Chapter 1

# Experimental Watersheds at Coshocton, Ohio, USA: Experiences and Establishing New Experimental Watersheds

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Additional information is available at the end of the chapter

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**Abstract**

The North Appalachian Experimental Watershed (NAEW) in Ohio was established in 1935 to improve economical and physical sustainability in agriculture. The objectives were to test management practices on small watersheds, investigate scaling of runoff and erosion to larger areas, and research ways to extrapolate the results to ungauged areas. The facility was equipped with a permanent infrastructure consisting of runoff stations and rain gauges for watersheds ranging in size from 0.26 to 1854 ha, and 11 large (0.008 ha) monolith lysimeters to investigate small-scale water balances, all in an area greater than 2000 ha. After about 1970, the NAEW was reduced in size to 425 ha consisting of mostly small watersheds ("test beds") ranging in size from 0.26 to 3.07 ha. The NAEW was in operation for approximately 81 years generating a long record of runoff and other data for various watersheds, and closed in 2015. A wide variety of experiments were conducted on the NAEW with many high-impact accomplishments and addressing emerging issues that founders never envisioned. Nearly, 500 publications came from investigations during the history of the facility, and insights for establishing new experimental watersheds are presented covering site selection, funding, site specificity, extrapolation of results, generation of runoff in different physiographic regions, collaboration, off-site investigations, and instrumentation. The research on water quality was added to the research objectives in the 1970s, including nutrients (nitrogen and phosphorus) and pesticides in surface runoff and subsurface flow.

**Keywords:** experimental watersheds, lysimeter, precipitation measurement, runoff measurement, agriculture, hydrology, water quality

## 1. Background

In the decades leading up to the mid-1930s in the United States (USA), agricultural enterprises were increasingly physically and economically unsustainable due to soil erosion and flooding. The United States Department of Agriculture (USDA) recognized that there was insufficient underlying science supporting the management of agricultural lands that could be assembled into practical land-management guidance for producers. As a result, a national effort established large and small scale research projects that would test the effectiveness of land-management practices under natural-weather conditions in different regions of the country to minimize agricultural environmental problems nationwide.

Consequently, three large-scale experimental watersheds were established in the USA in the mid-1930s [1]. In 1935, one of the large-scale areas established was the outdoor laboratory for land and water management research at the North Appalachian Experimental Watershed (NAEW, also known as the "Coshocton watersheds") near Coshocton, Ohio, the focus of this chapter. This chapter draws heavily from three prior publications that describe the NAEW. Reference [1] describes the NAEW as part of the three original large-scale experimental watersheds, Ref. [2] concentrates on the NAEW history and capabilities, and Ref. [3] describes the types of NAEW data available.

The purposes of this chapter are to: (1) present the history and design of the NAEW, instrumentation, physical features, unique capabilities, data available, research portfolio, and examples of accomplishments, and (2) discuss challenges likely to be encountered when establishing new experimental watersheds and suggest possible remedies. This chapter summarizes the information given in the NAEW history, research portfolio, and capabilities found in [2]. It differs from the other publications on the NAEW listed above in that it raises challenges and provides guidance for establishing new experimental watersheds based on the research experiences at the NAEW. Some of the information in [2] is reiterated here, and the reader is referred to that publication for more detailed information. As noted in this chapter, the NAEW was unique in data collected and physical features found nowhere else in the USA.

The founding document for the NAEW [4] listed three overall objectives:

1. "To determine the effect of land use and erosion control practices upon the conservation of water for crops and water supply and upon the control of floods under conditions prevailing at the North Appalachian Region [NAR] of the US";

2. "To determine the effect under (1) for small and large areas and to trace variations in this effect from the smallest plot and lysimeters through a series of intermediate watersheds to the largest watershed on the project"; and

3. "To determine the rates and amounts of run-off for precipitation of different amounts and intensities for watersheds typical of the NAR of different configuration, size, shape, topography, cover, underground conditions, land use, and erosion control practices. To furnish data needed for use in the design of erosion control structures and in the design and operation of the Muskingum Watershed Conservancy District and other flood control projects lying within the NAR."

The originators of the experimental watershed program were visionaries as the concepts above are the needs required for ideally researching landscapes to minimize environmental damage and maximize sustainability even today. The objectives above were to investigate, within a region (hill lands of the North Appalachian Region, NAR), conservation practices at the small field scale (areas manageable by the producer—objective 1), to investigate the watershed response when the smaller nested areas (possibly not owned by the same producer) collectively interact at increasingly larger areas (objective 2—scaling), and to generalize/extrapolate the site-specific field results to ungauged areas (todays "modeling"—objective 3—recognizing the site-specificity of monitored watersheds). The founders recognized the temporal and spatial variability of weather and the landscape, the complex nonlinear areal behavior of runoff and erosion processes, the need for measuring watershed responses, and the need for developing guidance for producers in the absence of field data for unmonitored fields and watersheds.

The NAEW was originally operated by the USDA—Soil Conservation Service, Division of Research, and in 1954 became part of the newly created Agricultural Research Service (ARS). NAEW has worked collaboratively throughout the 81-year history with The Ohio State University, especially through its agricultural research center located in Wooster, Ohio. Throughout its history, NAEW scientists have collaborated with university scientists and students worldwide, state and Federal agencies, and persons in the private sector. These collaborations supplied scientific expertise required for specific project objectives and facilitated addition of new capabilities for the NAEW.

Construction of administrative and shop buildings, and instrumentation infrastructure started at the NAEW in about 1935 using workers from the Works Progress Administration (WPA), Civilian Conservation Corps (CCC), and the Civilian Public Service (CPS) program for construction and data collection in the early years. The NAEW was closed in December, 2015, a duration of about 81 years since the construction began. The earliest data records began in about 1937 spanning 78 years of data collection on the NAEW (instrumentation and data to be presented later).

## 2. Physical setting

The NAEW was chosen for its "representativeness" in the NAR which included southeast Ohio, eastern Pennsylvania, northern Kentucky, and northern West Virginia (**Figure 1**). Physical features considered for "representative" experimental watershed selection included soil types, climate, and other factors. Determining representativeness using physical map overlays at the time was comparable to the use of modern-day geographical information systems (GIS). The selected site was one of 86 candidate sites [2, 4].

The NAEW consisted of agricultural lands in east-central Ohio (Ohio map inset in **Figure 2**) with slopes typically ranging from 18 to 25% and elevations ranging from about 250 to 350 m. About half of the area was in grassland with corn, soybeans, wheat, and forest comprising the remaining area [2]. The latitude of the NAEW is about 40.4$^{o}$ N.

Originally, the NAEW comprised a 1854-ha watershed area with several nested gauged watersheds (Little Mill Creek [LMC] watershed, **Figure 2**, left). This watershed was chosen to address

Figure 1. View of NAEW landscape and administrative buildings.

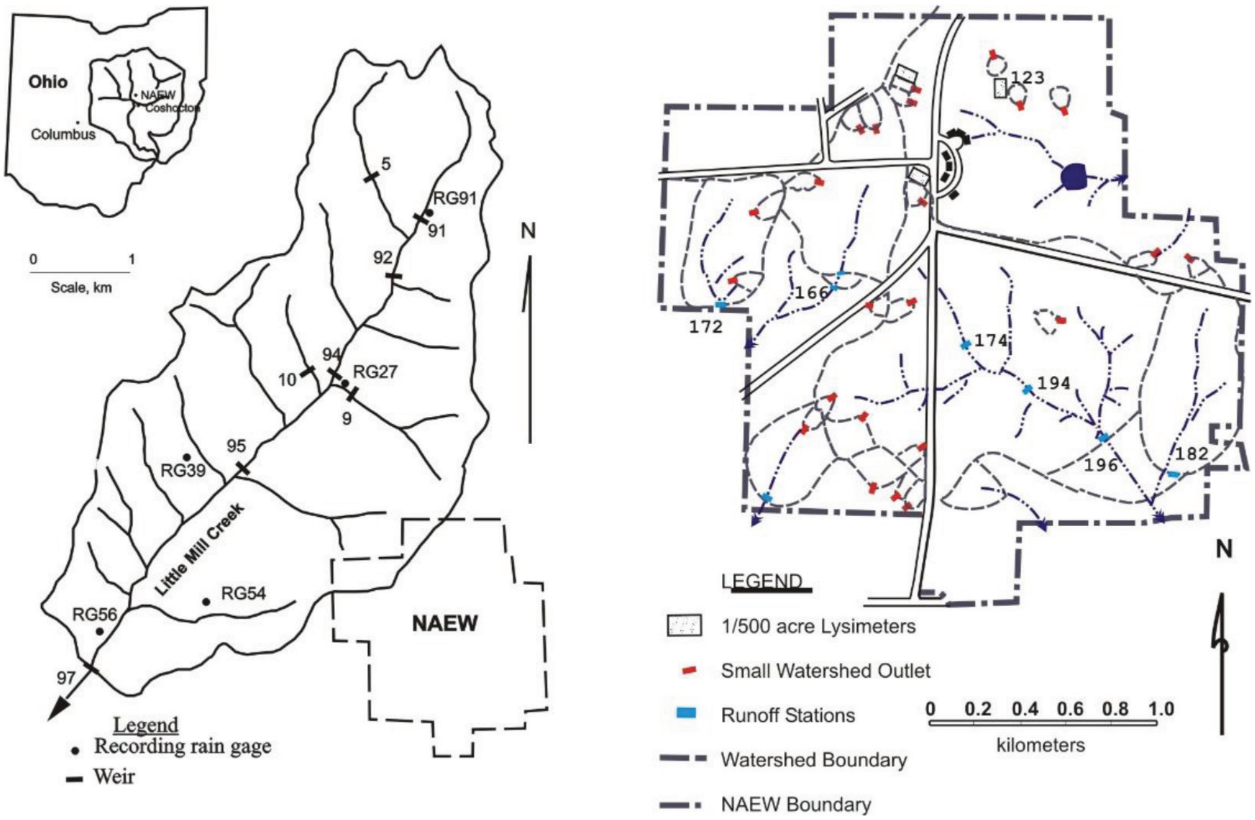


Figure 2. The North Appalachian Experimental Watershed (NAEW) comprises the 1854-ha Little Mill Creek (LMC) watershed (left) and the smaller 425-ha NAEW area (right). Inset shows the location of the NAEW within the state of Ohio.

mainly objective 2—scaling issues. Additionally, part of the NAEW included 425-ha in the southeast area of LMC (**Figure 2**, right). On this area were several small monitored watersheds of the order of 0.4 ha to address mainly objective 1—evaluating impacts of specific practices on a small (producer-managed) areas, where there were no confounding influences of other land-management activities. In approximately 1970, monitoring in the LMC watershed ceased and the NAEW was reduced in size to 425-ha with the largest gauged watershed at 123 ha (**Figure 2**, right).

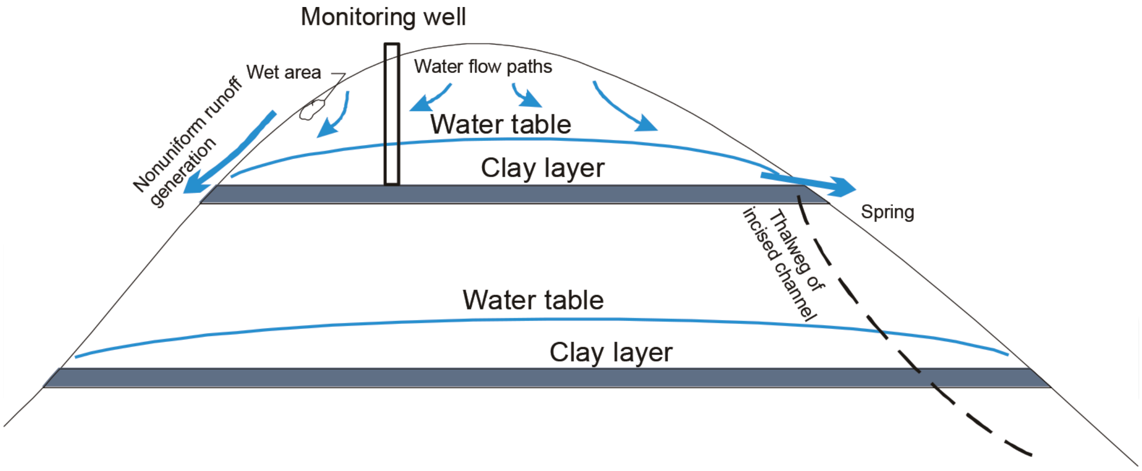


**Figure 3.** Schematic drawing of perched water table due to geological clay layers in unglaciated sedimentary strata on the NAEW in a hilltop, landscape incision of a stream channel intercepting these water sources, and elements of nonuniform runoff generation.

The average annual air temperature is 10.4°C and the average annual precipitation is 959 mm. Cool air from the northwest and moist air from the south often converges to form storms over the NAEW [2]. Soil during winter often freezes for short periods causing precipitation to immediately runoff. Snowmelt also is a source of runoff.

The geology of the NAEW consists of unglaciated sedimentary strata composed of mostly sandstone and shale, with interbedded strata of coal, clay, and limestone. An underlying anticline, local synclines, and strata slightly dipping to the southeast characterize the structure of geological formations [5], (**Figure 3**).

Soils of the NAEW were developed in residua of weathered sandstone and shale. Three dominant soil types include well-drained sandstone-derived soils (Inceptisols), soils with an argillic horizon derived from shale (Alfisols & Ultisols), and soil between these extremes [2, 5].

Small watersheds were chosen from many swale areas on the landscape. They were characterized by ephemeral areas that shed water only during heavy rain storms and snowmelt, with no incised channel. Larger watersheds have incised channels and drain areas with multiple land-management areas.

## 3. Serendipitous physical features affecting hydrology and water quality

Using general factors such as geology, soils, weather, etc., to select a "representative" site for the NAEW was necessary. Other hydrologically beneficial features of the NAEW location, however, became apparent as experiments were conducted on the site. For examples:

1. *The imperviousness of geological clay layers underlying coal seams supported perched water tables* [2]. These perched water bodies allowed an index measure of the ground-water impacts of surface land-management treatments. Ground-water impacts were evaluated, where the intersection of geological clay layers intersected the landscape surface forming springs that were monitored beneath treated hilltops [5], (**Figure 3**). Ground water beneath areas as

large as 15 ha have been monitored by using springs because of this favorable geological structure. Impacts of land management on ground water became a significant area of research on the NAEW.

2. *Nonuniform runoff generation* [2]. Due to springs at the ground surface and persistently high soil-profile-water-content areas, runoff is generated nonuniformly on the surface and with time during an event. NAEW measurements of natural-precipitation infiltration showed that water simultaneously emerges from the soil (exfiltration) and infiltrates into it during a runoff event at different locations. Watershed models today are deficient in modeling this runoff-generating process. Superimposed on these physical processes are wide ranging anthropogenic influences on the land surface as watershed areas increase that also help to generate runoff nonuniformly over a landscape.

3. *Interflow process* [2]. Closely related to nonuniform runoff generation is the interflow process in which water moves laterally within the soil profile. This process was apparent on the NAEW and is also not well simulated in watershed models (**Figure 3**).

4. *Natural lysimeter* [2]. A lysimeter (discussed under "Instrumentation" section) is usually considered an isolated block of soil that accounts for the sources and distribution of water in a contained area. It was discovered that a thick clay layer underlying a coal seam outcropped along the periphery of a hilltop enclosed an approximate area of 2.8 ha (known as Urban's Knob). The synclinal structure of the sedimentary bedrock within the hilltop forced all water entering the hilltop to its center where it discharged to a surface spring. Consequently, the source of all water within the hilltop was from precipitation as no ground water flowed from adjacent areas as often occurs in ground-water studies, forming a "natural" lysimeter. The area was instrumented with a network of wells and piezometers, a spring, two watersheds, a rain gauge, and profiles of ceramic suction cup lysimeters to investigate unsaturated flow of water and chemicals.

5. *Macropore flow* [2]. There is significant transport of chemicals and water in larger pores in the soil (particularly holes caused by earthworms), a poorly simulated process in watershed models. This became a significant area of research at the NAEW as explained later.

## 4. Instrumentation

Instrumentation was planned to achieve the general objectives listed above under natural precipitation and weather conditions—small scale evaluations of treatments, evaluations of watershed responses at larger scales, and "modeling." Generally, instrumentation for measuring watershed responses to treatments was to be permanently available for experiments. This allowed the immediate use of experimental watersheds with a long runoff record to be used in comparisons when evaluating land treatments and reduced the cost of monitoring runoff.

Small watersheds, ranging in size from 0.26 to 3.07 ha, were installed on the smaller 425-ha area (**Figure 2** right) in natural-swale, ephemeral, overland-flow areas on the hillsides where runoff occurs during large intensity rains and snowmelt. These watersheds were used as "test beds" to determine the effectiveness of different land-management treatments. The treatment for an individual watershed was implemented over the entire area so that runoff-response data were not confounded by runoff from other areas with different land managements. Runoff from the smaller watersheds were measured using H flumes ([6], **Figure 4**). More recently, two watersheds were monitored using drop-box weirs which provide better flow measurement in sediment-laden runoff water [7], (**Figure 5**). Because of spatial variability of precipitation, each watershed was instrumented with a weighing-bucket rain gauge. Runoff and precipitation data were historically tabulated with depth and time resolutions of 0.25 mm and 1 min, respectively, and when a change in flow depth or precipitation intensity was apparent. Larger watersheds on the 425-ha area up to 123 ha were monitored using Parshall flumes initially and later short-crested V-notch weirs replaced them [6], (**Figure 6**).

The LMC watershed was instrumented with a network of recording rain gauges and weirs (**Figure 2**, left). Nested watersheds ranged in size from approximately 39 to 1854 ha. As mentioned before, LMC was closed in about 1970 so there is approximately 30 years of runoff and precipitation data available from most of these watersheds and rain gauges. These watersheds were useful for documenting the nonlinearity of runoff ("scaling," **Figure 7**) at Coshocton, and have potential for other investigations such as for regional model parameterization and routing.

**Figure 4.** H flume and original Coshocton wheel rotating-slot sampler.

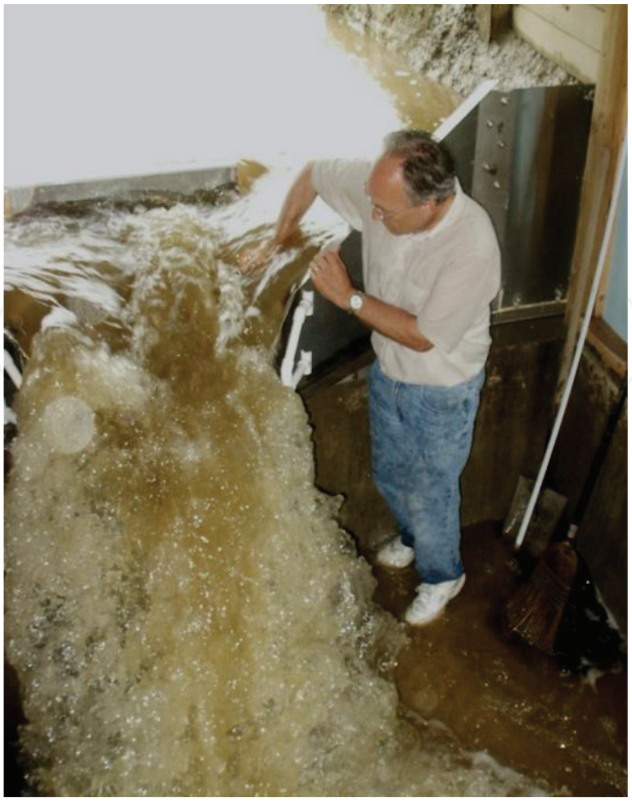

**Figure 5.** Turbulent flow in a NAEW drop-box weir for flow measurement in sediment-laden runoff.

**Figure 6.** Short-crested V-notch weir replaced the Parshall flume upstream in the view on a larger NAEW watershed.

**Figure 7** shows how watersheds in different physiographic and climatological regions in the USA respond to climate as watershed area increases. For the unglaciated watersheds in the Coshocton area, the nonlinearity of watershed area vs. runoff relationship reflects the increase in baseflow to a relatively constant value as more and larger stream channels intersect perched water tables in this region of sedimentary strata (dashed line in **Figure 3**).

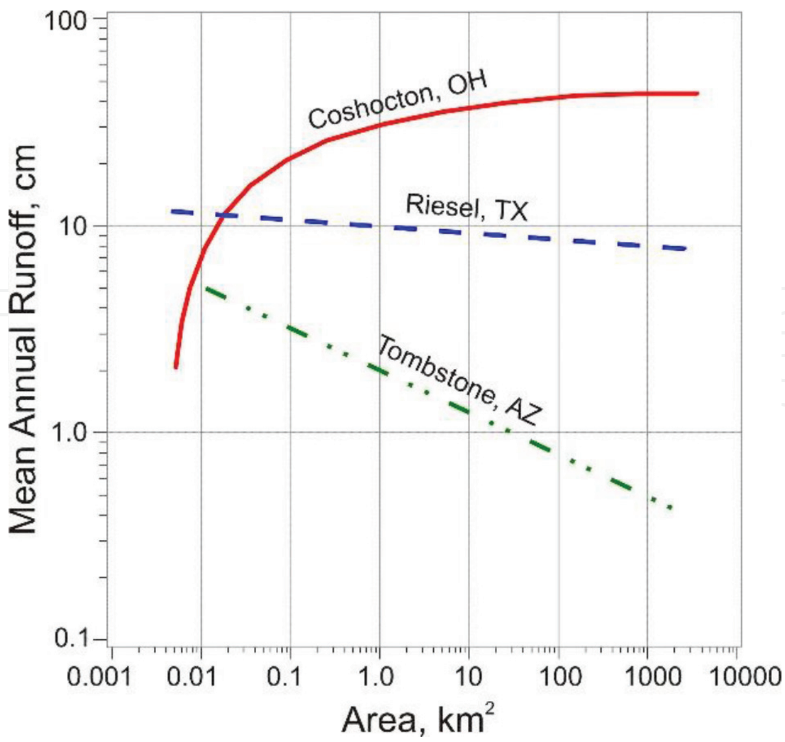


**Figure 7.** Watershed area versus annual runoff for different physiographic locations in the USA. Graph from [8, 9].


**Figure 8.** Construction and installation of three lysimeters at the NAEW.

While small watersheds provided data on runoff responses at a small watershed scale, the originators of the experimental watershed program wanted to investigate on a very small scale the water balance on isolated blocks of undisturbed soil ("monolith lysimeters," **Figures 8** and **9**). Eleven lysimeters were installed in the three dominant soil types on the NAEW, four each on two soil types and three on the third soil type. Each lysimeter had a horizontal surface area of ~0.0008 ha (width ~1.8 m and length ~4.3 m), depth was ~2.4 m, and enclosed an undisturbed monolith of the soil profile. The 2.4-m depth included undisturbed surface soil and weather bedrock. Each lysimeter measured percolation (ground-water recharge) from

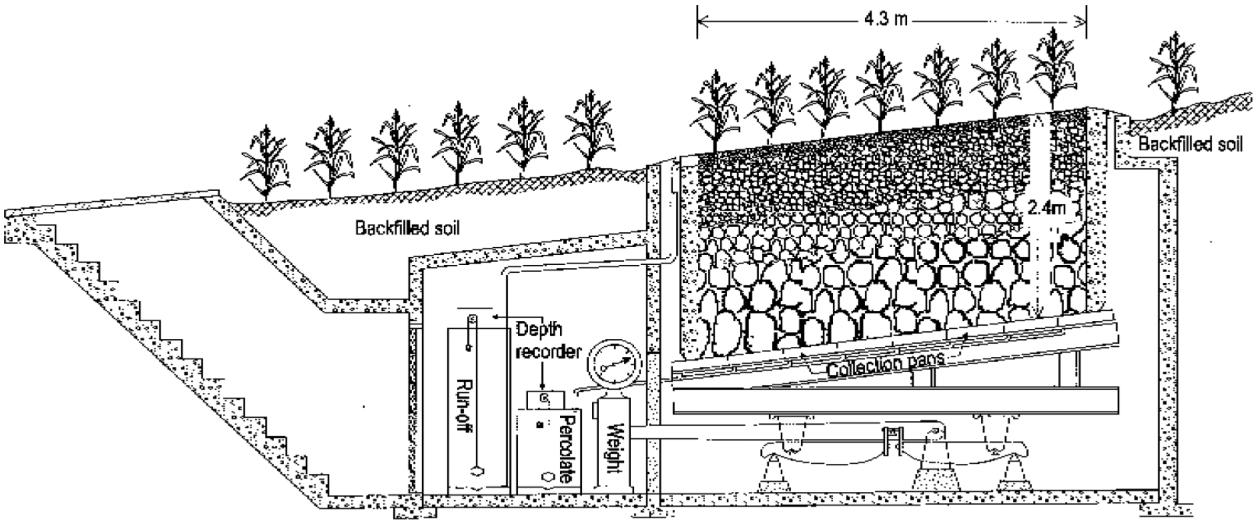


**Figure 9.** Schematic profile of an underground weighing lysimeter with and undisturbed profile of weathered bedrock near the bottom and soil at the top.

the bottom and runoff from the surface. Additionally, one lysimeter at each set of lysimeters within a soil type was weighed to provide evapotranspiration and ground-level precipitation data.

Recognizing the spatial variability of precipitation over small areas (especially during summer months), precipitation data were monitored by using weighing-bucket rain gauges with orifices placed approximately 1 m above the ground at most small watersheds. Gauges were similarly placed at each of the three sets of lysimeters.

Weather data were measured at a single weather station on the NAEW and included wind speed and direction, air temperature, humidity, solar radiation, evaporation pan, barometric pressure, soil temperature, and precipitation. Since about 1985, data loggers were used to monitor all NAEW data (except precipitation) with a radio-telemetry system. This system allowed more frequently measured weather, runoff, and precipitation data to be recorded. Prior to ~1985, runoff and other charts were hand tabulated. For the entire period, manual measurements were made of some weather elements.

Soil loss from the small experimental watersheds was an original concern; however, no reliable water sampler was available to measure sediment concentration during a runoff event. Consequently, the "Coshocton Wheel" was invented in about 1945 to obtain a flow-weighted composite measurement of the total sediment concentration during runoff events (**Figure 4**). The sampler consisted of a water (runoff)-powered wheel with a rotating slot (no power requirements), and obtained a constant fraction of the total sediment load from the watershed (single sample). The sampler has been used worldwide. When event concentration is multiplied by total runoff, an estimate of event sediment load is obtained for the treatment on the small watershed. Prior to the NAEW invention of the Coshocton Wheel, all runoff and sediment were collected in concrete troughs that were dug out manually to obtain a measurement of sediment yield (**Figure 10**). Note that the flume is full of sediment after the runoff event flowed over the bare, steep soil. This photo demonstrates the need for an automatic water sampler and the desirability of using a drop-box weir that will keep sediment moving through the flume (**Figure 5**).

In the 1970s, water quality beyond sediment concentrations became important [3]. Pesticides, major anions and cations, and nutrient losses, especially nitrogen, from the small watersheds became a concern and various land management treatments were evaluated using these measures as well as runoff volumes and sediment loads, and subsurface flow. The Coshocton Wheel provided the sample needed for laboratory analyses of these constituents and loads were similarly computed as for sediment concentrations.

Occasionally, new watershed and plots sites on and off the NAEW were required such as for coal surface-mine (**Figure 11**), paper-mill byproduct, and manure studies. NAEW scientific and technical personnel provided the needed expertise.

The small NAEW experimental watersheds were managed with a new treatment following an old one on the same watershed. This allowed comparisons of current treatments with previous ones. Occasionally, a paired watershed approach was used.

**Figure 10.** H flume and downstream sediment trough that catches all sediment from the bare, steep watershed after an extreme event.

**Figure 11.** NAEW scientists investigated the effects of drastic land disturbances due to surface mining for coal before and during mining, and after reclamation on ground and surface water hydrology and water quality.

## 5. Data

The basic data types collected include runoff, precipitation, weather, and water-quality data. Tables listing details of runoff, precipitation, lysimeter, weather, land-management, and other data are listed in [3] through about 2009 and are not repeated here. Due to specific project, financial, and personnel constraints during NAEW history, data for some watersheds such as runoff, precipitation and other data were not obtained for the entire 79-year period of monitoring. ARS operation of the NAEW ceased in late 2011, however, data collection continued from seven watersheds as part of a grant-funded project through Dec 2015 when all monitoring operations were discontinued. Through 2015, approximately 2125 station years of runoff data and 1126 station years of precipitation data were collected.

At the time of this writing, the NAEW data are being reviewed, corrected, and uniformly formatted from variety of original formats. The location for the data on the internet is yet to be determined. As part of the NAEW data-review process, a GIS of the NAEW has been developed documenting locations of runoff, precipitation, weather stations, etc. GIS will become part of the NAEW data base posted on the web site. The list of NAEW publications will also be posted.

Even though data collection has ceased, the database is valuable for further investigations of hydrology and water quality. Watershed modeling, in particular, can be studied at large (LMC —scaling, spatial parameterization of watershed models, and hydrology) and small scales (small watersheds—watershed modeling, hydrology, and water quality). The long precipitation and runoff records are valuable because they have experienced a wide array of weather conditions, even during a period of trending climate. Other precipitation, infiltration, soil moisture, ground water, and soil characterization data bases have not been analyzed and are available in hard copy form in the NAEW files. These data would have to be converted from hard copy to electronic form.

## 6. Examples of accomplishments of the NAEW

The outdoor laboratory of the NAEW has historically addressed the challenges of emerging national issues and addressing stakeholder's needs. Over 500 reports and peer-reviewed publications originated from NAEW research. The NAEW was a world-class facility and examples of accomplishments of the NAEW are [2]:

*Crop rotations:* The early record of runoff measurements (first ~28 years) documented the benefits of rotating crops and planting on the contour to reduce erosion in agricultural fields in the hill lands of Appalachia.

*No-till/Conservation tillage:* No-till farming reduces (and can essentially eliminate) soil losses and runoff (**Figure 12**). The USDA funds a national farm program and recommends the no-till practice for improving agricultural lands as a best practice. The NAEW was the first facility in the world to evaluate the water quality benefits of no-till on a watershed basis with experiments beginning in 1964 and continuing through 2011 [8]. The practice allows more frequent harvesting of high value crops, produces yields that are the same or greater than with conventional tillage (especially during droughts), increases soil-carbon storage (resulting in larger soil moisture for crops), and reduces energy needs. The environmental benefits of other types of conservation tillage have also been investigated [9–12].

*Grazing:* The NAEW developed environmental recommendations for pasture fertilizer application rates based on nitrogen [13, 14], sources of nitrogen fertility for pastures [15], and overwintering practices on grazing lands [16].

*Management-Intensive Grazing (MIG):* The NAEW management-intensive grazing (MIG) project investigated the water-resource benefits of frequent rotation of livestock between small paddocks in a pasture for organic and non-organic production, and included impacts on surface and subsurface water quality, animal health, and changes in plant species [17]. Potential benefits of MIG to the producer include extended grazing season, less cost, and more leisure time.

*Nutrient movement in stormflow vs. baseflow:* Major transport of nutrients can occur in both baseflow and stormflow from mixed agricultural watersheds [18].

*Preferential movement of water in soil:* Fundamental knowledge from NAEW experiments on the fate of infiltrated water and chemicals in the subsurface through preferred pathways (e.g., earthworm burrows and cracks) has been used by scientists worldwide and in the development of a macropore component of a watershed model [19–21]. Additionally, guidance was developed on manure application in tiled fields [22, 23].

*Evaluation of best management practices:* A method was published to estimate the variability of chemical concentrations in runoff when there are few water samples and a history of runoff using duration curves [24].

*Pesticide transport:* Research on herbicide concentrations for weed control on watersheds showed that concentrations in runoff can reach levels of concern, particularly in the first few events after application, and that by reducing application rates by replacing herbicides with short half-life types, concentrations can be reduced [25–27].

**Figure 12.** Original no-till experiments on steeply sloping experimental watershed.

*Climate change:* Climate was changing starting in about 1980 at the NAEW. Several studies of precipitation showed that underlying runoff parameters in the “curve number” method of estimating runoff were changing as extreme precipitation events were increasing in magnitude, and that air temperature was trending upward [28]. Watershed data were used for modeling watersheds for climate change impacts [29].

*Organic agriculture:* The NAEW investigated the organic-agriculture component of a large nationwide study on the effect of climate on corn production (data still being analyzed). Other organic-related research included comparing impacts of continuous and MIG as they underwent transition to organic agriculture.

*Precipitation modeling:* Several studies on modeling short-time increment precipitation data (of the order of minutes) for modeling purposes have been completed. Studies on parameterization, data quality, seasonal variation, times between storms, climate change, etc., support a model that generates independent storms of any duration [30, 31].

*Ground-water recharge:* The Glugla method for estimating ground-water recharge was verified by using the NAEW lysimeters [32]. This method is used nationwide in Germany.

*Evapotranspiration (ET):* Lysimeter data have been useful for investigating ET losses under different management practices. The Glugla method also estimates long-term ET losses. The lysimeters were used in modeling the ET component for verifying the engineering design procedure for alternate and cheaper landfill covers [33].

*Watershed modeling:* Models of some small watersheds allowed the evaluation of climate change and runoff, and the adequacy of a model-parameterization procedure [34]. NAEW data are currently being used to nationally update a runoff-estimation procedure used worldwide (“curve number” model).

*Biofuel removal:* It was documented that removal of large amounts of crop residue for ethanol production can negate many soil and water-quality benefits of long-term no till [35, 36].

*Urbanization:* It was shown that a low level of imperviousness, either close to or far from a stream channel, on a 3-ha watershed had no effect on runoff. It was also shown that minor surface disturbances can increase runoff potential, but that the land surface can recover, using grazing a surrogate for urban land surface disturbance [37].

*Winter application of manure:* Data from large runoff plots of various sizes and treatments, and experimental watersheds were used to provide guidance for applying manure during the winter [38].

*Pathogens from manure applications:* The winter-manure application project provided an opportunity to add another dimension to NAEW research—pathogens. The data were used to provide pathogen guidance for winter application of manure.

*Instrumentation:* NAEW scientists developed and adapted many hydrological and water-quality instruments required for specific research objectives and not commonly available commercially. Examples are the Coshocton Wheel water sampler (invented in ~1945 and used worldwide in remote areas), Coshocton Vane water sampler, large sediment particle runoff sampler, drip-flow meter and sampler, hydraulic studies of the drop-box weir, adaptation of the Coshocton Wheel for the drop-box weir [39], natural-precipitation infiltrometer, worm-burrow infiltrometer, and rainfall simulator for macropore studies.

*Filter sock performance:* Coshocton data showed that there were limits to use of on-field control of pesticides on watersheds. Netting in the form of tubes filled with materials that can adsorb pesticides and nutrients from surface runoff have been studied and published. The results are useful for contractors that use filter socks in controlling chemical and sediment water quality from construction sites and farm fields [40, 41].

*Paper mill byproducts:* In collaboration with the State of Ohio and the paper industry, NAEW studies on use of paper-mill sludge (waste product) applied to surface mines showed that the State's upper limit of land application rate was environmentally acceptable [42]. This provided paper mills a cheaper, more environmental beneficial, alternative to landfill disposal, and at the same time provide a good source material for revegetating and controlling erosion when reclaiming surface mines.

*Carbon sequestration:* The long-term nature of the management practices on the small watersheds including continuous no-till corn with over 40 years of runoff records have enabled numerous investigations into the impact of land management on carbon sequestration (**Figure 13**). Sediment-bound carbon losses from various conservation tillage practices and organic carbon losses in subsurface flow were also measured [43, 44].

*Surface mining and reclamation:* A landmark study on effects of coal mining and reclamation on surface and ground water in three watersheds (~16 ha) showed the temporary and permanent effects of this drastic land disturbance (**Figure 11**). Watersheds were monitored before, during, and after mining and reclamation. Monitoring could not have been possible without the use of the drop-box weir [7] due to the large sediment-laden flows from areas such as shown in **Figure 5**. Runoff potential increased (large curve number) to a near constant after reclamation regardless of original geology, and erosion can be controlled to near pre-mine levels with the right reclamation practice [45–47]. The results have been used in court cases and in regulations.

**Figure 13.** Soil carbon increases in soil planted to continuous no-till corn (bottom right) compared with soil from conventionally tilled soil (upper left).

*Landfills:* Lysimeter data validated an engineering design model for a new type of landfill cover that utilized the ET processes in the soil to minimize water percolating to ground water [33].

*Other research:* Other research conducted at the NAEW (not exhaustive list) were projects related to water quality of spent foundry sand, dairy wastes, and nursery operations. Frozen soil, rain gauges, soil moisture, soil characterization, etc., have also been topics.

*Emerging issues:* A significant advantage of the NAEW facility is its long-term data base and the permanent monitoring infrastructure. It has been used for many investigations which were never imagined at the outset. Examples are placement of impervious structures for urbanization studies, evapotranspiration landfill caps, macropore investigations, advanced modeling, organic agriculture, climate change, ground-water recharge studies, spent foundry sand, nursery operations, dairy wastes, filter socks, carbon sequestration, pathogens and estrogens in runoff [48], biofuels, surface mining and reclamation, paper mill sludge, and long-term water-quality response times in natural systems.

## 7. Insights from NAEW experiences for establishing new experimental watersheds

Many paths can be followed to establish new experimental watersheds to conduct watershed-science research ("outdoor laboratories for water and land-management research") such as the NAEW. Watershed science involves expertise in the biological and physical sciences to solve national problems. Occasionally required expertise can be acquired from university, government, and private-sector partners and stakeholders. The 81-year experience of managing experimental watersheds may be useful for establishing new experimental sites at the scale of the NAEW, and some important considerations from the NAEW experience are listed below.

1. When establishing new experimental watersheds, "representativeness" is important, and newer GIS technology should be used to identify potential sites. However, there will be other research benefits discovered as a facility is managed. In the case of the NAEW, the geological and soil characteristics became important for potentially providing new knowledge on hydrological processes such as nonuniform runoff generation, interflow, macropore flow, perched water tables, etc. Other potential site benefits should be considered in site selection.

2. For an ideal comprehensive watershed-science program, the three original NAEW objectives are required. However, funding may become a problem and pursuit of the three objectives can be spread at more than one location (e.g., one location can perform modeling and another field experimentation). However, having modelers conducting field research is also of value to experience data characteristics and natural variability found in landscapes to help formulate algorithms. It is important to have field data for validation of watershed models.

3. Monitoring a large experimental watershed requires sufficient funding to sustain scientists, support staff, and experimental resources. The value of experimental watersheds is that they can provide an uninterrupted record of runoff, water quality, etc., spanning years, with dry years producing insufficient numbers of runoff events and longer periods of runoff records may be required. Furthermore, *watershed-science research can be considered long-term and high risk* because experiments are subject to weather extremes (e.g., droughts and other project factors that are affected by the weather). It is expensive to maintain such a record, and continuous funding must be maintained—temporary grants will interrupt long-term records after the grant period is completed, and a sufficient record of runoff may not be recorded.

4. It can be difficult to exploit characteristics unique to a site (e.g., at the NAEW—understanding and quantifying interflow, nonuniform runoff generation, etc.) because of funding and a wide range of expertise needed. At the NAEW, some of these features were not fully exploited.

5. **Figure 7** shows the wide variety of watershed behaviors for three experimental watersheds in different physiographic and climatological regions of the USA [49, 50] and generally describes how runoff is generated on landscapes. It is apparent from **Figure 7** that the unglaciated NAEW area will follow a convex-upward curve where smaller overland flow areas do not support baseflow (annual runoff is small). For larger areas, however, baseflow is increasing as incising stream channels drain water from intersected water tables, and the curve approaches an apparent constant. For arid areas (Tombstone, AZ), runoff decreases with area in a log-log manner due to channel transmission losses and isolated storms. For the location at Reisel, TX, the response is nearly flat due to its climate and soil conditions leading to a more uniform generation of runoff. The reader is referred to [49] for more particulars of **Figure 7**. If a network of experimental watersheds is developed, a plot of data in a similar manner may lead to a general characterization of watershed sites under consideration, and may help differentiate proposed sites.

6. Site specificity of experimental watersheds must be expected. Soil and geology are important factors that can affect different responses of two similarly treated small adjacent watersheds subjected to similar precipitation and weather drivers. This variability affects project results, numbers of watersheds needed for experiments, and highlights the need for watershed modeling to extrapolate field data to ungauged areas. Furthermore, the history of an individual watershed is known and quantified with permanently monitored sites. Some watersheds may still be responding to prior treatments when a new treatment is initiated. In the case of new watersheds, the effects of prior treatments may be unknown, yet they may affect interpretations of the data.

7. Seasonal air temperatures and percent of snow in a precipitation record are important for seasonal runoff generation mechanisms that can affect water quality also. At the NAEW, lower winter air temperatures did not always insure frozen soil, and sometimes frozen soil occurred intermittently. Consequently, latitude and climate are important to consider.

8. Instrumentation selection is important in managing experimental watersheds. Two important measurements are runoff and precipitation. For runoff, it is known that large sediment concentrations in runoff can affect the rating curve of H flumes [51], a commonly used flow-measuring device. A weir that has been tested for a wide range of field conditions under large sediment loads (including rocks) is the drop-box weir [7]. Drop-box weirs of any size can be constructed from small runoff/erosion plots to large watersheds with incised channels. It is important to house weirs from freezing weather to prevent damage and maximize the opportunity for good winter runoff records.

9. Precipitation measurement is a persistent problem because the gauge shape and orifice height affect the wind flow around the orifice, resulting in an under catch of precipitation. This is because smaller diameter rain drops and light weight snowflakes are carried with the wind away from the orifice. This error can be as high as a 20% under catch on average during the winter and approximately 2% during the nonwinter months [52]. True ground-level precipitation measurements for individual events can be much higher during events with high wind speeds. Furthermore, often-used tipping bucket rain gauges do not measure snowfall, and under catch of precipitation is complicated by using heaters to melt the snow because precipitation is evaporated [53], and snow intensities will not be measured. In arid areas this may not be a problem. The effects of under estimating precipitation are to under estimate runoff, erosion, and water quality in watershed modeling [49] in a nonlinear manner. Suggestions for improved precipitation measurement include shielded gauges such as the dual fence gauge of the Climate Reference Network [54] that was evaluated by US Forest Service [55]. Their study suggested that the CRN gauge is the best available. A set of dual gauges (one shielded and one not shielded) were not tested in the Forest Service study, but is likely to be a contender and should be investigated [56]. Furthermore, weighing buckets are preferred measuring technology compared with tipping buckets. Advances in other emerging technologies should also be explored.

10. Water quality sampling is important for evaluations of the performance of land treatments. Two types of sampling are possible—composite and discrete sampling. For composite sampling, the same fraction of the flow is sampled for each flow rate during the runoff event and only one sample is obtained for the event. The Coshocton Wheel has been a useful tool for composite sampling of small watersheds [6, 39]. Larger watersheds require smaller fractions of flow sampling to manage the size of a composite sample and for a range of runoff volumes. Commercial samplers and the Coshocton Vane sampler [57] are available for this purpose. An instantaneous sample is pumped for discrete sampling a preselected times or changes in runoff depth, and many samples are obtained for an individual event. This type of sampling is more expensive and may not be as useful as composite sampling unless there is a research objective for this sampling strategy. For evaluations of water quality effects of land treatments, a composite sample is adequate (and may be preferred). For either sampling type, a flow measurement record is required.

11. It is possible that experimental watershed investigations can be affected by a changing climate. Climate was found to be changing at the NAEW.

**12.** It should be recognized that some investigations will be affected by watersheds with low runoff potential (e.g., some forested sites). It may take many years for such watersheds to provide enough data for evaluations to experience larger infrequent rainfalls.

**13.** Knowledge of challenges in conducting watershed research in disturbed lands in particular is presented in [58] and is pertinent to selecting new watersheds.

**14.** It is highly likely that as an emerging issue arises, that an experimental watershed facility would be a likely place for pertinent investigations. The permanent monitoring infrastructure allows for a relatively rapid implementation of a proposed land treatment and monitoring. Funding for such issues is important.

**15.** Another opportunity for monitoring experimental watersheds is off site from the home site. This was necessary for monitoring watersheds with three different coal seams in the disturbed land (coal mining) project conducted at the NAEW [58], **Figure 11**.

**16.** It is important for all data to be checked and be made available on the internet as soon as possible after collection.

## 8. Summary

The North Appalachian Experimental Watershed (NAEW), in east-central Ohio near Coshocton, Ohio, was one of the three large watershed facilities established in 1935 to advance watershed science of agricultural lands to improve their economical and physical sustainability. It was an outdoor laboratory for land and water management research. The original objectives were to test management practices on small watersheds (small swales in the hilltops), investigate scaling of runoff and erosion to larger areas, and provide a way to extrapolate the results to ungauged areas (modeling). The NAEW was in an unglaciated sedimentary geological setting (strata nearly horizontal) and originally spanned an area of approximately 2000 ha. The facility was equipped with a permanent infrastructure consisting of runoff stations and rain gauges for watersheds ranging in size from 0.26 to 1854 ha. After about 1970, the NAEW was reduced to a 425-ha area consisting of mostly small watersheds ("test beds") ranging in size from 0.26 to 3.07 ha but with a few up to 123 ha. The smaller watersheds were equipped with the well-known Coshocton Wheel composite runoff samplers. The NAEW was in operation for approximately 81 years with an approximate 79-year record of runoff and other data for various watersheds, and was closed in 2015. Eleven large monolith lysimeters were also constructed to investigate small scale water balances.

A wide variety of experiments were conducted on the NAEW with many high impact accomplishments (listed in the section titled, Examples of Accomplishments of the NAEW). Many investigations used the facility for emerging national issues that the founders never envisioned (e.g., surface mining impacts, landfill caps, organic agriculture, climate change, filter socks, carbon sequestration, pathogens in runoff, biofuels). Nearly 500 publications were developed from investigations during the 81-year history of the facility.

Experiences in the operation of the facility during the 81 years provide insights for establishing new experimental watersheds in the future. Watershed science involves the expertise in the biological and physical sciences and engineering to solve national problems. Sixteen suggestions for new facilities are presented covering site selection, funding, site specificity, extrapolation of results, generation of runoff in different physiographic regions, collaboration, off-site investigations, and instrumentation. Instrumentation suggestions are particularly important for precipitation because it is a major driver of watershed responses and must be more accurately gauged than commonly measured. Runoff measurements also can be affected by large sediment concentrations using common flow-measuring devices. Watershed modeling will be sensitive to precipitation inputs and validation of runoff amounts in modeling will be affected by runoff measurements.

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