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Key Points:
- Agricultural Research Service's Experimental Watersheds and associated mission-driven research have operated for over half a century
- High-resolution watershed observations and experimentation have produced a deep watershed process knowledge and database
- The research network has been critical to developing and validating numerous watershed models and management methods, resulting in extensive societal benefits

Supporting Information:
- Supporting Information S1

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The USDA-ARS Experimental Watershed Network: Evolution, Lessons Learned, Societal Benefits, and Moving Forward

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Abstract The U.S. Department of Agriculture-Agricultural Research Service's (ARS) Experimental Watershed Network grew from Dust Bowl era efforts of the Soil Conservation Service in the mid-1930s with the establishment of small experimental watersheds. In the 1950s, five watershed research centers with intensively instrumented watersheds at the scale of 100 to 700 km^2 were established. Primary network research objectives were to quantify on-site and downstream effects of conservation practices and develop rainfall-runoff relationships for design of water conservation structures. 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. Many of the watersheds within the network have served, and continue to serve, as core validation sites for satellite sensors. As a result of the network's long history and intensive monitoring, coupled with mission-driven research, a deep knowledge base of watershed processes has been developed. This has led to the extensive development and validation of numerous watershed models that are in widespread use today. The visionary investments in building and maintaining this network and associated scientific investigations for more than half a century have not only resulted in numerous high-impact research accomplishments but also a wide array of accomplishments that directly benefit society. The ARS Experimental Watersheds formed the core of the Conservation Effects Assessment Project (CEAP) as well as the recently established Long-Term Agroecosystem Research (LTAR) network. LTAR will expand the mission of the ARS Watersheds Network to include agricultural intensification, maintaining or improving ecosystem services while enhancing rural prosperity.

Plain Language Summary Understanding how watersheds respond to precipitation, agricultural management, and other land use changes is critical to maintaining clean water, viable food production, and predicting flood hazards and soil loss from erosion. To understand watershed responses and processes, the Soil Conservation Service, followed by the USDA-Agricultural Research Service, established experimental watersheds across the United States. These watersheds were instrumented with equipment to make detailed measurements of weather and watershed response. Experiments were designed to observe how runoff, erosion, and water quality might change with changing agricultural practices to change agricultural practices and observe how runoff, erosion, and water quality would change. From these experiments, predictive computer models were developed and tested with data from the watersheds. The watershed observations, the process knowledge developed, and associated research and models have resulted in numerous societal benefits. Billions of dollars of conservation measures and drainage infrastructure investment were guided by these models and methods. The ARS Experimental Watersheds formed the core of the recently established Long-Term Agroecosystem Research (LTAR) network. LTAR will expand the mission of the ARS Watershed Network to include producing more food on the same amout of land, maintaining or improving ecosystem services (clean water and air, healthy soils, etc.) while enhancing rural prosperity.

1. Introduction

This paper will review the background and history of the network (some of the following history and background material is derived from Goodrich et al., 2015) and provide a cursory description of the experimental watersheds with citations to special journal sections providing greater detail. Major accomplishments with direct societal benefits derived from the network or individual Agricultural Research Service (ARS) Experimental Watersheds and their associated research will be described. Some lessons learned from the long-term operation of a national-scale network through its evolution from analog to digital instrumentation and internet accessibility will then be discussed. Finally, a discussion of the expanded mission of the experimental watersheds under the flag of the Long-Term Agroecosystem Research (LTAR) network will be presented.

2. Background and History

Erosion gained national prominence in 1928 in the United States with the publication of Circular 33, *Soil Erosion: A National Menace* by H. H. Bennett and W. R. Chapline. They argued that soil erosion removed valuable nutrients needed for crop production, thus wasting the land's productive potential. They further argued that society should take a watershed perspective by considering a direct link between soil conservation in agriculture and flood prevention. Bennett and Chapline (1928) quoted geologist T. C. Chamberlin's 1908 White House address in saying: "The solution of the problem for the tiller of the soil essentially solves the whole train of problems running from farm to river and from crop-production to navigation." They also emphasized the need for research, specifically stating: "it will be observed in reading this circular that little information other than estimates and observations have been given. This is because exceedingly little research work has been done on the subject." Bennett and Chapline were also strong proponents of the Buchanan Amendment to the 1930 Agricultural Appropriations Bill, funding 10 soil erosion experiment stations.

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 (Kelly & Glymph, 1965). Initial research was motivated by the 1930 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 empirical, focusing on instrumentation development and accurate data collection. It was focused at the field scale on watersheds up to roughly 10 ha employing paired watershed analyses (Kelly & Glymph, 1965; Richardson & King, 1995). In 1935, there was an expansion in scope to examine fields and watersheds up to several square kilometers in size (Harmel et al., 2007). The experimental watershed studies included both management control and improved observations of the water budget, including installation of large weighing lysimeters to measure evapotranspiration (ET).

C.W. Thornthwaite became Chief of the SCS Climatic and Physiographic Research Division in 1935 and stayed with the agency until 1946. This SCS research division studied the physical and chemical factors related to soil erodibility, the hydraulics of small structures, and evaporation (Helms, 2007; Phelan & Basinger, 1993; Thornthwaite & Holzman, 1942). In the mid-1930s to the early 1940s, SCS researchers also began collecting data outside the experimental sites by monitoring runoff from over 100 small watersheds. Sedimentation studies were undertaken in 20 valleys using cross sections to better understand the downstream movement of sediment. The SCS performed the initial topographic surveys of hundreds of reservoirs to calculate rates of sedimentation.

There was early recognition of scaling problems in transferring knowledge from small to larger watersheds (Harrold & Stephens, 1965). As a result, national programs were developed in the 1950s 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. This committee requested that USDA "make a study of facility needs for research on soil and water problems ..." resulting in Senate Document 59 (U.S. Senate, 1959) which 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

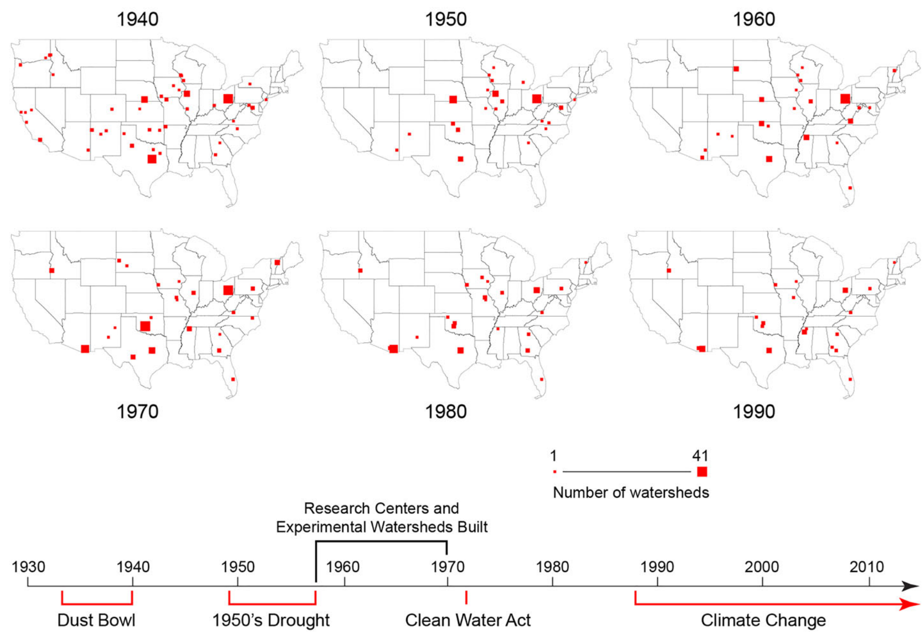

Figure 1. Location and number of ARS Experimental Watersheds by decade from 1940 to 1990 and important events in the development of the program.

in size from 1 to 400 sq. miles." While cyber-infrastructure had not been contemplated in the late 1950s, the document did recommend measurement of a common set of variables with standard protocols, periodic review of network data, and a central ARS data repository in Beltsville, Maryland. 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 the Critical Zone Observatories (CZO) (NRC, 2008). Like NEON, they recommended core experimental watershed sites with satellite locations and a strong multidisciplinary approach.

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; University Park, PA; Boise, ID; Tifton, GA; and Tucson, AZ. In addition, the existing Columbia, MO, research unit was directed to become the North Central Hydrologic Laboratory in 1961. The core experimental watersheds established at these new centers were on the order of 100 to 600 km^2. However, to more thoroughly investigate scale effects, nested watersheds and unit source areas on major soil types were included in the core watershed designs. A significant and still valuable outcome of this work was the development and publication of Handbook 224—Field Manual for Research in Agricultural Hydrology (Brakensiek et al., 1979). By 1992, ARS had operated over 600 watersheds in its history. Of the 600 watersheds, a comprehensive database is available from the Hydrology and Remote Sensing Laboratory in Beltsville, Maryland, 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 hyetographs and hydrographs and hyetographs with approximately 16,600 station years of data. Records in the Beltsville database run through 1992 to 1994. Various types of ancillary data are also maintained, including air temperature, land management practices, topography, and soils information. Due to budgetary constraints, post 1992–1994 records were maintained at individual watershed centers. Figure 1 illustrates the location and number of ARS watersheds by decade from 1940 to the 1990s.

3. Description of ARS Experimental Watersheds

DeCoursey (1992) provided an overview of the ARS Experimental Watershed Network (EWN) 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. In many of the locations depicted on Figure 1, multiple watersheds, many nested, exist or have existed.

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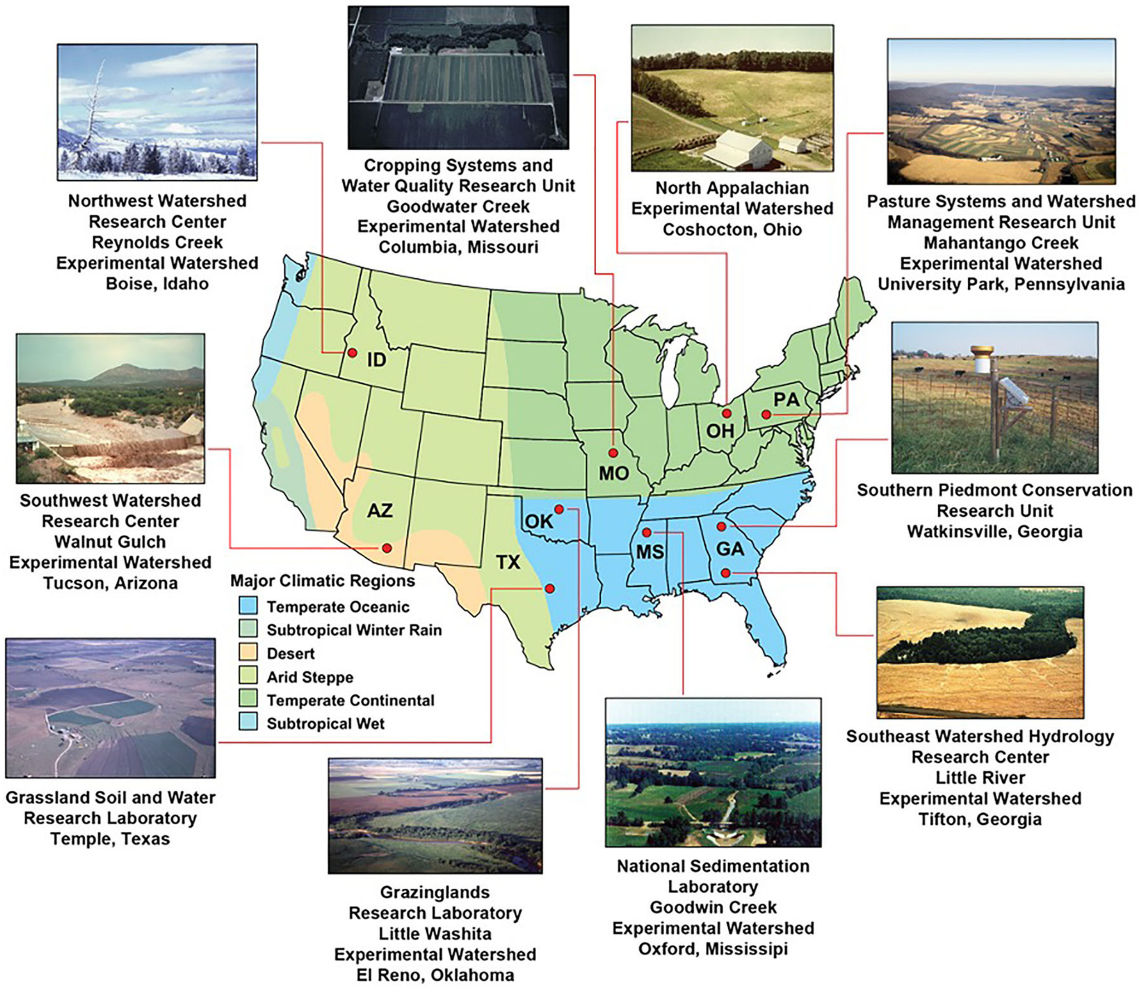

Figure 2. Location of primary ARS Experimental Watersheds and associated representative photographs.

Figure 2 illustrates the location of primary ARS Experimental Watersheds and associated representative photographs. Table 1 contains a number of their attributes. Table 2 contains additional information of the characteristics of these watersheds, several top scientific findings derived from each of the experimental watersheds, and web links to the observations made at each location.

The guidance on instrumentation, installation, calibration, and maintenance described in detail in Handbook 224 (Brakensiek et al., 1979) led to a relatively uniform national EWN 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 across the wide range of environments and hydroclimatic conditions with existing technology. ARS watersheds have pioneered the testing and development of watershed instrumentation including the drop-box weir for high-energy, high-bedload systems (Bonta & Pierson, 2003) and supercritical flumes for arid, sediment laden regions (Smith et al., 1982). Stream sampling methods for water quality such as the Coshocton Wheel (Dowding et al., 1967), the total load automatic traversing slot sampler (Renard et al., 1986), and widely used instream samplers have also come from ARS watersheds. Other advances include state-of-the-art hydrometeorological field sensors, watershed-wide telemetry, archival equipment and systems, the dual-gage precipitation measurement system, load cell precipitation gages, and advanced snow monitoring (Hanson, 1989). Figure 3 presents photographs for a subset of the instruments noted above.

With passage of the Clean Water Act (CWA) in 1972, many of the ARS watersheds began collecting water quality data (see bottom of Figure 1). Due to regional differences in agriculture production and practices,

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Table 1
Selected Attributes of ARS Experimental Watersheds (Updated From Table 1 of DeCoursey, 1992)

ARS experimental watersheds						Monitoring conducted				
ARS research unit	Unit location	Description	Size	Land cover/use	Years of operation	Climate and type	Discharge	Sediment	Water quality	Other
Southern Piedmont Conservation Research Unit	Watkinsville, GA	7 fields	130 ha	Forest/pasture/ crops	1937–2016	X Humid-Subtropical	X	X	1, 3, 4	4
Grassland Soil and Water Research Laboratory	Temple, TX	Riesel, 20 fields	350 ha	Mixed cropping/ forage	1937 to present	X Humid-Subtropical	X	X	1, 3	4
North Appalachian Experimental Watershed	Coshocton, OH	19 fields 6 watersheds	420 ha	Mixed cropping/ forage	1939–2015	X Humid-Subtropical	X	X	1, 3, 4	1
Pasture Systems and Watershed Management Research Unit	University Park, PA	Mahantango	420 km^2	Forest/pasture/ crops	1967 to present	X Humid-Temperate	X	X	1	4
National Sedimentation Laboratory	Oxford, MS	Goodwin Creek	21.5 km^2	Mixed cropping/ forage	1981 to present	X Humid-Subtropical	X	X	1	4
Cropping Systems and Water Quality Research Unit	Columbia, MO	Goodwater Creek	73 km^2	Mixed cropping/ forage	1971 to present	X Humid-Subtropical	X	X	1, 3	4
Southwest Watershed Research Center	Tucson, AZ	Walnut Gulch	149 km^2	Rangeland	1954 to present	X Semiarid	X	X		1, 3
Northwest Watershed Research Center	Boise, ID	Reynolds Creek	240 km^2	Range/forest/ forage	1960 to present	X Semiarid	X	X	1, 2	1, 2, 3, 4
Southeast Watershed Hydrology Research Laboratory	Tifton, GA	Little River	334 km^2	Forest/mixed cropping	1967 to present	X Humid-Subtropical	X	X	1, 2, 3	1, 3, 4
Grazinglands Research Laboratory	El Reno, OK	Little Washita	610 km^2	Grazing with mixed crops	1936 to present	X THS[5]	X	X	1	1, 3, 4

Note. Water quality: 1 = nutrient, 2 = temperature, 3 = pesticides, and 4 = pathogens. Other: 1 = flux, Bowen ratio, 2 = snow, 3 = remote sensing, 4 = groundwater, and 5 = temperate humid subtropical.

Table 2
Additional Information on Those ARS Experimental Watersheds Continuing as Part of the Long-Term Agroecosystem Research (LTAR) Network

	LTAR ARS Experimental Watersheds			
ARS research unit	LTAR designation/ ARS watershed name	Special issue introduction paper	Data access	Selected research accomplishments
Grassland Soil and Water Research Laboratory	Texas Gulf	Harmel et al. (2014)	STEWARDS[a]	-Quantified the effects of conservation practices on runoff, erosion, and water quality -Hydrologic processes of heavy clay soils—cracking, shrink, and swelling (Baird, 1948; Haney et al., 2011; Harmel et al., 2004, 2006, 2008, 2013; Kishne et al., 2014; Smith et al., 2019; 2020; Wagner et al., 2012)
Pasture Systems and Watershed Management Research Unit	Upper Chesapeake Bay	Bryant et al. (2011)	STEWARDS	-Overcoming historical P imbalance and legacy impacts -Identifying critical sources of P export from watersheds (Flaten et al., 2019; Kleinman, 2017; Liu et al., 2017; McDowell & Sharpley, 2001; Miller et al., 2018; Smith et al., 2019; Spiegal et al., 2020; Veith et al., 2020)
National Sedimentation Laboratory	Lower Miss. River Basin	Langendoen et al. (2009)	STEWARDS	-Stream instabilities and sediment yield responses -Aquatic habitat improvement by instream structural stabilization measures (Murphey & Grissinger, 1985; Shields et al., 1995, 1998)
Cropping Systems and Water Quality Research Unit	Central Miss. River Basin	Sadler et al. (2015)	STEWARDS	-Shallow claypan hydrologic processes - Assessment and prediction of conservation practice effects on surface WQ (Al-Qudah et al., 2016; Baffaut et al., 2015, 2019; Blanco-Canqui et al., 2002; Hjelmfelt & Wang, 1994; Kitchen et al., 2015, 1998; Lerch et al., 2005, 2011; Wendt et al., 1986)
Southwest Watershed Research Center	Walnut Gulch	Moran, Emmerich, et al. (2009), Moran, Hutchinson, et al. (2009)	www.tucson.ars.ag.gov/dap/	-Semiarid and monsoon influenced precipitation, runoff, and erosion -Influent hydrologic processes and instrumentation (Goodrich et al., 1997; Osborn et al., 1980; Paige et al., 2003; Polyakov et al., 2010; Renard et al., 2008; Smith et al., 1982)
Northwest Watershed Research Center	Great Basin	Slaughter et al. (2001)	data.nal.usda.gov/search/type/dataset?query=reynolds+creek&sort_by=changed&sort_order=DESC	-Snow, freeze/thaw, and snow dominated water supply -Effects of fire and conservation practices on rangeland runoff and erosion (Kormos et al., 2018; Marks et al., 2013; Pierson et al., 2011; Pierson & Williams, 2016; Williams et al., 2019; Winstral et al., 2013)
Southeast Watershed Hydrology Research Lab.	Gulf Atlantic Coastal Plain	Bosch et al. (2007)	STEWARDS	-Coastal plain hydrological processes -Assessment, prediction, and remediation of nutrient, agrochemical, and animal waste impacts on surface and groundwater (Bosch et al., 2007, 2017; Hubbard et al., 2004; Lowrance et al., 1984)
Grazinglands Research Laboratory	Southern Plains	Steiner et al. (2014)	STEWARDS	-Assessment of overall impacts of flood control and watershed protection programs -Quantified effects of projected climate change on soil erosion, surface water resources, and impoundments on water quality and ecosystems (Garbrecht & Starks, 2009; Moriasi et al., 2018; Schoof et al., 1987; Van Liew et al., 2003)
	Middle Cheasepeake	McCarty et al. (2014)	STEWARDS	-Impacts of conservation practices on water quality

Table 2
Continued

LTAR ARS Experimental Watersheds				
ARS research unit	LTAR designation/ ARS watershed name	Special issue introduction paper	Data access	Selected research accomplishments
Hydrology and Remote Sensing Laboratory				-Test bed for remote sensing approaches for monitoring winter cover crops, residue management, and wetland ecosystem function (Du et al., 2020; Hively et al., 2020; Lee et al., 2020; McCarty et al., 2014; Plummer et al., 2020)
National Lab. for Agriculture & the Environment	Upper Mississippi River Basin	Hatfield et al. (1999)	STEWARDS	-Impacts of row-crop agriculture in a tile-drained landscape -Assessment of pesticide and nitrate transport -Identified decoupling of N mineralization with plant uptake in early spring as a cause of nitrate transport, demonstrated the late-spring nitrate test as a conservation practice (Jaynes et al., 1999, 2004)

[a]https://data.nal.usda.gov/node/146

the constituents affecting water quality (e.g., sediment, herbicides, pesticides, and nutrients) vary substantially across the network. These differences along with budgetary limitations led to a divergence in network data collection. 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.

In the 1990s, improved internet connectivity and budgetary constraints for the Beltsville Laboratory on archiving data post 1994 led many individual locations to undertake specific efforts to organize and make their experimental watershed data available in digital form. These efforts have proven to be expensive and time-consuming. As part of these data availability efforts, a number of special journal sections with data and/or research papers were developed (see Table 2). With resources from Conservation Effects Assessment Project (CEAP; Richardson et al., 2008), a broader data services tool integrated with GIS named STEWARDS (Sustaining the Earth's Watersheds, Agricultural Research Data System; https://data.nal.usda.gov/node/146) was developed starting in the mid-2000s (Sadler et al., 2008; Steiner et al., 2008). STEWARDS houses data from a number of the ARS cropland-dominated experimental watersheds as well as CEAP watersheds.

3.1. Comparison to Several Other Watershed Observatory Networks

The ARS EWN shares many of the attributes of other hydrologic observatories but with a different emphasis. It is one of the few experimental watershed networks in operation before the relatively rapid rise in global temperature starting in the mid-1970s. The ARS EWN started with a focused national goal of understanding the effect of agricultural conservation practices on runoff (on-site and downstream). With this goal, the ARS watersheds focused on high-quality collection of a limited number of hydroclimatic measurements. Like many early watersheds, the ARS network has evolved to be much more interdisciplinary (Tetzlaff et al., 2017). Selection of the physical location of ARS watersheds was closely coupled with the predominate type of agriculture in the area. By design, the ARS watershed labs did not acquire ownership of the land containing the watersheds. This fostered the need for close collaboration with producers and monitoring the impacts of their land management. Moving forward, the network is more actively targeting research toward the water-food-ecosystem nexus and the welfare of rural areas and producers. This expansion of research and observations is discussed in more detail in section 6.

Bogena et al. (2018) present an overview and comparison of both individual experimental watersheds as well as several networks but do not include the ARS-EWN. One of the individual watersheds within the ARS-EWN (Reynolds Creek, Idaho) is included in Bogena et al. (2018). Several selected networks are described below to provide comparisons and contrasts to the ARS-EWN. They include CZO, Terrestrial

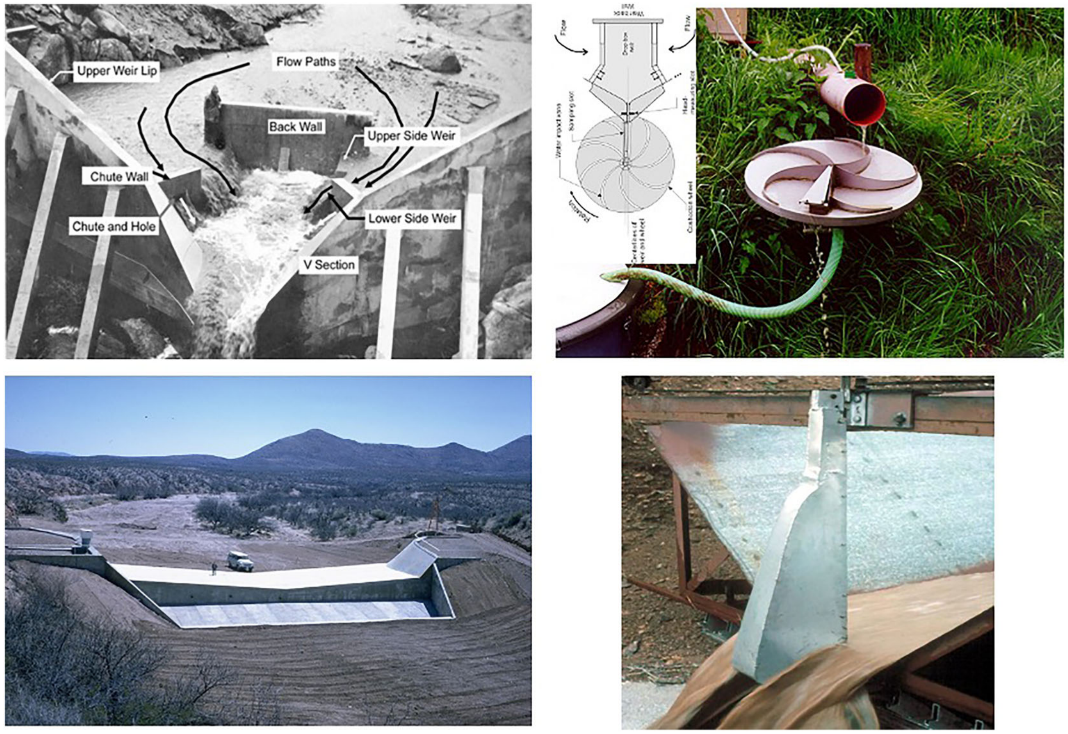

Figure 3. Watershed measurement and sampling instrumentation developed as part of the evolution of the ARS EWN: Upper left: drop-box weir for high-energy, high-bedload systems; lower left: supercritical flumes for arid, sediment laden regions; upper right: Coshocton wheel, a non-powered constant portion flow sampler; lower right: total load automatic traversing slot sampler.

Environmental Observatories (TERENO), the HiWATER observatory, and the Community Conservation Research Network (CCRN).

The CZO network, initiated in 2007, contains well-monitored catchments (including the ARS Reynolds Creek watershed). A primary goal of the CZO program is monitoring, understanding, and modeling the critical zone or "living skin" of the Earth from unweathered parent material to the top of vegetation in nine locations within the United States. A key motivation for the CZOs came from the geoscience and soils community to understand the biogeochemical processes involved in the genesis of soils (Brantley et al., 2017). The CZO model has expanded internationally, currently with 46 CZOs across the globe.

The TERENO network consists of four primary locations in Germany spanning the lowlands in the north to alpine conditions in the south. TERENO's observation goals are to collect multiscale, long-term social and ecological time series using modern instrumentation, geophysics, and remote sensing methods. Research goals include analyzing these observations to quantify the states, fluxes, and feedbacks from groundwater to the lower atmosphere to assess the environmental and economic impacts of global change, land use, and land management. Like the ARS-EWN, the TERENO investigators would like to bridge the gap in scales between observations and management. TERENO has similar goals to CZO with the exception of soil genesis and with the added goal to acquire social and economic data (Zacharias et al., 2011).

The HiWATER network was initiated in 2010 in the Heihe River Basin (HRB, ~1,432,000 km^2) in the cold arid northwestern region of China (Li et al., 2013). HiWATER is focused on ecohydrology, and a primary goal is to develop and build a watershed observing network that will focus on watershed science as well as water resources management. It will take a multiscale, multidisciplinary, and ecosystem dynamics approach to attempt to obtain high-quality observation of all water balance components. The network of observatories consists of three key experimental areas (KEAs) where long-term, intensive measurements will be made. The cold region KEA contains nested basins with drainage areas ranging in scale from 23 to 2,452 to 102,000 km^2. The artificial oasis KEA, in the middle of the HRB, is irrigated and produces several major commodity crops. The natural oasis KEA downstream of the HRB receives <50 mm per year of precipitation. This KEA supports terminal lakes and contains riparian vegetation adjacent to surface water. Observation infrastructure includes a variety of hydrological, ecological, and meteorological instruments in the HRB that will include a wide array of remotely sensed imagery (Li et al., 2017). Focused observation periods will also be conducted on a periodic basis at the three KEAs.

The CCRN (www.communityconservation.net) approach is entirely different from what most of the readers of this journal are familiar with. It is an opt-in international initiative that is headquartered out of Saint Mary's University in Halifax, Canada. CCRN employs a social-ecological systems (SES) approach to develop community-based climate change adaptation strategies and case studies (Ban & Cox, 2017; Berkes, 2009; Ostrom, 2009). This consists of a partnership of government and non-governmental groups, universities, communities, and indigenous peoples. The website provides a resource center for projects around the world and highlights lessons learned and the success of conservation projects. CCRN also conducts and guides capacity building and community-based research. Projects explore governance issues and how communities can enrich their natural environment and local economies for the long term (Berkes et al., 2016).

3.2. Summary of ARS Experimental Watersheds Output

Research emanating from the ARS-EWN, including its extensive knowledge base and long-term, high-resolution observations, is substantial. The research is summarized in thousands of papers appearing in the peer-reviewed literature ranging from basic to applied research, including technology transfer to producers and land managers (see Appendix A; the total number of returns from the searches is conservatively estimated to be greater than 10,000). The USDA-Natural Resources Conservation Service (NRCS), the U.S. Army Corps of Engineers (USACE), the U.S. Environmental Protection Agency, state agencies, and producers are major consumers and beneficiaries of the research and observations made at the ARS Experimental Watersheds. Many of the conservation and management practices deployed across the nation by NRCS were developed by ARS and validated with experiments and observations from the watershed network. Many of the accomplishments arising from long-term ARS watershed research and watershed observations, often over decades, have direct benefits to society at large. The following section provides further detail on accomplishments judged to have substantial social benefit.

4. Major Accomplishments With Direct Societal Benefits

Societal benefits increase the welfare of a society from a particular course of action. In some cases, these benefits can be quantified, and in some cases, they cannot be quantified with monetary metrics. An example of non-quantifiable benefits are improvements of non-market ecosystem services (e.g., clean water, the educational value of graduate students using ARS watershed data, development and validation of models, and carbon sequestration). For an example of methods to quantify non-market attributes (hydrologic condition, riparian habitat quality, and biodiversity) in monetary terms, see Broadbent et al. (2015). Many societal benefits arise when management practices and design criteria are put into widespread use by farmers as conservation programs are implemented and as a result of building drainage and flood control infrastructure. In this section, examples of accomplishments arising from the ARS Experimental Watersheds and associated research are described. The examples are grouped into two categories. The first are network-level accomplishments, when observations from multiple experimental watershed and their associated scientists are involved. The second set of accomplishments arise from individual experimental watersheds.

4.1. Network-Level Accomplishments

4.1.1. Mapping Crop Water Use and Stress From Space Using Satellite Remote Sensing

A satellite-based ET mapping toolkit developed by ARS scientists is improving drought monitoring and agricultural water management in the United States and internationally (Anderson et al., 2011). Long-term surface flux, soil moisture, and biophysical observations collected in multiple ARS watersheds have been critical in the development and verification of this toolkit at both regional and field scales (Anderson et al., 1997, 2000, 2008; Norman et al., 2003). For example, flux measurements made in semiarid grasslands in Walnut Gulch watershed were critical to understanding the differential coupling between soil and canopy energy and water exchanges with the atmosphere (Anderson et al., 1997, 2000), while intensive ground and airborne measurements over the Little Washita helped to verify spatial variability in the modeled energy budget and carbon fluxes (Anderson et al., 2008). These remote sensing methods have been demonstrated to provide timely and robust geospatial information about crop water use at scales resolving individual farm fields (Kustas & Anderson, 2009) up to continental and global scales, and these products are being used operationally. At the regional scale, NASA uses the ARS ET toolkit to generate a regional Evaporative Stress Index (ESI) of agricultural drought for U.S. and global domains. The ESI is an early indicator of developing flash drought (Otkin et al., 2016) and has been integrated into the USGS Quick Drought Response Indicator (QuickDRI; quickdri.unl.edu). Both ESI and QuickDRI are used in the construction of widely used weekly U.S. Drought Monitor (USDM) reports. Drought systems based on the USDM paradigm have been developed in Brazil and the Czech Republic and are routinely ingesting the global ESI product (Anderson, Hain, et al., 2016; Anderson, Zolin, et al., 2016). These products are also used by the USDA Foreign Agricultural Service (FAS) for international crop monitoring to make adjustments to imports or domestic marketing allotments to ensure an adequate supply for the domestic market, avoid forfeitures, and prevent or correct market disruptions.

4.1.2. ARS Experimental Watersheds Are Essential in Calibrating and Validating Remotely Sensed Soil Moisture Products

In 2002, soil moisture monitoring began in earnest across four ARS Experimental Watersheds. Initially, these networks were developed to provide validation for the Advanced Microwave Scanning Radiometer-E (AMSR-E; Jackson et al., 2010) on the AQUA satellite. The Japanese Space Agency (JAXA) ADEOS-II mission used the Little River watershed soil moisture network for validation of its products (Choi et al., 2008). These networks were able to establish the baseline accuracy that met mission accuracy requirements for the respective global soil moisture products for AMSR-E; the Soil Moisture Ocean Salinity mission (SMOS; Jackson et al., 2012); and the Soil Moisture Active Passive (SMAP) mission (Chan et al., 2016; Colliander et al., 2017). For SMAP, a total of six ARS watersheds were included in the set of 15 core validation sites. If the ARS watersheds were not included in the validation data set, the mission accuracy would not have met the mission requirements. The utility of improved soil moisture products has provided for great advances in hydrologic science that benefit society in a multitude of ways. Purdy et al. (2018) demonstrated that SMAP soil moisture products can improve the estimation of ET. Zhang et al. (2019) developed a method for improving Global Precipitation Mission estimates of precipitation in near real time. Soil moisture satellite products are being used to improve drought analysis (Sun et al., 2019; Yin et al., 2018) as well as flood forecasting (Seo et al., 2017). These products are also being incorporated operationally to improve the continental National Weather Service (NWS) Noah Model (Yin et al., 2019). Currently, eight ARS watersheds are conducting satellite-scale soil moisture calibration and validation activities at increasingly smaller scales, toward a goal of eventually bringing remote soil moisture monitoring down to the farm and ranch management scale. These data are available at the SMAP Data Archive (https://nsidc.org/data/NSIDC-0712/versions/1).

4.1.3. ARS Water Erosion Model Saved Taxpayers Billions of Dollars in the Clean-Up of Superfund Site

The Water Erosion Prediction Project (WEPP; Nearing et al., 1989) was developed by ARS scientists from multiple locations and verified by data from a number of ARS experimental watersheds and experimental rainfall simulator plots. Even though modeling of radioactive particle transport was not an intended application, WEPP became a critical tool in assessing and designing remediation to clean up the Rocky Flats Superfund site near Denver, Colorado. This achievement was best summarized in the last paragraph of a 2006 *Physics Today* article (Clark et al., 2006). They noted that particle transport mechanisms of plutonium and americium mobility provided a scientifically sound approach to clean up and mitigate radioactive contamination rather than addressing aqueous sorption-desorption processes. The contractor was thus able to rapidly apply soil erosion and sediment transport models that led to a sitewide design of erosion control technology, resulting in the most extensive clean-up in the history of Superfund legislation. "Consequently, the project finished one year ahead of schedule, saved taxpayers billions of dollars, and removed an annual liability of more than $600 million from the DOE budget." In addition to cropland applications of WEPP, the Forest Service widely applies WEPP to disturbed forestland conditions through a database of WEPP outputs with a web interface (Elliot, 2004).

4.1.4. Fundamental Research of Phosphorus Losses Have Led to Development of the Phosphorus (P) Index, a Nutrient Management Planning Tool, and Adoption by 47 U.S. States

Phosphorus is at the core of modern agricultural nutrient management, representing both a valuable resource with finite global reserves and an environmental concern, as exemplified by its role in degrading the water quality of the Chesapeake Bay, Lake Erie, and the Gulf of Mexico (Jarvie et al., 2015; Kleinman et al., 2019). Fundamental relationships describing the source and transport of phosphorus from agricultural landscapes to water bodies were first developed in the ARS watersheds, beginning in the Mahantango Creek Watershed (PA) and extending to watersheds in Georgia, Idaho, Missouri, Mississippi, Ohio, and Texas (King et al., 2015; Kleinman et al., 2017; Sharpley et al., 2017). This basic understanding of phosphorus loss from agricultural sources led to the development of the Phosphorus Index, a nutrient management planning tool that has been adopted by 47 U.S. states (Sharpley et al., 2003). Recently, ARS scientists at the University Park, Pennsylvania location, in collaboration with ARS scientists at other watershed locations and university partners across the country, led efforts to evaluate and update nutrient management planning using the Phosphorus Index (Sharpley et al., 2003). Their efforts were capped by a global review of the state of the science, comprised by over 20 peer-reviewed publications on phosphorus site assessment (Kleinman et al., 2017). Included are new, state-of-the-art tools that harness weather forecasting for use in nutrient management decision support tools and new methods for verifying nutrient management planning tools to support intended water quality outcomes (Buda et al., 2013; Collick et al., 2016; Drohan et al., 2019; Easton et al., 2017).

4.1.5. Validation of the Benefits of Conservation Spending by the NRCS Supports Continued Investments

The 2002 Farm Bill increased conservation spending by nearly 80% above the levels in the 1996 Farm Bill and created the Conservation Security Program (CSP). Much of this increase was intended to not only protect land in production but also increase off-field environmental benefits. Substantial research has been undertaken (much of it on ARS Experimental Watersheds) to quantify edge-of-field effects of conservation practices; however, the environmental benefits had not previously been quantified for reporting at watershed and regional scales (Mausbach & Dedrick, 2004). To ensure legislators and the public that these increased expenditures would be well spent, the NRCS and ARS initiated the Conservation Effect Assessment Project (CEAP). Goals of this project included the development of sufficient scientific understanding of conservation practice effects at the field and watershed scales to enable regional and national assessments with watershed models. CEAP started in cropland environments on 14 benchmark ARS Watersheds. Six of the 14 benchmark watersheds are part of the long-term ARS EWN described herein. Special issues of the *Journal of Soil and Water Conservation* have been published at the 5-, 10-, and 15-year marks of the CEAP program (Duriancik et al., 2008; Moriasi et al., 2020; Tomer et al., 2014). Moriasi et al.'s 15-year retrospective study indicated that 13 of 21 ARS benchmark CEAP watersheds demonstrated measurable water quality improvements at subwatershed or watershed scales for at least one of the water quality constituents monitored. These findings have supported continued investments in conservation practices (~$4B in FY2019).

4.1.6. Development, Experimentation, and Quantification of Conservation Management and Practices Effects Led to Rapid Global Adoption of CA

USDA-ARS scientists from multiple research centers and associated experimental watersheds in cropland-dominated regions conducted pioneering work in the development of conservation agriculture (CA) and quantification of its benefits (Barnett, 1958; Carreker & Barnett, 1953; Hendrickson et al., 1963). In a multiyear study, Langdale, Mills, et al. (1992), Langdale, West, et al. (1992), and Bruce et al. (1995) determined that no-till planting of grain sorghum into crimson clover increased soil carbon in the top 15 mm of soil, greatly improving infiltration. Further evidence of long-term soil improvement was demonstrated with hydrology data from 27 years of conservation tillage and cover cropping where runoff ratios declined by more than a factor of 8, from 16.5% to 2%, and soil losses declined from 129.3 to 1.8 kg/ha/mm rainfall (Endale et al., 2000). A CA practice developed from one experimental watershed needs to be validated before applying it to a new region, as it may require modification to accomadate different soils, crops, or climate. This was apparent when no-till CA developed in the Watkinsville watershed in Georgia by Langdale, Mills, et al. (1992) and Langdale, West, et al. (1992) was tested by Ghidey and Alberts (1998) in claypan soils in the Goodwater Creek Experimental Watershed in Missouri. While the CA (no-till) tested by Langdale et al. reduced sediment losses as expected, it more than doubled soluble pollutant losses of phosphorus and pesticides (Ghidey et al., 2005, 2010) because no-till did not reduce runoff in Missouri due to clay pan soils. Thus, a trade-off exists between the benefits of retaining soil in the field and greater pesticide and nutrient losses that degrade water quality. However, further research at Goodwater Creek found no-till in combination with cover crops, a longer crop rotation, site-specific N, variable-rate or zonal P, K and lime, and split application of atrazine brought nutrient and pesticide losses in surface runoff to levels similar to those from a tilled system (Baffaut et al., 2020). Adoption of various CA practices has been relatively rapid and widespread. In Georgia in 2008, 46% of the 1.37 million hectares of planted cropland was under conservation tillage. Nationwide, "Conservation tillage was used on a majority of wheat (67% in 2017), corn (65%, 2016), and soybeans (70%, 2012) …" (Claassen et al., 2018). Conservation tillage practices are credited with decreasing soil erosion on U.S. cropland by 43% from 1982 to 2007, preventing close to 0.7 billion Mg of soil from leaving croplands and entering wetlands and waterways (USDA-NRCS, 2010). Globally, CA increased from 2.8 million hectares in 1974 to approximately 175 million hectares in 2015 (Kassam et al., 2015). Testing and modification of CA across much of the ARS-EWN has resulted in more robust and widely applicable methods and increased interest in adoption. Gobally, incorporating CA into cropping management has and continues to reduce soil erosion, improve water quality and soil health, and increase producer income.

4.1.7. Development and Validation of Field- and Watershed-Scale Models That Are Widely Used in Applications From Land Use Management to Infrastructure Design

4.1.7.1. Field Scale

The long-term ARS-EWN greatly aided expansion of hydrological process knowledge used to improve representation of processes and effects of land use and conservation practices in simulation models. In addition, the experimental watersheds provide high-quality validation data across a wide hydro-agro-climatic spectrum. Perhaps the best-known model in this regard is the Universal Soil Loss Equation or USLE (Laflen & Flanagan, 2013; Wischmeier & Smith, 1965). This empirical model summarized over 10,000 plot years of data collected over decades as well as hundreds of rainfall simulator experiments. Together with the concept of soil loss tolerance ("T") value, USLE and its successors (revised USLE, RUSLE, and revised USLE 2, RUSLE2; e.g., Renard et al., 1997) are used in conservation planning and compliance by NRCS. If the calculated erosion rate was >T, alternative erosion rates could be calculated under conservation or farming practices to reduce erosion, thus guiding investment of conservation dollars. Even today, USLE, RUSLE, and RUSLE2 are widely used internationally as erosion components in watershed models and to derive global soil erosion maps (Borrelli et al., 2017).

Field-scale models with more explicit representation of the water budget and biogeochemistry include the Chemicals, Runoff, and Erosion from Agricultural Management Systems or the CREAMS model (Knisel, 1980). The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987) was developed to assess agricultural chemical movement in runoff and its leaching toward groundwater. A number of models that also incorporated plant production were developed in Temple, Texas, including the Modified USLE, or MUSLE, (Williams, 1975); the Erosion/Productivity Impact Calculator (EPIC); and the Agricultural Policy/Environmental eXtender (APEX; Williams & Sharpley, 1989). More recently, the Root Zone Water Quality model (RZWQM, Ahuja et al., 2000; Ma et al., 2012) has incorporated treatment of biological processes and preferential flow. The Rangeland Hydrology and Erosion Model (RHEM), an erosion model explicitly developed for rangelands, has been developed and released (Hernandez et al., 2017). More explicit process-based field-scale erosion models include the WEPP (Nearing et al., 1989). Elliot (2004) extended WEPP's use into a risk-based variant ERMiT for many U.S. Forest Service applications to quantify erosion in disturbed forested conditions (Robichaud et al., 2007). Another significant non-cropland application of WEPP was for the clean-up of the Rocky Flats superfund site detailed in section 4.1.3.

4.1.7.2. Watershed Scale

Given the need to address watershed-scale issues, the ARS-EWN has also developed a number of watershed-scale simulation models. The most widely applied model for water quality applications is SWAT, the Soil and Water Assessment Tool (Arnold et al., 2012; Gassman et al., 2007; http://swat.tamu.edu/software/). SWAT has been widely used in the United States to support the Conservation Effects Assessment Program (CEAP; Richardson et al., 2008) and national-, state-, and watershed-level water quality programs. A large international community works to adapt and apply the model to local conditions. SWAT is arguably one of the most widely used watershed models in the world. A crude index supporting this statement is the approximate total number of hits on a Google Scholar search (search entry: "acronym of the watershed model"): SWAT—34,400; HEC-HMS—8,700; HSPF—8,480; SWMM—7,820; and PRMS—2,570. Based on research carried out in the Little River Experimental Watershed (LREW), scientists at the

Southeast Watershed Research Laboratory (SEWRL) developed the Riparian Ecosystem Management Model (REMM), described further in section 4.2.2. The AGNPS model (a non-point source pollution model for evaluating agricultural watersheds; Young et al., 1989) was developed by ARS and tested at numerous ARS experimental watersheds and is in common use today. The KINematic runoff and EROSion model (KINEROS; Goodrich et al., 2012; Woolhiser et al., 1990) has evolved over many years at several ARS laboratories and has been validated using observations from several ARS experimental watersheds.

In addition to developing models themselves, ARS-EWN scientists have also developed tools to support modeling. The Topographic Parameterization Software model (TOPAZ; Garbrecht & Martz, 1997) has been widely used to delineate flow pathways and subwatersheds in low-relief watersheds. The Automated Geospatial Watershed Assessment tool (AGWA; Miller et al., 2007) is designed for watershed delineation, model parameter assignment, model execution, as well as temporal and spatial display of model results for KINEROS and SWAT. AGWA has been adopted by the Department of Interior National Burn Area Emergency Response (BAER) team and has been applied in over 50 wildfires that burned more than 1.6 million hectares (>4 million ac). The ARS has also developed tools to generate climate inputs for areas without detailed long-term measurements. The Climate Generator, CLIGEN (Nicks & Lane, 1989) uses a skewed normal distribution to generate daily precipitation as well as wind, radiation, and temperature. CLIGEN is widely incorporated as a component in hydrologic and natural resource models including WEPP (Flanagan & Nearing, 1995), SWAT (Arnold et al., 1998, 2012), and RHEM. More recently, the SYNthetic daily weather generaTOR (SYNTOR) was developed to generate climate realizations for future climate scenarios and was successful in generating daily weather sequences with more accurate replication of precipitation statistics (Garbrecht & Zhang, 2003; Garbrecht et al., 2014).

4.2. Individual Experimental Watershed and Associated Research Unit Accomplishments

4.2.1. Foundational Development of CN and SCS Unit Hydrograph Methods to Design and Guide Conservation and Drainage Infrastructure Spending Worldwide: ARS NAEW

The North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio, in operation for 81 years, has investigated emerging watershed science issues in agriculture since the mid-1930s (Bonta et al., 2018; Harmel et al., 2007; Owens et al., 2010). The monitoring infrastructure consisted of gauged experimental areas ranging from very small lysimeters (0.001 ha) to small (0.4–0.8 ha) to larger (~18 km^2) watersheds. The NAEW precipitation and runoff database provided a significant number of watersheds with different land management that were used in the development and testing of the curve number (CN) watershed runoff estimation procedure. The SCS needed tools to estimate daily runoff and peak flows to protect watersheds from erosion and frequent flooding, as authorized by the Watershed Protection and Flood Prevention Act of 1954 (PL-566). The history of the development of the CN by Victor Mockus is not well documented, having been published as a method in early versions of the SCS National Engineering Handbook (Mockus, 1971), rather than the peer-reviewed literature. In the same handbook, the application of a SCS unit hydrograph to estimate peak runoff rates also appears, and both are often referred to as CN methods (Fennessey et al., 2001). In a 1996 interview, Mockus noted that he had worked at Coshocton for a long time and understood that data set (Ponce, 1996). Ultimately, the CN was tested with data from a total of 24 experimental watersheds (Hawkins et al., 2008). It has been incorporated into numerous watershed and water quality models including the TR-20 and TR-55 models used for stormwater management and drainage infrastructure design. The CN is still widely used on watersheds with a variety of land uses around the world.

4.2.2. Quantification and Modeling of Riparian Ecosystem Services in Agricultural Landscapes: ARS LREW

Scientists at the SEWRL were the first to document the role of riparian buffers in controlling non-point pollution from agricultural watersheds (Lowrance et al., 1985). Research on the LREW documented the contributions of riparian buffers as long-term nutrient (i.e., N, P, Ca, and Mg) and sediment sinks. This pioneering work set in motion a line of research that continues to this day by scientists at numerous national and international agencies and universities. Further studies at the SEWRL/LREW and in the geographically diverse locations focused on understanding the effects of riparian ecosystems management on water quality and soil functions (Lowrance & Sheridan, 2005; Vellidis et al., 2003). The first NRCS Riparian Forest Buffer Specifications were based on this research. This research also led to development of the widely used REMM (Lowrance et al., 2000), one of the only management tools for simulation of the water quality functions provided by riparian buffer systems (Graff et al., 2005; Inamdar, Lowrance, et al., 1999, Inamdar, Sheridan, et al., 1999). According to the Chesapeake Riparian Forest Buffer Network, riparian buffers are among the best practices for improving stream health, habitat, and water quality per dollar invested (http://chesapeakeforestbuffers.net/). NRCS Practice 391 specifications coupled with REMM modeling have guided the expenditure of substantial conservation dollars to install and upgrade riparian buffers across the United States and internationally.

4.2.3. Dominance of Channel Sediment Leads to Use of Bank Erosion Models in Designing Multiple Billion-Dollar Flood Reduction and Bank Stabilization Projects in Major River Systems Across the United States: ARS GCEW

The Goodwin Creek Experimental Watershed (GCEW) has been in operation since 1981 to study the impact of climate, land use, and channel stabilization measures on runoff, sediment transport, channel morphology, and aquatic habitat. Both conventional sediment budget methods (surveying and stream gaging techniques) and the signatures of naturally occurring radionuclides showed that approximately three-fourths of the fine sediment in the GCEW originates from channel sources (Grissinger et al., 1991). The significance of channel contributions to overall watershed-scale fine sediment load was verified using several other ARS CEAP Experimental Watersheds (Wilson et al., 2008). Similar methods were used to quantify the relative effects of contemporary land use change and channel stabilization on instream suspended sediment load at the watershed scale (Kuhnle et al., 1996). These findings spurred the development and verification of bank erosion models from long-term field experiments and observations in the GCEW (Langendoen & Simon, 2008; Simon et al., 2000; Simon & Collison, 2002). The bank erosion models have been incorporated into the ARS CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) and Bank Stability and Toe Erosion Model (BSTEM) as well as the USACE's HEC-RAS and the U.S. Bureau of Reclamation's (USBR) SRH-2D computer models. These models have been deployed in multiple billion-dollar flood reduction and bank stabilization projects in major river systems across the United States (Barr Engineering, 2012; Rivas et al., 2019). USACE and USBR are also using these models to assess reservoir sediment strategies in several river systems, including the Missouri and Rio Grande Rivers.

4.2.4. Rainfall Characteristics From Dense Rain Gauge Network (80 Gauges in 149 km^2) Have Been Used to Design Billions of Dollars of Storm Water Infrastructure in the Southwest: ARS WGEW

Stormwater infrastructure designs are dependent on intensity-duration-frequencies (IDF) and area-depth-frequency (ADF) relationships and on the size of the project's drainage area. IDF curves from NOAA Atlas 2 (Miller et al., 1973) were substantially lower than IDFs estimated from the Walnut Gulch Experimental Watershed (WGEW) gauge network for less frequent events (50- and 100-year return periods; Osborn & Lane, 1981; Osborn & Renard, 1988). On the other hand, ADF analysis of the WGEW rainfall data indicated that the reductions from point-to-area rainfall depths were substantially more rapid from the WGEW than those from NOAA Atlas 2 (Osborn et al., 1980; Myers & Zehr, 1980). These results indicate that WGEW storms are more compact and more intense than those analyzed in NOAA Atlas 2. The NWS (National Weather Service, 1984; Zehr & Myers, 1984) extrapolated the results of Osborn et al. (1980) into zones across Arizona and western New Mexico. The NWS highlighted the importance of the long-term dense, subdaily, rain gauge networks by noting: “This report carries out the engineering necessity of extracting practical [depth-area] ratios of importance to design of structures that in the aggregate cost very substantial sums. … Such data cannot be secured within the time frames of individual projects.” (Zehr & Myers, 1984, p. 35). The ADF curves derived from the WGEW, or minor variants of them, are still being applied in Arizona, western New Mexico, Nevada, and the southern California desert areas, including large portions of Los Angeles and San Diego counties (Arizona Dept. Water Res. Flood Mitigation, 2007; California DOT, 2018; Nevada DOT, 2006). More accurate estimates of design storm rainfall characteristics from the WGEW provide safe designs without wasting dollars in overdesign that would have occurred using NOAA Atlas 2 IDFs and ADFs.

4.2.5. Developing Next Generation Water Supply Forecasting Tools for Water Managers in the Mountainous West: ARS RCEW

In mountainous regions of the western United States, water resources are largely derived from springtime mountain snowmelt. Understanding and forecasting this process is essential to critical western agricultural and urban systems. The extensively instrumented Reynolds Creek Experimental Watershed (RCEW), with 55 measurement sites across the 2,000-m elevation range, provided the critical testbed for the development and validation of a robust set of physics-based modeling tools capable of simulating the deposition, development, and melting of snow over a mountain basin (e.g., Marks et al., 2002; Reba et al., 2011). In a joint project initiated in 2013 with NASA/JPL, ARS scientists adapted the modeling tools developed over RCEW and applied them in real-time across a 60,000 km^2 region of California's Sierra Nevada mountains at 50-m resolution (Havens et al., 2017; Hedrick et al., 2018). This provided critical weekly snow cover storage and melt summaries to forecasting groups across the region. Groups using the weekly model forecasts include the California Department of Water Resources, the USBR, NRCS, San Francisco Public Utilities Commission, and the following water authorities and irrigation districts: Turlock, Friant, Merced, Kaweah Delta, Kings River, and Mammoth. The region on average generates 1,230,000 ha-m of runoff from rain and snowmelt, representing approximately one third of California's agricultural water supply. The value of water resources from this region for agriculture, ecosystems, and power generation is estimated to be $1 to $5 billion dollars per year.

4.2.6. Linking Complex Hydrologic Processes in Restoring the Chesapeake Bay and Protecting New York's Drinking Water Supply: ARS MCEW

The sloping landscapes of the eastern United States are highly variable in their hydrologic connection to surface waters (Pionke et al., 2000). Distribution of restrictive features in soils, such as shallow pans, acts as a primary control for surface runoff potential (Buda et al., 2009; Gburek & Sharpley, 1998). The small fields of this region, often <3 ha, offer the opportunity to target management within hydrologic gradients (Piechnik et al., 2012; Veith et al., 2005) and support nutrient management strategies that can be applied at field and watershed scales (Amin et al., 2018; Buda et al., 2009). Hydrologic research within the upper Chesapeake Bay watershed underpins modern critical source area management strategies, now adopted by 47 of 50 U.S. states (Sharpley et al., 2003), and locally serves as the basis for nutrient management in the six states participating in the Chesapeake Bay total maximum daily load (Amin et al., 2020; USDA-ARS 2010). Simulations with SWAT in the Mahantango Creek Experimental Watershed (MCEW) illustrate how targeting practices to fields with high runoff potential prevent roughly three times more N and P annually from reaching the streams, for 30% less than the cost of implementing practices under conventional, blanket strategies. As Chesapeake Bay states have adopted these strategies, 97% of cultivated farmland is now estimated to have some form of erosion control (USDA-NRCS, 2013), and progress has been documented in reducing long-term, flow-normalized nutrient and sediment levels (Chesapeake Bay Program, 2020; Northey, 2020). Similar application of targeting hydrologically active areas in New York's Cannonsville Reservoir watershed has improved the water quality to the point that mandated source filtration of New York City drinking water (Bryant et al., 2008) is not needed. The approximately $2 billion spent on upstream water quality mitigation efforts along with a recent $1.5 billion UV treatment facility have prevented requirement of an $8 billion full treatment facility for this source of New York City drinking water (Hu, 2018).

The benefit of the ARS-EWN, including its knowledge and observational database, in the education of future hydrologists is also an important benefit of the network. While comprehensive records have not been kept at each location on the number of theses and dissertations produced using ARS watershed data, a good count is available at the WGEW. To date, 127 PhD dissertations and 81 MS theses have either used Walnut Gulch data or the watershed itself has served as the location for experiments.

5. Lessons Learned

A number of important lessons were learned in the initiation, development, maintenance, and evolution of the ARS-EWN that may benefit other national observation-based research efforts. Several are offered herein, not in order of importance.

1. Facilitate strong connections within the network. A network leadership team, with rotating membership of mid- and late-career scientists, that meets on a regular basis can help maintain information flow among locations and provide oversight and feedback to individual locations as needed. Efficient collaboration software is critical for network scheduling and communications as well accommodation of smaller working groups for both research topics and network operation tasks.
2. Maintain reliable, long-term communication with landowners, managers, producers, and local politicians. Watershed site leaders should regularly engage and do everything they can to be flexible with research plans to help meet local and site-specific needs, including providing public data summaries.

3. Support long-term personnel who can be trained over time to acquire more skills and who can help maintain continuity in high-quality data collection. Innovative individuals with technical instrumentation (e.g., programming dataloggers, electronics), field, and fabrication skills are in short supply, and current hydrology and environmental science degree programs typically do not provide these diverse skills sets.
4. Establish formal collaboration policies that cover

   i. data-sharing both within the network and for public release;
   ii. publication procedures for the network that include notification of planned research and analysis to foster more interdisciplinary interaction and synthesis, guidance for coauthorship inclusion, and necessary acknowledgements; and
   iii. site access guidance and recommendations for visiting scientists and graduate students to specify terms of collaboration and to ensure they do not disturb existing experiments, they respect the wishes of local landowners and producers (e.g., close gates and no litter), and if approached by local persons, they take the time to answer questions and explain current research.

5. Budget realistically. The time and expense for permitting and acquiring access to measurement locations can be considerable and should not be underestimated, and routine funding increases must match inflation to sustain long-term measurements. Additionally, the costs of initial data delivery (e.g., telemetry, cell service), QA/QC, standardized metadata across the network, a flexible database design, archiving, and a well-designed user interface that can easily locate and download data are substantial.
6. Expect variation in data collection parameters across sites. Commercial instrumentation may not be universally suitable over the diverse range of environments across the network. Commercial instrumentation should be tested in the local watershed over an expected range of conditions by a knowledgeable person that can interpret the observations to ensure they are realistic. If possible, they should be checked by an independent measurement method.
7. Duplicate and overlaping measurement instrumentation to support long-term QA/QC. Keep old systems running in parallel when transitioning to new measurement technology, until old and new time series have been compared to ensure the new technology is not responsible for erroneous observations over time. Likewise, it is recommended to install duplicate measurement instrumentation to increase the probability for recording infrequent events (e.g., runoff in arid ephemeral channels).
8. Mimimize data uncertainty by routinely corroborating and reevaluating processes. Some degree of trial and error is inevitable in selecting or developing suitable instruments and siting them to acquire meaningful observations. If your network of instrumentation has telemetry (highly advised), daily status reports (e.g., voltage, temperature) should be generated and forwarded to responsible staff to facilitate rapid repair and minimize down time. Annual, or more frequent, instrument calibrations and inspection of site conditions should be performed and results made part of the archive. Records/observations should also be kept of equipment malfunctions or down time (e.g., vandalism, flood damage, sediment covering sensors or altering weir ratings, and field operations).

The points noted above largely cover lessons learned in the construction and operation of a watershed observatory and a larger network. But to keep a network of hydrologic observatories relevant, our experience is that watershed networks have to refresh research objectives to adapt and expand to encompass new and more socially relevant challenges. In the case of the ARS-EWN, noted expansions included adding water quality when the CWA was passed in the early 1970s. The rising importance in global change induced many watersheds to add observations on water, energy, carbon, and trace gas fluxes in the 1990s. These events fostered a drive toward interdisciplinary research. In addition, as time progressed, landowners, managers, and policy makers have had to address more complicated decisions that require more integrated knowledge on interactions and feedbacks between multiple systems and cycles. As we increase our scope of consideration from hillslope and field management toward landscape and watershed systems, the increasing degrees of heterogeneity and complexity complicate the understandings we have acquired at smaller scales.

A good example of this draws from the accomplishments discussed in sections 4.2.2 and 4.2.3. Early ARS erosion research was primarily conducted on field and hillslope scales. To minimize off-field effects, the LREW group in Georgia conducted extensive research on the effectiveness of riparian buffer strips.

Adequately addressing the effectiveness of buffers required understanding biogeochemistry of nutrient cycling, sediment transport, and aquatic ecology. Increasing in scope, the GCEW group in Mississippi identified that approximately 75% of downstream channel sediments originated from bank erosion and from upstream in-channel sediment. This required skills in trace elements and isotope geophysics, geomorphology, hydraulic engineering, and numerical modeling to develop complex bank erosion models. These findings have important implications for making conservation investments. Without the GCEW research and monitoring, conservation expenditures would have mistakenly focused on upland fields and riparian buffers with minor downstream improvement to show for it. The CEAP project, which has been mentioned throughout this paper, is built upon such interdisciplinary research. The project has successfully combined scientists of natural resources, computer modeling, and sociology to successfully quantify the impacts that conservation practices have historically had on the land. However, without the framework provided by the watershed network, it would not have been possible to characterize these impacts at larger scales. This step of scaling up from the field scale to the watershed scale has been a critical component of communicating the results to the general public.

The next phase of network disciplinary expansion more directly examines the food-water nexus, sustainable intensification of agriculture, and socioeconomic factors to grow more food and maintain or improve ecosystem service. This began to take shape in the early 2010 under the umbrella of the LTAR network that is briefly described in the following section.

6. Moving Forward as Part of the LTAR Network

Moving forward, eight of nine operational long-term ARS Experimental Watersheds are now part of the LTAR network (Steiner et al., 2015). In addition, four more recently established ARS Experimental Watersheds have been added to the LTAR network and are briefly described below. The Choptank River watershed (1,756 km^2) on the eastern shore of Maryland has been an ARS watershed since 2004 under CEAP and was incorporated into LTAR in 2014. This watershed has been a study site for assessments of conservation practice performance (cover crops, wetlands), water quality monitoring/modeling, and application of various remote sensing approaches. In Iowa, the South Fork of the Iowa River and the South and North Fork of Walnut Creek are part of the LTAR effort. The South Fork of the Iowa River watershed (780 km^2) is a low-relief landscape composed of glacial till with poor drainage conditions (hydric soils). Major subbasins include Tipton Creek (199 km^2), Beaver Creek (182 km^2), and the upper South Fork (256 km^2), all of which are instrumented with separate gaging stations. Two small drainage districts (500 and 2,500 ha) in Tipton Creek are also instrumented. The North Walnut Creek drains 51.30 km^2 and is underlain by glacial till deposites. Subsurface tile drains and ditches installed over the past 120 years accelerate drainage and transport of several dissolved contaminants. The Fort Cobb Reservoir watershed near El Reno in south-central Oklahoma was established in 2005 (787 km^2). It is sparsely populated with agricultural land use consisting of mixed cropland and grazing land (Starks et al., 2014). Conservation practices include pasture and hay planting, terraces, grassed waterways, fencing, grade stabilization structures, and critical area planting. Prior to about 1950, few conservation practices were undertaken, but extensive soil conservation measures were implemented in the second half of the 20th century. Using remote sensing for watershed characterization over time, reservoir bathemetry, and measurements of suspended sediment from the 1940s and the 2000s, the effects of upstream conservation practices can be quantified at the basin scale.

The vision of the LTAR network is to enable multidecadal, transdisciplinary, and cross-location science to ensure the long-term sustainability of U.S. agriculture. LTAR's primary goals are to (1) intensify agricultural productivity, (2) improve the ecosystem services related to agricultural production; and (3) improve rural prosperity. LTAR will 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, ecosystem services, and rural well-being under changing environmental, economic, and societal conditions. Additional details on the LTAR network can be found online (https://ltar.ars.usda.gov/) and in Kleinman et al. (2019).

A central data portal for a portion of the experimental watershed network was developed for the cropland CEAP resulting in STEWARDS. STEWARDS was developed to provide data search, viewing, and downloading capabilities. The portal is a data delivery system with a geographic information system interface, using space, time, and topic as key fields for searching an extensive database of soil, water, climate, and land management data from multiple long-term research watersheds (Steiner et al., 2008; https://data.nal.usda.gov/node/146). As can be seen in Table 2, it serves as the data portal for the majority of the long-term ARS Experimental Watersheds. STEWARDS also contains observations from the four newer LTAR Experimental Watersheds noted above. To address the goals of LTAR, a wider set of data types than those typically associated with experimental watersheds will need to be achieved (e.g., productivity, economic, social, biodiversity, and nutrition data, among others). This and federal open data requirements have elevated data archive and access needs to an agency-level archival system called AgCROS (Agricultural Collaborative Research Outcomes System; Delgado et al., 2018).

AgCROS is a cloud-based integrated platform designed to eventually be a "one-stop shop" for USDA agricultural research data and metadata, along with providing access to relevant data from other organizations. It is a growing "network of networks" that presently contains a wide variety of data sets from multiple agricultural research networks, such as the Nutrient Uptake and Outcome Network (NUOnet), the Greenhouse gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet), the Resilient Economic Agricultural Practices (REAP), the Dairy Agriculture for People and the Planet (DAPP; Dairy Grand Challenge), the Soil Health Assessment Network (SHAnet), the Agricultural Antibiotic Resistance (AgAR), and more recently, the LTAR network. By integrating these diverse data networks into a well-described and organized open access database, AgCROS facilitates the ease and access of research data and increases efficiency and collaboration among researchers. Intended to be more than just a data repository, AgCROS already contains a variety of analysis tools, geospatial and otherwise, to accompany its data sets. In the future, AgCROS could provide data that can be used in more advanced tools, including artificial intelligence and machine learning. The National Agricultural Library also enables the discovery of these data sets (in AgCROS) by publishing and hosting metadata through Ag Data Commons. Ag Data Commons is a project that complies with the U.S. Project Open Data to facilitate greater adoption of open data practices within the federal government. In 2017, an effort was started to provide metadata from all available data sets for the 18 LTAR locations, resulting in 378 metadata entries to Ag Data Commons. This effort will allow ready discovery of both legacy and ongoing data sets produced by the LTAR network. Metadata for these data sets is compatible with Project Open Data and metadata can be accessed programmatically in JSON and RDF formats.

The existing links to ARS Experimental Watersheds data, or historic and future LTAR data, accessed through AgCROS can be used to calibrate and validate hydrologic models; evaluate the effects of management and conservation practices; calibrate and verify unmanned aerial vehicle or satellite-based remotely sensed retrieval algorithms (e.g., Landsat, RADARSAT, SMAP, SMOS, ASTER, GPM, among others, as well as future earth observation missions); gain a greater understanding of the transport and fate of agrochemicals and animal waste; and improve our basic knowledge of hydro-agro-ecosystems across a wide range of conditions. The historic data will be augmented by new LTAR measurements related to social well-being, economics, productivity, and genomics. AgCROS will enable rapid multilocation analysis to provide more integrated understanding of agricultural and mixed-use watersheds and improve management of these lands across a spectrum of climates, soils, and agricultural systems.

7. Conclusion

It is our opinion that the accomplishments noted above more than justify the initial and on-going investments made in establishing the ARS watershed research program and its experimental watersheds and the commitment to operate them for the long-term. This includes more than maintaining the observational infrastructure. Ongoing investments in evolving instrumentation, data telemetry, QA/QC, data archival, and readily available open access must be made. Many of the ARS Experimental Watersheds have operated for over half a century and the intent is their continued long-term operation. The LTAR ARS Experimental Watersheds will continue to provide a detailed look into the past, and observations from them enable watershed and climate change quantification at much higher temporal and spatial resolutions than available through national networks maintained by NOAA and USGS. For an example on rain gauge density, see Goodrich et al. (2008).

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LTAR and the USDA-ARS-EWN must tackle several challenges to ensure continued relevancy to society and to the nation's natural resource science and management priorities. What new core observations, beyond the existing observations of weather, climate, precipitation, runoff, erosion, and numerous water quality constituents, should be added to the entire network? Candidates include trace gases, wind erosion, ET and CO_2 fluxes, carbon and nutrient balances, soil health, and groundwater imaging. 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 solutions. Yet the network must maintain a core of observations and common experiments to enable cross-site analysis and continental-scale assessments over the long term. It is the capacity of this long-term network to address national issues across the physiographically and environmentally diverse regions of the continent that define the network, not the assemblage of region-specific data of the various ARS watersheds and rangelands dispersed across the continent.

Appendix A: Google Scholar Searches to Estimate the Number of Publications From Each ARS Experimental Watershed and Other Networks to Which Each Watershed Belongs

Table A1
Google Scholar Search Terms to Acquire the Numbers of Returns for Each of the ARS Experimental Watersheds and Other Networks to Which They Belong

USDA-ARS research unit	Google scholar search term[a]	Approx. number of returns	Other networks associated with the watershed[b]
Southern Piedmont Conservation Research Unit	watershed “Watkinsville” Georgia	770	CEAP
Grassland Soil and Water Research Laboratory	watershed “Riesel” Texas	520	CEAP, SCAN
North Appalachian Experimental Watershed	watershed+experimental+Coshocton+Ohio	1,680	
Pasture Systems and Watershed Management Research Unit	watershed “Mahantango Creek” Pennsylvania	580	Ameriflux, CEAP, DAPP, DAWG, GraceNet, NUONet, Phenocam, REAP, SCAN
National Sedimentation Laboratory	watershed “Goodwin Creek” Mississippi	1,110	Ameriflux, CEAP, SCAN, SURFRAD
Cropping Systems and Water Quality Research Unit	watershed “Goodwater Creek” Missouri	400	CEAP, Phenocam, SCAN
Southwest Watershed Research Center	Walnut Gulch experimental watershed Arizona	3,020	Ameriflux, CEAP, COSMOS, Phenocam, NWEN, SCAN, EOS
Northwest Watershed Research Center	watershed “Reynolds Creek” Idaho	1,710	Ameriflux, CEAP, COSMOS, Phenocam, SCAN, SNOTEL, CZO
Southeast Watershed Hydrology Research Laboratory	watershed “Little River” Georgia	3,850	AgMIP, CEAP, GEOGLAM, JECAM, Phenocam, SCAN
Grazinglands Research Laboratory	watershed “Little Washita” Oklahoma	1,360	CEAP, COSMOS, NWEN, SCAN
	Subtotal	15,000	
Subtract 20% for duplicates and erroneous matches (no attempt was made to remove duplicates)		3,000	
Total—approximate estimate of papers/abstracts matching the search term		~12,000	

[a]Search procedures employed: Go to Scholar.Google.com, ensure the “include patents” and “include citations” boxes are NOT checked. Every fifth page was then quickly examined for unrelated returns. Unrelated returns were relatively rare and were typically only found far down in the return list (~last 10%). To be conservative, 20% of the total number of returns were excluded to account for duplicates, abstracts, and unrelated returns. [b]Networks names and abbreviations. *AmeriFlux* is a member of the global FLUXNET network of networks. *AgMIP* (Agricultural Model Intercomparison and Improvement Project). *CEAP* (Conservation Effects Assessment Project). *COSMOS* (COsmic-ray Soil Moisture Observing System). CZO (Critical Zone Observatories). *DAPP* (Dairy Agriculture for People and the Planet). *DAWG* (Dairy Agroecosystem Working Group). *EOS* (Earth Observing System). *GEOGLAM* (Group on Earth Observations Global Agricultural Monitoring). *GRACEnet* (Greenhouse gas Reduction through Agricultural Carbon Enhancement network). *NUOnet* (Nutrient Uptake and Outcomes). *JECAM* (Joint Experiment for Crop Assessment and Monitoring). *NWEN* (National Wind Erosion Network). PhenoCAM. *REAP* (Resilient Economic Agricultural Practices). *SCAN* (Soil Climate Analysis Network) is a subset of the International Soil Moisture Network (ISMN). SnoTel. *SURFRAD* (Surface Radiation Network).

Conflict of Interests

There are no real or perceived financial conflicts of interests for any author to our knowledge. There are no other affiliations for any author that may be perceived as having a conflict of interest with respect to the results of this paper.

Data Availability Statement

URLs for all of the ARS-EWN data for every location and for early watershed observations that are housed in the ARS Water Database at the Hydrology and Remote Sensing Laboratory in Beltsville, MD, USA, are included in the paper.

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