THE USDA-ARS EXPERIMENTAL WATERSHED NETWORK – EVOLUTION, LESSONS LEARNED, AND MOVING FORWARD

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Abstract—The USDA-Agricultural Research Service's Experimental Watershed Network grew from Dust Bowl era efforts of the Soil Conservation Service in the mid 1930's with the establishment of watersheds in three States; one of which is still in operation. In the mid-50's five centers with intensively instrumented watersheds at the scale of 100 to 700 km^2 were established. Primary network research objectives were to quantify the field-scale and downstream effects of conservation practices and develop rainfall-runoff relationships for design of water conservation structures. USDA-ARS has operated over 600 watersheds in its history and continues to operate roughly 120 watersheds, many of which consist of gauged subwatersheds nested within larger gauged watersheds to enable investigation of scaling. With passage of the Clean Water Act in 1972, research objectives have evolved to add a variety of observations relevant to the water quality issues in their respective regions resulting in a more diverse, but less homogeneous network. The core instrumentation and related long record of high-quality observations have led to initiation of a series of multi-location projects to examine trends and directions of these observations across the network. As a result of their long history, intensive monitoring, and well described processes, the USDA-ARS watersheds have been used extensively in the development and validation of numerous watershed models. In addition, they served, and continue to serve as validation sites for aircraft and satellite based remotely sensed instruments. Many of the USDA-ARS Experimental Watersheds have now joined the Long-Term Agro-ecosystem Research Network (LTAR) (Maddox, 2013). This presentation will review major activities and advances derived from the network in addition to discussing some lessons learned in the long-term operation of a national scale network through its evolution from analog to digital instrumentation and internet accessibility.

INTRODUCTION

Much of the following introductory material is derived from Goodrich and others (1993). Depression era efforts by the Civil Conservation Corps (CCC) and the Soil Conservation Service (SCS) were the catalyst for the early USDA-ARS Experimental Watershed Program. The early history of the watershed program as we know it today is described in more detail by Kelly and Glymph (1965). Initial research was motivated by the 1930's conservation motto of "stop the water where it falls." It focused on the merits of upstream watershed conservation to infiltrate precipitation and hold or slow runoff to reduce runoff and erosion. The research was largely concerned with on-site problems at the field scale on watersheds up to roughly 10 hectares. To a large extent the research utilized paired watershed analyses. In 1935 there was an expansion in scope to examine fields and watersheds up to several square kilometers in size with the establishment of major research stations in Coshocton, OH, and Hasting, NE (Harmel and others, 2007). Plot and lysimeter studies were incorporated into the research at these locations in addition to continuing the research on on-site effects of tillage and management practices. The research during this period is largely empirical with emphasis on instrumentation and accurate data collection (Kelly and Glymph, 1965). There was early recognition

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of scaling problems in transferring knowledge from small to larger watersheds (Harrold and Stephens, 1965). As a result, national programs were developed in the 1950's for controlling floodwaters and sediment, as well as assessing downstream effects of conservation practices on watersheds up to 1,000 km^2. The USDA-ARS was created in 1953 and operation and management of many of the experimental watersheds established by USDA's SCS were transferred to USDA-ARS.

A major impetus for expansion of the USDA-ARS experimental watershed program resulted from hearings by the Senate Select Committee on National Water Resources. In 1958 this committee conducted nationwide hearings and a review of US water resources and policy and requested USDA "to make a study of facility needs for research on soil and water problems…" The USDA study resulted in Senate Document 59 (US. Senate, 1959) which identified "Hydrology of Agricultural Watersheds" as high priority. The recommendations in this document mirror more recent calls for improved research and continental-wide observations for water, ecology and soils emanating from the National Ecological Observatory Network (NEON) and Critical Zone Observatories (CZO) (NRC, 2008). Senate Document 59 laid out the following national research objective: "Hydrologic studies are urgently needed on precipitation-runoff relationships and the effect of all types of conservation treatments on runoff … from agricultural watersheds ranging in size from 1 to 400 square miles." Like NEON they recommended core experimental watershed sites with satellite locations ("Experimental watersheds are needed in all 15 major land resource regions…to provide the maximum opportunity for interpolating values between locations with markedly contrasting conditions each should include a number of satellite locations …"). The interdisciplinary nature of the challenge was also recognized as Senate Document 59 stated "...agricultural watershed behavior is a complex problem…research centers must be large enough to represent numerous disciplines." While cyber-infrastructure had not been contemplated in the late 1950's they did recommend measurement of a common set of variables with standard protocols, periodic review of network data, and a central data repository in Beltsville, Maryland.

As a result of Senate Document 59, appropriations were made to establish new watershed research centers in a number of hydroclimatic regions in Chickasha, OK; State College, PA; Boise, ID; Tifton, GA; and Tucson, AZ. In addition, the Columbia, Missouri research unit was directed to become the North Central Hydrologic Laboratory in 1961 as a direct result of Senate Document 59. Analysis of observations from the earlier, smaller watersheds indicated the difficulty in extrapolating hydrologic response characteristics to larger scales. Consequently, the core experimental watersheds established at these new centers were on the order of 100 to 600 km^2, roughly an order of magnitude larger than watersheds established in the 1930-40's. The goal of the watershed research centers was to select a representative core watershed and establish satellites that were less well instrumented. Nested watersheds and unit source areas on major soil types were included in the watershed designs to further investigate scale effects.

A key early challenge in establishing the larger experimental watersheds over a wider range of hydroclimatic regions was development and acquisition of instrumentation and procedures for their installation, operation, and maintenance. A significant, and still valuable, outcome of this work was development and publication of Handbook 224 - Field Manual for Research in Agricultural Hydrology (Brakensiek and others, 1979). Measurement quality control was and still is an important ongoing effort. Johnson et al. (1982) described ARS Experimental Watershed data acquisition programs and an assessment of the quality of collected data at many of the watersheds. Based on data from the Hydrology and Remote Sensing Laboratory in Beltsville, Maryland, by 1990, ARS had operated over 600 watersheds in its history. Of the 600 watersheds, a comprehensive database is available from the Hydrology Laboratory for 333 of these watersheds (www.ars.usda.gov/ba/anri/hrsl/wdchome). This database consists of variable time-series readings for precipitation and runoff from small agricultural watersheds with sufficient detail to reconstruct storm hydrographs and hyetographs with approximately 16,600 station years of data. Records in the Beltsville database run through 1992. Due to budgetary constraints, post 1992 records were maintained at individual watershed centers. DeCoursey (1992) provided an overview of the ARS Experimental Watershed Network in operation at that time including a description of the size distribution, length of record and primary land use of the active watersheds. Approximately 120 ARS watersheds are currently active and collecting a variety of data. The geographic location of active watersheds is illustrated in Figure 1. In many of the locations depicted on this figure, multiple watersheds, many nested, exist or have existed. Table 1 lists the primary ARS Experimental Watersheds and a number of their attributes.

The guidance on instrumentation, installation, calibration, and maintenance described in detail in Handbook 224 led to a relatively uniform national experimental watershed network that focused primarily on observations of weather, climatology, precipitation, and runoff, in addition to detailed characterization of the watersheds. Many lessons were learned during the development of the large USDA-ARS watersheds. An important finding was that meaningful observations were not always possible

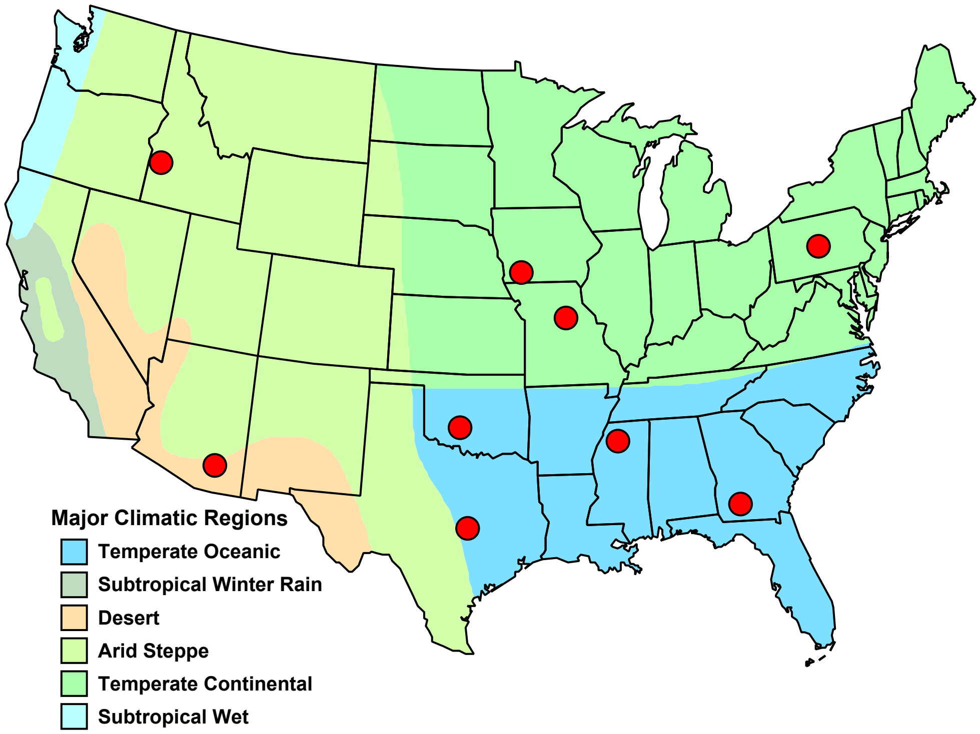

Figure 1—Location of primary ARS Experimental Watersheds.

across the wide range of environments and hydroclimatic conditions. Therefore some specialized instrumentation or installation procedures were developed to collect meaningful data. For example, the snow dominated Reynolds Creek Experimental Watershed in Idaho has two precipitation gauges at each measurement location. One is shielded to reduce wind effects and the second is unshielded. When precipitation is primarily in the form of snow (at temperatures less than –2.2°C) this installation provides more accurate precipitation estimates and also enables the interpretation of unshielded dual gauge measurement locations (Hanson, 1989).

With passage of Clean Water Act (CWA) in 1972 many of the ARS watersheds began collecting water quality data. Due to regional differences in agriculture production and practices, the constituents impacting water quality (sediment, herbicides, pesticides, nutrients, etc.) vary substantially across the network. These differences and budgetary limitations led to a divergence in network data collection. As digital instrumentation and technology advanced the ARS watersheds began the process of converting from analog to digital instrumentation, primarily in the 1990s and 2000s. However, this was done on a location-by-location basis and not uniformly across the network. This is largely the result of the ARS budgetary framework where individual locations are allocated annual budgets. There is not a "network" budget for multi-location purchasing and hiring. The changeover to digital instrumentation was in many cases more about retrofitting existing instrumentation with data loggers and telemetry capabilities so the central core measurements of climate, weather, precipitation and runoff could still maintained. However, a number of new automated sensors became available, such as soil moisture probes. The performance of these sensors tended to vary across soil types and across dry to wet environments. This resulted in location-specific choices of soil probes. However, coordinated efforts for validation of remotely sensed soil moisture products did result in a common soil moisture probes for four of the core experimental watersheds (Jackson and others, 2010). As climate change awareness, increased many locations added energy and carbon flux monitoring and more recently soil respiration and biogeochemistry. As with soil moisture, these additions were done on a location-by-location basis depending on available expertise and research goals.

With improved internet connectivity and lack of a central data repository, many individual locations undertook specific efforts to organize and make their experimental watershed data available in easy to use digital form. These efforts have proven to be expensive and time consuming. Estimated costs of the Data Access Project (DAP) for the Walnut Gulch Experimental Watershed in Arizona were ~$700,000 to put eight data sets up on the web with metadata published in a peer-reviewed journal. Annual maintenance was estimated to be $20,000/year for IT upgrades, basic QA/QC, and maintenance of data loggers and instrumentation (Moran and others, 2009).

Table 1—Selected Attributes of ARS Experimental Watersheds

ARS Experimental Watersheds						Monitoring				
ARS Research Unit	Unit Location	Description	Size	Land Cover/Use	Year Established	Climate	Discharge	Sediment	Water Quality	Other
Southern Plains Range Research Station	Woodward, OK	4 plots	16 ha	Grazing	1977	X	X	X	1	
Southern Piedmont Conservation Research Unit	Watkinsville, GA	7 plots	130 ha	Forest/pasture/crops	1937	X	X	X	1,3,4	5
Grassland Soil and Water Research Laboratory	Temple, TX	20 plots	350 ha	Mixed cropping/forage	1937	X	X	X	1,3	5
North Appalachian Experimental Watershed	Coshocton, OH		400 ha	Mixed cropping/forage	1935	X	X	X	1,3,4	1
Pasture Systems and Watershed management Research Unit	University Park, PA	Watershed WE-38	730 ha	Forest/pasture/crops	1967	X	X		1	5
National Sedimentation laboratory	Oxford, MS	Goodwin Creek	21.5 km^2	Mixed cropping/forage	1981	X	X	X		4
Cropping Systems and Water Quality Research Unit	Columbia, MO	Goodwater Creek	73 km^2	Mixed cropping/forage	1971	X	X	X	1,3	5
Southwest Watershed Research Center	Tucson, AZ	Walnut Gulch	150 km^2	Rangeland	1954	X	X	X		1,3
Northwest Watershed Research Center	Boise, ID	Reynolds Creek	240 km^2	Range/forest/hay	1960	X	X	X	2	2
Southeast Watershed Hydrology Research Center	Tifton, GA	Little River	334 km^2	Mixed cropping	1967	X	X	X	1,3	1,3,5
Grazinglands Research Laboratory	El Reno, OK	Little Washita	610 km^2	Grazing with mixed crops	1936	X	X	X	1	1,3,5

Water Quality: 1 = Nutrient, 2 = Temperature, 3 = Pesticides, 4 = Pathogens I Other: 1 = Flux, Bowen Ratio, 2 = Snow, 3 = Remote Sensing, 4 = Doppler Radar, 5 = Groundwater

As part of these data availability efforts, a number of special journal sections with data and/or research papers were developed. They include Slaughter et al. (2001) for Reynolds Creek, Idaho; Bosch and others (2007) for the Little River, Georgia; Moran and others (2008) for Walnut Gulch, Arizona; Langendoen and others (2009) for Goodwin Creek, Mississippi; Owens and others (2010) for Coshocton, Ohio; Bryant and others (2011) for Mahantango Creek, Pennsylvania; Harmel and others (2014) for Riesel, Texas; and, Sadler and others (2015) for Goodwater Creek, Missouri. While not technically part of the early ARS watershed network, Ames, Iowa (Walnut Creek) and Oxford, Mississippi (Beasley Lake) were established as part of the Management Systems Evaluation Areas (*MSEA*) and Agricultural Systems for Environmental Quality (ASEQ) Projects. Synthesis publications describing these watersheds and related project research are presented by Hatfield and others (1999) and Locke (2004). A broader data services tool integrated with GIS services named STEWARDS (Sustaining the Earth's Watersheds, Agricultural Research Data System) was developed starting in the mid-2000's (Steiner and others, 2008; Sadler and others, 2008). It houses data from a number of the ARS cropland dominated experimental watershed as well as CEAP (Conservation Effects Assessment Project) watersheds.

ACCOMPLISHMENTS

The USDA-ARS Watershed Research program and its experimental watershed network have a lengthy record of high-impact accomplishments. Some of the most significant include:

- Quantifying the effectiveness of conservation practices and BMPs in reducing runoff, erosion, and water quality impacts of agricultural production
- Quantifying the environmental impacts of agricultural fertilizers and chemicals at the watershed scale
- Developing guidelines for reclamation of disturbed lands
- Quantifying the value of riparian ecosystems in improving water quality
- Instrumentation development and hydraulic structure design
- Quantifying the effects of floodwater retarding structures
- Development and validation of numerous remote sensing products
- Improved water supply forecasting
- Development of numerous, widely used, watershed, water quality, and natural resource management models

Through its history the ARS Experimental Watersheds have been able to maintain continuity of core observations (climate, weather, precipitation, runoff) while adapting to meet changing research needs and regional issues.

CURRENT RESEARCH

The rich history of long-term observations within the USDA-ARS Experimental Watershed Network has afforded the ability to conduct multi-location research projects. Current multi-location projects include:

- Indicators of ecosystem services in agricultural watersheds
- Utility of remote sensing for ET and drought monitoring and for assimilation into ARS hydrologic models
- Remotely-derived estimates of net primary production using remotely sensed data across precipitation regimes
- Hydro-climatic trends across North America—a comparative analysis of historical soil water trends in us agricultural lands
- Continental-scale synthesis of high-resolution observations from USDA-ARS and other experimental watersheds and ranges
- Comparison of eddy covariance flux measurements of H_2O vapor and CO_2 in different environments
- Estimating the impacts of projected climate change on regional water availability and quality across diverse physiographic regions of the US

LESSONS LEARNED

A number of important lessons were learned in the initiation, development, maintenance, and evolution of the ARS Experimental Watershed Network that may benefit other national observation based research efforts. Several are offered herein in no particular order of importance. Off-the-shelf instrumentation may not be universally suitable over a diverse set of environments. Some degree of trial and error will be inevitable in developing suitable instruments and siting them to acquire meaningful observations. The time and expense for permitting and acquiring access can be considerable and should not be underestimated. Likewise, the costs of QA/QC for observations, archiving, and data delivery are substantial and should be examined when contemplating adding other core observations to the network. Personnel with good technical, field, and fabrication skills are in short supply, and current hydrology and watershed management degree programs typically do not provide this diverse set of skills. Science and societal challenges will emerge that the network designers did not anticipate, and therefore our observational networks had to adapt. Without a centralized funding model for the entire network, our watersheds have not been able to uniformly integrate these adaptations. In many cases, this makes good economic sense. Collecting and analyzing runoff samples for a suite of nutrients, pesticides, and herbicides is typically of little value in western rangeland where those constituents are not part of common agricultural practices.

MOVING FORWARD AND CONCLUSIONS

Many of the long-term ARS Experimental Watersheds are now part of the Long-Term Agro-ecosystems Research (LTAR) network (Steiner and others, 2015). The vision of the LTAR network is to enable multi-decadal trans-disciplinary and cross-location science to enhance the sustainability of the nation's agro-ecosystems and delivery of goods and ecosystem services. Its primary goal is to sustain a land-based infrastructure for research, environmental management testing, and education that enables understanding and forecasting of the Nation's capacity to provide agricultural commodities and ecosystem services under changing environmental, economic, and societal conditions. Additional details on the LTAR network are reported elsewhere in proceedings of this conference (Steiner and others, 2015). Several efforts are also underway to provide centralized experimental watershed data access. One is through the National Agricultural Library. The other is to utilize community water data services based on the Hydrologic Information System (HIS) developed by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI - https://www.cuahsi.org/wdc). The Reynolds Creek and Walnut Gulch Experimental Watershed Centers have reformatted their core data into the Observations Data Model (ODM) that allows spatial queries for point time series data via WaterOneFlow web services. The companion HydroDesktop (http://hydrodesktop.codeplex.com) is an open source GIS enabled desktop application for searching, downloading, visualizing, and analyzing hydrologic and climate data registered with the Hydrologic Information System.

Moving forward, the USDA-ARS Experimental Watershed Network and LTAR must tackle several challenges to ensure its continued relevancy to the nation's natural resource science and management priorities. What new core observations, beyond the existing observations of weather, climate, precipitation and runoff, should be added to the entire network? Candidates include trace gases, water and wind erosion, ET and CO_2 fluxes, and imaging, among others. In addition to an expanded set of core observations, how will the network evolve to not only incorporate new technology and address new regional issues, but also collect measurements that may be regionally important for a subset of the network and not for other portions of the network? A key point is that these are research networks and not purely data collection observatories. As such, watershed network evolution cannot be solely driven by standardized instrumentation, uniform long-term data collection for all variables, and centralized database management. As a research network it should address common national issues that require region-specific data collection to address region-specific problems, and develop high-impact region-specific solutions. It is the capacity of this unique network to address national issues across the physiographically and environmentally diverse regions of the continent that defines the network, not the assemblage of region-specific data of the various ARS watersheds and rangelands dispersed across the continent.

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