United States Government Accountability Office
Science, Technology Assessment, and Analytics
Natural Resources and Environment

Report to Congressional Requesters

November 2019

TECHNOLOGY ASSESSMENT

Irrigated Agriculture

Technologies, Practices, and Implications for Water Scarcity

GAO-20-128SP

Cover art: The cover image displays photos, from left to right, of drought, micro irrigation, sprinkler irrigation, and gravity irrigation. Source: USDA photo by Bob Nichols (far left), USDA photo by Alice Welch (center left), USDA photo by Lance Cheung (center right), Saeid Tadayon, USGS (right)

Highlights of GAO-20-128SP, a report to congressional requesters

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Why GAO did this study

Demand for freshwater surpasses the amount naturally available in some areas of the United States. The agriculture sector competes for this limited resource, and withdraws and consumes the most freshwater of any user in the nation. GAO was asked to conduct a technology assessment around agricultural water use.

This report provides an overview of irrigation technologies and on-farm water conservation practices, factors influencing the adoption of these technologies, and implications of their use for water scarcity.

In conducting this assessment, GAO reviewed scientific literature; convened an expert meeting with the assistance of the National Academies; visited farmers, academics, and industry representatives; interviewed officials from federal agencies; modeled water use in an illustrative watershed; and performed a regression analysis on U.S. Department of Agriculture irrigation, crop, and technology data.

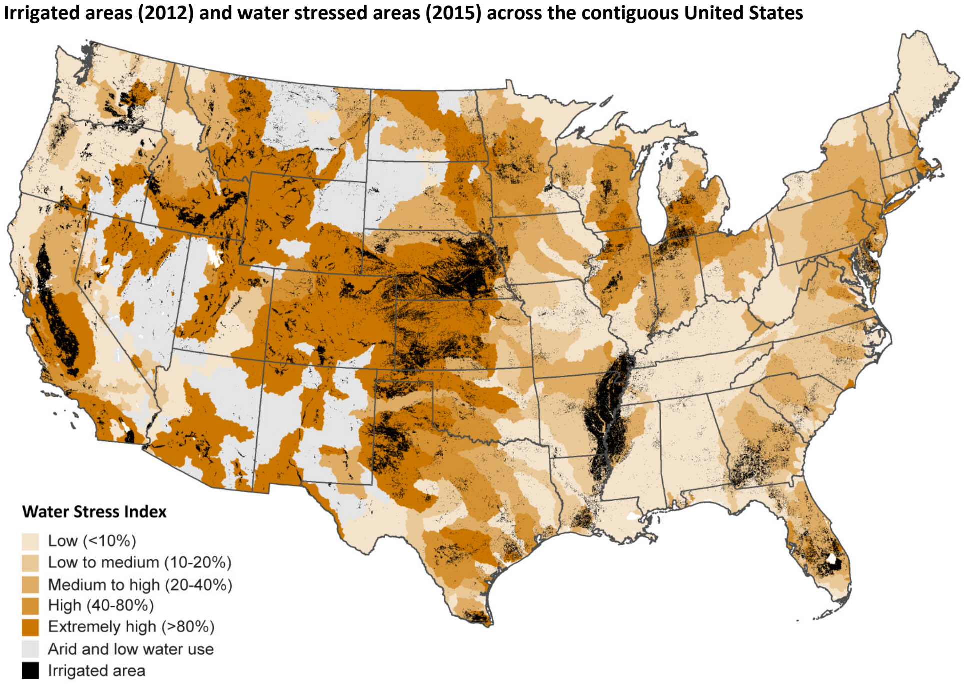
GAO describes two policy options that federal policymakers could consider relating to irrigation technology and discusses their benefits and challenges.

View GAO-20-128SP. For more information, contact Timothy M. Persons at (202) 512-6412 or personst@gao.gov or Steve D. Morris at (202) 512-3841 or morriss@gao.gov.

What GAO found

In the United States, irrigation accounts for more than 40 percent of freshwater use. Several areas in the nation are both heavily irrigated and considered water stressed. Farmers can select irrigation technologies and water conservation practices to better manage freshwater, an increasingly limited natural resource. Farmers have access to multiple irrigation technologies that could increase efficient use of water. Irrigation technologies include micro irrigation, which applies small amounts of water close to the plants; sprinkler systems, which spray water through nozzles; and gravity systems, where water floods the field or runs down furrows. In addition, practices such as irrigation scheduling may help farmers avoid over-irrigation. Farmers can also use precision agriculture technologies, such as soil moisture sensors, computer or smartphone decision support tools, and remote control of irrigation equipment to help optimize irrigation scheduling.

Irrigated areas (2012) and water stressed areas (2015) across the contiguous United States

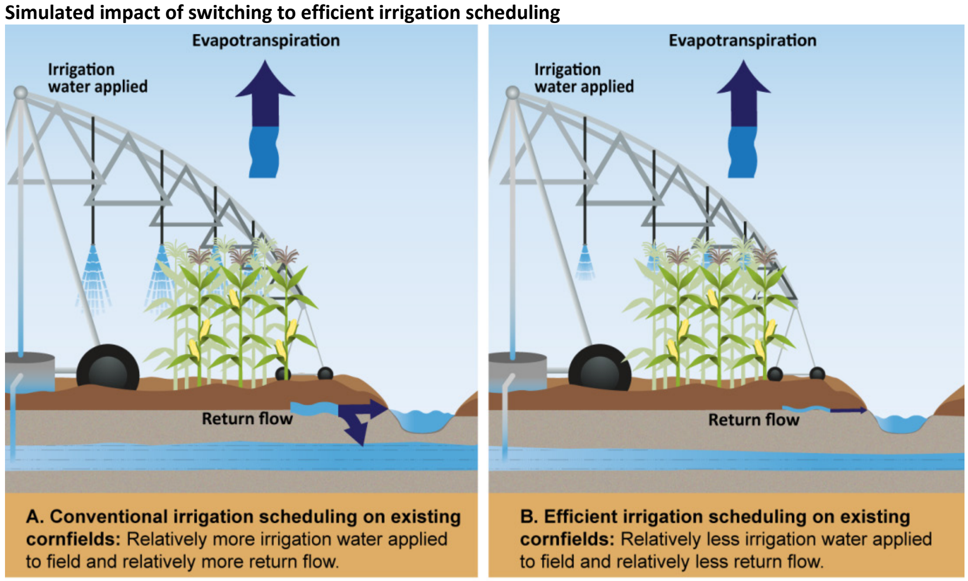


Source: GAO analysis of data from World Resources Institute Aqueduct, accessed on February 21st, 2018, and Moderate Resolution Imaging Spectroradiometer Irrigated Agriculture Dataset for the United States for 2012. | GAO-20-128SP

Farmers adopt and use efficient irrigation systems to maximize farm-level profitability, through improved crop yields and decreased costs and other inputs. Drivers of farmer adoption of irrigation technology include increasing profits and reducing risks, but we did not find much evidence that conserving water was a factor in adoption of technology. Barriers limiting adoption of more efficient technology include small farm size, large capital investments, and lack of available information on the technologies. For precision agriculture technologies, lack of connectivity, such as access to broadband, can be a barrier, particularly in rural areas.

Farmers' use of efficient irrigation technologies alone may not conserve water. GAO's modeling of an illustrative irrigated watershed shows farmers' use of efficient irrigation scheduling—such as using data from soil moisture sensors to schedule irrigation—can reduce the amount of water applied to the field, resulting in less water withdrawn from a source, which in this model was groundwater. At the same time though, GAO's modeling shows water that is consumed through evapotranspiration does not change with efficient irrigation scheduling, while return flows to the source bodies of water may be reduced. While, in some instances, reduced return flows may be beneficial, as such flows can convey pollutants downstream, reduced return flows may also result in less water available to downstream users.

Simulated impact of switching to efficient irrigation scheduling



Source: GAO simulations using the Soil and Water Assessment Tool (SWAT) computer model for sample watershed in south central Nebraska. | GAO-20-128SP

GAO's analysis of survey data on farms that converted to more efficient irrigation systems shows there is no change in the amount of water farmers apply to a field with more efficient technology, except for a few technologies and crop types. One such exception is in orchards and vineyards, where switching to micro irrigation was associated with less water applied per acre. Efficient technology may actually increase water use, as it provides farmers with additional flexibility to expand irrigated land or to switch to more water-intensive crops.

Policy Options

The request for GAO to conduct this study specified a policy goal of reducing the impact of irrigated agriculture in locations facing water scarcity in the United States. With that goal in mind, GAO identified the following options federal policymakers could consider:

- Promote the use of more efficient irrigation technology and practices, such as irrigation scheduling.
- Promote the use of precision agriculture technologies, such as soil moisture sensors and weather stations.

However, in light of GAO's findings, these options may need to be combined with appropriate agreements in order to enable and encourage water savings. Such agreements could include incentives to farmers for conserving water. Both policy options have the potential benefit of reducing the amount of water applied during irrigation. However, challenges include ensuring that water savings on the farm translates to water conservation on the larger watershed level.

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Abbreviations

4G	fourth generation mobile wireless technology
ARMS	Agricultural Resource Management Survey
CSP	Conservation Stewardship Program
EQIP	Environmental Quality Incentives Program
FCC	Federal Communications Commission
FRIS	Farm and Ranch Irrigation Survey
GPS	global positioning systems
LEPA	Low Energy Precision Application
LTE	long-term evolution
Mbps	megabits per second
NASS	National Agricultural Statistics Service
PAM	polyacrylamide
psi	pounds per square inch
SWAT	Soil and Water Assessment Tool
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

U.S. GOVERNMENT ACCOUNTABILITY OFFICE

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Introduction

November 12th, 2019

The Honorable Raúl Grijalva
Chairman
Committee on Natural Resources
House of Representatives

The Honorable Alan Lowenthal
Chairman
Subcommittee on Energy and Mineral Resources
Committee on Natural Resources
House of Representatives

The Honorable Edward J. Markey
United States Senate

The Honorable Peter DeFazio
House of Representatives

Water covers about 70 percent of the earth's surface. However, freshwater—from lakes, rivers, streams, and underground aquifers—that is available for use by humans and ecosystems makes up less than 1 percent of the earth's water. As demand for freshwater surpasses the amount naturally available in some areas of the United States, different sectors are competing for this limited resource. Agriculture consumes the most freshwater of any sector in the nation.

Pressure on water resources often intensifies in times of drought. A drought in California from 2013 to 2016 exacerbated groundwater overdraft, primarily due to withdrawals for irrigation, resulting in declining aquifer levels. In the Great Plains, drought conditions in 2012 caused widespread harvest failures for corn, sorghum, soybeans, and other crops. Drought risk is expected to rise with climate change. In addition to droughts, evaporation rates will increase due to higher temperatures, which will increase plant stress, reduce yield, and deplete surface and groundwater, according to the Fourth National Climate Assessment Report. [1]

In view of current and potential future freshwater scarcity in the United States, you asked us to conduct a technology assessment of current and developing technologies that could reduce water use and address water scarcity in the energy, municipal water, and agricultural sectors.[2] This report focuses on the agricultural water sector in water stressed areas and discusses (1) irrigation technologies and practices that could reduce water used in irrigation, (2) factors that influence the adoption of efficient irrigation technology, and (3) how efficient irrigation technologies impact water conservation.

To address these objectives, we reviewed key reports and scientific literature describing technologies and interviewed agency officials, farmers, industry, and academics. We conducted site visits to Nebraska and California where we observed the technologies in use and obtained perspectives of the industry representatives, farmers, and academics on the application of these technologies. We used a hydrologic model—the Soil and Water Assessment Tool—to analyze a watershed in Nebraska to illustrate potential water savings impacts of adopting efficient irrigation scheduling.[3] We also examined the determinants of farmer adoption of these technologies from economic literature and analyzed data for the frequency and type of use of the technologies. We used regression analysis and modeling of U.S. Department of Agriculture (USDA) survey data to assess the potential to conserve water and the realized association between irrigation technology and on-farm water use.[4]

In addition, with the assistance of the National Academies, we convened a 2-day meeting with 19 experts to discuss irrigation technologies and practices and what impacts they might have on water scarcity. These experts were selected from federal government agencies, academia, farmers, and industry, with expertise covering all significant areas of our review. We continued to draw on the expertise of these individuals who agreed to work with us during the rest our

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[1] Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Agriculture and Rural Com- munities. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 391–437. doi: 10.7930/NCA4.2018.CH10

[2] Technology Assessments to address the energy sector and municipal sector based off this request are: Technology Assessment: Water in the Energy Sector: Reducing Freshwater Use in Hydraulic Fracturing and Thermoelectric Power Plant Cooling, GAO-15-545 (Washington, D.C.: Aug. 7, 2015), Technology Assessment: Municipal freshwater scarcity: Using technology to improve distribution system efficiency and tap nontraditional water sources, GAO-16-474 (Washington, D.C.: Apr. 29, 2016).

[3] Results of the hydrologic modeling are not generalizable to other areas of the country.

[4] We determined the data were reliable enough to use for contextual descriptive statistics, regression analysis and modeling, and as input to a hydrological model; see Appendix I for more information.

study. Consistent with our quality assurance framework, we provided those experts with a draft of our report and solicited their comments, which we incorporated as appropriate.

We limited the scope of our review to technologies used on cropland. We did not include technologies used in landscaping, or other areas of agriculture, such as aquaculture, livestock, or in covered agriculture (greenhouses). We also did not assess agriculture’s impact on water quality. In addition, we did not include nontechnology approaches, such as rate structures and pricing strategies, or water purchases from another entity. Appendix I provides additional details on our scope and methodology.

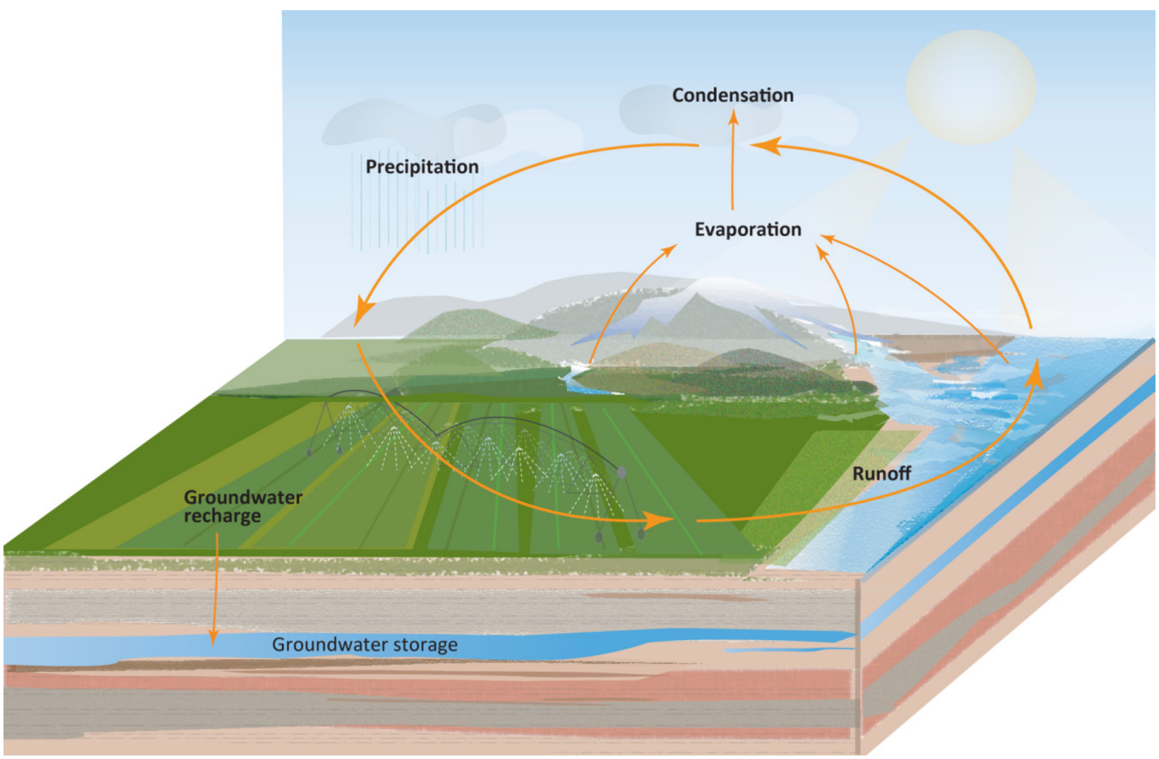
We conducted our work from June 2017 to November 2019 in accordance with all sections of GAO’s Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for the findings and conclusions in this product.

1 Background

1.1 The water cycle

Overall water cycle. Water is a renewable resource—the water that was here long ago is still here today, continuously moving back and forth between the earth's surface and atmosphere through the hydrologic cycle. In this cycle, evaporation occurs when the sun heats water in rivers, lakes, or the ocean, turning it into vapor that enters the atmosphere and forms clouds. When the water returns to earth as precipitation, some of it runs into streams, rivers, lakes, and finally the ocean. Some of it soaks below the earth's surface into aquifers composed of water-saturated permeable material such as sand, gravel, and soil, where it is stored as groundwater. The replenishment rates for these sources vary considerably—water in rivers is completely renewed every 16 days on average, but the renewal periods for groundwater and the largest lakes can extend to hundreds or thousands of years. Figure 1 below shows the overall water cycle.

Figure 1: **Overall water cycle**



Source: GAO. | GAO-20-128SP

Water covers about 70 percent of the earth's surface. However, freshwater that is available for use by humans and ecosystems makes up less than 1 percent of the earth's water. While freshwater flows abundantly through lakes, rivers, streams, and underground aquifers, people do not always have access to freshwater when and where they need it, nor in the amount or quality they need.

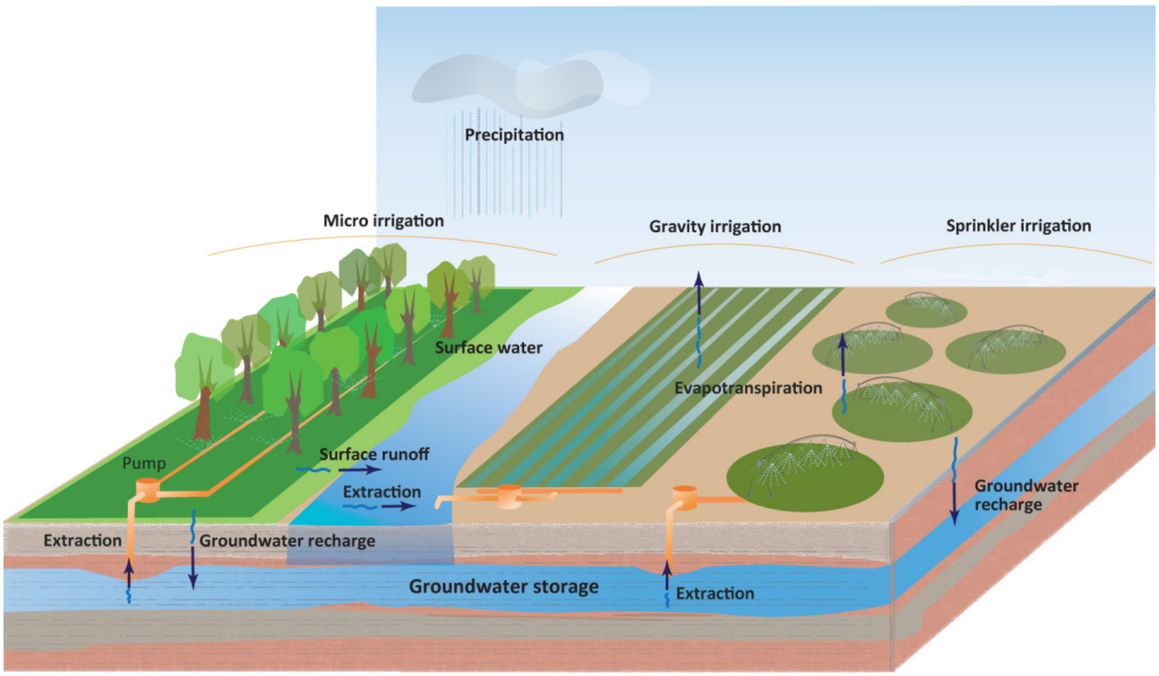
Water on the irrigated farm. In agriculture, irrigation is used to supplement natural precipitation to meet a crop's water needs. Water for irrigation generally comes from either surface water or groundwater.[5,6] Surface water is diverted from a stream, lake, or reservoir, whereas groundwater is pumped from an underground aquifer. Once water is applied to the field the water is absorbed into the soil, evaporates, or runs off.

Any excess irrigation water generally either runs off the field to surface water, or percolates through the soil as groundwater recharge.[7] The return flows from agriculture may be reused depending on where it drains to and its quality, as the return flows can also contain agricultural pollutants such as salts. Figure 2 shows the water cycle around irrigated farms.

[5] Surface water is on the Earth's surface, such as in a stream, river, lake, or reservoir. Groundwater is water that flows or seeps downward and saturates soil or rock, supplying springs and wells, as well as water stored in an underground aquifer.
[6] Reclaimed wastewater can also be used for irrigation; however, less than one percent of irrigation water in the Unites States is reclaimed wastewater as of 2015.

[7] According to U.S. Geological Survey (USGS), groundwater recharge is the inflow of water to a groundwater reservoir from the surface. Infiltration of precipitation and its movement to the water table is one form of natural recharge.

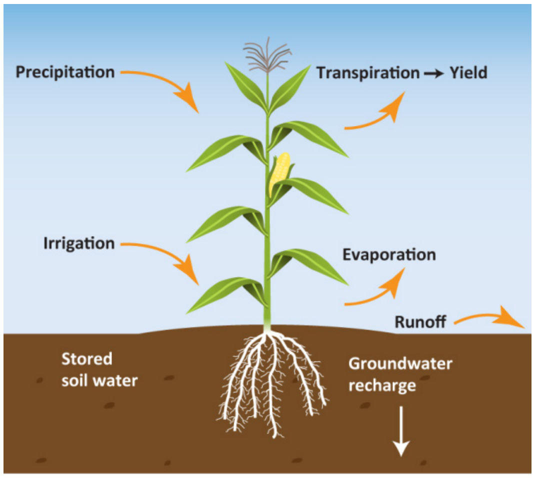
Figure 2: **Water on the irrigated farm**



Source: GAO adapted from graphic by Quentin Grafton, the Australian National University. | GAO-20-128SP

Crop and water. Plants need water to grow. The plant uptakes water stored as moisture in the soil; water in the soil comes from either rain or irrigation. The amount of moisture the soil can hold depends on the soil's texture, along with other factors such as organic matter content. The process of a plant absorbing water from the soil through the roots and then water evaporating from the plant surface is called transpiration. Transpiration is essential for plant growth. Transpiration results in water lost to the atmosphere. The amount of water a plant transpires depends on several factors, including the growth stage of the plant, temperature, and humidity. The combined water losses from evaporation in the vicinity of the plant, and transpiration by the plant are called evapotranspiration. Figure 3 below shows the simplified crop water cycle.

Figure 3: Simplified crop water cycle



Source: GAO adapted from NASA/Goddard Space Flight Center Conceptual Image Lab. | GAO-20-128SP

Delivering surface water to the farm for irrigation may require infrastructure, such as reservoirs, dams and canals. Water can be lost in the conveyance from the source to the farm, by spills, seepage, evaporation, consumption by vegetation, or leakage. To use groundwater, a well is dug deeper than the groundwater level. Water then seeps into the well, from which it can be pumped out. Pumping a well lowers the water level around the well. Over the long term, pumping water out of the ground faster than it is replenished causes groundwater depletion.

Farms in the western United States that receive off-farm water for irrigation can be supplied by different entities: a federal agency (for example, by the Bureau of Reclamation), the state, or a private supplier.[8] The state or federal agencies usually work with an irrigation district. Farmers generally pay fees to the irrigation district for water delivery. State law generally governs the distribution of water from water projects and primarily governs water rights. The price and availability of water can vary substantially based on variations in state policies, as well as source, supply, and demand.

1.2 Agriculture and its use of water

The location of agriculture depends on environmental, economic, and societal factors. Environmental factors include those necessary for a plant to grow: space, light, warmth and moisture. Some modifications to the environment—such as irrigation or drainage—can allow plants to grow where the unaltered environment may not meet their needs. In the United States, cropland occupies around 13 percent of the total land area, and grassland and rangeland occupy another 41 percent.[9] Regionally, corn and soybeans grow well in the Midwest. California's Central Valley can grow a wide variety of crops due to its temperature and sunlight conditions. Citrus is primarily grown in areas of California, southern Texas, and Florida, where the climate has enough days over a certain temperature to allow the plants to grow to maturity. Rice—of which all is irrigated—is concentrated in northern California, Texas, Missouri, Arkansas, Louisiana, and Mississippi.

[8] Wichelns, Dennis, 2010, *Agricultural Water Pricing: United States*, Organisation for Economic Co-operation and Development (OECD).

[9] Statistics from 2011 report: Baker, N.T., and Capel, P.D., 2011, Environmental factors that influence the location of crop agriculture in the conterminous United States: U.S. Geological Survey Scientific Investigations Report 2011–5108, 72 p.

According to the U.S. Geological Survey's (USGS) *Estimated Use of Water in the United States in 2015*, irrigation accounts for the most freshwater withdrawals (42 percent) than any other category of use (other categories include, among other things, thermoelectric power and public supply).[10] Of the water withdrawn for irrigation, 62 percent was consumed. [11] For 2015, total irrigation withdrawals were 118 billion gallons per day.

According to USDA's Census of Agriculture, in 2017, U.S. farmers irrigated 58 million acres. Even though just a fraction of total crop and pastureland, in 2017, crops from farms with any irrigated land contributed about 27 percent of the nation's farm sales—over $103 billion. In 2017, the top irrigated crops by harvested acres were hay, corn, and soybeans.[12]

Irrigation predominantly occurs in the western states.[13] In 2015, the western states accounted for 81 percent of total irrigation withdrawals and had 74 percent of the total irrigated lands in the United States.[14] However, according to USDA, since around 1997, there has been a trend in decreasing irrigated acres in the western states and increasing irrigated acres in eastern states—such as Arkansas, Mississippi, and Georgia. In 2012, the states with the most irrigated acres were Nebraska, California, and Arkansas. Also based on 2012 data, the most irrigated acres by crop in the western states were corn, forage (hay, silage, etc.) and orchards. In the east, the top irrigated acres by crop were soybeans, corn, and rice.

In irrigated agriculture, there are three types of irrigation technologies: gravity, sprinkler, and micro irrigation.[15]

- Gravity irrigation systems flood the surface of the field with water and gravity distributes the water across the field or down furrows.
- Sprinkler systems use pressure to spray water through nozzles across fields.
- Micro irrigation systems are low pressure systems that frequently apply water close to the plants or underground to plant roots.

Irrigation equipment can also be categorized as unpressurized or pressurized. Generally, gravity irrigation methods are unpressurized,

[10] The USGS definition of "irrigation" for water estimates includes crops, golf courses, parks, nurseries, cemeteries, and some landscape. However, GAO has scoped this technology assessment to irrigation of crops in the open, consistent with our scoping to the agriculture sector.

[11] Freshwater consumption refers to the portion of the water withdrawn that is no longer available to be returned to the water source, such as when it has evaporated. Freshwater withdrawal refers to water removed from the ground or diverted from a surface water source, such as a river or lake.

[12] The statistics presented above are in terms of acreage and dollar values, rankings may differ in terms of water consumption.

[13] In this report, western states refers to the following 17 states: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington State, and Wyoming.

[14] Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2018, Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, 65 p., https://doi.org/10.3133/cir1441.

[15] In this report, we use the terms systems and technologies interchangeably.

whereas sprinkler and micro irrigation methods are pressurized.

1.3 Snapshot of irrigation in Nebraska, California, and Arkansas

According to the USDA, in 2012, Nebraska led the nation in the number of irrigated acres with 8.3 million, 15 percent of the nation's irrigated acres. Of cropland in Nebraska, 38 percent is irrigated, primarily by sprinkler. Nebraska's most profitable irrigated crops are corn and soybeans. According to the USGS report *Estimated Use of Water in the United States in 2015*, irrigators in Nebraska withdrew 6,830 thousand acre-feet of water each year. [16] This ranks seventh among the states in amount withdrawn for irrigation. In 2015, 89 percent of irrigation water in Nebraska was groundwater. Portions of Nebraska are over the Ogallala aquifer which declined 15.8 feet between 1950 and 2015, primarily due to irrigation withdrawals.[17] According to *The Fourth National Climate Assessment,* current irrigation withdrawals far exceed recharge for the Ogallala aquifer. Some of these statistics are displayed in figure 4.

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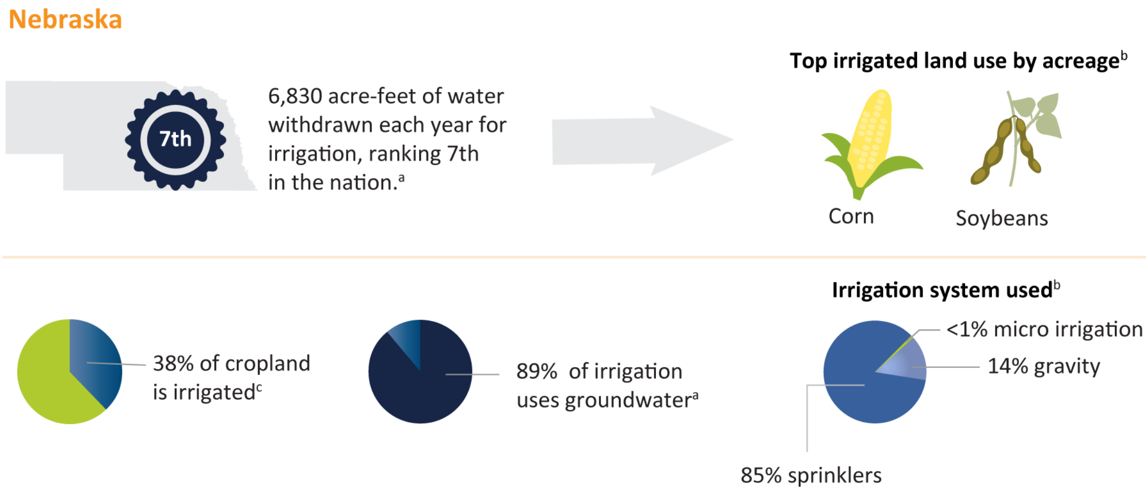
[16] One acre-foot is 325,851 gallons.

[17] McGuire, V.L., 2017, Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2015 and 2013–15: U.S. Geological Survey Scientific Investigations Report 2017–5040.

Figure 4: Irrigated agriculture in Nebraska



Source: GAO analysis from USGS's report *Estimated Water Use in the United States in 2015*, and USDA data from the 2012 Census of Agriculture and the 2013 Farm and Ranch Irrigation Survey. | GAO-20-128SP

[a] USGS report, Estimated Use of Water in the United States in 2015
[b] Data from the USDA's 2013 Farm and Ranch Irrigation Survey
[c] Data from USDA's 2012 Census of Agriculture

After Nebraska, California had the most irrigated acres in 2012 with 7.9 million, or 14 percent of the nation's irrigated acres. According to the USGS report, *Estimated Use of Water in the United States in 2015*, irrigators in California withdrew 21,300 thousand acre-feet of freshwater, leading the nation. In California, 82 percent of the cropland is irrigated, and the top irrigated land use is orchards and vineyards.[18] The primary irrigation method in California in 2013 was gravity; with 51 percent gravity irrigation, and 31 percent micro irrigation.[19]

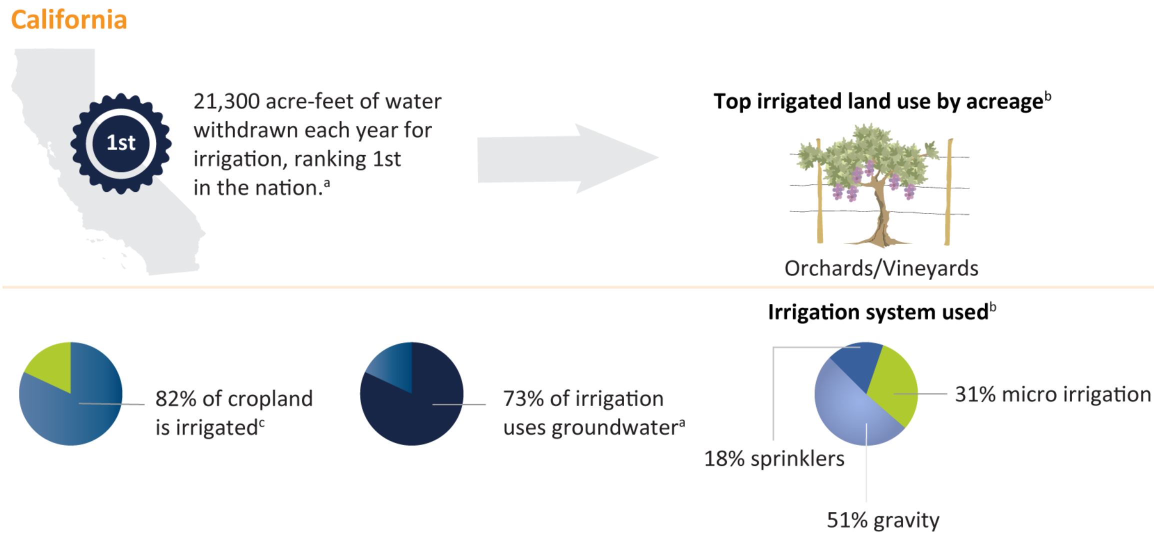
In 2015, groundwater accounted for 73 percent of withdrawals for irrigation in California. About a third of California's water supply originates as snowpack in the Sierra Nevada Mountains. However, in times of drought—such as the recent multi-year drought beginning in 2012—the snowpack declines. For example, although the snowpack is typically highest in April, there was no snow in April 2015. Many compensated by using groundwater, causing a decline in groundwater levels from 2011 to 2014.

See Figure 5 for statistics around agriculture and water use in California.

[18] Percent of cropland irrigated from the USDA 2012 Census of Agriculture; top land use data from our analysis of the USDA 2013 Farm and Ranch Irrigation Survey.

[19] Data from the USDA's 2013 Farm and Ranch Irrigation Survey.

Figure 5: Irrigated agriculture in California



Source: GAO analysis from USGS's report *Estimated Water Use in the United States in 2015*, and USDA data from the 2012 Census of Agriculture and the 2013 Farm and Ranch Irrigation Survey. | GAO-20-128SP

[a] USGS report, Estimated Use of Water in the United States in 2015

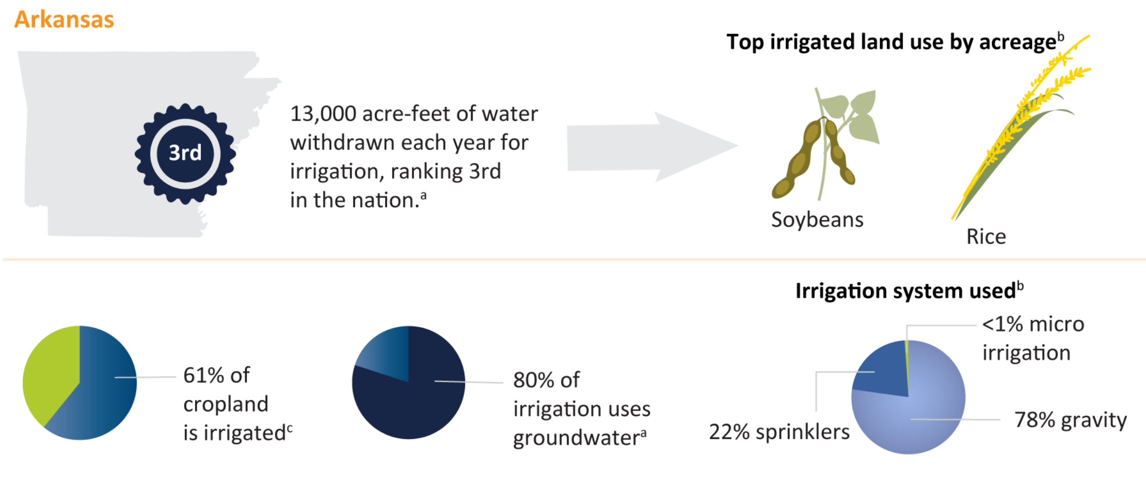
[b] Data from the USDA's 2013 Farm and Ranch Irrigation Survey

[c] Data from USDA's 2012 Census of Agriculture

The state with the third most irrigated acres in 2012 was Arkansas, with 4.8 million acres. About 61 percent of the cropland in Arkansas is irrigated. The dominant irrigation method in Arkansas is gravity irrigation, accounting for 78 percent of acres under irrigation in 2012. According to our analysis of 2013 USDA data, Arkansas's top irrigated crops are soybeans and rice. According to the USGS report, *Estimated Use of Water in the United States in 2015*, irrigators in Arkansas withdrew 13,000 thousand acre-feet of water in 2015, ranking third largest in the nation. Similar to both Nebraska and California, the majority of water withdrawn to irrigate in 2015 in Arkansas —80 percent—was groundwater. Most of the groundwater used in Arkansas comes from the Mississippi River Valley alluvial aquifer, which is declining.[20]

[20] USGS reported that, in 2005, 96 percent of groundwater in Arkansas was supplied by the Mississippi River Valley alluvial aquifer. Holland, T.W., 2007, *Water use in Arkansas, 2005: U.S. Geological Survey Scientific Investigations Report 2007-5241*, 32 p.

Figure 6: Irrigated agriculture in Arkansas



Source: GAO analysis from USGS's report *Estimated Water Use in the United States in 2015*, and USDA data from the 2012 Census of Agriculture and the 2013 Farm and Ranch Irrigation Survey. | GAO-20-128SP

[a] USGS report, Estimated Use of Water in the United States in 2015

[b] Data from the USDA's 2013 Farm and Ranch Irrigation Survey

[c] Data from USDA's 2012 Census of Agriculture

1.4 Terminology

Terms used in this report include: consumptive, non-consumptive, beneficial, non-beneficial, irrigation efficiency, water conservation, and water scarcity. In this section we describe how we are using these terms in this report. These terms may be defined differently under state laws.

Types of irrigation water uses

We use several terms to describe the impact irrigation has on water availability (see table 1). Consumptive use refers to water removed and no longer available. At the field level, examples include evapotranspiration from crops and weeds, evaporation from soil, irrigation water used for cooling the crop, and frost protection. The water that remains falls into the category non-consumptive use, which is available for reuse. Examples include runoff or deep percolation.

Within the consumptive water use, beneficial use includes water being used by the crop. Within non-consumptive uses, beneficial uses include water used for leaching, which is, carrying salt from the root zone. Non-beneficial consumption includes evaporation from soil, and evapotranspiration by weeds. Non-consumptive non-beneficial use includes flows to the ocean, flows to very deep aquifer and flows whose quality is compromised.

Table 1: Examples of water use on an irrigated farm

	Consumptive Use	Non-consumptive Use
Beneficial Use	Transpiration from crops Evaporation for climate control (e.g. frost protection, crop cooling)	Water for removing salt from the root zone
Non-beneficial Use	Evapotranspiration from weeds Evaporation from soil and wetted crop surface	Flows to salt sinks Flows that are uneconomical to retrieve

Source: GAO adapted from presentation at expert panel | GAO-20-128SP

Note: The quality of the water is not considered in this chart. This table defines these terms as used in this report, not as these terms might be defined in state law.

Water conservation

According to a USDA report we reviewed, water conservation in sustainable agriculture includes ensuring a viable irrigated agriculture sector and adequate agricultural water availability for future generations, while also protecting offsite environmental services. This approach to water conservation takes into account the fate of the water once it leaves the farm and specific hydrology. How effectively water is conserved may vary with farmer behavior, local hydrology, size and type of farm, and legal and institutional measures governing water use.

Efficiency in irrigation systems

In irrigation systems, efficiency is typically defined as the amount of water used by the plant divided by the total amount of water applied to the field.[21] The amount of water used by the plant typically includes crop evapotranspiration as well as various other water uses beneficial to the crop, such as water to leach salts from the root zone and frost protection. Another common term used with irrigation is “crop per drop,” the idea of growing more food with the same amount of water or less, generally increasing the productivity of water.

Of the three major irrigation systems, in general, gravity irrigation systems are considered the least efficient, sprinkler systems more efficient, and micro irrigation the most efficient. Using the pressure terminology, unpressurized systems are generally less efficient than pressurized systems.

Efficiency of irrigation is useful for farmer’ management decisions on a field; however, at a broader level—like the basin— the term often does not consider water reuse. For example, an irrigation system with 70 percent efficiency means that 70 percent of the water applied is actually used by the plant. The rest of the water—in this case 30 percent --was not used by the plant. However, the efficiency measure does not take into account if the 30 percent of water that is lost to the system, returns to the stream or groundwater, or is used elsewhere.

[21] The term “water applied” is used throughout this report, generally referring to the water applied by irrigation to a field. The term is used by USDA in their survey to irrigators, the Irrigation and Water Management Survey, previously called the Farm and Ranch Irrigation Survey.

Generally, increasing efficiency of irrigation conserves water on the farm, but water conservation or savings at a broader level—such as the basin or watershed—depends on what happens once excess irrigation water leaves the farm. Determining if a particular irrigation system saves water when compared to another system would be based on how much more water is available due to the improvement. For example, a more efficient irrigation system could result in less water needing to be applied, and therefore less water diverted, resulting in water conserved at the source—such as the stream or aquifer. Or, a more efficient irrigation system could reduce the amount of water running off the field. In some cases, there are downstream users—agricultural, municipal and industrial, and environmental—that use the water that runs off the field. By reducing the runoff in this case, there would be less water available for a downstream user.

The amount of water "saved" refers to the fraction of the diverted water that becomes available as a result of a conservation practice or system improvements. In water-scarce areas, water savings in irrigation may occur when non-beneficial uses are reduced. For example, improving irrigation efficiency can reduce non-beneficial uses—flows to sinks that are unrecoverable, or evaporation—which can save water.

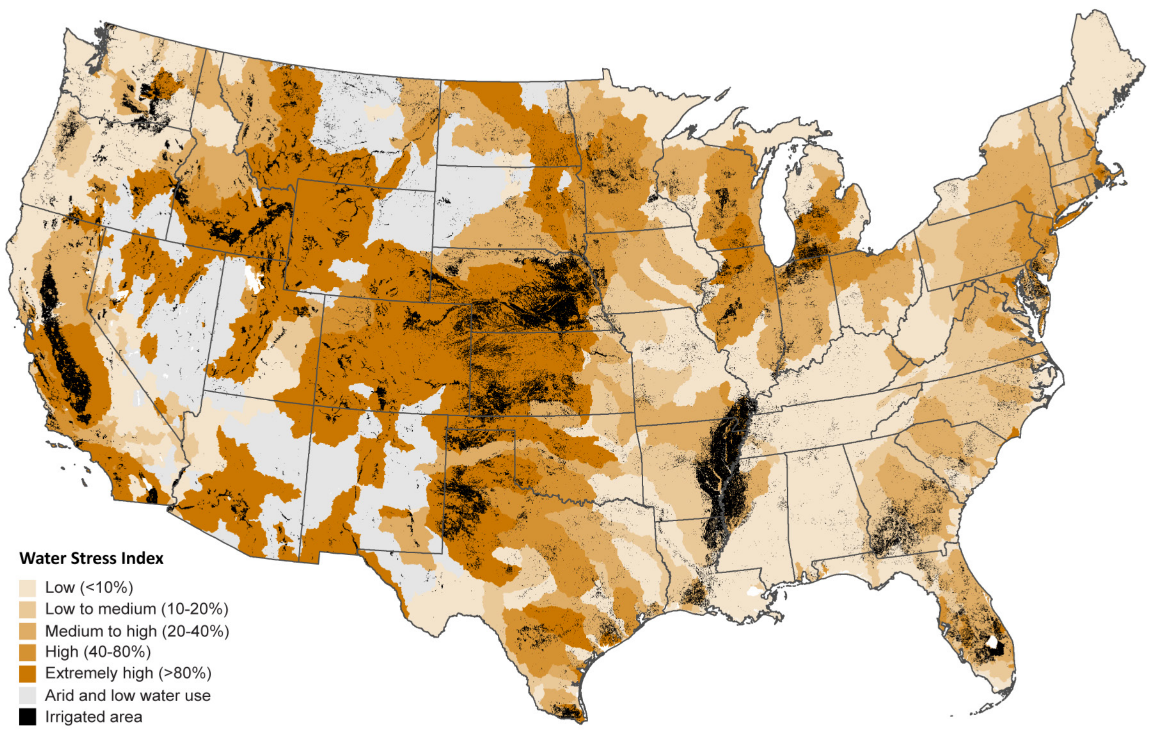
1.5 Water scarcity

Water scarcity occurs when demand for water approaches or exceeds available water supplies in a region, and, in reference to agriculture, when the water required for sustaining the region's crop production becomes difficult or impossible to obtain.

There are several ways to measure water scarcity, depending on factors relevant to a particular location. Figure 7 maps baseline water stress and irrigation density.[22]

[22] The water scarcity index is based off a working paper that may be subject to change. Gassert, F., M. Luck, M. Landis, P. Reig, and T. Shiao. 2014. "Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators." Working Paper. Washington, DC: World Resources Institute. Data for irrigation location is from the 2012 Moderate Resolution Imaging Spectroradiometer Irrigated Agriculture Dataset for the Unites States: https://earlywarning.usgs.gov/USirrigation.

Figure 7: **Irrigated areas (2012) and water stressed areas (2015) across the contiguous United States**



Source: GAO analysis of data from World Resources Institute Aqueduct, accessed on February 21st, 2018, and Moderate Resolution Imaging Spectroradiometer Irrigated Agriculture Dataset for the United States for 2012. | GAO-20-128SP

As shown in figure 7, there are several areas in the United States that are heavily irrigated and considered water stressed, such as areas of California, Nebraska and Kansas. Part of the reason for the overlap is the lack of precipitation. Especially in the west, agricultural regions are typically in areas where precipitation is insufficient to support crops without irrigation. According to the USDA's Economic Research Service, irrigated areas change over time, and one factor, among other things, is regional water supply and demand.

Whereas water scarcity generally refers to longer-term water shortages, droughts are a temporary decrease in available water. A drought is a period of deficient precipitation or runoff with no set standard by which to determine the amount of deficiency needed to constitute a drought. When surface water is unavailable, many farmers increase groundwater withdrawals to make up the difference. Groundwater has historically been viewed as a limitless supply of freshwater. However, groundwater is a finite resource that can be—and often is—drawn down at an unsustainable rate, a condition known as groundwater overdraft. For example, the rate of groundwater withdrawal for irrigation in the Ogallala Aquifer far exceeds the rate of natural recharge, resulting in large groundwater depletions.[23] In another recent example, a drought in California from 2013 to 2016 led to groundwater overdraft, primarily due to withdrawals for irrigation. A third example is the overdraft of the alluvial aquifer in eastern Arkansas where groundwater pumping has led to substantial, widespread water-level declines. In addition to producing long-term declines in aquifer levels, groundwater overdraft can lead to saltwater intrusion into formerly freshwater sources and the sinking or settling of land. For example, the National Academy of Sciences has reported that more than 80 percent of the identified land subsidence in the United States is a consequence of our use of groundwater.[24] Land subsidence can damage infrastructure such as roads, pipelines, and aqueducts, and is sometimes irreversible, causing a permanent loss of groundwater storage capacity.

In addition to water sources being stressed during times of drought, agricultural productivity also decreases with drought-induced crop failures. For example, according to The *Fourth National Climate Assessment Report,* in the Great Plains, drought conditions in 2012 caused widespread harvest failures for corn, sorghum, soybean, and other crops. [25] Between 2010 and 2015, irrigated acres in California decreased by 10 percent likely due to drought conditions.

Future projections of climate change predict increasing water scarcity, and drought risk. According to The *Fourth National Climate Assessment Report*, water supplies for irrigation are expected to deplete with climate change.[26] This depletion is expected to accelerate due to higher temperatures and insufficient precipitation, among other factors. In addition to water supplies, climate change is expected to affect water demands in agriculture, as higher temperatures can increase the amount of water that crops need.

We previously reported on freshwater supplies in 2014.[27] In that report, we found that freshwater shortages are expected in the future, according to state water managers, experts, and the literature. In particular, 40 out of 50 state water managers expected shortages in some portion of their states under average conditions in the next 10 years. We found that from 2003 to 2013 states have taken a number of steps to improve management of freshwater availability and use. These include conducting freshwater resource studies and assessments, developing drought preparedness plans, developing water management tools, taking conservation

[23] The Ogallala aquifer spans parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

[24] National Academy of Sciences, Prospects for Managed Underground Storage of Recoverable Water (Washington, D.C.: 2008).

[25] Lall, U., T. Johnson, P. Colohan, A. Aghakouchak, C. Brown, G. McCabe, R. Pulwarty, and A. Sankarasubramanian, 2018: Water. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment ,Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 145–173.

[26] Gowda, P. et al, pp. 391–437.

[27] *Freshwater: Supply Concerns Continue, and Uncertainties Complicate Planning,* GAO-14-430 (Washington, D.C.: May 20, 2014).

actions, and taking steps to address climate change impacts on water resources. We found that federal agencies had taken various actions to support freshwater management. For example, the Department of the Interior's USGS initiated the National Water Census to assess water availability and use across the nation. Another example is the National Integrated Drought Information System program that coordinates and integrates drought research, building upon existing federal, tribal, state, and local partnerships in support of creating a national drought early warning information system. In addition, state water managers, experts, and literature we reviewed identified actions the federal government could take to support state water management efforts, including increased collaboration among federal agencies and with states and other stakeholders, and maintaining and collecting key data.

This report focuses on water scarcity, though water abundance can also be harmful to agriculture. Recent flooding in 2019 significantly impacted agriculture, specifically resulting in flooded farmland and reduced crop planting acreage in Ohio and Indiana. USDA reported that the 2019 floods and heavy rainfall prevented many farmers in Midwestern States from planting crops. According to a USDA official, both overly wet and water scarce conditions are symptoms of an inability to manage water resources.

1.6 Legal framework governing water use

The federal government derives authority to manage certain water resources from several constitutional sources but recognizes the states' authority to allocate and use water within their jurisdictions. The Commerce Clause,[28] one source from which federal authority is derived, permits federal regulation of water that may be involved in or may affect interstate commerce,[29] including efforts to preserve the navigability of waterways.[30] In addition, the Property Clause[31] permits federal regulation of water as necessary for the beneficial use of federal property.[32] Federal laws often require federal agencies engaged in water resource management activities to defer to state laws or cooperate with state officials in implementing federal laws. For example, under the Reclamation Act, the Bureau of Reclamation must defer to and comply with state laws governing the control, appropriation, use, or distribution of water unless applying the state's law would be inconsistent with an explicit congressional directive regarding the Reclamation projects.[33] Other federal acts—including the Water Supply Act of 1958, Clean Water Act,

[28] U.S. Const. art. I, § 8, cl. 3.

[29] *See e.g.,* Utah v. Marsh, 740 F.2d 799, 803 (10th Cir. 1984); United States v. Byrd, 609 F.2d 1204, 1210 (7th Cir. 1979).

[30] United States v. Rio Grande Dam & Irrigation Co., 174 U.S. 690, 703 (1899).

[31] U.S. Const. art. IV, § 3, cl. 2.

[32] Rio Grande Dam & Irrigation Co., 174 U.S. at 703.

[33] 43 U.S.C. § 383; see California v. United States, 438 U.S. 645 (1978).

and the Endangered Species Act—explicitly recognize nonfederal interests in water supply development.[34]

Various state laws govern the allocation and use of surface and ground water. Specifically, the allocation and use of surface water can generally be traced to two basic legal doctrines: (1) the riparian doctrine, often used in the eastern United States, and (2) the prior appropriation doctrine, often used in the western United States. States may rely on either doctrine, a mix of both, or, in a few cases, other approaches.[35] Under the riparian doctrine, water rights are linked to land ownership, where owners of land bordering a waterway have a right to use the water that flows past their land for any reasonable purpose. Landowners may, at any time, use water flowing past their land even if they have never done so before; all landowners have an equal right to use the water, and no one gains a greater right through prior use.

In contrast, the prior appropriation doctrine does not link water rights with land ownership. Water rights are instead linked to prior and beneficial water use—parties who obtain water rights first (known as "senior water rights holders") generally have seniority for the use of water over those who obtain rights later (known as "junior water rights holders"), and rights holders must put the water to beneficial use or abandon their right to use it. Simply put, "first in time, first in right" and "use it or lose it." Because water rights are not tied to land, water rights can be bought and sold without any ownership of land, although the rights to water may have specific geographic limitations. For example, a water right generally provides the ability to use water in a specific river basin taken from a specific area of the river. When there is a water shortage in prior appropriation states, shortages fall first on those who last obtained a legal right to use the water. As a result, a shortage can result in junior water rights holders losing all access to water, while senior water rights holders retain access to their entire prior allotment.

While groundwater allocation can follow principles of surface water management, many states use different approaches. For example, many states use the prior appropriation doctrine to allocate groundwater rights in a manner similar to surface water. Other approaches to groundwater allocation include granting rights to all the water that landowners can capture; granting landowners the right to water beneath their land, provided the use is restricted to an amount necessary for

[34] The Water Supply Act of 1958 states that it is the policy of the Congress to recognize the primary responsibilities of the states and local interests in developing water supplies for domestic, municipal, industrial, and other purposes and that the federal government should participate and cooperate with states and local interests in developing such water supplies in connection with the construction, maintenance, and operation of federal navigation, flood control, irrigation, or multiple purpose projects. 43 U.S.C. § 390b. The Clean Water Act states that it is the policy of the Congress that the authority of each state to allocate quantities of water within its jurisdiction shall not be superseded, abrogated, or otherwise impaired by the act, and that federal agencies shall cooperate with state and local agencies to develop comprehensive pollution solutions in concert with programs for managing water resources. 33 U.S.C. § 1251(g). The Endangered Species Act states that it is the policy of the Congress that federal agencies cooperate with state and local agencies to resolve water resource issues in concert with conservation of endangered species. 16 U.S.C. § 1531(c)(2).

[35] Other approaches can include no regulation of water allocation by the state.

reasonable use; dividing rights among landowners based on acreage; and not regulating groundwater allocation.

1.7 Federal policy and programs in agricultural water conservation

As we have previously reported, many federal agencies play a role in managing the nation's freshwater resources.[36] Specifically, federal agencies collect and share water availability and use data; assist in developing and implementing water-management agreements and treaties; construct, operate, and maintain large water storage and distribution facilities; hold water rights for federally managed lands and act as trustees for tribal water rights; and administer clean water and environmental protection laws.

For example, the Bureau of Reclamation has constructed irrigation projects throughout the 17 western states. The Bureau of Reclamation also provides federal funds for irrigation projects such as dams, reservoirs, and canals. These projects provide water to one out of five western farmers, accounting for 10 million acres of farmland.

While many federal agencies play a role, no one agency has primary oversight of water resource management. Rather, many agencies influence states' management activities through the implementation and enforcement of federal laws, as well as various federal programs. The states have primary responsibility for managing freshwater resources. Water rights are primarily state-created property rights.[37] States may rely on local entities to accomplish water goals. For example, California's Sustainable Groundwater Management Act, signed in 2014, provides local groundwater agencies with the authority and the technical and financial assistance necessary to sustainably manage groundwater. In Nebraska, natural resources districts—based on river basin boundaries—carry out programs related to local water supply and conservation, among other natural resource concerns. Each Nebraska natural resources district is governed by locally-elected officials and may establish taxes on property within the district. Collaboration between the various stakeholders is often necessary as water does not stop at political boundaries. For example, the Colorado River Compact is an agreement between seven states providing for the apportionment of the waters of the Colorado River System, where the Bureau of Reclamation manages several water supply facilities.[38] Under the Colorado River System Conservation Pilot Program, the Bureau and several local water management agencies assessed the feasibility of various voluntary, temporary and compensated methods to manage farmers' use of irrigation water, for example through temporary fallowing, deficit irrigation and alternative cropping. [39] The pilot

[36] GAO-14-430 .

[37] Tarlock, Law of Water and Water Rights and Resources, § 1.1 (West 2018)

[38] States included are Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming.

[39] The municipal water users who participated in the Colorado River System Conservation Pilot Program included Central Arizona Water Conservation District, Southern Nevada Water

was a collaborative effort between the federal government—through the Bureau of Reclamation—and four Colorado River municipal water users. According to the Upper Colorado River Commission report, the pilot demonstrated, among other things, farmer interest in the water-savings program and how voluntary reductions in their consumptive use may help, for example, in protecting critical reservoir levels in the Upper Basin of the Colorado River during drought.[40]

Additionally, USDA has explicit policy goals on water availability and agriculture. One of the department's goals in its strategic plan is to strengthen the stewardship of private lands through technology and research. Under this goal, there are several objectives, including to enhance conservation planning with science-based tools and information, as well as to enhance productive agricultural landscapes, which includes water availability. Within USDA, three agencies—the Natural Resources Conservation Service, the Agricultural Research Service, and the Farm Service Agency—discuss water quantity in their strategic plans. One objective in the Natural Resources Conservation Service's strategic plan for fiscal years 2016 to2018 is to enhance and improve water quality and water quantity. In the 2018 to2020 Agricultural Research Service strategic plan, one goal is to effectively and safely manage water resources, including water availability. The Farm Service Agency's strategic plan for fiscal years 2016 to 2018 has an objective of developing and implementing measures to conserve surface and ground water supplies.

Furthermore, the Environmental Quality Incentives Program (EQIP) provides technical and financial assistance to landowners—farmers and ranchers—who voluntarily implement conservation practices on agricultural lands.[41] According to a USDA report, in 2008, nearly 57 percent of the farms that received financial assistance for irrigation technology adoption did so through this program; however, only about 4 percent of farms that made irrigation investments in 2008 participated in the program.[42] The USDA report further states that nationally, irrigation practices accounted for roughly a quarter of the program's total obligations ($5.7 billion) for 2004 through 2010. The program also funds water conservation practices that can be used along with irrigation. The 2018 Farm Bill authorized EQIP assistance for entities such as irrigation districts and groundwater management districts to implement water conservation or irrigation practices that, among other things, provide for drought-related environmental mitigation.[43]

Authority, Metropolitan Water District of Southern California, and Denver Water

[40] Upper Colorado River Commission Staff and Wilson Water Group, *Final Report: Colorado River System Conservation Pilot Program in the Upper Colorado River Basin*, 2018

[41] GAO previously reviewed the Environmental Quality Incentives Program, see GAO-17-225.

[42] Schaible, Glenn D., and Marcel P. Aillery, *Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands,* EIB-99, U.S. Department of Agriculture, Economic Research Service, September 2012.

[43] Pub. L. No. 115-334, § 2304, 132 Stat. 4490, 4558 (Dec. 20, 2018) (codified at 16 U.S.C. § 3839aa–2(h)(2)(A)).

The 2018 Farm Bill also authorized EQIP assistance for, “on-farm conservation innovation trials” to test new or innovative conservation approaches, which include new or innovative irrigation systems.[44] The trials are to be carried out by USDA either directly with farmers or through third-party entities. [45]

In addition to EQIP, several other agricultural programs have water conservation as a part of their objectives, including the Regional Conservation Partnership Program, the Conservation Stewardship Program (CSP), and the Agricultural Management Assistance program. One of the Regional Conservation Partnership Program’s purposes is to further the conservation, protection, restoration, and sustainable use of water, among other resources. The purpose of the CSP is to encourage farmers to address priority resource concerns, and improve and conserve the quality and condition of natural resources in a comprehensive manner. Additionally, under the Agricultural Management Assistance program, USDA may provide financial assistance to covered farmers for, among other things, the construction or improvement of irrigation structures.

See Appendix II for a table of a select number of federal programs, descriptions of the programs, and examples of initiatives under each program.

[44] Pub. L. No. 115-334, § 2307, 132 Stat. 4490, 4562 (Dec. 20, 2018) (codified at 16 U.S.C. § 3839aa–8(c)).

[45] An eligible entity is (1) a third-party private entity the primary business of which is related to agriculture;

(2) a nongovernmental organization with experience working with agricultural producers; or

(3) a governmental organization. 16 U.S.C. § 3839aa–8(c)(1)(A).

2 Irrigation technologies and practices can help reduce water applied to irrigated agriculture

Any of the three major irrigation systems—gravity, sprinkler and micro irrigation—can be used to help farmers reduce water applied to cropland during irrigation. Several water conservation practices could also help reduce the amount of water applied on the farm level.

2.1 All three major types of irrigation systems can help reduce water applied to irrigated agriculture

Irrigation systems are used to provide supplemental water to crops, orchards, vineyards, and vegetables in areas where natural precipitation will not support desired production of crops being grown. These systems are differentiated from each other by the method used to deliver water to the crops on the field and cover most types of irrigation systems in the United States.

While any of these systems can be used to irrigate any agricultural field in the United States, there may be crop, soil and location factors to be considered. Typically, some crops and climates are better suited to one system than another. For row crops—such as corn or potato—a sprinkler system can be used but the characteristics of the crop, such as crop height, need to be considered in selecting the type of sprinkler.

Perennial tree crops are better suited to drip irrigation, than high-pressure sprinklers, that would saturate the trees. Micro irrigation (or drip and trickle) methods are often used with high-value crops because of micro irrigation's relatively high cost and management requirements. Factors that are typically considered in selecting an irrigation method include soil type, climate and crop type. There is no single system that would be ideal for all crops, climate or regions.

Figure 8: Irrigation systems: how they work

Source: GAO analysis and photos by Saeid Tadayon, USGS (left); USDA photo by Lance Cheung (middle); USDA photo (right). | GAO-20-128SP

Efficiency and uniformity of irrigation systems

Though there are different definitions of efficiency used when examining water use in irrigation, we define it as the percentage of applied irrigation water that is beneficially used by the crops and not lost to evaporation, percolation or run-off.[46] While much of the water applied to the field during irrigation is used by the crop to grow, some water may run off the field, and some may evaporate or seep into the soil below the root zone. The goal of irrigation is to achieve good distribution uniformity—that is, water should soak evenly into the ground throughout the field.

In general, gravity methods are considered less efficient than sprinkler and micro irrigation systems that are pressurized. Both sprinklers and micro irrigation systems provide management with easier control of the total application of water than a gravity system.

From our review of literature we found that there are no agreed upon set of efficiency values for these three irrigation systems, but potential values or a range of potential values are often reported for their irrigation system efficiency. Table 2 cites one source—the United Nation's Food and Agriculture Organization (FAO) reported values.

Table 2: Food and Agriculture Organization (FAO): Indicative irrigation efficiencies by system type

System Type	Irrigation Efficiency
Gravity	60 percent
Sprinkler	75 percent
Micro irrigation	90 percent

Source: United Nation's Food and Agriculture Organization | GAO-20-128SP

Food and Agriculture Organization (FAO) of the United Nations, 1989. The FAO refers to this as "field application efficiency" or the efficiency of the water application in the field. While there are several types of irrigation efficiencies, these are potential or indicative efficiency values.

Some sources we reviewed in the agriculture literature that published efficiency values reported wide and overlapping ranges. We did not independently assess the reliability of these numbers and the source provides no direct evidence to support them. The values in table 2 are comparable to other reported values, for these three irrigation systems, and are reasonable estimates of potential performance. A review of irrigation efficiency studies reported attainable (or potential) field efficiency values for some types of gravity and sprinkler systems. The gravity values ranged from 70 to 90 percent and sprinkler values from 80 to 90 percent. The only value reported for micro irrigation was trickle at 95 percent. The review's author also stated that while high efficiency is possible for many systems, it is a common misconception that improving irrigation efficiency will

[46] "Irrigation efficiency" is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and promote better or improved use of water resources, particularly those used in agriculture and turf/landscape management. Irrigation efficiency is defined in terms of: 1) the irrigation system performance, 2) the uniformity of the water application, and 3) the response of the crop to irrigation. Each of these irrigation efficiency measures is interrelated and will vary with scale and time. The spatial scale can vary from a single irrigation application device (a gate, a sprinkler, a micro irrigation emitter) to an irrigation set (basin plot, a furrow set, a single sprinkler lateral, or a micro irrigation lateral) to broader land scales (field, farm, a whole irrigation district, a basin or watershed, a river system, or an aquifer).

automatically result in water conservation with "extra" water available for supply.

In general, micro irrigation is considered a more efficient system as it applies water directly to the plant or its roots, as compared to sprinkler systems and gravity systems. However, irrigation performance in terms of the efficiency of water used—that is, the ratio of water used to the water applied is influenced by the degree of system management. At a minimum, half of the irrigated acres in the United States may be able to irrigate more efficiently by using different irrigation technologies or practices.[47]

Role of distribution uniformity in water use and crop productivity

Although high irrigation efficiency is possible for many systems, crop productivity is more directly related to distribution uniformity. Uniformity is a measure of how evenly the applied water is distributed over the field. Most irrigation systems have low application efficiencies when the application is distributed to adequately irrigate all points in a field. Although this practice usually results in uniform crop growth and yield, excess water is applied. Under-irrigating a portion of the field (for example 5 or 10 percent) could increase the on-farm application efficiency by 10 percent or more.[48] The optimum operating point must be determined by an engineering, agronomic, and economic analysis.

For gravity irrigation, uniformity in distribution can be increased with the use of land leveling, and the reuse of tail-water runoff can increase efficiency. Sprinkler systems can be used to apply water using low pressure through nozzles placed close to the soil surface to reduce evaporation losses and energy consumption. Other tools to decide when and how much irrigation water to apply, such as use of soil moisture sensors, irrigation scheduling services, or crop growth simulation models are considered 'modern' practices to improve irrigation decisions. However, data from USDA's Farm and Ranch Survey (FRIS) show that only about 19 percent of irrigated farms in the west used one of more modern means of deciding when and how much irrigation water to apply.

Table 3 summarizes features of the three irrigation systems.

[47] Schaible and Aillery, *Water Conservation in Irrigated Agriculture*.

[48] Howell, Terry, *CRC Handbook of Engineering in Agriculture, Volume 1*, *Crop Production Engineering*, CRC Press (Florida: 1988).

Table 3: Major features of the three main irrigation systems

Systems	Gravity	Sprinkler	Micro irrigation
System types	Flood, basin, furrow.	Center pivot, linear move tower, wheel move, or big gun. Includes medium and high pressure sprinklers.	Drip, trickle, surface and sub-surface drip, and low-flow micro sprinklers or spray.
Common Crops	Rice, corn. Close-growing crops are suited for gravity.	Corn, soybeans, potatoes. Widely spaced field crops do not need total field saturation.	Often used with vines, nuts, berries (high value plants).
Soil factors (soil type, infiltration rate)	Low infiltration rates of clay soil are ideal for gravity.	Sandy soils with high infiltration rates do better with sprinkler.	Sandy soils with high infiltration rates do better with micro irrigation.
Water quality factors	Can use sediment-heavy water.	Clogging risk with sediment (sand, silt and clays) heavy water.	High quality, filtered water needed. Clay, silt, soil particles, fungi, spiders, worms, and precipitates from chemical injections can plug emitters.
Relative energy and equipment costs	Lower energy and capital costs. Little mechanical equipment.	Energy requirements to pressurize system. Costs relatively large. Large initial capital costs.	Energy required for system pressure. Large initial capital costs.
Maintenance issues	Periodic field grading and dredging of the tail-water system.	Moderate- Change worn nozzles and sprinkler heads. Periodic maintenance of motors, gear drives, guidance systems, and tires.	Periodic flushing needed to prevent clogging.
Labor needs	Less skilled labor, but can be labor-intensive. The bulk of labor is through land forming measures.	Highly automated systems can require high level of technical knowledge.	Management is more important. Managers require more training and proficiency than for surface or other sprinkler systems.
Operational factors	Less control over amount of water applied than other systems. Need large flows for an irrigation event.	Easily control speed and amount of water applied. Small water supply streams can be used.	Each drip is applied specifically to the site.
Other disadvantages	Not good at applying small amounts of water. Fields with variable soil types are hard to irrigate uniformly.	Energy required to create pressure. Nozzles can clog.	Emitters can clog. Buried tubing can be damaged by gophers or other rodents.

Source: GAO | GAO-20-128SP

Types of irrigation systems and operational considerations

Gravity irrigation

Gravity irrigation systems—sometimes called surface irrigation systems— distribute water laterally across the entire field or into furrows. Generally, these types of systems divert water from a source to flood over a crop area via land-forming measures, such as canals, ditches, basins, and furrows. The different types of gravity systems include basin, furrow, and border irrigation systems. With furrow irrigation, fields are typically graded to allow water to flow more easily across the soil surface while still being confined within borders.

Figure 9: Gravity system

Source: Saeid Tadayon, USGS. | GAO-20-128SP

Operational considerations. Gravity systems work well with clay soils with low water infiltration rates and sediment heavy irrigation water. With gravity systems, experience is required to judge when to turn off the water, as soil type, soil moisture content at the start of irrigation, and opportunity time affect the depth of water infiltration.

Modifications to improve efficiency and uniformity. While gravity systems are considered to be less efficient than other irrigation systems, there are modifications that can improve their performance, including, use of above or below ground pipe, use of tail-water pits, and laser land leveling. USDA has identified these and other water management practices as ways to improve the efficiency of gravity flow irrigation systems.[49] The land leveling process of reshaping a field helps improve the uniform distribution of water applied to a crop area without creating puddles in low sections and dry spots in high sections.

Geographical distribution. Gravity irrigation is the oldest method and was practiced on about 62 percent of the irrigated land in the United States in 1984, but this percentage declined as of 2013. The 2013 FRIS reported data show that 34 percent of all irrigated acres in the west are irrigated with gravity systems and gravity accounts for almost 40 percent of total irrigated acres across the United States. California and Arkansas are the leading states by acreage. Nationally, 85,159 farms reported using gravity irrigation, with California and Colorado being the top two states with farms using gravity irrigation

[49] An ERS report summarizing the results of the irrigation survey states that efficient gravity irrigation includes furrow irrigated acres using above- or below-ground pipe or a lined open-ditch field water-delivery system, plus acres in flood irrigation (between borders or within basins) on farms using laser-leveling and pipe or lined open-ditch field water-delivery systems.

(about 15,000 and 9,000 farms respectively). Idaho, New Mexico and Nebraska have between 7,000 and 8,000 farms each using this irrigation method.

Sprinkler irrigation systems

Sprinkler irrigation applies water through pipes and nozzles to form a spray pattern creating artificial precipitation. Sprinklers use pressurized water, a pipe network to distribute the water throughout the field, sprinklers to spray the water over the ground, and valves to control the water. The different sprinkler-based systems include:

- *Center pivot* sprinklers are attached to a wheel-driven frame that rotates around a central point to irrigate a large circular area.
- *Linear move tower* sprinklers are attached to a continuous, self-moving system that moves in a straight line and irrigates a rectangular area.
- *Solid set or permanent* sprinklers are attached to either an above ground portable pipe system or a permanent buried system, typically arranged in a diamond or triangular pattern.
- *Hand move, side roll* sprinklers are attached to an above ground portable lateral pipe system that can be moved by hand or lifted and carried or rolled on wheels.
- *Big gun or traveler* sprinklers are large, gun-type sprinklers that are periodically moved by tractor.

There is a wide variety of sprinkler configurations and operating parameters. For example, a rotary sprinkler can apply water at a high pressure such as 30 to 80 pounds per square inch (psi), and cover a large area with an 18 to 100 foot radius throw. It is economical for large open spaces. A 160 acre center pivot system can irrigate about a 130-acre circular area. Some sprinkler configurations can have specialized uses, for example a big gun can also be positioned on the end of a center-pivot system to spray water at a high pressure wetting the distant corners of a field which the center-pivot itself can't reach. Figure 10 shows a center pivot sprinkler system.

Figure 10: Sprinkler system: center pivot

Source: USDA photo by Lance Cheung. | GAO-20-128SP

Operational considerations. The different sprinkler systems vary in type and configuration. In cases where sprinklers throw water in the air, for example, water can be lost to both drift from wind and evaporation. One review of studies reported that droplet evaporation losses from sprinkler systems are estimated in the 1 to 2 percent range.[50] In addition, a fast-moving center-pivot applies a

[50] Schneider, A.D., *Efficiency and Uniformity of the LEPA and spray sprinkler methods: A review.* Transactions of the ASAE, pg 937-944 (vol 43:4, 2000).

smaller depth of water and wets the soil less deeply, leaving the crop leaves and soil surface wetted. But these wetted surfaces quickly lose water to evaporation.

Figure 11: Another configuration of center pivot

Source: GAO. | GAO-20-128SP

Sprinkler irrigation systems have allowed the agricultural development of marginal lands unsuitable for gravity irrigation such as where mostly light sandy soils have large variations in topography within the same field. Center pivot and lateral move systems provide a vehicle to apply chemicals and fertilizers. The center pivot provides a suitable platform on which to mount various types of sensors, including global positioning systems (GPS).

Modifications to improve efficiency. Loss to evaporation and surface runoff can sometimes be addressed with modifications to improve efficiency.

The Low Energy Precision Application (LEPA) is an operational modification to center pivot and linear move systems.[51] For example, a standard center-pivot irrigation system could be converted to low pressure, allowing water to be applied directly into furrows through nozzles placed close to the soil surface to reduce evaporation losses and energy consumption. With LEPA methods, water is delivered directly to the surface at very low pressure through drop tubes and orifice-controlled emitters, rather than spraying water into the air at moderate to high pressures. They are generally attached to moving center pivot or linear advance lines to allow continuous advance over large areas. LEPA has “drop” tubes spaced about every meter that extend to the soil surface where a low-pressure bubbler is attached in place of a sprinkler. Water is applied directly to the furrow and evaporation losses are minimized since the canopy is not wet. Run-off needs to be controlled to achieve the high application efficiency with LEPA. One review of studies found that the reported application efficiencies for LEPA sprinklers are typically in the 95 to 98 percent range.[52]

Sprinkler systems can operate with very low (under 15 psi), low (15-30 psi), medium (30-59 psi) or high (60 + psi) pressure. LEPA’s operating pressure requirement may only be

[51] Low energy systems also refer to the amount of pressure (low PSI) used to distribute the water.

[52] Schneider, “Efficiency and Uniformity” pp. 937-944.

a pressure of 15 psi, while the traveling gun system may require 130 psi of pressure or more.

Geographical distribution. Sprinklers are used to irrigate 65 percent of all the irrigated acres in the United States.[53] Nebraska, Texas, and Idaho are the states with the largest number of acres using sprinklers. The center pivot systems account for 70 percent of all the pressure sprinkler irrigated acres across the United States. Of those center pivots though, only about 5 percent of them use high pressure systems. The automatically-applied, light irrigation of the center-pivot enabled the cultivation of the sand hills area of Nebraska, where gravity systems could not be used due to the sandy soil's poor water-holding capacity, but farmers can now raise crops under center-pivot irrigation.

Micro irrigation

Micro irrigation is an irrigation system to apply water to the crop root zone by means of surface or sub-surface methods. The different types include trickle, drip (surface and subsurface), bubbler, and low-flow microspray. Drip or trickle use applicators such as orifices, emitters (small holes), porous tubing and perforated pipes. These irrigation systems apply frequent applications of small quantities of water on the soil surface as drops, tiny streams or miniature spray through emitters or applicators placed along a water delivery line. The bubbler application applies a small stream of water to the soil surface. A surface drip applies the water through small emitters to the soil surface, usually at or near the plant to be irrigated. Subsurface systems, on the other hand, use buried drip lines and apply water directly to the root zone of the crop, typically 12 to 18 inches below the surface. The micro irrigation concept is that small, frequent, and localized water applications which do not wet the entire soil surface, but different variations are available.

A properly designed, installed, and managed micro irrigation systems can eliminate surface runoff and associated soil erosion, efficiently and uniformly apply water-soluble fertilizers and achieve high uniformity and efficiency of water application. Uniformity in plant growth across a field, due to uniform water and nutrient distributions, also contributes to overall yield increases. A 2010 National Research Council report noted that the shift to drip and trickle irrigation had been a strategic improvement in water-use efficiency and energy savings over the past three decades.[54] Figure 12 shows two types of micro irrigation systems.

[53] We report the FRIS data for sprinklers here which include low pressure sprinklers.

[54] National Research Council 2010. Toward Sustainable Agricultural Systems in the 21st Century. Washington, DC: The National Academies Press. https://doi.org/10.17226/12832.

Figure 11: **Micro irrigation systems**

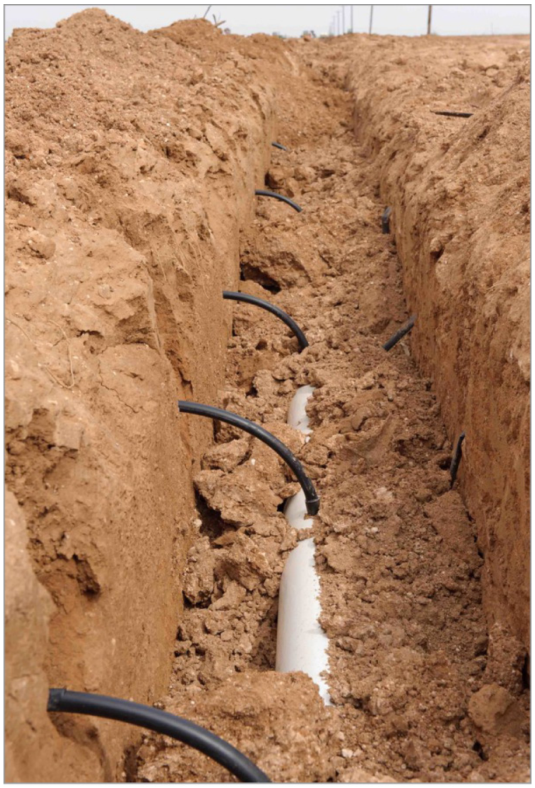
Source: USDA photo by Alice Welch (Left), USDA photo by Lance Cheung (Right). | GAO-20-128SP

Operational considerations and efficiency. These systems can be used on most agricultural crops, although they are most often used with high-value specialty crops such as vegetables, berries, fruit crops, olives, nuts, and avocados. Subsurface drip irrigation is used on some row crops, like cotton. A main disadvantage of micro irrigation systems is that the costs to install and maintain can be high. The low pressure, low flow method requires small flow channel openings in the emission devices that are prone to plugging so all need some degree of water treatment. Subsurface emitters maybe plugged and not be noticed until the plants are wilted. Success hinges on filtering and treating the irrigation water to match actual water quality conditions throughout the year with both surface and groundwater. It is sometimes not economically feasible to treat a water source to make it suitable for micro irrigation and other irrigation methods should be considered.

Micro irrigation tubing can be physically damaged by a number of mechanical and natural causes. Damage by farm equipment commonly occurs. Insects and spiders can plug emitters, but may also enlarge orifices when searching for water. Tall grass, weeds, spider webs, and large insects can stop the rotation of micro-spinners. Research literature and our site visit interviews also noted the harm gophers, coyotes and field mice can inflict on subsurface drip irrigation systems by chewing on the tubes and driplines of subsurface systems.

Micro irrigation systems need to be intensely managed, but are noted as extremely flexible irrigation systems. They can be installed as either a surface or subsurface water application system. The crop’s water needs can be dependent on adequate soil moisture at one or more critical periods in crop growth. With relatively uniform application and negligible or zero evaporation losses, the typical efficiencies of these systems reportedly exceed 90 percent.

Figure 12: **Subsurface drip irrigation**



Source: USDA. | GAO-20-128SP

Modifications to improve efficiency. Runoff and evaporation are usually not a significant part of water losses for micro irrigation systems. A potential added advantage of these systems is that the soil surface is not wetted during water application, leading to less soil water evaporation. The design and management requirements suitable for humid areas may not work in arid areas.

Geographical distribution. There are different types of micro irrigation used across the country. In 2013, four states accounted for 80.9 percent of all the drip/trickle or low-flow micro sprinklers irrigated acres, according to the FRIS survey results: California, Florida, Texas and Washington. California and Florida also have the largest number of farms using the above ground type of micro irrigation. Texas and Nebraska, after California, are the biggest users, in terms of number of farms, of sub-surface drip. And, Florida has about 2,000 farms using low-flow micro-sprinklers, while many states have farms with less than 100 farms irrigating with low-flow micro-sprinklers.

2.2 Water conservation practices can reduce the amount of irrigation water applied to a field, and using precision agriculture may help optimize irrigation scheduling

Several water conservation practices or methods can further reduce the amount of water necessary when using irrigation technologies. These conservation practices can provide environmental benefits, which will vary depending on the practice used. Choosing to implement one practice, or a suite of practices, depends on the farmer's goals and operation, and organizations supporting different aspects of conservation may encourage a particular practice to achieve a specific environmental outcome, such as water conservation. According to a 2018 USDA report, its conservation programs are only one of many ways to inform farmers of conservation opportunities and incentivize farmers to adopt conservation practices.[55] For example, there are state conservation programs, programs managed by

[55] U.S. Department of Agriculture, Office of the Chief Economist, *Agricultural Conservation on Working Lands: Trends From 2004 to Present*, Technical Bulletin Number 1950(Washington, D.C.: Nov. 2018).

nongovernmental organizations, private-sector initiatives and coalitions, stewardship programs, and farmer groups that encourage farmers to improve environmental outcomes. A wide diversity exists in the type and location of practices adopted across these programs. In addition, farmers may choose to adopt a conservation practice on their own, without a financial incentive. USDA and other organizations encourage a wide variety of on-farm water conservation practices, such as reduced tillage and irrigation management. According to USDA officials, the amount of water used to irrigate a specific crop or saved by an agricultural practice, such as water use and land management practices, varies by location, climate, crop traits, local cropping practices, type of irrigation systems, and institutional and social constraints. Furthermore, over-irrigation can still occur even when using irrigation technology and water conservation practices if crop growth cycles and evapotranspiration rates are not taken into account when scheduling irrigation events. In order to optimize irrigation scheduling, or the amount of irrigation water necessary, precision agriculture technologies can be used to collect data that help farmers make decisions remotely on how much water to use, when to apply it to their crops, and where it should be applied in their fields.

2.2 Water use management and improving soil health are among several practices that can help conserve water

We identified several water conservation practices that could reduce the amount of water applied to the field. Water use management includes practices, such as irrigation scheduling, intended to optimize the amount of irrigation water applied to crops. Soil health improvement allows soils to retain more moisture, which reduces the amount of irrigation water needed to maintain the necessary amount of moisture. Other practices manage the land surface to increase uniformity of the water applied to the field, improve water conveyance so water loss is reduced before it gets to the field, and use alternatives to relying on irrigated agriculture, such as dryland farming.

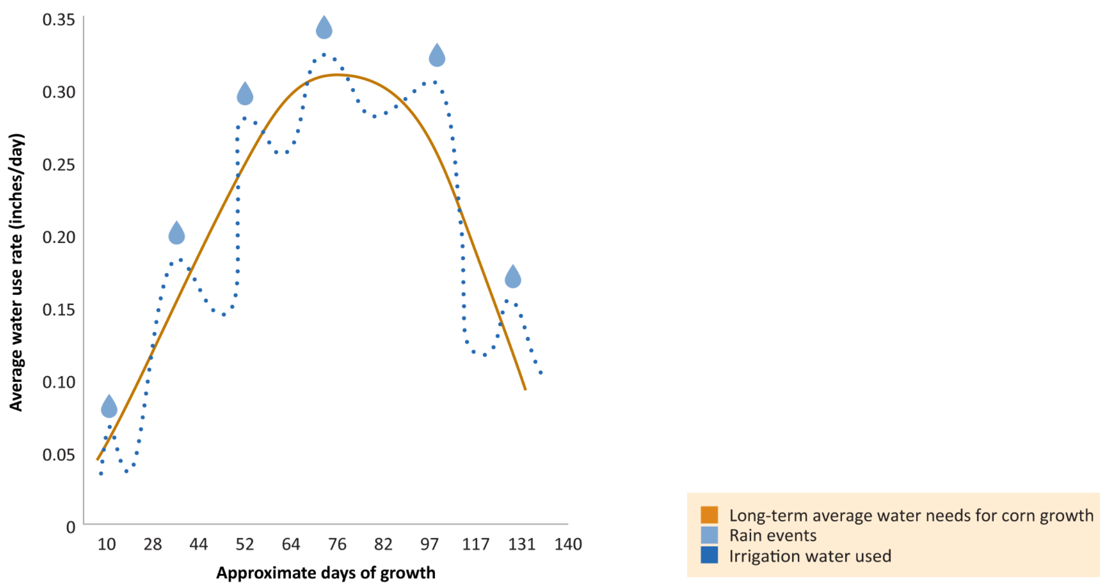
Water use management

Irrigation scheduling

A key practice in water use management is irrigation scheduling, which is used to determine when and how much to irrigate a crop. It helps farmers reduce the chance that too much or too little water is applied to an irrigated crop. Scheduling can be a challenge because both a crop’s water demand and the availability of irrigation water vary with time. For example, in some areas surface water may be controlled by irrigation districts that prescribe water delivery to individual farms without being flexible to the needs of modern irrigation systems or the needs of the crop. There are critical periods during crop growth when the yield or quality of irrigated crops can be very dependent on adequate water availability. Because of these critical periods of growth, ideally an irrigation scheduling program is established prior to the first irrigation of the crop, but it could be implemented at any time during the growing season.

Figure 13: **Example of how water needs can vary with the stage of growth**

Corn water needs (solid line) can vary with the stage of growth. The dotted line shows how the amount of irrigation water necessary for growth could decrease after rain events (rain drops).



Source: GAO analysis of data from the University of Nebraska-Lincoln Extension, Institute of Agriculture and Natural Resources. | GAO-20-128SP

The amount of water saved by implementing advanced irrigation scheduling may be difficult to quantify each year, because it is strongly influenced by weather, quality of the irrigation water, crop choice, and cropping practices, among other factors. However, irrigation scheduling may lead to a reduced number of irrigation events overall, resulting in water savings under a wide range of conditions. Figure 14 is an example of corn's growth cycle and hypothetically how rain and plant needs can change the long-term average amount of irrigation water that is necessary at different periods of growth.

Volumetric water measurement

Another water use management practice that could help reduce water use is volumetric water measurement through on-farm water audits or analysis. This practice can identify potential water efficiency measures by monitoring the total volume of water entering the farm from surface water or groundwater, inventorying and calculating on-farm water uses, and calculating water-related costs. For example, using a flow meter or other manual methods to measure water use provides data that helps determine and monitor overall irrigation system efficiency, among other things. This information could help determine additional water conservation practices to implement, increase irrigation water efficiency, and measure the impact of those changes that may save water.

According to the Bureau of Reclamation's Water Measurement Manual, the four most common water measurement devices used by irrigators are weirs, flumes, submerged orifices, and current meters.[56] A measuring weir is an overflow structure built perpendicular to an open channel axis to measure the rate of flow of water and is one of the oldest methods for open channels. Flumes are shaped, open-channel flow sections that force flow to accelerate by bringing the sidewalls closer together, raising the bottom, or a combination of both. A submerged orifice is usually a circular or rectangular and well-defined, sharp-edged, vertical opening in a wall or bulkhead perpendicular to the flow. Finally, current meters are velocity measuring devices that sample at a point, which is then assigned to a meaningful part of the entire cross-section of flow. Several classes of current meters are used in water measurement, but only the anemometer and propeller current meters are commonly used in on-farm irrigation and off-farm watershed measurements.[57] These devices use anemometer cup wheels or propellers to measure velocity.

Tailwater recovery

According to USDA, a tailwater recovery system is a water use strategy that re-uses irrigation and storm water runoff on the farm. It decreases the amount of groundwater and surface water needed for irrigation water applied to the farm by allowing farmers to capture and store water from irrigation runoff and storms in a reservoir. This captured water can be used in the next irrigation event, so it conserves water on the farm, but may affect downstream users, because that runoff is no longer available to them.

Deficit irrigation and drought-tolerant crops

Deficit irrigation and the use of drought-tolerant crops are two water management practices that may allow a farmer to limit the amount of irrigation water given to crops during the growing season to less than needed for maximum productivity. Typically higher crop yield is achieved with optimal water supply. However, under water stress, some crops can adapt to produce yields with less water. For example, a type of regulated deficit irrigation called “primed acclimation” first applies deficit amounts of irrigation water followed by full irrigation for the remaining season. Some researchers are investigating a strategy that incorporates primed acclimation into an irrigation schedule and preliminary data indicated that yield with primed acclimation surpassed yields of the other scheduling methods studied.[58] Understanding how different crops respond to water stress can help inform water management practices. According to a 2002

[56] Department of the Interior, Bureau of Reclamation, *Water Measurement Manual*, 3rd edition revised and reprinted (Washington, D.C.: 2001).

[57] According to the Water Measurement Manual, electromagnetic velocity meters, which produce voltage proportional to the velocity of flow, are very popular among water districts.

[58] Rowland, Diane L., Wilson H. Faircloth, Paxton Payton, David T. Tissue, Jason A. Ferrell, Ronald B. Sorensen, and Christopher L. Butts, “Primed acclimation of cultivated peanut (*Arachis hypogaea* L.) through the use of deficit irrigation timed to crop developmental periods,” *Agricultural Water Management*, vol. 113(2012): pp. 85-95. And K.W. Migliaccio, K. T. Morgan, G. Vellidis, L. Zotarelli, C. Fraisse, B. A. Zurweller, J. H. Andreis, J. H. Crane, and D. L. Rowland, “Smartphone Apps for Irrigation Scheduling,”*Transactions of the American Society of Agricultural and Biological Engineers*, vol. 59 (2016): pp. 291-301.

joint report by two United Nations organizations, substantial savings of water can be had with little impact on quantity and quality of the crops, if the farmer has thorough knowledge of crop behavior.[59]

Some crops, such as wheat, cotton, and sorghum, have developed drought tolerance, which is drought resistance or compensatory growth to deal with periods of water stress, although tolerance varies considerably by species, cultivar and stage of growth.[60] In addition, some newer crop variants have been genetically engineered or bred for drought tolerance, though their ability to reduce the amount of water needed for irrigation needs additional investigation, according to experts at our meeting and a USDA report (see text box).[61]

Drought Tolerant Corn

Commercial selective breeding research of seeds has increased drought tolerance in crops over time. Pre-market drought –tolerant (DT) strains of rice and soybeans are in development through irradiation and breeding techniques, according to the International Atomic Energy Agency's Mutant Variety Database.

There are at least three commercially-available lines of DT hybrids, according to a USDA report. DT corn has been commercially available since 2011. Drought tolerance in corn has been developed both through selective breeding and through genetic engineering.

DT corn is often combined with other water conservation practices, such as crop rotation and conservation tillage. The combination of these technologies can result in lower herbicide applications and more plant mass per unit of applied water. However, because DT corn is a relatively new product and is often used together with other water conservation technologies, it is currently difficult to evaluate if DT corn may reduce applied irrigation water needs. For example, while DT corn has been quickly adopted in Nebraska and Kansas, irrigation rates on DT corn fields were not statistically significant from those of non-DT corn fields in 2016, according to a USDA report.

Source: U.S. Department of Agriculture, Economic Research Service, *Development, Adoption, and Management of Drought-Tolerant Corn in the United States*, Economic Information Bulletin 204 (Washington, D.C.: Jan. 2019)

With deficit irrigation, the crop is intentionally exposed to a certain level of water stress either during a particular period or throughout the growing season. According to USDA officials, deficit irrigation can include reducing irrigation water applied to the field and reducing the number of times irrigation water is applied. According to the United Nations Food and Agriculture Organization, deficit irrigation has been found to lead to (1) greater economic gains than maximizing yields per unit of water for a given crop; (2) farmers who are more inclined to efficiently use water; and (3) farmers choosing more

[59]Food and Agriculture Organization and International Atomic Energy Agency of the United Nations, *Deficit Irrigation Practices*, Water Reports 22 (Rome, Italy: Food and Agriculture Organization, 2002).

[60]According to USDA officials, a crop's tolerance to water stress also depends on the severity of the drought and that row crops cannot maintain adequate productivity without or with very limited water.

[61]U.S. Department of Agriculture, Economic Research Service, *Development, Adoption, and Management of Drought-Tolerant Corn in the United States*, Economic Information Bulletin 204 (Washington, D.C.: Jan. 2019).

water-efficient crops when water supply is scarce or under drought conditions. For example, using deficit irrigation to save water or attain a desirable crop growth or quality objective has been more successful with vine (grapes) and tree crops (almonds) than with annual crops, such as corn.

Soil health improvement

Improving soil health through water conservation practices has been shown to reduce irrigation water demand over time. According to USDA officials, healthier soils will not only hold onto moisture longer from irrigation, but also from rain, which may further reduce the amount of irrigation water applied to a field by a farmer during the growing season or decrease the number of irrigation events in a given year. According to USDA documents and officials, soil health is a combination of physical, chemical, and biological characteristics, which can impact the function and productivity of the soil.

Some of the characteristics important for water conservation are (1) improving soil organic matter, (2) improving available water holding capacity, and (3) improving or maintaining soil structure. According to USDA documents, soil organic matter functions and contributes to several beneficial changes in soil health over the long-term, such as increased water and nutrient holding capacity, water infiltration rates, soil aggregate stability, and to an extent soil structure. In addition, healthier soils increase infiltration by improving soil characteristics, such as porosity, which in turn reduces runoff and evaporation from the surface, so irrigation water is used more efficiently. In addition, decreased runoff can reduce erosion so that healthy soils are not washed away. There are practices that farmers can use to improve these soil health characteristics to conserve water, which include tillage methods, cropping patterns, and soil conditioner.

Tillage methods

Tillage, which is turning the soil to control for weeds and pests and to prepare for seeding, is a standard practice in agriculture. Reduced tillage methods, such as no-till or conservation tillage, reduce erosion and promote water conservation by improving the soil moisture holding capacity and the supply of organic material from crop residue, which increases the infiltration rate and biological activity of the soil (see fig. 15).[62] According to a USDA report, although not specifically required, tillage practices are often part of conservation plans that must be in use to meet eligibility requirements (conservation compliance) for most federal agricultural programs, including commodity programs and (after 2014) crop-insurance premium subsidies.[63]

No-till is generally the least intensive form of tillage, followed by conservation tillage,

[62]According to a USDA official, no-till practices have led to soil consolidation and reduced rainfall infiltration in some semi-arid regions and soils.

[63]U.S. Department of Agriculture, Economic Research Service, *Conservation-Practice Adoption Rates Vary Widely by Crop and Region*, Economic Information Bulletin 147 (Washington, D.C.: Dec. 2015).

where at least 30 percent of plant residue remains on the field following harvest, and both are less intensive than conventional tillage. In another type of reduced tillage--strip-till for row crops--seeds are planted into a narrow strip (e.g., approximately one-third of the row width) that has been tilled while not disturbing the soil between the rows. Residue management and conservation tillage allow a farmer to manage the amount and distribution of crop and other plant residue on the soil surface year-round.

According to USDA reports, the vast majority of crops grown annually—as much as 93 percent from Conservation Effects Assessment Program data—are grown using some type of conservation tillage and of those acres, more crops were grown using continuous reduced tillage methods, instead of seasonal reduced tillage, although adoption varies across crops and regions.[64] Another USDA report found that farmers may use no-till or strip-till on crops that are thought to be well suited for the practice, such as soybeans (see fig. 16) and use conventional tillage or other conservation tillage methods for crops, such as corn, where no-till or strip-till is perceived as more risky.[65] Furthermore, those farmers who used no-till or strip-till applied that practice to all of their acreage for an individual crop, regardless of tillage practices on other crops. In addition, this report found 56 percent of all land used for corn, soybeans, wheat, and cotton was located on farms that used no-till or strip-till on at least some portion of land: 23 percent of land was on farms that used no-till or strip-till on all their acres in 2010-2011, while 33 percent of land was on farms that used a mix of no-till, strip-till, and other tillage practices. For example, we visited a farm in California that used three different types of tillage on their fields: no-till, reduced tillage and conventional tillage.

[64]U.S. Department of Agriculture, Office of the Chief Economist, *Agricultural Conservation on Working Lands: Trends From 2004 to Present*, Technical Bulletin Number 1950 (Washington, D.C.: Nov. 2018); U.S. Department of Agriculture, Economic Research Service, *Tillage Intensity and Conservation Cropping in the United States*, Economic Information Bulletin Number 197 (Washington, D.C.: Sep. 2018).

[65]U.S. Department of Agriculture, Economic Research Service, *Conservation-Practice Adoption Rates Vary Widely by Crop and Region*, Economic Information Bulletin 147 (Washington, D.C.: Dec. 2015).

Figure 14: **Example of corn residue left after a harvest in California to protect the soil**

Source: GAO. | GAO-20-128SP

Figure 15: **Example of no-till planting of soybeans into the previous year's corn residue**

Source: Courtesy of USDA-NRCS, Iowa. | GAO-20-128SP

Cropping practices

Cropping practices, such as crop rotation and cover crops, can be beneficial for soil health, which in turn can lead to water conservation, by keeping the soil more protected for a greater portion of the year from erosion, weeds, and soil compaction. Crop rotations are planned sequences of crops that change over time on the same field, according to USDA. Rotating crops provides productivity benefits by improving soil nutrient levels and breaking crop pest cycles and may be economically advantageous to the farmer by reducing their production risk through diversification. According to a USDA report, conservation crop rotation is a sequence of crops on the same field for the purpose of supporting soil health, conserving natural resources, and improving environmental outcomes from farming. Specifically, the report defines a conservation rotation to include at least one high-residue crop (e.g., corn), at least one low-nitrogen crop (e.g., grass or legume), and as attaining a threshold level of average annual residue.

Cover crops can improve soil health, recycle nutrients, and reduce weeds, among other things. Cover crops can be grown during fallow periods or simultaneously with the main crop. However, some disadvantages to using cover crops are reduced soil moisture, not all cover is compatible with the main crop, and the additional costs involved in maintaining them. According to a USDA report, approximately 4 percent of farmers adopted cover crops on some portion of their fields, which amounted to 1.7 percent of cropland (6.8 million acres) in 2010-2011.[66] It

[66]U.S. Department of Agriculture, Economic Research Service, *Conservation-Practice Adoption Rates Vary Widely by Crop and Region*, Economic Information Bulletin 147 (Washington, D.C.: Dec. 2015).

also suggested that benefits may also be realized more quickly if cropping practices are adopted with no-till or strip-till systems, but multi-practice adoption is used only on a few acres. According to a USDA official, it is typical for those farmers who use cover crops to use three to four different types of plants, while others opt for up to 10 different types of cover crops to maximize diversity.

Soil conditioner

One soil conditioner that could increase water conservation in irrigated furrows is polyacrylamide. The application of polyacrylamide, commonly called "PAM," is a practice that can reduce soil erosion and improve water infiltration. PAM is a synthetic, water-soluble polymer composed of molecules of acrylamide, which binds soil particles together and reduces the negative effects that tillage and cultivation can have on soil. PAM has many forms and application techniques that make it suitable for use for repeated applications once it is setup in an irrigation operation. According to the Oregon State University Extension Service, PAM has been shown to reduce soil erosion by 90 to 95 percent when added to irrigation water. PAM may result in an increase in surface irrigation infiltration of up to 60 percent on fine-to-medium-textured soils, with 15 percent being typical on medium-textured soils, according to USDA, but application on coarse soils may actually decrease infiltration.

Other practices

A number of other practices can also facilitate or promote water conservation. These include land management practices, rain-fed or dryland farming, and on-farm or near-farm water conveyance improvements.

Land management practices

Land management practices can include changing the actual topography of the farmed land to increase uniformity of water applied to crops. For example, using furrow dikes—small earthen dams formed between furrow ridges of agricultural row crops—can reduce runoff from the soil surface and increase infiltration of rain or irrigation water. Furrow dikes can complement conservation tillage season when they are installed in rows where the crop bedding has been prepared to enhance capture of rainwater or irrigation water. During periods of higher rainfall or irrigation use, furrow dikes may need to be reinstalled or maintained as necessary, or even removed where the additional moisture would be harmful to the crop.

Land leveling, another topography improvement that smooths land to a uniform slope or grade, increases the uniformity and efficiency of irrigation and infiltration across a field by increasing the amount of time water is on the soil surface. However, land leveling can have detrimental effects to soil health. For example, it can strip too much of the soil, which may be inadequate for root growth leading to unsatisfactory crop production, if the amount of leveling necessary is severe.

Rain-fed and dryland farming

Rain-fed and dryland farming are similar methods that avoid irrigating altogether and instead rely on local precipitation and maintaining soil moisture in order to grow crops. Rain-fed agriculture is used throughout the United States, even in areas with significant irrigation, but is most dominant in the eastern half of the country where precipitation exceeds 20 inches per year, according to an article by USDA researchers.[67] The article also describes how in some areas, like the Midwest, high precipitation combined with relatively high soil organic matter and limited internal drainage means subsurface or tile drainage needs to be used to remove excess water, which is detrimental to certain crops.

Dryland farming is a subtype of rain-fed farming used in areas where annual precipitation is less than the evapotranspiration potential, which also saves water because it does not require irrigation. Dryland farming relies on conserving soil moisture through a combination of tillage, surface protection, and drought-resistant crops. Dryland farming can result in successful yields for certain crops, such as cotton, sorghum, wine grapes and olives, but also has been used for other fruits and vegetables like melons and squashes. Crop yields from dryland farming vary season to season depending on the amount and timing of precipitation. Dryland farming can be significantly less costly than irrigated farming. However, the decision to convert to dryland farming needs to be considered carefully, because crop yields can often be lower and the risk of crop failure may be significantly higher. In addition, the amount of profit per acre of dryland is usually less than from irrigated land.

Water conveyance improvements

Conveyance improvement methods reduce water losses during delivery to the farm irrigation system. It can be thought of as a connected water delivery system where on-farm and off-farm water losses have similar causes and effects. For example, lining of ditches or canals or replacing open channels with pipes reduces or prevents water from infiltrating back into the ground or evaporative losses before it reaches the field. Open channels, such as irrigation canals and ditches can have significant seepage and evaporation losses. These losses reduce efficiency for the farmer, but not typically for a downstream user, unless that water loss is due to evaporation. Pipes can also be used for distribution within a field for sprinkler laterals, micro irrigation, and have gates when used for surface irrigation.

In areas with irrigation districts that distribute water to their users, water delivery systems can be managed in ways to better match delivery with application or consumption of the irrigation water. For example, irrigation districts that have the ability to store and regulate their water have the ability to time and more efficiently provide irrigation water, rather than just by when water is available, according to a Bureau of Reclamation

[67] Franzluebbers, Alan, Jean L. Steiner, Doug Karlen, Tim Griffin, Jeremy Singer, and Don Tanaka, "Chapter 20 Rainfed Farming Systems in the USA," in *Rainfed Farming Systems*, eds. Philip Tow, Ian Cooper, Ian Partridge, and Colin Birch (Netherlands: Springer, 2011), 511-560.

report.[68] Automation and supervisory control and data acquisition systems, or SCADA, have improved opportunities to control water delivery to when farmers want to irrigate as opposed to a schedule set by the irrigation district.[69] In addition, these control systems may be used to cease water withdrawals and irrigation when pressure is not sufficient at the delivery point so that water can be applied to the field at the targeted levels of efficiency and distribution uniformity. For example, some irrigation types, such as micro irrigation, may not be able to achieve the highest uniformity and application efficiency without sufficient and stable water pressure. Finally, these systems may be able to send data back to the irrigation district that could help evaluate the delivery service provided and a farmer's irrigation scheduling practice.[70]

[68]Agricultural Water Conservation, Productivity, and Transfers Workgroup, "Chapter 4 Agricultural Water Conservation, Productivity, and Transfers" In *Moving Forward Phase 1 Report,* (Bureau of Reclamation, May 2015).

[69]A supervisory control and data acquisition (SCADA) system is an industrial automation and control system that uses multiple software and hardware elements to monitor, gather, and process data; record events into a log file; and interact with and control external machines and devices such as valves, pumps, and motors. For water, a SCADA system allows for dynamic pressure management, where pressure sensors permanently installed at high and low points within each pressure zone in the distribution system collect and forward real time pressure data to control systems. Data are continuously analyzed, and when conditions fall outside normal operating parameters, operators are alerted and pressure-reducing valves or pumping rates, for example, are remotely adjusted to normalize the pressure.

[70] Levidow, Les, Daniele Zaccaria, Rodrigo Maia, Eduardo Vivas, Mladen Todorovic, Alessandra Scardigno, "Improving water-efficient irrigation: Prospects and difficulties of innovative practices," *Agricultural Water Management*, vol. 146 (2014): p. 84-94.

2.3 Using precision agriculture technologies may help optimize irrigation scheduling and reduce over-irrigating

Precision agriculture technologies provide data to perform advanced irrigation scheduling that may help optimize irrigation scheduling and reduce over-irrigating. According to USDA, precision agriculture, as applied to crop production, is also known as site-specific crop management. It uses a variety of technologies, especially those that are GPS-enabled, to manage different parts of a field separately, tailoring the application of irrigation water, fertilizer, and pesticides, among other things. Over-irrigating is a problem nationally, according to USDA officials, because water is generally cheap and thus farmers may err on the side of more, rather than an optimal amount of irrigation water.[71]

In addition, following a scientifically-based irrigation strategy requires more time and effort on the part of the farmer. The natural, inherent variability within fields meant that mechanized farming could traditionally apply only crop treatments, such as irrigation water, for "average" soil, nutrient, moisture, weed, and growth conditions. Some newer technologies and practices give the farmer more control and a better understanding of the amount of water needed and when and where to apply it to avoid over-irrigating their

[71] We have heard the phrases used to describe this as, "if one drop is good, then two drops is probably better" and "when in doubt irrigate."

fields with potentially less time and effort than in the past. More broadly, these technologies fall under a larger category of technologies referred to as precision agriculture.

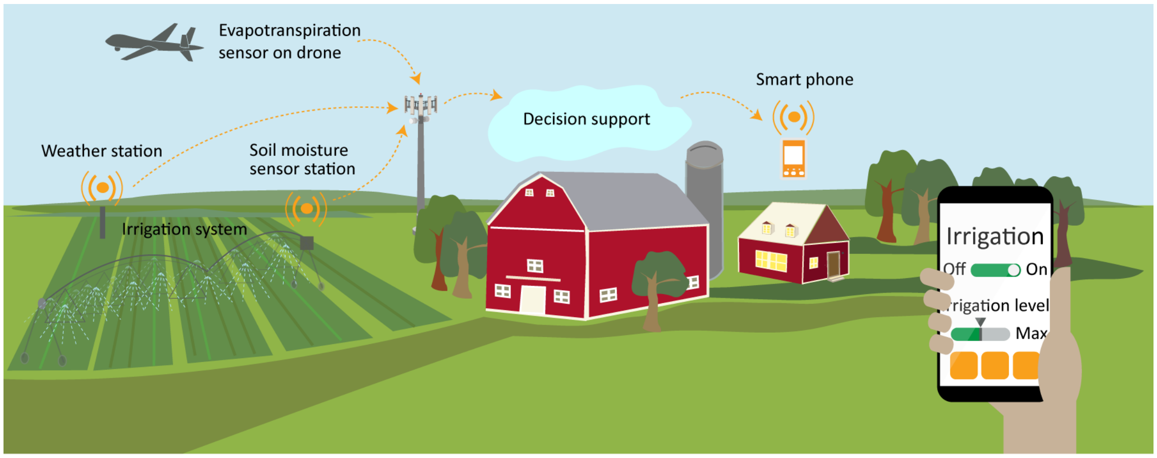
All farmers who use irrigation schedule their irrigation activities, to one degree or another. According to USDA FRIS data, the decision to irrigate may be made by experience-based means—such as a personal calendar, a water delivery schedule, observing when neighboring fields are irrigated, physical feel of the soil, and visual and physical inspection of crop condition—to more science- and technology-based means—such as computer simulation, soil moisture sensor data, an irrigation scheduling service, and plant moisture sensor data. These latter methods, which can be part of a precision agriculture system, provide data for advanced irrigation scheduling. According to experts at our meeting, farmers want to know when and how much to irrigate. However, fewer than 10 percent of farmers surveyed in the 2013 FRIS use soil or plant moisture sensing devices or commercial irrigation scheduling services. Furthermore, fewer than 2 percent made use of computer-based simulation models to determine irrigation requirements, such as models based on consumptive use needs by crop growth stage under local weather conditions. According to our analysis of FRIS data, the use of advanced irrigation scheduling methods has increased about 27 percent since 2003. If more farmers switched to advanced irrigation scheduling methods enabled by precision agriculture, it could reduce the amount of water applied to a field by integrating a variety of data that inform and optimize when to irrigate, how much water to apply, and where to apply it.

Because this report is focused on water, we discuss technologies that typically would be integrated into a system of technologies for data collection, decision support, and finally water application. Generally speaking, most precision agriculture technologies currently use precise GPS combined with location-specific measurements—either in-field data collection (such as soil variables) or remotely sensed data (such as from aircraft or satellites)—to quantify spatially variable field conditions. Within-field operations adjust water applications based on spatially referenced management decisions recorded on maps of management zones. Precision agriculture technologies are being developed that can sense microsite-specific conditions in real time and can automatically adjust applications to meet each site's unique needs (such as variable rate irrigation). These latter types of technologies require no previously collected spatial information, but rely, instead, on the ability to simultaneously measure soil or plant conditions and to effect applications.

Precision agriculture technologies can support irrigation scheduling in four general ways: (1) data collection, (2) decision support, (3) water application and (4) connectivity, see figure 17.

Figure 16: Components of a Precision Agriculture System

Weather, soil moisture, and evapotranspiration data are collected and sent remotely to a decision support system, which then provides actionable information to the farmer.



Source: GAO. | GAO-20-128SP

Data collection

In order for farmers to make a decision to water their crops, data from a variety of tools, such as soil moisture sensors, may be used. Some examples of these technologies are given below.

Soil moisture sensors. According to our analysis of 2013 FRIS data, over 75 percent of farms with irrigated land still used visual inspection of the crop as a method of deciding when to irrigate. In comparison, only about 12 percent of farms used a moisture sensing device as a method of deciding when to irrigate. Based on our site observation, a more traditional method of feeling the soil by taking a soil sample (see fig. 18) to check the moisture level can be labor intensive. However, a farmer told us it can also be labor intensive to use soil moisture sensors that are not remotely accessible due to the distance and time necessary to collect their data.

Experts at our meeting acknowledged the benefits of using soil moisture sensors and noted that although their use may not be widespread it is rapidly growing. According to our analysis of FRIS data between 2003 and 2013, the number of farms using a soil moisture sensing device grew by approximately 45 percent. Furthermore, soil moisture sensing devices were the second fastest growing method of irrigation decision-making from 2003 to 2013, only behind using computer simulation models.

There are some challenges to using these devices. For example, placement of the sensor can be important for the accuracy of the information provided. During one site visit, we learned that placing probes in depressions or swales, where the water tends to collect, can skew the results, as it is not representative of the general area.

Figure 17: Soil sampled with a hand held soil probe to check the soil moisture

Source: GAO.| GAO-20-128SP

Evapotranspiration measurement. Evapotranspiration is the sum of evaporation from the ground surface and plant transpiration of water. Remote sensing of evapotranspiration allows estimates of in-season irrigation management, water resource allocation, and yield estimation, among other things. There are a variety of instruments that measure evapotranspiration, such as lysimeters, neutron probes and remote sensors on satellites and aircraft, including drones. Data from these methods can be used to model evapotranspiration, which is an estimate of crop water use at field and regional scales. A farmer at one site told us that aerial imagery of evapotranspiration is good for showing long-term changes in yield across the field. An expert at our meeting told us that while early season irrigation scheduling can be done using a soil moisture probe, evapotranspiration may be better for measuring crop stress later in the season.

Weather stations. Farmers that we visited relied on weather stations to provide additional information about rainfall in order to schedule their irrigations (see fig. 19). Real-time weather data can provide humidity, temperature, and other values that affect evapotranspiration rates. Some commercially available weather stations can connect via telemetry or cellular service to transmit their data.

Figure 18: Wireless weather station at a farm in Nebraska

Source: GAO. | GAO-20-128SP

Decision support

Once information is collected from data sources or sensors, it can be combined with other information within a decision support system on a smartphone or computer. The final output of such a system is an actionable recommendation or prescription, interpretation, or prediction for the farmer regarding the situation of interest, such as when to irrigate and how much. According to experts at our meeting, some experts think decision support systems are too complex, while others think they generally exist to help the farmer make faster and easier decisions.

Some of these systems even allow information to be displayed and changes to be made remotely from a smartphone or computer. For example, we visited farmers who demonstrated applications that showed when a field had last been irrigated and how much, real-time weather reports, and recommendations on when and how much to irrigate. However, although industry is working to provide products that can make it easier for farmers to use data, some farmers and experts at our meeting told us in some cases there is too much extraneous information, and farmers do not know what action they should take based on the information given. In other cases according to experts at the meeting, information from service providers may not be in useable form (e.g., give them something easy like actual evapotranspiration in the field or a red-yellow-green visual cue on a map). In addition, data may not be standardized. For example, companies can use the same soil moisture probes but use different algorithms to project crop water use, which can make synthesis at the field-level difficult and the moisture reading of the same probe in two kinds of soils can mean different things. For example, when reading a probe the farmer should use the calibration curve for the type of soil in the field in order to know the amount of irrigation water to apply.

Water application

Once data have been collected, an actionable recommendation is provided to the farmer. If the farmer decides to follow that recommendation, additional precision agriculture technologies, which allow remote control of farm equipment, such as pivot controls, and variable rate irrigation, give them more control over water application on their farms. Some of those controlling technologies are given below.

Remote pivot controls. Remote pivot controls give a farmer the ability to direct irrigation systems using their smartphone, tablet, or computer rather than driving out to the fields and adjusting their systems manually (see fig. 20). For example, these controls give farmers the ability to start and stop pivots, to adjust pivot speeds, as well as to monitor the system’s location. Some systems can also alert farmers through email or text message if a pivot shuts off unexpectedly or experiences a technical issue.

Figure 19: Example of the equipment on a center pivot that allows it to be remote controlled

Source: GAO. | GAO-20-128SP

Variable Rate Technology (or Variable Rate Irrigation). Similarly, variable rate technology allows farmers to prescribe different watering intervals or amounts for different zones of their crop fields to improve irrigation efficiency by using GPS location.[72] For example, farmers can program a pivot to pulse on and off rather than watering crops continuously, or by speeding up the pivot on areas of a field that do not need as much water so they are not over-irrigating.[73] Farmers whose soil conditions vary within fields can use variable rate technology to apply water at different rates based on soil type rather than apply water uniformly. This can prevent over- and under-watering different areas of the field. For example, one site we visited in California used two different irrigation schedules based on soil type ("light" and "heavy"), where light soils receive six 4-hour irrigations per week and heavy soils receive two 12-hour duration irrigations per week.

Although use has increased substantially since 2004, wheat and corn had relatively low percentages of acres grown using variable rate technology, according to a USDA report using Agricultural Resource Management Survey (ARMS) data. For example, variable rate technology was used on approximately 5 percent of corn acres in 2005, approximately 10 percent in 2010, and approximately 28 percent in 2016.[74] In comparison, variable rate technology was applied to approximately 7 percent of wheat acres in 2004, and approximately 11 percent in 2009.

Broadband connectivity

While not specifically a precision agriculture technology, broadband is essential to facilitating connectivity between technologies, such as soil moisture probes, weather stations, and decision support systems.[75] According to the American Farm Bureau Federation, many precision agriculture techniques require broadband connections for data collection and analysis performed both on the farm and in remote data centers, which allow farmers to make

[72] Variable rate technology also allows farmers to customize the application of fertilizer, seeds, and pesticides.

[73] Farmers can also slow down the pivot to allow more irrigation on areas of a field that need more water.

[74] U.S. Department of Agriculture, Office of the Chief Economist, *Agricultural Conservation on Working Lands: Trends From 2004 to Present*, Technical Bulletin Number 1950 (Washington, D.C.: Nov. 2018).

[75] The term "broadband" commonly refers to Internet access that is high speed and provides an "always-on" connection, so users do not have to reestablish a connection each time they access the Internet. Broadband infrastructure may include burying fiber-optic or copper cables, stringing cable on existing poles, or erecting towers for wireless microwave links, which relay wireless Internet connections from tower to tower.

decisions about, among other things, how much water is needed for their crops. Farmers and experts at our meeting told us that for precision agriculture systems basic broadband connectivity can be a problem, is too slow for farmers' data collection needs, or is less affordable. In fact, one expert at our meeting paid for their own broadband in order to remotely access data, such as weather station and soil moisture probes, because they are more labor intensive to use without this connectivity.

Similarly, in 2017, we found that spectrum congestion and interference could slow Internet of Things growth, in areas such as precision agriculture, unless the Federal Communications Commission (FCC) makes additional efforts to assess the risks to effective spectrum management by focusing on high-bandwidth and unlicensed-spectrum devices.[76] In 2018, we reported on the federal programs that support increasing broadband deployment in rural and unserved areas.[77] For example, the FCC is responsible for implementing Universal Service Fund programs, one of which, the Connect America Fund, we reported, provides approximately $4.5 billion annually to support broadband service in underserved and unserved areas. Another program we reported on is the Rural Utilities Service's (a component agency of USDA) Community Connect Grant Program, which provides grant funding to improve broadband service.

Despite these programs, the gap in broadband availability is notable between rural and urban areas, where about 31 percent of Americans in rural areas lack access to fixed (terrestrial) 25 megabits per second (Mbps)/3 Mbps broadband, which their precision agriculture devices need, as compared to only about 2 percent of Americans in urban areas that lack this access, according to the FCC 2018 Broadband Deployment Report.[78] The FCC also reported in 2017 that while about 99 percent of the rural population by census block is covered by at least one provider of mobile broadband, it is only about 70 percent of total rural square miles.[79] However, the situation in rural America could be worse than these figures suggest, as GAO reported in 2018 that the FCC's method of collecting broadband availability data overstates access in less populated areas.[80]

According to USDA officials, some of their financial support for precision agriculture and

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[76] GAO, *Internet of Things: FCC Should Track Growth to Ensure Sufficient Spectrum Remains Available*, GAO-18-71 (Washington, D.C.: Nov. 16, 2017).

The Internet of Things generally refers to connected devices (or "things") that use a network to communicate with one another and process data.

[77] GAO, *Tribal Broadband: Few Partnerships Exist and the Rural Utilities Service Needs to Identify and Address Any Funding Barriers Tribes Face*, GAO-18-682 (Washington, D.C., Sep. 28, 2018).

[78] FCC, *Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion,* 33 FCC Rcd 1660 (2018) (2018 Broadband Deployment Report).The Federal Communications Commission set a speed benchmark for high speed broadband as meeting or exceeding 25 Megabits per second download and 3 Megabits per second upload.

[79] For the purposes of this report, mobile broadband refers to long-term evolution (LTE) services. LTE is an industry standard that is part of the fourth generation (4G) of wireless telecommunications technology.

[80] GAO, *Broadband Internet: FCC's Data Overstate Access on Tribal Lands*, GAO-18-630 (Washington, D.C.: Sep. 7, 2018).

water management goes toward telemetry, satellite, or cellular technology that support data gathering of remote field data or control their center pivots for example. These officials noted that this support is not intended to upgrade the whole farm or farmstead. Therefore, the ability to use precision agriculture technologies may still be limited by lack of access to broadband and cellular service, among other things. However, only 47 percent of surveyed farmers used computers as part of their farm business, even though 73 percent have computer access, according to USDA's Farm Computer Usage and Ownership report in 2017. In addition, 39 percent of farmers reported using a tablet or smartphone for farm business. However, the survey did not specifically ask whether lack of access affected whether farmers chose to use computers, smartphones or tablets for farm business, such as precision agriculture activities.

3 Farmers adopt and use efficient irrigation technology primarily to increase profits and reduce risks, but many factors can influence a farmer's decision to adopt

Since one of the primary objectives of a commercial farm is to maximize profits, the decision of whether to adopt efficient irrigation and irrigation-related precision agriculture technology depends in large part on whether the expected benefits from the new technology outweigh the anticipated costs, relative to the production system currently in use. Higher profits can be achieved through lower input costs—such as water, energy, or labor—and/or increasing revenue from higher crop yields or prices, as well as extending the land which can profitably grow crops. USDA FRIS data show that irrigation costs have generally increased over the 15 year period, from 1998 through 2013 while data on yields vary according to location and types of irrigated agriculture. The adoption of more efficient irrigation technology can reduce a farmer's risk through adjusting to adverse weather and soil conditions in certain locations, leading to more stable year-to-year crop yields and revenues.[81]

Factors influencing farmers' adoption of irrigation technology include economic factors and farm size, locational factors such as soil quality and climate, type of crop grown, demographic factors, and institutional factors. Barriers to adoption can include small farm size, cost of installation of irrigation equipment, and a lack of knowledge about these irrigation alternatives. Studies and data show that farmer adoption of irrigation-related precision agriculture equipment is similarly hindered by many barriers, including high capital and maintenance costs, a lack of expertise to set up and maintain decision support software, and few research and education programs, among others things.

Rates of adoption of irrigation systems that boost water efficiency have increased over the period from 1998 through 2013 in the western U.S. with rates increasing for sprinklers and micro-irrigation. The adoption of major irrigation technologies also varied significantly across regions of the country and across types of irrigation technologies during this period with the highest numbers of adoption taking place in the Pacific with micro irrigation and the Mountains and Plains regions of the country with sprinkler irrigation. The numbers of new gravity irrigation systems however has decreased over this period in all regions.

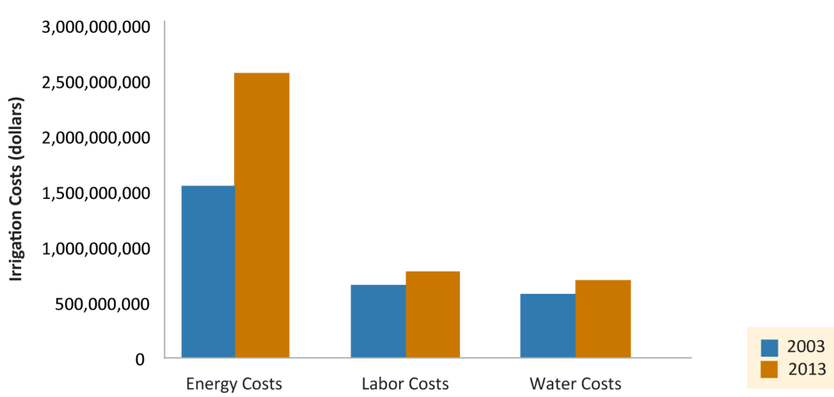
[81] For purposes of the irrigation adoption analysis, of the three major irrigation systems in general, we define gravity systems as the least efficient, sprinklers systems are considered more efficient, and micro irrigation systems are the most efficient. As well, irrigation-related precision agriculture technology is designed to optimize a farmer's decision-making regarding irrigation events.

3.1 Farmers adopt and use efficient irrigation technology primarily to increase profits and reduce risks

Farmers' economic rationale for adopting new irrigation technology is generally to maximize profits over a certain area of land and period of time. In general, the economics literature indicates that efficient irrigation technology is typically adopted to decrease water and energy costs, particularly for groundwater irrigation, and to increase revenues through higher and more stable crop yields or higher-value crops. The maximization of profits includes the present value of future revenues from the irrigation technology less any capital and variable costs related to implementing and using the technology. Profitability varies when economic cost factors vary, such as from water, energy, and labor. For instance, farmers who irrigate using groundwater would be affected when pumping costs or energy costs increase. In addition, when certain water or other input prices rise, farmers often invest in more expensive but more efficient irrigation technologies to reduce the cost of these inputs. Moreover, higher irrigation expenditures can be associated with the purchase of some efficient irrigation technologies, such as center-pivot or sub-surface drip irrigation systems.

We used the USDA FRIS data from 1998 through 2013 to examine recent trends in farmer irrigated costs for various types of irrigation. According to FRIS data, farmers' total irrigation costs, including irrigation equipment, energy, labor, and water costs have doubled from about \$3.2 billion to \$6.4 billion. As shown in figure 1, besides the capital cost of irrigation equipment, the largest part of these costs, energy, has gone from over \$1.5 billion to over \$2.5 billion from 2003 to 2013. The next largest, labor costs have risen from \$656 million to about \$778 million (see fig. 21).

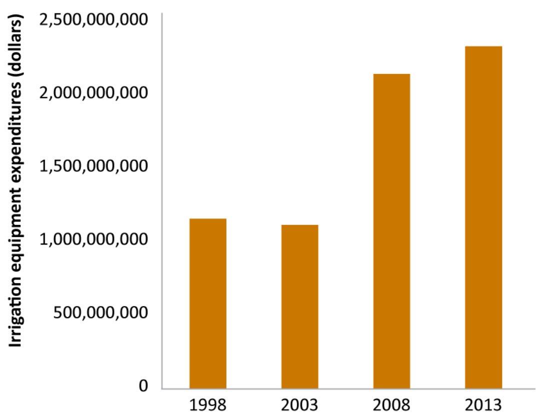
Figure 20: Farmers' irrigation costs for water, energy, and labor have increased from 2003 to 2013



Source: GAO analysis of USDA data from the Farm and Ranch Irrigation Survey. | GAO-20-128SP

As can be seen in figure 22, from 1998 through 2013, total irrigation equipment expenditures and capital costs have increased from about $1.2 billion to $2.3 billion. The major increase in irrigated acres has been from micro-irrigation (133 percent) and high-and-low-pressure center pivot irrigation (74 and 48 percent, respectively).

Figure 21: Farmers have increased total expenditures on irrigation equipment from 1998 through 2013



Source: GAO analysis of USDA data from the Farm and Ranch Irrigation Survey. | GAO-20-128SP

Farm crop revenue, the product of market price, crop yield, and harvested acreage, can also increase when a farmer begins using irrigation for the first time or updates to a more efficient irrigation technology. For instance, adopting drip irrigation has been shown to increase crop yields for a certain land area. Also, more efficient irrigation methods may make it possible to cultivate and produce on lower-quality lands, increasing the irrigated land base and increasing farm revenue. We used 2012 and 2017 Census of Agriculture data to illustrate differences in nationwide average yields for major crops between irrigated, partially irrigated, and non-irrigated agriculture (see table 4). As shown from these data, farms that grew crops that were partially and/or totally irrigated generally had higher crop yields per acre on average than farms that grew crops without any irrigation.

Table 4: National average crop yields for major crops, by irrigation level: entire crop irrigated, partially irrigated, and non-irrigated, 2012 and 2017

	Yield/Acre					
	Entire crop irrigated		Part of crop irrigated		Non-irrigated	
Crop (yield as measured in)	2017	2012	2017	2012	2017	2012
Barley (bushels (bu)/ acre)	110.6	100.7	75.2	58.1	56.2	55.8
Corn, grain (bu/acre)	193	171.1	175.3	129.4	172.7	111.1
Corn, silage (tons/acre)	25.6	23.8	20.6	15.8	17.8	13.5
Cotton (bales/acre)	2.3	2.3	1.7	1.6	1.7	1.6
Cotton, upland (bales/acre)	2.3	2.2	1.7	1.6	1.7	1.6
Cotton, pima (bales/acre)	2.7	3.1				
Beans, dry edible (hundredweight/acre)	25		21.7		19.2	
Oats (bu/acre)	77.2	87.1	66.2	66.2	61.2	59.4
Peanuts (pounds/acre)	4,147.50	4,362	4,116.20	4,347.70	3,806.90	3,875.10
Rice (hundredweight/acre)	73.6	74.3				
Sorghum, grain (bu/acre)	86.5	80.7	76.4	56.3	68.5	47.7
Soybeans (bu/acre)	56.3	49.4	52.3	41	47.3	37.6
Sugar beets (tons/acre)	35.5	32.8	28.5	28.2	28.6	26.2
Sugarcane (tons/acre)	40.7	35.7	(D)	35.1	(D)	34.7
Tobacco (pounds/acre)	2,393.70	2,616.10	2,238	2,372.10	2,121.90	2,153.80
Wheat (bu/acre)	88.2	81.8	52.4	43	43.8	42.9
Wheat, winter (bu/acre)	84.1	76.8	52.1	42.7	47.4	44.3
Wheat, spring, durum (bu/acre)	93.3	96	49	36.6	22.8	32.9
Wheat, spring (excl durum), (bu/acre)	94.2	89.1	52.1	43	39.9	40.8
Hay, alfalfa (aons/acre)	4.6	4.6	3	3.1	2.3	2.2
Hay, (excl alfalfa) (tons/acre)	2.5		2.2		1.9	
Haylage, alfalfa (tons/acre)	6.6	7.5	8.2	7.3	7	6.4
Haylage, (excl alfalfa) (tons/acre)	9.9	10.7	8.2	7.6	4	4.1

Source: GAO analysis using data from the 2017 Census of Agriculture, Chapter 1, Table 34 | GAO-20-128SP

Note: Certain crops such as rice and pima cotton are mostly irrigated and so have no non-irrigated or partially irrigated acreage. Values represented by (D) signify that there are disclosure issues associated with this crop.

In addition, the value of irrigated cropland is generally higher than non-irrigated cropland. First, because increased farm revenues, productivity, and expected profitability are capitalized into asset land values, farm land values of irrigated acres are generally higher than non-irrigated land values. Second, land value has been shown to be a factor that is positively and significantly related to the adoption of irrigation technology. Studies have found that permanent improvements to land, such as irrigation, increase asset land values.[82] Therefore, higher farm asset values provide a motivation for and are a result of irrigation adoption. Table 2 shows regional USDA survey data for average cropland values in dollars per acre between irrigated and non-irrigated cropland for 2016, 2017 and 2018.[83]

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[82] Xu, Feng, Ron C. Mittelhammer, and Paul W. Barkley "Measuring the Contributions of Site Characteristics to the Value of Agricultural Land," *Land Economics*, Vol. 69, No. 4, Nov., 1993; Shoemaker, Robbin, *How Technological Progress and Government Programs Influence Agricultural Land Values*, Economic Research Service, USDA, AIB# 582, January 1990; and Huang, Haixao, Gay Y. Miller, Bruce J. Sherrick, and Miguel J. Gomez, "Factors Influencing Illinois Farmland Values," *American Journal of Agricultural Economics,* Vol. 88, No. 2 (May, 2006).

[83] The survey methodology for these land values are based on an annual survey, the June Area Survey, conducted during the first 2 weeks of June and uses a complete, probability-based land-area sampling frame. Enumerators collecting data for the June Area Survey contact all agricultural producers operating land within the boundaries of the sampled land segments and record land value information for cropland and pasture within these segments. The regional and United States estimates are weighted by the amount of cropland and pasture in each state, based on the most recent Census of Agriculture.

Table 5: Cropland values for irrigated and non-irrigated land by regions, 2016, 2017, and 2018[a]

	2018		2017		2016	
U.S. Regions[b]	Irrigated $/acre	Non-irrigated $/acre	Irrigated $/acre	Non-irrigated $/acre	Irrigated $/acre	Non-irrigated $/acre
Corn Belt	4,770	3,380	4,940	3,450	4,830	3,470
Delta States	3,270	2,510	3,190	2,440	3,090	2,380
Mountain	4,610	1,060	4,460	1,040	4,360	1,020
Northern Plains	5,140	2,670	5,190	2,680	5,520	2,840
Pacific	12,150	2,250	11,740	2,200	11,290	2,080
Southeast	6,410	3,990	6,140	4,090	6,040	4,080
Southern Plains	2,140	1,770	2,010	1,750	1,920	1,680

Source: GAO analysis of USDA National Agricultural Statistics Service survey data for regional cropland values, 2016, 2017, and 2018. | GAO-20-128SP

[a] Cropland value is the value of land used to grow field crops, vegetables, or land harvested for hay. Irrigated cropland value is the value of land that normally receives or has the potential to receive water by artificial means to supplement natural rainfall. It may consist of both land that will be irrigated or land that will not be irrigated in the current year, but still has the facilities and equipment to do so. Non-irrigated cropland value is the value of land that only receives water from natural rainfall.

[b] Data for these regions only include states with significant irrigated acreage, specifically: 1) the Cornbelt region: Missouri; 2) Delta states: Arkansas, Louisiana, and Mississippi; 3) the Mountain region: Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming; 4) the Northern Plains region: Kansas, Nebraska, and South Dakota; 5) the Pacific region: California, Oregon, and Washington; 6) the Southeast region: Florida and Georgia; and 7) the Southern Plains region: Oklahoma and Texas.

Farmers also adopt more efficient irrigation technology to mitigate production risks and to obtain higher and more stable crop yields. USDA has stated that although farmers suffer from other risks such as flooding, pests, and early frosts, adverse weather risk such as drought is the most significant national driver of risk in production agriculture.[84] Drought risk can affect crop yield, acreage harvested, and farm income. For example, California and some of the other western states suffered multi-year drought conditions affecting agriculture in 1987-1993, 2002-2004, 2007-2009, and 2012-2016. One method that farmers have to provide more useable water to crops under drought conditions is to invest in more efficient irrigation equipment. Investment in high-efficiency irrigation systems, such as LEPA, or micro-irrigation, generally reduces water loss to evaporation or runoff. Advanced irrigation systems can also compensate for production risks due to adverse soil and field conditions such as overly sandy soil, soil with low water holding capacities, or surface soil slope. In addition, farmers have different risk tolerances for the adoption of new irrigation technologies. Some farmers may have perceptions of increased risk from new technologies which may inhibit adoption, although this uncertainty may decline with learning and experience, leading

[84] Wallander, Steven, Elizabeth Marshall, and Marcel Aillery, “Farmers Employ Strategies to Reduce Risk of Drought Damages,” *Amber Waves*, Economic Research Service, USDA, June 5, 2017

to increased adoption. Overall, those farmers with higher risk tolerance may also be the ones that are early adopters of new technology.

3.2 Factors influencing farmer adoption of efficient irrigation technology include economics and farm Size, location, crop choice, demographics, and institutional factors

We reviewed the agricultural economics literature primarily from 2000 to the present on factors leading to the adoption of more efficient irrigation technology and irrigation-related precision agriculture. Specifically, we identified 23 studies which looked at domestic U.S. irrigation technology adoption, of which we included 21in our review. We also reviewed and included 13 that examined domestic irrigation-related precision agriculture technology adoption. In general, while a certain technology may potentially be profitable for all farmers, technology adoption reflects an individual farmer's adoption behavior, or why one farmer decides to adopt a new technology while another does not.

As shown in table 6, we organized the factors leading to irrigation-related technology adoption into five major categories:

- Farm revenues, expenses, and size
- Locational and physical attributes
- Crop choice
- Demographic
- Institutional factors.

The studies supporting this table all contain economic analyses of at least one or a combination of these factors. See app. III for a complete list of the economic studies reviewed including which crops, locations, and irrigation and precision agriculture adoption technologies examined.

Table 6: Factors leading to adoption of irrigation-related and precision agriculture technology and relationship to adoption

Adoption factor	Sub-category	Relationship to Adoption
Farm Revenues, Expenses, and Size	Output price	Output or crop price is generally positively related to irrigation technology adoption.
	Expenses	Water costs, energy, and labor, as well as implementation of improved irrigation, are positively related to greater technology adoption. However, drip labor costs go down upon adoption.
	Farm Size	Farm size is a major determinant of technology adoption, although this depends on how size is defined. Larger farm size is highly related to the adoption of new irrigation and precision irrigation technologies.
Location and Physical Attributes	Land quality/physical attributes of the soil	Farmers with fields having lower land quality are more likely to adopt irrigation innovations. Farms with certain soil attributes, such as permeability and steep field slope, are correlated with new and upgraded irrigation technology adoption.

Adoption factor	Sub-category	Relationship to Adoption
	Source of water-surface water and groundwater	Farms relying on groundwater are more likely to adopt irrigation equipment than those with surface water. Farms using deeper wells for groundwater are more likely to adopt irrigation technology.
	Climate and weather	Several studies incorporated the influence of drought, climate risk, and climate change. They found that climate risk and recent climate events played an important role in increasing adoption. Certain types of irrigation are better suited to certain climates.
	Access to Information	Access to information, either through neighbors, extension services, or manufacturers, plays a role in a farmer's decision to adopt. Access to information plays a vital role for adoption of precision agriculture.
Crop Choice[a]	Adoption decision	Crop choice is an important driver of whether a farmer will update or adopt more efficient irrigation. The adoption of irrigation equipment, such as center pivot in Nebraska in the 1960s made it possible for farmers to switch to more water-sensitive crops, such as corn and soybeans.
	Crop type	Irrigation innovations are less likely adopted for lower-valued crops like hay or pasture. Special furrow techniques are more suited to row crops, such as corn but drip irrigation is widely adopted for cotton. Sub-surface drip has been adopted for crops needing precise water and nutrients, i.e., high-value crops like fruits and vegetables.
Demographic	Age of farmer	For irrigation technology adoption, older age or fewer years to retirement reduces the probability of adoption possibly due to a shorter payback period. However, for the adoption of precision agriculture, the picture is more mixed. Some studies show technology adoption negatively associated with age, while others show no significant relationship between age and adoption.
	Level of Farmer Education/Experience	More years of education is assumed to increase the probability of adoption. However, studies are mixed as far as the effect of level of experience on technology adoption
	Level and Source of Farmer Income	Higher net farm income was a positive predictor of whether a farmer would expand irrigation or adopt new irrigation technology. On-farm and off-farm income are both important factors in technology adoption, especially for precision agriculture.
Institutional	Land Tenure[b]	While some earlier studies found land tenure to be a significant driver of technology adoption, other findings were more mixed and depended on the nature of the technology.[c] Land ownership has been widely believed to be positively related to technology related to land such as irrigation. For tenants, adoption depended on whether the innovation was tied to the land and if benefits due to the innovation accrued to them.

Adoption factor	Sub-category	Relationship to Adoption
	Access to Credit	Earlier studies (1982, 1993, and 1999) found that a lack of credit availability was a factor in constraining adoption, although it depended on the type of technology.[d] Studies also confirmed that larger farms were more likely to have greater access to credit for capital investments, such as irrigation. As well, precision agriculture investments require capital intensive technology which could be limited by credit constraints.
	Water Rights[e]	Junior holders[f] of surface water rights with water supply uncertainty may be reluctant to invest in improved technologies. Reducing water rights of Senior holders may limit rebound effects of new irrigation technologies without reducing the incentives to adopt them.
	Farm Policy	Farm programs like EQIP and CSP have had a large impact on total irrigation investments. Also, it is assumed that farmers who participated in these cost-share programs are more likely to adopt precision agriculture technology.

Source: GAO summary analysis of irrigation and precision agriculture adoption factors from various articles identified in the agricultural economics literature. For the full list of articles reviewed, including the full citations and the type of irrigation technology, crops included, and region of the country see appendix III. See appendix I, the OSM, for our selection criteria and review methodology. | GAO-20-128SP

[a] USDA notes that crop choice and technology are often thought of as joint decisions and many of the factors listed in this table, such as land quality and water rights, likely drive the joint adoption decision.

[b] According to the Food and Agriculture Organization of the United Nations (FAO), land tenure refers to the laws, rules, and customs regarding the use, control, and transfer of land, including methods of gaining access to land and the associated arrangements. In agriculture, there are several types of interconnections between operations and landownership: 1) full-owner operations, where all of the land in the operation is owned by the operator; 2) full tenant operations -- farm operations in which all of the land is rented; and 3) part-owner operations – in which part of the land is owned by the operator and the remainder is rented.

[c] Jorge Fernandez-Cornejo et al. “Off-Farm Income, Technology Adoption, and Farm Economic Performance,” ERR #36, Economic Research Service, USDA, January 2007, p.18.

[d] For earlier studies, see Feder, Gershon, “Adoption of Interrelated Agricultural Innovations: Complementarity and the Impacts of Risk, Scale, and Credit,” *American Journal of Agricultural Economics*, Vol. 64, No. 1, Feb., 1982; Gershon Feder and Dina L. Umali, “The Adoption of Agricultural Innovations; A Review,” *Technological Forecasting and Social Change* Vol. 43, 215-239 (1993); David Sunding and David Zilberman, The Agricultural Innovation Process: Research and Technology Adoption in a Changing Agricultural Sector, for the *Handbook of Agricultural Economics*, 1999.

[e] Water rights are primarily state-created property rights. Tarlock, LAW OF WATER AND WATER RIGHTS AND RESOURCES, § 1.1 (West 2018).

[f] Under the prior appropriation doctrine, recognized in most of the western states, water rights are acquired by diverting water and applying it for a beneficial purpose. Colorado v. New Mexico, 459 U.S. 176, 179 n.4 (1982). A distinctive feature of the prior appropriation doctrine is the rule of priority, under which the relative rights of water users are ranked in the order of their seniority. Id.

As shown in table 6, economic considerations of the drivers of irrigation technology adoption included output price, input costs, and the size and structure of farms. One recent survey of the adoption of drip irrigation in California found that irrigation adoption increased with increasing output price and input prices.[85] Input costs such as for water and energy are in general positively related to the adoption of irrigation technologies. Our interviews with agricultural

[85] Taylor, Rebecca and David Zilberman, “Diffusion of Drip Irrigation: The Case of California,” *Applied Economic Perspectives and Policy* 39 (1) 2017.

irrigation experts verified this concept.[86] For example, one expert explained that farmers started to adopt center pivot irrigation mainly as a way to reduce labor, since the systems did not need to be manually moved. They adopted low pressure systems as another way to reduce energy costs, since dropping the pressure reduced energy usage. Another interview with the University of Nebraska Extension Service confirmed this effect, by noting that the adoption of low pressure systems also reduced energy consumption, with a reduction in costs.[87] These trends are driven by a gain in yield, a reduction in cost, and labor savings. Another common economic factor, in many of these studies, was that farm size was highly related to both irrigation adoption and irrigation-related precision agriculture adoption.[88] In addition, a report by USDA examined the relationship between off-farm income and technology adoption. They found that this relationship depended on managerial time, with managerially time-intensive innovations, such as yield monitors (an important component of precision agriculture), exhibiting a negative and statistically significant relationship to off-farm income.

Locational factors were among the most significant factors or drivers of technology adoption including: 1) land quality and physical attributes of the soil; 2) source of water, whether there was access to surface water or groundwater; 3) weather and climate; and 4) access to information. Many of these factors are directly related to where the farm is located. For example, a USDA expert explained that the High Plains has shifted away from gravity irrigation to center pivot, and are now starting to add drop nozzles and micro irrigation.[89] In California, farms went from gravity straight to micro-irrigation. Center pivot was not a good fit for California, according to this expert, since their soil is heavy, and their crops do not grow as well with center pivot. The Southeast has shifted from gravity to sprinklers, but most have adopted land leveling.

Certain types of irrigation equipment are better suited to the physical characteristics of the land or soil, water source, or specific types of climate. In studies we reviewed, land of lower quality (such as highly saline, sandy soils or soils with steeper slopes) was found to be a factor highly associated with the adoption of more efficient irrigation equipment. Studies cited that physical characteristics of the soil, such as soil permeability and slope, were found to be factors highly related to adoption.[90,91] In fact,

[86] Interview, NRCS, U.S. Department of Agriculture, December 2017.

[87] Interview, University of Nebraska Extension Service, University of Nebraska – Lincoln, North Platte, NE, July, 19 2018.

[88] For instance, see Skaggs (2001); Negri, Gollehon, and Aillery (2005); Shoengold and Sunding (2014); Schimmelpfennig, ERS/USDA, (2016); Frisvold and Bai (2016); and Schimmelpfennig and Ebel (2016), among others (full citations of these studies are in App. III, the technical appendix for the literature review of irrigation and precision agriculture technology adoption).

[89] Interview, Economic Research Service, US Department of Agriculture, October 3, 2017.

[90] For earlier articles incorporating the significance of soil attributes to technology adoption, see Negri, Donald H. and Douglas H. Brooks, "Determinants of Irrigation Technology Choice" *Western Journal of Agricultural Economics* Vol. 15, No.

irrigation technologies that improve the physical characteristics of the soil are called "land-quality augmenting" in this literature. Studies also cited proximity to a particular source of water supply as important in the adoption decision—for instance, farmers with groundwater sources of irrigation are much more likely to adopt efficient irrigation technology than farmers with surface water sources. Several recent studies found that weather, climate risk, climate change, and other factors that often depend upon farm location can be key determinants of a farmer's adoption decision. Results of these recent studies indicate that variability in natural precipitation and extreme climatic events often played a crucial role in a farmer's decision to adopt irrigation. For example, the adoption of sprinkler or drip irrigation was often made after periods of weather crisis, such as an extended drought.[92] Other studies show that irrigation adoption may be a significant factor in the adaptation to climate change. USDA notes that the efficiency of irrigation systems is particularly important in the arid West, where increases in competing demands and climate change impacts are expected to affect future water supplies.

Overall, access to information was one of the most vital factors cited in the literature for the adoption of irrigation technology or irrigation-related precision agriculture equipment. In studies we examined this information came from sources such as extension services, private manufacturers, or nearby neighbors.

Crop choice was another important driver of adoption, according to the studies we reviewed. Specific irrigation innovations are typically selected because they are better suited for the production of certain types of crops. For example, higher efficiency irrigation innovations are less likely adopted for lower-value crops, such as hay and pasture crops. Furrow irrigation and associated applications are more likely to be adopted for row crops, although center-pivot irrigation and low-energy precise application (LEPA) have also been adopted for corn and cotton in areas like Nebraska or the High Plains of Kansas and Texas. Micro-irrigation equipment is more likely to be adopted in those areas that produce higher-value crops, such as fruits and vegetables. In addition to the studies we reviewed, interviews with experts also confirmed the assessment that

2, December,1990; and Green, Gareth, David Sunding, David Zilberman, and Doug Parker "Explaining Irrigation Technology Choices: A Microparameter Approach" , *American Journal Agricultural Economics* Vol. 78, November 1996. For later studies on this topic see Mendelsohn and Dinar (2003); Moreno and Sunding (2005); Shoengold and Sunding (2014, precision agriculture); and Huang et al (2017) for permeability. For soil slope, see the same articles plus Schaible and Aillery, ERS, USDA (2012) and Frisvold and Bai (2016). Full citations for the later studies are listed in App. III, the technical appendix of the irrigation and precision agriculture adoption studies we reviewed.

[91] Soil permeability measures the rate at which water percolates or infiltrates into the soil. For example, irrigation technology such as sprinklers or drip, (higher efficiency irrigation) can distribute water more evenly and gradually, and are more suitable for crops grown on sandy, highly permeable soils (Moreno and Sunding, 2005).

[92] Taylor, Rebecca and David Zilberman, "Diffusion of Drip Irrigation: The Case of California" *Applied Economic Perspectives and Policy* 39 (1) 2017 or David Zilberman, Rebecca Taylor, Myung Eun Shim, and Ben Gordon, "How Politics and Economics Affect Irrigation and Conservation," *Choices*, 4th Quarter, 2017.

crop choice was an important factor in adoption.[93]

Demographic factors, such as a farmer's age, level of education, experience, and level of income, have all been found to significantly influence the adoption of newer irrigation technology. Factors such as advanced age or fewer years to a farmer's retirement tend to lead to lower farmer adoption rates of more efficient types of irrigation technology, while higher levels of education, experience, and income all tend to result in higher rates of farmer adoption of these technologies. Our interviews with experts also confirmed that more educated farmers are more likely to adopt more efficient irrigation technology.[94]

For adoption of irrigation-related precision agriculture, studies show that the relationship between operator age and the adoption of precision agriculture is not clear. Some show a negative relationship between a farmer's age and adoption, while others do not find a significant relationship between these two factors. The adoption of irrigation-related precision agriculture is also positively impacted by a farmer's level of education and income.

While institutional factors such as land tenure and credit availability have been included in studies of technology adoption for years,[95] and continue to be included, more recent studies incorporate other institutions such as water rights, water trading, and farm policy.. For example, as far as land tenure, technology adoption depends on whether the investment in technology is tied to the land and whether the benefits due to the innovation accrue to the farm owner or the tenant. Credit availability can be a major influence in constraining adoption, although the amount of constraint depends on the type and cost of the innovation. The actual impact of credit availability is often influenced by size of the farm, with larger farms having access to additional credit. Also, according to ARS, credit availability for irrigation improvements is different from credit availability for other farm operations. For example, farmers could find it easier to obtain credit for farm operations if they had irrigation in place and sometimes could not get credit or sufficient credit if irrigation was not in place.

Some studies that we examined found that institutions, such as farm policies and programs, can complement the adoption of more efficient irrigation technologies. Certain conservation farm programs, such as the EQIP provide financial assistance for covered irrigation activities. Awareness of cost-share

[93] However, the crop choice decision and irrigation adoption decision were modeled differently in various studies that we identified. In some studies, the crop choice and investment decision were assumed to be made sequentially while in other studies these decisions were assumed to be made and modeled jointly (See Green et al. (American Journal of Agricultural Economics, 1996) and Moreno and Sunding (American Journal of Agricultural Economics, 2005) in appendix X).

[94] Interview with Agricultural Research Service (ARS), USDA, December 11, 2017.

[95] For earlier studies, see Feder, Gershon, "Adoption of Interrelated Agricultural Innovations: Complementarity and the Impacts of Risk, Scale, and Credit, *American Journal of Agricultural Economics*, Vol. 43 (1), 1982; Gershon Feder and Dina L. Umali, "The Adoption of Agricultural Innovations: A Review" *Technological Forecasting and Social Change* .Vol. 43, 1993.

programs like EQIP is expected to increase acreage under newly adopted irrigation and precision agriculture equipment. However, some studies have shown that these programs and subsidies may lead to an increase in total water consumption by farmers due to a behavioral response called the rebound effect.[96] The rebound effect occurs when more efficient irrigation technology provides an incentive to extend acreage planted or switch to more water-intensive crops, leading to greater total water use.[97]

Other institutions, like water rights[98] and water appropriations, have been shown to affect farmer behavior toward technology adoption of more efficient irrigation. For instance, one USDA study explained that farmers who were junior water rights holders with uncertain supplies of water might be less likely to invest in more efficient irrigation technology. A 2018 study found that water rights could be instrumental in helping to ameliorate the negative rebound effects of newer more efficient technologies (such as LEPA) without affecting the incentive to adopt these newer technologies.[99] As for water trading, one study found that institutions that permit water trading allow for a better allocation of resources across farmers and provide incentives to adopt better irrigation technologies.

We did not identify many studies that explicitly examined water conservation as a factor in a farmer's decision to adopt more efficient irrigation technologies. One study (from 1993, which was outside of our time period for review) looked at factors affecting the adoption of drip irrigation for sugar cane production in Hawaii. The authors noted that while the choice of drip irrigation was motivated by water conservation in the earlier years, with increased experience with drip technology, yield increase took priority over water savings.[100] Also, a 2013 study found that farmers in western Kansas are extremely conservation minded, and much of the conversion from flood irrigation to center pivot, and then center pivot to drop nozzle center pivot, was because of their desire to reduce runoff, drift, and evaporation, as well as reductions in well capacity.[101] For precision agriculture, a 2012 study found that farmers

[96] Wallander, Steven and Michael Hand, "Measuring the Impact of the Environmental Quality Incentives Program (EQIP) on Irrigation Efficiency and Water Conservation," Selected Paper prepared for presentation at the Agricultural and Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, PA, 2011. Pfeiffer, Lisa and C.-Y. Cynthia Lin, "Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction? Empirical Evidence" *Journal of Environmental Economics and Management,"* 67, 2014.

[97] This effect was postulated by Jevons (1865) and concludes that the use of a new technology that enhances efficiency of a natural resource does not necessarily lead to a reduction in the consumption of that resource. This effect is used in the energy economics literature and has been found in vehicle use, space heating and cooling, and lighting.

[98] Water rights are primarily state-created property rights. Tarlock, LAW OF WATER AND WATER RIGHTS AND RESOURCES, § 1.1 (West 2018).

[99] Li, Haoyang and Jinhua Zhao, "Rebound Effects of New Irrigation Technologies: The Role of Water Rights," *American Journal of Agricultural Economics*, 100(3), March 2018.

[100] Shrestha, Rajendra B and Chennat Gopalakrishnan "Adoption and Diffusion of Drip Irrigation Technology: An Econometric Analysis," *Economic Development and Cultural Change*, Vol. 41, No. 2 (Jan., 1993).

[101] Pfeiffer, Lisa and C.-Y.Cynthia Lin, "Does Efficient Irrigation Technology Lead to Reduced Groundwater E xtraction? Empirical Evidence," *Journal of Environmental Economics and Management* 67(2014).

who use information from sources such as university publications adopt precision agriculture for its environmental benefit and to be at the forefront of technology.[102] Therefore, for this study, in addition to increased yields and decreases in the costs of irrigation water, some farmers also had conservation goals. Similarly, farmers that we visited in both California and Nebraska told us that they were conservation minded.

3.3 Barriers to adoption include small farm size, large capital investments, and barriers to information acquisition

In general, barriers to irrigation technology adoption consist of impediments to investment or use such as a lack of financial resources or credit, farmer-related demographics, and small farm size. Using the 2013 FRIS, we first examined data on the most recent percentages of farmers in both the western 16 States and non-western States that believed that certain factors, such as the cost of implementation or uncertainty of water supply, were barriers to the adoption of irrigation technology (see table 7). To supplement this data, we also identified several economic studies that have observed barriers to irrigation and precision agriculture technology adoption (see table 8).

One 2012 USDA report noted several barriers to adoption, including the cost of irrigation system upgrades which can be an important limiting factor in investment decisions. The installation of irrigation equipment often requires large capital investments as well as advanced on-farm management expertise. Moreover, using data from a 2008 FRIS survey, the report indicated that uncertainty about future water availability was a barrier to technology adoption by 17 percent of irrigators in the western states and 5 percent of irrigators in the eastern states. For instance, certain states allocate water rights based on seniority, making the supply of water uncertain for some farmers who are junior water rights holders, especially in drought years.[103] Using the most recent 2013 FRIS data, we found that farmers continue to experience uncertain future water availability at about the same levels as in 2008 and this remains a barrier to adoption (see table 7). We also confirmed from our examination of the 2013 FRIS data that the cost of implementation and the response from "cannot finance" are still important barriers to adoption. A sizeable percentage of respondents to the survey also did not perceive that irrigation adoption was a priority in their operation (22 and 21 percent in the western and non-western states, respectively).

[102] Pandet, Mahesh, Krishna P. Paudel, Ashok K. Mishra, and Eduardo Segarra, "Adoption and Nonadoption of Precision Farming Technologies by Cotton Farmers," Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2012 AAEA Annual Meeting, Seattle, Washington, August 12-14, 2012.

[103] Under the prior appropriation doctrine, recognized in most of the western states, water rights are acquired by diverting water and applying it for a beneficial purpose. Colorado v. New Mexico, 459 U.S. 176, 179 n.4 (1982). A distinctive feature of the prior appropriation doctrine is the rule of priority, under which the relative rights of water users are ranked in the order of their seniority. Id

Table 7: **Barriers to adoption of irrigation technologies from the 2013 USDA Farm and Ranch Irrigation Survey (FRIS) data**

Barriers to Adoption from 2013 FRIS Data	Western 16 States (percent)	Non-Western States (percent)
Cost of irrigation Implementation	15	12
Uncertainty about future water availability	17	5
Risk of Reduced Yield	9	8
Short-term operation	8	8
Not a priority	22	21
Cannot finance	18	15
Crop conditions	10	9
Other	7	7

Source: GAO analysis of USDA Farm and Ranch Irrigation survey (FRIS) data on barriers to adoption for the western and non-western states for 2013. | GAO-20-128SP

In addition to the 2013 FRIS data on irrigation adoption barriers, Table 8 summarizes several factors from the literature that we reviewed that act as barriers to the adoption of irrigation and precision agriculture technologies.

Table 8: **Barriers to adoption of irrigation and precision agriculture irrigation technologies from the literature reviewed**

Barriers to Adoption from the Literature	Reason for Barrier
Financial Constraints	Drip or sprinkler irrigation can require large capital costs. Irrigators often cite financial constraints as major barriers to investing in improved irrigation efficiency. (Frisvold and Bai, 2016)
Small size of farm	Small farm size affects water management information acquisition, investment in management-intensive irrigation improvements, and participation in conservation programs that encouraged improved irrigation practices. (Frisvold and Deva, 2012)
Impediments to investment such as credit availability	Adoption of large fixed capital equipment may be hampered by a lack of borrowing capacity. (Jorge Fernandez-Cornejo, Economic Research Service, USDA, 2007)
Farmer-related demographics	Limited producer management skills, producer age, and a lack of financial resources are barriers that may prevent the adoption of new irrigation technology (Schaible and Aillery, Economic Research Service, 2012)
Lack of available information	A lack of available information from extension or other sources is a barrier to adoption of precision agriculture. (Pandit, Paudel, Mishra, and Segarra, 2012)
Complexity and complex system requirements	Complexity is a barrier because the higher the irrigation complexity, the more difficult it is to manage water resources. (Evans, LaRue, Stone, and King, 2013 and Reints, Dinar, and Crowley, 2017)
Costly management control systems	For site-specific variable rate technologies, costly control systems and maintenance costs are barriers to adoption. (Evans and King, 2012)

Barriers to Adoption from the Literature	Reason for Barrier
Lack of expertise to set up decision support software	For precision agriculture, e.g., site-specific variable rate technologies, a lack of expertise to set up decision support software is a barrier. (Evans and King, 2012
A lack of public and private research for precision agriculture	A lack of public and private research is a barrier to precision agriculture adoption for site-specific variable rate equipment showing it will conserve water and/or increase net returns to production. (Evans and King, 2012)
Monetary and time opportunity costs	Opportunity costs of time and money stated as barriers to adoption. (Lambert, Paudel, and Larson, 2015)

Source: GAO analysis of various irrigation and precision agriculture adoption literature that examine barriers to technology adoption. For full citations of technology adoption studies see App. III of this report. | GAO-20-128SP

While large farm size is a major determinant of irrigation technology adoption, studies have shown that small farm size has been a formidable barrier to the adoption of improved water management systems. One study (see table 8) of irrigation barriers in Arizona and New Mexico, using 1998 FRIS survey data, found that farm size affects: 1) the use of water management information, 2) investment in irrigation improvements, and 3) participation in conservation programs.[104] The study explained that although farms in larger sales classes are more likely to access information on irrigation technology from any given source, unlike smaller farms, larger farms are more likely to obtain information from private, tailored sources. In both Arizona and New Mexico, the authors found that smaller farms are less likely to research or investigate irrigation technology improvements and use management-intensive methods for irrigation scheduling.[105] Overall, the study concluded that farms of different sizes have different information needs and incentives in water conservation.

Studies we examined also indicated several adoption barriers to irrigation-related precision agriculture technologies. For example, a 2013 study found that the adoption of site-specific variable rate irrigation had been low for several reasons, including high capital costs, complicated system requirements, and costly management control systems.[106] The authors concluded that such barriers could only be overcome by more private and public research and education programs to address these concerns. Another study looking at cotton production in the U.S. South found that, although irrigators in general were more likely than non-irrigators to adopt precision agriculture, cotton farmers saw monetary and time opportunity costs as significant barriers to adopting precision agriculture technologies.[107] A 2016 USDA report on precision agriculture found that there may be

[104] Frisvold, George B. and Shailaja Deva, "Farm Size, Irrigation Practices, and Conservation Program Participation in the US Southwest," *Irrigation and Drainage*, 61, 2012

[105] While the authors found that scientific irrigation scheduling was low across all size groups, it was particularly low for smaller-scale irrigators.

[106] Evans, Robert G., Jake LaRue, Kenneth C. Stone, and Bradley A. King, "Adoption of Site-Specific Variable Rate Sprinkler Irrigation Systems," *Irrigation Science*, 31, 2013

[107] Lambert, Dayton M., Krishna P. Paudel, and James A. Larson, "Bundled Adoption of Precision Agriculture by Cotton Producers," *Journal of Agricultural and Resource Economics*, 40, 2015.

additional financial risks to farmers who planned to adopt this type of equipment.[108] For example, the report explains that costs associated with precision agriculture are basically sunk costs (costs already incurred that no longer can be recovered) compared with other types of capital investments like land and tractors. Therefore, to adjust for these risk factors, farmers would require a higher expected return on their investment. Specifically, the report cited that compared to GPS soil and yield mapping and guidance systems, variable rate technologies were the most costly type of precision agriculture of the three. According to the 2010 ARMS, variable rate was adopted primarily by large farms, typically over 1,700 acres but was the least likely of the three to be adopted in each farm size category.

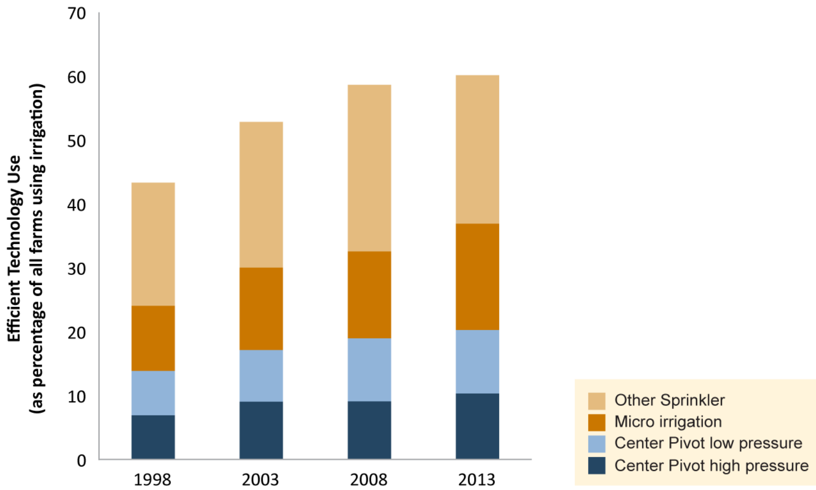
3.4 Rates of use vary across time by technology and location

While adoption measures can inform whether or not a particular farmer will invest in a certain technology, rates of adoption measure on an aggregate basis the percentage of farmers who have adopted a certain type of technology at a point in time. Rates of adoption can also measure how a new technology has spread across a certain geographic region or area. However, due to data limitations, we were only able to measure the rates or percentages of total farms that used a certain (efficient) irrigation technology in a particular year. Technically, irrigation adoption is when a farmer starts to use or invests in a certain technology. For irrigation-related technologies, we used USDA FRIS data for the 17 western states to examine rates of use from 1998 through 2013 and found that these rates have varied across different types of efficient irrigation technologies.[109] Figure 23 shows that during this time period more efficient irrigation technologies, such as the use of low-pressure center pivot irrigation went from about 7 percent in 1998 to 10.3 percent in 2013 and micro irrigation technologies experienced higher rates of use, from 10.2 percent in 1998 to 15.6 percent in 2013.

[108] Schimmelpfennig, David, “Farm Profits and Adoption of Precision Agriculture,” Economic Research Service, USDA, Economic Research Report Number 217, October 2016, pp. 12-13.

[109] In fig. 23, the rate or percentage of use is the total number of farms using a certain efficient technology (in this case other sprinkler, micro irrigation, center pivot low pressure, and center pivot high pressure) divided by the total number of farms that used all irrigation technologies in a particular year.

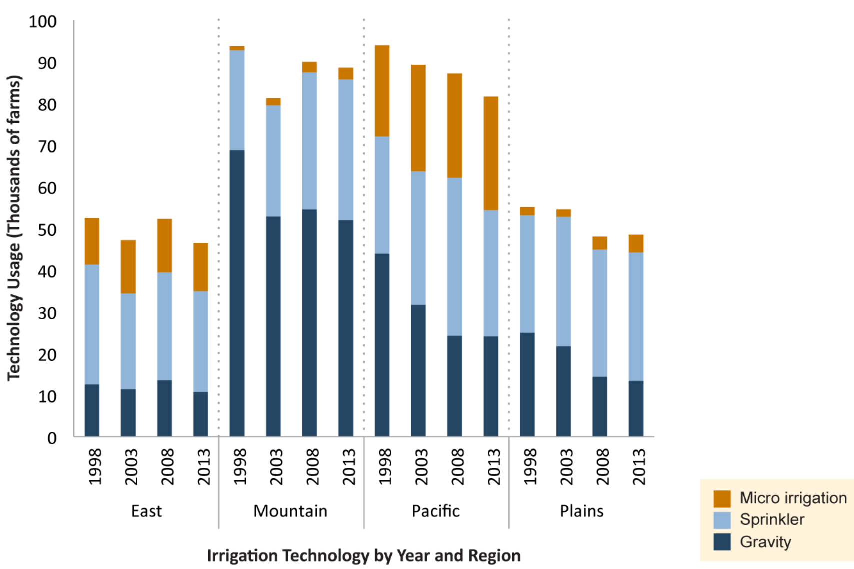
Figure 22: Rates of use of irrigation technologies for the 17 western states increased from 1998 to 2013



Source: GAO analysis of USDA data from the Farm and Ranch Irrigation Survey. | GAO-20-128SP

Figure 24 breaks down the use of major irrigation technologies by region from 1998 through 2013, such as gravity, sprinkler, and micro-irrigation systems. The Pacific region showed the most absolute growth of micro irrigation systems. However, the Plains and Mountain regions, while starting at much lower absolute levels of use in 1998 (1,920 and 969, respectively), had higher levels of percentage growth rates of micro irrigation (120 and 181 percent from 1998 to 2013, respectively). In the Plains region, sprinkler came to predominate over gravity, while irrigation use in the Mountain region saw a similar but more modest trend. The Eastern region saw small growth in the use of micro-irrigation technology systems but at much lower levels than the other three regions. Overall, the number of gravity irrigation systems decreased in all four regions of the country between 1998 and 2013.

Figure 23: Use of major irrigation technologies by U.S. region, 1998 through 2013



Source: GAO analysis of USDA data from the Farm and Ranch Irrigation Survey. | GAO-20-128SP

4 Efficient irrigation may have mixed effects on water conservation due to farmers' decisions regarding expanding acreage and crop choice, among other factors

To assess the impact of efficient irrigation practices, we modeled scenarios of switching to more efficient irrigation scheduling and expanding cropland, for a sample watershed in Nebraska. Efficient irrigation scheduling can reduce the amount of water applied to the field if farmers do not use efficient irrigation scheduling to expand their irrigated cropland but can increase water consumption if they do. However, regardless of whether or not farmers use efficient irrigation scheduling in expanding their irrigated cropland, efficient irrigation scheduling may reduce return flows.

In addition, we used multi-year USDA survey data in an econometric model to assess the relationships between irrigation technology, water applied per acre, and crop production, for selected irrigated crops. We found that efficiency improving technology conversions may reduce the amount of water applied per acre for certain crops and technology conversions. But our analysis also suggests that some technology conversions were not associated with water reductions for any of the crops examined. In some of these circumstances, our analysis found yield increases associated with more efficient irrigation technology.

USDA survey data shows the use of more efficient irrigation technology has increased over time, while the trend in overall irrigation water used declined during the same time period. Literature and experts note that various factors will affect irrigation and water conservation, such as farmers' decisions regarding expanding acreage and crop choice, as well as water policy.

4.1 Efficient irrigation scheduling may have both positive and negative impacts on water scarcity

To assess the potential impacts of efficient irrigation scheduling, we used a computer model to simulate various irrigation scenarios on a sample watershed in south central Nebraska. We found that efficient irrigation scheduling could have both positive and negative impacts. In terms of positive impacts, our simulations suggest that efficient irrigation scheduling has potential to reduce the amount of irrigation water applied to the field if farmers do not subsequently expand their irrigated cropland. In terms of negative impacts, however, efficient irrigation scheduling could increase the amount of water consumed through evapotranspiration if farmers do expand their irrigated cropland. Regardless of whether or not farmers expand their irrigated cropland, our simulations suggest that efficient irrigation scheduling could reduce return flows to the stream. The results of our analysis are not generalizable to other locations nor are they precise forecasts of the potential impacts of efficient irrigation scheduling.

Simulation model of irrigation scenarios

To evaluate the potential impacts of efficient irrigation scheduling, we used the Soil and Water Assessment Tool (SWAT), a computer model that simulates hydrological outcomes under specified land management scenarios. We applied the SWAT model to a watershed covered by corn, soybeans and rangeland in south central Nebraska. We selected this watershed because it has a mixture of land covers and is located in one of the most heavily irrigated regions of the country. We used local data on land cover, weather, soil type, irrigation amounts, crop yield and other characteristics to simulate irrigation scenarios between 1986 and 2015 on 7 soil types where corn is grown in the watershed.

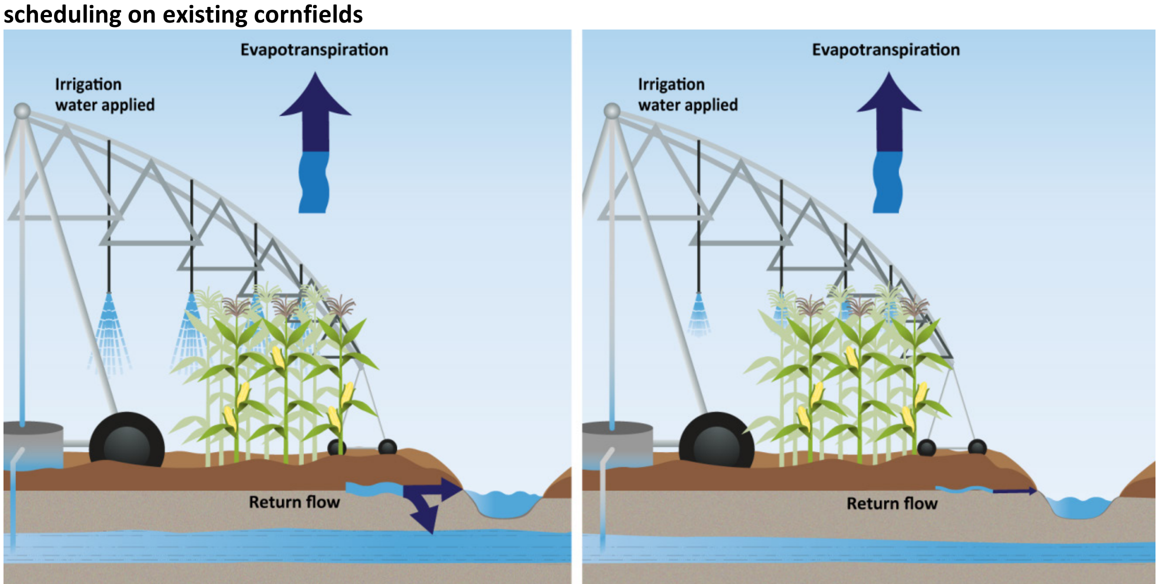
We used the SWAT model to simulate two scenarios. In the first scenario, we simulated farmers switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cornfields. To simulate conventional irrigation scheduling, we instructed the model to apply a fixed amount of irrigation water at regular time intervals during the growing season. We varied the number of water applications from year to year based on historical precipitation data. This approximated farmers irrigating their corn according to a fixed schedule while increasing the number of water applications in dry years and decreasing the number of water applications in wet years. To simulate efficient irrigation scheduling, we instructed the model to apply a fixed amount of irrigation water only when the plant water demand reached a certain threshold. This approximated farmers using technology, such as moisture sensors, to determine when to irrigate.

In the second scenario, we simulated farmers converting non-irrigated rangeland to cornfields irrigated with efficient scheduling. We simulated such land conversions because one possible impact of efficient irrigation technology is to expand acreage. We focused on non-irrigated rangeland because these lands were the primary uncultivated land in the watershed and because USDA/National Agricultural Statistics Service (NASS) data showed an increase in irrigated cropland during our study period. For each of these two scenarios, we examined the impact of efficient irrigation scheduling on the amount of water applied to crops, the amount of return flow to streams, the amount of water consumed through evapotranspiration and crop yield. Our simulations capture the potential impacts of efficient irrigation practices under a range of conditions and are consistent with local data on irrigation rates and crop yield. We present the results as illustrations of the potential order-of-magnitude effects of adopting efficient irrigation practices, rather than as precise estimates or forecasts of these effects. See Appendix IV for more details about our analysis.

Efficient irrigation scheduling can reduce the amount of water applied to the field if farmers do not expand their irrigated cropland

Our simulations suggest that efficient irrigation scheduling may reduce the amount of water applied to crops, but its precise impact depends upon whether farmers subsequently expand their irrigated cropland. If farmers were to switch from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland, our simulations suggest they could apply less water to the field without compromising crop yield. In modeling this scenario, we found that the amount of irrigation water applied to the field decreased markedly while crop yield remained similar across a range of soil types and weather conditions. Figure 25 illustrates this difference. In panel A, which represents conventional irrigation scheduling on existing cornfields, the amount of irrigation water applied to crops is higher than the amount applied with efficient irrigation scheduling, which is represented by panel B. If farmers were to switch from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland, therefore, they may be able to produce a comparable amount of corn while leaving additional water in the aquifer for future years, according to our simulations.

Figure 24: Simulated impact of switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cornfields



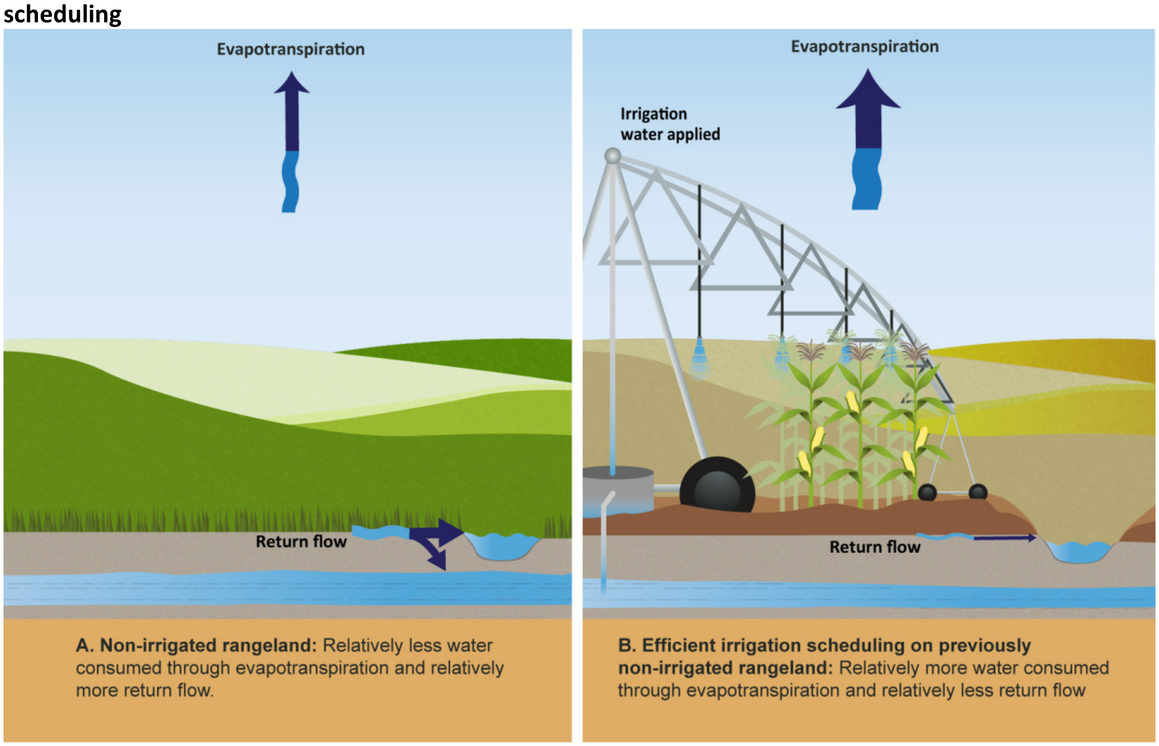
A. Conventional irrigation scheduling on existing cornfields: Relatively more irrigation water applied to field and relatively more return flow.

B. Efficient irrigation scheduling on existing cornfields: Relatively less irrigation water applied to field and relatively less return flow.

Source: GAO simulations using the Soil and Water Assessment Tool (SWAT) computer model for sample watershed in south central Nebraska. | GAO-20-128SP

If farmers were to subsequently expand their irrigated cropland, however, we found that efficient irrigation practices could have a different impact. In particular, if farmers were to convert non-irrigated rangeland into cropland irrigated with efficient scheduling, our simulations indicate they would increase crop yield but would also apply more irrigation water than if they had not expanded their irrigated acreage. Because non-irrigated rangeland would not have previously produced corn, converting these lands to irrigated cropland would also increase crop yield. Figure 26 illustrates this difference. The net impact on the amount of irrigation water applied and on corn produced would depend upon the amount of non-irrigated rangeland converted to irrigated cropland. In our analysis, however, if farmers were to convert non-irrigated rangeland into cropland irrigated with efficient scheduling, they may still be able to reduce the amount of irrigation water applied to crops, but by a lesser amount than if they had not expanded their irrigated cropland.

Figure 25: Simulated impact of converting non-irrigated rangeland to cropland irrigated with efficient scheduling



Source: GAO simulations using the Soil and Water Assessment Tool (SWAT) computer model for sample watershed in south central Nebraska. | GAO-20-128SP

Efficient irrigation scheduling can increase water consumption if farmers use it to expand their irrigated cropland.

Our simulations suggest that efficient irrigation scheduling can increase water consumption but whether it has this impact depends upon whether farmers expand their irrigated cropland. If farmers were to switch from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland, our simulations suggest that the amount of water consumed through evapotranspiration may not change markedly. In modeling this scenario, we found that the amount of water consumed through evapotranspiration increased slightly on some soil types and in some weather conditions but decreased slightly on other soil types and in other weather conditions.

If farmers were to use efficient irrigation scheduling in expanding their irrigated cropland, however, our simulations indicate that the amount of water consumed through evapotranspiration could increase. In modeling this scenario, we found that the amount of water consumed by evapotranspiration increased markedly across a range of soil types and weather conditions.[110] Figure 26 illustrates this difference. In panel A, which depicts non-irrigated grassland, the amount of water consumed by evapotranspiration is less than the amount in panel B, which depicts the same rangeland converted to cropland irrigated with efficient scheduling. Based on this scenario, the impact of efficient irrigation scheduling on water consumption primarily depends upon whether farmers subsequently expand their irrigated cropland.

Efficient irrigation scheduling may reduce return flows, regardless of whether or not farmers use it in expanding their irrigated cropland.

Regardless of whether farmers use efficient irrigation scheduling on existing cropland or on non-irrigated rangeland, efficient irrigation scheduling could reduce return flows to streams. When irrigation water is applied to the field, the water that does not evaporate or transpire either runs off the field or percolates through the soil to groundwater. When farmers irrigate with greater efficiency, a larger fraction of the water applied to the field is used by the plants. When modeling the scenario (where groundwater is the source) in which farmers switch from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland, for example, we found that the amount of return flow to streams decreased markedly across the range of soil types and weather conditions in our simulation. Figure 25 illustrates this difference, with the amount of water returning to streams being lower with efficient irrigation scheduling as compared to either conventional irrigation scheduling or non-irrigated rangeland. We found a similarly consistent change when we modeled farmers converting non-irrigated rangeland to irrigation cropland, as illustrated by fig. 26. In

[110] We selected non-irrigated rangeland as the original land cover in our simulations because it was the primary land cover other than corn or soybeans in our sample watershed. If the original land cover were to consume more water than rangeland, the results of our analysis may have differed.

some instances, return flows can be beneficial by increasing the amount of water available to downstream users, but in other instances, return flows can be harmful by conveying pollutants.

4.2 More efficient irrigation systems used to grow the same crop can reduce water applied to the field or increase yields

Our analysis of USDA data found that, when holding the type of crop constant, there are some circumstances where irrigation technology leads to less water use and others where it is used to improve yields.[111] To assess the relationships between irrigation technology and water applied to the field (an acre of cropland), we used an econometric model to examine the relationships among three variables—irrigation technology, water applied per acre, and crop production—for 15 selected irrigated crops in the 17 western states.[112,113] This analysis is limited to farms that responded to the 1998, 2003, 2008, and 2013 USDA FRIS at least two times, in order to examine irrigation technology conversions over time. Looking at the 17 western states, our analysis suggests that, depending on the combination of technologies and crops, converting to more efficient irrigation technology was sometimes associated with less water applied per acre. We found that efficiency improving technology conversions may reduce the amount of water applied per acre for hay,[114] corn, orchards, and vegetables for certain technology conversions, such as conversions to micro irrigation, lower pressure sprinklers, or more efficient gravity systems. Our analysis also suggests that some technology conversions, such as converting from gravity to sprinkler irrigation, were not associated with water reductions for any of the crops examined. In some of these circumstances, such as conversions to low-pressure sprinklers, our analysis found yield increases associated with more efficient irrigation technology.

Our estimates suggest that converting to more efficient irrigation systems reduced the amount of water applied per acre for certain crops and technology conversions. Specifically, for hay, going from unlined ditches to the more efficient lined ditches or pipes for water conveyance to gravity irrigated fields was associated with less water applied per acre. In 2013, there were 1.8M acres of hay irrigated with gravity irrigation.[115] For orchards, vineyards, and vegetables, our estimates suggest a decrease in water applied

[111] See Appendix V for additional information about the data, methods, and limitations of our analysis.

[112] Crops examined include: alfalfa, vegetables (along with tomatoes, a subset of vegetables), barley, beans, corn for grain and silage, cotton, orchards, hay, pastureland, sorghum, soybeans and wheat. Irrigation technology examined include: gravity irrigation, which was further categorized as unlined, lined, or piped gravity; sprinkler irrigation, which was further categorized by pressure for mechanical move systems; and micro irrigation.

[113] We use the term 'water applied' to be consistent with the question asked on the survey. This analysis is based off self-reported survey data. However, a USDA official noted that farmers may not know how much water they apply, or may report how much water they received, which does not account for water lost when it is conveyed to the field.

[114] In our analysis, hay is a crop type that includes small grain, and other tame or wild hay (dry hay, greenchop, and silage). Since, alfalfa is defined as a separate crop type in FRIS, our definition of hay excludes alfalfa and alfalfa mixtures.

[115] According to the 2013 Farm and Ranch Irrigation Survey.

when converting from sprinkler to micro irrigation.[116] Additionally, our results suggest decreased water per acre for orchards and vineyards when converting from gravity to micro irrigation. However, when converting from gravity to micro irrigation in vegetables, our estimates do not indicate a change in water applied per acre. As of 2013, orchards and vegetables were the top crops by acres that use micro irrigation. There were approximately 2.6 million acres of orchards that used micro irrigation and 700,000 acres of vegetables using micro irrigation in the United States.[117]

In our analysis, statistically significant associations were limited to certain crops, and some technology conversions we examined were not associated with water reductions for any crops. For example, converting from gravity to sprinkler irrigation is often considered a jump towards efficiency that would result in needing less water. However, our estimates did not find conversions from gravity to sprinkler systems to be associated with reduced water applied per acre for any of the relevant crops we considered. USDA officials did note that efficiencies range within gravity and that the shift into sprinklers has come from more efficient gravity systems, which may explain some of our results.

[116] Referred to as orchards, this category includes land in bearing and non-bearing fruit orchards, citrus or other groves, vineyards, and nut trees.
[117] GAO analysis of USDA data from the 2013 Farm and Ranch Irrigation Survey

Additionally, we found going from unlined to lined or piped gravity irrigation resulted in only one crop—hay—to be associated with a reduction in water applied per acre to the field. However, for other crops we examined—alfalfa, cotton, and wheat—our estimates did not indicate a change in water applied per acre associated with converting to a lined or piped gravity system.

Farms can modify irrigation to improve efficiency, for example, going from unlined to lined or piped conveyance systems for gravity irrigation, or going from high pressure sprinkler irrigation to low pressure sprinkler irrigation. For example, while some crops, such as alfalfa and wheat, were commonly associated with modifications from high pressure sprinklers to lower-pressure sprinklers, and from less to more efficient gravity systems during our study period, neither crop was associated with reductions in water applied per acre.

In addition, crop level results suggest that some technology conversions, such as conversions to micro irrigation and low-pressure sprinklers were associated with higher yields for some crops. Generally, for these circumstances, the yield increased while there was no statistically significant change in water applied per acre of cropland.[118] This finding could imply that

[118] Our estimates suggest that orchards and vineyards converting from gravity to micro irrigation systems are associated with less water applied per acre. Although yield information is not available for these crops, our models suggest an increase in the likelihood of fertilizing crops through irrigation systems associated with this conversion.

while there is little evidence of water savings, there is more productivity using the same amount of water. Our estimates suggest increased yields for corn, cotton, and sorghum were associated with sprinklers modified to low pressure.[119] With sprinklers, low pressure modifications use hanging pipes instead of spraying water higher in the air in order to increase precision application and reduce water losses from evaporation. However, when we additionally included pressure reductions to medium-pressure sprinkler, only one crop—sorghum—was associated with increased yield.

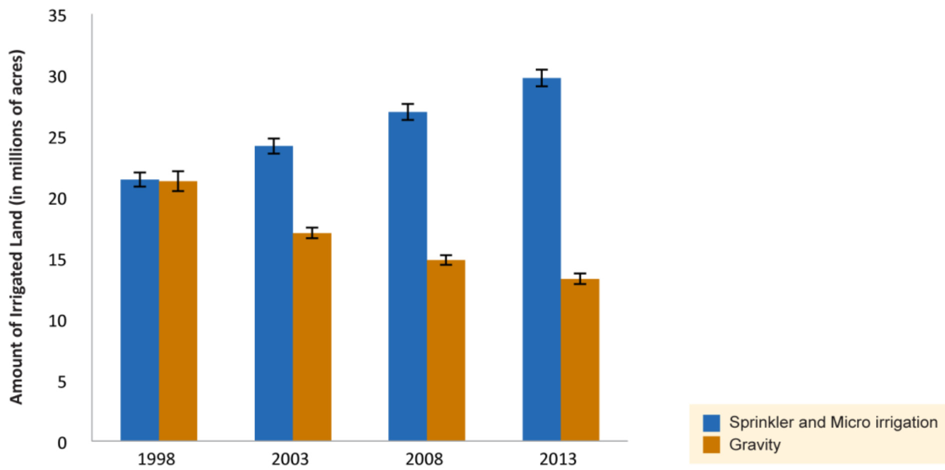
4.3 Efficient irrigation technology alone may not conserve water

Survey data shows more efficient irrigation technology being used over time, as well as a reduction in total water applied

When looking at overall data in the 17 western states, as shown in figure 26, the number of acres being irrigated by more efficient systems—sprinkler and micro irrigation—has increased over time, whereas the number of acres with gravity systems is declining. At the same time, overall water use has declined. For efficient technology, in 1998, the number of acres irrigated with a sprinkler or micro irrigation was comparable to the number of acres being irrigated with a gravity system. However, in 2013, the number of acres irrigated with a sprinkler or micro irrigation system was approximately 30 million acres, compared to approximately 13 million acres irrigated by a gravity system.

[119] Sprinkler systems pressured with less than 15 psi are considered low pressure systems for this analysis. Sprinkler pressure ranges from 2 psi to over 75 psi.

Figure 26: In the 17 western states: the number of acres irrigated under sprinkler and micro irrigation compared to gravity[a]

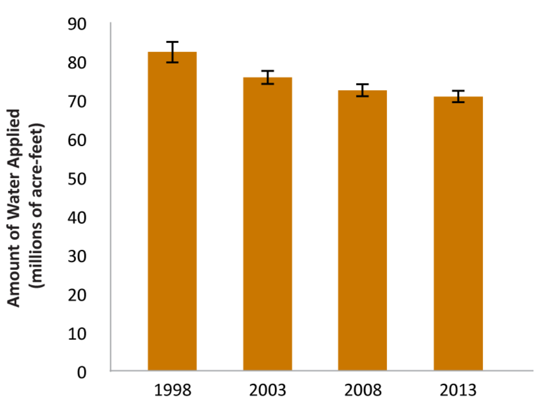


Source: GAO analysis of USDA Farm and Ranch Irrigation Survey data. | GAO-20-128SP

[a] The 17 western states are: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming.

As shown in figure 28, the total amount of water applied decreased from 1998 to 2013. Therefore, total water applied decreased while more efficient irrigation technology was used.

Figure 27: Amount of total water applied, for the 17 western states[a]



Source: GAO analysis of USDA Farm and Ranch Irrigation Survey data. | GAO-20-128SP

[a] The 17 western states are: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming.

Literature and experts note various factors that affect irrigation and water conservation, such as expanding acreage, crop choice, and water policy

According to a USDA report, while improving irrigation efficiency generally reduced water applied on the farm, it is not clear if this conserves water on a broader scale, such as at the watershed or the basin.[120] There are many factors in addition to irrigation efficiency that contribute to water conservation at a broad level, including local hydrology and topography, water source, and climate. Efforts to translate on-farm irrigation efficiency gains to broader water

[120] Schaible, Glenn D., and Marcel P. Aillery, *Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands,* EIB-99, U.S. Department of Agriculture, Economic Research Service, September 2012.

conservation must consider what happens to the irrigation water when it goes off the farm. For example, the Center for Irrigation Technology, when reporting on agricultural water use in California, noted that switching from flood irrigation to micro irrigation causes flows to change within the basin, but generally does not create new water outside the basin.[121] One expert told us that a report they authored and academics cannot demonstrate any volumetric water savings resulting from technology; however, another expert disagreed with this statement. One USDA official stated that the hydrological system is often misunderstood, and policy actions affecting the system sometimes oppose the intended goal noting that, in general, improving irrigation efficiency does not conserve water. The official also noted that every situation is dependent on geography and objectives. The official stated that in some places, higher irrigation efficiency creates extra water to go back to the river. However, in other places, higher irrigation efficiency dries out streams as it reduces irrigation runoff.

Detailed data are needed to see how efficient irrigation technology affects water conservation. For example, data is needed on groundwater extraction and levels, crop acreage, and irrigation decisions. Experts also mentioned difficulty in assessing the effect of irrigation. One expert noted that monitoring and measuring water use is difficult due to a current lack of data in the area. Another expert told us that it is often hard to assess the effect attributable to new technology on water savings. For example, it can be difficult to find comparable fields, and to determine effects given yearly weather changes.

Adopting efficient irrigation equipment alone may not be enough to relieve pressure on water demands. According to one report, water use sustainability is likely to be achieved through effective policies that might include, for example, regulation of groundwater pumping or water pricing schemes.[122] Water savings measures can fail with unmanaged incentives. According to one study, other potential policy choices that could reduce irrigated water demand include constraining the amount of irrigated land in certain situations, and reducing water rights.[123] Irrigation technology and practices are tools that can help save water in some circumstances; however, there is no one-size-fits-all solution.

In some cases, efficient technology may lead to an increase in water use. Certain researchers point out there may be unintended consequences of promoting efficient irrigation technology, in that there may be an increase in irrigated land overall or switching to more water-intensive crops. These unintended consequences would result

[121] The Center for Irrigation Technology, California State University, Fresno. "Agricultural Water Use in California: A 2011 Update." November 2011.

[122] David Zilberman, Rebecca Taylor, Myung Eun Shim, and Ben Gordon, *How Politics and Economics Affect Irrigation and Conservation*, Choices 4th Quarter 2017.

[123] Gomez, Carlos Mario, Carlos Dionisio Pérez Blanco, David Adamson, and Adam Loch. "Managing Water Scarcity at a River Basin Scale with Economic Instruments." Water Economics and Policy, Vol 3, No. 04 (2017): 1750004. doi:10.1142/s2382624x17500047.

in more water going towards crop production—more consumptive use of water—which would offset any potential savings from efficient irrigation. Literature points to a rebound effect, where an efficient irrigation technology does not necessarily lead to less consumption of water. Specifically, studies published in 2014 and 2018 examined the Ogallala Aquifer in Kansas, which showed a moderate increase in groundwater use with the adoptions of LEPA irrigation technology.[124]

In some cases, a tradeoff may exist between water use and crop yield. For example, water may not be conserved with more efficient irrigation technology when that water savings is used to increase yield. In some cases, farms may apply more water per acre in order to increase yields. One USDA official noted that, on a whole, improving irrigation efficiency does not save water, but achieves higher yield, higher production, and probably uses more water. The official said if the goal is to save water, evapotranspiration also needs to be reduced, which generally means reduced yields. Another expert noted irrigation can be used to extend the growing season, and therefore increase yield. However, another USDA official said reducing evapotranspiration does not generally mean reduced yields, since reducing the evaporation component can reduce evapotranspiration without reducing yield.

This USDA official went on to note that some crops—specifically cotton in west Texas—see an increase in yield with reduced evapotranspiration.

Another reason efficient irrigation technology may not broadly conserve water is that farmers may switch to more water intensive crops or expand irrigated acres. Since more water gets to the crop with efficient technology, this lowers the relative cost of crops that are more water intensive. Farmers may also switch to higher revenue crops that are more water intensive, leading to an overall increase in water consumption. One academic researcher told us that micro irrigation does not save water, as there is often a rebound effect as the farmer irrigates more acres. An expert at our meeting noted that while farmers will work within water regulations, all want to grow and expand their business.

According to the USDA, one way on-farm irrigation can conserve water on a broader scale is by reducing irrecoverable water losses or water deemed unusable due to impaired water quality. Examples of such areas that could be reduced include evapotranspiration from weeds, evaporation for soil and plant surfaces, percolation that is uneconomical to retrieve, or runoff that is not useable. Other ways for farms to contribute to water conservation on a broader level include better capturing rainfall and reducing crop evapotranspiration—such as by deficit irrigation. While irrigation efficiency improvements may be limited in the effect on water supplies, efficient irrigation can help

[124] Li, Haoyang and Jinhua Zhao, *Rebound Effects of New Irrigation Technologies: The Role of Water Rights.* Amer. J. Agr. Econ. 2018. Lisa Pfeiffer, and C.-Y. Cynthia Lin. *"Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction? Empirical Evidence."* Journal of Environmental Economics and Management 67 (2014): 189-208.

with water quality, improve regional economics, and achieve environmental goals. According to the USDA, efficient irrigation allows more crops to be grown with less water, which is critical for the future of sustainable agriculture. One USDA official told us that efficient irrigation can achieve goals other than water saving, namely: (i) increased production (ii) increased profits, and (iii) stabilized production. This same official stated that efficient irrigation can also improve water quality by reducing deep percolation and reducing runoff. The official did note that water quality concerns can drive the irrigation, as efficient irrigation generally increases the quality of water.

Experts at our meeting told us policy in the area should be more encompassing. One expert stated that water conservation should be considered on a broader level. Specifically, on-farm efficient technology should be integrated with watershed scale water management policies. The expert explained that this means investing in the human capital to enable "optimal timing and rate of irrigation by crop growth stage." The expert said this also includes combining efficient technology with practices—such as deficit irrigation, and acreage idling. According to this expert, this would allow farmers to offset any yield decline. Another expert proposed practicing integrated water management, taking into account all perspectives, such as energy and municipal needs, in addition to agriculture. A third expert said rotating fallowed lands is one management option to promote conservation without permanently retiring acreage.

Many sources—including western state policymakers, agricultural economists, and federal government officials—find that for irrigation technologies or practices to be used to conserve water, they should be accompanied by a policy or agreement that incentivizes conserving water. Without accompanying policies or agreements that incentivize conserving water, increased irrigation efficiency may not translate to less water consumed at the larger watershed level. The addition of agreements enabling and encouraging water conservation, could, on a voluntary basis, both allow farmers to get value from their conserved water as well as make water available for other uses. Experts as well noted that policy should include some consideration towards water regulation or preventing expansion of irrigated agriculture. One expert went so far as to say promoting efficient irrigation technology without accompanying agreements on water restrictions will exacerbate the problem. Other experts noted the promotion of efficient irrigation technologies and practices could be focused in areas where there are already local policies that align with federal policy goals, for example in areas that are already limiting expansion of irrigated land.

However, two experts noted that saving water is not just for the sake of saving water. Water use should be informed by consideration of the outcomes of using the water, for example, understanding where water use could have the best return on investment. Two experts noted that the economic benefit of water must be considered in the discussion of saving water.

5 Strategic implications

Irrigation is a major user of freshwater in the United States. According to the USGS, irrigation withdrawals in 2015 were 118 billion gallons per day, accounting for 42 percent of total freshwater withdrawals for all uses. Of the water withdrawn for irrigation, 62 percent was consumed.

We found that more efficient irrigation systems, such as sprinklers and micro irrigation, give the farmer more control over the application of water, and thus help ensure that more of the applied water is used by the crop. Though there are different definitions of efficiency used when examining water use in irrigation, it is typically defined as the amount of water used by the crop compared to the amount applied to the field. Efficiencies of 75 to 90 percent are indicative of pressure-based sprinkler and micro irrigation systems, respectively. Low-pressure versions of center pivot and linear move sprinkler systems in some cases can rival micro irrigation in efficiency. These systems can provide a significant increase in efficiency over traditional gravity-based systems, which have potential water application efficiencies around 60 percent.

There are also complementary water conservation practices that can help reduce the amount of water necessary when using irrigation technologies. These include water use management practices such as irrigation scheduling, a key practice used to determine when to irrigate a crop. Irrigation scheduling can be optimized through the use of precision agriculture technologies such as soil moisture sensors, which can be used to collect data that help farmers make decisions remotely on how much water to use, when to apply it to their crops, and where it should be applied in their fields. Other water conservation practices include those that improve soil health to allow soils to retain more moisture, practices to manage the land surface to increase uniformity of the water applied, and practices to improve water conveyance so water loss is reduced before it gets to the field.

However, it is not clear if improving irrigation efficiency on the farm conserves water on a broader scale—such as the watershed or the basin. In fact, some researchers point out that promoting efficient irrigation technology may lead to unintended consequences, such as farmers increasing the acreage they irrigate or switching to more water intensive crops. These unintended consequences would result in more water going towards crop production—more consumptive use of water.

Indeed, our analysis of factors influencing adoption of these technologies found that farmers often adopt and use efficient irrigation technology to increase profits and reduce risk, not necessarily to save water. And while many factors influence a farmer's decision to adopt, such as economics, farm size, location, crop choice, demographics, land tenure, and access to credit, we found few studies that explicitly examined water conservation as a factor.

Moreover, when we looked at USDA data on farmers' irrigation technology conversions over time, we found that, when holding the type of crop constant, there are some circumstances where irrigation technology leads to less water use and others where it is used to improve yields. Specifically, we found that some conversions to more efficient technology—such as conversions to micro irrigation, lower pressure sprinklers, or more efficient gravity systems—may reduce the amount of water applied per acre for some crops. However, our analysis also suggests that other common technology conversions, such as converting from gravity to sprinkler irrigation, were not associated with water reductions for any of the crops examined. In some of these circumstances, such as conversions to low-pressure sprinklers, our analysis found yield increased with more efficient irrigation technology.

This suggests that—as we found in our analysis of adoption factors—farmers may in some cases be using the technology to increase revenues through higher and more stable crop yields. While the increased efficiency means that less water could be applied without compromising crop yield, in practice, farmers might continue to apply the same amount of water or more to increase yield.

This has important implications for water availability at both the farm and basin level. One implication of increased efficiency is that it can be used to increase crop yield, which in turn could increase crop transpiration. Transpiration is essential for crop production, but results in water that is consumed and no longer available for other use. In our modeling we found that a switch to efficient irrigation scheduling can increase water consumption if farmers use it to expand their irrigated cropland. But we also found that even if farmers do not increase cropland, use of efficient irrigation scheduling may not markedly change water consumption. Unless consumption is offset through the use of practices that, for example, limit the amount of water given to the crop—such as through deficit irrigation, or use of drought-tolerant crops—a switch to more efficient irrigation technology will not reduce crop water consumption either at the farm or basin level.

There are other implications from increased on-farm irrigation efficiency. In some cases, increased efficiency can mean there is less return water for downstream users. A properly designed, installed, and managed micro irrigation system, for example, can eliminate surface runoff. Our modeling, as well, found that efficient irrigation scheduling may reduce return flows, regardless of whether or not farmers use it in expanding their irrigated cropland. While reduced agricultural runoff might help with, for example, downstream and aquifer quality issues due to a reduction in overall contaminants typical in those flows, less runoff also means less water for downstream agricultural, municipal, and environmental users, which in some cases could interfere with the water rights of the downstream users. If basin-level water conservation is a goal of using efficient irrigation technology, additional measures will likely be needed to motivate farmers to generate water savings.

The U.S. Department of Agriculture has explicit policy goals on water availability and agriculture. Within USDA's strategic plan, for example, one of the goals is to strengthen the stewardship of private lands through technology and research. Under this goal, there are several objectives, including to enhance conservation planning with science-based tools and information, as well as to enhance productive agricultural landscapes, which includes water availability.

USDA's EQIP provides technical and financial assistance to landowners—both farmers and ranchers—who voluntarily implement conservation practices on agricultural lands. According to a USDA report, in 2008, nearly 57 percent of the farms that received financial assistance for irrigation technology adoption did so through this program; however, only about 4 percent of farms that made irrigation investments in 2008 participated in the program. The report further states that nationally, irrigation practices accounted for roughly a quarter of the program's total obligations ($5.7 billion) from 2004 through 2010. The program also funds water conservation practices that can be used along with irrigation. The 2018 Farm Bill authorized EQIP assistance for entities such as irrigation districts and groundwater management districts to implement water conservation or irrigation practices that, among other things, provide for drought-related environmental mitigation.[125]

While many federal agencies play a role in managing the nation's freshwater resources, no one federal agency has primary oversight of water resource management. Rather, many federal agencies influence states' management activities through the implementation and enforcement of federal laws, as well as various federal programs. The states have primary responsibility for managing freshwater resources. Water rights are primarily state-created property rights.[126] States may rely on local entities to accomplish water goals. For example, California's Sustainable Groundwater Management Act, signed in 2014, provides local groundwater agencies with the authority and the technical and financial assistance necessary to sustainably manage groundwater. In Nebraska, natural resources districts—based on river basin boundaries—carry out programs related to local water supply and conservation, among other natural resource concerns. Each Nebraska natural resources district is governed by locally-elected officials and may establish taxes on property within the district.

Finally, collaboration between the various stakeholders is often necessary as water does not stop at political boundaries. For example, the Colorado River Compact is an agreement between seven states providing for the

[125] Pub. L. No. 115-334, § 2304, 132 Stat. 4490, 4558 (Dec. 20, 2018) (codified at 16 U.S.C. § 3839aa–2(h)(2)(A)).

[126] Tarlock, Law of Water and Water Rights and Resources, § 1.1 (West 2018).

apportionment of the waters of the Colorado River System, where the Bureau of Reclamation manages several water supply facilities.[127] Under the Colorado River System Conservation Pilot Program, the Bureau and several local water management agencies assessed the feasibility of various voluntary, temporary, and compensated methods to manage farmers' use of irrigation water, for example through temporary fallowing, deficit irrigation and alternative cropping. [128] The pilot was a collaborative effort between the federal government—through the Bureau of Reclamation—and four Colorado River municipal water users. According to the Upper Colorado River Commission report, the pilot demonstrated, among other things, farmer interest in the water-savings program and how voluntary reductions in their consumptive use may help, for example, in protecting critical reservoir levels in the Upper Basin of the Colorado River during drought.[129]

[127] States included are Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming.

[128] The municipal water users who participated in the Colorado River System Conservation Pilot Program included Central Arizona Water Conservation District, Southern Nevada Water Authority, Metropolitan Water District of Southern California, and Denver Water.

[129] Upper Colorado River Commission Staff and Wilson Water Group, *Final Report: Colorado River System Conservation Pilot Program in the Upper Colorado River Basin*, 2018

6 Policy options

We identified two policy options related to technologies that could address the policy goal of reducing the impact of irrigated agriculture in locations facing water scarcity in the United States, which was specified in the request for GAO to conduct this study. Local jurisdictions, such as state and local authorities, may have differing goals when facilitating the use of irrigation technologies. We have not evaluated the effectiveness of these options, and express no view regarding the extent to which statutory or regulatory changes would be needed to implement them.

Policy Option #1: Federal policymakers could promote the use of more efficient irrigation technology and practices, in conjunction with appropriate agreements to use the technology and practices to conserve water.[130]

We found that irrigation systems and practices have the potential to reduce water usage. For example, modifications to existing irrigation equipment, such as installing pipes with gravity irrigation or adding drop tubes on sprinkler irrigation systems, can assist with on-field efficiencies. Water management practices, such as deficit irrigation, irrigation scheduling, and reduced tillage, can all be used to reduce the amount of water applied on the farm. At a minimum, half of the irrigated acres in the United States may be able to irrigate more efficiently by using different irrigation technologies or practices.

However, we also found that using efficient irrigation technology will not necessarily result in water savings at a basin or watershed level, which would be needed to alleviate water scarcity. For example, we found one of the primary reasons farmers adopt efficient irrigation technology is to increase profits, whereas we were unable to identify many studies that explicitly examined water conservation as a factor in farmers' decisions to adopt irrigation technology. Many sources—including western state policymakers, agricultural economists, and federal government officials—have said that for irrigation technology and practices to be used to conserve water, it should be accompanied with an agreement that incentivizes conserving water.[131]

[130]We define "promote" as furthering the goal of using these technologies and practices to save water. In doing so we recognize existing programs may not have water savings as a primary goal.

[131] By "incentivize the conservation of water" we mean provide legally-available, voluntary ways that a farmer can get competitive value from their water other than by using it to irrigate their own cropland.

Benefits. By promoting efficient irrigation technology and practices, federal policymakers could help ensure that farmers have one of the tools needed to enable sustainable agriculture. Actions that encourage water conservation, could, on a voluntary basis, both allow farmers to get value from their conserved water and make water available for other uses.

Challenges. Without accompanying policies that incentivize conserving water, increased irrigation efficiency may not translate to less water consumed at the larger watershed level. For example, one USDA official stated that some efficiency policies can have the opposite effect of that intended, noting that, in general, improving irrigation efficiency does not conserve water. Experts noted that policy should include some consideration towards water regulation or preventing expansion of irrigated agriculture. One expert went so far as to say promoting efficient irrigation technology without accompanying water restrictions will exacerbate the problem. Others noted the promotion of efficient irrigation technologies and practices could be focused in areas where there are already local restrictions, such as limits on expanding irrigation.

Policy Option #2: Federal policymakers could promote the use of precision agriculture technologies, in conjunction with appropriate agreements to use the precision agriculture technologies to conserve water.

We found that precision agriculture technologies can be used to conserve water by helping farmers reduce over-irrigation. All farmers who use irrigation schedule their irrigations to some degree. However, according to USDA data, only about 30 percent of farms used advanced scheduling methods in 2013. Precision agriculture relies on remotely accessed data from soil moisture sensors and weather stations, among other data sources, and enables farmers to make informed decisions about when and how much to irrigate. In addition, precision agriculture gives farmers greater spatial control over where they are irrigating, for example, through the use of variable rate irrigation. However, like other more water efficient technologies and practices, some experts in water policy told us that without appropriate agreements on how the conserved water can be used, it may be used by the farmer to switch to more water intensive crops or expand irrigated cropland. According to the report *Water Transfers in the West,* the addition of agreements to enable and encourage water conservation—for example by providing competitive incentives for conserving water—could both allow farmers to get value from their water other than by using it and at the same time water could be made available for other uses within the basin.[132]

[132] The Western Governors' Association and Western States Water Council, *Water Transfers in the West: Projects, Trends, and Leading Practices in Voluntary Water Trading,* 2012.

Benefits. If federal policymakers were to promote the use of precision agriculture technologies for advanced irrigation scheduling, then it may be possible for farmers to reduce the amount of water they use for irrigation. Closely scheduling irrigation to the water needs of the plant throughout its growth cycle and collecting information about the amount of water available in the soil may also conserve water. USDA officials told us that many of these technologies are an evolution or add-on to existing technologies. For example, adding variable rate sprinklers to existing center pivot irrigation.

In addition, some of these technologies, such as satellites with sensors that can measure evapotranspiration, could also be used to remotely monitor water use to facilitate compliance with existing water laws by federal, state, or local entities, according to some experts in water policy and a USGS report. Similarly, any changes in water policy could be monitored for their effectiveness over time.

Challenges. Federal policymakers should be aware that several barriers exist to implementing precision agriculture technologies, including connectivity, complexity, and lack of expertise. Connectivity, such as cellular or broadband, is not universally available. According to the Federal Communications Commission, around a third of rural Americans lacked access to fixed terrestrial broadband in 2018. A lack of network connectivity can make these technologies too labor intensive to operate, but the ability to remotely access data from fields without having to manually check individual data collection technologies facilitates using the data in irrigation decisions. Additionally, some farmers may not find the information generated by these technologies to be usable. Farmers told us that information may not be standardized, or may not be displayed in a form that leads to actionable decisions. Finally, without accompanying policies incentivizing the conservation of water, water saved on the field level may not translate directly to water conserved on the larger watershed level.

7 Agency and expert comments

We provided a draft of this report to three federal agencies for review and comment. They were the U.S. Department of Agriculture, Department of the Interior, and the Environmental Protection Agency. Although we made no recommendations in this technology assessment report, the agencies were asked for feedback on the draft in its entirety.

We invited the 19 participants from our meetings of experts to review our draft report. We asked them to review the draft with respect to factual accuracy, scientific and technical quality, and for errors of omission. Of the 9 participants who responded, 4 provided technical comments.

We are sending copies of this report to the appropriate congressional committees, relevant federal agencies, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Timothy M. Persons at (202) 512-6412 or personst@gao.gov or Steve D. Morris at (202) 512-3841 or morriss@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VII.

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Appendix I Objectives, scope, and methodology

Because of current and potential future freshwater scarcity in the United States, we were asked to conduct a technology assessment of current and developing technologies that could reduce water use and address water scarcity in the energy, municipal water, and agricultural sectors.[133] In response to that request, this report focuses on the agricultural water sector in water stressed areas and discusses (1) irrigation technologies and practices that could reduce water applied, (2) factors that influence the adoption of efficient irrigation technology, and (3) how efficient irrigation technologies impact water conservation. We also determined options that federal policymakers could consider based on our findings from those three objectives.

For all three objectives, we limited the scope of our review to irrigation technologies and practices used on open cropland, such as row and field crops, fruits, and nuts. We did not include technologies and practices used in landscaping, or other areas of agriculture, such as aquaculture, livestock, or in covered agriculture (greenhouses). We did not assess agriculture's impact on water quality. In addition, we did not include the nontechnology approaches, such as rate structures and pricing strategies, or water purchases from another entity.

We reviewed reports; documents; and scientific literature including conference papers, articles published in peer reviewed journals or written by federal and state agencies, nonprofit organizations, and industry; and relevant books describing irrigation technologies, practices, and their uses. We reviewed relative efficiencies of various irrigation technologies and practices, including differences in use by crop type and region, among other things. We attended multiple technical conferences and workshops to gather data and learn about the latest irrigation technologies and practices. These included the Soil and Water Conservation Society Annual Conference in 2017; the Irrigation Association Show and Education Conference in 2017; and a Soil and Water Assessment Tool Workshop. We interviewed officials from the U.S. Department of Agriculture (USDA), including the Economic Research Service and Natural Resources Conservation Service, in addition to state extension agents to learn how the federal government supports irrigation technology and practices and how these technologies and practices may be used to conserve water. We also interviewed officials from the Department of the Interior, including the Bureau of Reclamation and United States Geological Survey, and the Environmental Protection Agency to learn about how they monitor water sources that may be used for irrigation. Additionally, we interviewed representatives from industry, such as irrigation

[133]Technology Assessments to address the energy sector and municipal sector from this request are: *Technology Assessment: Water in the Energy Sector: Reducing Freshwater Use in Hydraulic Fracturing and Thermoelectric Power Plant Cooling,* GAO-15-545 (Washington, D.C.: Aug. 7, 2015), *Technology Assessment: Municipal Freshwater Scarcity: Using Technology to Improve Distribution System Efficiency and Tap Nontraditional Water Sources,* GAO-16-474 (Washington, D.C.: Apr. 29, 2016)

equipment and precision agriculture technology designers, academia, and farmers in Nebraska and California to learn about irrigation equipment and practices in the field.

To learn about irrigation technologies, practices, and the decision process for choosing them, we visited farmers, academics, extension agents, and industry representatives on two trips, one to California and one to Nebraska. The sites were selected based on, among other things, the types of irrigation, crops grown, and if farms were operating, along with availability of individuals or organizations to meet with us. We were able to see different types of irrigation and practices used in operation during our visits. While the information we gathered during our site visits with farmers does not represent a generalizable sample of types of irrigation technologies and practices used, farmers gave us additional insight into why they chose to use certain irrigation technologies and practices.

We collaborated with the National Academies of Sciences, Engineering, and Medicine (National Academies) to convene a 2-day meeting with 19 experts to discuss irrigation technologies and practices and what impacts they might have on water scarcity. These experts were selected from federal government agencies, academia, farmers, and industry, with expertise covering the significant areas of our review. We included among the experts (1) those that had irrigation technology expertise, (2) those with expertise in water conservation practices or other technology experience, (3) those with expertise on water policy and other broad areas of water and agriculture, and (4) farmers. These experts were identified by the National Academies as having sufficient knowledge or experience in these technologies to discuss the issues addressed in this report, and they expressed a willingness to participate in this meeting. We asked experts at our meeting to identify any potential conflicts of interest, which were considered to be any current financial or other interest that might conflict with the service of an individual because it could impair objectivity. The group of experts as a whole was judged to have no inappropriate biases. This meeting of experts was planned and convened with the assistance of the National Academy of Science to better ensure that a breadth of expertise was brought to bear in its preparation, however all final decisions regarding meeting substance and expert participation are the responsibility of GAO. Any conclusions and recommendations in GAO reports are solely those of the GAO. The experts are listed in appendix VI. In addition to these experts we had an additional participant from USDA, Hamid Farahani, who provided an additional perspective during this meeting and throughout our review. During this meeting, we solicited input from the experts on the topics of our work. In particular, we moderated discussion on the areas listed above. The meeting was recorded and transcribed to ensure that we accurately captured the experts' statements. After the meeting, we used the transcripts (1) to add greater depth to our discussion of technologies, practices, and farmer behavior, among other things and (2) to summarize broader perspectives on economic, legal and oversight, and social or equity issues that contribute to agriculture's demand on water. To add greater depth to our objectives, we used the discussion topics from the agenda and keyword searches to focus our review of the transcript to add expert comments to each objective as appropriate. To summarize broader perspectives on agriculture's water demand, we used the strategic implications session of the transcript to identify related experts' comments and group them. Following the meeting, we continued to draw on the expertise of these individuals who agreed to work with us during the rest of our study. Consistent with our quality assurance framework, we provided those experts with a draft of our report and solicited their comments, which we incorporated as appropriate.

Descriptive statistics of technologies

To determine the number and type of irrigation equipment used and any change in the number of farms using irrigation scheduling from precision agriculture technologies, we used summary descriptive statistics from the USDA's Farm and Ranch Irrigation Survey (FRIS).[134] We used data from the 1998, 2003, 2008, and 2013 surveys to develop descriptive statistics, such as the use of irrigation scheduling. We determined these surveys were reliable enough for the purposes of supplementing other evidentiary sources to develop findings and would not be used to make recommendations. We used an adjusted coverage weight for the 1998 survey year that a USDA statistician created for us in order to compare across years. We also corrected for changes in the surveys across years where appropriate, such as removing horticulture (greenhouses) irrigation, because it was out of our scope. Within this technology assessment, we provided standard error bars where necessary when using the survey data.

Some additional data limitations are based on what USDA publishes in their survey methodology and errors for each survey year of their data. According to USDA, because FRIS contains both farm and non-farm records, the response rate is an indicator of replying to the data collection effort, but does not reflect whether those responding met the farm definition or had the items of interest for the survey. For example, in 2013, they note that the response rate for the 2013 survey was 77.8 percent, compared to 79.4 percent in 2008. USDA also reported that the statistics in their reports are estimates derived from a sample survey. There are two types of errors possible in an estimate-based sample survey: sampling and nonsampling. Sampling error is the error caused by observing only a sample instead of the entire population. The sampling error is subject to sample-to-sample variation. Nonsampling errors include all other errors and can arise from many different sources. These sources may include respondent or enumerator error or incorrect data keying, editing, or imputing for missing data. Nonsampling error due to

[134]Once every five years, the USDA surveys the people who operate U.S. farms and ranches, called the Census of Agriculture. From the Census of Agriculture, the USDA selects a subset of irrigators for a follow-up survey called the Irrigation and Water Management Survey (prior to 2018 called the Farm and Ranch Irrigation Survey). The USDA National Agricultural Statistics Survey (NASS) publishes aggregate statistics from the FRIS survey. We chose to conduct our analysis at a NASS data lab using microdata of individual farmer survey responses because publically available data were too coarse for the purpose of our analysis. In 2013, the sample size of the FRIS survey increased to approximately 35,000 farms.

mail list incompleteness and duplication, as well as misclassification of records on the mail list, is referred to as coverage error.   One potential source is undercoverage that could arise due to farms that erroneously report specific factors, such as not irrigating. Another potential source is overcoverage that could arise if a farm decides to stop irrigating in the survey year.

Literature review of the economic studies on the determinants for farmer adoption of irrigation and precision agriculture technology

To determine factors leading to the adoption of more efficient irrigation technology, we conducted an economic literature search of selected databases, including ProQuest, Scopus, and Ag Econ Search. We used search terms, such as “technology adoption, “irrigation technology adoption,” and “agricultural technology adoption,” and various combinations of these words to search in peer-reviewed literature, working papers, government reports, and other published research articles. First, we identified several foundational agricultural technology adoption papers to understand the historical evolution of technology adoption in agriculture in general and to understand the drivers of technology adoption . During our review of the remaining irrigation technology adoption literature, we identified and reviewed 23 articles that met the following criteria: (1) they were based on research conducted and published in the United States, (2) , they were primarily published since the year 2000, and (3) contained empirical analyses or conceptual analysis of the determinants of irrigation-based technology adoption. Of these 23 articles, we eliminated 2 articles because of limitations, such as lack of rigor and transparency based on the key elements of economic analysis from a prior GAO report.[135] The irrigation technology adoption studies included various irrigation technologies, crop types, geographic locations, databases, methods and models, and specific topics dealing with irrigation technology adoption.

Furthermore to determine what factors influence the adoption of precision agriculture technology, we conducted an economic literature search of selected databases, including ProQuest, Scopus, and Ag Econ Search using search terms, such as “precision agriculture” “irrigation” and “variable rate technology” and “technology adoption” and combinations of these words in peer-reviewed literature, working papers, government reports, and other published research articles. Similar to the selection criteria for irrigation-related technology adoption, the criteria for irrigation-related precision agriculture adoption included: (1) they were based on research conducted and published in the United States, (2) they were primarily published since the year 2000, and (3) they contained empirical analyses or conceptual analysis of the determinants of irrigation-based precision agriculture technology adoption. We also identified and reviewed 13 domestic precision agriculture irrigation technology adoption studies which met our criteria. For more information on our economic literature review, see Appendix III.

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[135]GAO, *Assessment Methodology for Economic Analysis*, GAO-18-151SP (Washington, D.C.: April 2018).

Simulations of irrigation scenarios in a sample watershed

To assess the potential impacts of efficient irrigation scheduling, we used the Soil and Water Assessment Tool (SWAT), a computer model that simulates hydrological outcomes under specified land management scenarios. We applied the model to a watershed in south central Nebraska covered by corn, soybeans and rangeland. We simulated two scenarios. In the first scenario, we simulated farmers switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland. In the second scenario, we simulated farmers converting non-irrigated rangeland to cornfields irrigated with efficient scheduling. For each scenario, we examined the impact of efficient irrigation scheduling on the amount of irrigation water applied to the field, the return flow that reaches streams, the amount of water consumed through evapotranspiration and crop yield. The results of our simulations suggest that efficient irrigation scheduling could decrease the amount of irrigation water applied to the field, assuming that farmers do not expand their irrigated cropland. However, our results also suggest that efficient irrigation scheduling could increase the amount of water consumed through evapotranspiration if farmers do subsequently expand their irrigated cropland. To evaluate our results, we calibrated the model to local data on crop yield, irrigation amounts, and planting dates and we tested the sensitivity of our results to these inputs. Based on this, we believe our simulations reliably illustrate the potential impacts of efficient irrigation scheduling in one of the most highly irrigated regions of the country. However, our results are not generalizable to other locations or to other crops nor are they precise quantitative forecasts. For more information on our simulations of irrigation scenarios using SWAT, see Appendix IV.

Regression analysis of USDA data

In order to assess both the potential to conserve water and the realized association between irrigation technology and on-farm water use, we estimated two sets of models:

- "Water" model: Examined the rate of water applied on a per acre basis (e.g., holding area constant) for farmland switched to a more efficient technology to grow the same crop (i.e. holding crop constant).
- "Yield" model: Examined crop production on a per acre basis. For select crops, as a proxy for yield, we examined fertilization practices that can enhance yields.

These models attempt to identify the changes associated with more efficient irrigation technology both for water—when holding crop and acres constant (water per acre) and for yield (crop production per acre. We examined these outcomes to identify potential benefits of efficient technologies, and to assess the extent that yield and water application rate could be factors that link technology to water consumption on the farm. We applied inferences across multiple models based on the irrigation efficiency literature and broader literature assessing behavioral responses to more efficient technology.[136] One study about low-energy precision application sprinkler technology in Kansas summarized the overall intuition of these responses: "More efficient irrigation technology generally increases the 'effectiveness' of a unit of water, but it also can lead to changes in yields, crop choices, crop rotation patterns, or expand irrigated acreage."[137] Our results are consistent with this view and extend the scope of evidence across a range of technology conversions, crop types, and regions. As such, our models examine relationships between irrigation technologies and the amount of water applied per acre and crop yields.

Our main estimation strategy across both water and yield models was difference-in-differences and aimed to better understand how changes in water use could be associated with the adoption of more efficient irrigation technology. These models use repeated observations of farms to compare the change in water use and crop yields over time for a treatment group – farms that use more efficient irrigation over time—to a group—farms that always use the same technology.

All variables are based on data for four years—1998, 2003, 2008, and 2013—including irrigation, crop, and technology variables from the FRIS, and climate variables from the PRISM Climate Group.[138] FRIS is a survey of roughly 25,000 irrigators every five years that asks about irrigation technology and on-farm water use, and includes information about amount of water and land devoted to irrigate specific crops or other activities across a farm.[139] Because FRIS was not administered as a longitudinal survey, we took several additional steps to prepare the dataset used for our models. To create a panel dataset, we matched farms across survey years and restricted our sample to farms with at least two repeated observations. We further restricted our sample to irrigators operating in the 17 western states to focus our analysis on regions affected by water scarcity.

[136] Part of this literature attempts to compare the technical potential, realized savings, and behavioral mechanisms that influence resource consumption under more efficient technologies. Our study mimics the research design used in the transportation, energy, water literature.

[137] See Pfeiffer, Lisa & Lin Lawell, C.-Y. Cynthia. (2013). "Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction?: Empirical Evidence." *Journal of Environmental Economics and Management.* We adopted an approach that was similar to the methods used in this study.

[138] To account for weather within each state, we added PRISM climate data. We used variables such as monthly or annual averages for total precipitation (inches), daily mean temperature (degrees Fahrenheit), daily maximum temperature (degrees Fahrenheit), and maximum vapor pressure deficit. We reviewed related documentation on the PRISM data, and we found these data to be sufficiently reliable for our purposes.

[139] Once every five years, the USDA surveys the people who operate U.S. farms and ranches, called the Census of Agriculture. From the Census of Agriculture, the USDA selects a subset of irrigators for a follow-up survey called the Irrigation and Water Management Survey (prior to 2018 called the Farm and Ranch Irrigation Survey). The USDA National Agricultural Statistics Survey (NASS) publishes aggregate statistics from the FRIS survey. We chose to conduct our analysis at a NASS data lab using microdata of individual farmer survey responses because publically available data were too coarse for the purpose of our analysis.

All crop-level models used an unbalanced panel dataset with 1–15 crops for each farm per year and 2–4 years of data. Crop-level variables include information on acres harvested, water applied per acre, yields, and the primary system used to irrigate each crop. Farm-level information from FRIS includes total volume of water from different sources (e.g., wells and off-farm sources), acres of land in each technology, acres of total land area (including non-irrigated land). For more information on our regression analysis of the FRIS, see Appendix V.

Policy options

We identified two policy options related to technologies and practices that could reduce the impact of irrigated agriculture in locations facing water scarcity in the United States. The goal of reducing the impact of irrigated agriculture in locations facing water scarcity in the U.S. was specified in the request for GAO to conduct this study. Local jurisdictions may have differing goals when facilitating the use of irrigation technologies. We identified policy options related to technologies and practices that could reduce the impact of irrigated agriculture in locations facing water scarcity in the United States, especially those that could be affected by change at the federal level. GAO has not evaluated the effectiveness of these options, and expresses no view regarding the extent to which statutory or regulatory changes would be needed to implement them. We also limited our set of options to those resulting from the findings from our objectives (or scope), but recognize that there may be other policy options unrelated to irrigation technology or practices. First, we assessed irrigation technologies and practices to determine if they could be used to save water in our first objective. This assessment led us to develop the first policy option, with the recognition that some programs already exist that could meet this end. We also found that while more efficient irrigation technology and practices exist, they may not be used in the most efficient way, especially with respect to when to irrigate. We assessed technologies and practices that would enable irrigation scheduling in a more efficient way, which are collectively called precision agriculture. This led us to develop the second policy option, with the recognition that some programs already exist that could meet this end. From our second and third objective, we determined through our economic literature review that farmers are driven to maximize efficiency for productivity gains and therefore profit, which could be counterproductive if the goal is to maximize water conservation. This led us to include challenges acknowledging that without accompanying policies that incentivize saving water, increased irrigation efficiency may not translate to less water consumed at the larger watershed level. We also asked 3 of our experts in water policy and USDA officials to review the policy options and incorporated their comments as appropriate.

We conducted our work from June 2017 to November 2019 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II Select federal programs relating to agricultural water conservation

The table shows a select number of federal programs, a description of the program, and examples of initiatives under that program.[140]

Table 9: Select federal programs relating to water scarcity and agriculture

Program and Federal Agency	Description	Examples of Initiatives
Environmental Quality Incentives Program *U.S. Department of Agriculture – Natural Resources Conservation Service*	The program is to, among other goals: • assist farmers with complying with regulatory requirements concerning surface and groundwater conservation. • provide assistance to farmers to install and maintain conservation practices that sustain production while enhancing soil, water, and related natural resources.	According to the USDA Conservation Innovation Grants projects include: • $1.9M grant to the Nature Conservancy CA (2017) to use data analytics and water markets to meet water conservation goals. • $1.4M grant to Trout Unlimited (2017) to develop and pilot investment opportunities to improve agricultural water sustainability in the Colorado River Basin. • $950K grant to Auburn University (2017) to demonstrate technologies such as variable rate irrigation, sensor-based irrigation scheduling, and deficit irrigation—to reduce water withdrawals and enhance producers' profitability. • $800K grant to Flint River Soil and Water Conservation District (2017) to maximize agricultural production and minimize impacts to natural resources through integrating precision irrigation technologies to demonstrate variable rate irrigation.
Conservation Technical Assistance Program *U.S. Department of Agriculture – Natural Resources Conservation Service*	According to the USDA, one purpose of the program is to protect and improve water quality and quantity. Technical assistance provided through this program related to irrigation efficiency has included practices to assist in properly designing, installing and maintaining irrigation systems to ensure uniform and efficient distribution of water.	• According to USDA data, in FY 2018, the program had 319,625 acres receiving conservation for irrigation efficiency practices.

[140]The table shows select programs, and is not intended to be comprehensive.

Program and Federal Agency	Description	Examples of Initiatives
Agricultural Management Assistance *U.S. Department of Agriculture – Natural Resources Conservation Service, Agricultural Marketing Service, and Risk Management Agency*	This program provides financial assistance to farmers in 16 states, including 3 western states (Nevada, Utah, and Wyoming) to construct or improve water management and irrigation structures, among other things.	• According to USDA data, in FY 2018, 17,284 acres receiving a conservation practice related to irrigation efficiency. • Between FY 2009- FY 2018, under acres receiving conservation for irrigation efficiency, 32% of acres for irrigation pipeline, 26% acres with micro irrigation, and 16% towards sprinkler irrigation, among other practices.
Regional Conservation Partnership Program *U.S. Department of Agriculture – Natural Resources Conservation Service*	One of the regional conservation partnership program's purposes is to further the conservation, protection, restoration, and sustainable use of water, among other resources.	According to the USDA, projects in Fiscal Year 2018 include: • $10M proposed investment for a project in Arizona partnering with the Gila River Indian Community to address insufficient water supply and related problems. Project will work to reduce water losses and maintain ground and surface water balances to ensure the long-term sustainability of water quantity. • $3.7M proposed for a California project partnering with a conservation district to conserve water by incentivizing deficit irrigation and organic production, to (among other things) help conserve water for Lake Mead, which is at critically low levels. • $4.9M proposed for an Oregon project partnering with tribes to improve irrigation efficiency to conserve water and increase flow while enhancing overall watershed health. Project includes irrigation efficiency improvements, among other things.
Conservation Stewardship Program *U.S. Department of Agriculture – Natural Resources Conservation Service*	This program's purpose is to encourage farmers to address priority resource concerns and improve and conserve the quality and condition of natural resources in a comprehensive manner. According to USDA, in fiscal year 2019, the program included a resource concern of insufficient water.	• According to the USDA, in fiscal year 2018, the program obligated over $1M in technical and financial assistance. Activities under the program include advanced automated irrigation water management using soil moister or water level monitoring and no till to increase plant available moisture.

Program and Federal Agency	Description	Examples of Initiatives
WaterSMART *U.S. Department of the Interior – the Bureau of Reclamation and the U.S. Geological Survey*	According to Department of the Interior, WaterSMART grants provide cost-shared funding on a competitive basis to non-Federal partners to implement, among other things, projects to conserve water and increase water use efficiency.	According to Department of the Interior, projects include: • Watsonville Area Water Recycling Project provides 4,000 acre-feet of recycled water per year for irrigation. • As of 2016, Three Sisters Irrigation District in Oregon is converting open ditches to pipe through a grant, with an expected result of 1,850 acre-feet of water annually.
Pilot System Conservation Program *U.S. Department of the Interior – Bureau of Reclamation is a Federal Partner*	Partnered with water districts to test water conservation concepts that reduce water use and help to determine if voluntary, measurable reductions in consumptive use of Colorado River water constitute a feasible and cost-effective approach to partially mitigate the impacts of long-term drought on the Colorado River System.	• According to the Bureau of Reclamation, projects related to irrigation, among other things, include deficit irrigation and fallowing land.

Source: GAO analysis of USDA and Interior information. | GAO-20-128SP

Appendix III Literature review of the economic studies on the determinants for farmer adoption of irrigation and precision agriculture technology

We reviewed the agricultural economics literature primarily from 2000 to the present on factors leading to the adoption of more efficient irrigation technology. For example, what would determine a farmer's actual individual adoption behavior or why would one farmer adopt a new irrigation technology while another would not. Specifically, we first looked at several articles that examined technology adoption in general and some seminal articles of technology adoption in irrigation technology adoption. We reviewed 21 studies from the year 2000 to the present which looked at U.S. irrigation technology adoption and 13 that examined domestic irrigation-related precision agriculture technology adoption. All studies were identified from peer-reviewed journal articles, peer-reviewed conference papers, or government reports. Most were empirical analyses while some were historical articles or conceptual on this subject. For an explanation of how these studies were selected and reviewed, see the OSM in Appendix I. Table 10 displays a list of the articles that we reviewed and a summary of the crop and irrigation or precision agriculture technologies that each study examined.

Table 10: Economic studies reviewed for determinants of irrigation and precision agriculture technology adoption

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
	Irrigation Technology Adoption Studies	
Predicting drip irrigation use and adoption in a desert region	R.K. Skaggs, *Agricultural Water Management*, 2001	Chili peppers, New Mexico Adoption and attitudes toward drip irrigation and advanced irrigation technologies.
Climate, Water, and Agriculture	Robert Mendelsohn and Ariel Dinar, *Land Economics*, Aug. 2003	All crops, across the counties of the United States Probability of using either gravity, sprinkler, or drip
Irrigation Technology Adoption and Gains from Water Trading under Asymmetric Information	Chokri Dridi and Madhu Khanna, *American Journal of Agricultural Economics*, May, 2005	Fruits and Vegetables, Arizona and Southern California Adoption of traditional (furrow) versus modern irrigation technology (sprinkler or drip)
Joint Estimation of Technology Adoption and Land Allocation with Implications for the Design of Conservation Policy	Georgina Moreno and David L. Sunding, *American Journal of Agricultural Economics*, 2005	Citrus, deciduous, vines, truck, and field crops, the major crop categories produced in the study area of Kern County, California. (1) high-efficiency, low-pressure irrigation technologies such as drip and micro sprinkler systems, (2) traditional gravity or furrow technology, and (3) high-pressure sprinkler technologies

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
The Effects of Climatic Variability on US Irrigation Adoption	Donald H. Negri, Noel R. Gollehon and Marcel P. Aillery, *Climatic Change,* 2005	Agricultural Resource Management Survey (ARMS) data for corn, soybeans, and cotton for 24 states, mostly southern and central United States. Irrigation adoption versus dryland
Off-Farm Income, Technology Adoption, and Farm Economic Performance	Jorge Fernandez-Cornejo et al, Economic Research Service/USDA, January 2007	2000 data set in 17 soybean (corn) producing states Combinations of off-farm work and technologies of varying managerial intensity, including herbicide-tolerant crops, precision agriculture, conservation tillage, and Bt (Bacillus thuringiensis) corn
Irrigation Technology Adoption and Its Implication for Water Conservation in the Texas High Plains: A Real Options Approach	Sangtaek Seo, Eduardo Segarra, Paul D. Mitchell, and David J. Leatham; *Agricultural Economics* 2008	Irrigated cotton in Lubbock County in the Texas High Plains (contains irrigated and non-irrigated farmland. Entry and exit of Low Energy Precision Agriculture (LEPA) systems.
Irrigation Technology Adoption Under Factor Price Uncertainty: Groundwater-Irrigated Production in Nebraska, 1960 -- 2005	Jeff Savage and Nicholas Brozović, Selected Paper Agricultural & Applied Economics Association's 2009 Meetings	Irrigated corn, dryland corn, wheat, sorghum, soybeans, and small grains in the High Plains region of Nebraska. Switch from dryland production to groundwater irrigated production using center-pivot technology
Dynamic Adjustment of Irrigation Technology/Water Management in Western U.S. Agriculture: Toward a Sustainable Future	Glenn D. Schaible, C.S. Kim, and Marcel P. Aillery, Canadian Journal of Agricultural Economics 58, 2010	Data from the Farm and Ranch Irrigation Survey (FRIS), NASS 1984–2003, for the 17 Western states, all crops For 3 different levels of conserving gravity irrigation and conserving pressure (sprinkler and drip/trickle) irrigation.
Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands	Glenn D. Schaible and Marcel P. Aillery; EIB-99, Economic Research Service, U.S. Department of Agriculture September 2012	Extensive literature review plus USDA's Censuses of Agriculture (1982-2007) and FRIS for 1984-2008**,** 17 Western and 31 Eastern States. Covers shift away from gravity to more efficient irrigation systems such as sprinkler, drip, and LEPA systems.
Farm Size, Irrigation Practices, and Conservation Program Participation in the US Southwest	George B. Frisvold and Shailaja Deva, Irrigation and Drainage, 61, October 2012	Arizona and New Mexico data from the USDA FRIS (Farm and Ranch Irrigation survey) to test economic hypotheses concerning irrigator behavior. The authors examine the relationship between farm size and (i) sources and uses of water management information, (ii) barriers to improving irrigation systems, and (iii) participation in government conservation programs.
Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction? Empirical Evidence	Lisa Pfeiffer and C.-Y. Cynthia Lin, *Journal of Environmental Economics and Management* 67, 2014	Kansas monocrops including corn, alfalfa, wheat, soybeans, and sorghum. The effect of conversions from center pivot to dropped nozzle irrigation center pivot.

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
Subsurface Drip Irrigation in California - Here to Stay?	J. E. Ayars, A. Fulton, and B. Taylor; *Agricultural Water Management*, 157, January 2015	The study highlights previous research and case studies from CA existing commercial operations for four crops --processing tomatoes, French prunes, almonds, and walnuts. Adoption of subsurface drip irrigation
Adoption of Irrigation Technology and Best Management Practices under Climate Risks: Evidence from Arkansas, United States	Ying Xu, Qiuqiong Huang, and Grant West; Selected Paper prepared for the Southern Agricultural Economics Association's 2015 Annual Meeting, Atlanta, Georgia, January 31-February 3, 2015	USDA FRIS and Census of Agriculture for 1988, 1994, 1998, 2003 and 2008 and represents 2,140 farm-level observations for corn and cotton in the state of Arkansas. Considers adoption of sprinkler versus dis-adoption of gravity. Looks at six alternatives/technology packages of best management practices (BMPs) with gravity and sprinkler irrigation.
Irrigation Decisions for Major West Coast Crops: Water Scarcity and Climatic Determinants	Beau Olen; JunJie Wu; Christian Langpap *American Journal of Agricultural Economics*, Volume 98, Issue 1, 1 January 2016.	West Coast (California, Oregon, Washington) farms that grow at least one of the regions' six major crops, including specialty crops (orchard/vineyard and vegetable), wheat, and forage crops (alfalfa, hay, and pasture). Adoption of discrete irrigation technologies --gravity, sprinkler, or drip.
Irrigation Water Sources and Irrigation Application Methods Used by U.S. Plant Nursery Producers	Paudel, K. P., M. Pandit, and R. Hinson, *Water Resources Research*, 52, 698–712, February 2016	Nursery plants from the National Nursery Survey, 2009 – trees plants/shrubs; bedding plants, vines, foliage, and other. For 4 U.S. regions of the U.S. -- the Midwest, Pacific, Northeast, Southeast. They looked at overhead, drip, sub-irrigation, and other irrigation methods.
Irrigation Technology Choice as Adaptation to Climate Change in the Western United States	George Frisvold and Ting Bai; *Journal of Contemporary Water Research & Education*, Issue 158, August 2016	A special tabulation of the 1998 and 2008 USDA Farm and Ranch Irrigation Survey (FRIS) for 17 Western States. Proportion of acreage irrigated (all crops in Western States, except drip). Authors focus on choice between gravity flow and sprinkler irrigation.
Diffusion of Drip Irrigation: The Case of California	Rebecca Taylor and David Zilberman, *Applied Economic Perspectives and Policy* 39 (1) January 2017	Review of literature. Looked at high value crops from California. Drip irrigation technology.
Analysis of Factors that Influence the Use of Irrigation Technologies and Water Management Practices in Arkansas	Qiuqiong Huang, Ying Xu, Kent Kovacs, and Grant West; *Journal of Agricultural and Applied Economics*, 49, 2 April 2017	Major crops in Arkansas including rice, soybeans, corn, cotton, and others. Gravity irrigation or Sprinkler irrigation. Also, combinations of (1) gravity irrigation without any water management practices (WMP), (2) gravity irrigation with one or more WMPs, and (3) sprinkler irrigation.
Dealing with Water Scarcity: California Avocado Growers Adopting Water Saving Technologies and Management Practices	Julie Reints, Ariel Dinar, and David Crowley; University of California Riverside, Working Paper Series, May 2017, WP#17-02	Avocado production in California Discrete bundles of water management practices and irrigation technology combinations systems

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
Rebound Effects of New Irrigation Technologies: The Role of Water Rights	Haoyang Li and Jinhua Zhao, *American. Journal Agricultural. Economics* 100(3): March, 2018	Ogallala High Plains Aquifer region of Kansas for corn, soybeans, alfalfa, wheat, sorghum, fallow/dryland, and other crops. The adoption of LEPA replacing center pivot irrigation.
Irrigation-related Precision Agriculture Adoption Studies		
Factors Affecting the Location of Precision Farming Technology Adoption in Tennessee	Roland K. Roberts, Burton C. English, and James A. Larson; *Journal of Extension,* Vol. 40, No. 1, University of Kentucky, 2002	Likelihood of adoption in all 95 Tennessee counties. A yield monitor with Global Positioning System (GPS), yield monitor without GPS, grid soil sampling, variable rate fertilizer or lime application and any precision ag technology.
Economic Feasibility of Precision Irrigation in the North Texas High Plains	Almas, Lal K., Steven H. Amosson, Thomas Marek, W. Arden Collete; Paper for the Southern Agricultural Economics Association Annual Meeting, Mobile, Alabama, February 1-5, 2003	For grain crops – corn, sorghum, soybeans and wheat in the North Texas High Plains. Assessed the economic feasibility of alternative variable rate irrigation (VRI) controller technology.
Farm and Operator Characteristics Affecting the Awareness and Adoption of Precision Agriculture Technologies in the US	Stan G. Daberkow and William D. McBride, *Precision Agriculture*, 4(2), June, 2003	Farm types included cash grains and oilseeds, vegetables, fruits and nuts, and other crops in all regions of the U.S. from the ARMS survey – U.S. agricultural sector. Farmers adopting one or more of precision ag technologies including grid soil mapping, input applications at variable rates, yield monitoring, yield mapping, and remote sensing
Adoption of Site-Specific Information and Variable-Rate Technologies in Cotton Precision Farming	Roland K. Roberts, Burton C. English, James A. Larson, Rebecca L. Cochran, W. Robert Goodman, Sherry L. Larkin, Michele C. Marra, Steven W. Martin, W. Donald Shurley, and Jeanne M. Reeves; *Journal of Agricultural and Applied Economics*, 36, 1 (April 2004)	Cotton farmers in the Southeastern U.S. -- Alabama, Florida, Georgia, Mississippi, North Carolina, and Tennessee in 2001 Site-specific information technology and variable rate technology.
Factors Influencing the Adoption of Precision Agricultural Technologies: A Review for Policy Implications	Yeong Sheng Tey and Mark Brindal, *Precision Agriculture* July (2012) 13	Review of the literature for precision agriculture adoption in “experienced” (had experience in irrigation) countries. Review of the literature on various precision technologies such as GPS, yield monitoring systems, remote sensing systems, soil sampling regimens, and variable rate applicators.

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
Adoption and Non-adoption of Precision Farming Technologies by Cotton Farmers	Mahesh Pandit, Krishna P. Paudel, Ashok K. Mishra, and Eduardo Segarra, Selected Paper from the Agricultural & Applied Economics Association 2012 Annual Meetings, August 12-14, 2012	2009 Southern Cotton Precision Farming Survey collected from farmers in twelve U.S. States (Alabama, Arkansas, Florida, Georgia, Louisiana, Missouri, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia). Precision agriculture in general -- did not specify precision agriculture technology in study but noted survey in Mooney et al. University of Tennessee, May 2010.
Adoption of Site-Specific Variable Rate Sprinkler Irrigation Systems	Robert G. Evans, Jake LaRue, Kenneth C. Stone, and Bradley A. King; *Irrigation Science*, 31, 2013	General conceptual article gives a historical overview of site-specific variable rate sprinkler systems. No particular crop or location. Advanced site-specific variable rate irrigation systems (SS-VRI) technologies for center pivot and linear move sprinkler systems
The Impact of Water Price Uncertainty on the Adoption of Precision Irrigation Systems	Karina Schoengold and David L. Sunding; *Agricultural Economics* 45, 2014	A region in California that contains a mix of crops including perennial crops such as grapes and oranges, annual crops such as carrots and onions, and field crops such as hay and alfalfa. The type of irrigation system used in that area includes drip, sprinkler, gravity, and micro-sprinkler. The authors define precision agriculture as drip or sprinkler.
Bundled Adoption of Precision Agriculture Technologies by Cotton Producers	Dayton M. Lambert, Krishna P. Paudel, and James A. Larson; *Journal of Agricultural and Resource Economics* 40 (2), 2015	Cotton production in 2013 for the states of Alabama, Arkansas, Florida, Georgia, Kansas, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. Yield monitors, grid soil sampling, zone soil sampling, soil electrical conductivity, digital map use, aerial imagery, satellite imagery, soil survey maps, handheld GPS devices, and the decision aid COTMAN.
Sequential Adoption and Cost Savings from Precision Agriculture	David Schimmelpfennig and Robert Ebel; *Journal of Agricultural and Resource Economics* 41, January 2016.	USDA's ARMS of corn producers for corn-producing regions of the U.S. Three adoption scenarios including various combinations of yield monitoring, yield mapping, GPS soil properties mapping, and machinery auto-guidance systems (GSYS).

Title of study	Author(s), Journal, Year	Crop, Location and Type of Irrigation or Precision Agriculture Technology
Factors Influencing the Adoption of Precision Agriculture Technologies by Nebraska Producers	Castle, Michael H.; Bradley D Lubben; and Joe D Luck; Presentations, Working Papers, and Gray Literature: *Agricultural Economics*. 49, Spring 2016.	Nebraska row crop farmers (predominately corn and soybeans). Usage of a cell phone with internet access, GPS guidance, auto-steer, variable rate technology, automatic section control, satellite/aerial imagery, chlorophyll/greenness sensors, soil sampling, yield monitor, and prescription maps.
Farm Profits and Adoption of Precision Agriculture	David Schimmelpfennig, Economic Research Service (ERS); ERR 217, Oct., 2016	National data – adoption model of corn farms from the ARMS of USDA. Information mapping, variable rate systems, and guidance systems.
Productivity and Profitability of Precision Agriculture Technologies on Peanut Farms	Monica Saavoss, Paper given at the Southern Agricultural Economics Annual Meetings, Jacksonville, FL, February 2 - 4, 2018.	Nationwide ARMS USDA survey of peanuts and rice producers. The three binary treatments considered in this article are adoption of soil maps, adoption of guidance systems, and adoption of variable rate applicators.

Source: GAO analysis of literature presented in table | GAO-20-128SP

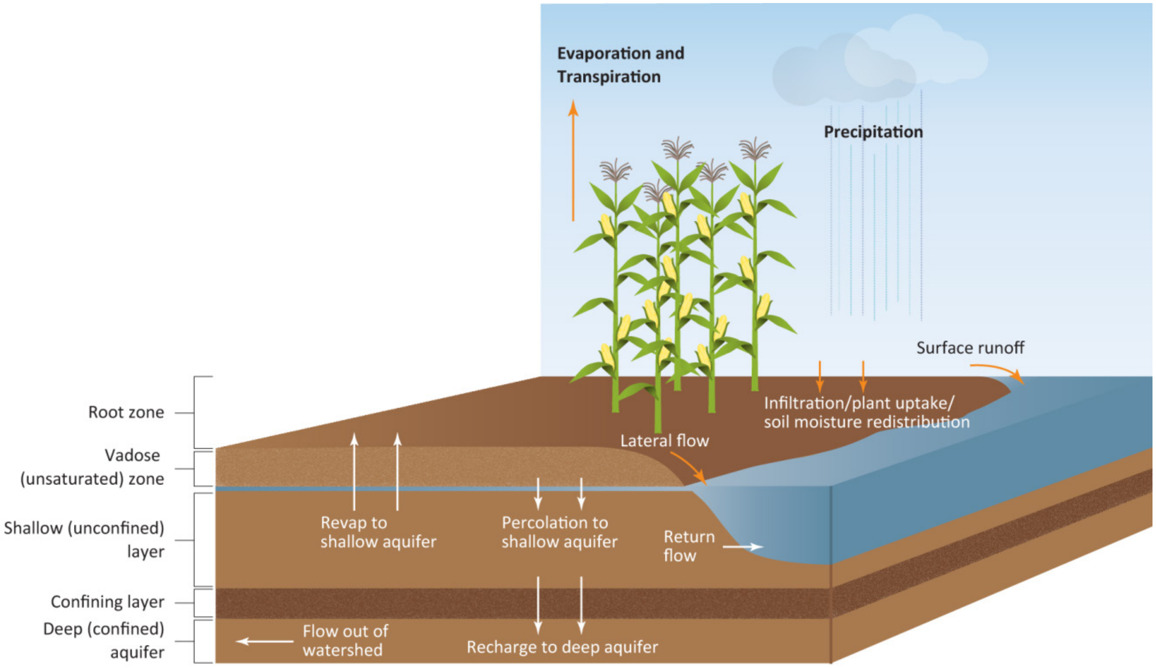
Appendix IV Simulations of irrigation scenarios in sample watershed

To assess the potential impacts of efficient irrigation scheduling, we used the Soil and Water Assessment Tool (SWAT), a computer model that simulates hydrological outcomes under specified land management scenarios. We applied the model to a watershed in South Central Nebraska covered by corn, soybeans and rangeland. We simulated two scenarios. In the first scenario, we simulated farmers switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland. In the second scenario, we simulated farmers converting non-irrigated rangeland to cornfields irrigated with efficient scheduling. For each scenario, we examined the impact of efficient irrigation scheduling on the amount of irrigation water applied to the field, the return flow that reaches streams, the amount of water consumed through evapotranspiration and crop yield. We calibrated the model to local data on crop yield, irrigation amounts, and planting dates and we tested the sensitivity of our results to these inputs. The results of our simulations suggest that efficient irrigation scheduling could decrease the amount of irrigation water applied to the field, assuming that farmers do not expand their irrigated cropland. However, our results also suggest that efficient irrigation scheduling could increase the amount of water consumed through evapotranspiration if farmers do subsequently expand their irrigated cropland. We believe our simulations reliably illustrate the potential impacts of efficient irrigation scheduling in one of the most highly irrigated regions of the country. However, our results are not generalizable to other locations or to other crops nor are they precise quantitative forecasts.

Watershed simulation model

The SWAT is a computer model that can be used to predict the long-term impact of land management practices in a watershed. The SWAT model simulates the flow of water in the watershed, as illustrated in figure 29. By varying the assumptions about these land management practices, such as the methods that farmers use to irrigate their crops, it is possible to simulate the impact of efficient irrigation practices on hydrological outcomes, such as the amount of irrigation water that leaves the watershed through evapotranspiration, the amount that returns to the stream and the amount that percolates into the groundwater. Researchers at Texas A&M University and USDA developed the SWAT model and the model has been used for more than 25 years and has resulted in more than 2,500 peer-reviewed publications.

Figure 29: Elements of the hydrological cycle captured by the SWAT model



Source: GAO presentation of output of HAWQS 1.0 (Hydrologic and Water Quality System). US EPA (2017). HAWQS 1.0 (Hydrologic and Water Quality System) Modeling Framework. Office of Water, Washington, D.C. https://www.epa.gov/hawqs. Accessed 31 July 2019. | GAO-20-128SP

To run our simulations in the SWAT model, we used empirical data for a watershed in South Central Nebraska covered by corn, soybeans and rangeland. A watershed is a geographic area within which all surface water drains to a single point, such as a river outlet. For our analysis, we selected a watershed at the 8-digit Hydrological Unit Code (HUC) level, which is also called a sub-basin. There are 2,270 8-digit HUC watersheds in the United States. We selected Nebraska because it is one of the most heavily irrigated areas in the country. We applied the model to cornfields in the selected watershed because corn is the most heavily irrigated crop in the state. The selected watershed allowed us to simulate the potential impacts of efficient irrigation scheduling across a range of soil types and a range of weather conditions.

To prepare the input data for our selected watershed, we downloaded a SWAT project database from the Hydrologic and Water Quality System (HAWQS). HAWQS is a web-based implementation of the SWAT model hosted by the United States Environmental Protection Agency (USEPA) Office of Water and supported by the USEPA, Texas A&M University Spatial Sciences Laboratory and USDA.[141] To characterize major soil types in the watershed, our project database contained data from the Digital General Soil Map of the U.S., commonly referred to as STATSGO, which was developed by the National Cooperative Soil Survey. To represent land cover in the watershed, it contained data from the National Land Cover Dataset, developed by

[141] US EPA (2017). HAWQS 1.0 (Hydrologic and Water Quality System) Modeling Framework. Office of Water, Washington, D.C. https://www.epa.gov/hawqs.

the Multi-Resolution Land Characteristics consortium of federal agencies, and the Cropland Data Layer (CDL), developed by the National Agricultural Statistics Service of the U.S. Department of Agriculture. To characterize weather in the watershed, it contained data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for 1980-2015, developed by the PRISM Climate Group at Oregon State University. We assessed the classification accuracy of these databases and determined that they were sufficiently reliable for our purpose of creating a SWAT project database to simulate irrigation scenarios.

Irrigation scenarios

To gauge the potential impact of efficient irrigation scheduling, we simulated two scenarios. In the first scenario, we modeled farmers switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland. In the second scenario, we modeled farmers converting non-irrigated rangeland to cornfields irrigated with efficient scheduling. This scenario approximated farmers using some of the water they save from efficient irrigation practices to expand their irrigated cropland. We selected non-irrigated rangeland for this scenario for two reasons. First, rangeland was the most prevalent land cover in our selected watershed other than corn or soybeans. Second, expansions of irrigated cropland have been common in our study area, according to the U.S. Census of Agriculture.

To simulate conventional irrigation scheduling, we instructed the model to apply irrigation water to the field in 2-inch increments at regular time intervals. We varied the number of irrigation applications from year to year based on precipitation. This approximated farmers applying the total amount of irrigation water they have historically applied in the region based on a fixed schedule. For each year, we calculated the amount of precipitation during the peak of the growing season, which we defined as May through August. We then subtracted this number from the total amount of water that corn requires to reach maturity, which we determined to be approximately 26 inches in our study area. For example, we instructed the SWAT model to apply 8 inches of irrigation water in 1996, which had approximately 19 inches of precipitation during the growing season, and to apply 16 inches of irrigation water in 2003, which had approximately 10 inches of precipitation.

To simulate efficient irrigation scheduling, we specified the SWAT model to apply a fixed amount of irrigation water when the plant water demand reached a certain threshold. This approximated farmers using technology, such as moisture sensors, to determine when to irrigate. We tested 21 combinations of irrigation amounts and thresholds for plant water demand. Specifically, we tested irrigation amounts between 1.0 inches and 3.0 inches in quarter-inch increments and thresholds in which the available water met between 50% and 95% of the plant's water demand. We removed combinations that caused crops to experience more than 5 days of water stress and those that caused a reduction in yield to differ by more than 1% of the crop yield simulated with conventional irrigation scheduling. Among the remaining combinations, applying 2.0 inches of water when the available water reached 95% of the plant's water demand produced the median total irrigation water applied. Therefore, we used this combination to represent efficient irrigation scheduling.

To test the sensitivity of our results to our assumptions about conventional and efficient irrigation scheduling, we also modeled our scenarios with alternative specifications. For the alternative specification of conventional irrigation scheduling, we assumed that corn would require 24 inches of water during the growing season, rather than 26 inches. For the alternative specification of efficient irrigation scheduling, we selected the combination of irrigation amount and plant water demand that met our constraints on water stress and crop yield but that produced the highest total amount of irrigation water applied. We then estimated the impacts of efficient irrigation scheduling using these alternative specifications and found that they were consistent with the direction and consistency of impacts we reported from our primary model specification.

Model calibration

In addition to specifying the irrigation amounts, as described above, we calibrated the model to historical data on several parameters. First, we adjusted the parameters in the model that govern crop planting and crop growth, namely, the number of heat units at which planting occurs and the number of heat units at which the crop reaches maturity.[142] Of the values for these parameters that we tested, specifying crops to reach maturity at 1700 heat units and specifying planting to occur at 0.15 of the total heat units best replicated the empirical data. Second, we assumed that farmers would draw their irrigation water from the underground aquifer. Based on estimates from the U.S. Geological Survey in 2015, most of the irrigation water used for agriculture in Nebraska is withdrawn from wells. In addition, we instructed the model to apply sufficient fertilizer so that crop growth was not constrained by nutrient stress.

We assessed the extent to which our simulations of conventional irrigation scheduling replicated historical estimates of crop yield, the amount of irrigation water applied and planting dates. To determine historical crop yields and the amount of irrigation water applied, we analyzed responses to the USDA/NASS Farm and Ranch Irrigation Survey for a statistical sample of farmers in the counties that encompass our selected watershed. We analyzed responses to survey questions about corn yield on irrigated land and the amount of irrigation water applied for 1998, 2003, 2008 and 2013, the four years with available data from this survey. We calculated the 95% confidence intervals for each estimate for each of the four years. We determined these data were sufficiently reliable for calibrating the SWAT model for our simulations. To determine historical planting dates, we examined a USDA/NASS publication on the usual planting dates for corn in Nebraska.[143] We compared our simulated estimates to these

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[142] A heat unit is a measure of the amount of heat that a crop receives during the growing season.

[143] USDA National Agricultural Statistics Service. Field Crops: Usual Planting and Harvesting Dates. Agricultural Handbook Number 628. October 2010.

historical estimates and found that they were similar. Crop yield under our conventional irrigation simulation was within the 95% confidence interval of the estimated historical crop yield in 2 of the 4 years for years we analyzed (table 11). The amount of irrigation water applied was also within the 95% confidence interval in 3 of the 4 years (table 12). Finally, the simulated planting dates ranged between April 25 and May 22, depending on the year of the simulation, as compared to the USDA/NASS estimates that farmers in Nebraska usually plant corn between April 19 and May 21. Based on the correspondence between our simulated and historical estimates, we determined that the specifications for our simulations were reasonable.

Table 11: Simulated crop yield under conventional irrigation scheduling compared to estimated historical crop yield for our selected watershed

Year	Simulated corn yield (bushels/acre)[a]	Estimated historical corn yield in counties that encompass the watershed (bushels/acre)[b]		
		lower bound[c]	mean	upper bound[d]
1998	169	149	159	169
2003	173	180	186	192
2008	179	169	180	191
2013	161	198	203	208

Source: GAO | GAO-20-128SP

[a]The mean crop yield across corn fields in the selected watershed for our baseline simulation with the Soil and Water Assessment Tool (SWAT) model.

[b]Based on our analysis of data from the USDA/NASS Farm and Ranch Irrigation Survey for the counties that encompass the selected watershed in Nebraska.

[c]Represents the lower bound of 95% confidence interval.

[d]Represents the upper bound of 95% confidence interval.

Table 12: Simulated amount of irrigation water applied under conventional irrigation scheduling compared to estimated historical amount for our selected watershed

Year	Simulated amount of irrigation water applied in watershed (inches/year)[a]	Estimated historical total irrigation water applied in counties that encompass the watershed (inches/year)[b]		
		lower bound[c]	mean	upper bound[d]
1998	12	8.6	11.2	13.7
2003	16	11.6	14.9	18.2
2008	8	9.0	10.9	12.8
2013	12	11.7	13.3	15.0

Source: GAO | GAO-20-128SP

[a]Based on our analysis of PRISM data for the selected watershed used in the SWAT model, the amount of precipitation between May and August for these years was approximately 13.5, 9.9, 22.0 and 13.3 inches, respectively.

[b]Based on our analysis of data from the USDA/NASS Farm and Ranch Irrigation Survey for the counties that encompass the selected watershed in Nebraska.

[c]Represents the lower bound of 95% confidence interval.

[d]Represents the upper bound of 95% confidence interval.

Model implementation

To ensure that we executed these simulations appropriately, we attended training on the SWAT model and we collaborated with a developer of the model. Specifically, two GAO analysts completed beginning and advanced training on the SWAT model at Texas A&M University in College Station, Texas in April and May 2018. To refine our analysis, we conducted telephone interviews with a developer of the SWAT model, Professor Raghavan Srinivasan at Texas A&M University, on four occasions between 2018 and 2019 and we met with him for two days in June 2019 in at Texas A&M University. Professor Srinivasan and his colleagues reviewed our analysis.

To verify that the model was functioning correctly, we took several additional steps. Two analysts independently conducted the simulations and compared their results to verify the accuracy of the model implementation. We conducted basic validity tests of the model output to ensure the model was functioning correctly. For example, we examined our simulations to make sure that crop growth was unconstrained by nutrient stress or water stress. In addition, we examined our results across the range of soil types and range of weather conditions to confirm that the results were reasonable.

For each scenario, we calculated the percentage of change in the amount of water applied to cornfields, the amount of return flow to the stream, the amount of water consumed through evapotranspiration and the amount of crop yield between 1986 and 2015. We treated the model results for each unique combination of year and soil type as an independent case in our analysis. We excluded two years—1993 and 2012--because precipitation in those years exceeded the bounds of empirical data we used for model calibration. Because there were 28 valid years in our simulations and 7 soil types in our study area, our simulations produced 196 cases. By examining the data in this manner, we sought to evaluate the potential impacts of efficient irrigation scheduling under a range of soil types and a range of weather conditions. To characterize this range, we report the 2.5th percentile, median and 97.5th percentile values across the 196 data points for each of the four outcomes. These ranges capture natural variability across different soil types and weather conditions but not uncertainty in the simulated estimates.

Results

The results of our simulations showed that efficient irrigation scheduling could decrease the amount of water applied to crops, decrease the amount of return flow and increase the amount of water consumed through evapotranspiration. These effects depended upon whether we compared efficient irrigation scheduling to conventional irrigation scheduling on existing cropland or whether we compared efficient irrigation scheduling to non-irrigated rangeland. The magnitude of these effects differed based on soil type and based on level of precipitation but the direction of these effects was consistent across different soil types and different years in our simulations. We provide these quantitative results to illustrate the potential order-of-magnitude effects of adopting efficient irrigation practices, rather than as precise estimates or forecasts of these effects.

Our simulations in which farmers switched from conventional irrigation scheduling to efficient irrigation scheduling on existing cornfields suggested that efficient irrigation scheduling could decrease the amount of water applied to crops, but in doing so, could also decrease the amount of return flow. Specifically, in these simulations, switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland reduced the amount of irrigation water applied to crops by roughly 20% to 100% per year, depending on the type of soil and weather conditions (table 13).

Because farmers could apply less water to their crops with efficient irrigation scheduling, we found that the amount of return flow to streams could also decrease. In our simulations, switching from conventional irrigation scheduling to efficient irrigation scheduling on existing cropland reduced return flows by roughly 35% to 99% per year, depending on the type of soil and weather conditions (table 13).

Table 13: Simulated impact of switching from conventional irrigation scheduling to efficient irrigation scheduling on cornfields in selected watershed, 1986-2015[a]

	Change in simulated outcomes		
Outcome[b]	2.5^{th} percentile	Median	97.5^{th} percentile
Crop yield	1% decrease	no change	1% increase
Evapotranspiration	7% decrease	2% decrease	3% increase
Irrigation water applied	100% decrease	63% decrease	20% decrease
Return flows	99% decrease	87% decrease	35% decrease

Source: GAO | GAO-20-128SP

[a]These results are based on simulations we conducted using the Soil and Water Assessment Tool (SWAT) model for a watershed in south central Nebraska. Because of the nature of the simulations, they approximate the order-of-magnitude of the potential impacts of switching from conventional irrigation scheduling to efficient irrigation scheduling on cornfields but are not precise estimates or forecasts of these impacts.

[b]Columns represent the 2.5^{th} percentile, median, and 97.5^{th} percentile, respectively, of the percentage change in each outcome for the 28 years and 7 soil types of the simulation (n=196). These ranges capture natural variability across different soil types and weather conditions but not uncertainty in the simulated estimates. We excluded two years – 1993 and 2012 – because precipitation in those years exceeded the bounds of empirical data we used for model calibration.

Our simulations in which farmers converted non-irrigated rangeland to cornfields irrigated with efficient scheduling suggested that efficient irrigation scheduling could increase the amount of water consumed through evapotranspiration and could decrease the amount of return flow. Specifically, in our simulations, we found that converting non-irrigated rangeland to cornfields irrigated with efficient irrigation scheduling could increase evapotranspiration by roughly 52% to

134%, depending on soil type and weather conditions (table 14). At the same time, our simulations estimated that such conversions could reduce the amount of return flow to streams by roughly 58% to 99%.

Table 14: Simulated impact of converting non-irrigated rangeland to cornfields irrigated with efficient scheduling in selected watershed, 1986-2015[a]

	Change in simulated outcomes		
Outcome[b]	2.5th percentile	Median	97.5th percentile
Crop yield	NA[c]	NA	NA
Evapotranspiration	52% increase	97% increase	134% increase
Irrigation water applied	NA	NA	NA
Return flows	99% decrease	87% decrease	50% decrease

Source: GAO | GAO-20-128SP

[a]These results are based on simulations we conducted using the Soil and Water Assessment Tool (SWAT) model for a watershed in South Central Nebraska. Because of the nature of the simulations, they approximate the order-of-magnitude of the potential impacts of converting non-irrigated rangeland to cornfields irrigated with efficient scheduling but are not precise estimates or forecasts of these impacts.

[b]Columns represent the 2.5th percentile, median, and 97.5th percentile, respectively, of the percentage change in each outcome for the 28 years and 7 soil types of the simulation (n=196). These ranges capture natural variability across different soil types and weather conditions but not uncertainty in the simulated estimates. We excluded two years – 1993 and 2012 – because precipitation in those years exceeded the bounds of empirical data we used for model calibration.

[c]The change in crop yield and the change in irrigation water applied could not be calculated because non-irrigated rangeland does not produce corn or receive irrigation water.

Strengths and limitations

This analysis is subject to certain strengths and certain limitations. In terms of strengths, this analysis is based on an established watershed hydrological model and captures the potential impacts of efficient irrigation scheduling on a range of soil types and under a range of weather conditions. Furthermore, our simulations provided a reasonable replication of planting dates, crop yield and the amount of irrigation water applied in the study area and our results were robust to an alternative model specification. At the same time, this analysis required us to make certain assumptions about both conventional and efficient irrigation practices and we lack sufficient information to calculate the uncertainty surrounding our estimates. Therefore, we believe our simulations are sufficient to approximate the order-of-magnitude of potential impacts of efficient irrigation scheduling on corn in this region but they are not precise estimates or forecasts of these impacts.

Appendix V Regression analysis of USDA data

Scope and data

We developed two sets of models to analyze water applied associated with irrigation technologies. These models attempt to identify the changes associated with more efficient irrigation technology both for water–when holding crop and acres constant (water per acre) – and for yield (crop production per acre). We examine these outcomes to identify potential benefits of efficient technologies, and to assess the extent that yield and water application rate could be factors that link technology to water consumption on the farm. We applied inferences across multiple models based on the irrigation efficiency literature and broader literature assessing behavioral responses to more efficient technology.[144] One study about low-energy precision application sprinkler technology in Kansas summarized the overall intuition of these responses: “More efficient irrigation technology generally increases the ‘effectiveness’ of a unit of water, but it also can lead to changes in yields, crop choices, crop rotation patterns, or expand irrigated acreage.”[145] Our results are consistent with this view and extend the scope of evidence across a range of technology conversions, crop types, and regions. As such, our models examine relationships between irrigation technologies and the amount of water applied per acre and crop yields.

Our objective was to assess both the potential to conserve water and the realized associations between irrigation technology and other factors that could influence on-farm water consumption, including yield and fertilization practices. We estimated two sets of models:

- “Water” models: These models examine the rate of water applied per acre.
- “Yield” models: These models examine crop production on a per acre basis. For select crops, as a proxy for yield, we examine fertilization practices that can enhance yields.

Our main estimation strategy across both water and yield models was difference-in-differences and aimed to better understand how changes in water applied could be associated with the adoption of more efficient irrigation technology. These models use repeated observations of farms to compare the change in water applied and crop yields over time for a treatment group – farms that use more efficient irrigation over time--to a comparison group–farms that always use

[144] Part of this literature attempts to compare the technical potential, realized savings, and behavioral mechanisms that influence resource consumption under more efficient technologies. Our study mimics the research design used in the transportation, energy, water literature.

[145] See Pfeiffer, Lisa & Lin Lawell, C.-Y. Cynthia. (2013). “Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction?: Empirical Evidence.” *Journal of Environmental Economics and Management.* We adopted an approach that was similar to the methods used in this study.

the same technology. See figure 30 for a selection of illustrative results from our crop-level difference-in-differences model.[146]

All variables are based on data for four years—1998, 2003, 2008, and 2013—including irrigation, crop, and technology variables from the Farm and Ranch Irrigation Survey (FRIS), and climate variables from the PRISM Climate Group.[147] FRIS is a survey of roughly 25,000 irrigators every five years that asks about irrigation technology and on-farm water use, and includes information about amount of water and land devoted to irrigate specific crops or other activities across a farm.[148] Because FRIS was not administered as a longitudinal survey, we took several additional steps to prepare the dataset used for our models. To create a panel dataset, we matched farms across survey years and restricted our sample to farms with at least two repeated observations. We further restricted our sample to irrigators operating in the 17 western states to focus our analysis on regions affected by water scarcity.

All crop-level models used an unbalanced panel dataset with 1–15 crops for each farm per year and 2–4 years of data. Crop-level information for each farm includes acres harvested, volumes of water applied per acre, yields, and the primary system used to irrigate each crop. Farm-level information from FRIS includes total volume of water from different sources (e.g., wells and off-farm sources), acres of land in each technology, and acres of total land area (including non-irrigated land).

Methods

Crop models: change in primary irrigation technology

For our crop models, to control for crop and irrigated area, we created data with a unit-of-observation at the crop-farm-year level and the main dependent variable is water per acre for the crop using a particular technology. For each of crop, we modeled the relevant irrigation technology conversions (ranging from 1 to 4 relevant conversions per crop). This includes a set of many models because each crop and irrigation technology is a separate model.

[146] Not all technology conversions were modeled for all crops. We only report findings for crops that had an adequate number of technology conversions to provide sufficient power to estimate effects (a sample of at least 13 farms for a particular type of technology conversion).

[147] We reviewed related documentation on the PRISM data, and we found these data to be sufficiently reliable for our purposes.

[148] Once every five years, the USDA surveys the people who operate U.S. farms and ranches, called the Census of Agriculture. From the Census of Agriculture, the USDA selects a subset of irrigators for a follow-up survey called the Irrigation and Water Management Survey (prior to 2018 called the Farm and Ranch Irrigation Survey). The USDA National Agricultural Statistics Survey (NASS) publishes aggregate statistics from the FRIS survey. We chose to conduct our analysis at a NASS data lab using microdata of individual farmer survey responses because publically available data were too coarse for the purpose of our analysis. In 2013, the sample size of the FRIS survey increased to approximately 35,000 farms.

Because irrigation systems may be chosen for reasons other than water conservation, we identified specific technology pairings that may be associated with improvements in irrigation efficiency. We initially categorized irrigation systems into three categories: micro irrigation, sprinkler, and gravity.[149] These categories and several sub-categories were used to define efficiency improving technology conversions as follows:

- Micro irrigation conversions, which include conversions from gravity to micro irrigation and from sprinkler to micro irrigation, were most common for specialty crops, such as orchards, vineyards, and vegetables.
- Sprinkler conversions, which include conversions from gravity to sprinkler systems, and sprinkler conversions designed to lower water pressure, were most prevalent with crops, such as corn, wheat, hay, or alfalfa. These same crops were also associated with gravity systems upgraded from unlined furrows to lined furrows or pipes.
- Comparison groups for each conversion were matched based on crop and original irrigation technology, with all comparison records maintaining the same sub-category of technology over time.

We ran the "water" and "yield" models separately on data for each set of crop and technology upgrade pairings. For example, to assess gravity to sprinkler upgrades for alfalfa crops, we ran models for a sample of farms that produced alfalfa and had an opportunity to convert from gravity to sprinkler. This sample of alfalfa-producing farms included both a treatment group of farms that upgraded from gravity to sprinkler and a comparison group of farms that always used gravity.

For each crop and technology upgrade pairing, we applied a fixed effects model with dependent variables of either water applied per acre or yield, and controls similar to those used in Pfeiffer and Lin (2014) and Li and Zhao (2018).[150] For example, the regression equation for one of these models is:

$$Water\ per\ Acre_{icjt} = \beta_{0_{ic}} + \beta_{1_{st}} + \beta_2 \left[EfficiencyUpgrade_{icj} * Post_{ict}\right] + \beta_3 Climate_{it} + \beta_4 WaterAccess_{ict} + \varepsilon_{icjt}$$

[149] Irrigation technology examined include: gravity irrigation, which was further categorized as unlined, lined, or piped gravity; sprinkler irrigation, which was further categorized by pressure; and micro irrigation. Crop-level technology variables are based on the primary system used to irrigate each crop.

[150] See Li, Haoyang & Zhao, Jinhua. (2018). "Rebound Effects of New Irrigation Technologies: The Role of Water Rights." *American Journal of Agricultural Economics.*

See Pfeiffer, Lisa & Lin Lawell, C.-Y. Cynthia. (2013). "Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction?: Empirical Evidence." *Journal of Environmental Economics and Management.*

- $Water\ per\ Acre_{ictj}$ is the annual rate of water application for farm i, crop c, year t, and upgrade j;
- $\beta_{0_{ic}}$ are fixed effects for the farm X crop;
- $\beta_{1_{st}}$ are fixed effects for the year X state;
- $[EfficiencyUpgrade_{icj} * Post_{ict}]$ is a dummy variable equal to one for all periods after technology upgrade for croplands that experienced an efficiency improving technology upgrade of type j, and equal to zero otherwise;
- β_2 is the coefficient of interest indicating the association between irrigation technology upgrade j, and water applied per acre for crop c;
- $Climate_{it}$ are controls for county-level climate factors such as, precipitation, which is expected to reduce irrigation needs, or temperature and humidity, which could jointly affect crop water needs;
- $WaterAccess_{ict}$ are controls for factors related to a farm's water access that may vary over time, such as the source of irrigation water or depth of wells; and
- ε_{icjt} is an error term clustered by farm.

Yield information (as a dependent variable) was also of interest since farmers may improve irrigation efficiency in order to boost crop production, rather than conserve water. Because yields can only be directly compared for the same crop, we used similar models to identify associations between primary irrigation technology and crop yields. [151]

Results and limitations

We estimated each of our crop-level models with alternative weighting functions, including a model without weights and a model using the area of irrigated land as weights. We report the direction of associations between irrigation technology conversions, water applied, and yields across relevant crops for a number of changes in primary irrigation technology. Specifically, we report on the sign of parameters estimates that were statistically significant at the 10 percent level or lower for at least one model (see figure 30). Our crop-level models suggest that—when holding the crop constant—more efficient irrigation technology was sometimes associated with either less water applied per acre, or higher yields, or a higher probability of fertilizing with an irrigation system, compared to conventional technologies used to grow the same crop. These

[151] For crops without information on yields, we used a binary variable indicating whether fertilizer was applied through irrigation systems – a practice that can increase yields – as a proxy for yield. Specifically, we used a logistic model with random effects at the farm-by-crop-level to estimate the change in likelihood of applying fertilizer through an irrigation system associated with conversion to a more efficient irrigation system. The model includes similar controls as the two-way fixed effects model. These yield and fertigation results add to existing literature, since leading studies, such as Pfeiffer and Lin (2014) lack the information needed to estimate effects on yield.

results are consistent across relevant crops for some technologies, such as conversions to micro irrigation.

In addition, crop level results suggest that upgrades to some types of irrigation technology conversions – such as conversions to low-pressure sprinklers or from gravity to micro irrigation– are associated with higher yields for some crops. The crops for which we find gains in yield were not associated with reduced water applied, a result that could indicate a tradeoff between use of efficiency gains to achieve water conservation or yield improvements. Specifically, our results suggest that conversions to low pressure sprinklers are associated with higher yields for three major field crops—corn, cotton, and sorghum. As another example, our results suggest that gravity systems upgraded to micro irrigation are associated with higher yields for tomatoes, and an increased probability of adding fertilizer to irrigation water for orchards, vineyards, and vegetables – a practice that may increase yields. These results are generally consistent with qualitative economic literature characterizing adoption of micro irrigation systems.

The results of our crop-level model did not identify associations between changes in primary irrigation technology and water applied and yield for some crops and technologies. For example, since upgrades from gravity to sprinkler systems are relatively common upgrades in our data, the lack of an association with water applied per acre could suggest that these upgrades have limited potential to conserve water. Similarly, we did not find changes in yield or water for some of the most prevalent crops with technology upgrades, such as wheat. In these cases, since we do not find associations for either water or yield, our results could also reflect the weaker associations from efficiency gains that have dual effects – on water conservation and yield improvement – that offset one another.

For figure 30, symbols indicate sign of coefficients with statistical significance of 10% or lower, where: (+) indicates a positive coefficient; (–) indicates a negative coefficient; a grey dot indicates a coefficient that was not statistically significant at the 10% level; and grey boxes indicate a crop-technology pairing with an inadequate sample size of fewer than 13 treated farms. Logit estimates are indicated by an asterisk (*) following the sign of coefficients with statistical significance.

Figure 30: Results for water per acre and yield by crop and technology improvement for select crops

	Gravity to Micro irrigation		Sprinkler to Micro irrigation	
	Water	Yield	Water	Yield
Vegetables	●	+*	–	●
Orchard/ Vineyard	–	+*	–	●
Tomato[a]	●	+	■	■

	To Low Pressure Sprinkler		Lower Sprinkler Pressure		More Efficient Gravity		Gravity to Sprinkler	
	Water	Yield	Water	Yield	Water	Yield	Water	Yield
Corn	●	+	–	●	■	■	●	●
Cotton	●	+	●	●	●	●	●	●
Sorghum	●	+	●	+	■	■	●	●
Wheat	●	●	●	●	●	●	●	●
Alfalfa	●	●	●	●	●	●	●	+
Hay	■	■	●	●	–	●	●	●

Source: GAO analysis of USDA Farm and Ranch Irrigation data. | GAO-20-128SP

Note: Symbols indicate sign of coefficients with statistical significance of 10% or lower, where: (**+**) indicates a positive coefficient; (**–**) indicates a negative coefficient; a grey dot indicates a coefficient that was not statistically significant at the 10% level; and grey boxes indicate a crop-technology pairing with an inadequate sample size of fewer than 13 treated farms. Logit estimates are indicated by an asterisk (*****) following the sign of coefficients with statistical significance. Each cell represents a difference in difference estimate (water per acre or yield) from a model that was either unweighted or weighted by acres based on a crop-technology specific sample. All OLS models included fixed effects for farm-by-crop and for year-by-state, and controls for climate and farm characteristics. Standard errors were clustered by farm-by-crop and sample size varied across models. We present select crops based on the relevance to specific technology conversions because not all crops experience all technology conversions in our sample. For crops without yield information - vegetables and orchards/vineyards - yield cells represent marginal effects estimates for the likelihood of fertilizing crops through irrigation systems estimated from a random effects logit model with similar controls as OLS models (excluding fixed effects for farm-by-crop).
[a] Tomatoes are also included as a subset of vegetables for our analysis.

Taken together, results for yield and use of fertigation collectively suggest that technology upgrades may be associated with increased crop production in some circumstances. Crop production could influence local water availability, since it can increase the amount of water consumed through evapotranspiration.

Since, our crop-level models assess outcomes on a per acre basis when changing technology to grow the same crop, these results aim to approximate a setting where a farmer replaces irrigation systems with a more efficient one to conserve water or improve yields. As such, our models may not reflect some other reasons why a farmer might adopt efficient technology, such as expanding irrigated area, switching to more water intensive crops, or otherwise using water savings to increase on-farm revenues. We also did not control for potential endogeneity in the decision to adopt an efficient technology.

Implicit in our difference-in-difference modeling approach is the assumption that treatment and comparison farms are reasonably similar—as a result, differences across groups related to selection into treatments, simultaneity bias, or mis-specified decision making, could introduce bias into results. We interpret our results in light of these potential limitations. Specifically, we do not interpret model results as precise estimates of effects on water consumption or yields, but rather to inform the strength and direction of associations based on agreement across models, technologies, and crops, and how those associations, in concert with other evidence, can improve understanding of the implications of adopting more efficient irrigation technology.

We mitigate risks associated with estimating this type of model by developing the model in the context of the well-established technology impact literature. That said, some inevitable limitations remain, including the potential omission of important factors related to technology selection and other approximations associated with our specification (e.g. our choice of linear functional form). Second, since primary technology may not characterize the technology used on all lands to grow a crop, our decision to treat all cropland switching to more efficient primary technology as "treated" may understate the extent of effects of the efficiency improvement.

While the panel data allows us to control for individual fixed effects, year effects that vary by state, and heteroskedasticity and intra-group correlation in the disturbances, our panel data based on FRIS is imperfect. First, in the context of panel data with few time periods and self-reported survey responses that provide imperfect measures, our models have potential to be underpowered with estimates biased towards zero. At the same time, results of our panel model for crop-level water applied and yield found associations that are consistent across a variety of settings, so the data were adequate to generate meaningful results. Second, since we exclude irrigators without repeated surveys, our panel dataset is not representative of all irrigators, so results based on these data may not be generalizable to all contexts. None-the-less, our results remain useful for understanding the strength and directions of associations, and how they could vary across technologies and crops.

Appendix VI List of experts

We collaborated with the National Academies to convene a two-day meeting of experts to inform our work on irrigation technologies and practices and how they impact water scarcity. The meeting was held on May 24-25, 2018. The experts who participated in our study are listed below. Many of these experts gave us additional assistance throughout our work, including four experts who reviewed our draft report for accuracy and provided technical comments.

Martha Anderson
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Steven Evett
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Dwane Roth
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Donald Sanborn
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Glenn Schaible
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Appendix VII GAO contact and staff acknowledgments

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In addition to the contacts named above, William Carrigg (Assistant Director), Jenn Beddor (Analyst-In-Charge), Steven Aguilar, Pille Anvelt, Ivelisse Aviles, Mark Braza, Lacey Coppage, Barbara El Osta, Dani Greene, Joe Maher, Anika McMillon, Jon Melhus, Katrina Pekar-Carpenter, Sam Portnow, Ben Shouse, Elaine Vaurio, and staff from GAO's Natural Resources and Environment team made key contributions to this report. Emma Bingham, Taylor Camacho, Nirmal Chaudhary, Philip Farah, Sarah Gilliland, Hayden Huang, Dennis Mayo, Rebecca Parkhurst, Kayla Robinson, Judy Schneider, Walter Vance, and Robert Ward also contributed to this report.

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Technology Assessment: Internet of Things: Status and implications of an increasingly connected world. GAO-17-75. Washington, D.C.: May 15, 2017.

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