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Agricultural Drainage: Past, Present, and Future

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Agricultural drainage is removal of excess water from land surface and soil profile to sustain and enhance crop production. Surface and subsurface conduits (open channels or pipes), or artificial drainage, become essential for removing excess water in soils that do not exhibit adequate drainage naturally. Worldwide, about 1,500 million ha (3,700 million ac) of land is cultivated, of which about 625 million ha (1,544 million ac; 40%) are estimated to need improved drainage (Smedema et al. 2000). Although the true extent of agricultural drainage is unknown, some estimates suggest that about one-third (160 to 200 million ha [400 to 500 million ac]) of the land needing improved drainage has received some form of artificial drainage (Smedema et al. 2000). The drained areas span across three major global drainage zones: (1) the temperate humid zone (64%), where soil aeration and trafficability are major concerns; (2) the arid/semiarid zone (24%) for aeration and soil salinity management; and (3) the humid/subhumid tropics zone (12%), where removing excess surface water and prevention of waterlogging (aeration) are of concern (Smedema 2007). Although horizontal drainage in the form of surface and

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subsurface drains is the most common, some areas of the world also rely on vertical drainage (using tube wells to pump out excess groundwater) and biodrainage (using trees with high consumptive water use to lower water table) (Schultz et al. 2007). In North America, about 37% (20.6 million ha [50.9 million ac]) of cropland in the eastern and midwestern United States, an unknown proportion of the irrigated areas of the western United States, and about 8 million ha (20 million ac) in Canada are estimated to be artificially drained (Pavelis 1987; Madramootoo et al. 2007; Zucker and Brown 1998).

The primary functions of drainage are to (1) remove excess surface water, (2) lower the soil water table, and (3) provide salinity control under irrigation. However, benefits of the practice extend well beyond the intended functions. Some benefits of the practice are (1) improved trafficability, (2) enhanced crop productivity, (3) timeliness of field operations, (4) improved aeration, (5) improved human health due to lesser risks of pests and diseases associated with waterlogged or marsh lands, (6) land conversion (i.e., bringing more land under intended uses such as cultivation), and (7) improved water quality by reducing surface runoff-induced erosion and nutrient loss. Conversely, drainage improvements may also lead to some negative impacts on cropping systems (e.g., limited water availability during the growing season due to loss of water from the soil profile), environment (e.g., accelerated nutrient and pesticide losses through drainage pathways), ecology (e.g., loss or alteration of habitat and associated species), socioeconomics (e.g., greater maintenance and operation costs of failing or outdated drainage infrastructure), and human health (e.g., impaired drinking water due to harmful algal blooms triggered by excessive nutrient contributions from drained landscapes in some watersheds). Nevertheless, in most systems, the benefits of drainage outweigh the negative impacts. In this chapter we discuss the past, present, and future of agricultural drainage. Although, the practice has a global presence and relevance, the primary focus of this chapter is on the surface and subsurface drainage in the context of the North American agriculture. We include additional resources that provide a more detailed assessment of the practice in the global context.

Past

Drainage for the purpose of improved agricultural production has evidence in ancient citations (Pavelis 1987) (table 1). Most early drainage was accomplished by surface ditches, with occasional reference to placing branches, stones, boards, etc. in the bottom of the trench. While ditches do enable some drainage of the soil profile, ditches were widely spaced and primarily intended to facilitate removal of ponded water on the soil surface. Early documented examples in the United States include the drainage of the Great Dismal

Table 1

A timeline of key milestones in the history of drainage by end of 20th century (Pavelis et al. 1987; Weaver 1964; LICA 2018).

Date	Event
400 BC	Earliest reference to drainage: Egyptians and Greeks drained land using a system of surface ditches to drain individual areas
250 BC	Oldest known engineering drawing of drainage system: A Greek plan of rectangular ditching illustrated on Egyptian papyrus
13th to 17th centuries	Early drainage work in Europe: • Dikes protect and reclaim lands in northern Europe, particularly Netherlands (13th to 14th century) • French use modified form of clay roofing tile (14th to 15th century) • Large drainage projects in England and Europe (15th to 17th century)
1763	Surveys of Dismal Swamp in the United States: George Washington leads surveys in Virginia and North Carolina with a view to land reclamation and inland water transport
1838	First tile drains in the United States: John Johnston installs first tile drains on his farm in Seneca County in New York State. Clay tile manufacturing begins in United States.
1840s	Large drainage project in Holland drains 17,800 ha of Haarlem Lake Some on-farm drainage in the United States using small open ditches
1850 to 1880s	Expansion of tile manufacturing in the United States: • Horseshoe tiles by John Dixon (1851) • Concrete drain tile manufacturing (1862) • Shinbone clay tiles (1870s) • Pipe tiles by forming clay mortar around a pole (1875)
1849 to 2019 (categorized by topic)	
Key acts and regulations	1849 Swampland Act, followed by Swamp Land Acts of 1850 and 1860 1862 An act to establish a Department of Agriculture (USDA) 1902 Reclamation Act, establishes US Bureau of Reclamation including a designated drainage specialist 1969 National Environmental Policy Act 1977 Clean Water Act (Section 404: Wetland Conservation Provisions – Swampbuster)

Recent important milestones in drainage science and engineering

1930s	Extension education programs begin at land grant institutions
1933	Establishment of the USDA Soil Conservation Service (SCS)
1940s	Early research on drainage practices and benefits
1941	Drainage and irrigation practices included by SCS for farm conservation plans
1954	US Soil Salinity Handbook 60
1957	First Agronomy monograph on drainage
1965	First ASABE Drainage Symposium (Chicago, Illinois)
1967	Commercial versions of the laser-beam grade-control system on the US market
1967	Manufacturing of corrugated plastic tubing (CPT) for drainage begins
1974	First ASTM Standard F405 "Standardization Specification for Corrugated Polyethylene Tubing"
1974	Second Agronomy monograph on drainage
1978	DRAINMOD model release
1978	USDA Drainage Manual published in 1978, updated in 1993
1979	First international drainage meeting held at Wageningen, the Netherlands
1983	First Working Group on Drainage of the ICID established
1980s to 2000	Awareness of water quality issues related to drainage (eutrophication due to nutrient losses from drained landscapes); development of drainage water management practices
1999	Third Agronomy monograph on drainage
2000s	Significant focus on water quality issues and solutions with emergence of more innovative structural and management practices for water quality improvement and resiliency of agroecosystems (saturated buffers, denitrifying bioreactors, phosphorus removal structures, capture-storage-recycling of drainage water, etc.)
2002	USDA Partnership Management Team authorized the formation of the Agricultural Drainage Management Systems Task Force; drainage industry partners organize Drainage Coalition
2019	Conservation Drainage Network replaced the Agricultural Drainage Management Systems Task Force

Swamp in the eastern coastal plain regions of Virginia and North Carolina and the 1860 Swamp Lands Acts passed by Congress to fund drainage of the glaciated lands in the north central United States to encourage economic development. Manufacture and use of fired clay drainpipes, or tiles, began sometime in the early 1800s, with the first recorded use in the United States in 1838 by John Johnston in upper New York State (Weaver 1964). The fired clay drainpipes were placed in hand-dug trenches, so the use was not extensive or common practice.

The first half of the 20th century brought significant innovations to agriculture, especially the introduction of tractors and electricity. Replacement of the horse as the primary source of power obviated the need for extensive production of oats and hay, the fuel source for the horse. Thus, a major change in crop rotation to more cash grain production began to emerge. Field size increased in both rainfed and irrigated areas. Drainage solutions for trafficability of wet soils and leaching of salt-affected soils became more prominent concerns. In the mid-1940s, commercial installation of clay and concrete drain tiles using gas powered trenching machines was commonplace. Land grant universities and US Department of Agriculture (USDA) personnel had developed research and extension programs to establish standards and procedures for farmers and the drainage industry. The state of the art and science of drainage up to that time is well documented in two major publications, namely American Society of Agronomy (ASA) Monograph 7, *Drainage of Agricultural Lands* (Luthin 1957), and USDA Agriculture Handbook 60: *Diagnosis and Improvement of Saline and Alkali Soils* (Allison and Richards 1954).

Present

Major shifts occurred in US agriculture following World War II. Much progress occurred in drainage design, materials, installation practice, and operation during these ensuing 75 years. In response to world population growth and food demand, soybean for export became a major crop. Higher yielding varieties of corn, wheat, and rice along with the introduction of commercial fertilizer yielded abundant production for foreign markets and spawned the growth of concentrated animal production facilities. As crop production practices evolved resulting in fewer producers, larger fields, and larger equipment, demand for more intensive drainage to ensure economical agricultural production occurred (Madramootoo et al. 2007). Off-site environmental impacts of this accelerated agricultural production became apparent and put agricultural water management practices directly in the environmental protection spotlight. Due to competition for water resources in irrigated production areas, alternative irrigation management schemes were developed to minimize the use of drainage to meet the leaching requirement. Two additional ASA Drainage Monographs (Van Schilfgaarde 1974; Skaggs and Van Schilfgaarde

1999) were produced to capture and document these accomplishments. Several of the most impactful accomplishments are described here.

Drainage materials and their installation were revolutionized in the 1960s in a project conducted jointly by USDA Agricultural Research Service (ARS) and The Ohio State University. Major steps in this revolution were the development of corrugated plastic tubing (Fouss 1973), demonstration of its installation using a plowed-in method, and machine control of the drain grade using a laser light source (American Society of Agricultural and Biological Engineers [ASABE] Historical Landmark Recognition). The tubing was light in weight and coil-able reducing transportation and handling costs. Industry adopted the proof of concept provided by this research, and drainage installation expanded rapidly as a result. Over the years, major modifications to this system have been replacement of the laser grade control with satellite-based differential global positioning system (GPS) grade control and geographic information system (GIS)-based integrated software tools for drainage design and automated installation (Shedekar and Brown 2017).

During the 1970s, at North Carolina State University, the mathematically based hydrology and drainage simulation model DRAINMOD (Skaggs 1978) was developed. This tool has allowed researchers to study aspects of drainage design, management, and performance in ways that would not be possible through field studies and has been useful to researchers around the world. Additionally, several other field- to watershed-scale models (ADAPT, AnnAGNPS, APEX, DAISY, HSPF, HYDRUS, ICECREAMDB, PLEASE, RZWQM2, SOIL, and SWAT) have been developed that incorporate drainage processes with varying degrees of detail, accuracy, and parameterization options (Qi and Qi 2017). Some drainage-focused decision support frameworks such as the Drainage Integrated Analytical Framework (DRAINFRAME) have been developed to provide a conceptual framework and methodology for integrated planning of drainage interventions (Slootweg et al. 2007). With the growing use of models for decision-making in local to regional and global policy frameworks, recent efforts have focused on improving their accuracy with high-resolution input data and by linking models across disciplines and spatio-temporal scales.

Drainage of “wetlands” emerged as an environmental concern in the early 1980s resulting in a shift of government funding of drainage as a supported production practice. These regulations were referred to as “swampbuster” legislation and caused public perception of drainage to cast a negative connotation on the practice. However, because producers realized the economic return on the investment in drainage, the practice rebounded as a producer-funded practice. Without the restrictions imposed by the previous government subsidy regulations, drainage intensity began to increase in the form of closer drain spacings that provided producers with more uniform field conditions for planting and harvesting operations. This, in turn, encouraged even larger fields and equipment, and accelerated the trend to corporate cash grain farming practices.

Soil salinity management emerged as an important challenge in irrigated and naturally saline landscapes. Initial research focused on understanding the crop susceptibility to soil salinity and solutions to manage soil salinity using irrigation and drainage systems. Guidelines were developed for estimating leaching requirements (minimum amount of water required to maintain soil salinity at or below prescribed levels) as part of the seasonal irrigation requirement and design and management of surface and subsurface drainage systems for salinity management. Recent research advancements allow for more sustainable solutions through enhanced crop tolerance to salinity, use of more efficient irrigation systems, and innovative approaches such as allowing salinity to increase during growing season and preplant irrigation to provide leaching (Ayars and Evans 2015).

In the early 1990s the USDA Partnership Management Team authorized the formation of the Agricultural Drainage Water Management Task Force (ADMS-TF) to coordinate efforts among USDA Natural Resources Conservation Service (NRCS), ARS, and National Institute of Food and Agriculture (NIFA) research, education, and technical assistance programs to develop practices and programs that could address hypoxic and algal bloom issues in the Gulf of Mexico, Chesapeake Bay, Lake Erie, and other areas of concern. The drainage industry collaborated by forming the Drainage Water Management Coalition that worked in concert with ADMS-TF to address these environmental concerns. This joint effort brought a marked new exposure and public awareness of agricultural drainage resulting in public funding for producer adoption of practices to prevent and mitigate the delivery of pollutants from agricultural production fields to streams. Edge-of-field practices, including woodchip bioreactors, saturated buffers, and drainage water management, were identified and recommended as best management practices that are applied to reduce off-site nutrient delivery (Fausey 2005). Such coordinated joint efforts were also initiated at international levels in the early 1990s, with formation of the Working Group on Drainage of the International Commission on Irrigation and Drainage. The organization of drainage-focused symposia and meetings by these groups facilitated the global exchange for science and engineering of drainage (Smedema 2007). Some notable initiatives are the 11 international drainage workshops by the

International Commission on Irrigation and Drainage, and the 10 international drainage symposia organized by the ASABE.

The Soil and Water Conservation Society was instrumental in advancing drainage research from a conservation point of view. A search in Web of Science Core Collection and CAB Abstracts for “drainage” in title, abstract, descriptor, and keyword fields retrieves 239 journal articles published in the Society’s *Journal of Soil and Water Conservation* (JSWC) out of a total of 3,408 indexed JSWC records (vast majority are journal articles). Since its inception in 1946, the JSWC has featured at least four special issues on subject areas related to drainage (e.g., Volume 67, Number 6, “Water Quality and Yield Benefits of Drainage Water Management in US Midwest;” and Volume 73, Number 1, “Edge-of-Field Monitoring for Nutrient Losses”).

More recent drainage research has focused on better management of drainage systems and integration with other practices with purposes of reducing negative environmental impacts and building water resiliency for future production systems. The traditional plot-scale or within-field drainage research has thus transitioned into on-farm, real-time research that aims to study “real-life” systems (for example, edge-of-field research network described by Williams et al. [2016]). Furthermore, interdisciplinary teams are joining forces to conduct holistic drainage research that combines field studies with multiscale modeling and socioeconomic aspects. The five-year, eight-state Transforming Drainage project (2020) is one such example that involves a team of agricultural engineers, soil scientists, agronomists, economists, social scientists, and database and GIS specialists. The objective is to transform the way drainage is implemented across the agricultural landscape. The core of the project has roots in the early work on subirrigation and wetland reservoir subirrigation systems (Allred et al. 2003), proving the feasibility of capture, storage, recycling, and reuse of drainage water for irrigation.

Future

As drainage research and technology evolve, significant changes may be expected in the design and operation of future drainage systems. The following excerpt from Ayars and Evans (2015) summarizes future challenges related to drainage:

- Drainage water quality will be a necessary criterion for system design.
- Active management of the groundwater table position and discharge to manage pollutant loads and to conserve water for crop use will be essential.
- Improved methods are needed for collection of soil physical and hydrologic properties to provide better spatial characterization to improve designs.

- The design will be an iterative process that includes agronomic production and environmental values.
- Methods of disposal of drainage water will have to be developed to minimize the environmental impact and maximize the use of the water resource.
- Impacted water supplies will be the future for irrigation and will have to be considered in the design and operation of drainage systems.
- Drainage in arid areas will become part of an integrated water management system that includes the design and operation of both the irrigation and drainage system to meet crop water requirements and provide maximum water productivity.

Subsurface drainage will be part of the solution to the world's future food and water security needs. The growing global population, climate change, and declining soil quality have put unprecedented pressure on shrinking agricultural lands to increase productivity and resource use efficiency. Integrated design and management of irrigation and drainage will be critical components of future agroecosystems. The shifting agroecological zones under changing future climatic conditions will likely increase the need for installation of new or intensification of existing drainage. This means the drainage materials and installation technology will continue to evolve. The application of autonomous robots and drones, or unmanned aerial vehicles (UAVs), mounted with multispectral sensors and GPS shows a great promise to the future of drainage-related assessments. Accurate assessment of the location and extent of drainage systems will become an important consideration for modeling and precision conservation planning at large scales (Jaynes and James 2007). To date, drainage research has primarily focused on water quantity, quality, and water level control. New frontiers of drainage research will emerge: linking drainage water quality and ecological health; assessing/modeling impacts of drainage on ecosystems; and integrating or stacking structural, behavioral, and ecological practices to mitigate negative impacts of drainage. As drainage water management will become important at field to community scales, networking and automation of water management infrastructure will become an important area of research. The complex interactions of drainage with the agricultural systems, connected ecosystems, and public infrastructure will require informed decision-making based on advanced decision support systems.

Advances in computer science, communication, and sensor technology have revolutionized the research capabilities of all fields of science, including those for drainage research. With availability of cheaper, faster technologies, high-frequency real-time monitoring and modeling of drainage systems has become possible. Furthermore, as regional-/global-/watershed-scale models are improving and becoming data intensive, the need for high-resolution data sets is growing. Future drainage research will likely adopt advanced monitoring and modeling tools. However, it will be critical to ensure the compatibility and transferability of the research data, methods, and models across various platforms and scales. Interdisciplinary collaborations and public-private partnerships will be crucial for the success of future drainage research, technology, and solutions. Furthermore, curricula (including extension education programs) at academic and research institutions that teach fundamentals of soil physics, soil water transport, and engineering and conservation aspects of drainage are and will remain essential to train the future generations of drainage professionals.

A new coalition of individuals, organizations, and government entities has been organized to carry on the collaboration that grew out of the ADMS-TF. Recently, the authorization for the Task Force expired, and the committed parties have formed the Conservation Drainage Network, which continues to provide coordination and leadership for addressing broad, national drainage-related issues. There are continuing needs at the producer level related to agricultural water management, especially emerging issues related to climate change effects on precipitation and the emphasis on recovery of soil health. Future attention needs to be directed to capture, storage, treatment, reuse, and recycling of drainage water as an irrigation water supply source. Drainage system design, installation, and operation will need to focus more on reducing water and pollutants export while still providing economically viable agricultural production. However, it has become increasingly clear that effective solutions to the environmental implications of intense drainage practice will need to be addressed on a broader, yet small, headwater watershed level. Collaborations will need to be developed between producers and elected local officials (township trustees, county government) to address problems holistically. Policy and programs are needed that reward producers for implementing win-win water management solutions for all watershed residents. With the need to translate complex drainage research for the general public and leaders, educational programs and outreach will be an inevitable part of the solution. With the diverse demographic of clientele, future educators will need to utilize traditional as well as modern delivery mechanisms for drainage education to ensure an inclusive outreach. Drainage, and its associated water management practices that address off-site effects and on-site water supply needs, will no longer be land manager issues; and will need to be addressed as public issues deserving of planning and development to achieve appropriate win-win solutions.

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Resources to Learn More

- The Mike Weaver Drain Tile Museum and John Johnston's House. https://genevahistoricalsociety.com/visit/johnston-house/
- 1960-1974 USDA Agricultural Research Service Drainage Materials and Equipment Research "Stories." https://transformingdrainage.org/resources/usda-ars-history/
- History of Corrugated Plastic Tubing. https://fabe.osu.edu/about-us/history-department/corrugated-plastic-tubing
- Drainage Media Library. https://transformingdrainage.org/media/
- Drainage Hall of Fame. https://library.osu.edu/sites/default/files/collection_files/2019-03/drainage_hall_of_fame_osu.pdf
- ASABE Historical Landmarks Collection (includes clay tile and machine control of the drain grade using a laser light source). https://www.asabe.org/About-Us/About-ASABE/History/ASABE-Historic-Landmarks
- Journal Issues with Special Focus on Drainage:
    - International Commission on Irrigation and Drainage (ICID) special issue: Drainage: An Essential Element of Integrated Water Management. 25th Anniversary of the ICID Working Group on Drainage (Vol. 56, Issue S1). https://onlinelibrary.wiley.com/toc/15310361/2007/56/S1
    - Journal of Soil and Water Conservation special issue: Edge-of-Field Monitoring for Nutrient Losses (Vol. 73, No. 1). https://www.jswconline.org/content/73/1
    - Journal of Soil and Water Conservation special issue: Water Quality and Yield Benefits of Drainage Water Management in US Midwest (Vol. 67, No. 6). https://www.jswconline.org/content/67/6
    - American Society of Agricultural and Biological Engineers special collections: Advances in Drainage: Select Works from the 10th International Drainage Symposium, Transactions of the ASABE (Vol. 61, No. 1). https://www.asabe.org/sc18AID

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