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Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline — 2018 Update

Energy Systems Division

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Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline — 2018 Update

by
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NOTATION

API	American Petroleum Institute
bbl	barrel
bbl/d	barrel per day
BC	Biochemical conversion.
BTX	Benzene, Toluene, and Xylene
CAPP	Canadian Association of Petroleum Producers
CO_2	Carbon dioxide
CT	Consolidated tailings
CSS	Cyclic steam stimulation
DDGS	Distillers dried grain and solubles
DOE	U.S. Department of Energy
E&P	Extraction and production
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EOR	Enhanced oil recovery
ET	Evapotranspiration
ft	feet
gal	gallons
gal/d	gallons per day
GHG	Greenhouse gas
LCA	Life-cycle analysis
MFT	Mature fine tailings
mln	million
NASS	National Agricultural Statistics Service
NEB	National Energy Board
NGO	Non-governmental organization
NRC	National Research Council
NREL	National Renewable Energy Laboratory
O&GJ	Oil and Gas Journal
PADD	Petroleum Administration for Defense District
PW	Produced water
PWTO	Produced water-to-oil ratio

RFA	Renewable Fuels Association
SAGD	Steam-assisted gravity drainage
SUSRIS	Saudi–U.S. Relations Information Service
TC	Thermochemical conversion
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WDG	Wet distillers grain

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CONSUMPTIVE WATER USE IN THE PRODUCTION OF ETHANOL AND PETROLEUM GASOLINE — 2018 UPDATE

UPDATE NOTES

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The 2018 update of the report includes water consumption data for the production of petroleum oil and ethanol feedstock that have become available since this report was last updated in 2011. This effort covers corn irrigation water withdrawal and consumption, corn acreages and yield, petroleum oil recovery, produced water management, and regional analyses. In the biofuel sections, this update incorporates state agriculture water-use data for corn in production year 2013. National land use and corn production data were extracted from Agriculture Census 2012 and the U.S. Department of Agriculture (USDA) National Agriculture Statistics Service (NASS) database. Irrigation data were estimated based on the 2013 USDA Farm and Ranch Irrigation Survey (FRIS) and a 2015 U.S. Geological Survey (USGS) report (Dieter et al. 2018a). Analysis of state level of water withdrawal and consumption for corn for 1998, 2003, 2008, and 2013 are further aggregated to the USDA region level for comparison. Results are summarized in Sections 3.1.1 and 3.1.4.

Several in-depth studies on water consumption in the various life stages of oil production have been published over the past decade. Water use estimated by Goodwin et al. (2012) and Mangmeechai et al. (2014) investigated site-specific horizontal and vertical oil wells in the State of Colorado. Veil (2015) developed a produced-water management report documenting state-level water to oil ratios and produced-water reinjection practices based on 2012 data. Ali and Kumar (2017) compared five major onshore and offshore oil-producing sites across the United States, Canada, and Mexico. These studies yielded valuable information about the state of technology and water management in the production processes and are the main sources of new data for this update. This update is based on production year 2014. States and the Petroleum Administration for Defense Districts (PADD) regional production data are extracted from the Energy Information Administration (EIA). These updates are presented in Sections 4.2.1–4.2.3, and 4.6.

The following sections and associated tables and figures are affected by the 2018 update:

- Executive Summary:
  - Table S-1, S-1.
- Introduction:
  - Figure 2,
  - Table 1.
- Section 3.1.1, Corn Irrigation:
  - Figures 9, 10, 11, 12, 13, and 14;
  - Table 4.

- Section 3.1.4, Consumptive Water Use in the Major Steps of Corn Ethanol Life Cycle:
  – Figure 19,
  – Table 5.
- Section 4.2, Onshore Recovery of Domestic Crude Oil:
  – Figures 25, 26, 27, 28, and 29;
  – Tables 7, 8, 9, 10, 11, 12, and 13.
- Section 4.6. Water Consumption in Major Steps of the Gasoline Life Cycle:
  – Table 16.
- Section 6, Conclusion:
  – Figure 39.

CONSUMPTIVE WATER USE IN THE PRODUCTION OF ETHANOL AND PETROLEUM GASOLINE — 2011 UPDATE

UPDATE NOTES

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In 2008, when the original version of this report was issued, the U.S. Department of Agriculture (USDA) conducted a major national irrigation survey and made the results available to the public in late 2009. The original version of this report was issued before those results were available. Ethanol production increased steadily in the past few years, reaching the EISA-mandated production goal. Meanwhile, the agricultural community made improvements in irrigation management and practice, with particular emphasis on water conservation in some of the relatively arid regions. In terms of ethanol plants, construction of newer plants with efficient process design continues to drive water consumption lower. For these reasons, we feel that it is the time for an update to reflect current water consumption in the biofuel industry.

This update covers primarily the analysis of corn irrigation water consumption discussed in Sections 3 and 3.1, and the feedstock conversion process discussed in Sections 3.2.2 and 3.2.3. Irrigation data from 1998, 2003, and 2008 FRIS (USDA) are presented, with a focus on 2008 data. Returning flow from irrigation for the states was analyzed and used in the estimate. The state estimate was then aggregated to the regional scale. These changes are reflected in the new results.

Since the 2009 report, biological conversion of cellulosic feedstock has been improved. In particular, an increase in ethanol yield and a decrease in associated process water use lead to a reduction in water requirement per unit of ethanol produced, according to a technology evaluation report by NREL (Humbird et al. 2011). These changes are incorporated into Section 3.2.2.

The co-product issue must be addressed in water analysis for biofuels. The co-product could play a significant role in determining water consumption in biofuel production (Scowns et al. 2011). An attempt has been made in this update to examine the effect of co-product allocation on the derivation of net water use for corn ethanol and cellulosic ethanol. Results from that analysis are documented in Sections 3.1.3, 3.1.4, 3.2.2, and 3.2.3.

The following tables and figures are affected by the updates:

- Table 4b
- Table 5
- Table 6
- Tables S1 and S2
- Figures 9, 10, 11, 13, 14, 19, 20, and 21

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CONSUMPTIVE WATER USE IN THE PRODUCTION OF ETHANOL AND PETROLEUM GASOLINE

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EXECUTIVE SUMMARY

The production of energy feedstocks and fuels requires substantial water input. Not only do biofuel feedstocks like corn, switchgrass, and agricultural residues need water for growth and conversion to ethanol, but petroleum feedstocks like crude oil and oil sands also require large volumes of water for drilling, extraction, and conversion into petroleum products. Moreover, in many cases, crude oil production is increasingly water dependent. Competing uses strain available water resources and raise the specter of resource depletion and environmental degradation. Water management has become a key feature of existing projects and a potential issue in new ones.

This report examines the growing issue of water use in energy production by characterizing current consumptive water use in liquid fuel production. As used throughout this report, "consumptive water use"[1] is the sum total of water input less water output that is recycled and reused for the process.[2] The estimate applies to surface and groundwater sources for irrigation but does not include precipitation. Water requirements are evaluated for five fuel pathways: bioethanol from corn, ethanol from cellulosic feedstocks, gasoline from Canadian oil sands, Saudi Arabian crude, and U.S. conventional crude from onshore wells. Regional variations and historic trends are noted, as are opportunities to reduce water use.

SCOPE

This study examines water use for the production of energy feedstocks and fuels from the perspective of life-cycle analysis. Fuel life cycles include resource extraction (feedstock farming), feedstock transportation, fuel production, fuel transportation, and operation of a vehicle on the fuel. In this study, we focus on two major steps in that life cycle —feedstock production (farming, oil recovery) and fuel processing/production (ethanol production and oil refining). For corn ethanol,[3] we focus on three of the 10 farm-production regions defined by the U.S. Department of Agriculture (USDA, see Figure 6). They are Region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas). These three regions consistently account for 85%–89% of

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[1] Consumptive water use, net water use, and water consumption are used interchangeably in this report to reflect the terminology typically used in various industries.

[2] For biofuel feedstocks, *consumptive water use* in this study is further defined as the irrigation water that is incorporated into the crop or lost to evapotranspiration (ET), because it cannot be reused for another purpose in the immediate vicinity.

[3] Unless otherwise noted, "ethanol," as used in this report, refers to denatured ethanol.

U.S. corn production (USDA–NASS 2007, 2008, 2013) and 90%–95% of its ethanol production (RFA 2007, 2013). We examine corn ethanol produced via dry milling and cellulosic ethanol produced via biochemical and thermochemical conversion technologies.

For domestic production of conventional petroleum gasoline, we developed analysis for oil-producing regions defined on the basis of the Petroleum Administration for Defense District (PADDs I, II, III, IV, and V, see Figure 22), which together represent 84% of U.S. total crude production and all of the onshore recovery (EIA 2008a, EIA 2018b). PADD II includes the states of Oklahoma, Kentucky, and Tennessee in addition to USDA Regions 5, 6, and 7; PADD III includes Texas, New Mexico, Arkansas, Louisiana, Mississippi, and Alabama; PADD V includes California, Alaska, Arizona, Nevada, Oregon, and Washington. We estimate consumptive water use for onshore crude exploration and production (E&P) and oil refining. We consider primary, secondary, and tertiary technologies and produced water reinjection for the recovery of crude oil. Typical consumptive water use is calculated as a weighted average.

For the production of petroleum gasoline from Canadian oil sands or from Saudi Arabian crude oil, we focus on the Athabasca, Cold Lake, and Peace River sites in Alberta (which represent 43% of Canadian oil production and 100% of Canadian oil sands production) and the Ghawar field (which represents 52% of Saudi Arabian oil production). Together, Saudi crude oil and Canadian oil sands accounted for 23% of U.S. crude oil imports in 2005 (EIA 2007a).

Study results are summarized below.

CORN ETHANOL

The agriculture sector is a significant water user. This study shows that crop irrigation is the most important factor affecting water consumption in the production of corn ethanol. Because of different climate zones and soil types, there are significant differences in irrigation among the three major corn-producing regions (Table S-1). Approximately 85% of U.S. corn and 90% of U.S. corn ethanol are produced in USDA production Regions 5 and 7, where 8.7–160 gallons of water are consumed (2013 data) per gallon of ethanol produced.[4] Water use is at the lower end in Regions 5 and 6. The three-region area uses an estimated weighted average of 76 gallons of water to produce a gallon of ethanol. This value would increase to 13–240 gallons of water per gallon of ethanol if the water used for coproducts is allocated to ethanol.

Corn ethanol production plants are relatively less water intensive compared to the water requirement for crop irrigation. The combination of newly built production facilities with better process integration and, to a lesser extent, production of wet distillers grain (WDG) co-products

[4] Since liquid fuel industries typically use a volume-based product metric, results are expressed as gal of water consumed per gal of fuel produced (not total water use). This unit metric also facilitates comparison of water consumed by major fuel production life-cycle stages and for different fuels, the goal of this effort.

TABLE S-1 Consumptive Water Use from Corn Farming to Ethanol Production in USDA Regions 5, 6, and 7 (Gallons water/gallons denatured ethanol produced)

USDA Region	Region 5	Region 6	Region 7
Share of US ethanol production capacity (%)[a]	49	13	28
Share of U.S. Corn Production (%)[b]	46	15	24
Corn irrigation, ground water[c]	9.7	15.2	220.2
Corn irrigation, surface water[c]	0.6	3.6	17.1
Ethanol production[d]	2.7	2.7	2.7
Total (corn irrigation and ethanol production without co-product allocation)	13.0	21.5	240.0
Total water consumption with mass-based co-product allocation[e]	8.7	14.3	160.0

[a] 2013 Ethanol production capacity in operation (RFA 2013, data available in Nebraska Energy Office http://www.neo.ne.gov/statshtml/121/2013/121_201309.htm)
[b] 2013 Corn production (USDA 2013)
[c] 2015 USGS water use report (Dieter et al. 2018), USDA 2013, assumed a yield of 2.72 gal ethanol per bushel.
[d] Mueller 2010.
[e] Mass-based and carbon displacement-based water allocation. According to the rule of thumb, one-third of biomass in corn kernel goes to ethanol, one-third goes to CO2, and one-third goes to DDGS. LCA results from GREET show 34% GHG are attributable to DDGS (Section 3.1.3.).

in dry mill plants (as compared with distillers dried grain and solubles, DDGS)[5] have reduced water use dramatically. Average consumptive water use in ethanol plants has declined from 5.8 gal/gal ethanol to 3.0 gal/gal ethanol in the past 10 years. A recent industrial survey conducted in 2009 found the value has been decreased further to 2.7 gal/gal (Mueller 2010).

CELLULOSIC ETHANOL

Cellulosic ethanol can be produced from a variety of feedstocks, such as perennial grasses, forest wood residues, agricultural crop residues, algae, and municipal wastes. The irrigation requirement of cellulosic biomass depends largely on the type of feedstocks. With an abundant supply and virtually no incremental irrigation water requirement for cultivation, forest wood residues could be viable feedstocks. Like other perennials, switchgrass is deep rooted to permit efficient use of nutrients and water in the soil and thus tends to be relatively drought tolerant. Grown where it is a native perennial, switchgrass is potentially feasible to reach a desirable yield without irrigation. This analysis focuses on ethanol production from switchgrass.

[5] WDG requires less steam for drying, thereby reducing water use. The major advantage of WDG, however, is in energy savings.

Water requirements for cellulosic ethanol production are based on process simulation results since the technologies are not yet fully commercialized. Nevertheless, they are likely to vary with technology. A recent estimate of ethanol production via biochemical process projected a requirement of 5.3 gal of water per gallon of fuel produced. This value decreases to 4.5–4.6 gal when the water use attributable to electricity that is co-produced from the refinery is allocated. Thermochemical conversion (TC) via gasification followed by catalytic synthesis requires much less water — less than 2 gal/gal for an optimized gasification to mixed alcohol process.

GASOLINE FROM CONVENTIONAL CRUDE OIL

Water consumption in oil E&P is highly sensitive to the age of the oil well, the recovery technology employed, and the degree of produced water[6] recycling and reuse. Primary oil recovery requires only 0.2 gallons of water per gallon of crude oil produced. U.S. onshore oil production relies heavily on secondary recovery via water flooding (42%) in 2014,[7] which decreased 8% from 2006. This technology requires an average of 15.7 gallons of water per gal of crude oil recovered and, as a result, accounts for 94% of the water injected into onshore wells for oil recovery. Use of water flooding technology has been in decline over the last decade; it decreased 25% from 2006 to 2014. In most regions, produced water supplies much of this injection water. It was estimated that on average 46% of produced water is reinjected to oil wells for production nationally. Thus, on a technology-weighted basis, it takes on average a net 4.5 gallons of water to produce 1 gallon of crude oil from U.S. onshore wells, with a range of 0–7.6 gallons for the five oil production regions (PADD I, II, III, IV, and V). Note that there are significant variations from field to field. Produced water is especially low in parts of West Texas, necessitating significant use of saline groundwater for injection.

Although enhanced oil recovery (EOR), via technologies like steam injection and CO_2 flooding, is less prevalent than water flooding, it accounts for an increasing share of onshore production — up to 9%. As of 2014, water inputs for steam injection and CO_2 flooding represented nearly 5.3% of total water injection in domestic onshore wells, which is a significant decrease from the previous estimate of 17% for 2006. CO_2 flooding is dominant in PADD III, whereas steam injection is prevalent in PADD V.

Alternative water sources for oil recovery have been explored to displace fresh groundwater. Using primarily desalinated seawater for injection, Saudi Arabian oil wells consume about 1.4–4.6 gallons of water/gallon of crude. Brackish water was also used as injection water in PADD III.

In contrast to E&P, oil refining consumes a relatively small amount of water — an average of 1.5 gallons per gallon of crude oil processed. Combining oil E&P and refining, producing 1 gallon of *gasoline* from conventional crude in Saudi Arabia or in the United States can consume

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6 Occurring naturally in the formation itself or due to water injection, produced water (PW) is the water portion of an oil-water mixture with a high concentration of dissolved solids that is pumped to the surface.

7 In 2014, 42% of U.S. crude oil production used water flooding (EIA 2018b).

as little as 1.4 gallons or as much as 8.6 gallons of water. The regional weighted average water intensity in the United States is an estimated 5.6 gallons of water per gallons of gasoline.

GASOLINE FROM CANADIAN OIL SANDS

The amount of water consumed in producing crude oil from Canadian oil sands varies with production technology, which, in turn, depends on geologic conditions. Surface or open pit mining and upgrading require 4.0 gallons of freshwater (primarily surface water from the Athabasca River) to produce 1 gallon of upgraded bitumen crude. The two dominant in-situ technologies, steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), require large quantities of steam for bitumen recovery. Utilizing extensive recycling to lower water use, in-situ recovery operations require 1.3 to 5.0 gallons of water to produce 1 gallon of upgraded bitumen crude. From E&P to refining, a total of 2.6–6.2 gallons of water is needed to produce 1 gallon of *gasoline* from oil sands.

ISSUES

Each fuel life cycle presents a unique pattern of opportunities and challenges related to its consumptive water use. There are, however, a number of common sustainability issues, including water quality and land degradation and ecosystem disruption. For the most part, these issues apply primarily to feedstock production. Fuel processing tends to be less water-intensive, due to a combination of integrated operations and more extensive water recycling and reuse.

Cumulative impact of various factors is a particularly critical issue with respect to oil sands development. The notion of individual impacts accumulating over time and across numerous nearby projects, in contrast to the per-gallon water use results examined in this study, is particularly applicable to questions of sustainability, and none more so than with respect to water resources.

CONCLUSIONS

This analysis found that consumptive water use for feedstock and fuel production varies considerably by region, type of feedstock, soil and climatic condition, and production technology for ethanol, as well as by age of oil well, recovery technology, and extent of produced-water reinjection and steam recycling for petroleum gasoline. There are significant regional differences, however, particularly for corn production. The consumptive water use for the fuels analyzed in this study is summarized in Table S-2.

Our analysis indicates that conservation measures to reduce consumptive water use are needed to achieve sustainable biofuel and gasoline production. Improved irrigation water management is particularly critical in those areas where water is scarce. Developments of drought-resistant strains that maintain corn yield are also desirable. For cellulosic feedstock, an emphasis on planning and selecting feedstock site at their native habitat is vital to minimizing irrigation

TABLE S-2 Water Consumption for Ethanol and Petroleum Gasoline Production

Fuel (feedstock)	Net Water Consumed[a]	Major Factors Affecting Water Use
Corn ethanol	8.7–160 gal/gal ethanol[b]	Regional variation caused by irrigation requirements due to climate and soil types
Switchgrass ethanol	1.9–4.6 gal/gal ethanol[b]	Production technology
Gasoline (U.S. onshore conventional crude)[c]	1.4–8.6 gal/gal gasoline	Age of oil well, production technology, and degree of produced water recycle
Gasoline (Saudi conventional crude)	2.8–5.8 gal/gal gasoline	Same as above
Gasoline (Canadian oil sands)[d]	2.6–6.2 gal/gal gasoline	Geologic formation, production technology

[a] In gallons of water per gallon of fuel specified.
[b] Water use for processing ethanol coproduct is allocated using mass-based method. Data cover water consumption for corn in USDA regions 5, 6, and 7.
[c] PADD I, II, III, IV, and V combined.
[d] Including thermal recovery, upgrading, and refining.

requirements while achieving desirable production. For oil E&P, the use of PW reinjection and saline water for oil recovery will further reduce water use.

In a fuel production plant, water consumption can be reduced by increasing the use of such measures as steam condensate reuse and treated process water recycling, and by implementing process modifications using existing commercial technologies. Newly built corn ethanol plants with efficient design and process integration can reduce net water use substantially. Since no commercial-scale cellulosic ethanol plants are currently in operation, development of a process design that optimizes water use should be encouraged from the outset.

Finally, there is an encouraging trend toward improved water management in the biofuel sector. In a 15-year period (1998–2013), statistics show a reduction in irrigation water applied across regions 5, 6, and 7. In particular, there was a reduction of about a half in irrigation for region 7, which is attributable to progress in water conservation and irrigation management. As a result, the upper end of irrigation consumption for corn dropped significantly, in comparison to that in 1998. With the emphasis on water resource and water use in energy development, this trend is likely to continue.

1 INTRODUCTION

With rising public awareness that U.S. dependence on foreign oil reduces energy security, retards economic growth, and exacerbates climate change, alternative and renewable fuels are gaining increased visibility and support. Venture capitalists are investing in new fuel and vehicle technologies. States and localities are adopting renewable fuel mandates, discussing carbon budgets and subsidizing industry startups. Furthermore, the 2007 *Energy Independence and Security Act* (EISA) is committing this country to produce 36 billion gallons of renewable fuels by 2022 — 16 billion gallons of cellulosic ethanol, 15 billion gallons of corn ethanol, and 5 billion gallons of biodiesel and other advanced biofuels. As a result of these actions, biofuels production is growing at an unprecedented speed.

At the same time, the United States is importing more unconventional crude oil, much of it derived from Canadian oil sands, and extracting a growing share of domestic crude by use of secondary and tertiary recovery technologies on existing wells.[8] All five of these fuel pathways — bioethanol from corn, bioethanol from cellulosic feedstocks, gasoline from Canadian oil sands, Saudi Arabian crude, and U.S. conventional crude from onshore wells — require water input and raise important sustainability questions. From time immemorial, water has nurtured human populations and supported their activities. Where plentiful, it has been taken for granted; where scarce it has been sought after and fought for. Few have appreciated that overuse or misuse of this precious resource can lead to serious and irreversible consequences. In addition, there is potentially a rush to rapidly expand production capacity. Given the pace of recent oil sands development, local infrastructure and manpower have been strained. Under the circumstances, it may be faster and easier to secure financing, permits, and approvals for projects incorporating conventional technologies than unproven, less water-intensive technologies.

Today, however, an increasing appreciation of the potential for truly catastrophic consequences is producing a dramatic change in business priorities. Sustainability considerations are becoming not only key inputs in business decisions but decisive factors affecting competition worldwide. In this context, a thorough examination of water consumption in biofuel and petroleum development is more than a useful exercise. It is a critical input to policy development. This study is a key part of that examination. It asks the following questions:

- How much water is consumed to produce a gallon of ethanol in the United States?
- How much water is consumed to produce a gallon of gasoline from conventional domestic or imported petroleum and from oil sands?
- What are the regional variations (if any) in water use to produce ethanol and petroleum gasoline?

[8] Canada has stepped up production of bitumen to more than 1 million barrels per day (CAPP 2008a).

1.1 WATER AND BIOFUEL FEEDSTOCKS

Water use for plant growth is an intrinsic part of the hydrologic cycle (water cycle). As illustrated in Figure 1, rainfall that precipitates on the ground follows several paths: absorption by plants, percolation into the soil, surface runoff to waterways, and infiltration into the underlying aquifer and groundwater.

Surface streams receive water from direct precipitation, surface runoff, and in some cases, interflow from water tables. A water table that is connected to a surface stream is able to receive input from or feed to the stream. If groundwater is located in a confined aquifer,[9] however, it is mostly isolated from surface streams, and its withdrawal represents a net water loss. In this case, water can be considered a non-renewable resource and overconsumption could lead to resource depletion.

Water is lost from the land to the air by evaporation from soils and streams, and by transpiration from plants. Transpiration accounts for the movement of water within plants and the loss of water vapor through stomata[10] in the leaves. The sum of transpiration and evaporation, termed "evapotranspiration" (ET), describes the water movement from plant, soil, and land surface to the atmosphere. The water that is incorporated into plants or lost to ET is called "consumptive water use" because it cannot be reused for another purpose in the immediate vicinity (NRC 2007).

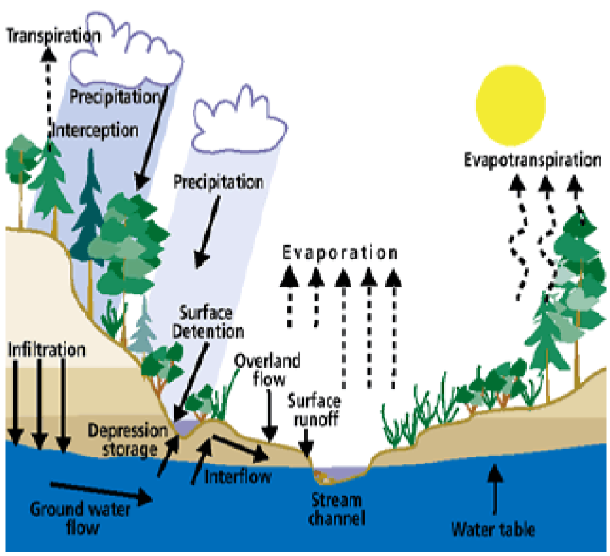

FIGURE 1 Hydrologic Cycle (Allen 2007, used with permission)

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[9] An aquifer is an underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, silt, or clay) from which groundwater can be usefully extracted using a water well.

[10] Stomata are minute orifices or slits in the epidermis of leaves, stems, and other parts through which gases are exchanged.

For biofuel feedstocks, this study focuses on consumptive water use from irrigation, which does not include precipitation. Precipitation is only included insofar as it affects the need for irrigation, the primary focus of this analysis. The study does not estimate crop ET directly, but instead examines consumptive irrigation water use for given feedstocks at an aggregate level.

Freshwater is withdrawn from surface water or groundwater to support agricultural operations or industrial processes or to be used as input to municipal water supplies. Such factors as climate, population, and the concentration and water intensity of the local economy affect the amount and sustainability of water withdrawals for a given locality and region.

The agriculture sector is a significant water user, especially for irrigation. Almost 60% of the world's freshwater withdrawals are used for irrigation. In the United States, irrigation withdrawals for crops, golf courses, parks, and other landscape uses accounted for 37% of all water withdrawals and 42% freshwater withdrawals in 2015 (Dieter et al. 2018).[11] In the agriculture sector, a primary water use is for irrigation, followed by livestock and aquaculture. Together, they required 40% all water withdrawals in 2015. Agricultural water withdrawal has declined for more than 25 years since 1980, mostly following the national overall trend of decreasing withdrawals (Figure 2), which is attributable to a concerted effort in water management across the nation. Irrigation water consumption was estimated since 1960 but interrupted between 2000 and 2010. Recently, USGS developed the estimate again in its reports for 2015 (Dieter et al. 2018). Figure 2 shows consumptive use of irrigation water continued to decline from its peak at 1980. By 2015, it was slightly lower than the level at 1970. Water withdrawal for thermoelectric generation accounts for 41% of all water withdrawals in the U.S. in 2015, less than 3% of the water is consumed (Dieter et al. 2018). Surface water is the source for 52% of irrigation water and for 79% of aquaculture use. Groundwater is the primary source for livestock (62%). Geographically, more than half of the irrigation withdrawals were in five arid western and mountain states (California, Idaho, Arkansas, Montana, and Colorado) in 2015. Nebraska was among the four most irrigated states in 2010 but dropped from that list in 2015.

As reported by USDA NASS, irrigated acreage has increased steadily since 1900, from less than 10 million acres to nearly 60 million acres. However, the amount of water applied per acre has decreased from 25 inches in the 1970s, to 20 inches today (Gollehon and Breneman 2007). This decline can be attributed to biotechnology, increased use of water-conserving irrigation practices, improved technical efficiency, higher energy costs, and a shift in irrigation from generally dry areas to more humid regions, which require less irrigation water per acre. Withdrawals for irrigation in 2015 were 118 Bgal/d, slightly increase from 2010 and approximately equal to estimates of irrigation water use in 1970. On national average, a majority (62%) of the water withdrawn for irrigation is consumed (evaporated, evapotranspired, or incorporated into the irrigated crops/plants). The rest is returned to the water body or remained in soil. At state level, the consumptive use irrigation water ranged from 22% to 100% of the withdrawn water.

[11] USGS reports total irrigation water withdrawals which includes irrigation for golf courses, parks, nurseries, and other landscape uses. Crop irrigation use was not separated from other uses.

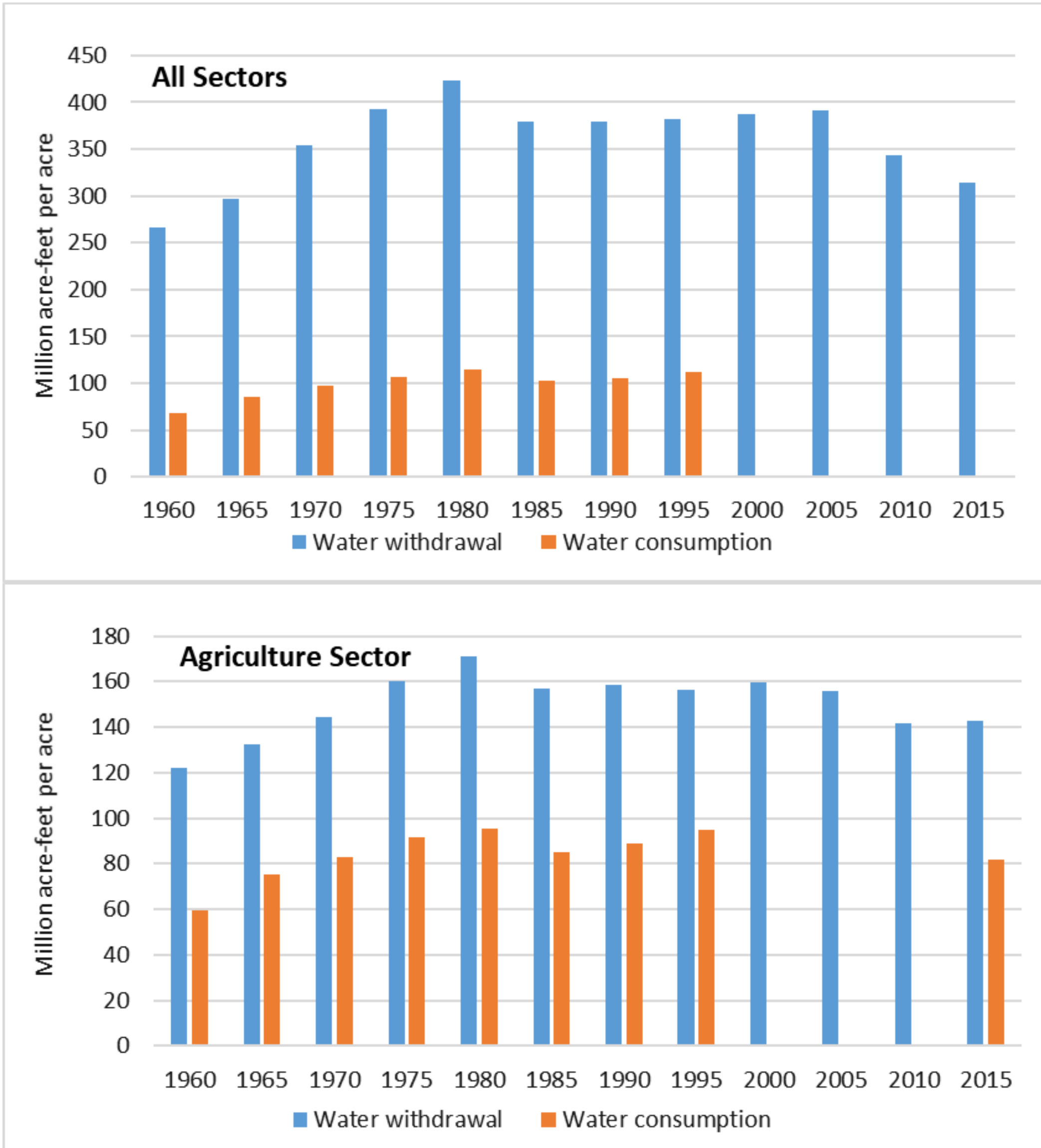

FIGURE 2 U.S. Freshwater Withdrawals and Consumption, All Sectors and Agricultural Sector, 1960–2015 (USGS 2015). The water consumption in agriculture sector represents consumptive use of applied irrigation water.

Historically, biofuels have been produced from grain-based crops with water supplied by precipitation and/or irrigation. Today, forest wood residues, agricultural residues, dedicated energy crops, and other herbaceous biomass are being considered as feedstocks for cellulosic ethanol. Cellulosic ethanol is believed to be the long-term biofuel solution. According to a series of Energy Department national assessments that have calculated the potential supply of biomass in the United States, the United States has the future potential to produce at least one billion dry tons of biomass resources (composed of agricultural, forestry, waste, and algal materials) on an annual basis by 2030 without adversely affecting the environment (Perlack 2005, USDOR 2011, DOE 2016). To that end, a water sustainability analysis of the potential future production scenarios to evaluate the impact of large-scale feedstock production on freshwater resources was conducted and available elsewhere (Wu and Ha 2016).

1.2 WATER USE IN CRUDE OIL RECOVERY

In the last decade, the United States has become increasingly independent in oil production, due to rapid development of shale oil and gas and advanced drilling technologies. Today, domestic crude oil has expanded from 40% (2005) to 54% (2017) of total production; within this amount, onshore crude production has doubled. The shift in production ended a 30-year decline (EIA 2018b, EIA 2008b). Today, Canada, Saudi Arabia, Venezuela, Mexico, and Iraq are the major suppliers of crude oil to the U.S. market, accounting for a combined 36% of crude imports. In 2017, the United States produced 9.4 million barrels of crude per day (bbl/d) and imported 7.9 million bbl/d. This is in contrast to the 5.1 million bbl/d domestic production and 10.1 million bbl/d import in 2005 (EIA 2007b, EIA 2008b, EIA 2018a, EIA 2018b). Table 1 provides an overview of U.S. crude oil production and net imports.

Saudi Arabia has the world's largest crude oil production capacity, 10.5–11.0 million bbl/d, and plans to expand capacity to 12 million bbl/d by 2009 (EIA 2007c). As shown in Table 1, Saudi Arabia currently supplies over 5.5% of U.S. crude oil. Outside the Middle East, Canadian oil sands are seen as the most readily available oil reserves. Since 2002, the Canadian oil industry has rapidly expanded capacity to produce crude oil from oil sands, nearly doubling production from 0.66 million bbl/d in 2001 to 1.2 million bbl/d in 2007 (CAPP 2008a). As shown in Table 1, Canadian crude has become the number 1 crude oil import to the United States, up to nearly 20% in 2017 from 10% in 2005. It is projected that Canada will produce 3.5 million bbl/d of crude oil from oil sands by 2020 (CAPP 2008c).

Water consumption has become an increasingly important factor in conventional and unconventional crude oil production. The petroleum industry has begun to emphasize water management practices and look for alternative water sources to reduce freshwater consumption, particularly in regions where water resources are scarce. Saline water, brackish water, and even desalinated seawater are being used for oil E&P. Large operators are implementing increasingly sophisticated water management practices. Smaller operators, constrained by limited resources, may be less able to do so.

TABLE 1 U.S. Crude Oil Supply[a]

		Domestic Production		Imports									
		Onshore	**Offshore**	**Canada**	**Saudi Arabia**	**Venezuela**	**Mexico**	**Nigeria**	**Algeria**		**Others**	**Total Imports**	**Total Supply[c]**
2005	Thousand b/d	3466	1712	1609	1235	1219	1121	937	385		3031	9537	14715
	Share of supply	22.7%	11.2%	10.5%	8.1%	8.0%	7.3%	6.1%	2.5%		19.8%	62.3%	100.0%
		Onshore	**Offshore**	**Canada**	**Saudi Arabia**	**Venezuela**	**Mexico**	**Angola**	**Iraq**	**Colombia**	**Others**	**Total Imports**	
2014	Thousand b/d	7306	1448	2882	1159	733	781	294	369	309	817	7,344	16098
	Share of supply	45.4%	9.0%	17.9%	7.2%	4.6%	4.9%	1.8%	2.3%	1.9%	5.1%	45.6%	100.0%
		Onshore	**Offshore**	**Canada**	**Saudi Arabia**	**Venezuela**	**Mexico**	**Nigeria**	**Iraq**	**Colombia**	**Others**	**Total Imports**	
2017	Thousand b/d	7660	1695	3421	943	618	608	309	602	333	1080	7,914	17269
	Share of supply	44.4%	9.8%	19.8%	5.5%	3.6%	3.5%	1.8%	3.5%	1.9%	6.3%	45.8%	100.0%

[a] Source: EIA 2008b; EIA 2008c, EIA2018a, 2018b.

[b] Others in 2017: Ecuador, Brazil, Kuwait, Angola, Algeria, Libya, Russia, Norway, Chad, UK, UAE, Indonesia, Ghana, Oman, Equatorial, Guatemala, Trinidad, Azerbaijan, Gabon, Congo, Denmark, Mauritanian, Thailand, Australia, Ivory Coast, Peru. Vietnam, Yemen, Malaysia, Brunei.

[c] Includes onshore and offshore production and total imports.

1.3 STUDY SCOPE

This study examines consumptive use of freshwater — a key aspect of the sustainability of fuel development — from the perspective of life-cycle analysis (LCA).[12] With this approach, water consumption is estimated by life-cycle stage: feedstock production (or farming, in the case of biofuel), feedstock transportation, fuel production, fuel transportation, and fuel utilization. Among life-cycle stages, feedstock production and fuel processing/production are by far the most water intensive. This is particularly true for biofuel feedstocks, such as agricultural crops. Therefore, this study focuses on these two life-cycle steps — feedstock production and fuel processing/production — for (a) ethanol from corn, (b) gasoline from domestic and imported conventional crude oil, and (c) gasoline from non-conventional oil sands. For conventional crude oil, the analysis focuses on two sources — domestic and Saudi Arabian crude. Water quality issues are not considered in this study.

This work is part of a multi-institution effort sponsored by the DOE Office of Biomass Programs. Collaborators include Energetics, Inc., the National Renewable Energy Laboratory (NREL), and Argonne National Laboratory (Argonne). For that effort, Energetics is focusing on national water resource impacts of the future feedstock production scenarios in DOE/USDA "Billion-Ton" study (Perlack 2005); NREL is analyzing optimized process simulations for biofuel production from cellulosic feedstocks (Aden et al. 2002); and Argonne is characterizing industry-wide water consumption for biofuel feedstock production and conversion, as well as petroleum recovery and refining. The scope remains in subsequent updates conducted in 2011 and 2018.

In this analysis, consumptive water use is estimated for the following life-cycle stages and processes:

- Feedstock production
  - Corn
  - Switchgrass
  - Conventional crude: U.S. and Saudi Arabian
  - Unconventional crude: Canadian oil sands

- Ethanol production
  - Corn dry mill
  - Cellulosic biorefinery: biochemical (BC) and thermochemical (TC)

- Petroleum refining

This analysis also notes regional variations and historic trends in consumptive water use for the selected fuels and identifies opportunities to reduce water use at specific life-cycle stages. Beyond this, our efforts on thorough and careful collection and examination of inventory and water intensity data are directed toward building a comprehensive LCA of water consumption in the

[12] LCA is a "cradle-to-grave" approach to analyzing the impact of a product from resource extraction, transportation and conversion to the product, to transportation and use of the product.

production of various liquid fuels and a critical baseline for decision makers planning sustainable large-scale expansion of biofuel production to reach overarching goals of energy independence.

2 METHODOLOGY

Estimates of consumptive water use for individual products and processes are available in the open literature — in publications and presentations by government agencies, non-governmental organizations (NGOs), national laboratories, universities, private organizations, etc., but prior to this effort no comprehensive inventory had been developed specifically focusing on fuel production. To develop such an inventory, an extensive literature search was conducted, relevant data were identified and organized, and results were analyzed and interpreted. This process required us to identify and assemble sources; extract and organize data by fuel type, feedstock source and location, and production process and technology; and summarize results by relevant parameter.

2.1 DATA COLLECTION AND PROCESSING

To focus on the products and processes most likely to affect water consumption, we identified representative feedstocks, fuel pathways and regions for each liquid fuel and used them to target the data search. The feedstocks and fuel pathways included in this analysis were discussed above. The states and regions selected to represent current production were identified from standard sources. Since data relevant to agricultural production and water resources (including information on precipitation, surface water, and groundwater and on production of PW in oilfield operations) are collected by state, this factor became the natural basis for analysis. However, since not all states are relevant to this analysis, and detailed state-level analyses are beyond the scope of this study, state data are aggregated to regional estimates and reported as such in this document.

Thus, for the bioethanol analysis, we focus on the USDA Regions responsible for most biofuel feedstock and ethanol production. For the gasoline analysis, we focus on PADD Regions responsible for most crude oil production and petroleum refining.

Process-level data on water use by fuel production technology were obtained from the literature and weighted by estimated market shares to derive averages for each life-cycle stage. Table 2 lists the data sources compiled for this study. Variations among regions were identified, characterized by a range of data values, and (in the case of relatively large variations) re-examined to identify responsible factors.

Since liquid fuel industries typically use a volume-based product metric, results are expressed as gallons of water consumed per gallon of product fuel. This analysis is intended to derive unit estimates of water consumed by major fuel production life-cycle stage, not total water use. In the future, the inventory compiled for this effort can be used to develop net water consumption LCAs of liquid motor fuels, as well as other regional and fuel-specific analyses.

TABLE 2 Data Sources for Fuel and Feedstock Water Use Analyzed in this Study

Feedstock	Fuel	Data Source and/or Author and Date of Reference
Corn	Ethanol	USDA National Agricultural Statistics Service (NASS) database for corn yield and harvested acreages (on-line) (USDA–NASS 2007, 2011, 2018) USDA Farm and Ranch Irrigation Survey (1998, 2003, 2008, 2013)[a] USGS database (USGS 1995)[b] Dieter et al. (2018a, 2018b) USDA–ARS Corn Dry Mill Model (Kwiatkowski et al. 2006) USDA Ethanol Plant Survey (Shapouri and Gallagher 2005) Mueller (2010a, 2010b) Keeney and Muller (2006) Wu (2008)[c]
Cellulosic	Ethanol	NREL report (Aden et al. 2002) NREL report (Phillips et al. 2007)
Conventional crude	Gasoline	EIA Petroleum and Other Liquids (2007, 2007a–d, 2008a–d, 2018a–b) Ali and Kumar (2017) Goodwin et al. (2012) DOE Report to Congress (Pate, et al. 2006) O&G J (2006, 2014) CH_2M Hill (2003) Petroleum company publications (Suncor 2007, Syncrude 2007) Veil et al. (2004) Ellis et al. (2001) Buchan and Arena (2006) Gleick (1994) Royce et al. (1984) Bush and Helander (1968)
Oil sands	Gasoline	Peachey (2005) Suncor (2007) Syncrude (2007) Isaacs (2005, 2007) Gatens (2007) CAPP (2006)

[a] At the time of this study, USDA's 2003 survey was the most recent source for irrigation data.
[b] Water consumption data estimates discontinued from 1996 to 2007.
[c] Contains an analysis of an ethanol plant survey conducted by the RFA (2007).

2.2 SYSTEM BOUNDARIES AND WATER BALANCE

As illustrated in Figure 3, this study defines consumptive water use as freshwater input during fuel production activities less output water that is recycled and reused.

In the ***fuel production system***, water can be both an input and an output stream. ***Total water input*** includes freshwater and recycled water. ***Total water output*** includes water losses (consumption) and recycled water. ***Total water input*** supports feedstock or fuel production as irrigation water, injection water for crude recovery, process water, or make-up water for process heating and cooling. ***Water loss*** can be in liquid (wastewater) or gaseous form (vapor). Water loss occurs through ET, evaporation, discharge, disposal, and by the incorporation of water into products. ***Water recycle*** is the throughput that is reused in the system. Examples include irrigation run-off returned to the water body (recharge), produced water reinjection for oil recovery and oil sands production, boiler condensate reuse as process water, and treated process water reuse as cooling tower make-up. Freshwater use for sanitation, equipment cleaning, fire protection, and drinking water are not considered in this study.

Ethanol production plants and oil refineries have well-defined system boundaries, and water consumption typically varies little from one location to another. By contrast, feedstock production requires much more water, and there can be considerable variation from one farm or oil well to another. Unfortunately, site-specific data (such as run-off from a particular cornfield to surface water or groundwater in its watershed, or injection water flow into a single well) are not readily available across the United States. Thus, we examined feedstock production on a macro scale (i.e. total water inputs and outputs in a region), focusing on those regions which account for the bulk of feedstock production.

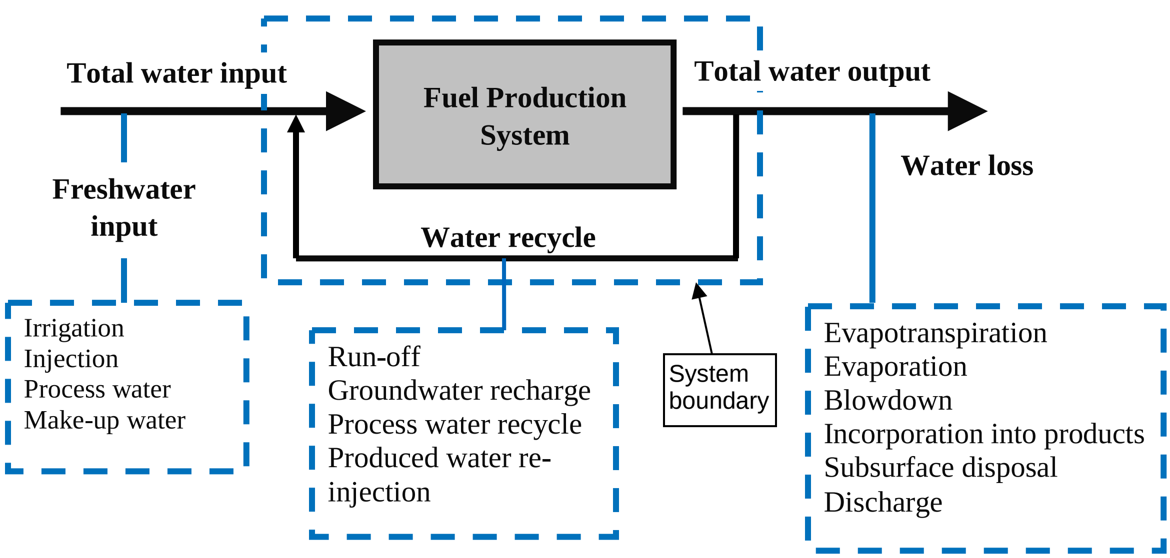

FIGURE 3 System Boundary, Water Inputs, Outputs, and Losses of a Conceptual Fuel Production System

Figure 4 depicts system boundaries and water inputs and outputs in feedstock production and fuel processing/production for ethanol and petroleum oil. As shown in Figure 4a, the farm receives freshwater from precipitation and irrigation water as needed. Irrigation water that runs off the field to surface streams and recharges groundwater is ultimately returned to the watershed and reused. For this analysis, we assume a system that includes the farm and its watershed; surface

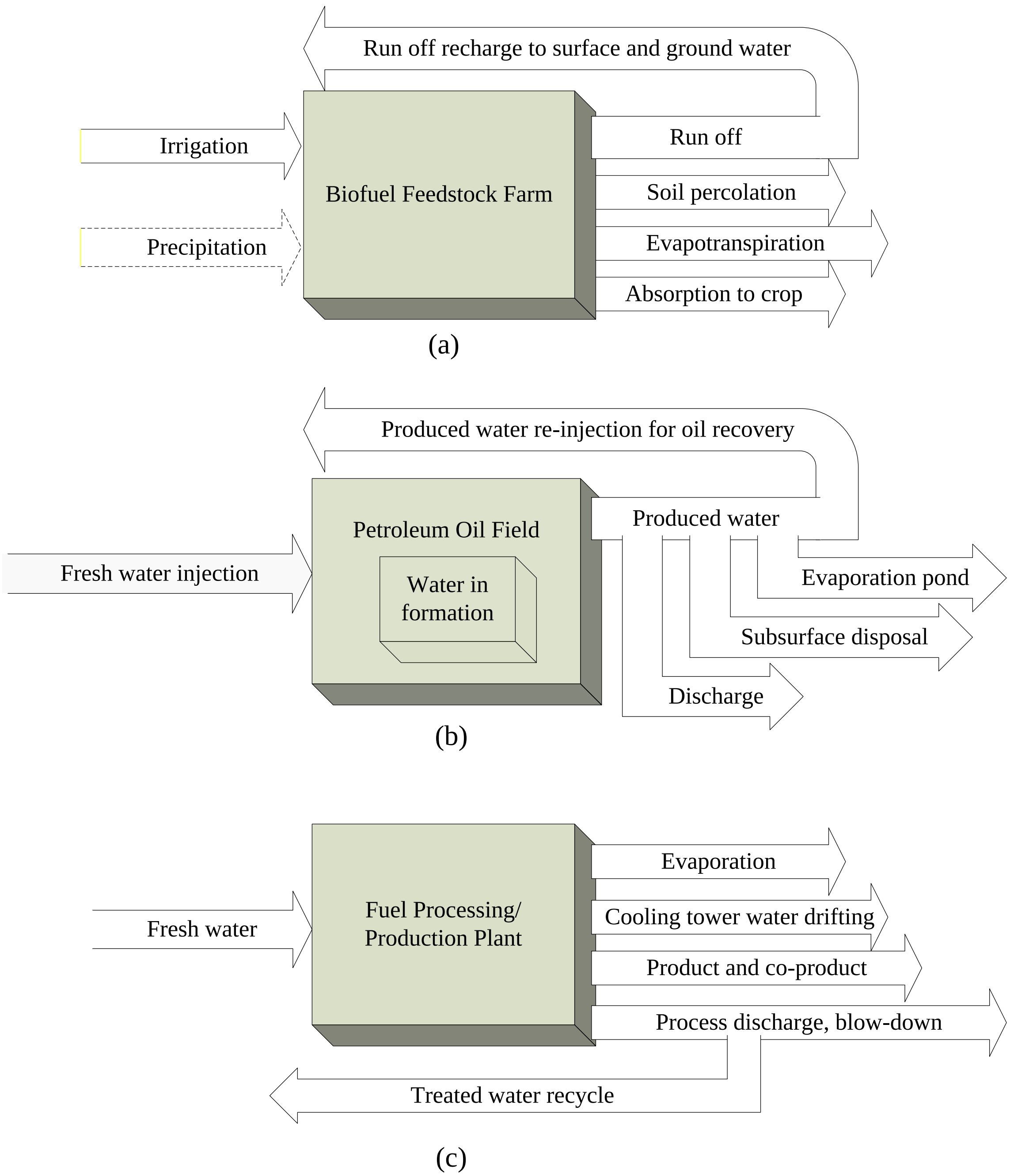

FIGURE 4 Water Inputs and Outputs for (a) Biofuel Feedstock Production, (b) Petroleum Oil Production, and (c) Biofuel Production/Oil Refining

water run-off and groundwater recharge are within this system.[13] Note that this assumption is appropriate because we focus on regional feedstock production, not individual farm operations. In this context, the consumptive use of corn irrigation water accounts for irrigation water loss from soil percolation, ET, and absorption to the crop (Figure 4a).

In an oil field, freshwater and a portion of produced water are introduced through an injection well. Produced water lifted from the production well could include previously injected water as well as saline water originally contained in the formation. Some of the produced water is disposed to the subsurface through disposal wells. For an individual oil field, local geology and hydrology strongly affect the system boundary — defining a closed system if injection water is retained in the formation or an open one if injection water flows to nearby formations. For this analysis, we assume a closed system — injection water is retained in the formation into which it is injected — and assume that disposal wells to which some produced water is pumped are outside the system boundary. Given these assumptions, produced water reinjection is conceptually equivalent to water recycle, and consumptive use of fresh injection water for oil production accounts for water loss by produced water disposal (to the subsurface, an evaporation pond, or discharge). Figure 4b illustrates this equivalence. Figure 5 depicts the physical arrangement of extraction and injection wells in a typical oil field.

As shown in Figure 4c, consumptive water use in the fuel production process includes water loss through evaporation, drifting,[14] and blow-down from the cooling tower, incorporation into products and co-products, and process water discharge.

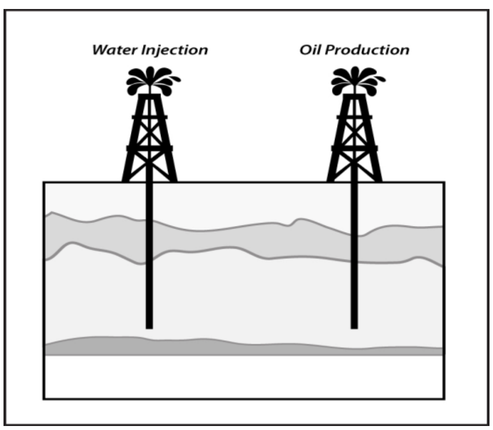

FIGURE 5 Typical Onshore Oil Field

[13] Since precipitation is not the focus of this study, it is shown as a dashed input.

[14] A small amount of water lost from cooling tower when the cooling water flowing downward contacts upward rising ambient air in the cooling tower. This loss is commonly referred to as “drifting” or “windage.”

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3 ETHANOL

Forest wood residue and perennial grass such as switchgrass tend to consume less water than corn. But conversion of cellulosic feedstocks to ethanol and other fuels could consume less or more water than conversion of corn to ethanol, depending on production technologies. The following discussion highlights these differences. As stated in Section 2, consumptive irrigation water use in biological feedstock production includes water use for the entire field within the system boundary, both irrigated and non-irrigated acreages.

3.1 CORN ETHANOL

Corn production and consumptive irrigation water use vary by state and region. The main corn production regions are in the upper and lower Midwest — USDA Region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas). Together, these regions account for 85%–90% of corn production (USDA–NASS 2007, 2008, 2013) and 90%–95% of ethanol production in the United States in 2006 (RFA 2007, 2013). The USDA farm production regions are shown in Figure 6.

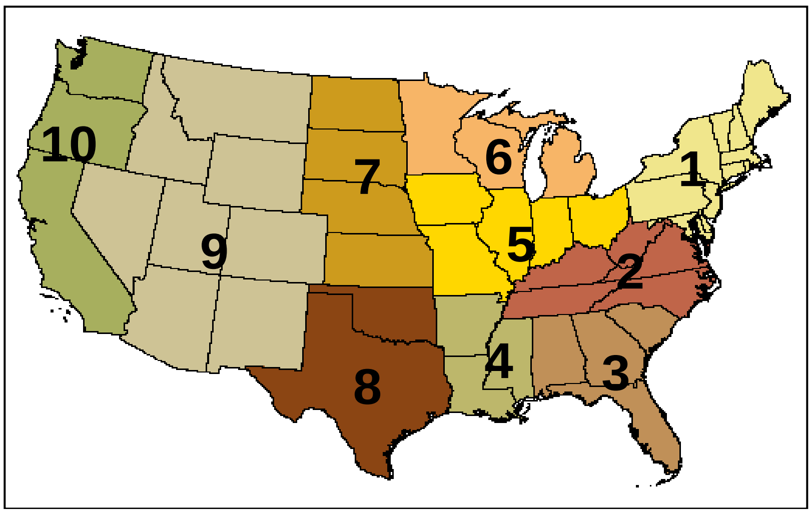


FIGURE 6 USDA Farm Production Regions

The water required to produce corn depends on several factors, the two most important being atmospheric demand and growth stage. Atmospheric demand for water is expressed as vapor pressure deficit, which is a result of solar radiation, wind, humidity, and temperature (Shaw 1977). An increase in vapor pressure deficit increases the amount of transpiration water required while a decrease reduces it (Sinclair 2008).

Vapor pressure deficit is also affected by growth stage. During peak growth stages (July and August for the U.S. Corn Belt), rainfall may be insufficient to satisfy the needs of the rapidly growing plant (White and Johnson 2003). Moisture stored in the soil from rainfall percolation generally supplies the remainder and eases stress on the crop during dry spells. The ability of the growing plant to use this stored moisture, in turn, depends on the amount of moisture in the soil and the soil's texture. Good soil can store as much as 40–50% of the total moisture needed for corn. White and Johnson (2003) suggest that seasonal water use for corn growing is typically in the range of 40–65 cm (16–26 in.).

3.1.1 Corn Irrigation

As shown in Figure 7, annual precipitation in the three regions has varied significantly over the past 45 years. Region 7 (Nebraska, North Dakota, South Dakota, and Kansas) is relatively arid and precipitation can be scarce (USDC 2007). This region receives an average of only 22 in. of rainfall per year. By contrast, Regions 5 and 6 receive 16 and 8 in. more rain, respectively (Table 3).

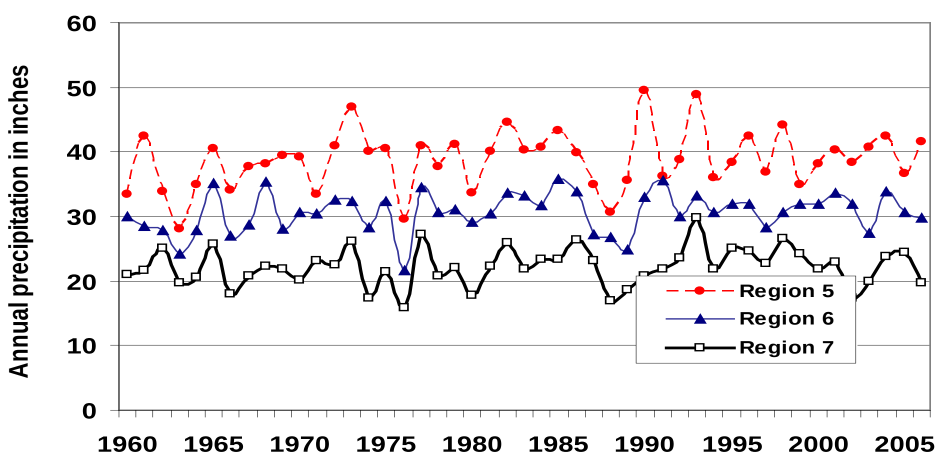


FIGURE 7 Annual Precipitation in USDA Regions 5, 6, and 7 (USDC 2007)

TABLE 3 Average Annual Precipitation[a] by Corn-Growing Region

USDA Region	Average Annual Precipitation[b] (inches)
Region 5	37.83
Region 6	29.49
Region 7	21.67

[a] Averaged over the years 1865–2006.

[b] Calculated as the sum of state average precipitation weighted by corn acreage. Source: USDC 2007.

In areas where water demand exceeds that available from soil moisture and precipitation, irrigation must be applied. Figure 8 shows that only 14% of total water withdrawals by all sectors in the East-Central Region (including USDA Regions 5 and 6, Arkansas, Mississippi, and Louisiana) is for irrigation, as compared with 64% in the Northern Plains (USDA Region 7). This result is not surprising since irrigation in a given area is highly dependent on regional conditions. In the United States, most water withdrawals (86%) and irrigated acres (75%) are in the 17 co-terminus western states (USGS 2007). The amount of water applied for irrigation in these states accounts for 88% of total U.S. irrigation water (USDA 2003). Irrigated acreage in these states typically receives less than 20 in. per year precipitation and cannot support crops without supplemental water.

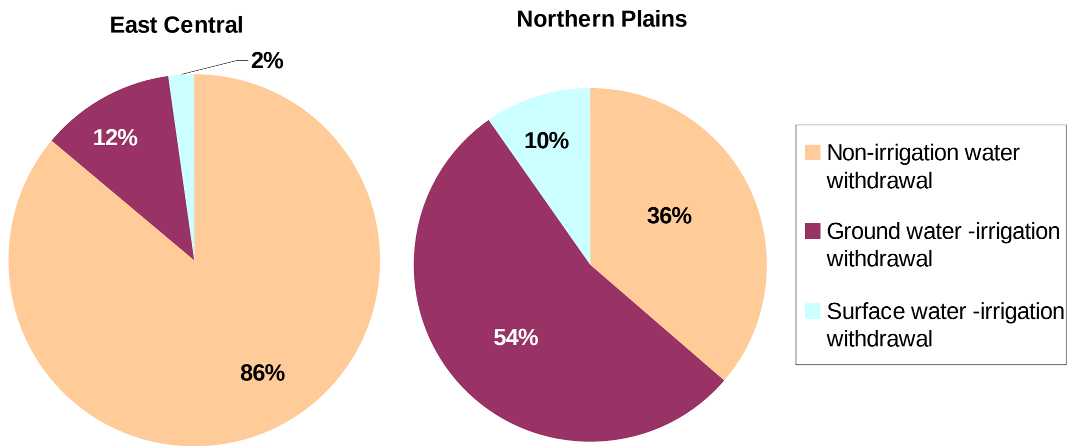


FIGURE 8 Distribution of Water Withdrawals for Irrigation and Non-irrigation Uses in U.S. Regions (USDA 2003). East-Central – USDA Regions 5 and 6, Arkansas, Mississippi, and Louisiana. Northern Plains – USDA Region 7.

Because of soil and climatic differences, feedstock crops may have different irrigation water requirements when grown in different regions. For example, corn generally requires <u>less</u> irrigation water than soybeans in Pacific and Mountain regions, while the two crops require similar amounts of irrigation when grown in North Central and Eastern regions. By contrast, corn grown in the Northern and Southern Plains states generally requires <u>more</u> irrigation per acre than soybeans (NRC 2007).

Therefore, the proportion of corn acreage that requires irrigation varies significantly across the United States depending on the location and soil characteristics. In Region 7, Nebraska relies heavily (56%–60%) on irrigation for growing corn (Table 4), as does Kansas (38%–49%). This finding compares with much more modest irrigation rates in Michigan (9%–14%), Missouri (11%–14%), and the other corn-producing states in the three regions (between 0.1% and 5.3%). On weighted average in 2013, 31% of harvested corn acres require irrigation in Region 7, as compared with 3% in Region 5 and 5% in Region 6. Overall proportion of irrigated corn grain acreages did not change substantially in the corn producing regions. From 2003 to 2013, although harvested corn grain acreages increased 21% from 60 million to 74 million acres in the three regions

(Table 4), irrigated areas decreased 9% in Region 7 and increased slightly (~1%) in Regions 5 and 6. Factoring in the 14 million acres where harvests increased (Table 4), the three-region average of the irrigated acreage remains 12% in 2013.

TABLE 4 Irrigation for Corn Grain by State and Major Corn-Producing Region in 2003, 2008, and 2013[a]

		Harvested acres			Irrigated acres (state)			Irrigated acres (region)		
State	**Region**	**2003**	**2008**	**2013**	**2003**	**2008**	**2013**	**2003**	**2008**	**2013**
IA	5	11,900,000	12,800,000	13,050,000	0.6%	0.8%	0.9%	2.2%	3.1%	3.1%
IL		11,050,000	11,900,000	11,800,000	2.0%	2.6%	3.2%			
IN		5,390,000	5,460,000	5,830,000	2.9%	4.5%	5.3%			
MO		2,800,000	2,650,000	3,200,000	10.9%	13.6%	10.9%			
OH		3,070,000	3,120,000	3,730,000	0.1%	3.5%	0.3%			
MN	6	6,650,000	7,200,000	8,140,000	2.7%	3.5%	3.3%	3.9%	5.0%	5.3%
WI		2,850,000	2,880,000	3,030,000	3.0%	3.7%	4.8%			
MI		2,030,000	2,140,000	2,230,000	9.2%	11.6%	13.5%			
SD	7	3,850,000	4,400,000	5,860,000	3.7%	4.0%	3.4%	39.7%	35.4%	31.1%
ND		1,170,000	2,300,000	3,600,000	4.9%	3.9%	2.5%			
KS		2,500,000	3,630,000	4,000,000	49.3%	37.7%	37.6%			
NE		7,700,000	8,550,000	9,550,000	59.8%	59.2%	56.0%			
Total		**60,960,000**	**67,030,000**	**74,020,000**						

[a] Source: Farm and Ranch Irrigation Survey (USDA 2003, 2008, 2013)
[b] Regional averages are weighted by harvested acreage of states in the region.

For the irrigated corn acreage, the amount of water applied varies considerably, from 0.3 to 3.1 acre-ft per acre of corn across the United States (Figure 9). Even in the Midwest regions 5, 6, and 7, there are significant differences in irrigation rates. The irrigation can be as little as 0.29-0.35 ft[15], as in Regions 5 and 6, or as much as 1.23 ft, as in Region 7 (Figure 9). From 1998 to 2013, irrigation water withdrawals fluctuated and moved downward. In particular, irrigation water use in corn-producing regions 5-7 decreased significantly, by more than a half, from previous survey years (Figure 9). Region 10 increased its irrigation in 2013 which is contributable to the draught in 2012-2013. According to the USDA *Farm and Ranch Irrigation Survey* and USGS 2015 report (Dieter et al. 2018), irrigation practices have changed in recent years due to the adoption of advanced irrigation technology. Water efficient irrigation systems, such as sprinkler and micro-irrigation systems currently accounted for 63% of total irrigated lands in 2015.

[15] Acre-ft per acre.

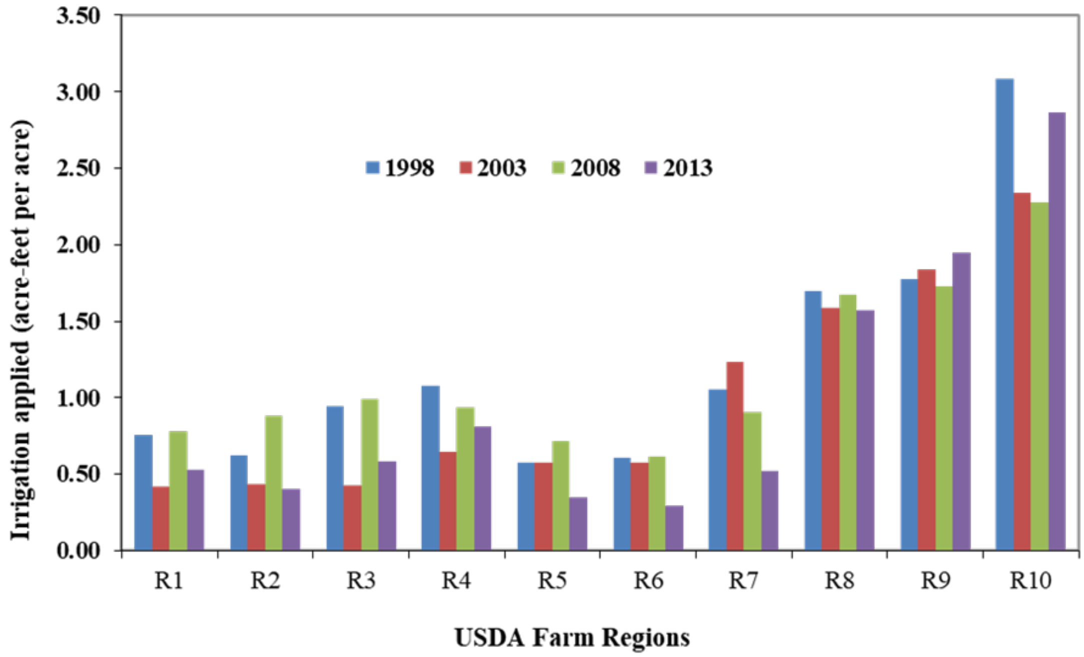


FIGURE 9 Irrigation Rate for the Irrigated Corn Acreage by USDA Region for 1998, 2003, 2008, and 2013. Multiply acre-ft per acre by 325760 to obtain gallons per acre.

On the basis of corn irrigation data for each state from the USDA *Farm and Ranch Irrigation Survey* (1998, 2003, 2008, and 2013), we calculated USDA regional total irrigation water applied. As noted in Section 1.1, a major portion of irrigation water is consumed. The remaining recharges to surface and groundwater. On the basis of state-level irrigation returning flow provided by USGS (1995), the percent of irrigation water consumed in the total irrigation water applied for corn was determined for each state and aggregated for each region. Using this proportion, we then estimated the consumptive irrigation water use for corn for each region. Dividing this figure by the total corn production in 1998, 2003, 2008, and 2013 (USDA-NASS 2008, 2011, 2018), we obtained a production-weighted consumptive irrigation water use per bushel of corn.

In all three regions, most of the water used for irrigation is withdrawn from groundwater aquifers. In the United States, 84% of the irrigation water used for corn is from groundwater aquifers; the remaining 16% comes from surface water (Dieter et al. 2018). A majority of applied irrigation water is consumed by crops. As shown in Figure 10, Region 7 stands out as the largest user of groundwater. Region 7 relies heavily on groundwater for irrigation because of several factors. The region accounts for a vast of area of cropland for corn; sitting on top of the largest aquifer — Ogallala Aquifer which is one of the world's great aquifers; and climate. As shown in Figure 7, while Region 5 received average precipitation in 1998 and 2003, Region 6 and 7 were dryer in 2003 than in 1998. In fact, Region 7 received 27 in. of rain in 1998 but only 20 in. in 2003.

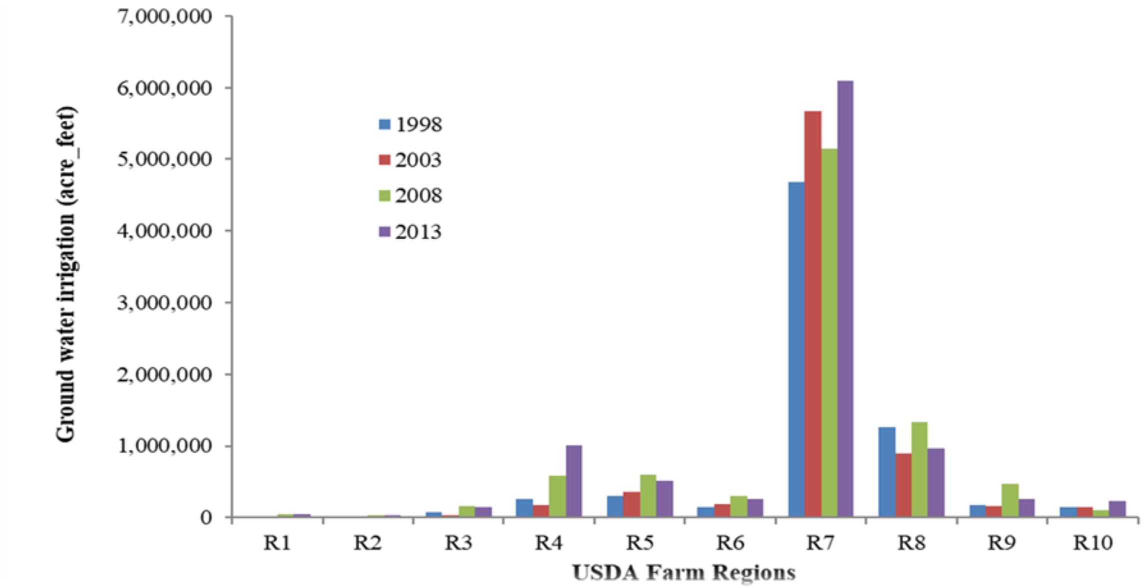


FIGURE 10 Groundwater Consumed for Corn Irrigation by USDA Region in 1998, 2003, 2008, and 2013. Multiply acre-ft value by 325760 to obtain gallons.

Producing one bushel of corn in USDA Region 7 consumes 667 gallons of freshwater from irrigation, which is similar to 2008 but a significant decrease from 2003 (Figure 11). Since most of the corn grown in Regions 5 and 6 receives sufficient water from precipitation, irrigation water consumption in those regions are lower, at 36 and 59 gallons per bushel in 2013, respectively. The irrigation intensities remains steady in the two regions from 1998-2013.

Historically, corn yield has risen by more than 1.4 – fold since 1970 (Figure 12) while increase of corn acreage was relatively small in the past three decades. In between 1998 and 2013, corn yield increased 18%, from 134 bushel to 158 bushel per acre corn harvested. In 2017, the yield has already reached 180 bushel per acre, a 31% increase from 1998 (Figure 12). In the United States, corn harvested for grain accounts for 82 million acres in 2013, increased 10 million acres from 1998. Among the major corn grain production regions, on average, 49% of the corn were produced by Corn Belt states (Region 5), 22% from High plains (Region 7), and 16% from Lake states (Region 6) (Figure 13). Three-region total production share in the United States decreased slightly from 88% in 2008 to 85% in 2013, suggesting other states increased production in last few years.

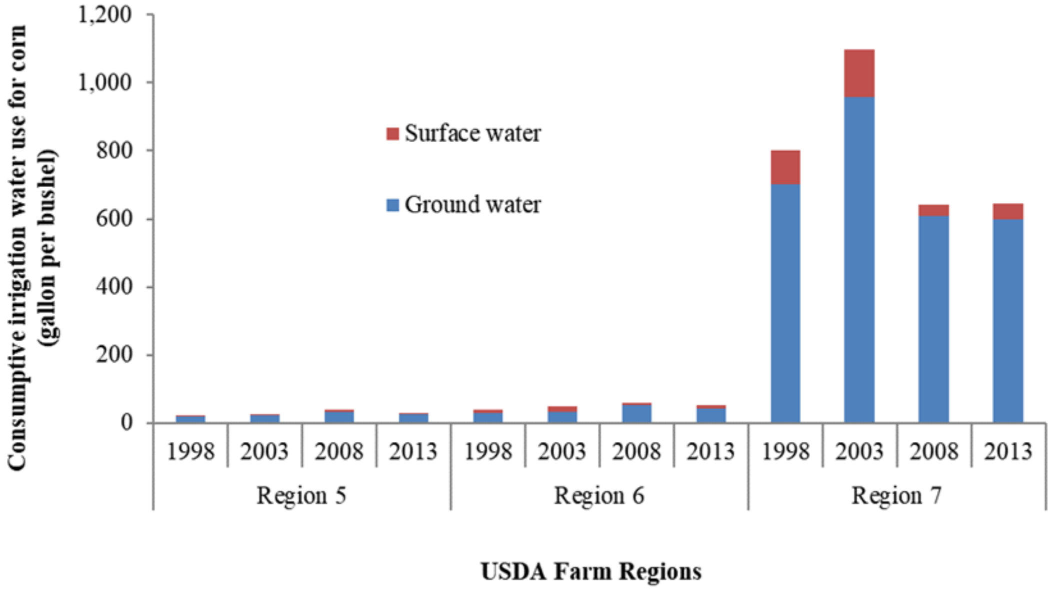


FIGURE 11 Consumptive Irrigation Water Use for Corn Grain from Ground and Surface Water per bushel of corn produced.

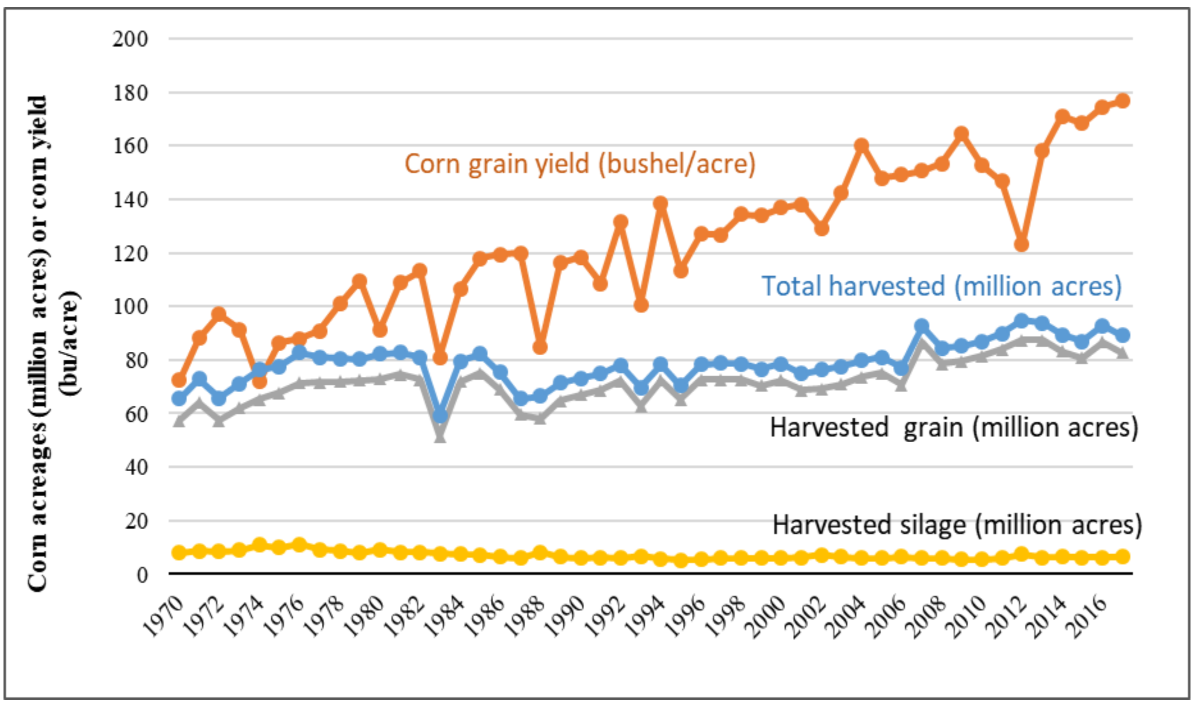


FIGURE 12 Historical Trend of Corn Yield and Harvested Corn Acreage in the United States

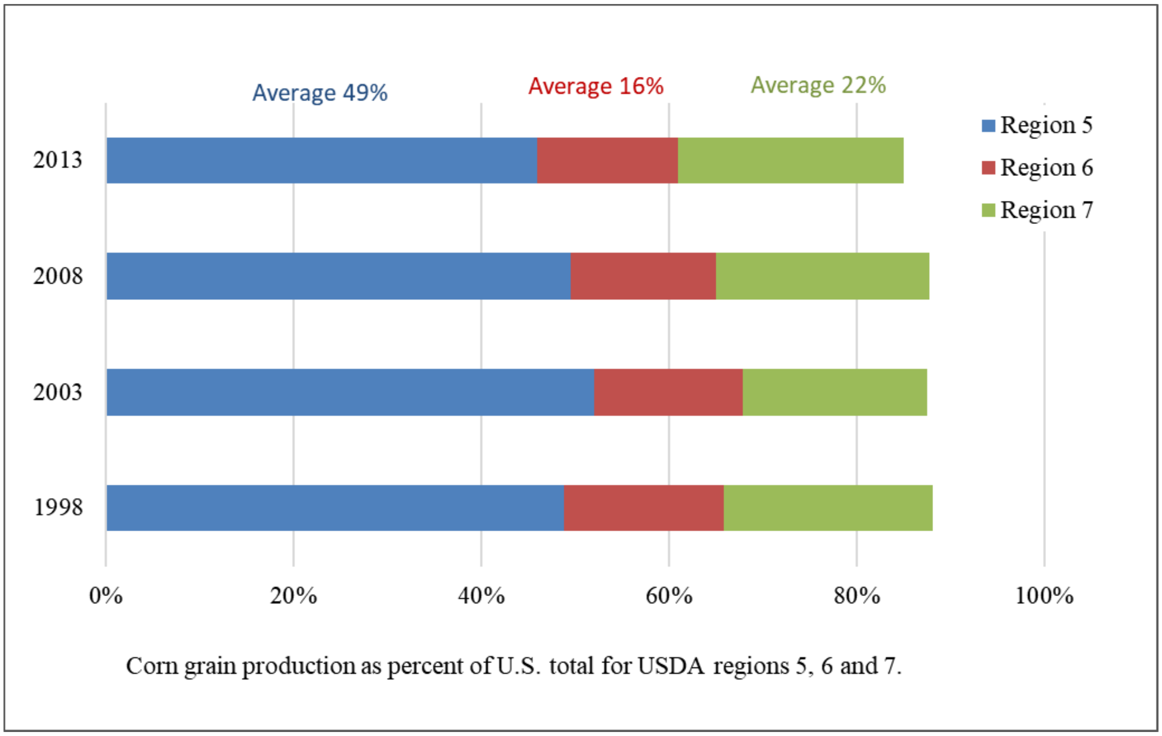
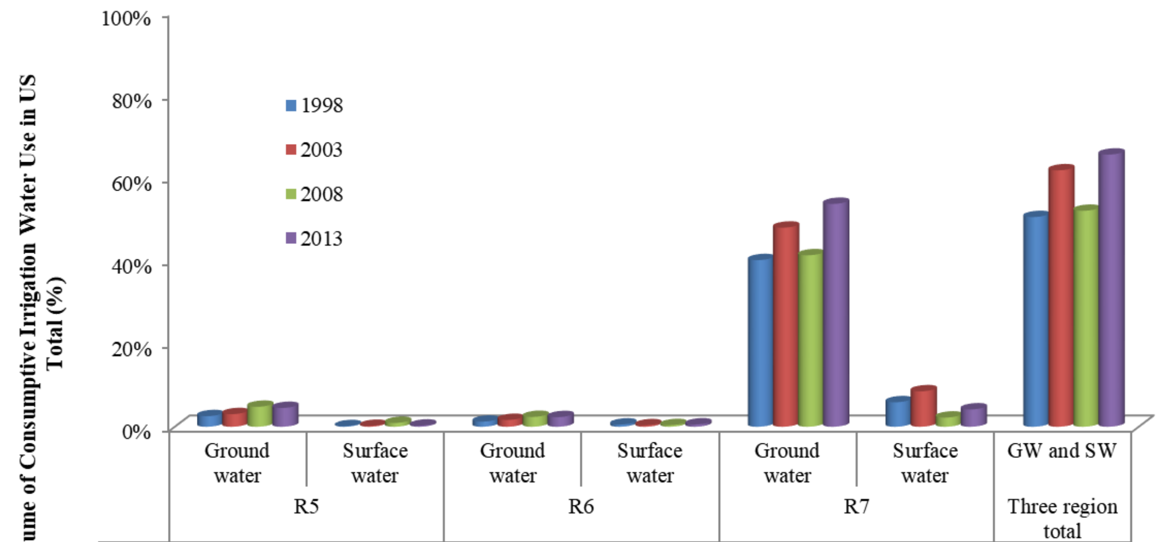


FIGURE 13 Corn production in USDA regions 5, 6, and 7 from 1998 to 2013.

Figure 14 illustrates the volume of consumptive irrigation water use for ground water and surface water in the three regions as percent of United States total. Shares of surface water consumptive use for irrigation remains minimal in the three regions, ranged from regional average of 0.4% to 5.2%. About half of the consumptive irrigative groundwater use for corn was attributed to region 7. The three regions required from 50% to 65% of consumptive irrigation water use for the grain in between 1998 to 2013. Compare the share of water use and share of production, we found that although Region 7 accounts for large amount of the consumptive irrigation water use for corn growing in the United States, it produced more than one-fifth of all U.S. corn (Figures 13-14). Region 5 is a near mirror image — it consumed only 5% of U.S. irrigation water for corn, but grew one-half of the crop. Together, the three regions accounted for 65% of total U.S. irrigation water consumption for corn while producing 85% of the U.S. corn crop in 2013 (Figures 13-14).



	R5 Ground water	R5 Surface water	R6 Ground water	R6 Surface water	R7 Ground water	R7 Surface water	GW and SW Three region total
1998	2.56%	0.15%	1.23%	0.53%	40.12%	5.90%	50.49%
2003	3.04%	0.22%	1.65%	0.36%	47.94%	8.54%	61.74%
2008	4.81%	0.92%	2.37%	0.40%	41.29%	2.21%	51.99%
2013	4.53%	0.28%	2.32%	0.56%	53.66%	4.18%	65.53%

FIGURE 14 Consumptive Irrigation Water Use for Corn as Percent of U.S. total for Corn by Source in USDA Regions 5, 6, and 7 from 1998 to 2013.

3.1.2 Corn Ethanol Production

Corn ethanol production requires water for grinding, liquefaction, fermentation, separation, and drying. Water sources can include groundwater, surface water, and municipal water supplies. Although many plants have recently come on line, the stock itself is a cross-section of plant sizes and ages. Since data tend to describe the entire mix, we estimated average water consumption for the existing stock of dry mill plants. The total consumptive water use is then weighted by the ethanol production.

Figure 15 illustrates the water system of a typical dry mill plant. Following the corn-growing portion of the ethanol life cycle (discussed in Section 3.1.1), corn is harvested and transported to ethanol plants for conversion. Water is required primarily for heating, cooling, and drying. Water losses occur through evaporation, drift, and blow down from the cooling tower; de-aerator leaks and blow down from the boiler; and evaporation from the dryer. A small quantity of water may also be contained in ethanol and the co-product, DDGS, which may be considered another water loss.[16] Water losses vary with the ambient temperature of the production plant, the percent of water vapor captured in the DDGS dryer (which is a function of dryer type) and the degree of boiler condensate reuse. It also depends on whether blowdown water is recycled. Assuming a temperature drop of 20°F (from 105°F to 85°F) for the cooling tower, no recapture of

[16] In this analysis, all water use in ethanol conversion process is allocated to ethanol. For more discussions see Section 6.2.3.

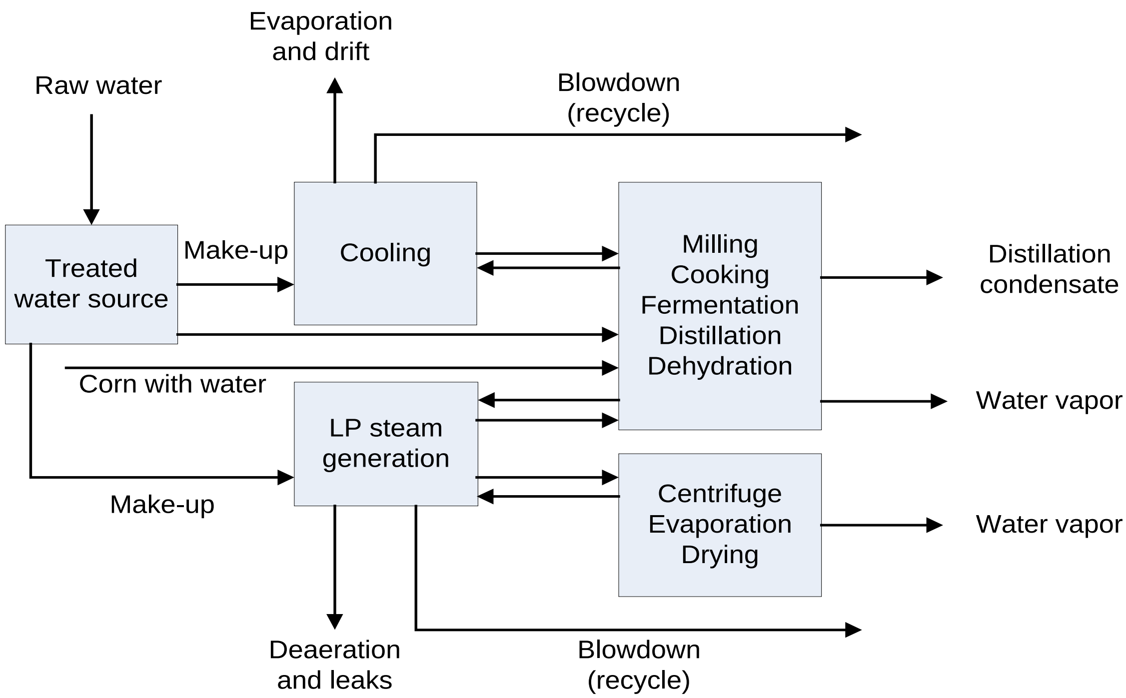


FIGURE 15 Water System in a Typical Dry Mill Ethanol Plant

water vapor from the dryer, and a boiler make-up water rate of 5%, USDA's corn dry mill model[17] estimates that a fairly new dry mill corn ethanol plant consumes approximately 3 gallons (25–26 lb) of water for every gallon of ethanol produced (Kwiatkowski et al. 2006; McAloon 2008). As shown in Figure 16, the cooling tower and dryer account for the majority (53% and 42%, respectively) of the water consumption.

This water consumption is significantly less than earlier estimates. Shapouri and Gallagher (2005) report that older dry mill ethanol plants use up to 11 gallons of water per gallon of ethanol, and Phillips et al. (2007) report that in 1998 the average dry mill consumed 5.8 gallons of water per gallon of corn ethanol produced. The downward trend is also documented in a comprehensive database maintained by the State of Minnesota (Keeney and Muller 2006).

[17] Developed at USDA ARS, the Corn Dry Mill Model simulates corn ethanol dry milling process using ASPEN PLUS and more recently SuperPro Designer® software.

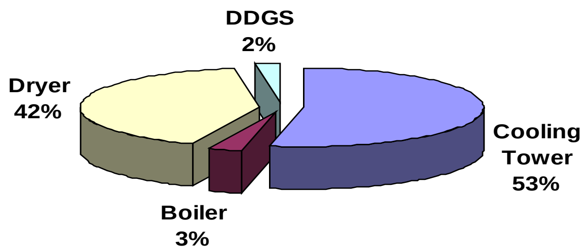


FIGURE 16 Breakdown of Water Consumed in Ethanol Production via Corn Dry Milling (determined by USDA Dry Mill Model)

This database shows a 21% reduction in water use by corn ethanol plants from 1998 to 2005, with an annual reduction rate of 3% (Figure 17). A similar trend is shown nationally in Figure 18.

With improved equipment and energy efficient design, water consumption in newly built ethanol plants is declining further. An analysis of the latest survey conducted by the RFA revealed that freshwater consumption in existing dry mill plants has declined to 3.0 gallons per gallon of ethanol produced, in a production-weighted average (Wu 2008), a significant drop of 48% in less than 10 years (Figure 18). This value is 17% lower than a typical dry mill design value — 3.6 gal/gal (Keeney 2007). In fact, some existing dry mills use even less by process modifications and production of WDG co-products in dry mill plants (as compared with DDGS) (Wang et al. 2007). The latest ethanol industry survey conducted by the University of Illinois at Chicago found the average water consumption in ethanol dry mills has already decreased to about 2.7 gal/gal (Mueller 2010), primarily because more new plants that have adopted efficient process design have come on-line.

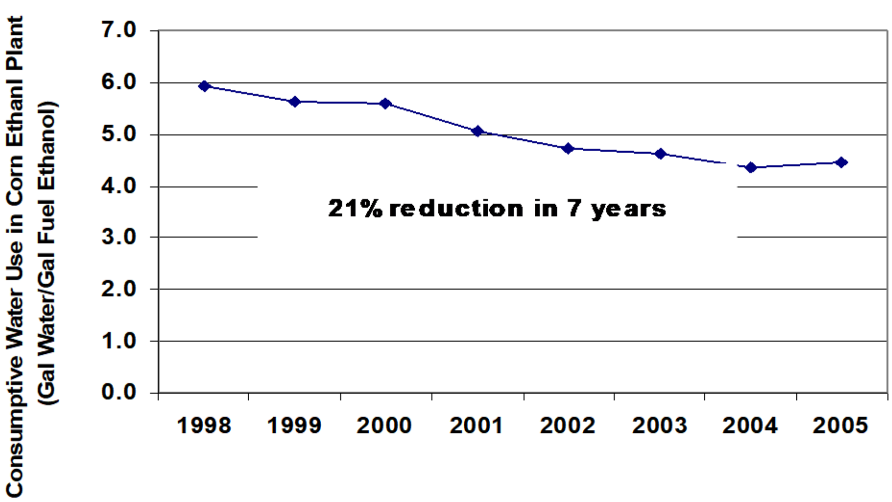


FIGURE 17 Consumptive Water Use in Minnesota Dry Mill Corn Ethanol Plants, 1998–2005 (Keeney and Muller 2006)

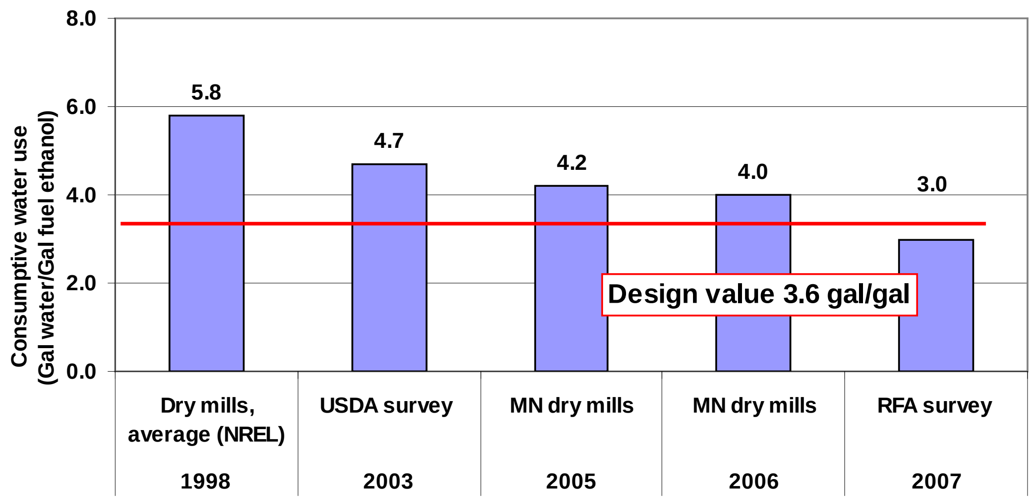


FIGURE 18 Average Water Consumption in Existing Corn Dry Mill Ethanol Plants

Water use can be minimized further through process optimization, capturing of the water vapor from the dryer, boiler condensate recycling to reduce boiler make-up rate, etc. The ethanol industry maintains that net zero water consumption is achievable by water reuse and recycling using existing commercial technology and with additional capital investment.

3.1.3 Co-Products

Most fuels are produced along with co-products. Although gasoline is typically the principal product, accounting for over half of refinery output in the United States (on the basis of energy content), refineries also produce a full slate of co-products. Similarly, dry mill ethanol plants produce DDGS, and biorefineries can produce multiple products, although the major co-product is currently electricity exported to the grid.

Alternative methods have been developed to allocate co-product contributions to such aggregates as energy use, greenhouse gas emissions, or criteria pollutant emissions. The choice of allocation method is a major analytical issue in life-cycle analysis, partially because different methods can produce different results. For gasoline, Wang et al. (2004) concluded that allocation methods based on energy, mass, or volumetric yields have similar effects; we implicitly used the volumetric allocation method in this study for gasoline estimates when reported as per gallon of gasoline.

For corn ethanol, Wang et al. (2010) estimated that 20–46% of total greenhouse gas burdens of the corn-to-ethanol cycle could be allocated to DDGS. In this update, an attempt was made to estimate corn ethanol co-product allocation by using mass-based allocation. In mass-based allocation, we adopt a rule of thumb in the corn dry mill industry, which estimates one-third of biomass in the corn kernel goes to ethanol, one-third is emitted as CO_2 during corn conversion to ethanol, and one-third ends up in DDGS co-product. Therefore, DDGS shares one-third of water used in the ethanol plant. Using the same proportion, irrigation water consumed is also allocated between corn for ethanol and corn for DDGS. Recently, by using the GREET model, it was found that 34% of GHG emissions associated with the corn ethanol life cycle are attributable to DDGS, on the basis of the coproduct displacement method (Wang 2011). The co-product allocation results are presented in Table 5.

3.1.4 Consumptive Water Use in Major Steps of the Corn Ethanol Life Cycle

Figure 19 graphically shows average water inputs and consumption to produce a bushel of corn in USDA Regions 5, 6, and 7. As noted previously, a percentage of input irrigation water is consumed via ET, soil percolation, and absorption. The remaining becomes surface run-off and groundwater recharge, which may be available for re-use as irrigation water. (For additional discussion of groundwater recharge, see Section 5.1.)

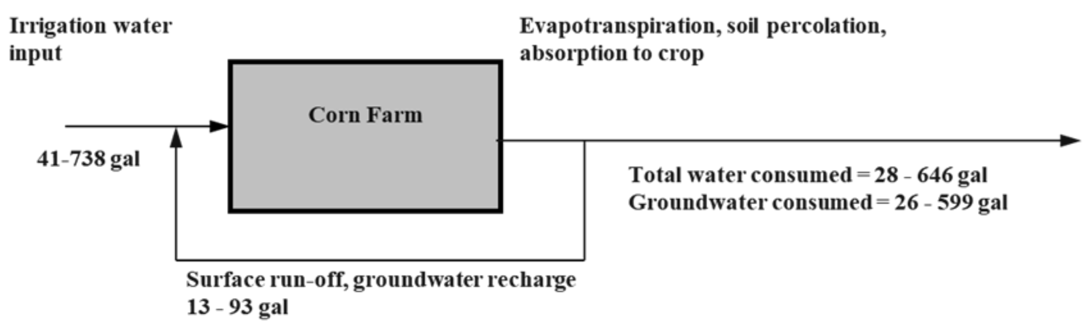


FIGURE 19 Irrigation Water Input and Consumption to Produce One Bushel of Corn in USDA Regions 5, 6, and 7 in 2013, before Co-Product Allocation. (The consumption value decreases by one-third if water use attributable to DDGS is considered.)

Figure 20 illustrates average water input and consumption to produce a gallon of ethanol in an existing dry mill. Data are from surveys of existing ethanol producers and include a range of plant sizes, ages, and water management schemes.

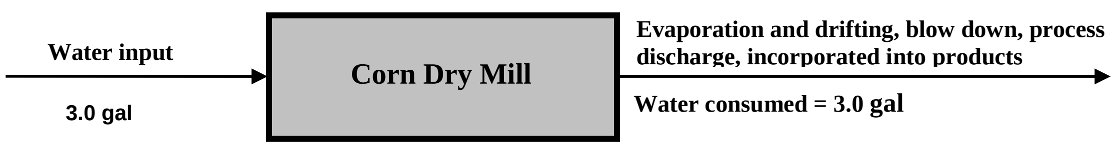


FIGURE 20 Water Input and Consumption of an Average Corn Dry Mill Producing One Gallon of Fuel Ethanol (RFA 2007), before Co-Product Allocation. (The consumption value decreases by one-third when water use attributable to DDGS is considered.)

Based on average consumption of 3.0 gallons of water/gallon of corn ethanol produced in a corn dry mill; average consumptive use of irrigation water for corn farming in USDA Regions 5, 6, and 7 (Figure 11); and dry mill ethanol yield of 2.72 gallons per bushel, we estimated total consumptive water use for current corn ethanol production for each region (Table 5). Since total groundwater and surface water use for corn growing vary significantly across the three regions, producing 1 gallon of corn-based ethanol consumes a net of 13–22 gallons of freshwater when the corn is grown in Regions 5 and 6, and 240 gallons when the corn is grown in Region 7. When taking into account of the water allocation to DDGS co-product, a net of 8.7–160 gallons of freshwater consumed per gallon of ethanol is produced from corn starch. This value is much smaller than our earlier 2009 estimate, due to a decrease in irrigation water withdrawal in 2008 and 2013 in Region 7 (Figure 11).

As with corn production, U.S. corn ethanol production is concentrated in the same three regions (Regions 5, 6, and 7). In 2013, these regions were responsible for 90% of ethanol production (RFA 2013) and 85% of corn production (USDA-NASS 2013). Accounting for the largest share of corn (46%) and ethanol (49%) production, Region 5 consumes the least amount of irrigation water (Table 5). On ethanol production weighted basis, we calculated a three-region average water consumption intensity of 76 gallons of water per gallon ethanol produced. The water intensity value weighted by corn production is similar.

TABLE 5 Consumptive Water Use from Corn Farming to Ethanol Production in USDA Regions 5, 6, and 7 (Gallons water/gallons denatured ethanol produced)

USDA Region	Region 5	Region 6	Region 7
Share of US ethanol production capacity (%)[a]	49	13	28
Share of U.S. Corn Production (%)[b]	46	15	24
Corn irrigation, ground water[c]	9.7	15.2	220.2
Corn irrigation, surface water[c]	0.6	3.6	17.1
Ethanol production[d]	2.7	2.7	2.7
Total (corn irrigation and ethanol production without co-product allocation)	13.0	21.5	240.0
Total water consumption with mass-based co-product allocation[e]	8.7	14.3	160.0

[a] 2013 Ethanol production capacity in operation (RFA 2013, data available in Nebraska Energy Office http://www.neo.ne.gov/statshtml/121/2013/121_201309.htm)
[b] 2013 Corn production (USDA 2013)
[c] USGS 2013, USDA 2013, assumed a yield of 2.72 gal ethanol per bushel.
[d] Mueller 2010.
[e] Mass-based and carbon displacement-based water allocation. According to the rule of thumb, one-third of biomass in corn kernel goes to ethanol, one-third goes to CO2, and one-third goes to DDGS. LCA results from GREET show 34% GHG are attributable to DDGS (Section 3.1.3.).

3.2 CELLULOSIC ETHANOL

Cellulosic ethanol can be produced from a variety of sources, including perennial grasses, forest wood residues, agricultural residues (corn stover, wheat straw, rice hulls, cotton gin, etc.), short-rotation woody crops, and algae. For this analysis, switchgrass is chosen as an example. Switchgrass is assumed to be grown in its native region and transported to local biorefineries for conversion to ethanol via biochemical or thermochemical processes.

3.2.1 Feedstock Irrigation

A recent study of the Department of Energy (DOE) and USDA estimated that more than a billion ton of biomass is available for biofuel production (Perlack 2005). Irrigation requirement of cellulosic biomass depends largely on the type of feedstocks and origin of the feedstocks, the climate in which they are grown, and soil conditions. Typically, forest wood does not require irrigation. Agricultural residues share the water requirements with crops (i.e. grain), which vary from region to region. Short-rotation woody crops and algae may require more water to achieve desirable yield. Switchgrass are deep-rooted and efficient in their use of water, and thus tend to be relatively drought tolerant. In its native habitat, switchgrass can yield 4.5 to 8 dry tons per acre (Downing et al. 1995; Ocumpaugh et al. 2002; Taliaferro 2002) without irrigation. Although irrigation could increase yield, it may not be sufficient to offset the additional cost (e.g., for pumping energy). If switchgrass were grown in regions where it is not native (e.g., certain parts of the northwestern United States) irrigation would be needed (Fransen and Collins 2008). In this study, we assume switchgrass is the primary feedstock for cellulosic ethanol, it is grown in its native habitat to yield 4–7 dry tons per acre, and irrigation is not required.

3.2.2 Cellulosic Ethanol Production and Co-products Allocation

Commercial-scale cellulosic biorefineries are still at an early stage in development. With strong supports from U.S. government and private sector in past several years, extensive efforts have been spent on research, development, and deployment (R&DD) to develop and validate various proposed processes to produce ethanol, butanol, bio-based gasoline, bio-based diesel, and other fuels from biomass. As of today, cellulosic ethanol can be produced via several processes[18]:

- Biochemical conversion (BC) using enzymatic hydrolysis and fermentation,
- Thermochemical conversion (TC) using gasification and catalytic synthesis,
- TC using pyrolysis and catalytic synthesis, or
- A hybrid approach of gasification followed by syngas fermentation.

The amount of water consumed during ethanol production depends on the production process itself and the degree of water reuse and recycling. Because of the differences in the co-products, energy consumption, and capital and operational cost, process comparison could be complex. Nevertheless, gasification and pyrolysis in general consume relatively little water. The

[18] The list represents selected major cellulosic biofuel process.

BC process requires additional water for pretreatment to break down the cellulosic feedstocks. Previous estimates of water consumption to produce 1 gallon of cellulosic ethanol via a BC process (such as dilute acid pretreatment followed by enzymatic hydrolysis) were 9.8–5.9 gallons; water consumption decreases as the yield increases (Aden et al. 2002; Wallace 2007). A more recent estimate further decreased this value 5.3 gal/gal (Humbird et al. 2011; Tan 2011). An optimized TC gasification process requires only 1.9 gallons of water to produce 1 gallon of fuel ethanol (Phillips et al. 2007).[19] On the other hand, fast pyrolysis of forest wood residue consumes 2.3 gallons of water to produce 1 gallon of biofuel (containing 50% bio-based diesel and 50% bio-gasoline) (Jones et al. 2009). This figure can be reduced further with additional capital costs.

Numerous efforts are underway to reduce water consumption. For example, advanced process simulation tools are being used to identify opportunities to minimize energy and water consumption through improved process integration. NREL is attempting to optimize the BC process by increasing water recycling and reuse. Private-sector developers are pursuing novel processes, including a syngas-to-ethanol process - a hybrid approach that combines biomass gasification with syngas fermentation to produce ethanol. The freshwater requirement for this latter process is claimed to be less than 1 gallon for each gallon of ethanol produced (Coskata 2008).

Cellulosic feedstock contains a considerable amount of lignin, which was not converted to sugar in the biochemical process for ethanol production. With its high carbon content, lignin provides an ideal fuel source for heat and power generation in the biorefinery. Lignin and the unconverted cellulose and hemicellulose from the feedstock, biogas from anaerobic digester, and biomass sludge from wastewater treatment were combusted to produce a co-product from the biorefinery — (Humbird et al. 2011) — which allows the refinery to be self-sufficient in energy requirements and export excess electricity to the grid. In a refinery scale of 2000 dry tons of biomass per day, 1.77 kWh of electricity can be generated from corn stover and 2.07 kWh can be generated from switchgrass for each gallon of neat ethanol produced (Humbird et al. 2011; Tan 2011). Assuming the excess bioelectricity is to displace U.S. average electricity mix, we calculated the amount of embedded water associated with electricity generated from the displaced electricity from the U.S. mix by using a power-water estimating tool (Wu and Peng 2010). Nationally, on a production-weighted basis, a total of 0.43 gal of freshwater is consumed per kilowatt-hour of electricity generated in the United States (Wu and Peng 2010). Thus, bioelectricity co-production can save an additional 0.89 gal of freshwater per gallon of cellulosic ethanol produced from the biochemical process. The water consumption estimate for cellulosic biofuels after co-product electricity allocation is presented in Table 6. Current gasification and pyrolysis-based cellulosic biofuel production process design do not produce excess electricity for export; therefore, there is no co-product credit from electricity generation.

[19] A mixed-alcohol process produces ethanol, methanol, butanol, and pentanol.

3.2.3 Consumptive Water Use in Major Steps of the Cellulosic Ethanol Life Cycle

If no irrigation water is used for feedstock production, switchgrass and forest wood residue derived cellulosic ethanol consumes only the water needed for conversion via BC, TC, or hybrid processes. As shown in Table 6, on the basis of current process simulations, production of 1 gallon of cellulosic ethanol consumes 1.9–5.4 gallons of freshwater. With co-product allocation, the values are reduced to 1.9–4.6 gallons. Figure 21 displays these data in an input-output format.

From a life-cycle perspective, cellulosic biofuels consume a minimal amount of water relative to most sources of corn ethanol. Producing cellulosic ethanol from switchgrass via a BC process consumes less than half the water consumed by producing ethanol from corn grown in Region 5 (11.0 gallons; see Table 5). Producing cellulosic ethanol from switchgrass via TC gasification requires even less water.

TABLE 6 Water Consumption for Switchgrass-Based Ethanol Production

Process	Average Water Consumption (gal/gal biofuel)	Electricity Export (kWh/gal biofuel)	Average Water Consumption after Co-product Allocation (gal/gal biofuel)	Reference
Biochemical				
Previous estimate	5.9[a]			Aden et al. (2002)
Current estimate	5.4[a]	1.77-2.07[c]	4.5–4.6	Humbird et al. (2011)
Thermochemical				
Gasification	1.9[a]	0	1.9	Phillips et al. (2007)
Pyrolysis	2.3[b]	0	2.3	Jones et al. (2009)

[a] Cellulosic ethanol produced from switchgrass
[b] Forest wood residue as feedstock
[c] Corn stover: 1.77kWh/gal; Switchgrass 2.07 kWh/gal, both from a 2000-dry-ton/day biorefinery

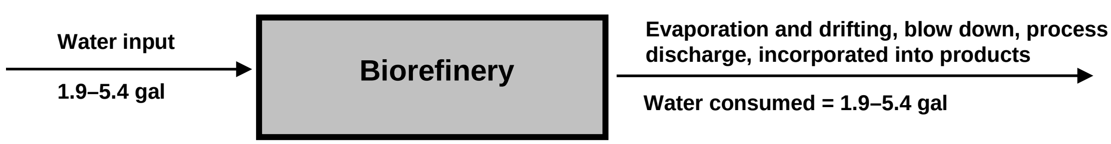


FIGURE 21 Water Input and Consumption for a Biorefinery Producing One Gallon of Cellulosic Ethanol, before Co-Product Allocation. (The values decrease to 1.9–4.6 gal when water use attributable to the excess electricity generation is considered.)

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4 GASOLINE

Petroleum gasoline production can consume substantial quantities of water, especially for crude oil recovery. For particular crude oil sources or oil reservoirs located in water-poor regions, water use can be a major concern in project development and in efforts to promote sustainability.

In this section, we examine water consumption in crude oil E&P and in oil refining. To estimate the effect of different types and sources of crude oil on average water use, we examine water consumption in the major life-cycle stages for conventional crude (from domestic onshore wells and a major Saudi Arabian field) and unconventional crude oil sands.

4.1 METHODOLOGY

In this analysis, consumptive water use is estimated for several major oil-producing regions. Since recovery technologies and the crude oil itself differ significantly from one region to another, this section describes methodologies employed for the analysis.

4.1.1 Domestic Crude Oil

Because of wide variations in the geology and characteristics of individual wells, there is no "typical" domestic recovery regime. Wells may be relatively new or nearing the end of their productive lives; field geologies may be complex or relatively simple; water resources may be plentiful or scarce. Rather than characterizing a range of wells, this analysis sought to construct a series of composite estimates of water intensity for the regions accounting for the bulk of domestic onshore production. For conventional gasoline, we examined regions as defined in terms of PADDs; these regions represent 100% of U.S. domestic onshore crude and 84% of total crude production (EIA 2018b). Shown in Figure 22, these regions are:

- PADD I (Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, New York, New Jersey, Pennsylvania, Maryland, Delaware, West Virginia, Virginia, North Carolina, South Carolina, Georgia, and Florida),

- PADD II (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, Ohio, Kentucky, and Tennessee),

- PADD III (Texas, New Mexico, Arkansas, Louisiana, Mississippi, and Alabama),

- PADD IV (Montana, Idaho, Wyoming, Utah, and Colorado), and

- PADD V (California, Alaska, Arizona, Nevada, Oregon, and Washington).

FIGURE 22 Petroleum Administration for Defense Districts

Water consumption is estimated for each of these PADDs. In crude oil recovery, water consumed is largely injection water that cannot be recycled and reused (Figure 4b). Oil recovery can be accomplished via several technologies, which have different water requirements. In addition, large amount of PW[20] is generated from oil wells and lifted up along with oils. The PW is typically reinjected into the oil well for reuse. Thus, in order to estimate average water consumption, or net water use for crude recovery, technology-specific water injection requirements, coupled with market shares for the technology, must be determined. Then, the amount of PW reinjected into the oil well must be subtracted from the total injection requirements. Figure 23 illustrates this approach.

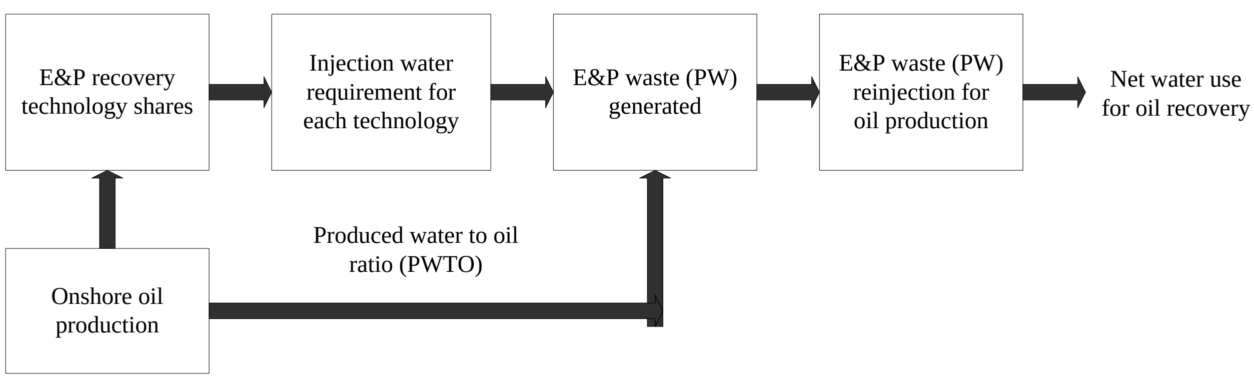

FIGURE 23 Calculation Logic of Net Water Use for Crude Oil Recovery

[20] E&P waste

Equations 1 and 2 describe the calculations. We first estimated technology-specific water requirement (gal/gal oil) from literatures and the market share of the technologies based on EIA data and Oil & Gas Journal publications. Once the contribution to oil production from each technology was estimated, we calculated the injection water requirement as a technology-weighted average (gal/gal oil) for the United States [Equation 1]. Because regional technology shares are not readily available, regional water usage is estimated by using national technology shares assuming similar market shares and intensity for each region of interest.

Technology share of oil production (%) Tech. 1 Tech. 2 Tech. 3 …… Tech. n	x	**Injection water required (gal/gal oil)** Tech. 1 Tech. 2 Tech. 3 …… Tech. n	⇒	**Technology weighted injection water requirement (gal/gal oil)**	… [Equation 1]

Technology weighted injection water requirement (gal/gal oil)	—	**PWTO ratio (gal/gal oil)**	x	**Percentage of PW re-injected for oil recovery**	=	**Net water use for oil E&P (gal/gal oil)**		… [Equation 2]
(1)		(2)		(3)		(4)		

Next, the ratio of PW-to-oil recovery (PWTO) was calculated and the percentage of PW that is reinjected for oil recovery was estimated for each region. Then, the amount of PW reinjection (calculated as the product of PW and the share of PW that is reinjected for oil recovery) was subtracted from this total. Both PW and the reinjection share for PADDs were obtained from the American Petroleum Institute (2000) and Veil et al. (2004, 2015). The remainder is net water use for crude oil recovery (see Equation 2).

4.1.2 Canadian Oil Sands

Extensive statistics on the Canadian oil sands industry are compiled by the Canadian Association of Petroleum Producers (CAPP), the Alberta Department of Energy, the Alberta Energy Resources and Conservation Board (formerly the Alberta Utilities Board), and other entities. For the most part, however, these organizations report production, broken down by location and recovery method. Data on water consumption are only available for select projects or specific technologies. For this effort, technology shares were estimated, and water use was analyzed by location and recovery method.

4.2 ONSHORE RECOVERY OF DOMESTIC CRUDE OIL

As discussed above, oil recovery is the major consumptive water use in the petroleum gasoline life cycle. However, there is considerable variation among wells as well as within the same well over time.

4.2.1 Recovery Technologies and Water Consumption

4.2.1.1 Recovery Technologies

Conventional recovery technologies have evolved to meet the need for maintaining oil production as wells age. Primary oil recovery uses the natural pressure of the well to bring a mixture of oil, gas, and water (produced water) to the surface. As individual wells age, production from primary recovery declines, and secondary recovery (or water flooding) becomes the major recovery technology. In secondary recovery, separate injection wells are drilled, and water is injected into the formation. Although much of the injection water is recycled PW, saline groundwater and freshwater are also used for injection. Secondary recovery increases oil production for a time. Eventually, however, increases in injection water do not increase oil production because the remaining oil is trapped in the reservoir rock by surface tension and/or the viscosity of the oil itself. Surface tension tends to trap the oil droplets, and less viscous water "short circuits" the more viscous oil (Barry 2007).

Tertiary or enhanced oil recovery (EOR) plays a critical role in preventing further declines in oil recovery. EOR uses various technologies to target trapped oil. For example, carbon dioxide (CO_2) injection and surfactant injection reduce surface tension, while steam injection (thermal EOR) and micellar polymer injection reduce viscosity contrasts. Figure 24 shows the well history of Shell's Denver City project. In the initial period of secondary water flooding, large volumes of injection water were used to build up the pressure in the reservoir. Over time, PW increased, and the gap between the volume of injection and produced water narrowed. Among tertiary recovery technologies, CO_2 injection has attracted growing interest in the petroleum industry for its potential role in CO_2 storage.

Onshore wells currently account for 84% of domestic oil production. Although offshore wells could contain both primary and secondary wells (Bibars 2004), most of them use seawater as an injection source, which is beyond the scope of this study. Among the technologies, EOR operation is well documented (O&G J 2006, O&G J 2014) for its production share, while primary and secondary data are scarce. Since secondary recovery tends to use more injection water, for this analysis, we assume a worst-case scenario where all secondary recovery and EOR are used in onshore production.

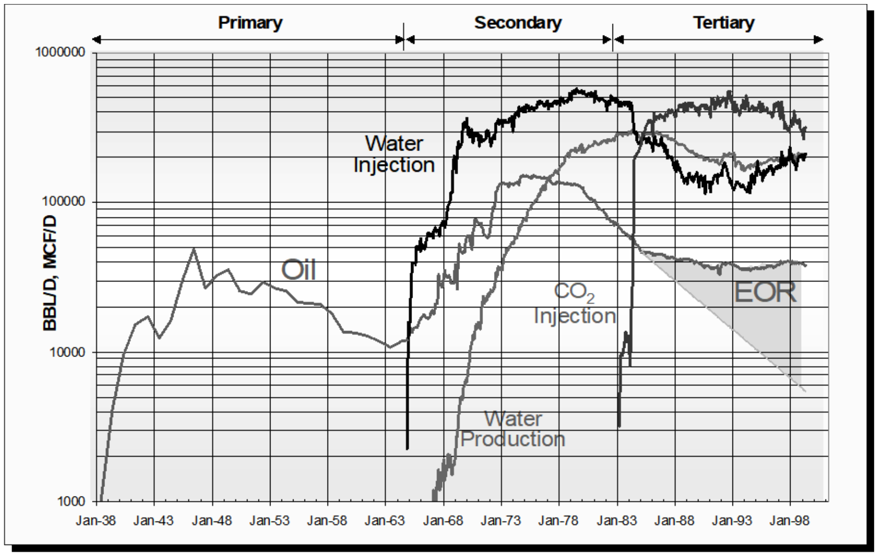

FIGURE 24 Water Injection and Oil and Water Production in Primary, Secondary, and Tertiary Recovery for Shell Denver City Project (Barry 2007; used with permission). BBL/D: bbl oil per day; MCF/D: million cubic feet gas per day

Figure 25 shows the distribution of U.S. onshore and offshore production and, within them, the distribution of recovery by primary, secondary, and tertiary (EOR) technologies. Of the total crude volume produced, a third is estimated to come from onshore primary, 42% from onshore secondary, and 9% from EOR. Table 7 provides the total production volumes (onshore plus offshore) and associated with these shares in 2014. In onshore production, half of crude recovery is from secondary technology, and EOR accounts for 11%.

Figures 26a and 26b break down onshore production by recovery technology between 2006 and 2014. The large increase in primary wells suggests a boom in oil E&P in the last decade. From a water-use perspective, water flooding was responsible for three-quarters of production in 2006; that figure decreased to half by 2014. Although thermal steam EOR was the dominant tertiary recovery technology (8.3%) in 2006, it decreased to 3.9% in 2014. CO_2 injection has been growing rapidly and is now the most commonly used EOR technology. Other EOR technologies include nitrogen gas injection, forward air combustion, hydrocarbon miscible/immiscible, and a small amount of hot-water injection. Together, these technologies represent about 2% of total EOR (O&G J 2014). Regionally, EOR is mostly used in PADD III and PADD V. Figure 26c presents the distribution of EOR technologies and their production volumes in the PADD regions. Currently, the largest crude volume produced via EOR is from PADD V, followed closely by PADD III. Among the EORs, CO_2 is widely adopted in PADD III, while steam technology is mostly used in PADD V. In addition, a majority of hydrocarbon and nitrogen gas-based EORs is practiced in PADD V. There is no recorded EOR use in PADD I.

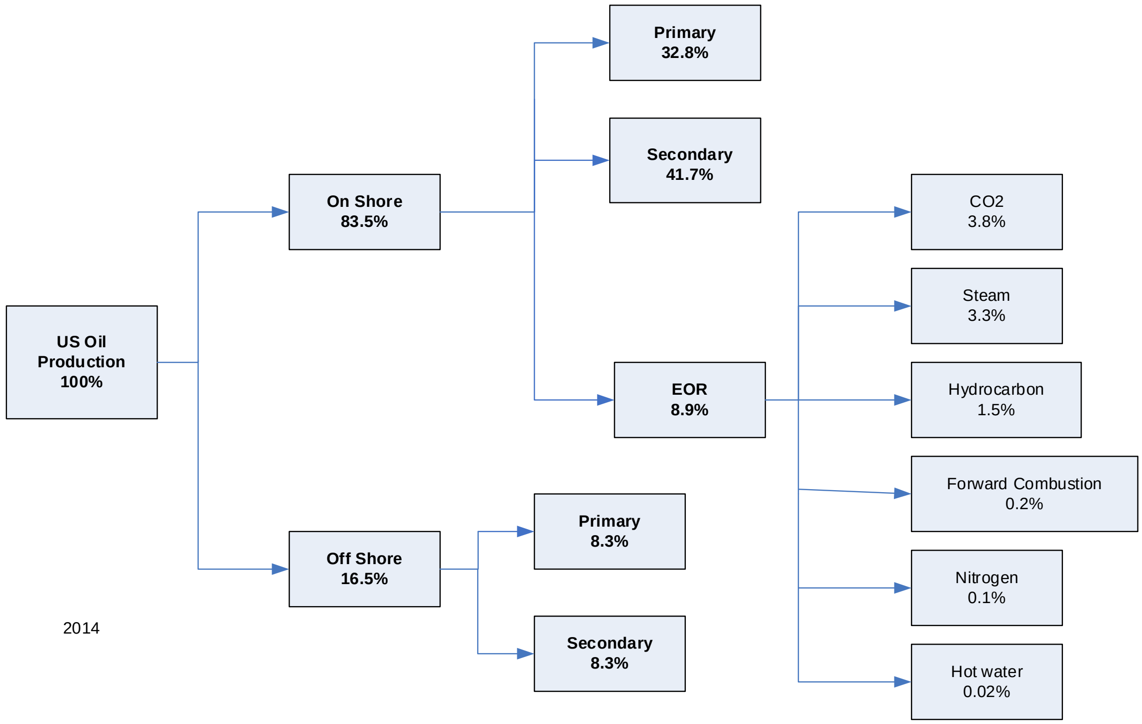

FIGURE 25 Technology Shares for Onshore and Offshore U.S. Crude Oil Recovery (EIA 2018b; O&G J 2014)

TABLE 7 Estimated U.S. Oil Production by Technology, 2014

Recovery Technology	Total Oil Recovery by Technology (thousand bbl/d)	Technology Share in Total Recovery (%)	Onshore Recovery by Technology[b] (thousand bbl/d)	Technology Share in Onshore Recovery (%)
Primary[b]	3599	41%	2875	39%
Secondary[c]	4377	50%	3653	50%
Tertiary (EOR)[d]	778	9%	778	11%
Total[a]	8,754	100%	7306	100%

[a] Total onshore and offshore production (EIA 2014.), accessed June 2018

[b] Primary recovery = total recovery - (secondary + EOR).

[c] Secondary US crude production accounts for about half of total production as per EIA Information sheet, here it is assumed as 50% in onshore and total production. Reference: http://www.eia.doe.gov/neic/infosheets/crudeproduction.html (accessed Dec 20, 2007). Offshore wells also used sea water flooding and primary technology.

[d] Source of EOR survey, Table 1, Page 78, O&G J Apr 17, 2014.

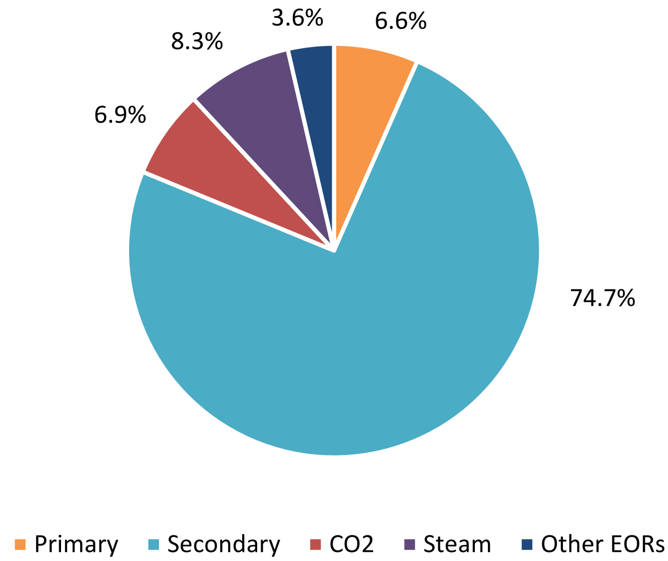

FIGURE 26a Onshore U.S. Crude Oil Recovery by Technology in 2005

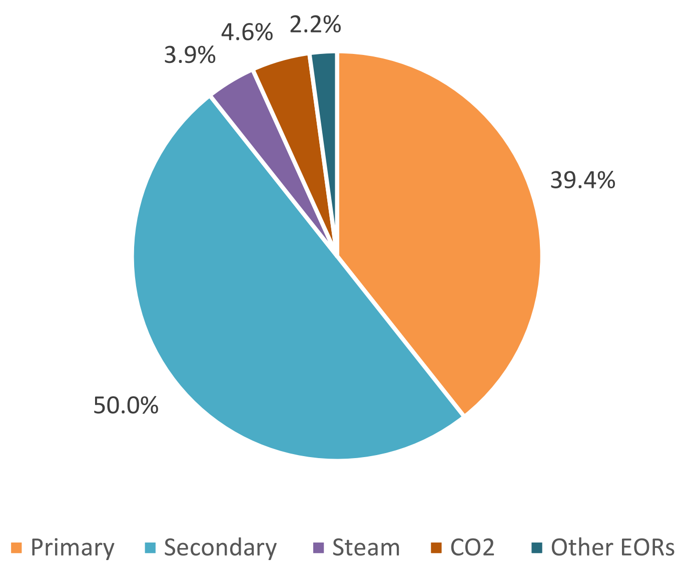

FIGURE 26b Onshore U.S. Crude Oil Recovery by Technology in 2014

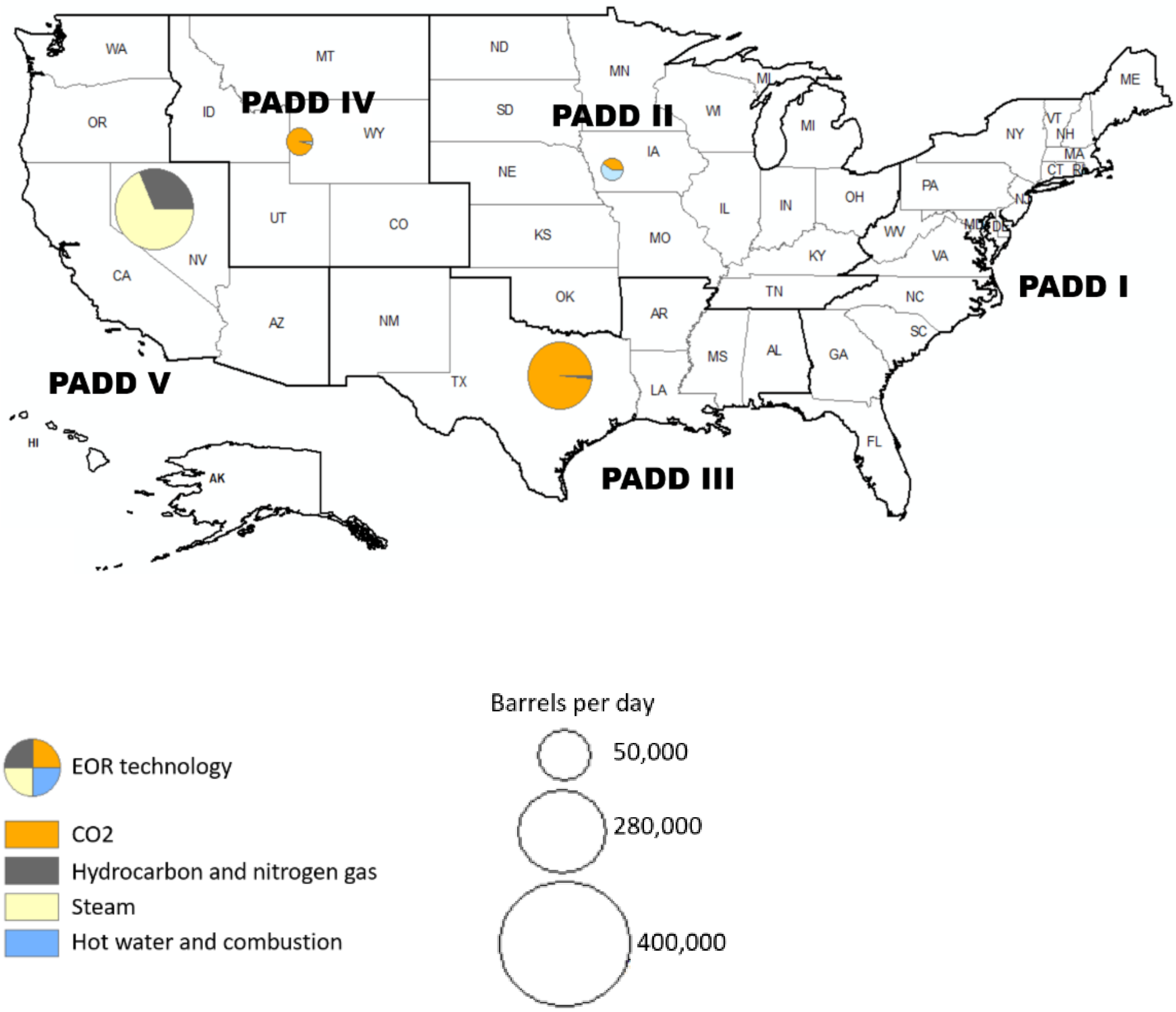

FIGURE 26c Distribution of EOR technology used in PADDs I–V (note there was no reported EOR use in PADD I).

4.2.1.2 Injection Water Consumption for Oil Recovery

Injection water requirements vary with production stage and technology. E&P drilling and primary recovery require an average of only 0.215 gallons of freshwater/gallon of crude oil recovered (Goodwin et al. 2012; Ali and Kumar 2017; Gleick 1994). As a general rule, secondary recovery is relatively water intensive (Table 8), but injection water requirements vary with the age and characteristics of the individual well and the formation in which it is located. Based on an analysis of the history of 68 U.S. secondary wells, Bush and Helander (1968) found that over their water-flooding lifetime, an average of 15.69 gallons of water is injected to recover 1 gallon of crude. Water flooding is common and effective, yet it increases overall water requirements (as compared with other recovery technologies) if injection water is supplemented by freshwater not otherwise used for oil recovery.

Injection water use for EOR, or tertiary oil recovery, can be as low as 1.9 gallons per gallon of oil recovered with forward combustion (Table 8) or up to 4.9 gallons of per gallon of oil with steam. Although micellar-polymer-based recovery consumes relatively large amounts of water (343 gallons per gallon of oil), it was phased out by 2014. There are no reported active projects employing this technology currently in the U. S. (O&GJ 2006, 2014). The same is true for caustic/alkaline, surfactant, and other polymer-based oil recovery methods (O&GJ 2006, 2014). Hence, these technologies are not included in this analysis. With CO_2 injection, reports of water use are highly variable. Based on a survey of 14 oil companies conducted in the early 1980s, Royce et al. (1984) reported water use of 13 gallons of injection water per gallon of crude oil recovered. In the early 1990s, Gleick (1994) reported 24.7 gallons of injection water per gallon of crude oil recovered. More recent data was based a 10-year (from 1988 to 1998) production record in Shell's CO_2 EOR Denver City project, which showed injection water averaged only 4.26 gallons per gallon of crude produced (see Figure 24). Royce et al. suggested that zero freshwater injection can be achieved for CO_2 EOR because injection water quality is not important with this technology. In this analysis, we adopted the latest available value of 4.26 gallons per gallon recovered with CO_2 EOR. For EOR technologies such as hydrocarbon miscible/immiscible, hot water, and N_2 technologies for which water use is not reported in the open literature, we estimated the average injection water use of CO_2 and steam EOR schemes weighted by their production shares (54% for CO_2 and 46% for steam), 4.55 gallons of water per gallon of crude.

By substituting the share of production (Table 7) and the amount of water injected per unit of oil produced of each recovery technology (Table 8) into Equation 1, we estimated total injection water use for domestic onshore oil production.

TABLE 8 Injection Water Use by Recovery Technology

Recovery Technology	Water intensity (gal/gal)	Reference
E&P, Drilling	0.005	Goodwin et al. (2012), Ali and Kumar (2017)
Primary	0.21	Gleick (1994)
Water flooding[4]	15.69	Bush and Helander (1968)
Steam	4.90	California Dpt. Of Conservation, "2006 Annual report of the state oil and gas supervisor", Division of oil, gas, geothermal resources, Sacramento (2007).
Combustion	1.93	Gleick (1994)
Hot water[1]	4.55	O&G J (2014)
Hydrocarbon miscible/immiscible [1]	4.55	O&G J (2014)
CO_2 miscible/immiscible	4.26	Barry, (2007), Technologies for Enhanced Oil Recovery, Shell Technology and Recruitment Webcast, 30 July
Nitrogen[1]	4.55	O&G J (2014)

1 Water intensity data for hot water, hydrocarbon, and nitrogen are not available, use EOR average. CO_2 production share 43.1% in EOR, Steam production share 36.6% in EOR, total 79.7%. Within the two, CO_2 accounts for 54% and steam 46%. Thus, EOR average= 4.26x 54%+4.9*45.9% = 4.55 gal/gal.
2 Data source: O&GJ 2014 EOR survey
3 Total production value is from Table 7. Value in this table excludes produced water recycle.
4 Average of water to oil ratio in well life time of 68 wells with a standard deviation +/- 7.2.

As of 2014, domestic onshore recovery operations required 2.6 billion gallons of injection water to produce 307 million gallons (7.3 million barrels) of conventional crude oil per day in the United States (Table 9a). The technology-weighted national average water injection was 8.41 gallons of water per gallon of crude; this compares to 8.0 gallons of water per gallon of crude in 2005, when oil production level was less than half of that in 2014 (Wu et al. 2009). This estimate does not include treated PW injected for oil recovery, which is discussed in Section 4.2.2. Secondary water flooding was responsible for 94.2% of injection water use in U.S. onshore oil production, a 13% increase from 2005; proportions of water use in CO_2, steam, and other EORs all decreased (Figures 27a and 27b).

The national results were further broken down to five PADD regions (Table 9b). Injection water use parallels oil production volume across all regions. PADD III accounts for more than 50% of total oil production in the United States; its injection water use also tops the list. Regional injection water intensity is strongly influenced by the volume of crude recovered through secondary technology (water flooding), as evidenced in PADDs II, III, and V. On weighted average, PADD V had the most intensive injection water use to recover a gallon of crude oil. Regardless of the technology, the injection water required for oil recovery varies considerably from well to well and sub-region to sub-region. For example, Texas Oil and Gas Districts 8 and 8A at West Texas injected 12.7–14.7 gallons of water to recover 1 gallon of crude oil in 2005 (Texas Railroad Commission 2008), which is 54%–78% higher than the estimated PADD III average, 8.25 gallons of water per gallon of crude.

TABLE 9a Water Injection in U.S. Onshore Oil Production by Recovery Technology

	Oil Production[a]		Water Injection		
Recovery Technology	**(bbl/d)**	**(mln gal/d)**	**(gal/gal crude)[b]**	**(mln gal/d)**	**Water Use by Technology (%)**
Primary	2,874,952	120.7	0.21	25.36	1.1%
Secondary	3,653,000	153.4	15.69	2407.25	93.3%
Steam	284,725	12.0	4.90	58.60	2.6%
Combustion	20,590	0.9	1.93	1.67	0.1%
Hot water	1,703	0.1	4.55	0.32	0.0%
Hydrocarbon miscible/immiscible	127,500	5.4	4.55	24.17	1.1%
CO_2 miscible/immiscible	335,530	14.1	4.26	60.04	2.7%
Nitrogen	8,000	0.3	4.55	1.52	0.1%
Total	**7,306,000**	**307**		**2579**	
Technology-weighted average water injection (excludes produced water reinjection)			**8.41**		

[a] See Table 7 for total, primary, and secondary production. 2014 production data for EOR technologies are from O&GJ 2014 EOR survey.

[b] See Table 8. Data on water injection rate are not publically available for hot water flooding, hydrocarbon miscible/immiscible, and nitrogen injection. Average value of CO_2 and steam is assumed for these EORs.

TABLE 9b Water Injection in U.S. Onshore Oil Production by Recovery Technology by PADD Regions

Recovery Technology, onshore	Oil Production[a] (mln gal/d)					Water Intensity (gal/gal crude)	Water Injection (mln gal/d)				
	PADD I	PADD II	PADD III	PADD IV	PADD V		PADD I	PADD II	PADD III	PADD IV	PADD V
Primary	0.99	35.09	67.95	12.04	4.78	0.21	0.21	7.37	14.27	2.53	1.00
Secondary	0.99	36.41	79.86	13.94	22.22	15.69	15.49	571.34	1,253.05	218.78	348.60
Steam	0.00	0.01	0.00	0.00	11.94	4.90	0.00	0.04	0.02	0.02	58.51
Combustion	0.00	0.78	0.01	0.08	0.00	1.93	0.00	1.50	0.02	0.15	0.00
Hot water	0.00	0.00	0.00	0.00	0.07	4.55	0.00	0.00	0.00	0.00	0.33
CO_2 miscible/immiscible	0.00	0.54	11.73	1.82	0.00	4.26	0.00	2.29	49.98	7.76	0.00
Hydrocarbon miscible/immiscible and nitrogen	0.00	0.00	0.17	0.00	5.42	4.55	0.00	0.01	0.77	0.00	24.67
Total	1.97	72.83	159.73	27.89	44.44		15.69	582.55	1,318.11	229.24	433.12
Production weighted average water injection (gal/gal) (excludes produced water reinjection)							**7.95**	**8.00**	**8.25**	**8.22**	**9.75**

[a] Regional EOR production value are estimated based on historical EOR PADD production share and 2014 EOR US production.

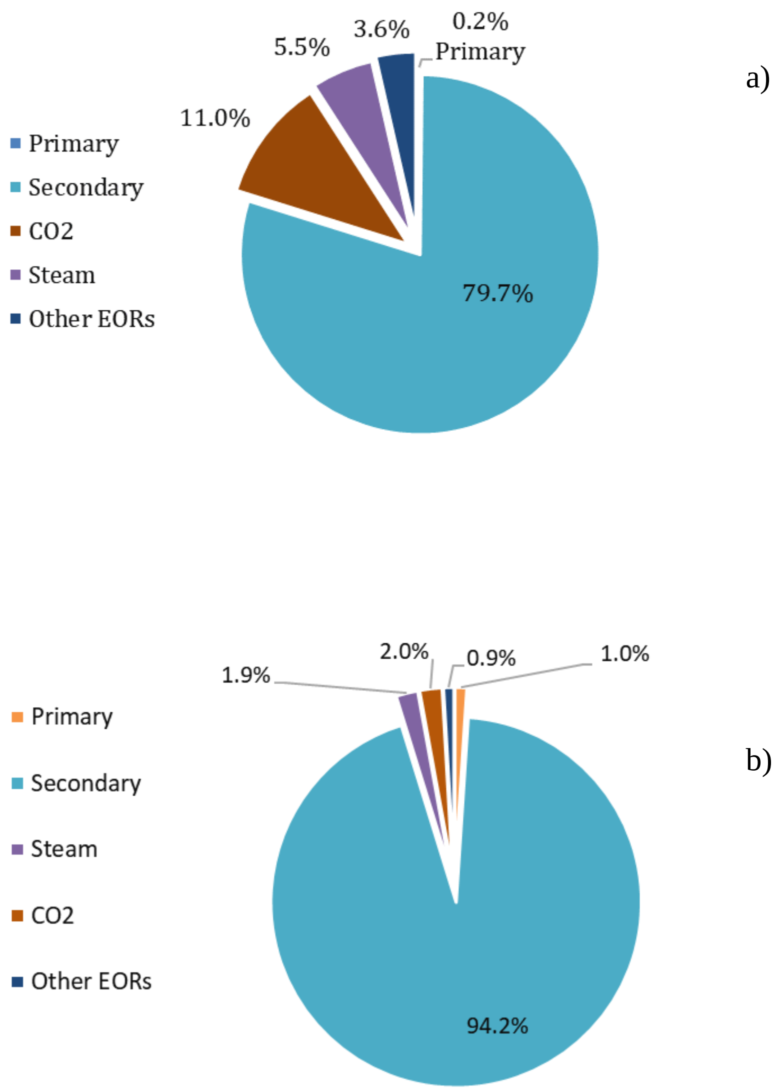

FIGURE 27 Injection Water Use by Crude Oil Recovery Technology in U.S. Onshore and Offshore Production for a) 2005, and b) 2014.

4.2.2 Produced Water Reinjection for Oil Recovery

Whether occurring naturally in the formation itself or due to water injection, PW is an inextricable part of the oil E&P process. Produced water is produced as a byproduct along with oil and gas, and is typically pumped to the surface as part of an oil-water mixture with a high concentration of dissolved solids. The oil is skimmed off, and the solids are removed to an acceptable level. The treated water is then reinjected for crude recovery, evaporated in an evaporation pond, discharged to surface water (where permitted), or injected to a separate inactive stripper well or a non-productive formation for disposal. Lifting, treatment, and disposal of PW have become significant operating costs for the oil industry.

Produced water is the largest waste stream generated by the oil and gas industry. In 1995, about 18 billion barrels of produced water were generated at U.S. onshore operations (API 2000). Total PW increased to 21 billion bbl. by 2012 (Veil 2015). Worldwide, 77 billion barrels of water were produced from oil wells in 1999 (Khatib and Verbeek 2003). As shown in Figure 24, the amount of produced water generally increases over the life of secondary recovery in a conventional oil well. In the later stages of water flooding, the produced water proportion of the total production from a well increases when the injected water eventually reaches the production wells. In terms of output, the oil production-weighted PW generation, the ratio of produced water to oil (PWTO), increased by 1.2 bbl/bbl on average from 1985 to 1995 for the United States (API 2000). Since then, an independent estimate by Veil et al. (2004) indicated that the ratio decreased 9% by 2002. Most recently, average PWTO reportedly increased to 9.2 bbl/bbl (Veil 2015; Table 10). For wells nearing the end of their productive lives, the PWTO ratio can be as high as 10–20, sometimes even 100 (Weideman 1996).

In response to water scarcity in several existing oil fields and tighter environmental regulations, reuse, recycling, and reclamation have become increasingly common in E&P water management. Since the 1980s, produced water has become a major source of injection water for

TABLE 10 U.S. Oil Production, Produced Water, and PWTO Ratio in 1985, 1995, 2002, and 2012

	Produced water (1000 bbl)	Oil Production (1000 bbl)[b]	PWTO Ratio
1985	20,608,505[a]	3,274,553	6.3
1995	17,922,200[a]	2,394,268	7.5
2002	14,160,325[c]	2,097,124	6.8
2012	21,180,646[d]	2,264,241[d]	9.2[e]

[a] API (2000)
[b] EIA (2008a)
[c] Veil et al (2004)
[d] Veil (2015). Value of PW volume represents the total volume from both oil and gas wells in onshore and offshore production.
[e] Accounted for PW from oil production in weighted average, calculated based on available state value.

oil recovery. According to API's 1995 survey (API 2000), 71% of the produced water in the United States is reinjected into the reservoir for oil recovery. As shown in Figure 28, about a quarter of PW is disposed to subsurface disposal wells. The discharged volume of PW is almost all from coal-bed methane operations, rather than oil production (API 2000). The management and practices for produced water have since evolved. Based on state reporting data, Veil (2015) found that the proportion of PW reinjection for oil recovery gradually decreased over the last two decades and was at 46% by 2012 (Figure 28). Meanwhile, the amount of PW that went to disposal increased. In 2012, 40% of total PW was injected to disposal wells, which doubled the proportion from 1995 (21%). These changes suggest that smaller and smaller proportions of PW are suitable for enhanced oil recovery. According to the USGS, total mining water withdrawal (primarily for oil and gas injection water use) in 2010 grew 39% compared with 2005. Within this amount, groundwater withdrawals increased 54%, and surface-water withdrawals 9% (USGS 2014). For the most part (97%), the increased groundwater withdrawals are saline water withdrawals. Saline water contains various levels of total dissolved solids (TDSs). Therefore, the produced water generated from this type of injection water is less likely to be appropriate for reinjection for oil recovery when TDS concentration reaches a certain limit. The constraint to increased PW recycling and reuse is the solids content and the associated cost of water treatment compared with other alternatives. From 1995 to 2012, new PW management methods such as evaporation, off-site commercial disposal, and beneficial use have been increasingly adopted (Figure 28). Beneficial reuse of PW is small (1%) but represents a water-conservation effort that is especially critical to regions where water resources are stressed.

Our estimate of the technology-weighted average quantity of injection water required for domestic onshore production (8.41 gallons per gallon of crude) was presented (Table 9b) and discussed in Section 4.2.1. That estimate reflects the calculation logic laid out in Figure 23 and Equation 1. At national average PWTO ratio of 9.2 gallons of PW per gallon of crude (Table 10) and an average of 46% of PW is reinjected for oil recovery (Figure 28); the national net water consumption is estimated to be 4.2 gallons of water per gallon of crude from U.S. onshore operations in 2014 (Equation 2). This aggregated estimate may differ from region-based calculations because of multiple averages for the PWTO and PW reinjection rates. Detailed regional analysis is provided in Section 4.2.3.

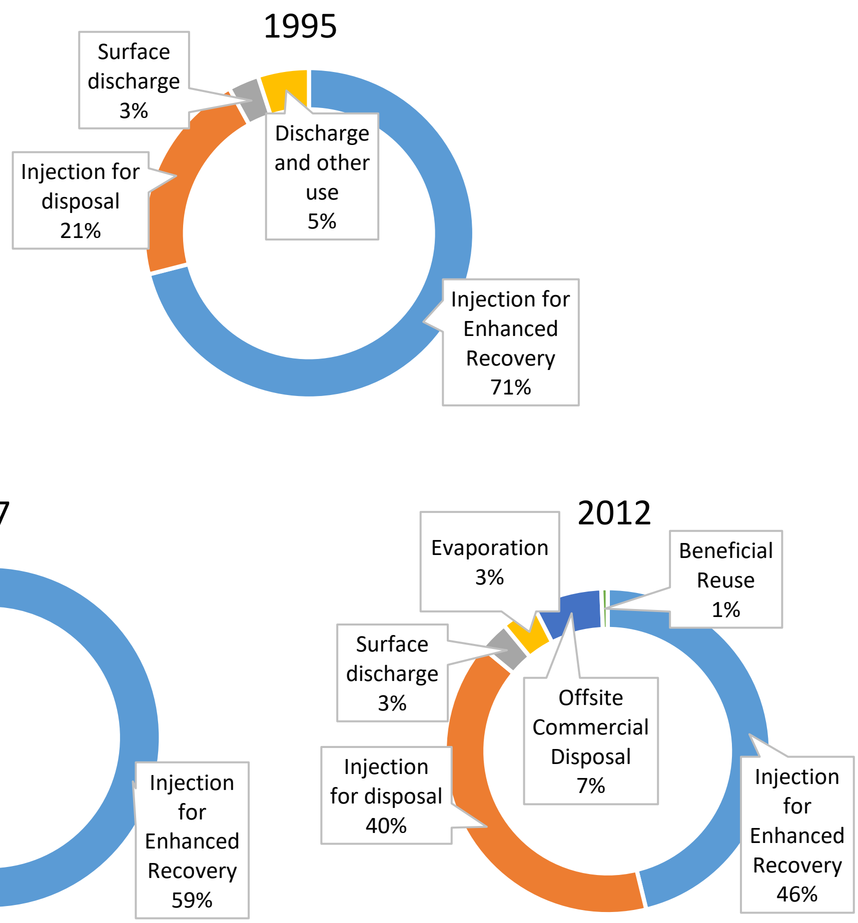

FIGURE 28 Fate of Produced Water from U.S. Oil Recovery in 1995, 2007, and 2012.

4.2.3 Regional Water Use

Like biofuel feedstock production, crude oil production relies on local and regional water availability in addition to oil reserve. In 2014, PADD III accounted for 52% of domestic onshore oil production, while PADD II accounted for a quarter (Tables 11a and 11b). PADD II experienced the fastest growth in last decade among all regions; its production quadrupled, and its production share doubled. In contrast, crude production in PADD V decreased from one-third of the domestic total in 2005 to 15% in 2014. Tables 11a and 11b show that the productivity of oil wells varies considerably among the PADD regions and changes over time (Tables 11a and 11b). During this period, onshore oil production volumes in PADD II increased significantly, whereas the total number of production wells decreased. In 2005, PADD II accounted for 40.7% of total production wells, which were responsible for producing 12.8% of total domestic onshore crude. By 2014, production wells decreased to 23.7% of total wells to produce 27.8% of the oil in PADD II.

PADD V is almost a mirror image. Compared to 2005, the percentage of productive wells in this region increased, yet their oil production share decreased by half. Changes in PADD I and IV were small.

State estimates of PW and crude produced (Veil 2015; Veil et al. 2004; API 2000) were summed to yield regional PWTO averages for 1995, 2002, and 2012 (Table 12). A regional study by Ali and Kumar (2017) provides site-specific estimates for PADD V, which served as verification points. Results in Table 12 show that the five-PADD range of PWTO widens over time (from 3.3–11.3 in 1995 to 3.4–14.7 in 2002, and 0.7–25.4 in 2012). PWTOs of individual region fluctuate substantially. The ratio for PADD IV changed from slightly above average in 1995 to about three fold higher by 2012, while those of PADDs II and I decreased by a half and more than 90%, respectively, over the same period. Similarly, PADD V's PWTO increased from the lowest in all regions to the second highest. Site-specific data obtained for PADD V by Ali and Kumar (2017) agreed with 1995 and 2002 estimates, but differ from the 2012 data (Veil 2015), suggesting significant site variability in this region.

TABLE 11a U.S. Oil Production and Producing Wells by PADD Region in 2005

PADD Region	Total Production[a] (1000 bbl/d)	Onshore Production (1000 bbl/d)[a]	Percent of U.S. Onshore Production	Number of Production Wells[b]	Percent of U.S. Production Wells
I	23	23	0.7	23,968	4.8
II	443	443	12.8	202,809	40.7
III	2,804	1,497	43.2	199,231	40.0
IV	340	340	9.8	24,251	4.9
V	1,569	1,163	33.6	48,225	9.7
Total	5,179	3,466	100.0	498,454	100.0

[a] 2005 data from EIA (2008a).
[b] World Oil (2007).

TABLE 11b Regional Oil Production and Producing Wells by PADD Region in 2014

PADD Region	Total production (1000 bbl/d)[a]	Onshore production (1000 bbl/d)[a]	Percentage US onshore oil production	Number of production wells[b]	Percentage of U.S. wells
I	47	47	0.6	20,701	4.4
II	1,734	1,734	23.7	130,166	27.8
III	5,200	3,803	52.1	231,865	49.6
IV	664	664	9.1	30,208	6.5
V	1,109	1,058	14.5	54,694	11.7
Total	8,754	7,306	100	467,634	100

[a] EIA 2018. Accessed May 9, 2018
[b] EIA US Oil and Natural Gas Wells by Production Rate report Appendix C, aggregated from state to PADD. OCS wells are included in PADD III (FG) and PADD V (FP) (https://www.eia.gov/petroleum/wells/).

TABLE 12 PWTO Ratios by PADD Region[1]

PADD Region	WTO 1995[2]	WTO 2002[3]	WTO 2017, field data[4]	WTO 2012[5]
I	8.7	9.8		0.7
II	8.3	11.1		4.8
III	11.3	10.9		8.7
IV	9.4	14.7		25.4
V	3.3	3.4	5.17, 3.0	9.8

[1] WTO, in gallons of produced water generated per gallon of crude oil produced.
[2] API, 2000.
[3] Veil et al. 2004, 2002 data. Calculated from state WTO and technology averaged value.
[4] Ali and Kumar 2017
[5] Veil GWPC report (2015), Table 4.5, Table 4.7.

The percent of produced water reinjected for crude recovery also differs from one region to another and changes over time (Tables 13a and 13b). In 1995, PADD I had the highest reinjection rate (99%), followed by PADDs IV and V; PADDs II and III reinject about half of the PW they generate. These figures dropped across all regions by 2012. Noticeably, reinjection rate in PADDs I and IV reduced by 30%–50%. As of 2012, PADD IV had the highest reinjection rate (60%), while PADD 2 had the lowest (41%). Over the last two decades, the proportion of PW reinjection for oil recovery in all PADDs moved toward a range of 40%–60%. This is in contrast to 55%–99% of reinjection reported for 1995 (API 2000). Based on these figures, we calculated regional PW used for reinjection (gal PW/gal oil). As shown in Tables 13a and 13b, PADD IV reinjects the largest amount of PW for each gallon of crude oil produced, followed by PADD V.

Meanwhile PADDs I and II inject the smallest amount of PW, about one-seventh of PADD IV or less.

As discussed in Section 4.2.1, injection water use for various recovery technologies (see Tables 9a and 9b) was employed to derive a national technology-weighted estimate of injection water per unit of oil produced. That estimate served as the starting point for deriving regional estimates for 2005 consumptive water use rates (Table 13a). Since then, a number of regional studies and reports became available that provided data for estimating regional technology-weighted injection water requirements per unit of oil (Table 9b) for 2014. Thus, regional EOR technology data (O&G J 2014), PWTO ratio (Veil 2015), and produced water reinjection data (Veil 2015) were used to directly calculate net water consumption rate for crude oil recovery (Table 13b). Using Equation 2, we subtracted the regional PW reinjection value (Tables 11a and 11b) from the technology-weighted average water injection requirements (Tables 9a and 9b) to yield net water use for oil recovery in the PADD regions; these results also appear in Tables 13a and 13b, for production years 2005 and 2014, respectively.

TABLE 13a Injection Water Consumption for Onshore Domestic Crude Production (2005)

PADD Region	Technology-Weighted Average Injection Water Use (gal/gal)[a]	Produced Water-to-Oil Ratio[b]	Percent of PW Reinjected for Oil Recovery (%)[c]	PW Used for Reinjection (gal/gal)	Net Water Needed for Injection (gal/gal)
I	8.0	9.8	99	9.7	negligible
II	8.0	11.1	53	5.9	2.1
III	8.0	10.9	52	5.7	2.3
IV	8.0	14.7	92	13.5	negligible
V	8.0	3.4	76	2.6	5.4

[a] Value from Table 9a.
[b] Value from Table 12, 2002 data.
[c] API (2000).

TABLE 13b Injection Water Consumption for Onshore Domestic Crude Production (2014)

PADD Region	Technology Weighted Average Injection Water Use (gal/gal)[a]	PW-to-Oil Ratio[b]	% of PW Reinjection for Oil Recovery[c]	PW Used for Reinjection (gal/gal)	Net Water Needed for Injection (gal/gal)
I	7.95	0.7	45	0.3	7.62
II	8.00	4.8	41	2.0	6.05
III	8.25	8.7	43	3.7	4.52
IV	8.22	25.4	60	15.3	0.00
V	9.74	9.8	54	5.3	4.49
			U.S. onshore weighted average		4.5

[a] Value from Table 9b.
[b] Value from Table 12, 2012 data.
[c] Source: Veil (2015).

A net of 0–7.6 gallons of water is consumed to produce 1 gallon of crude oil in U.S. onshore wells. This compares to 2.1–5.4 gal/gal estimated based on data available prior to 2009 (Wu et al. 2009). Nationally, we estimated a weighted average of 4.5 gal of water is consumed per gallon of crude oil, when summed from regional estimate. PADDs III and V are both at the national average. The national estimate derived from regional data improved fidelity compared to the estimate from national average PWTO ratio and PW reinjection rate (Section 4.2.2). As discussed, the type of recovery technology and the share of production contributed by that technology are important factors in water consumption for oil recovery. As shown in Table 13, PWTO and the degree of produced water reinjection for oil recovery also have significant effects on water consumption. Wells with large amounts of produced water can have low net water use if there is extensive PW reinjection (as in PADD IV). According to the Texas Railroad Commission, the net freshwater injection for oil recovery in Texas Oil and Gas District 8 and 8a during the early 2000s was about 2 gallons per gallon of crude, which was close to our estimate of 2.3 gal/gal for PADD III (Wu et al. 2009). A decade later, because of the total production increase, PWTO decrease, and the decrease in PW reinjection for oil recovery, the net water consumption rate increased to 4.5 gal/gal. For wells or regions with modest amounts of produced water (e.g., PADD II), an increased level of recycling or reuse of PW is critical to reducing net water use. For example, if PADD II increases PW reinjection from 41% to 80%, its net water consumption would decrease from 6.0 gal/gal to 4.1 gal/gal. A similar change in PW reinjection in PADD III (from the current 43% to 80%) could result a net water usage as low as 1.3 gal/gal. Further, production volume plays a dominant role in determining national net water consumption rates.

Figure 29 presents the net water consumption rate and total crude oil production from onshore wells in the PADD regions. PADD III has shares of onshore crude production that are similar to that of net water use (Figure 29), and so does PADD V. Although PADD IV consumes negligible amounts of injection water, its oil production shares are small (<10%). In contrast, PADD II accounts for 32% of total water consumption to produce 24% of total crude in the United

States. PADDs II and III together account for 76% of U.S. onshore crude oil production.

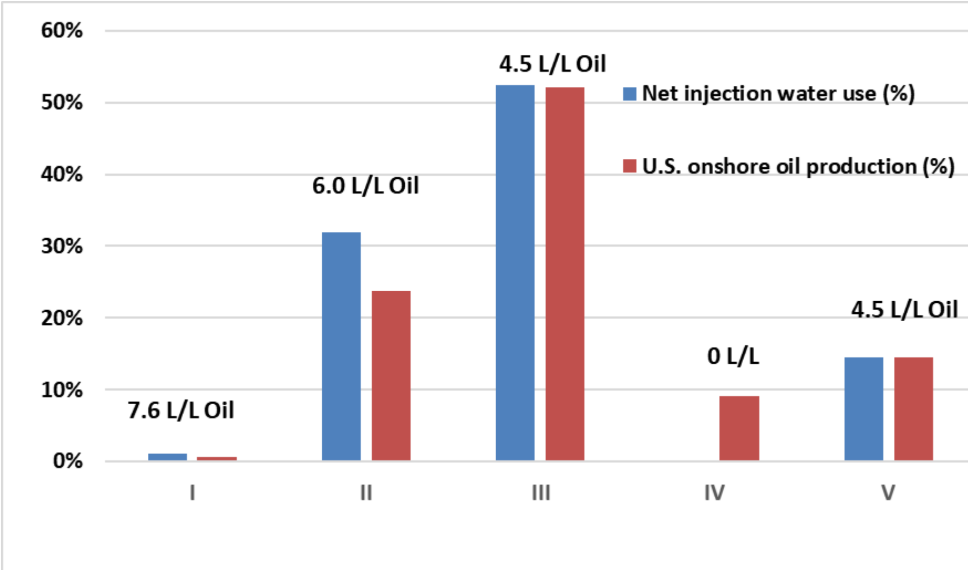

FIGURE 29 Onshore Oil Production and Water Consumption for Major U.S. Oil-Producing Regions

Reducing injection water consumption in these regions could have a much greater national impact than other regions.

4.3 RECOVERY OF SAUDI ARABIAN CRUDE OIL

Saudi Arabia is the largest oil producer in the world, and its Ghawar field is the world's largest oil field. Most Saudi wells are relatively young as compared to U.S. wells and require less injection water to maintain well pressure. Nevertheless, scarce rainfall and a lack of surface water make water supply a serious problem. Oil production consumes Saudi Arabia's most valuable water resource, which is groundwater contained in seven major aquifers, for which recharge rates are low.

Faced with accelerated groundwater depletion caused by industrial and urban development, Saudi Arabia has launched a major effort to develop new water supply sources and water conservation projects. A major portion of this effort has been focused on oil recovery (Al-Ibrahim 1990). Beginning in the late 1970s, Saudi Arabia's petroleum industry began replacing subsurface saline water flooding with desalinated seawater injection. Although a complete survey of net water use for Saudi crude oil production is not publicly available, results of individual projects provide an indicator of current practices and recent trends. For example, results of a six-year water management program at North 'Ain Dar indicate that water injection dropped from 6 gal/gal of oil recovered to 4.6 gal/gal (a 30% reduction), while oil and water production and reservoir pressure remained constant (Alhuthali et al. 2005). Saudi Arabia currently relies almost entirely on brackish water and desalinated seawater for oil recovery.

In the Ghawar field, which accounts for more than half of Saudi Arabia's crude oil production (EIA 2007c), currently about 7 million bbl/d of treated seawater was injected to produce 5 million bbl/d of crude (or 1.4 gal water/gal oil) (Durham 2005). The PWTO ratio has declined steadily for Ghawar, from 0.54 to 0.43, because of a shift in recovery technology to horizontal drilling and peripheral water injection (SUSRIS 2004; Durham 2005). Today, the ratio is reported to be 0.39 (SUSRIS 2004) for Saudi operation, as compared with average of 6.8 for U.S. onshore production. Although data on reuse and recycling of produced water are not available, little produced water from Saudi oil production is available for reinjection.

For this study, we used a range for water consumption, from 1.4 gallons (Durham 2005) to 4.6 gallons per gallon of crude recovered, the average for North 'Ain Dar (Alhuthali et al. 2005).

4.4 RECOVERY AND UPGRADING OF CANADIAN OIL SANDS

Canada is a major U.S. trading partner and one of its key oil suppliers. As was shown in Table 2, the United States imported 1.6 million bbl/d of Canadian crude oil (10.5% of its supply) in 2005. Almost 70% of that crude was produced from oil sands (Table 2). Together with heavy oil and oil sands, Canadian proven oil reserves are recognized as the 2nd place among oil-rich nations (Radler 2008).

TABLE 14 Canadian Crude Oil Production by Source, 2005 and 2006

Recovery Method	Production (mm bbl/d)	Share of Crude Oil Production (%)	Share of Oil Sands Production (%)
2005			
Conventional oil	1.363	53.9	
Oil sand – surface mining	0.551	21.8	55.6
Oil sand – in-situ recovery	0.440	17.4	44.4
Pentanes and condensate	0.173	6.8	
Total crude oil production	2.528	100.0	
2006			
Conventional oil	1.343	50.7	
Oil sand – surface mining	0.663	25.1	58.6
Oil sand – in-situ recovery	0.468	17.7	41.4
Pentanes and condensate	0.173	6.5	
Total crude oil production	2.647	100.0	

Source: CAPP (2008a, 2008b).

Of Canada's 179 billion bbl of proven reserves, 175 are contained in oil sands (Radler 2008). Production of oil-sands-derived crude oil grew from 0.66 million bbl/d (CAPP 2008b) in 2001 to 1.1 million bbl/d (43% of Canadian crude oil production) in 2006 (Table 14). This growth has been spurred by increased demand for transportation fuels, particularly in the United States, as well as technological improvements that have reduced production costs, fiscal policies that have provided incentives for oil sands investment, and record world oil prices. In the past decade, production has routinely exceeded forecasts, prompting repeated upward revisions.[21] However, a number of critics caution that annual output may be limited by water resources. Unless techniques are developed to reduce water use, they contend that there is only enough water available to support production of 2–3 million bbl/d of oil-sands-based crude oil (Peachey 2005), a level that may be reached by 2012–2016 (CAPP 2008c). Further, some argue that because of the rapid pace of new project development, current technologies are being used in preference to advanced technologies that might take longer to implement but have the potential to reduce water intensity over their lifetime (Griffiths et al. 2006). For additional discussion of this issue, see Section 5.

4.4.1 Oil Sands Recovery

Oil sands are recovered by open-pit or surface mining of relatively shallow deposits,[22] or by thermal in-situ techniques[23] for deeper deposits. Surface mining accounted for 59% of Canadian oil-sands-based crude oil production in 2006 (up from 56% in 2005) while in-situ extraction accounted for 41%. In-situ operations are expected to dominate future oil-sands recovery operations. This section provides detailed process description for a better understanding of the production technologies and their impact on water use.

4.4.1.1 Surface Mining

In the early years of oil sands development, surface mining was the dominant recovery technology since the largest and most heavily developed deposit, near Fort McMurray in Northern Alberta[24] includes all of Canada's surface-minable reserves. This region also includes extensive reserves that can only be recovered by in-situ techniques. As the deeper Peace River and Cold Lake deposits (as well as non-minable portions of the Athabasca deposit) have been developed, in-situ extraction has grown to account for a larger share of oil-sands-derived crude oil.

Approximately 18% of Canada's remaining oil sands reserves are amenable to surface mining (CAPP 2008c), which recovers about 90% of the oil in the deposit (NEB 2004). Figure 30 provides a general overview of surface mining process.

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[21] See Section 1.2. For example, in 1995 the Alberta Energy and Utilities Board predicted production of 1.1 million bbl/d by 2030. By 2006, however, forecasts had grown to 3.0 million bbl/d in 2015 (CAPP 2006).

[22] Surface (strip) mining is generally feasible at depths of up to 250 ft from the surface to the top of the deposit (Dunbar 2008).

[23] Oil sands recovery technologies that extract the bitumen without removing the rock matrix from its bed.

[24] Commonly called the "Athabasca deposit."

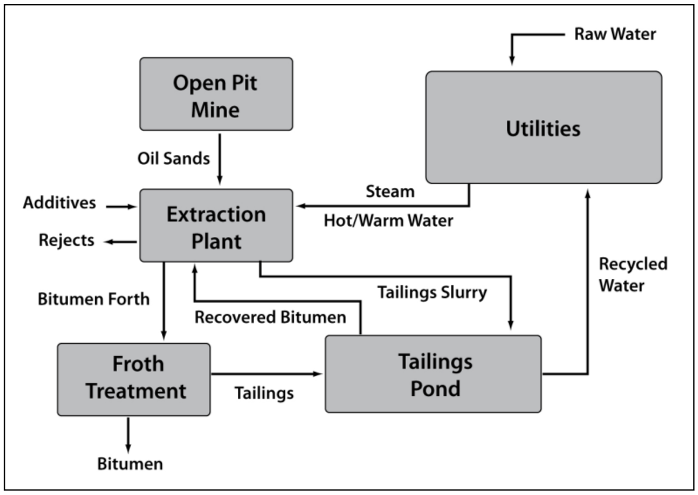

FIGURE 30 Major Process Steps and Water Flow in Oil Sands Recovery by Surface Mining (adapted from Masliyah 2004)

As shown in the figure, oil sand feed ore[25] is transported to an extraction plant. Steam and hot/warm water separate the feed ore into bitumen froth[26] and tailing slurry. The bitumen froth mixture goes to a froth treatment, where the bitumen is extracted by solvent. The solvent is then recovered, and tailings[27] from extraction and froth treatment are sent to a tailing pond (Flint 2005). After settling of fine solids and recovery of additional bitumen in the tailing pond, water can be collected and recycled. Bitumen is then upgraded into synthetic crude on-site or in a nearby facility.

Water is used extensively in the extraction step. The choice of solvent in froth treatment affects water use in surface mining. If naphtha is used for froth treatment, over 98% of the bitumen can be recovered, but residual water and solids pass into the bitumen stream, creating downstream problems in upgrading operations. If a paraffinic solvent is used for froth treatment, residual water and solids can be reduced to around 2.5 bbl per bbl of bitumen recovered with current technology, but yield tends to decline (Flint 2005).

4.4.1.2 In-Situ Recovery

Approximately 82% of Canada's oil sands reserves are only recoverable via in-situ technologies (CAPP 2008c). These in-situ processes typically involve drilling into the reservoir, heating it with steam so the bitumen separates from the sand and clay, and lifting it to the surface. The dominant in-situ technologies are cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD). Both require large volumes of steam, which in turn requires water and energy.

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[25] Oil sands are thick, tar-like substance consists of bitumen, salts, solids, and rock and about 10–12% crude bitumen and high levels of sulfur and nitrogen compounds (Alberta Energy 2004).

[26] Froth contains 60% bitumen, 30% water, and 10% fine solids (Flint 2005).

[27] Tailings include residue solids, residue bitumen, and water.

As shown in Figure 31a, CSS involves cycling or intermittent injection of high pressure steam into the reservoir at single injector/producer wells[28]. Although CSS is a mature technology that was originally limited to vertical wells, combinations of vertical and horizontal wells are now used (Flint 2005).

Figure 31b illustrates the SAGD process, which is becoming the most common method for in-situ recovery. In SAGD, an upper well injects steam to warm up a zone around a series of injectors. As the bitumen warms and becomes less viscous, it flows to a second well (below the injection well) where it is collected and pumped to the surface. Advances in horizontal drilling have made SAGD possible to extend well length up to 1,000 meters long and reduce its cost.

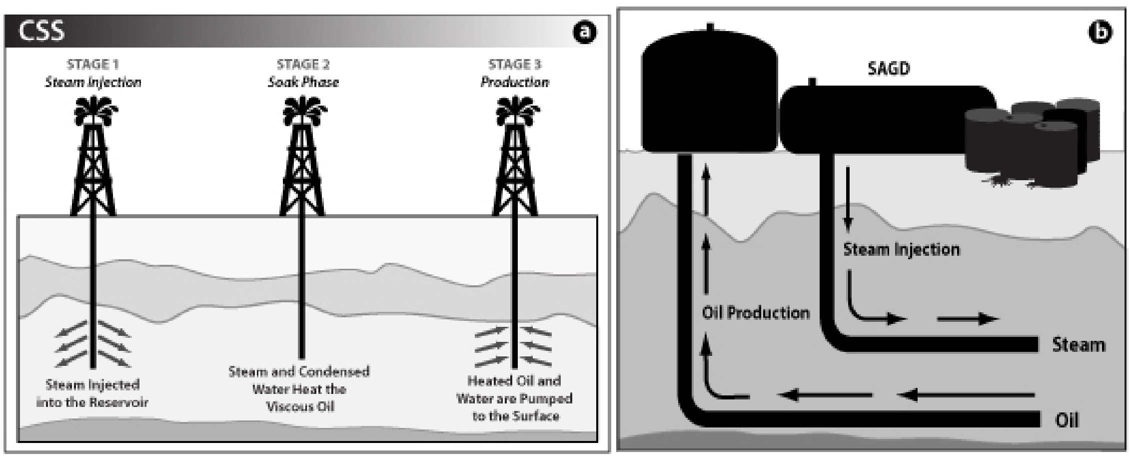


FIGURE 31 In-Situ Oil-Sands Recovery Schemes: (a) Cyclic Steam Stimulation and (b) Steam-Assisted Gravity Drainage (adapted from Flint 2005)

The choice of in-situ technology depends on the geology of the formation — CSS tends to work best in deep, thicker reserves with good horizontal permeability (like those near Cold Lake and Peace River) while SAGD works better in deposits with thinner reserves and good vertical permeability (like the Athabasca deposit near Fort McMurray). SAGD tends to require lower injection pressures and results in lower steam/oil ratios, making it somewhat less water intensive and with lower operating costs than CSS. However, these reductions may be as much a function of the geology and hydrology of the formation as the characteristics of the technology.

As compared with surface mining, which can recover 90% of the bitumen in the oil sands, in-situ methods have lower recovery rates. SAGD reportedly can recover 60–65% of the bitumen in the reservoir (Flint 2005; Woynillowicz et al. 2005), while CSS can recover 20–35% (Flint 2005).

[28] During a soak phase, between injection and production, additional steam may be injected.

4.4.2 Oil Sands Upgrading

As compared with petroleum, oil sands bitumen requires more intensive processing. In this process step, bitumen is upgraded into synthetic crude oil[29]. Upgrading can be achieved in one of two ways, or a combination of both. The raw bitumen can be processed in specially equipped refineries (many in the northern tier states in the United States) if pipelines are available to transport the bitumen (which is mixed with a diluent so that it is fluid enough to flow through a pipeline). Alternatively, a wider range of conventional refineries can be served by a synthetic crude produced at the bitumen production site, as part of integrated operation in surface mining. Today, virtually all surface-mined oil sands are upgraded to synthetic or "refining-ready" crude oil in Northern Alberta while bitumen recovered via in-situ processes historically has been transported by pipeline to refineries, mostly in the United States (CAPP 2008c) where it is upgraded.

Although net water use has dropped dramatically in the past few years, strains on local water resources (primarily the Athabasca River), as well as labor and infrastructure, suggest that onsite upgrading capacity may not be expanded as recovery operations grow in the Fort McMurray area (Griffiths and Dyer 2008). Upgrading for surface-mined bitumen is already migrating toward Edmonton[30]. Known as "Upgrader Alley," this area may contain over 40% of Alberta's upgrading capacity within the next decade (Griffiths and Dyer 2008). Nevertheless, many plans are now on hold pending a more attractive economic climate. In addition, there are increasing interests and plans to upgrade oil sand bitumen in the United States, where refinery expansions and upgrades are less capital intensive.

4.4.3 Technology Shares

Isaacs (2007) estimates that synthetic crude oil recovered via in-situ processes accounts for 38.4% of Canadian oil sands production, of which, 19.0% is recovered via SAGD (Athabasca), 18.4% is recovered via CSS (Cold Lake), and 1.0% is recovered via multi-scheme techniques[31] (Peace River). By contrast, CAPP (2008b) data indicate that in-situ recovery accounted for 44.4% of oil sands production in 2005 (Table 14). Using CAPP's share for in-situ recovery and Isaacs' shares for recovery technologies, we estimated technology-specific shares for in-situ production in 2005 (Table 15).

As with conventional oil, oil-sands recovery technology has a major effect on water consumption (Table 15). Surface mining and multi-scheme techniques are considerably more water intensive than SAGD or CSS with current levels of water recycle and reuse. Surface mining — which is utilized primarily at the Athabasca projects — withdraws water from the Athabasca

[29] Since the thick crude oil is deficient in hydrogen, upgrading requires hydrogenation or coking to convert it to an acceptable refining feedstock.

[30] In 2003, Shell added an upgrader to its refinery at Scotford, just northeast of Edmonton. Eight other upgraders with a combined capacity to upgrade almost 2 million bbl/d into synthetic crude oil are now in various stages of planning or construction.

[31] Multi-scheme technologies include various elements of CSS, SAGD, and other recovery techniques.

River, where public concerns regarding resource use, emissions, and waste generation have prompted extensive efforts to conserve and better manage water resources. According to Gleick (1994), the oil sands industry used an average of 4.8 gallons of freshwater to produce 1 gallon of bitumen oil (before upgrading) via surface mining in 1994. By 2005, that average had dropped to 4 gal/gal including upgrading (Peachey 2005). More recently, Heidrick and Godin (2006) as well as Isaacs (2007) reported that water consumption in Alberta is 2.18 gal/gal, including upgrading. For our estimate, we used Peachey's (2005) industry average (4.0 gal/gal), which is shown in Table 15.

TABLE 15 Net Water Use for Oil-Sands-Based Synthetic Crude Oil Production by Location, Recovery Method, and Technology[a]

Location and Recovery Method	Bitumen Recovery Technology	Share of Oil-Sands Crude Production (%)	Water Consumption[b] (gal/gal oil sands)	
			Recovery	Upgrading
Athabasca – mining	Shovel and truck	55.6[c]	4.0[a]	–
Athabasca – in-situ	SAGD	22.0[d]	0.3	1.0
Cold Lake – in-situ	CSS	21.2[d]	1.2	1.0
Peace River – in-situ	Multi-scheme	1.2[d]	4.0	1.0

[a] Including water recycle and bitumen upgrade.
[b] Surface mining net water use (consumption): Isaacs (2007); Peachey (2005); Heidrick and Godin (2006); SAGD, CSS, and multi-scheme net water use: Gatens (2007).
[c] CAPP (2008b, Table 14).
[d] Isaacs (2007).

Table 15 also provides water consumption (net water use) by recovery technology. Although both SAGD and CSS are steam intensive, their water consumption is relatively low since over 80% of the steam used for oil extraction and processing is recycled (Isaacs 2007). Despite water conservation efforts, the use of cold-water flooding is on the rise for surface mining. Cold water flooding reduces the high energy cost associated with oil sands mining by using low temperature water for bitumen extraction, but may increase freshwater consumption. Alternatively, saline water can be used in this technology (Griffiths et al. 2006). As shown in Table 15, upgrading requires less than 1 gallon of water/gallon of crude (Peachey 2005).

Figure 32 presents the share of oil-sands-derived crude oil production by location and recovery technology, along with our estimates of total water consumption for recovery (including upgrading) by location and recovery technology. Viewed in this light, surface mining is a major water user (since Athabasca produces 56% of oil-sands-derived crude yet consumes 78% of the water used for production). By contrast, in-situ recovery by means of SAGD at Athabasca uses the least water relative to its share of oil-sands-derived crude production.

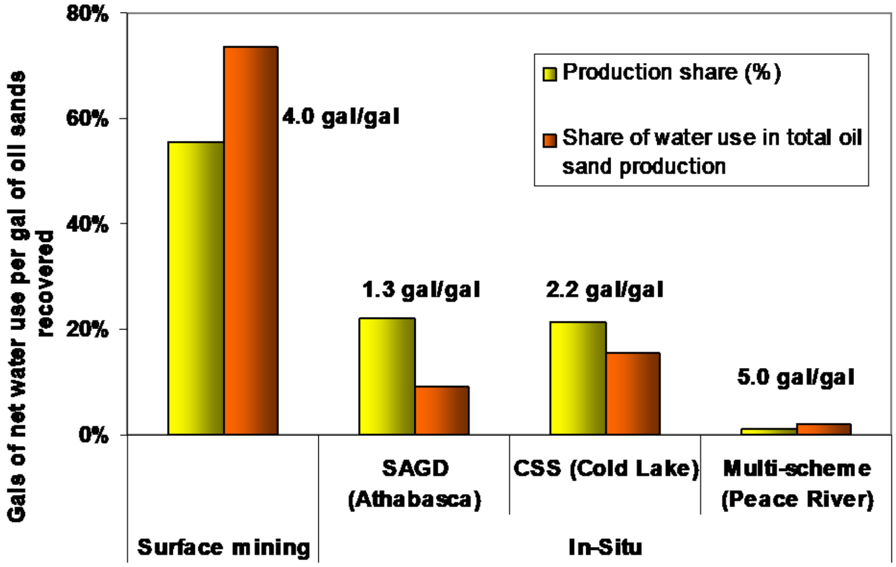


FIGURE 32 Shares of Synthetic Crude Oil Production and Net Water Use from Bitumen Recovery through Crude Upgrading by Recovery Technology (Gatens 2007; CAPP 2008a; CAPP 2008b)

4.5 REFINING

Conventional crude and upgraded oil-sands-crude are transported to oil refineries where they are refined to petroleum products, like gasoline and diesel oil. In response to growing demand for oil products, refining capacity is expanding worldwide. New refineries are being built in regions with scarce water resources. This trend is likely to continue in the years ahead. By 2025, forecasts suggest that 40% of global refining capacity may be in water-scarce regions (Buchan and Arena 2006). In the United States, water scarcity is a perennial issue in certain regions — such as notoriously drought-prone West Texas and the West Coast, where most refinery facilities located — and water management is already a fact of life in these areas.

Water consumption in refining is process specific. Refining includes various processes, such as crude desalting, distillation, alkylation, fluid catalytic cracking (FCC), hydrocracking, and reforming, among others. Crude distillation and FCC require the majority of the steam and cooling water use[32]. Figure 33 illustrates the water system of a typical North American oil refinery. According to CH_2MHill (2003), approximately half of refinery water requirements is from the cooling tower. Evaporation, blow down, and drift are the principal routes of water loss in cooling and boiling operations, which together account for 96% of refinery water consumption (Figure 34). Recycling of blowdown water can also occur.

[32] Distillation and FCC generate 44% and 26% of refinery wastewater, respectively, from a typical North American refinery (Buchan and Arena 2006).

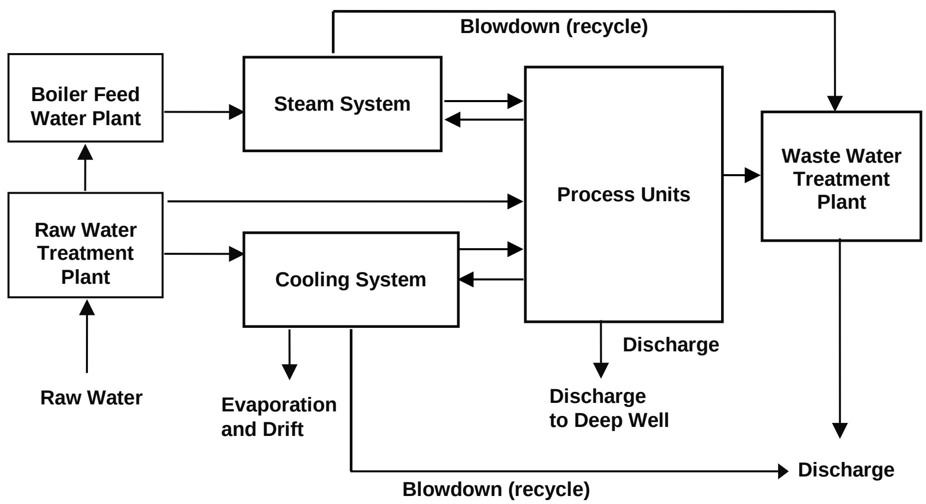
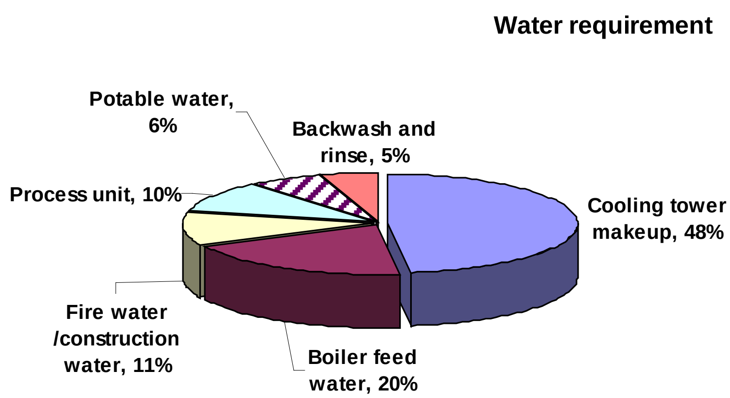


FIGURE 33 Water System in a Typical North American Refinery (CH_2MHill 2003, used with permission). Blowdowns are recycled in some facilities.



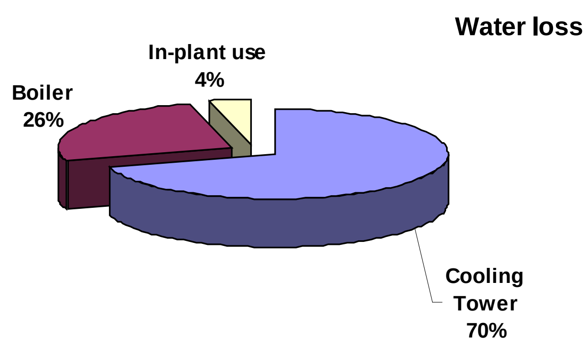


FIGURE 34 Water Requirements and Losses in a Typical Refinery (data source: CH_2MHill 2003)

Based on estimates from 1994 to 2006 (Gleick 1994; Ellis et al. 1998; Buchan and Arena 2006), processing 1 gallon of crude oil in U.S. refineries consumes 1.0 to 1.85 gallons of water (Figure 35). On average, 1.53 gallons of water is consumed for each gallon of crude. Because of yield gain during crude processing (i.e., 42 gallons of crude generate 44.6 gallons of refined product), consumptive water use can also be expressed as 1.4 gallons of water per gallon of refined product. Depending on the refining process, water consumption can be as low as 0.5 gal/gal or as high as 2.5 gal/gal (Figure 35).

The synthetic crude oil produced from oil sands passes through the refining process in much the same way as conventional crude oil and has comparable water requirements. In this study, we assume refining water use to be 1.53 gallons of water per gallon of synthetic crude oil (after upgrading).

As with crude-oil recovery operations, refineries are initiating water management projects in response to increased competition for limited freshwater supplies. Many refineries depend on municipal water supplies to meet their needs. Individual refineries are reducing consumption by identifying alternative water sources, increasing steam condensate recovery, and maximizing water and wastewater recycling and reuse. Today, approximately 70% of steam condensate is recovered in well-maintained and newer refineries around the world, as compared with only 30% recovery in older refineries (Seneviratne 2007). Wastewater recycling and reuse are also becoming increasingly common. At Chevron's El Segundo refinery, nearly 80% of the water used in refinery processes and landscaping is recycled or reclaimed by means of tertiary water treatment (Chevron 2008). Reclaimed water from municipal wastewater treatment plants to supply refinery water needs shows substantial cost benefits in Australia (Buchan and Arena 2006). Cogeneration, which uses less water for on-site power generation than the same power generated by coal-fired boilers or steam-condensing turbines, is yet another area of potential water savings. These options are being examined by refineries. Water reuse in oil refining is expected to rise 350% from 2004 to 2015 globally (Buchan and Arena 2006).

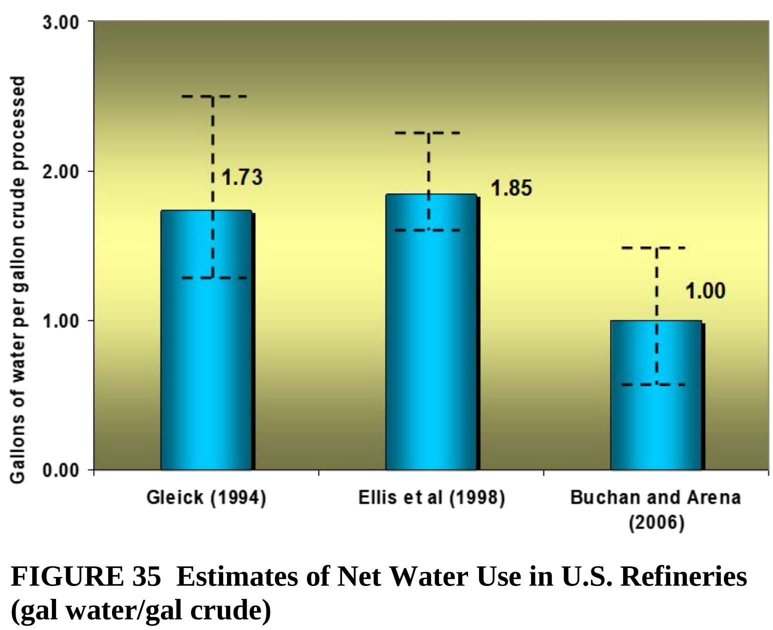


FIGURE 35 Estimates of Net Water Use in U.S. Refineries (gal water/gal crude)

4.6 WATER CONSUMPTION IN MAJOR STEPS OF THE GASOLINE LIFE CYCLE

4.6.1 Conventional Petroleum to Gasoline Life Cycle

As indicated above, U.S. regional onshore oil production consumes from 0 to 7.6 gallons of water for each gallon of crude oil recovered in PADDs I–V (Table 13b). Together with an average of 1.5 gal/gal consumed for refining, a total of 1.5–9.1 gallons of water is required to produce and process 1 gallon of crude oil in the PADD regions. Similarly, for Saudi Arabian crude, 2.9–6.1 gallons of water is consumed for each gallon of crude oil produced and processed. Table 16 summarizes consumptive water use during the major steps of the conventional petroleum gasoline life cycle. Results are expressed in terms of both gallons per gallon of crude oil and gallons per gallon of gasoline.

TABLE 16 Water Consumption from Crude Oil Recovery to Refining for Conventional Gasoline (2014)

	U.S. Conventional Oil (Onshore)					Saudi Arabian Conventional Oil[a]
	PADD I	PADD II	PADD III	PADD IV	PADD V	
E&P[b] (gal water/gal crude)	7.6	6.1	4.5	0.0	4.5	1.4–4.6
Refining (gal water/gal crude)	1.5	1.5	1.5	1.5	1.5	1.5
Total water use (gal/gal crude)	9.1	7.6	6.0	1.5	6.0	2.9–6.1
Total water use (gal/gal gasoline)[c]	8.6	7.1	5.7	1.4	5.7	2.8–5.8
Share of on shore crude production in the United States (%)[d]	0.6%	23.7%	52.1%	9.1%	14.5%	
Share of water use for crude recovery and refining in the United States (%)[e]	1.1%	32.0%	52.4%	0.0%	14.5%	

[a] Alhuthali et al. (2005); Durham (2005).
[b] From Table 13b.
[c] Conversion to gasoline includes process gain of 1.06% (44.6 bbl of petroleum product produced from a bbl of crude oil).
[d] From Table 11b.
[e] Calculated from Tables 11b and 13b.

Figure 36 illustrates the water flows in crude oil recovery from conventional sources and oil refining. The data represent the range of values reported in the literature for input water, water reuse/recycling, and consumption, as well as consumed water disposition. On the basis of weighted crude production, we estimated that the five PADD regions have an average water intensity of 5.6 gallons of water per gallon gasoline produced from U.S. onshore wells.

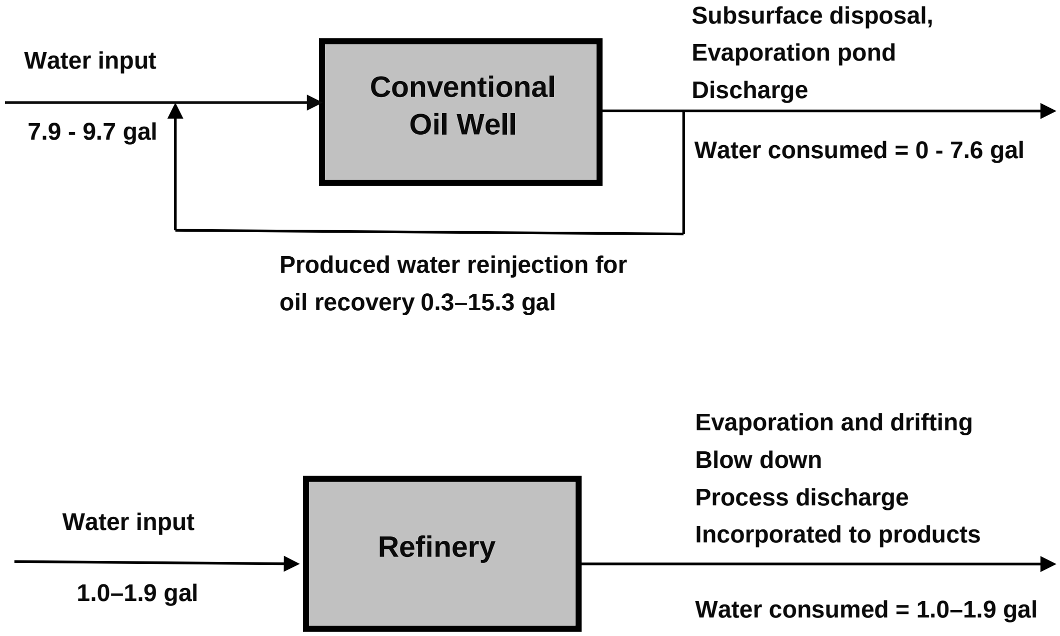


FIGURE 36 Water Input and Consumption in Conventional Crude Oil Production and Refining to Process One Gallon of Crude in the United States

4.6.2 Oil Sands to Gasoline Life Cycle

It takes 2.8–6.5 gallons of water to produce and process 1 gallon of crude from Canadian oil-sands (Table 17). Using reported shares and water intensity by production technology, we found that 56% of oil-sands-based crude is produced and refined from 5.5 gallons of water per gallon of bitumen.

Figure 37 presents these data in input-output format, with bitumen recovery and upgrading consuming 1.3–5.0 gal/gal and refining consuming 1.0–1.9 gal/gal.

TABLE 17 Water Consumption from Crude Recovery to Refining for Canadian Oil-Sands-Based Gasoline

	Surface Mining	In-Situ Recovery		
	(Athabasca)	SAGD (Athabasca)	CSS (Cold Lake)	Multi-Scheme (Peace River)
Mining and upgrading[a] (gal water/gal bitumen)	4.0	1.3	2.2	5.0
Refining[b] (gal water/gal bitumen)	1.5	1.5	1.5	1.5
Total water use (gal water/gal bitumen)	5.5	2.8	3.7	6.5
(gal water/gal gasoline)	5.2	2.6	3.5	6.2
Share of bitumen production (%)	55.6	22.0	21.2	1.2
Share of water use for oil sands production (%)	73.4	9.2	15.4	1.9

[a] From Table 15.
[b] Assumes same as conventional refining.

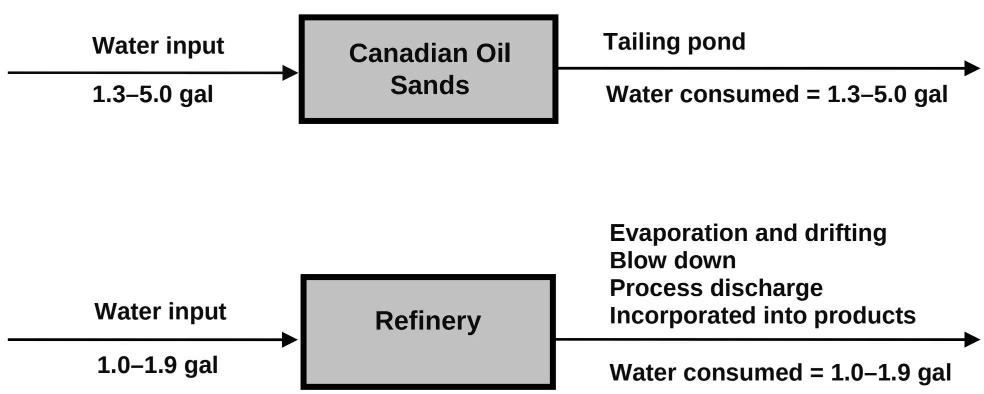


FIGURE 37 Water Input and Consumption for Bitumen Production and Refining to Process One Gallon of Canadian Oil Sands Crude

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5 ADDITIONAL ISSUES

The issue of sustainability of fuel development involves a complex interplay of local, regional, and global actions over time, as well as different technologies and resources. Individuals and decision makers may ask whether an isolated project is sustainable. While the answer may be a qualified “yes”, there are a number of caveats. Much as consumptive water use for individual projects may differ from the regional averages estimated here, so too might individual projects (or collections of projects, which combine to form ethanol or gasoline life cycles) differ with respect to sustainability. By themselves, even projects with relatively high consumptive water use may be sustainable if there is an ample supply, little demand by other users, or a concerted effort to recycle water or conserve water elsewhere in the watershed. Conversely, individual projects with relatively low consumptive water use may be unsustainable under some circumstances. The context is critical.

So too is the cumulative effect of individual projects. Since many impacts accumulate over time and exacerbate impacts of other projects, a given water-consuming project may be sustainable at a particular point in time, but not in the context of many proximate projects over time in the same region. It is only when viewed from the perspective of aggregate impacts that the sustainability of groups of projects (or activities) can be scrutinized.

Aggregate impacts are an important issue in oil sands development, and a growing one with respect to the sustainability of corn ethanol and cellulosic ethanol. Given that U.S. onshore oil resources are increasingly concentrated in areas with limited groundwater, the issue may become increasingly applicable to domestic oil production as well. The following discussion focuses on five water-related aspects of sustainability — aquifer depletion, soil erosion, water quality, land degradation, and ecosystem disruption associated with petroleum gasoline, oil-sands-based gasoline, corn ethanol, and cellulosic biofuel life cycles.

5.1 AQUIFER DEPLETION

In regions where surface water and precipitation are scarce, groundwater from deep aquifers is withdrawn to satisfy crop needs for food, feed, and fiber production, urban development, power generation, fuel production, and other industrial activities. If not managed, intensive water withdrawal from such aquifers can result in a net loss of water and potential resource depletion. Historically, aquifer depletion has been more closely associated with agricultural activities, but the production of fossil fuel feedstock could potentially affect aquifers as well.

Water rights are an important and complex issue affecting water use and the risk of aquifer depletion. Rules requiring water users to consume their allocations or risk losing them in certain regions in the United States are particularly problematic. Water allocations are also a continuing issue with respect to surface water — both for mining operations using water from the Athabasca River and upgrading projects using water from the Saskatchewan River. However, the entire issue of water rights and allocations is beyond the scope of this effort.

Agriculture is the largest water-consuming sector among all sectors. In agriculture, it is not unusual for groundwater withdrawals to exceed recharging during periods of peak water demand or unusually dry spells. But when such imbalance occurs over a sustained period in a watershed, the water level and saturated thickness of the aquifer will decline. We can illustrate this effect by analyzing the High Plains aquifer (also known as the Ogallala Formation), which underlies an area of about 174,000 square miles and includes parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. About 20% of U.S. irrigated farmland overlies this aquifer, and about 30% of U.S. groundwater use for irrigation is withdrawn from it (USGS 1996). The combination of a semi-arid climate, steady winds that hasten ET, and overlying rock that is practically impermeable limits the amount of water able to recharge the aquifer in some places. According to the USGS (1996), annual withdrawals have exceeded annual natural recharge since the mid-1960s, and by 1995, water levels have dropped more than 100 ft (from predevelopment levels) in places where agricultural crop irrigation is most intense. As shown in Figure 38, water levels have dropped most precipitously in West Texas, and parts of western Kansas and the Oklahoma panhandle.

A comparison to Figure 6 shows that Midwestern corn-growing regions barely overlap with the problematic regions of the High Plains aquifer (i.e., West Texas, West Kansas, and the Oklahoma Panhandle in Figure 38). Corn produced for ethanol currently accounts for a fraction of the crop production (wheat, corn, soy, sorghums, etc.) from the entire High Plains and, a majority (50-60%) of the corn produced is used as animal feed to support meat production. Nevertheless, this issue is particularly critical with respect to future biofuel development. Expansion of existing feedstock or planning of large-scale cellulosic biorefineries in the water-stressed regions should be thoroughly examined.

As stated above, oil recovery can also affect aquifers. Although most of the produced water from oil E&P is recycled as injection water, some PW is discharged to retention ponds (or lagoons) for evaporation or injected to disposal wells. This consumed water is not available to recharge the aquifer.

5.2 WATER QUALITY

While this report focuses on the quantity of water consumed to produce fuels, the effect of fuel production on the quality of that water can never be ignored. While all water is created equal, the quality requirements for water that is used in different sectors, such as crops irrigation water, industrial cooling water, or oil-field injection water, etc. and the waste discharge from the sectors is not equal. Further, water discharged from feedstock and fuel production processes has a unique chemical profile that can have a significant environmental impact. If not carefully managed, it could degrade the water utility by adding contaminants, raising water temperature, or disrupting the ecosystem function of that water source.

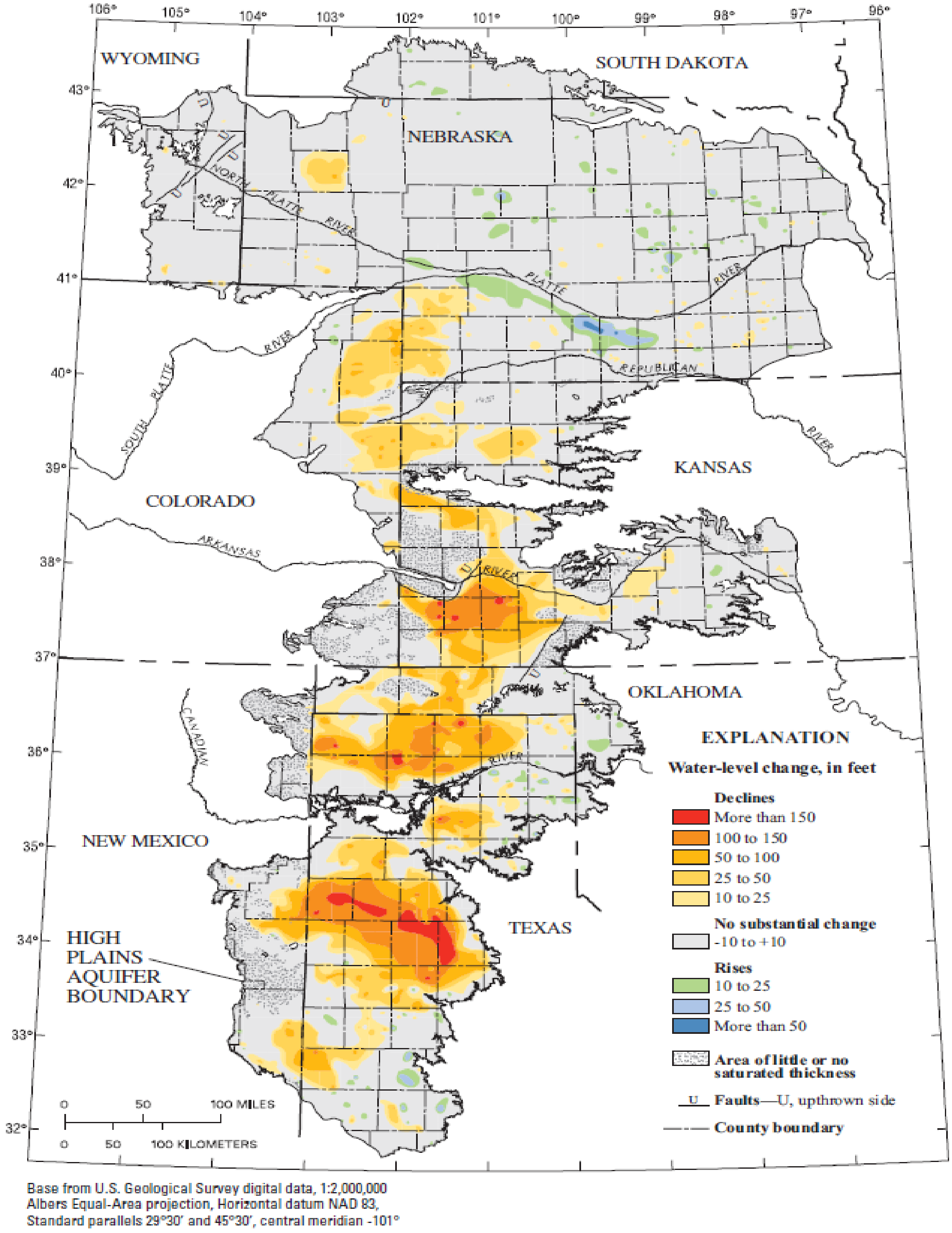

FIGURE 38 Water Level Changes in the High Plains Aquifer, Predevelopment to 2005 (McGuire 2006)

Primarily due to fertilizer run-off from agricultural cropping land, nitrate contamination has been found in the groundwater of certain parts of the U.S, and nitrogen and phosphorus have been accumulating in surface waters, resulting in eutrophication downstream in the Mississippi River and the Gulf of Mexico.[33] Reducing such run-offs to watersheds would require diligent irrigation water management and farming practice. For the areas in which the groundwater has already been contaminated, a promising strategy merged recently that involves combining biomass production with nutrient reduction. For example, municipal wastewater and animal feedlot discharges may provide nutrients for biofuel feedstock production (Gopalakrishnan et al. 2008). In addition to supplying process water, these sources of nitrogen and phosphorus could displace fertilizer. With careful planning, it may be possible to produce biofuel feedstocks requiring much less freshwater per unit of feedstock.

Oil production facilities are not immune to water quality issues. Process waste streams may contain toxics and other chemical contaminants. Liquid wastes from conventional oil recovery, oil sands recovery and upgrading (including sand storage and tailing ponds from surface mining), and oil refineries may contain highly toxic substances such as benzene, toluene, and xylene (BTX); arsenic; heavy metals; naphthenic acids; and various organic compounds. Their leakage to surface and groundwater could have devastating health effects and lasting environmental impacts. Therefore, monitoring and control of the waste discharge are critical in preventing the migration of these substances into ground and surface waters.

As with water quantity, the compounding effect of many projects on water quality in a sub-region could be significant. Watersheds with concentrated fuel and feedstock production activities tend to have greater water quality impacts than those with fewer such facilities, all else being equal. The resulting impact may be greater than the sum of its parts. This is especially true for oil fields and oil sands operations.

5.3 SOIL EROSION

Any activity that alters the land has the potential to promote soil erosion. In agriculture, intensive tillage and crop residue removal can cause soil erosion. Since the 1980s practices like minimal-tillage, no-tillage, and strip-tillage have helped prevent soil erosion in crop farming. If cellulosic feedstocks are likely to come from crop residues, sustainable practices will be required to reduce the potential for soil erosion.

Native perennials could reduce soil erosion since their deep root systems make them better able to hold the soil and less susceptible to drought. Therefore, using perennials such as switchgrass as cellulosic feedstocks for biofuel production would potentially reduce soil erosion.

Soil erosion also occurs in conjunction with oil sands development. The extensive land alterations associated with overburden removal, site drainage, and flood control have potential for

[33] Eutrophication is the process whereby a body of water becomes rich in nitrogen and phosphorus, thereby encouraging the growth of algae, which in turn depletes dissolved oxygen in the water and harms organisms, causing "dead zones" in water bodies.

extensive soil erosion. If not properly managed at the outset of the project or upon project completion and reclamation, soil erosion could be a major issue.

5.4 LAND DEGRADATION

Land degradation is a key deterrent to oil sands development. Land disruption in surface mining is extensive — from site clearing, to the mining process itself and the long-term storage and containment of consolidated tailings (CT) and mature fine tails (MFT)[34]. It is estimated that 2–2.5 m^3 of tailing material (CT) is produced per barrel of oil from surface-mined Canadian oil sands (Grant 2008). Most of this material is discharged into tailing ponds or lagoons. As the tailing settles, it becomes MFT. On average, 1.5 bbl of MFT is generated per bbl of bitumen produced. The tailing ponds/lakes have changed the landscape around the Athabasca deposit.

To address this issue, extensive research has been underway to eventually rehabilitate the land to equal or better than the original (Flint 2005). Although plans have been developed to reclaim the land upon completion of the oil-sands recovery operations, there is considerable uncertainty about the lifetime of much of the waste (MFT, the naphthenic and other toxic compounds in the ponds, residual hydrocarbons, etc.), how long it must be contained, and how its ultimate release into the Athabasca River.

5.5 ECOSYSTEM DISRUPTION

In surface mining, removing the overburden and draining the mine pit typically destroys the biodiversity of vegetation and wildlife in much of the original terrestrial ecosystem. For example, the boreal forest, which performs important ecosystem services such as purifying water and sequestering carbon, was disturbed by currently operating oil sands mines in the Athabasca region (Grant et al. 2008). Tailing ponds are toxic to marine organisms and already harm migratory birds. Today, scarecrows and water cannons are used to prevent birds from alighting on the ponds. Nevertheless, there is an immense challenge of how the boreal forest can be restored after oil sands have been exploited, or whether it is even possible.

In biofuel production, ecosystem disruption refers primarily to the impacts associated with replacing one feedstock with another. If cropland were devoted to the cultivation of a single species (monoculture), then the impacts could include an increased susceptibility to certain pests or diseases or the potential for the monoculture to become an invasive species to other crops. These differences highlight the importance of considering regional conditions and sources in feedstock selection.

[34] MFT — a paste-like substance remaining after long-term settling in the tailing pond

5.6 ENERGY–WATER INTERDEPENDENCE

As stated in DOE's Report to Congress (Pate et al. 2006), "Water is an integral element of energy resource development and utilization." It is used directly in thermoelectric generation and as discussed above, as a key input to production of biofuel feedstock, biofuel production, and crude oil recovery and refining. Conversely, energy is consumed to recover and treat water, deliver it to consumers, and dispose of waste and other contaminants in an environmentally acceptable way.

While available surface water supplies have not increased in the past 20 years, population growth and economic development continue apace, particularly in areas with already limited water supplies. Meanwhile, new ecological water demands and climate change could reduce available freshwater supplies even more (Pate et al. 2006). It is against this backdrop that we are examining consumptive water use in biofuel and gasoline production. Water is increasingly at the nexus of a competition for limited resources to supply the energy and material needs of our society. Accommodating those needs within the constraints of available resources will be a key challenge in the years ahead. Many of the water reduction strategies discussed elsewhere in this report will assist in that effort.

6 CONCLUSIONS

On average, corn ethanol production tends to consume more water than cellulosic ethanol on a life-cycle basis. Net water use for cellulosic ethanol production is comparable to that of gasoline from conventional crude or oil sands. Water use is declining because of rapidly evolving technologies for second-generation biofuel (cellulosic ethanol) and steady improvement of existing first-generation corn ethanol production. This is also true for crude oil recovery and refining. While individual projects and facilities vary considerably, the most noticeable differences seem to occur between regions. There is also uncertainty in the underlying data and the mechanics of the calculations. These issues are discussed below.

6.1 COMPARATIVE WATER CONSUMPTION

Biofuel feedstock production exhibits substantial regional differences. Consumptive water use for corn ethanol production varies significantly in the major corn-growing regions in the United States. As shown in Table 5, excluding precipitation, producing a gallon of corn ethanol could consume as little as 8.7 or as much as 160 gallons of water in 2013, depending on the amount of irrigation water used to grow corn in the region where it is harvested. On average, about 90% of U.S. corn ethanol is produced at a water intensity of 76 gallons of water per gallon of ethanol in USDA Regions 5, 6, and 7.

Similarly, switchgrass-based cellulosic ethanol production, when grown in its native habitat in the United States, can consume from 1.9 to 9.8 gallons of water (Table 6), depending on process technology. This latter figure could be dropped to 6.0 gallons because of yield improvement.

Feedstocks rely largely on water from precipitation. Substantial variation on irrigation water use for corn ethanol in USDA Region s 5, 6, and 7 is primarily due to different climate zones and soil conditions. For cellulosic feedstock such as switchgrass, irrigation may be required in certain regions where it is not adapted to. Therefore, feedstock selection is an important determinant of water needs. Generally speaking, feedstocks that use little irrigation water are preferable in drought-prone areas.

Figure 39 compares water consumption to produce a gallon of gasoline from the conventional and nonconventional crude sources examined in this study. As shown in the figure, net water use varies from less than 2 gallons in PADD IV to more than 8 gallons in PADD I. PADDs II, III, and V have water intensities that range from 5.7 to 7.1 gallons of water per gallon of gasoline, which account for 90% of U.S. onshore crude production. The water intensity of gasoline production using crude from Saudi Arabia conventional wells and Canadian oil sands sites falls in between, with a range of 2.6–6.2 gal/gal.

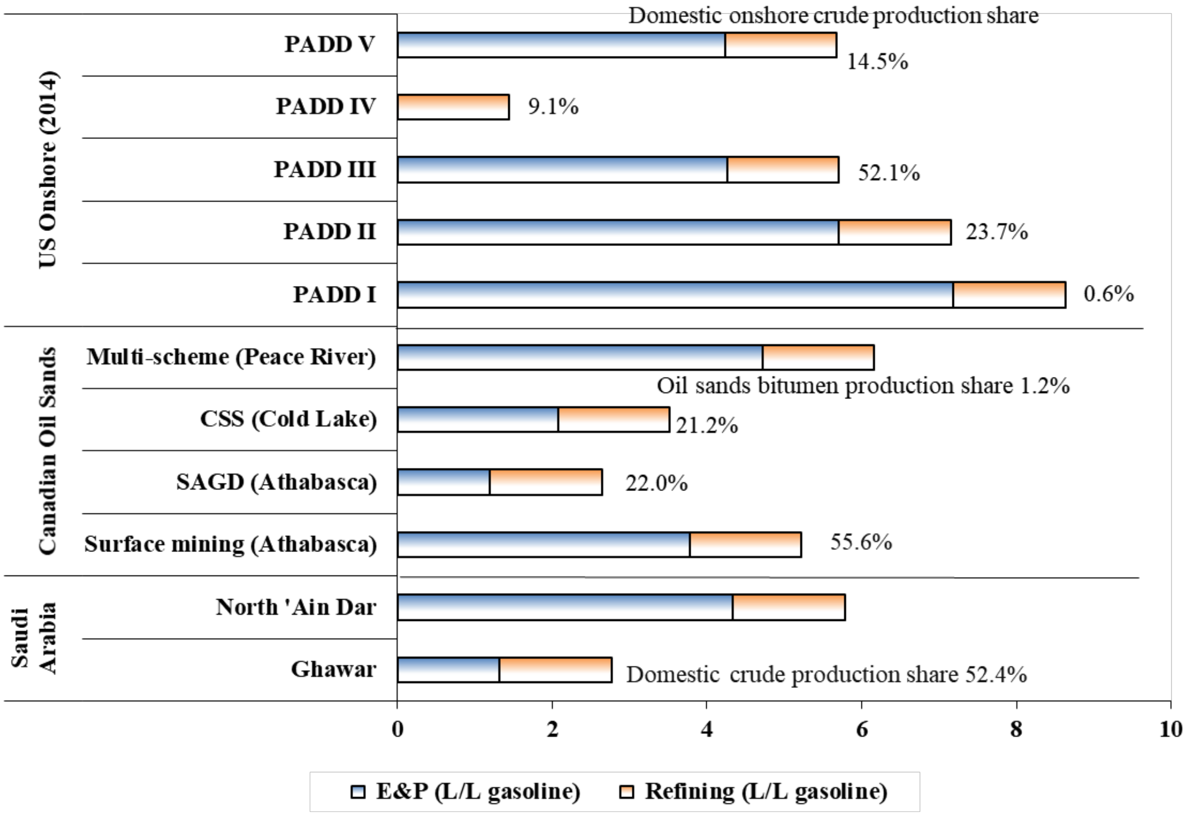

FIGURE 39 Net Water Use for Gasoline Production from Conventional (United States and Saudi) and Non-Conventional Crude (Oil Sands) by Life-Cycle Stage, Location, and Recovery Method.

Clearly, water consumption is variable. For biofuel production the key determinants are feedstock and the amount of irrigation water needed to generate acceptable yields. For gasoline production, the key determinants are the characteristics of the individual oil reservoir, the crude deposit itself, the recovery technology used, and the degree of produced water recycling.

6.2 LIMITATIONS AND UNCERTAINTIES

Production and consumption information scattered in a number of different databases and sources was assembled for this effort. While the resulting data are broad, they are far from complete. Various assumptions were made to impute missing data and focus the analysis on fuel pathways that account for the bulk of water use. Though streamlining the analysis, these assumptions may introduce additional uncertainties.

6.2.1 Data Gaps

Statistics compiled by the USDA, USGS, API, and individual energy companies contain a number of gaps and inconsistencies. For the most part, data on water use in oil production life-cycle stages contain more gaps than comparable data for biofuel life-cycle stages. The following list summarizes the major data gaps encountered in this analysis, and the actions taken to deal with them.

- Data describing the *production* of domestic conventional crude oil and agricultural feedstocks are reasonably complete for calendar year 2005, 2013, and 2014. However, data describing domestic *water use* may or may not be available for those years. Although crop irrigation and precipitation data is well documented, USGS efforts to document agricultural irrigation water consumption have been stalled for more than two decades and were restored in a 2015 report.

- Commercial-scale production of cellulosic ethanol is not yet underway, and data on cellulosic ethanol in this study are limited to process simulation results.

- Reporting of oil recovery by primary and secondary crude recovery technologies by the United States, PADD, and state is incomplete.

- PW from U.S. oil wells. Although most oil wells also produce a fraction of gas and vice versa, PW is reported as a total quantity from gas and oil wells. Thus, a portion of PW and its injection could be attributable to gas production. For this analysis, all PW was allocated to oil extraction.

- Sparse international data on injection water use and PW generation. Such data are very limited. For oil sands operations, data on PW and PW-reinjection are not reported.

6.2.2 Representative Fuel Pathways

This study examined consumptive water use for a select number of gasoline pathways representative of U.S. petroleum liquid fuels supply. Although domestic onshore conventional crude, Saudi Arabian conventional crude, and Canadian oil-sands-derived crude together accounted for only 41% of the U.S. crude oil supply in 2005, the proportion increased drastically to about 70% over the last decade (Table 1). Production of these crudes presents a broad range of water issues and, particularly in the case of oil sands, accounts for a growing share of U.S. crude supply. From the perspective of liquid petroleum fuel production in the United States, the PADDs examined in this study account for all domestic motor gasoline production.

6.3 SUMMARY

Consumptive irrigation water use for biofuel feedstock varies considerably by growing region, type of feedstocks, soil characteristics, and climatic condition; consumptive water use for biofuel production varies with processing technology. There are significant regional differences, particularly for corn production. Accounting for major life-cycle stages, cellulosic ethanol from switchgrass using state-of-the-art technology consumes less water — at the low end of the range for corn ethanol. As compared to corn growing, water consumption in ethanol processing plants is less intensive and continues to decline.

Water consumed for oil recovery, the dominant water-consuming activity in the gasoline life cycle, is highly sensitive to the type and source of crude, geological condition, the recovery technology employed, the age of the well, and the degree of produced water reinjection. Data show considerable variation in the degree of produced water recycling from one region to another. Although some oil-sands recovery techniques consume large quantities of water, average water use for recovery and upgrading is not significantly different from that for conventional oil recovery. Like ethanol plants, oil refineries consume relatively small amounts of water as compared with the much greater water intensity of feedstock recovery.

Our analysis indicates that conservation measures to reduce consumptive water use are needed to achieve sustainable biofuel and gasoline production. Improved irrigation water management is particularly critical in those areas where water is scarce. Developments of drought-resistant strains that maintain corn yield are also desirable. For cellulosic feedstocks, an emphasis on planning and selecting feedstock site at their native habitat is vital to minimizing irrigation requirements while achieving desirable production. For oil E&P, the use of PW reinjection and saline water for oil recovery will further reduce water use.

There is an encouraging trend toward improved water management in the biofuel sector. In a 10-year period (2003–2013), statistics show a reduction in irrigation water use in the region with high irrigation water intensity for corn, which is attributable to progress made on irrigation management and practice in USDA Region 7. As a result, the upper end of the irrigation consumption for corn dropped significantly from 2003. With the emphasis on water resource and water use in energy development, this trend is likely to continue.

In a fuel production plant, water consumption can be reduced by increasing the use of such measures as steam condensate reuse and treated process water recycling, and by implementing process modifications using existing commercial technologies. Newly built corn ethanol plants with efficient design and process integration can reduce net water use substantially. Since no commercial-scale cellulosic ethanol plants are currently in operation, development of a process design that optimizes water use should be encouraged from the outset.

Groundwater use and management is especially critical in arid regions and in locations with high concentrations of biofuel or oil production facilities. This conclusion is particularly true for areas overlying the High Plains aquifer, where there is growing competition for limited groundwater supplies, and where new oil and gas projects and fuel production facilities are being proposed. In these regions, improved irrigation management, increased treatment and recycling of process discharges, and reuse of produced water not only conserve scarce resources but also improve water quality.

The energy industry is a major consumer of water. As shown in this analysis, consumptive water use varies by process, region, and technology. How a rapid increase of consumptive water use affects water quality is less clear. As discussed in Section 5.3, nutrient releases and toxic contaminant leakage into waterways (surface water and groundwater) can have devastating environmental impacts and, production process discharges have distinctive chemical profiles that can affect downstream wastewater treatment needs, opportunities for treated wastewater recycling, and final solids disposal. At the extreme, degraded water quality can also affect the treatment needed for input water. Although the required quality of input water varies with type of fuel and feedstock, agricultural crops and biofuel feedstocks generally require higher quality water than that needed for oil E&P (for example, injection water for oil recovery can allow higher levels of total dissolved solids than irrigation water for crops). A study is underway to access potential synergies from using contaminated groundwater for biofuel development. Further investigations will address the impacts on water quality due to various liquid-fuel production processes not only from individual projects, but also from multiple projects for entire regions and over extended periods.

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