank concept.*** L&D perhaps were visionary on this point, although the fulfillment of the vision likely was in a way not foreseen at the time. In the 1980s and into the 1990s, there was a general attempt by organizations to centralize data storage. As the Internet was developed and grew in the last 15-20 years, as computing power grew, and as the need for water-data expanded, the capabilities of the Internet and still-developing data-sharing standards have been exploited by the water-data community to, among other things, move away from the "central-data-bank concept." The release of the Water Quality Data Portal

(www.waterqualitydata.us) in 2011 was an important milestone in this regard – satisfying a decades-old goal of federating water-quality data from states, tribes, and Federal agencies using common syntax and semantics. Most Federal water data collectors in the United States (U.S.) make their data freely available, although there are many instances in which data are not readily discoverable.

The water-data community now is emphasizing data sharing through interoperable web services using a standardized information model formalized in XML. Some explanation is in order. Web services are a means for facilitating interoperability among different applications, databases, and platforms (computer and operating system) over a network. XML (Extensible Markup Language) defines a set of rules for encoding and decoding data in a format that is both human- and machine-readable and is the most widely used approach for representing data structures in web services. Through the Open Geospatial Consortium (Open Geospatial Consortium, 2014) and the WMO, the Hydrology Domain Working Group has adopted WaterML 2.0, as the standard for transmitting hydrologic data via web services. WaterML greatly facilitates the ability to publish, find, and share data with known provenance, more-or-less realizing the prediction of L&D.

• ***The increasingly active role that will be played by State organizations.*** L&D correctly anticipated this change. The greatest driver of this change likely was the creation of the USEPA and the passage of several key pieces of environmental legislation. In most cases, USEPA delegated authority for implementation of regulations formed under the legislation to States. Implementation generally required increased water-data collection by States, often funded by Federal grants.

DRIVERS OF CHANGE, 1974-2014

L&D discussed funding of U.S. Geological Survey (USGS) water programs, noting an increase in funding in constant (1964) dollars of almost 50% during the decade. By comparison, total funding to USGS Water programs in the last decade has declined almost 20 percent in constant dollars, although it is 12% higher today than it was in 1974. Of course, the funding landscape for water-data collection has changed in the last 40 years, with the emergence of National Aeronautical and Space Administration (NASA), National Oceanographic and Atmospheric Administration (NOAA), and U.S. Department of Agriculture as purveyors of water data, the growth of water-data collection funded by the National Science Foundation, and contributions of NGOs to water-data. Nevertheless, water-data monitoring remains poorly funded, networks suffer from instability, and infrastructure is in need of enhancements (Federal Interagency Panel on Climate Change and Water Data and Information, 2011). Unfortunately, maintenance and enhancement of existing networks suffers in comparison to new initiatives (Cody and Carter, 2009).

L&D noted that the "onslaught of legislation aimed either directly at the water-resources field or at the broader environmental area" had a major effect on water-data activities during the first decade of the AWRA. Although there arguably have been fewer major environmental Acts since 1974, The Toxics Substances Control and the Resource Conservation and Recovery Acts of 1976 being exceptions, most of the Acts passed during 1964-1974 have been re-authorized or amended. These Acts and subsequent regulations continue to affect the need for and use of water data.

The Safe Drinking Water Act Amendments of 1986 and 1996 had an impact on water-data collection and dissemination of the data to the public. These amendments made public information and source-water protection major elements of the Act, and required utilities to collect and disseminate source water-data and treated water-data information.

L&D failed to mention two pieces of legislation passed during 1964-1974 that subsequently became major drivers of change in the water-resources community. First, the Endangered Species Act of 1973 has resulted in a major paradigm shift in water-resources management and in the need for a different kind of water-resources data. One of the first reports on the relation between streamflow and the health of aquatic ecosystems was published in 1964 (Rantz, 1964), with a subsequent early paper on recommended instream flow regimes published in 1974 (Tennant, 1976). Subsequently, understanding of the relations between flow regimes and ecological health has blossomed (e.g. Poff and Zimmerman, 2010), with an attendant demand and use for water data.

The Water Resources Research Act of 1964 (P.L. 88-379 codified at 42 U.S.C. 10301 *et seq.*) authorizes a water resources research institute (WRRI) in each state and territory of the U.S. The establishment of 54 WRRIs, the organization of National Institutes for Water Resources, and the subsequent growth of degree programs in hydrology and environmental sciences together have changed water-resources higher education in the U.S. Although the strength and influence of the WRRIs vary, in many states, the WRRIs were instrumental in the improvement of water-resources academic programs and in enhancing water-resources undergraduate and graduate experiences. WRRIs also helped improve connections between academia and practitioners in State and local agencies.

As late as the mid-1990s, most water data were delivered months after measurement. Since about the mid-1980s, there has been a revolution in water data collection and delivery suggesting that the major developments around water data in the last 40 years have been "more technical than philosophical," in contrast to changes during 1964-1974. Major advances have been made in measurement technology and in information communication. Of particular note are the following developments.

• ***The replacement of mechanical current meters with hydroacoustic methods for measuring velocity (USGS, 2014a) –*** Hydroacoustic meters (1) can be used to profile velocity in the entire water column; (2) allow the measurement of river discharge from a moving boat, whether manned or unmanned; (3) permit the measurement of river discharge in previously-unmeasurable locations and conditions; and (4) greatly improve the safety,

speed, and information content of discharge measurements.

• ***The development of new and greatly improved water-quality sensors –*** The technology for real-time, in situ water-quality measurements has been developed since 1974. Currently, there are a limited number of water-quality measurements that can be made using in situ sensors (e.g., temperature, conductivity, dissolved oxygen, total dissolved gas, dissolved carbon dioxide, pH, turbidity, nitrate, dissolved organic carbon, chlorophyll a, photosynthetically-active radiation, and oxidation-reduction potential), with some additional measurements available using field-ready instruments that traditionally have been used in the laboratory (e.g., water isotopes, nitrate, ammonium, and phosphate). Demand for these types of data, as well new water-quality measurements likely will grow.

• ***The near real-time delivery of water-data information from the measurement site to the database using satellite and cellular technology –*** In 1974, water data were stored and transmitted in analog format, with digital storage devices becoming more common in the mid-1980s, although data from these devices had to be retrieved through a visit to the site. By the mid-1990s, transmission of data directly to the database via satellite was growing more common, with continued growth in use of cellular and satellite technology to transmit water data from the field. The availability of the real-time data has created high expectations among the user community for always-available, real-time data and has driven a greatly increased demand for the data. For example, in 2000 fewer than 1 million USGS water-data pages were viewed per month, whereas in 2014 the number has increased to well over 40 million pages per month and more than half of the requests are automated through web services.

• ***The use of the Internet and web services to deliver water-data, which was previously discussed.***

• ***The development and application of Geographic Information Systems (GIS) –*** With the growth of computing power came the development of GIS in the 1980s. GIS allows users to visualize and analyze spatial data (i.e., data that are associated with a specific location on the Earth). GIS has found wide use in water resources, and the subsequent National Hydrologic (NHD) and Watershed Boundary Datasets (WBD), have standardized the way in which water data are represented within GIS. The NHD represents the surface drainage network, including natural channels, canals, control structures, and other water-related features. Water-data collection points can then be associated with a location on the NHD, as well as with other geospatial themes such as land use, topography, geology, etc. The WBD is a set of standardized watershed boundaries for the U.S. at eight different scales (see http://nhd.usgs.gov/).

The primary water-resources issue in 1974 was improvement of the Nation's ground- and surface-water quality. Although there has been significant improvement, primarily through reductions of point-source inputs, water-quality improvements in many regions have stagnated in recent years (e.g., Sprague *et al.*, 2011). However, because of recent droughts, growing population, rapidly increasing domestic energy production, the desire to maintain environmental flows, depletion of groundwater in some aquifers, and concerns about effects of a warming climate on the water cycle, the sustainability of water resources in both the U.S. and internationally is a growing concern and a new driver for robust water data.

In addition to the need to sustainably manage water resources, the increased availability of global data sets, increased computing power, and the need to better understand effects of a warming climate on water availability, research on and understanding of the global water cycle has greatly increased in recent years (e.g., Dettinger and Diaz, 2000; Lavers, *et al.*, 2010). The development, still ongoing, of coupled climate – terrestrial models that simulate the connections between climate and the water cycle have huge data demands, generally for gridded data. In the past, water data generally were supplied as point measurements, so new methods have been developed to move between point measurements and gridded data, and new data sets have been generated from both *in situ* measurements and remotely-sensed measurements. The ability to rapidly assimilate new data in near real-time into models and decision support tools has the potential to vastly improve water-resources management.

A relatively recent development is the explosive growth of social media, loosely defined as interactions among people in which they create and share information and ideas in virtual communities that are dependent on mobile and web-based technologies to create highly-interactive platforms. Social media already have changed, and likely will continue to change the water-data community. For example, USGS has an application (WaterNow; https://water.usgs.gov/waternow/) that allows a user to type in a streamgage number on a mobile device and immediately retrieve current information at the gage, and an application (WaterAlert; http://maps.waterdata.usgs.gov/mapper/wateralert/) that sends the user a message when the current reading at a streamgage, water-quality monitor, or monitoring well exceeds a user-selected threshold. Applications such as these are available from numerous other Federal agencies for a variety of water-information uses. Commercial water-information applications, some of which are free, also are available for download for use on mobile devices.

Social media have increased the use and potential of crowdsourcing, which provides content from a large number of people. A common example of crowdsourcing is the real-time traffic information which is provided to Internet mapping applications and is based on the speed at which a large number of mobile devices are moving along highways. An example of crowdsourcing in the geosciences is the USGS "Did you feel it?" web site (http://earthquake.usgs.gov/earthquakes/dyfi/) in which individuals report their location and the intensity of ground movement. Crowdsourcing water-information is in its infancy (e.g., http://crowdhydrology.geology.

buffalo.edu/CrowdHydrology/Home.html), and there remain major issues of data quality and sustainability (Lowry and Fienen, 2013). Nevertheless, the use of crowdsourcing to report routine water data, as well as information on floods and droughts, needs to be creatively explored.

FUTURE CHALLENGES

In 1952, Congressman John R. Murdock noted that he had "long been interested in this problem of more adequate basic data for our programs to develop our water resources" (U.S. Congress House Committee on Interior and Insular Affairs, 1952) Congressman Murdock went on to note the lack of detailed information "for each catchment area and geographic unit … the respective quantities of water consumed in beneficial uses, the net gain or loss to surface and subsurface storage, the volume of outward drainage and the quantities dissipated in evaporation," as well as poor understanding of "the magnitude and basic physical characteristics of the Nation's ground-water resources and of the facilities and techniques of subsurface-water management." In many ways, the information needs outlined by Congressman Murdock remain unmet, at least at the scale at which much water-resources management occurs (National Science and Technology Council, 2007), although efforts are underway to address those needs (e.g., Alley *et al.*, 2013). As a consequence, some of the challenges facing the water-resources data community are similar to those in 1974 and even in 1952, but there are new challenges as well.

Some of the challenges for the water-data community and areas in which significant advances need to be made include the following.

- For a variety of reasons, the Nation's investments in critical scientific infrastructure have lagged in the last decade, including water-monitoring capabilities. As previously noted, there often is a tendency to invest in new initiatives rather than maintain and enhance existing core capabilities. It will be a continuing challenge to maintain robust water-resources monitoring capabilities, and new types of water data will be required to support modern modeling and growing water management requirements.

- In the last decade, the Nation has made major advancements in satellites that currently (or will soon) provide global information on precipitation, evapotranspiration, groundwater volume, ocean topography, snow cover, sea ice, and others. Satellites have a finite life, and in some cases replacement satellites are planned, but in other cases there may be gaps in the data. Data from various sensor types – *in situ*, airborne, and satellite – are not effectively integrated in an operational sense, although there is progress (National Research Council, 2008). Although there is a need, it is not inevitable that remotely-sensed information will be fully integrated with in situ measurements. Creative thinking that ignores institutional boundaries will be required to move forward on this front, but effective use of the Nation's investments requires that this occur.

- The climate community has developed effective global modeling capabilities for both short-term weather prediction and long-term climate forecasts. These models effectively ingest and assimilate a wide variety of data types. An earth-system, water-resources modeling capability is needed in the near future to connect climate models to terrestrial water-resources prediction models. Climate models have yet to demonstrate forecasting skill in terms of hydrologic outcomes over time scales of years to decades (e.g. Alkama *et al.*, 2011), so there is a great need for improvement. Moreover, there is a need for the water-resources community to clearly articulate in an unbiased manner the uncertainty of our future water availability forecasts.

- It is clear that groundwater availability in the U.S. is declining (Konikow, 2013). Since 2002, NASA GRACE mission has provided information on changes in groundwater volume, but this information is provided at a coarse scale not necessarily suitable for day-to-day management, nor is information available on the reason for the identified changes in volume. USGS is conducting groundwater availability assessments of major aquifers (USGS, 2014b), but these assessments take years to complete. There is a need to improve the Nation's ability to provide a continuing assessment of available groundwater resources, as groundwater sustains streamflow, provides a buffer to droughts in many parts of the Nation, and is the source of water supply for more than 40 percent of the U.S. (Kenny *et al.*, 2009).

- Assessments of groundwater rely on numerical models for understanding current and future availability. It is important that there be a stronger link between geophysics and groundwater models. Hydrogeophysical data – borehole, surface, airborne, and satellite – should be more strongly linked to input for groundwater models. This will improve our hydrogeologic characterization, which will improve our models and thus improve our assessments of current and future availability.

- The Nation is making big investments in the public sector and imposing requirements on the private sector with the goal of improving water quality. Determination of the success of these efforts is difficult because of natural variability and the lag times that can exist between actions on the landscape and changes in downstream water quality. Detection and documentation of these changes is a large challenge for the water-science community and requires temporally and spatially dense data sets on water quality and water quantity, as well as high-quality ancillary data on human activities, which are major drivers of water quality.

- Methods for determining water quality conditions in real or near-real time have advanced tremendously in the last 40 years, but further improvement is needed. The use of *in-situ* sensors has grown greatly in the last decade. These sensors have provided new process understanding and can be instrumental in making operations decisions. Nevertheless, lab-on-a-chip technology is widely used in the health-care field and

elsewhere, and needs to be transitioned to water-resources applications. Moreover, the use of autonomous underwater vehicles for freshwater surveys is just being explored (Jackson, 2013). It seems reasonable to expect that significant advancements will be made in the measurement and delivery of a variety of new and expanded real-time water-quality information. Along with advancements in water-data interoperability, new water-quality data delivery technologies promise to be one of the most exciting possibilities for the next decade.

- There are more than 5.8 million lakes, ponds, and reservoirs in the U.S. Water data for these features is sparse with little organization nationally, in spite of the fact that reservoir storage is an essential component of a reliable water supply. Remote sensing techniques can be especially effective at characterizing these water resources, although currently bathymetry, which is required for estimating storage, must be measured from the waterbody surface.

- As in 1974, transforming water-resources data into meaningful information for operational decisions is an ongoing challenge. Making sense of water data in the face of the "data deluge" is our new challenge (Porter *et al.*, 2012). In order to interpret water data from automated sensors using automated methods, we need new ways to treat sensor data streams, and water observations generally, with local context. This likely will involve indexing observations to frameworks and automatically connecting within the database inter-related observations, e.g., streamflow and water chemistry, or precipitation and streamflow.

Nevertheless, there is reason for optimism for the future of water-data in the U.S. Water-resources professionals are creative, energetic, and passionate about their mission. Progress, however, is not inevitable and will require continued vigilance and communication. It is important that the American Water Resources Association continue to be a voice for enhanced and coordinated water-data collection and use in the U.S.

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COMMENTS BY R. HAL LANGFORD OF SPRINGFIELD, VIRGINIA, ON THE BALES' ARTICLE

In reviewing the excellent article by Jerad Bales, I found that I was overwhelmed by the progress made in the field of water information. The co-author of that 1974 paper, Bill Doyel, shares my feelings. His superb comments are included herein (after my comments) for consideration by the author.

To illustrate the changes that have taken place over the past 40 years, I can recall the time when I almost left the U.S. Geological Survey (USGS). The event that caused me to harbor such thoughts took place in mid-winter in the sandhills of Nebraska. I was measuring the flow and collecting water quality samples of the Calamus River near Burwell, Nebraska, standing in chest waders in about three feet of water, dodging small ice floes that were moving downstream, with light-blowing snow in my face, a Price current meter on a wading rod in my right hand and earphones in my ears, counting "clicks" and timing them with a stop watch in my left hand. When I was about mid-stream during my measurement, a mallard duck came flying towards me beneath a small bridge over the river about 100 yards upstream. He did not see me until he was about 15 feet in front of me, and he then went through all kinds of gyrations to avoid hitting me in the face. Luckily he succeeded by gaining just enough altitude to sail over my head and go on his way.

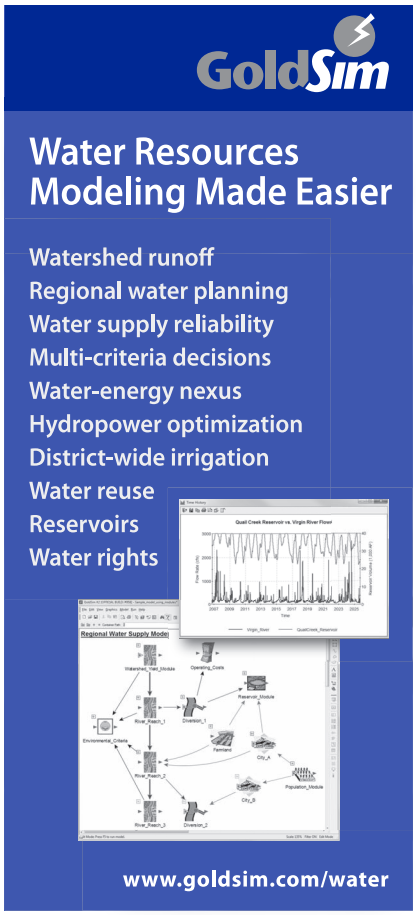
My first thought was "Why am I here doing this? There must be a better way of making a living!"

The advances in water-data collection and dissemination described excellently by Dr. Bales illustrate most vividly that there are now many better ways of collecting and disseminating information. Makes me almost want to go back to work for the USGS!

COMMENTS BY WILLIAM W. DOYEL OF WILLIAMSBURG, VIRGINIA ON THE BALES' ARTICLE

Reading the article made me realize I was truly living in a different century. I expected progress but nothing like he reports.

From my somewhat "antiquated" point of view, his descriptions of the scope of current data collection and dissemination, the spread of the information users and the role electronics has and will continue to play is succinct and informative.

I gave a talk some years ago, the subject of which was the amount of data being collected and its usage. Various individuals were commenting on the volume as being "engulfed or swamped by" or being lost (not retrievable). Added to this was the problem of data quality – weeding out "bad" or misleading data – and of the possible misuse of data accidentally, wrong interpretation or purposely. The problem of "purging the files" also came up. If data with no possible future use were erased, retrieval would benefit. Perhaps it's time for a "traffic cop" or data oversight group, if these real or potential problems aren't already under survey. If these matters aren't being given attention it would seem appropriate to complete this paper with such a statement.

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