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Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline — 2011 Update

Energy Systems Division

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of Ethanol and Petroleum Gasoline — 2011 Update

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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 — 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

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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.

(North Dakota, South Dakota, Nebraska, and Kansas). These three regions consistently account for 89% of U.S. corn production (USDA–NASS 2007, 2008) and 95% of its ethanol production (RFA 2007). 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 focus on three major oil-producing regions defined on the basis of the Petroleum Administration for Defense District (PADD II, III, and V, see Figure 22), which together represent 90% of U.S. onshore crude production and 81% of refinery output (EIA 2008a). 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 re-injection 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 88% of U.S. corn and U.S. corn ethanol are produced in USDA production Regions 5 and 7, where 14–336 gallons of irrigation water are consumed per gallon of ethanol produced.[4] Corn irrigation is at the lower end in Regions 5 and 6.

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

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[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 (gal water/gal denatured ethanol produced)

USDA Region	Region 5	Region 6	Region 7
Share of U.S. ethanol production capacity (%)[a]	*50*	*15*	*23*
Share of U.S. corn production (%)[b]	*50*	*16*	*23*
Corn irrigation, groundwater[c]	12	19	224
Corn irrigation, surface water[c]	2	3	12
Ethanol production[d]	3	3	3
Total (corn irrigation and ethanol production) without co-product allocation[e]	17	25	239
Total water consumption with mass-based co-product allocation[f]	11	17	160

[a] Based on 2008 ethanol production capacity in operation (RFA 2011).
[b] Based on 2008 corn production (USDA-NASS 2011).
[c] Source: USDA (2008).
[d] Source: Wu (2008); production-weighted average.
[e] Before co-product allocation.
[f] Mass-based and carbon-displacement-based allocation. According to the rule of thumb that one-third of biomass in corn kernel goes to ethanol, one-third goes to CO_2, and one-third goes to DDGS. LCA results from GREET show 34% GHG attributable to DDGS. See 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.

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

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

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. oil production relies heavily on secondary recovery via water flooding.[7] This technology requires an average of 8 gallons of water per gal of crude oil recovered and, as a result, accounts for 80% of the water injected into onshore wells for oil recovery. However, since produced water supplies much of this injection water, on a technology-weighted basis, average net water use for U.S. crude oil production ranges from 2.1 to 5.4 gallons per gallon of crude oil for the three major oil production regions (PADD II, III, 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. As of 2005, water inputs for steam injection and CO_2 flooding represented nearly 6% and 11%, respectively, of total water injection in domestic onshore wells (Table 9).

Alternative water sources for oil recovery have been explored to displace groundwater. Using primarily desalinated seawater for injection, Saudi Arabian oil wells consume about 1.4–4.6 gallons of water/gal crude.

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 one gallon of <u>gasoline</u> from conventional crude in Saudi Arabia or in the United States can consume as little as 2.8 or as much as 6.6 gallons of water.

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

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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 2005, half of U.S. crude oil production used water flooding (EIA 2007b).

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 re-injection 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 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 re-injection 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.

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

Fuel (feedstock)	Net Water Consumed[a]	Major Factors Affecting Water Use
Corn ethanol	11–160 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. conventional crude)[c]	3.4–6.6 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] All water used in ethanol conversion is allocated to the ethanol product. Water consumption for corn and switchgrass farming includes irrigation.
[c] PADD II, III, and V combined.
[d] Including thermal recovery, upgrading, and refining.

Finally, there is an encouraging trend toward improved water management in the biofuel sector. In a five-year period (2003–2008), statistics shows 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 irrigation consumption for corn dropped significantly, in comparison to that in 2003. 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?

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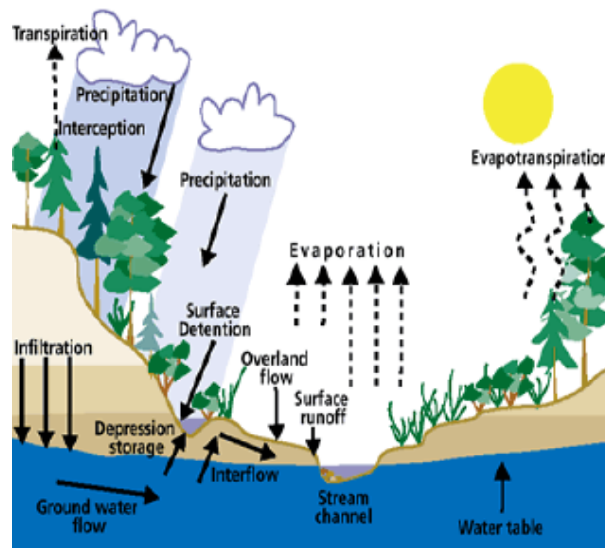
FIGURE 1 Hydrologic Cycle (Allen 2007, used with permission)

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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 accounted for 37 percent of all freshwater withdrawals in 2005 (USGS 2007). A majority of the water withdrawn for irrigation in the U.S. agricultural sector is consumed. The rest is returned to the water body. USGS tracks the total withdrawal water for irrigation, irrigation loss, conveyor loss, and the returning irrigation flow. Although recent data are not available, the ratio of consumption to total withdrawals for the agricultural sector may have stabilized since 1985 (Figure 2). Nationwide, 85% of U.S. freshwater consumption is attributable to agricultural activities. Although water withdrawal for thermoelectric generation accounts for 39% of total U.S. consumption from 1960 to 1995, less than 3% of the water is consumed (USGS 2007).

Surface water is the primary source of irrigation water in the arid western and mountain states. Groundwater is the primary source for the central states. Four states — California, Idaho, Colorado, and Nebraska — account for one-half of U.S. irrigation withdrawals.

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 2005 were 128 Bgal/d, about 8 percent less than in 2000 and approximately equal to estimates of irrigation water use in 1970.

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 study led by USDA and DOE, about 300 million tonnes of biomass (26 million dry tons of energy crops, 130 million dry tons of forest wood, and 152 million dry tonnes of crop residues) suitable for conversion to ethanol could be available by 2017, and 1.3 billion tonnes could be available by 2050 (Perlack 2005). Although forest wood generally does not require irrigation, the impact of large-scale production of energy crops (especially dedicated energy crops) on water resource availability has not been fully examined.
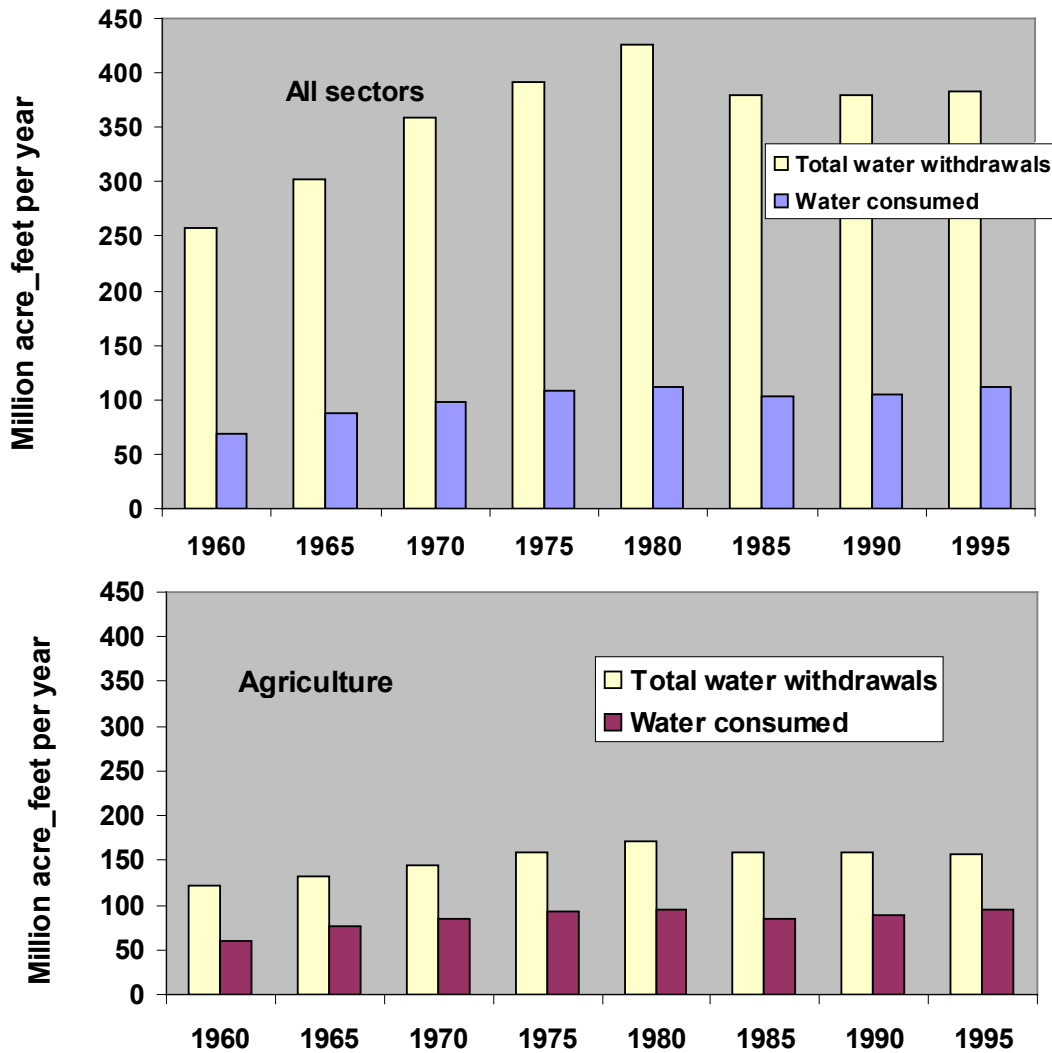
FIGURE 2 U.S. Freshwater Withdrawals and Consumption, All Sectors and Agricultural Sector, 1960–1995 (USGS 2007)

1.2 WATER USE IN CRUDE OIL RECOVERY

As domestic crude oil production declined in the last 30 years (EIA 2008b), the United States has become increasingly import dependent. Today, Canada, Mexico, Saudi Arabia, Venezuela, and Nigeria are the major suppliers of crude oil to the U.S. market, accounting for a combined 64% of crude imports. The remainder comes from Bahrain, Iran, Iraq, Kuwait, Qatar, the United Arab Emirates, the United Kingdom, the Virgin Islands, and Puerto Rico. In 2005, the United States produced 5.1 million barrels of crude per day (bbl/d) and imported 10.1 million bbl/d, or two-thirds of its crude oil supply (EIA 2007b; EIA 2008b). Table 1 provides an overview of U.S. crude oil production and net imports.

TABLE 1 U.S. Crude Oil Supply^a

	Domestic Production		Imports							Total Supply
	Onshore	**Offshore**	**Algeria**	**Nigeria**	**Saudi Arabia**	**Venezuela**	**Canada^b**	**Mexico**	**Others^c**	
Thousand bbl/d	3,466	1,712	385	937	1,235	1,219	1,609	1,121	3,031	15,272
Share of supply (%)	22.7	11.2	2.5	6.1	8.1	8.0	10.5	7.3	19.8	100.0

^a Source: EIA 2008b; EIA 2008c
^b Includes 1.1 million bbl/d of oil sands production.
^c Includes Bahrain, Iran, Iraq, Kuwait, Qatar, United Arab Emirates, the United Kingdom, the Virgin Islands, and Puerto Rico.

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 8% 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, oil-sands-derived crude has become the No. 1 crude oil import to the United States. It is projected that Canada will produce 2.8 million bbl/d of crude oil from oil sands by 2015 and 3.5 million bbl/d 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.

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).[11] 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

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[11] 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.

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.

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 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 (on-line) (USDA–NASS 2007, 2011) USDA Farm and Ranch Irrigation Survey (1998, 2003, 2008)[a] USGS database (USGS 1995)[b] USDA–ARS Corn Dry Mill Model (Kwiatkowski et al. 2006) USDA Ethanol Plant Survey (Shapouri and Gallagher 2005) Keeney and Muller (2006) Wu (2008)[c]
Cellulosic	Ethanol	NREL report (Aden et al. 2002) NREL report (Phillips et al. 2007)
Conventional crude	Gasoline	DOE Report to Congress (Pate, et al. 2006) CH$_2$M Hill (2003) Petroleum company publications (Suncor 2007, Syncrude 2007) Gleick (1994) Royce et al. (1984) Veil et al. (2004) Ellis et al. (2001) Buchan and Arena (2006) 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] Data monitoring 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
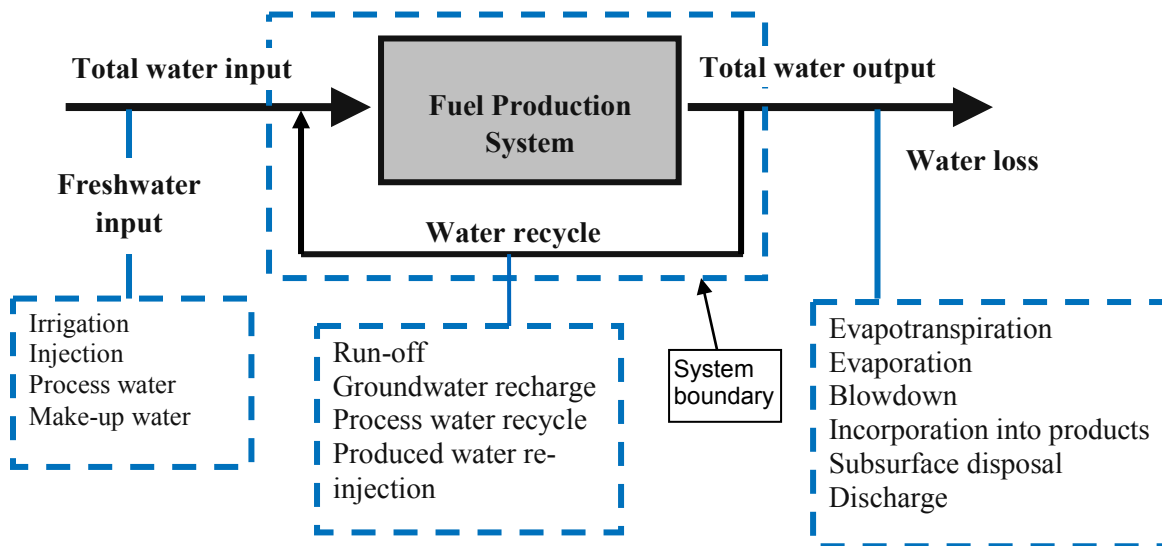
FIGURE 3 System Boundary, Water Inputs, Outputs, and Losses of a Conceptual Fuel Production System

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 re-injection 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 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 water run-off and groundwater recharge are within this system. [12] 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).

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

(a)

(b)

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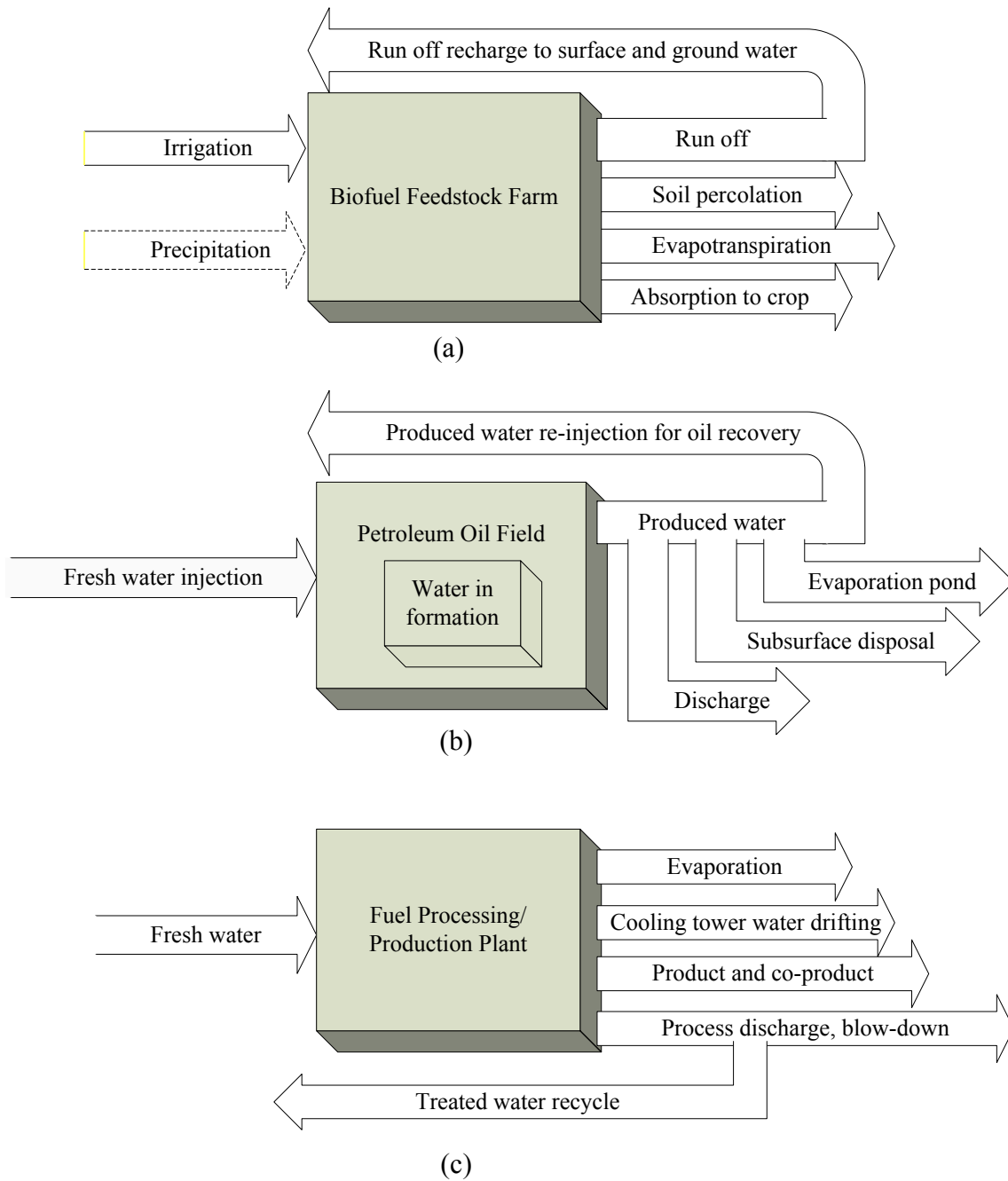
FIGURE 4 Water Inputs and Outputs for (a) Biofuel Feedstock Production, (b) Petroleum Oil Production, and (c) Biofuel Production/Oil Refining

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 re-injection 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,[13] and blow-down from the cooling tower, incorporation into products and co-products, and process water discharge.
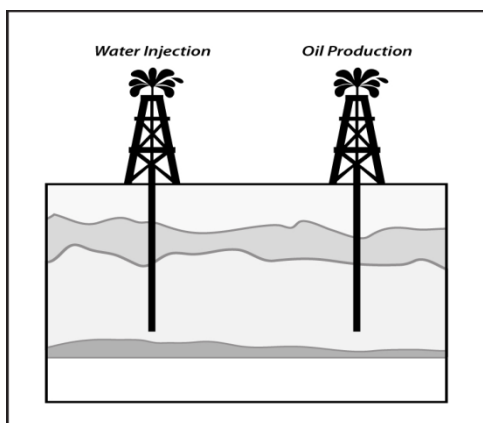
FIGURE 5 Typical Onshore Oil Field

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[13] 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 89% of corn production (USDA–NASS 2007, 2008) and 95% of ethanol production in the United States in 2006 (RFA 2007). The USDA farm production regions are shown in Figure 6.
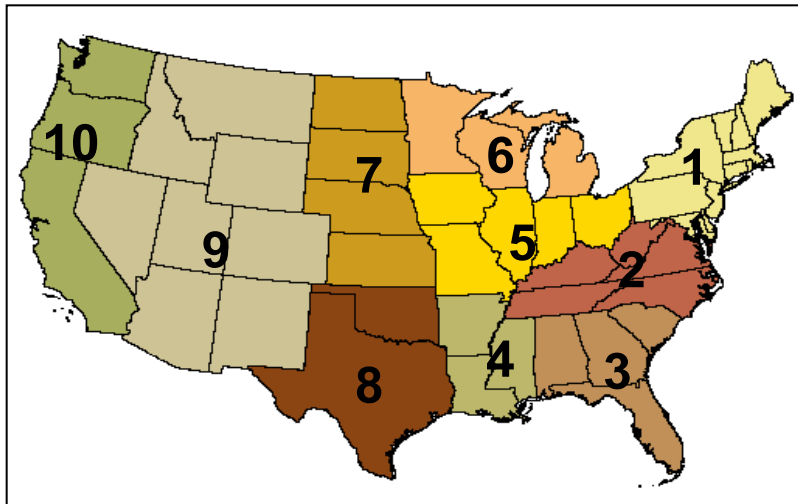
FIGURE 6 USDA Farm Production Regions

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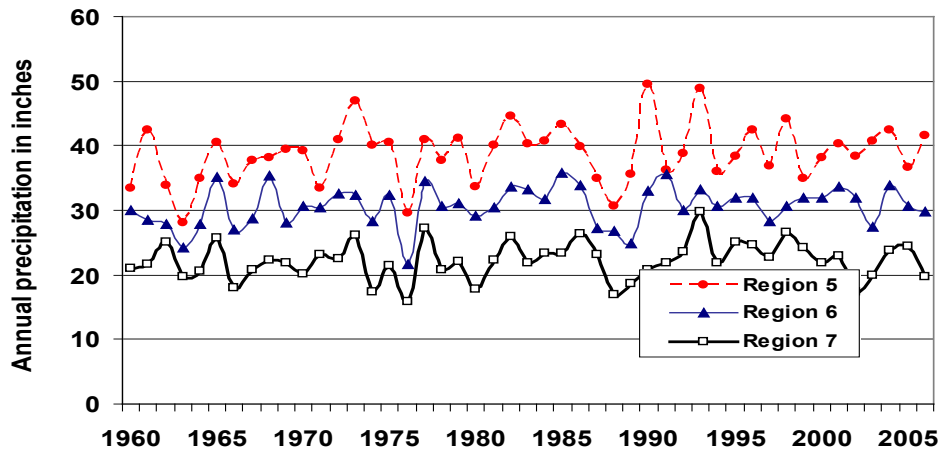
FIGURE 7 Annual Precipitation in USDA Regions 5, 6, and 7 (USDC 2007)

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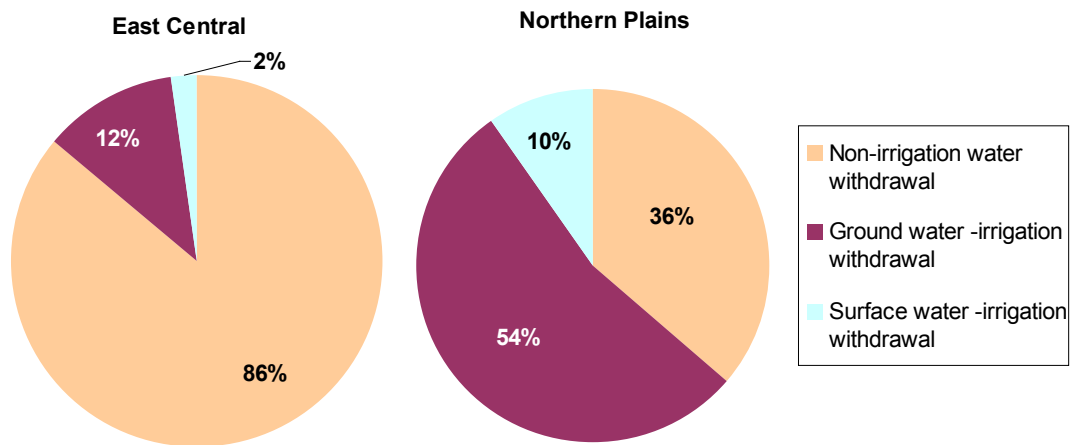
FIGURE 8 Distribution of Water Withdrawals for Irrigation and Non-irrigation Uses in U.S. Regions (USDA 2003). East-Central – USDA Regions 5 and 6, Arkansas, Mississippi, and Louisiana. Northern Plains – USDA Region 7.

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. In Region 7, Nebraska relies heavily (60%) on irrigation for growing corn (Table 4), as does Kansas (49%) in 2003. This finding compares with much more modest irrigation rates in Michigan (9.2%), Missouri (10.9%), and the other corn-producing states in the three regions (between 0.1% and 4.9%). On a yield-weighted average, 39.7% of harvested corn acres require irrigation in Region 7, as compared with 2.2% in Region 5 and 3.9% in Region 6. The three-region average of the irrigated acreage is 12%. This value remains stable in 2008 (Table 4b).

TABLE 4a Irrigation by State and Major Corn-Producing Region in 2003

				Percent of Acreage Irrigated	
State	USDA Farm Region	Irrigated Acres[a]	Harvested Acres[b]	State Average (%)	Regional Average[c]
IA	5	71,262	11,900,000	0.6	
IL	5	222,459	11,050,000	2.0	
IN	5	157,415	5,390,000	2.9	
OH	5	3,188	3,070,000	0.1	
MO	5	304,295	2,800,000	10.9	Region 5: 2.2
MN	6	177,272	6,650,000	2.7	
WI	6	85,477	2,850,000	3.0	
MI	6	185,788	2,030,000	9.2	Region 6: 3.9
SD	7	142,149	3,850,000	3.7	
ND	7	57,865	1,170,000	4.9	
KS	7	1,231,918	2,500,000	49.3	
NB	7	4,605,499	7,700,000	59.8	Region 7: 39.7
Total		7,244,587	60,960,000	11.9	

[a] Source: 2003 Farm and Ranch Irrigation Survey (USDA 2003).
[b] Source: USDA NASS Quickstat database (USDA-NASS 2007, 2008).
[c] Weighted by harvested acreage of each state in the region.

TABLE 4b Corn Irrigation by State and Major Corn-Producing Region in 2008

				Percent Acre Irrigated	
State	USDA Farm Region	2008 Irrigated Acreage	2008 Total Corn Acres Harvested for Grain	State Average	Regional Average
IA	5	107,979	12,800,000	0.8	
IL	5	309,187	11,900,000	2.6	
IN	5	244,574	5,460,000	4.5	
Mo	5	361,275	2,650,000	13.6	3.1
OH	5	107,979	3,120,000	3.5	
MN	6	254,960	7,200,000	3.5	
WI	6	105,809	2,880,000	3.7	
MI	6	248,790	2,140,000	11.6	5.0
SD	7	175,593	4,400,000	4.0	
ND	7	90,271	2,300,000	3.9	
KS	7	1,368,126	3,630,000	37.7	
NE	7	5,058,195	8,550,000	59.2	35.4
Total		8,432,738	67,030,000	12.6	

[a] Source: 2003 Farm and Ranch Irrigation Survey (USDA 2003).
[b] Source: USDA NASS Quickstat database (USDA-NASS 2007, 2008).
[c] Weighted by harvested acreage of each state in the region.

For the irrigated corn acreage, the amount of water required varies considerably, from 0.4 to 3.0 acre-ft per acre of corn in the United States (Figure 9). Even in the Midwest, there are significant differences in irrigation rates. The irrigation can be as little as 0.57–0.58 ft[14], as in Regions 5 and 6, or as much as 1.0 ft, as in Region 7 (Figure 9).

On the basis of corn irrigation data for each state from the USDA *Farm and Ranch Irrigation Survey* (1998, 2003, and 2008), 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, and 2008 (USDA-NASS 2008, 2011), we obtained a production-weighted consumptive irrigation water use per bushel of corn.

Producing one bushel of corn in Region 7 consumes 634 gallons of freshwater from irrigation (Figure 10). Since most of the corn grown in Regions 5 and 6 receives sufficient water from precipitation, irrigation water consumption in those regions is only 39 and 70 gallons per bushel in 2008, respectively. In all three regions, most of the water used for irrigation is withdrawn from groundwater aquifers. In the United States, 77% of the irrigation water used for corn is from such aquifers; the remaining 23% comes from surface water (USDA 2003).
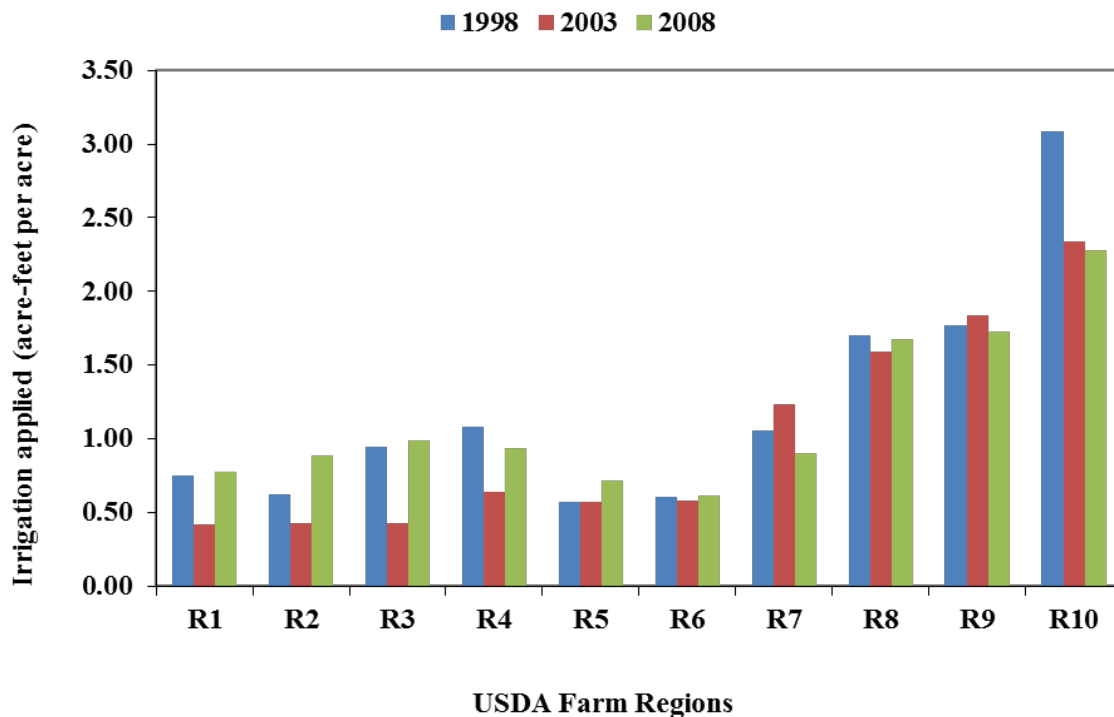
FIGURE 9 Irrigation Rate for the Irrigated Corn Acreage by USDA Region (USDA 2003, 2008). Multiply acre-ft per acre by 325760 to obtain gallons per acre.

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[14] Acre-ft per acre.
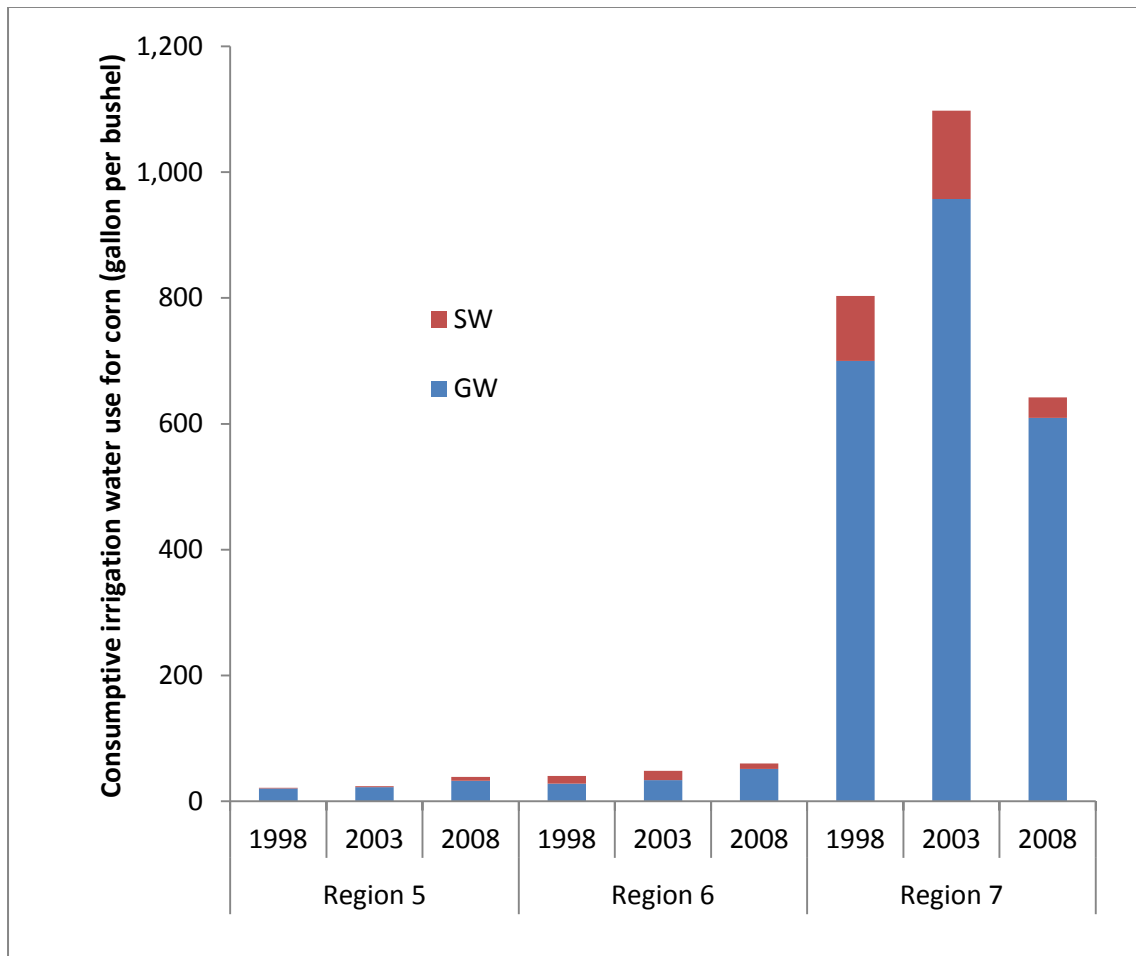
FIGURE 10 Consumptive Irrigation Water Use for Corn from Ground and Surface Water (USDA 2003, 2008)

According to the USDA *Farm and Ranch Irrigation Survey*, irrigation practices have changed in recent years (USDA 1998, 2003, and 2008). As shown in Figure 11, groundwater consumed for corn irrigation fluctuated over the last ten years and has varied from place to place. The higher irrigation demand in Region 7 can be attributed primarily to climate. As shown in Figure 7, while Region 5 received average precipitation in both years, 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.

Nationally, corn yield has risen by over 50%, but corn acreage has remained relatively flat over the past three decades (Figure 12). In between 1998 and 2003, the proportion of the crop converted to ethanol was doubled (RFA 2007) and corn yield increased 6% (from 134 bushel to 142 bushel per acre corn harvested, USDA-NASS 2007).

Although Region 7 accounts for 44% of the consumptive irrigation water use for corn growing in the United States (Figure 14), it produced one-fifth of all U.S. corn. Region 5 (Iowa, Illinois, Indiana, Ohio, Missouri) is a near mirror image — it consumed only 5% of U.S. irrigation water for corn, but grew one-half of the crop. Figure 13 compares shares of corn

production and groundwater consumptive use among the three regions (USDA 2003; USDA–NASS 2007, 2011). Together, the three regions accounted for 52% of total U.S. irrigation water consumption for corn while producing 88% of the U.S. corn crop in 2008 (Figure 14).
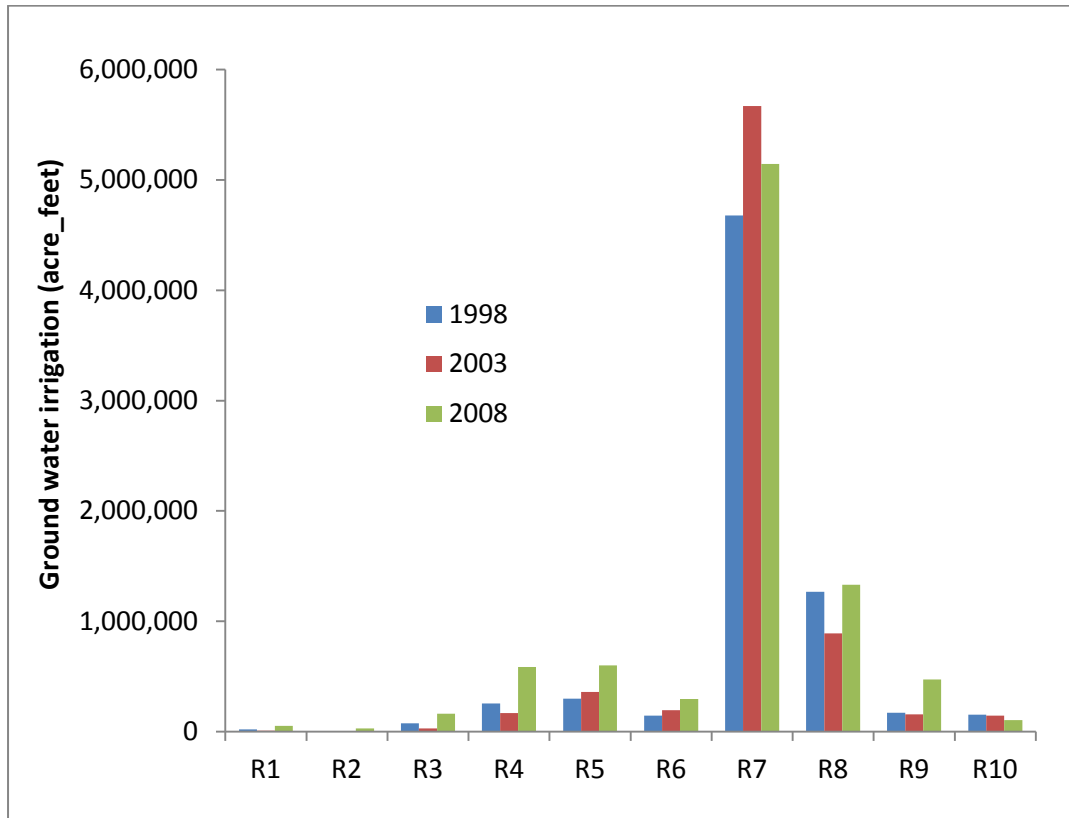
FIGURE 11 Groundwater Consumed for Corn Irrigation by USDA Region in 1998, 2003, and 2008 (USDA 2003, 2008). Multiply acre-ft value by 325760 to obtain gallons.
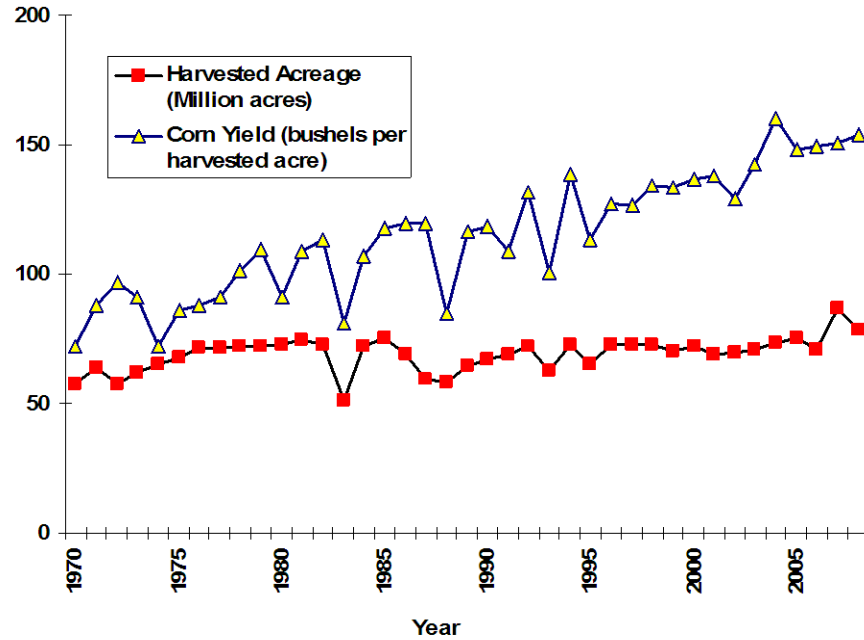
FIGURE 12 Historical Trend of Corn Yield and Harvested Corn Acreage in the United States
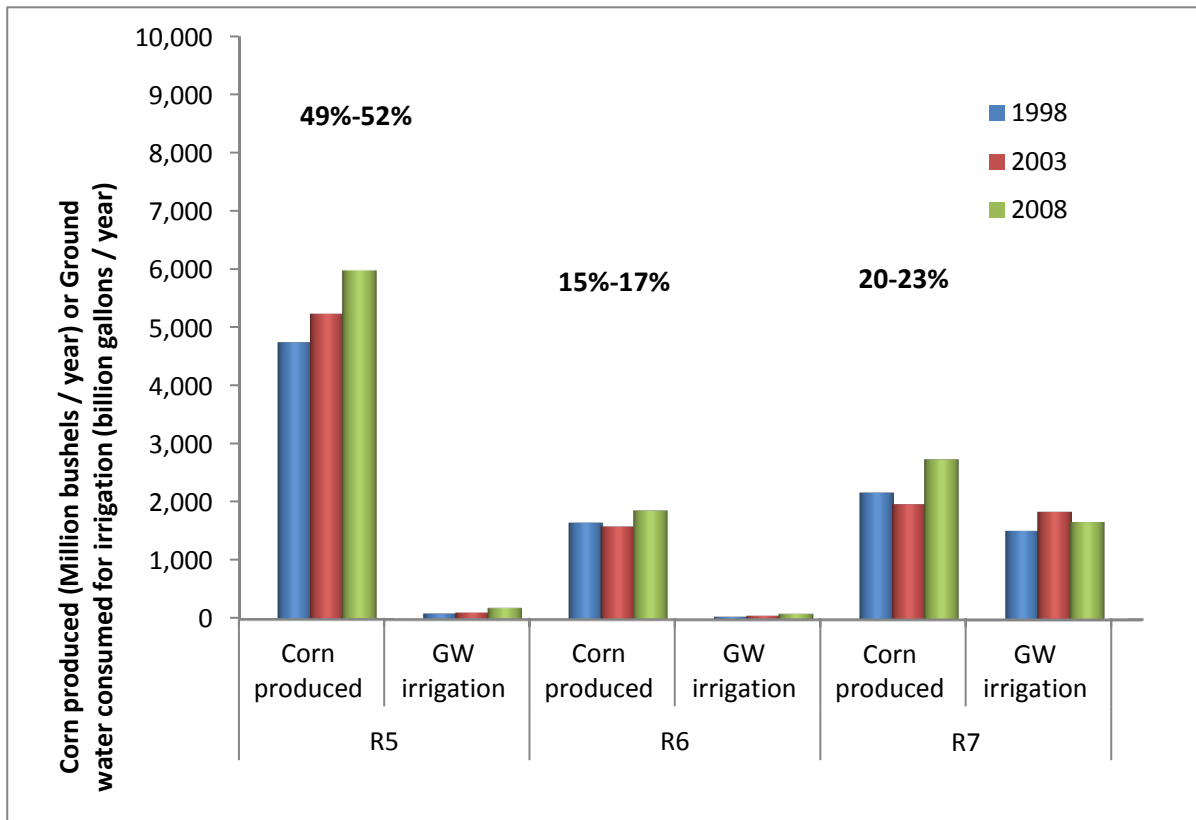
FIGURE 13 Corn Production and Consumptive Irrigation Groundwater Use in USDA Regions 5, 6, and 7 (USDA–NASS 2007, USDA 2008)
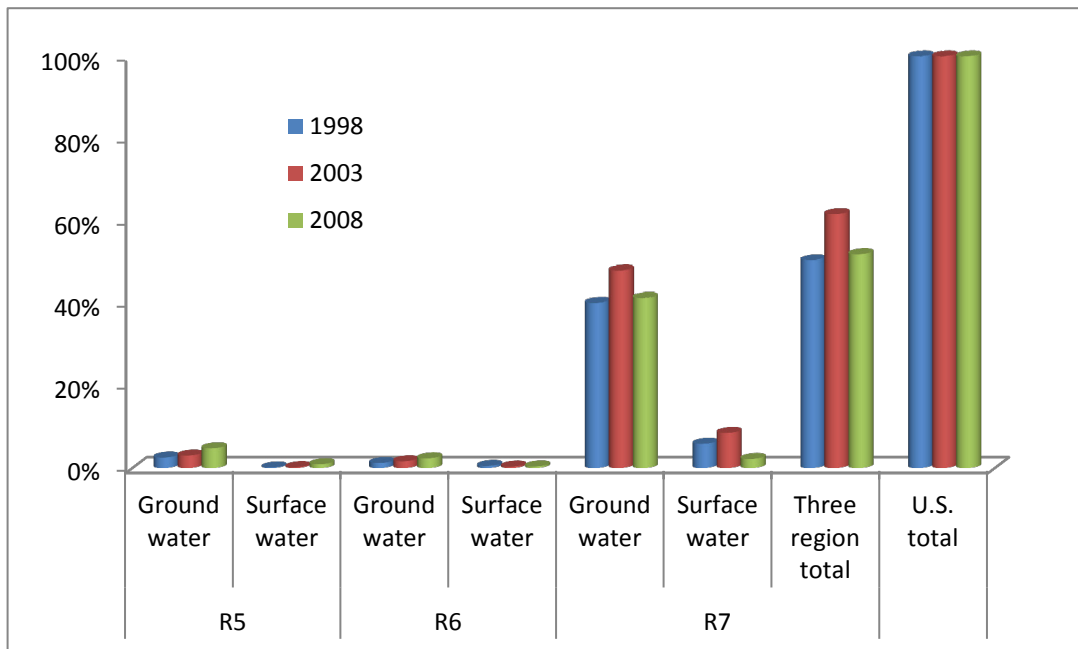
FIGURE 14 Consumptive Irrigation Water Use for Corn as Percent of U.S. Total for Corn by Source in USDA Regions 5, 6, and 7 (USDA 2003, 2008)

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. [15] 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 water vapor from the dryer, and a boiler make-up water rate of 5%,

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[15] In this analysis, all water use in ethanol conversion process is allocated to ethanol. For more discussions see Section 6.2.3.
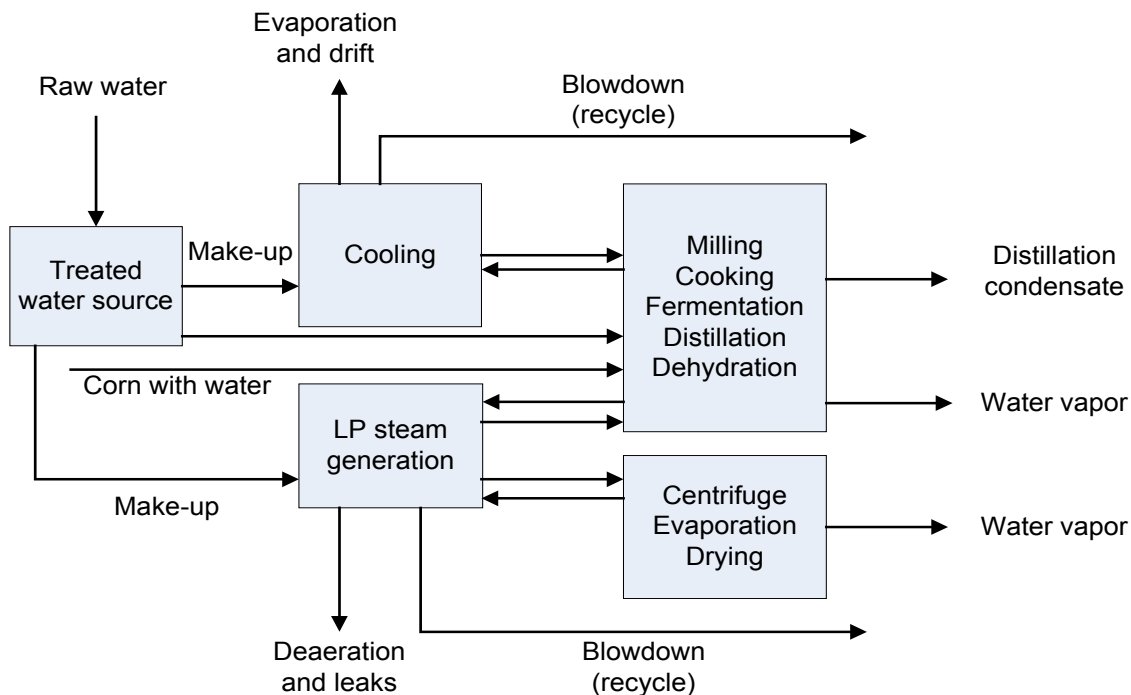
FIGURE 15 Water System in a Typical Dry Mill Ethanol Plant

USDA's corn dry mill model[16] 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).

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[16] Developed at USDA ARS, the Corn Dry Mill Model simulates corn ethanol dry milling process using ASPEN PLUS and more recently SuperPro Designer® software.
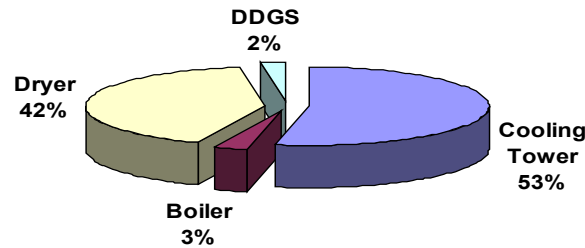
**FIGURE 16 Breakdown of Water Consumed
in Ethanol Production via Corn Dry Milling
(determined by USDA Dry Mill Model)**

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.
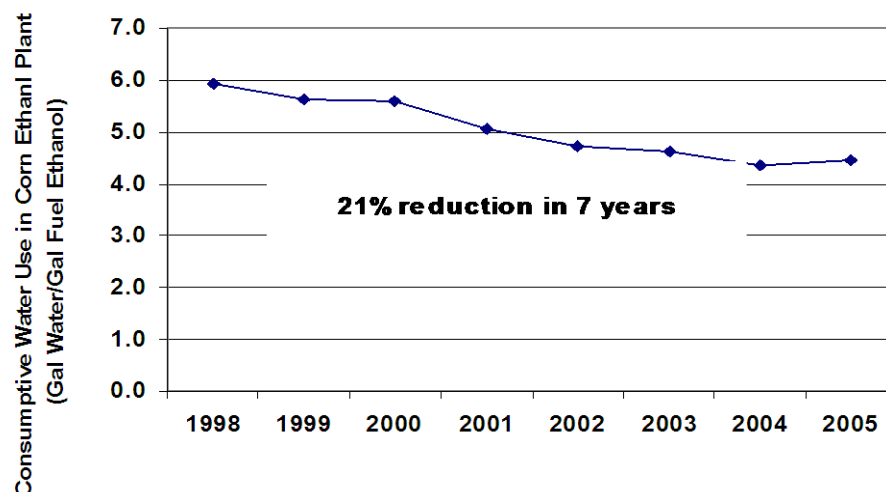
**FIGURE 17 Consumptive Water Use in Minnesota Dry Mill Corn
Ethanol Plants, 1998–2005 (Keeney and Muller 2006)**
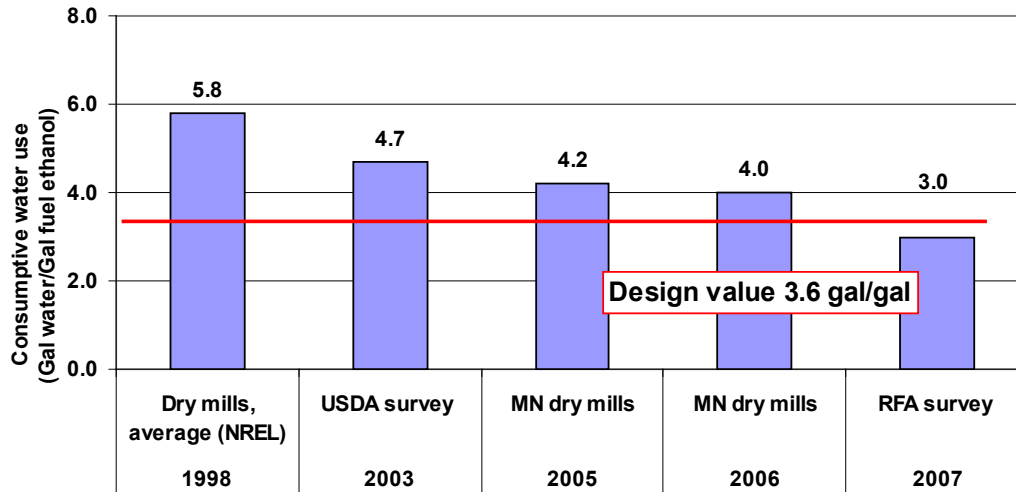
FIGURE 18 Average Water Consumption in Existing Corn Dry Mill Ethanol Plants

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 co-product 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.)

Irrigation water input

Corn Farm

Evapotranspiration, soil percolation, absorption to crop

44─715 gal

Total water consumed = 39─642 gal

Surface run-off, groundwater recharge 5─73 gal
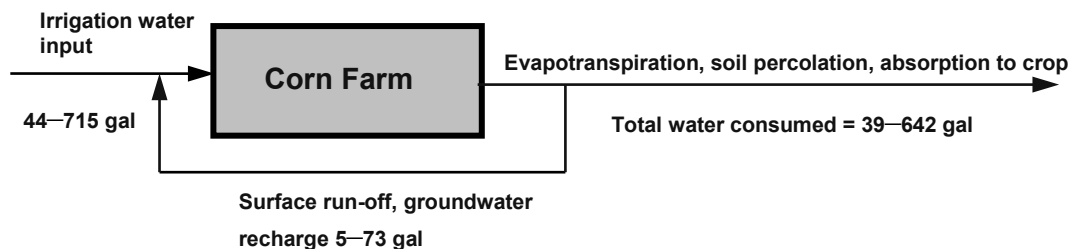
FIGURE 19 Irrigation Water Input and Consumption to Produce One Bushel of Corn in USDA Regions 5, 6, and 7 in 2008 (USDA 2011; USGS 2008), before Co-Product Allocation. (The consumption value decreases by one-third if water use attributable to DDGS is considered.)

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.

Water input

Corn Dry Mill

Evaporation and drifting, blow down, process discharge, incorporated into products

3.0 gal

Water consumed = 3.0 gal

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 9); 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 17–25 gallons of freshwater when the corn is grown in Regions 5 and 6, and 239 gallons when the corn is grown in Region 7. When taking into account of the water allocation to DDGS co-product, a net of 11–160 gallons of freshwater consumed per gallon of ethanol is produced from corn starch. This value is much smaller than our earlier estimate in 2009 due to a decrease in irrigation water withdrawal in 2008 in Region 7 (Figure 14).

As with corn production, U.S. corn ethanol production is concentrated in the same three regions (Regions 5, 6, and 7). In 2008, these regions were responsible for 88% of ethanol production (RFA 2011) and 88% of corn production (USDA-NASS 2011). Accounting for the largest share of corn and ethanol (50%) production, Region 5 consumes the least amount of irrigation water (Table 5).

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

USDA Region	Region 5	Region 6	Region 7
Share of U.S. ethanol production capacity (%)[a]	*50*	*15*	*23*
Share of U.S. corn production (%)[b]	*50*	*16*	*23*
Corn irrigation, groundwater[c]	12	19	224
Corn irrigation, surface water[c]	2	3	12
Ethanol production[d]	3	3	3
Total (corn irrigation and ethanol production) without co-product allocation[e]	17	25	239
Total water consumption with mass-based co-product allocation[f]	11	17	160

[a] Based on 2008 ethanol production capacity in operation (RFA 2011).
[b] Based on 2008 corn production (USDA-NASS 2011).
[c] Source: USDA (2008).
[d] Source: Wu (2008). Production-weighted average.
[e] Before co-product allocation
[f] Mass-based and carbon-displacement-based allocation. According to the rule of thumb that one-third of biomass in corn kernel goes to ethanol, one-third goes to CO_2, and one-third goes to DDGS. LCA results from GREET show 34% GHG attributable to DDGS. See 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[17]:

- 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 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;

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

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).[18] 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.

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

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

allocation, the values are reduced to 1.9–4.6 gallons. Figure 21 displays these data in an input-output format.

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.)

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.

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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, three regions were examined. Defined in terms of PADDs, these regions represent 90% of U.S. domestic onshore crude oil production and 81% of U.S. refinery output (EIA 2007d). Shown in Figure 22, these regions are:

- 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 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[19] is generated from oil wells and lifted up along with oils. The PW is typically re-injected 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 re-injected into the oil well must be subtracted from the total injection requirements. Figure 23 illustrates this approach.
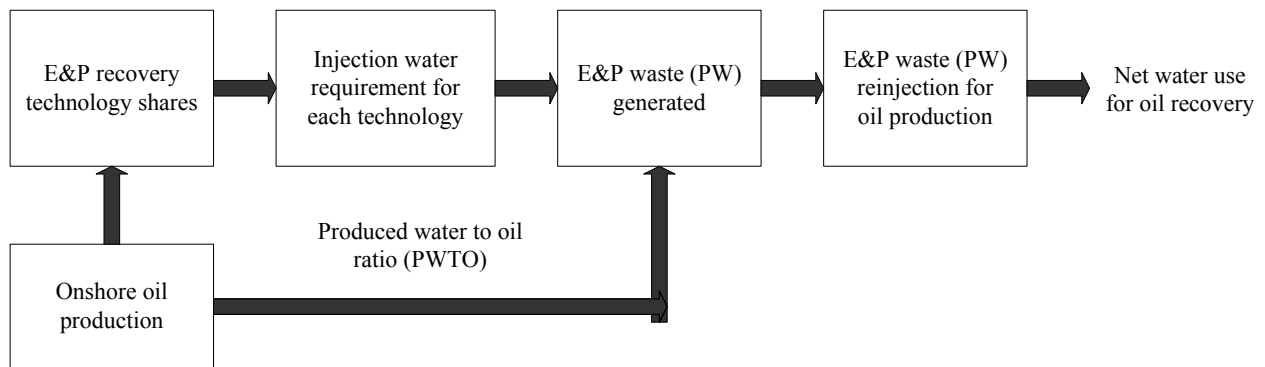
FIGURE 23 Calculation Logic of Net Water Use for Crude Oil Recovery

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[19] 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 re-injected for oil recovery was estimated for each region. Then, the amount of PW re-injection (calculated as the product of PW and the share of PW that is re-injected for oil recovery) was subtracted from this total. Both PW and the re-injection share for PADDs were obtained from the American Petroleum Institute (2000) and Veil et al. (2004). 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 67% of domestic oil production. Although offshore wells could contain both primary and secondary wells (Bibars 2004), no technology-specific statistics are publicly available at the time of this study. Among the technologies, EOR is onshore operation and well-documented (O&G J 2006) 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.
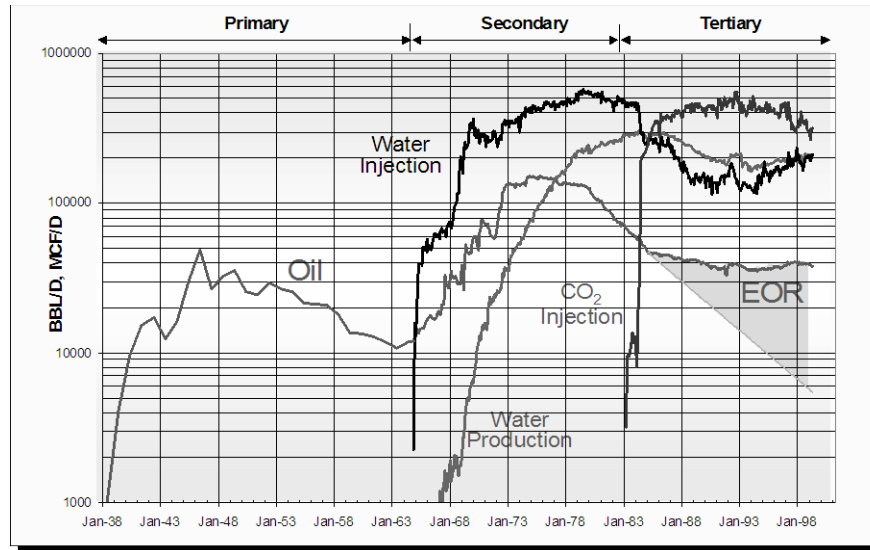
FIGURE 24 Water Injection and Oil and Water Production in Primary, Secondary, and Tertiary Recovery for Shell Denver City Project (Barry 2007; used with permission). BBL/D: bbl oil per day; MCF/D: million cubic feet gas per day

Figure 25 shows the distribution of U.S. onshore and offshore production and, within them, the distribution of recovery by primary, secondary, and tertiary technologies. Half of total production is estimated to come from secondary water flooding, 13% from EOR, and 38% from primary recovery. Table 7 provides the total production volumes (onshore plus offshore) associated with these shares.
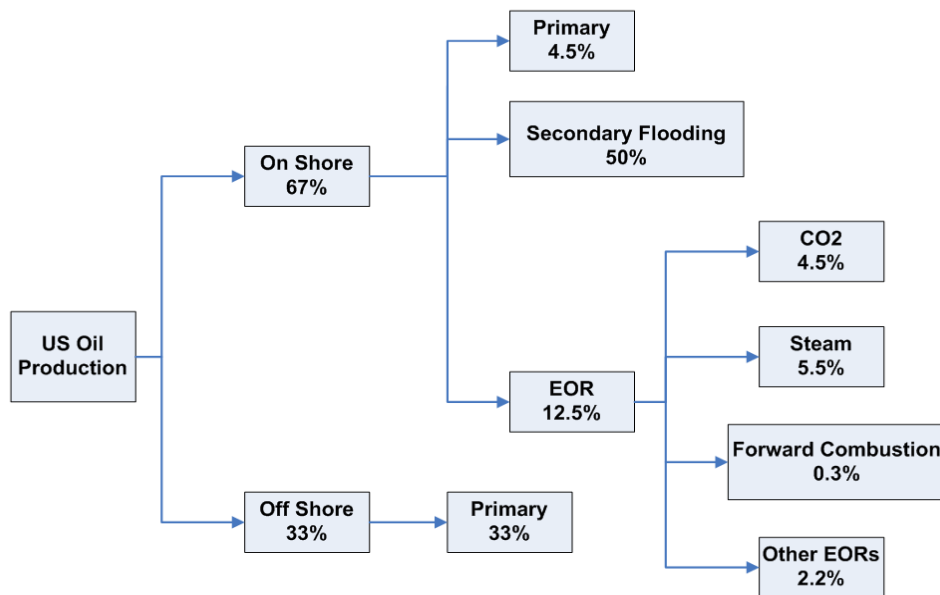
FIGURE 25 Technology Shares for Onshore and Offshore U.S. Crude Oil Recovery (EIA 2007b; O&GJ 2006)

TABLE 7 Estimated U.S. Oil Production by Technology, 2005

Recovery Technology	Oil Production[a] by Recovery Technology (thousand bbl/d)	Recovery Technology Share (%)	Onshore Recovery by Technology (thousand bbl/d)
Primary	1940	37[b]	228[c]
Secondary (water flooding)	2589	50[d]	2589
Tertiary (EOR)	649[e]	13	649
Total	5178	100	3466

[a] Total onshore and offshore production (EIA 2007 Table 5.2; EIA 2008a).
[b] Primary recovery = total recovery – (secondary + EOR).
[c] Assumes all offshore wells are primary recovery (1940 total – 1712 offshore = 228 onshore).
[d] EIA 2007b.
[e] O&GJ 2006.

Figure 26 provides a further breakdown of onshore production by recovery technology. For onshore wells, water flooding is responsible for three-quarters of production. While thermal steam EOR is the most widely used tertiary recovery technology, CO_2 injection (miscible) has been growing rapidly and is now the second 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. Each of these technologies represents about 2% of total EOR (O&GJ 2006).
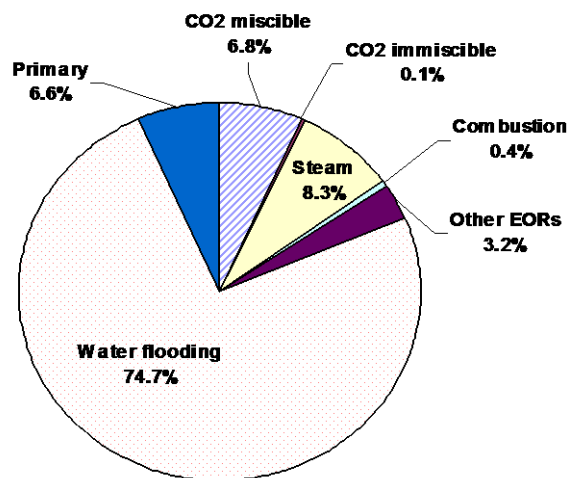
FIGURE 26 Onshore U.S. Crude Oil Recovery by Technology (EIA 2007b; O&GJ 2006)

4.2.1.2 Injection Water Consumption for Oil Recovery

Injection water requirements vary with recovery technology. Primary recovery requires an average of only 0.21 gallons of freshwater/gallon of crude oil recovered (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 their analysis of the history of 80 U.S. secondary wells, Bush and Helander (1968) found that over their water-flooding lifetime, an average of 8.6 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 as high as 343 gal/gal of oil with more water-intensive techniques like micellar polymer injection. With CO_2 injection, reports of water use are extremely 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 gal/gal recovered. At the same time, based on 10 years of data (from 1988 to 1998) on Shell's CO_2 EOR Denver City project, injection water averaged only 4.3 gal/gal (see Figure 24). Royce et al. have 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 assume 13 gallons per gallon recovered with CO_2 EOR. For those EOR technologies for which water use is not reported in the open literature (such as hydrocarbon miscible/immiscible, hot water, and N_2 technologies), we assume 8.7 gal/gal, the average injection water use of CO_2, steam, and combustion EOR schemes.

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 production.

TABLE 8 Injection Water Use by Recovery Technology

Recovery Technology	Injection Water (gal water per gal crude)[a]	Reference
Primary recovery	0.2	Gleick (1994)
Secondary water flooding	8.6	Bush and Helander (1968)
EOR steam injection	5.4	Gleick (1994)
EOR CO_2 injection	13.0	Royce et al. (1984)
EOR caustic injection	3.9	Gleick (1994)
EOR forward combustion/air injection	1.9	Gleick (1994)
EOR micellar polymer injection[b]	343.1	Gleick (1994)

[a] Excludes E&P water production and recycle.
[b] No active projects under way (O&GJ 2006).

As of 2005, domestic onshore recovery operations required 1,171 million gallons of injection water to produce 146 million gallons of conventional crude oil (Table 9). The technology-weighted national average water injection was 8.0 gallons of water per gallon of crude. This estimate does not include treated PW injected for oil recovery, which is discussed in Section 4.2.2. Secondary water flooding is responsible for 79.7% of injection water use in U.S. onshore oil production (Figure 27). Although micellar-polymer-based recovery consumes relatively large amounts of water, there are no reported active projects employing this technology currently in the U. S. (O&GJ 2006). The same is true for caustic/alkaline, surfactant, and other polymer-based oil recovery methods (O&GJ 2006). Hence, these technologies are not included in this analysis. Regardless of the technology, the injection water required for oil recovery varies considerably from region to region. For example, Texas Oil and Gas District 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 60-80% higher than the estimated national average.

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

Recovery Technology	Oil Production		Water Injection		
	(bbl/d)[a]	(mln gal/d)	(gal/gal crude)[b]	(mln gal/d)	Technology Share (%)
CO_2 miscible	234,315	9.8	13.0	127.9	10.9
CO_2 immiscible	2,698	0.1	13.0	1.5	0.1
Steam	286,668	12.0	5.4	65.0	5.5
Combustion	13,260	0.6	1.9	1.1	0.1
Other EOR[c]	112,276	4.7	8.7	40.9	3.5
Secondary water flooding	2,589,000	108.7	8.6	933	79.7
Primary recovery	227,783	9.6	0.2	2.0	0.2
Total	3,466,000	145.6		1171	100
Technology-weighted average water injection (excludes produced water re-injection)			**8.0**		

[a] 2005 production data for EOR technologies from O&GJ (2006). See Table 7 for total, primary, and secondary production.
[b] See Table 8.
[c] Data on water use are not publicly available for "other EOR" technologies, including hydrocarbon miscible/immiscible, hot-water flooding, and nitrogen injection. Average values of CO_2, steam and air combustion assumed for other EOR.
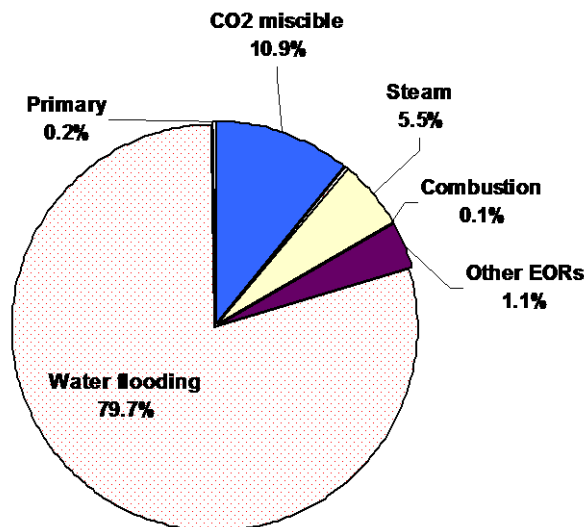
**FIGURE 27 Injection Water Use by Crude
Oil Recovery Technology, U.S. Onshore**

4.2.2 Produced Water Re-Injection 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 the saline water 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 re-injected 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). 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 terms of output, the oil production weighted PW generation, ratio of 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 (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).

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

	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

[a] API (2000).
[b] EIA (2008a).
[c] Veil et al. (2004).

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 waste management. Since the 1980s, produced water has become a major source of injection water for oil recovery. According to API's 1995 survey (API 2000), 71% of the produced water in the United States is re-injected 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).

Our estimate of the technology-weighted average quantity of injection water required for domestic onshore production (8.0 gallons per gallon of crude) was presented (Table 9) and discussed in Section 4.2.1. That estimate reflects the calculation logic laid out in Figure 23 and Equation 1. Assuming that the national average PWTO ratio is 6.8 gallons of PW per gallon of crude (Table 10) and that 71% of PW is re-injected for oil recovery (Figure 28), the national net water consumption is estimated to be 3.2 gal/gal of crude from U.S. onshore operations (Equation 2).
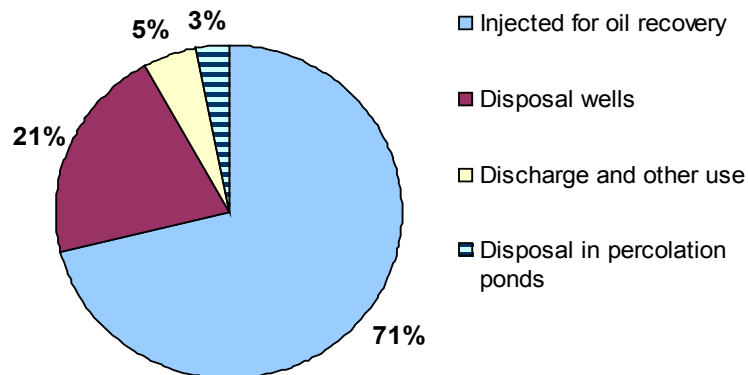
FIGURE 28 Fate of Produced Water from U.S. Oil Recovery (API 2000)

The PWTO varies considerably from one well or region to another, and within an individual well as it ages. According to the Texas Railroad Commission (2008), the PWTO is about 1.0–1.2 gallons of PW per gallon of crude in the Texas Oil and Gas Districts 8 and 8a, as compared to the average ratio in PADD III, 10.9. This low PW yield could not meet the injection water demand of 12.7–14.7 gallons per gallon of oil in these two districts, as discussed in Section 4.2.1. In fact, fresh water as well as a large amount of saline/brackish water from an underground aquifer was used for oil recovery.

Indeed, for individual wells that employ water management practices diligently, it is possible that 100% of PW can be re-injected for oil recovery and the net water consumption could approach zero (Figure 24). The constraint to increased PW recycling and reuse is the associated cost for water treatment as compared with other alternatives.

4.2.3 Regional Water Use

Like biofuel feedstock production, crude oil production depends on local and regional water availability. Three PADD Regions (II, III, and V) account for the bulk of total and onshore crude production in the United States. As shown in Table 11, PADD III accounts for more than 43% of domestic onshore oil production, while PADD V accounts for one-third. Well productivity varies considerably among the three regions. Although PADD II and III have nearly equivalent numbers of production wells, PADD III produces three times the oil of PADD II. Similarly, PADD V accounts for a third of domestic production but less than a tenth of the wells.

State estimates of PW and crude produced (Veil et al. 2004; API 2000) were summed to yield regional PWTO averages for 1995 and 2002 as seen in Table 12. Clearly, the range of PWTO widens over the years (from 3.3–11.3 in 1995 to 3.4–14.7 in 2002) and PADD V's PWTO is much lower than that of the other regions. While PADD IV has the highest PWTO, it is only moderately higher than that of PADDs II and III.

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

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 12 PWTO Ratios by PADD Region

PADD Region	PWTO in 1995[a]	PWTO in 2002[b]
I	8.7	9.8
II	8.3	11.1
III	11.3	10.9
IV	9.4	14.7
V	3.3	3.4

[a] API (2000).
[b] Veil et al. (2004).

The percent of produced water re-injected for crude recovery also differs from one region to another (Table 13). PADD I has the highest re-injection rate (99%) followed by PADD IV and V; PADD II and III re-inject about half of the PW generated. Based on these figures, we calculated regional PW used for re-injection (gal PW/gal oil). As shown in Table 13, PADD V has the lowest PW re-injection rate, about half of PADD III.

As discussed in Section 4.2.1, injection water use for various recovery technologies (see Table 9) 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. Using equation 2, we subtracted regional PW re-injection value from technology-weighted average water injection requirement to yield net water use for oil recovery in the three regions (PADD II, III, and V), and the results also appear in Table 13.

TABLE 13 Injection Water Consumption for Onshore Domestic Crude Production

PADD Region	Technology-Weighted Average Injection Water Use (gal/gal)[a]	Produced Water-to-Oil Ratio[b]	Percent of PW Re-Injected for Oil Recovery (%)[c]	PW Used for Re-Injection (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 9.
[b] Value from Table 12, 2002 data.
[c] API (2000).

A net of 2.1–5.4 gallons of water is consumed to produce one gallon of crude oil in PADD II, III and V. According to the Texas Railroad Commission, the net freshwater injection for oil recovery in Texas Oil and Gas District 8 and 8a is about 2 gallons per gallon of crude, which is close to our estimate of 2.3 gal/gal for PADD III. As discussed earlier, 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 re-injection 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 re-injection (as in PADD IV). For wells or regions with small amounts of produced water (e.g., PADD V), recycling or reuse of PW is critical to reducing net water use. For example, increasing PW re-injection in PADD V from current levels (76%) to 99% could cut injection water consumption to 4.7 gal/gal; a similar change in PW re-injection in PADD II and III (from 52–53% currently to 80%) could result in net zero injection water usage. Although PADD I and IV consume negligible injection water, their oil production shares are small (<10%, Table 11). In contrast, PADD II, III, and V together account for 90% of U.S. onshore crude oil production (Figure 29). Reducing injection water consumption in these regions could have a much greater national impact.
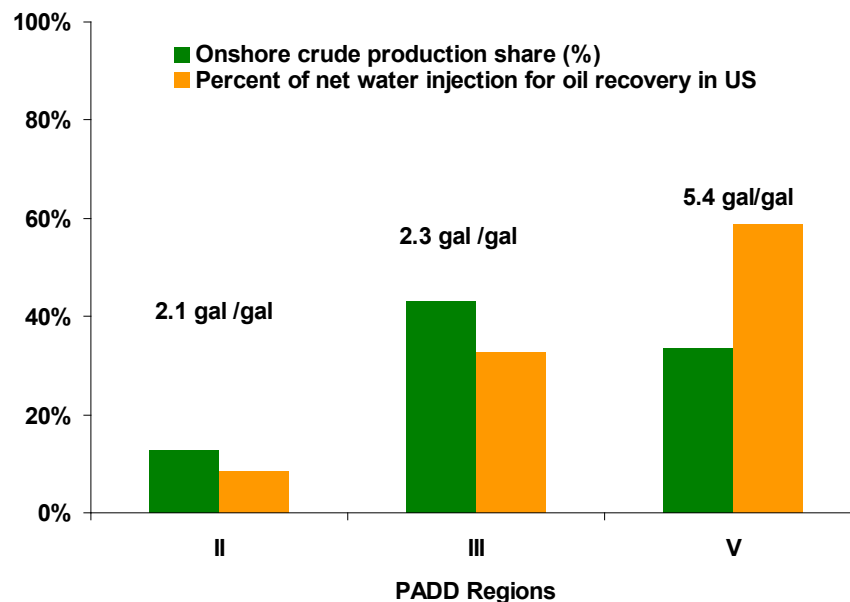
FIGURE 29 Onshore Oil Production and Water Consumption for Major U.S. Oil-Producing Regions

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 re-injection.

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.[20] 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.

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[20] 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).

4.4.1 Oil Sands Recovery

Oil sands are recovered by open-pit or surface mining of relatively shallow deposits,[21] or by thermal in-situ techniques[22] 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[23] 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.

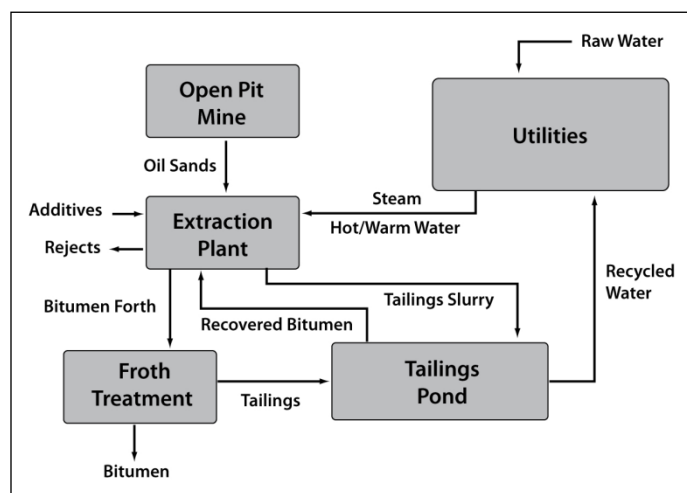**FIGURE 30 Major Process Steps and Water Flow in Oil Sands Recovery by Surface Mining (adapted from Masliyah 2004)**

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

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

[23] Commonly called the "Athabasca deposit."

As shown in the figure, oil sand feed ore[24] is transported to an extraction plant. Steam and hot/warm water separate the feed ore into bitumen froth[25] 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[26] 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.

As shown in Figure 31a, CSS involves cycling or intermittent injection of high pressure steam into the reservoir at single injector/producer wells[27]. 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.

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[24] 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).

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

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

[27] During a soak phase, between injection and production, additional steam may be injected.
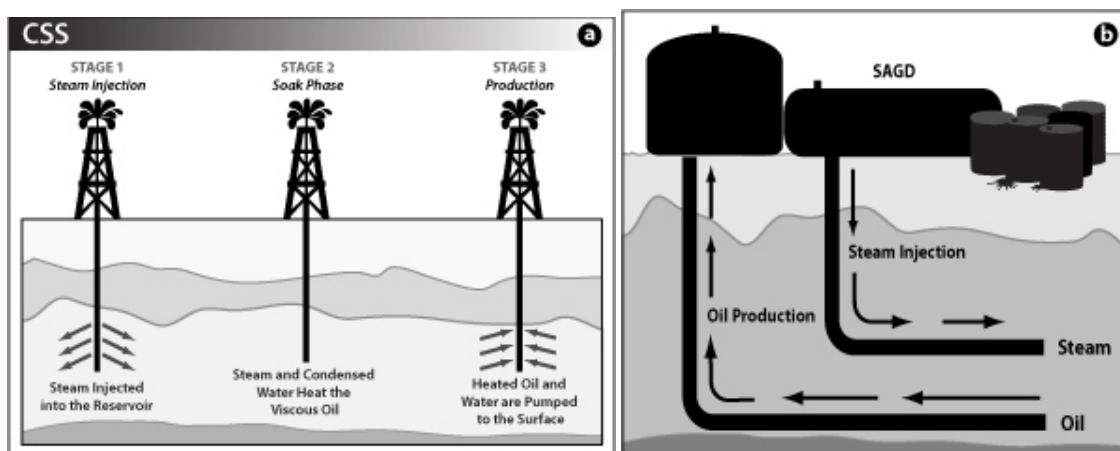
FIGURE 31 In-Situ Oil-Sands Recovery Schemes: (a) Cyclic Steam Stimulation and (b) Steam-Assisted Gravity Drainage (adapted from Flint 2005)

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).

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[28]. 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

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

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[29]. 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[30] (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 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.

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[29] 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.

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

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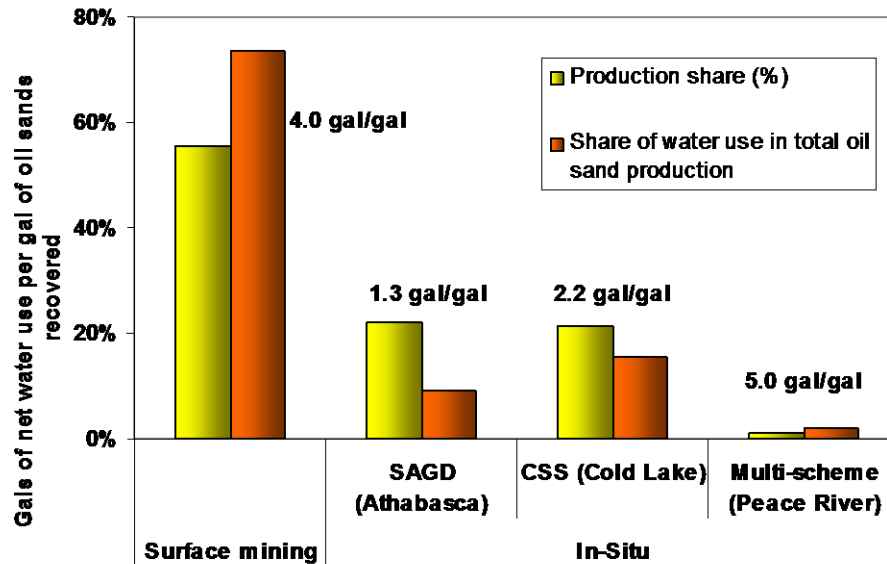
FIGURE 32 Shares of Synthetic Crude Oil Production and Net Water Use from Bitumen Recovery through Crude Upgrading by Recovery Technology (Gatens 2007; CAPP 2008a; CAPP 2008b)

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[31]. Figure 33 illustrates the water system of a typical North American oil refinery. According to CH2MHill (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.

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[31] 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 (CH₂MHill 2003, used with permission). Blowdowns are recycled in some facilities.

FIGURE 34 Water Requirements and Losses in a Typical Refinery (data source: CH₂MHill 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, 1.5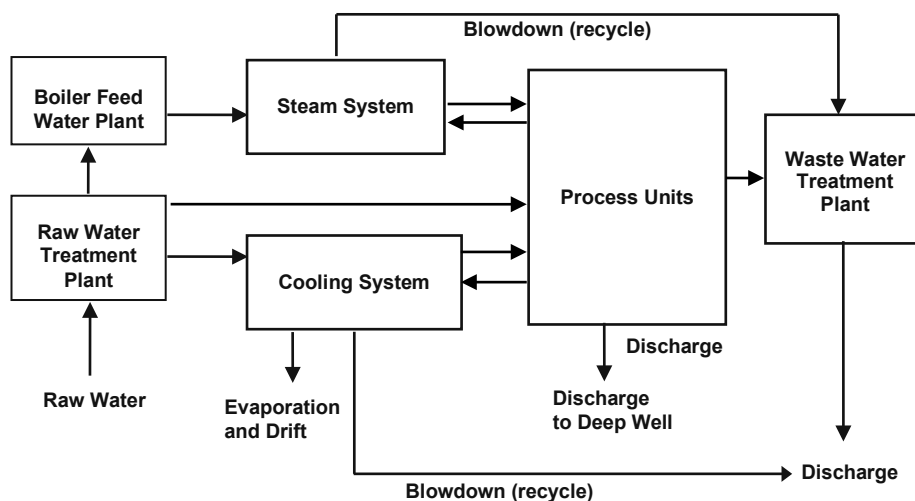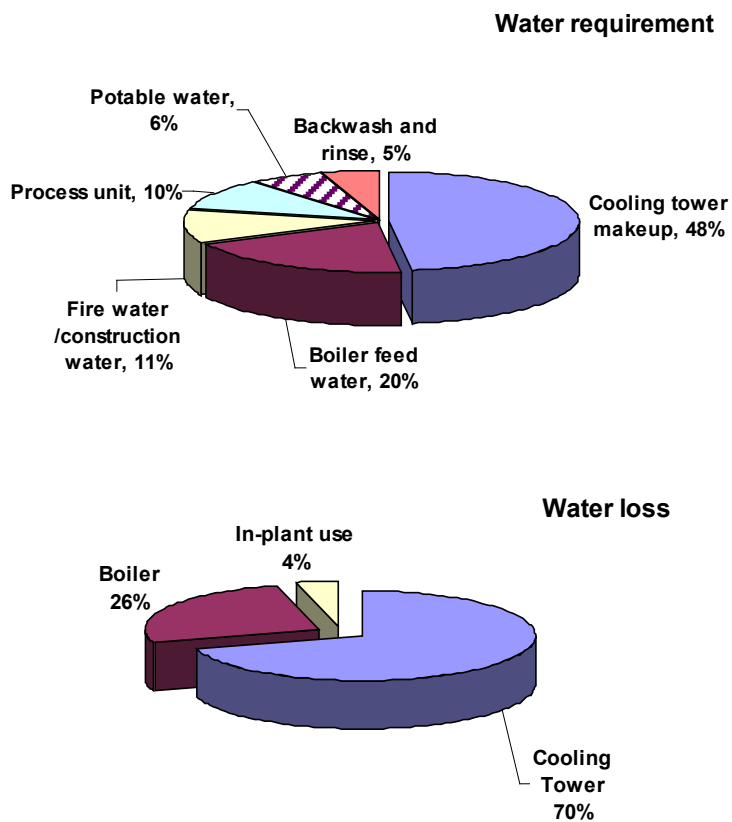3 gallons of water is consumed for each gallon of crude. Because of yield gain during crude processing (i.e., 42 gallons of crude generate 44.6 gallons of refined product), consumptive water use can also be expressed as 1.4 gallons of water per gallon of refined product. Depending on the refining process, 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).

4.6 WATER CONSUMPTION IN MAJOR STEPS OF THE GASOLINE LIFE CYCLE

4.6.1 Conventional Petroleum to Gasoline Life Cycle

As indicated above, 90% of U.S. onshore oil production consumes from 2.1 to 5.4 gallons of water for each gallon of crude oil recovered (PADD II, III, and V, Table 11 and 13). Together with an average of 1.5 gal/gal consumed for refining, a total of 3.6–7.0 gallons of water is required to produce and process 1 gallon of crude oil in the three major PADD Regions (II, III, and V). 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.
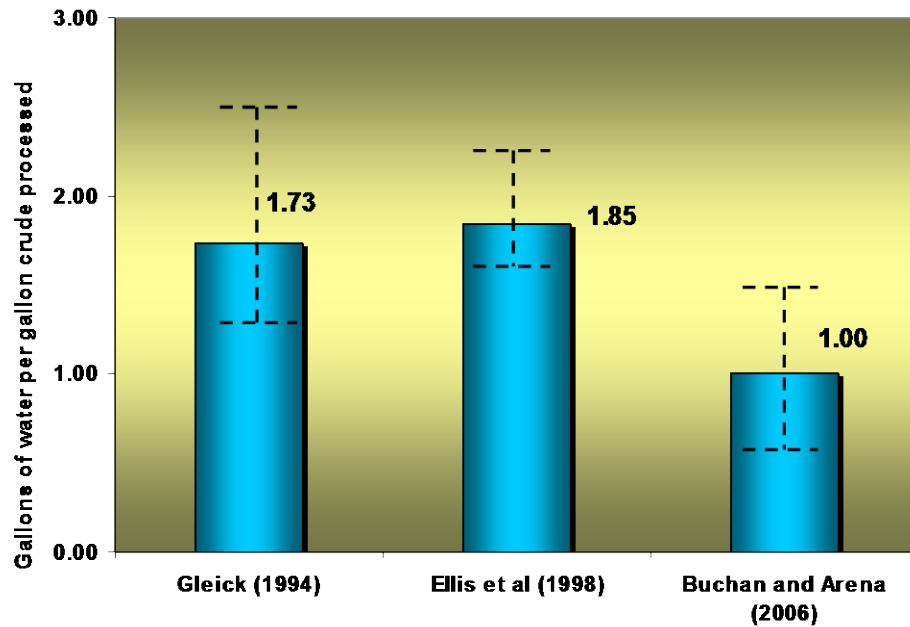
FIGURE 35 Estimates of Net Water Use in U.S. Refineries (gal water/gal crude)

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

	U.S. Conventional Oil (Onshore)			Saudi Arabian Conventional Oil[a]
	PADD II	**PADD III**	**PADD V**	
E&P[b]				
(gal water/gal crude)	2.1	2.3	5.4	1.4–4.6
Refining				
(gal water/gal crude)	1.5	1.5	1.5	1.5
Total water use				
(gal/gal crude)	3.6	3.9	7.0	2.9–6.1
(gal/gal gasoline)[c]	3.4	3.7	6.6	2.8–5.8
Share of crude production in the United States (%)[d]	12.8	43.2	33.6	
Share of gasoline production in the United States (%)[e]	20.7	42.4	18.2	
Share of injection water use for crude recovery in the United States[f]	8.6	32.6	58.8	

[a] Alhuthali et al. (2005); Durham (2005).
[b] From Table 13.
[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 11.
[e] 2005 value, EIA (2007d).
[f] Calculated from Tables 11 and 13.

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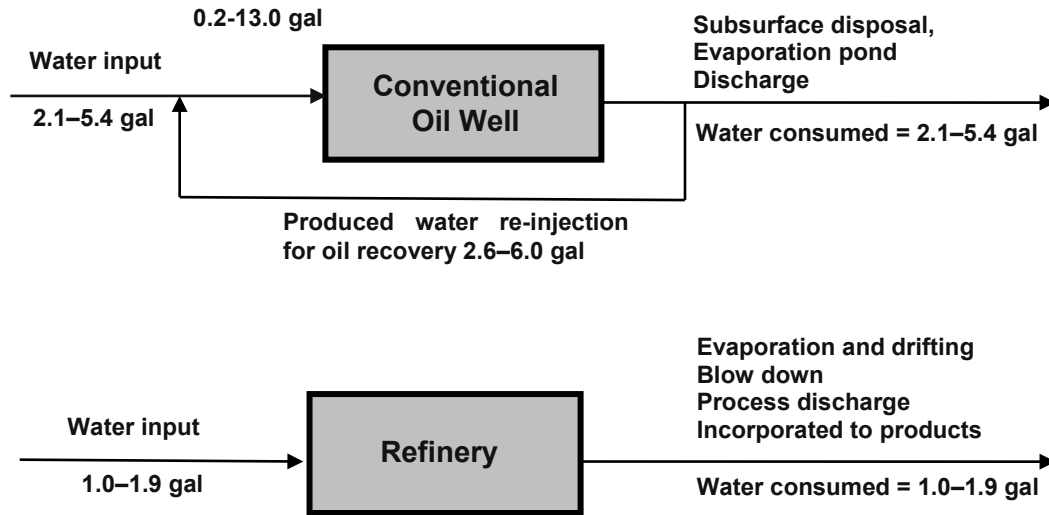
FIGURE 36 Water Input and Consumption in Conventional Crude Oil Production and Refining to Process One Gallon of Crude in the United States

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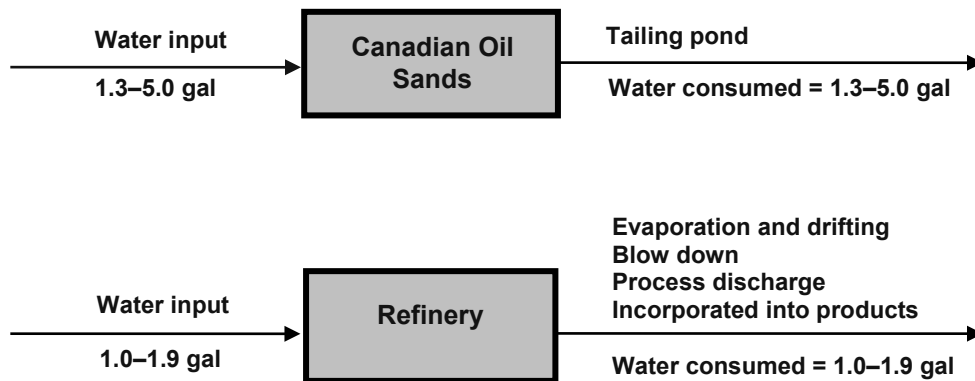
FIGURE 37 Water Input and Consumption for Bitumen Production and Refining to Process One Gallon of Canadian Oil Sands Crude

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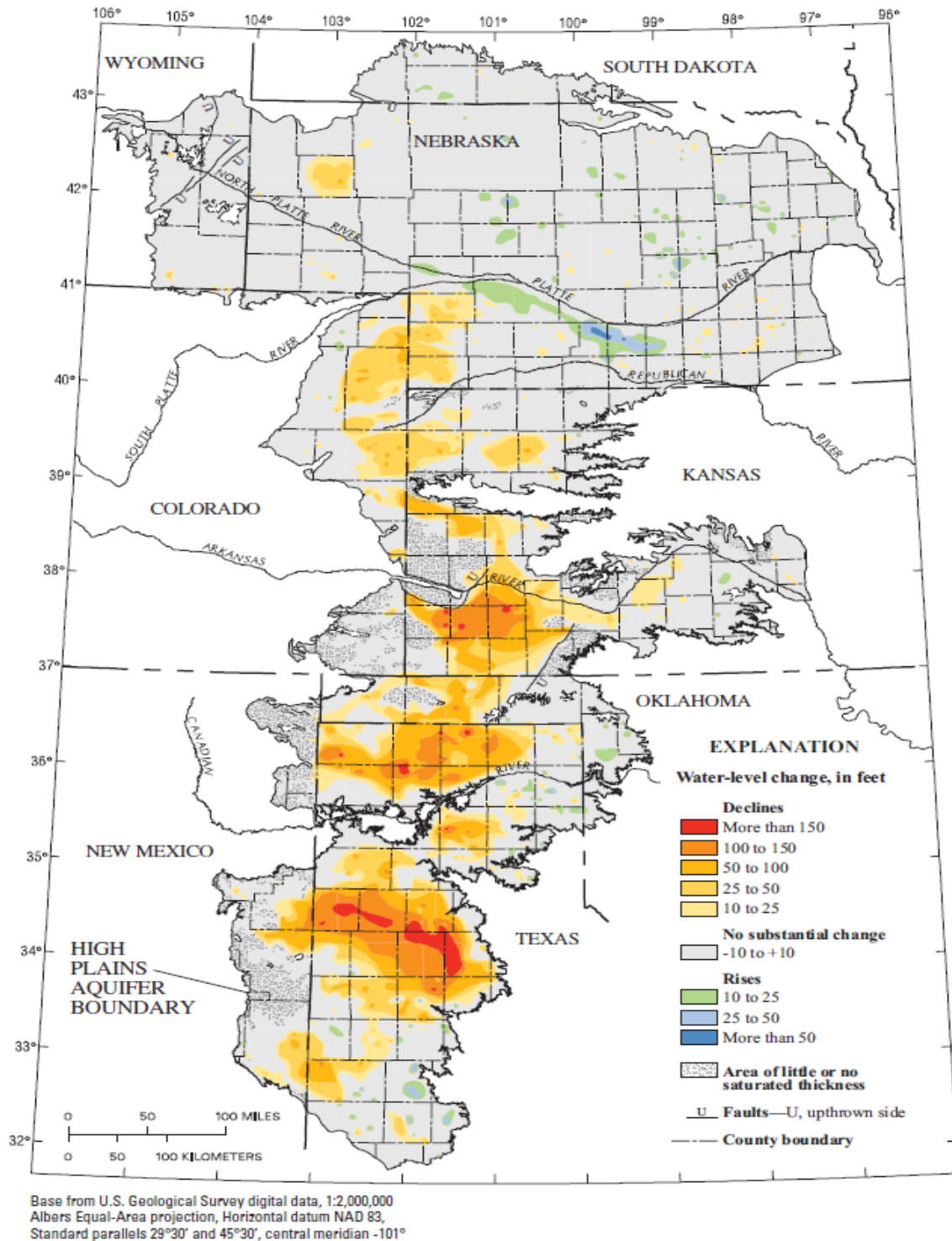
FIGURE 38 Water Level Changes in the High Plains Aquifer, Predevelopment to 2005 (McGuire 2006)

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.[32] 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

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[32] 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.

for 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)[33]. 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.

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[33] 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 U.S. major corn-growing regions. As was shown in Table 5, excluding precipitation, producing a gallon of corn ethanol can consume as little as 10 or as much as 324 gallons of water, depending on the amount of irrigation water used for corn growing in the region in which it is harvested. On average, more than half of the U.S. corn ethanol is produced at a water use rate of 10 gallons of water per gallon of ethanol (USDA Region 5).

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 non-conventional crude sources examined in this study. As shown in the figure, net water use varies from less than 3 gallons in Ghawar (conventional technology) and Athabasca (SAGD) to nearly 7 gal in PADD V (conventional technology). Gasoline produced from multi-scheme techniques in Peace River, as well as from conventional oil in North 'Ain Dar, are close to this latter value.

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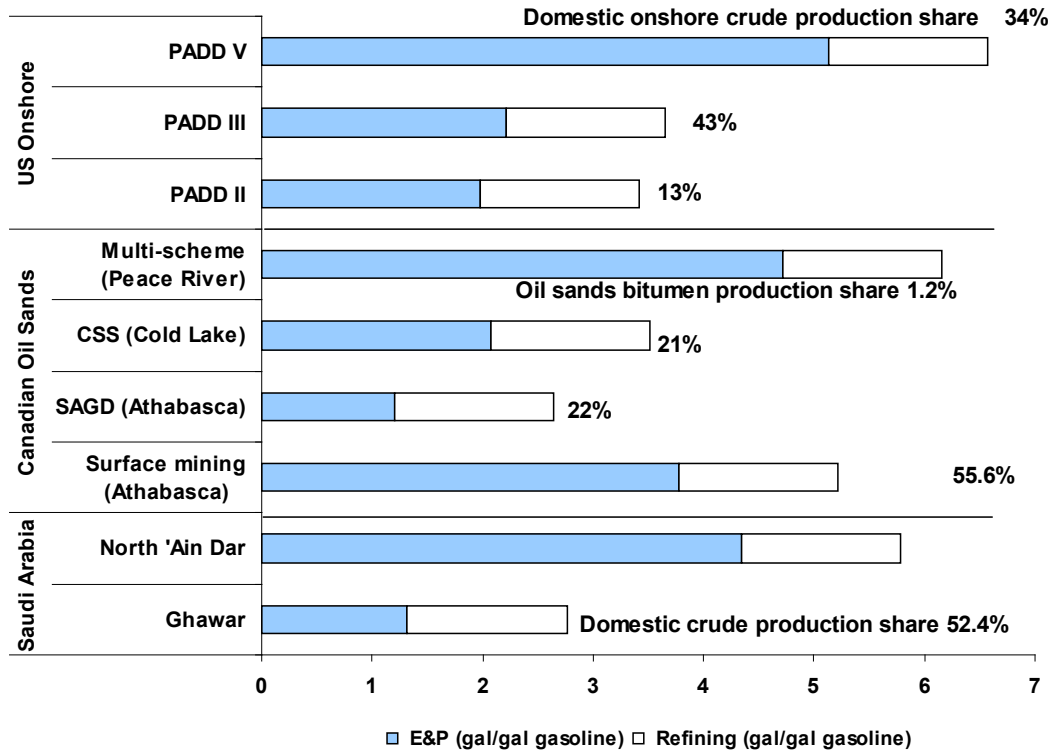
Figure 39 Net Water Use for Gasoline Production from Conventional (United States and Saudi) and Non-Conventional Crude (Oil Sands) by Life-Cycle Stage, Location, and Recovery Method

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.

- Inconsistent base year data. Data describing the <u>production</u> of domestic conventional crude oil and agricultural feedstocks are reasonably complete for calendar year 2005. However, data describing domestic <u>water use</u> may or may

not be available for that year. 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. Thus, the ratio of water consumption to water withdrawals for crop irrigation in the United States used in this analysis is based on the last available national data, which was reported for year 1995.

- Lack of production data on cellulosic ethanol. Since commercial-scale production is not yet underway, data on cellulosic ethanol are limited to process simulation results.

- Lack of recent data on U.S. injection water use by recovery technology. Data on this subject were last analyzed in 1994 (Gleick). Recent statistics are scarce. At the time of this analysis, an API bench-marking study for water use for several major energy companies was underway, but results were not yet available.

- Lack of complete reporting of oil recovery by technology by the United States, PADD, and state. For E&P of domestic onshore crude oil, neither U.S. nor PADD and state production is reported by recovery technology. In particular, offshore data is scarce. Thus, we allocated all secondary recovery wells to onshore production and applied national technology shares for our regional analyses. Likewise, international statistic data rarely report production by recovery technology.

- 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 account for only 38% of U.S. crude oil supply (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 three PADDs examined in this study account for 81% of 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 re-injection. 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 re-injection 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 five-year period (2003–2008), statistics shows 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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