# Consumptive Water Use in the Production of Bioethanol 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 bioethanol, 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” is the sum total of process water input less water output that is recycled and reused for the process.[1] The estimate applies to surface and groundwater sources but does not include precipitation. Water requirements are evaluated for five fuel pathways: bioethanol from corn or cellulose, and gasoline from Canadian oil sands, Saudi Arabian crude, or U.S. conventional crude from onshore wells. Regional variations and historic trends are noted, as are opportunities to reduce water use.

<u>Scope</u>

This study examines water use for the production of energy feedstocks and fuels from the perspective of lifecycle analysis. Fuel lifecycles 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 (corn or switchgrass farming, oil extraction and production) and fuel processing/production (ethanol production and oil refining). For corn ethanol,[2] we focus on three of the 10 farm production regions defined by the U.S. Department of Agriculture (USDA, see Figure 6). They are Region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas). These three regions consistently account for 88 percent of U.S. corn production (USDA–NASS 2007) and 95 percent of its ethanol production (RFA 2007). We examine corn ethanol produced via dry milling and cellulosic ethanol produced via biochemical and thermochemical conversion technologies.

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[1] For biofuel feedstocks, consumptive water use is further defined as the water that is incorporated into the crop or lost to evapotranspiration (ET), because it cannot be reused for another purpose in the immediate vicinity (NAS 2007).

[2] Unless otherwise noted, “ethanol”, as used in this report, refers to denatured ethanol.

For domestic production of conventional petroleum gasoline, we focus on three major oil-producing regions defined on the basis of Petroleum Administration for Defense District (PADDs II, III and V, see Figure 21), which together represent 90 percent of U.S. onshore crude production and 81 percent 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, 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, and calculate typical consumptive water use 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 percent of Canadian oil production and 100 percent of Canadian oil sands production) and the Ghawar field (which represents 52 percent of Saudi Arabian oil production), respectively. Together, Saudi crude oil and Canadian oil sands accounted for 23 percent of U.S. crude oil imports in 2005 (EIA 2007a).

Study results are summarized below.

<u>Corn Ethanol</u>

Crop irrigation is the single most important factor affecting water use 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 68 percent of U.S. corn and 66 percent of U.S. corn ethanol are produced in Regions 5 and 6, where 11–17 gal of irrigation water are consumed per gal of ethanol produced. Corn irrigation is much higher in Region 7.

**Table S-1. Corn Ethanol Production and Water Consumption for Three USDA Regions**

| | **Region 5** | **Region 6** | **Region 7** |
|---|---|---|---|
| *Share of corn production in U.S. (%)* | *52* | *16* | *20* |
| *Share of ethanol production in U.S. (%)* | *52* | *14* | *30* |
| Irrigation water consumed in corn farming (gal/gal ethanol) | 7.0 | 13.8 | 320.6 |
| Water consumed in ethanol production (gal/gal ethanol) | 3.0 | 3.0 | 3.0 |
| Total water use in corn ethanol (gal/gal ethanol) | 10.0 | 16.8 | 323.6 |

Ethanol production plants are relatively less water intensive. The combination of newly-built production facilities with better process integration and, to a less extent, production of wet distillers grain (WDG) co-products in dry mill plants (as compared with dried distillers grain and solubles, DDGS)[3] have reduced water use dramatically. Average consumptive water use in ethanol plants has declined from 6.8 gal/gal ethanol to 3.0 gal/gal ethanol in the past ten years.

Cellulosic Ethanol

This analysis focuses on ethanol production from switchgrass. 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 yields of 4.5–8 dry tons per acre are feasible without irrigation.

Water requirements for cellulosic ethanol production vary with technology. The current biochemical conversion (BC) process requires nearly 10 gal of water to produce a gal of cellulosic ethanol. Increased ethanol yield can reduce this requirement to about 6 gal. Thermochemical conversion (TC) via gasification followed by catalytic synthesis requires much less water — less than 2 gal for an optimized gasification to mixed alcohol process and about a gal of water per gal of ethanol for a TC/BC hybrid syngas-to-ethanol 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 water recycling and reuse. Primary oil recovery requires only 0.2 gal of water per gal of crude oil produced. With the exception of offshore wells (which account for a third of production), U.S. oil production relies heavily on secondary recovery via water flooding. This technology requires an average of over 8 gal of water per gal of crude oil recovered and, as a result, accounts for 80 percent of the water injected into onshore wells for oil recovery.[4] 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 to 5.5 gal per gal of crude oil for the three major oil production regions (PADDs 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 percent and 11 percent, respectively, of total water injection in domestic onshore wells (Table 9).

In the absence of a major technological change, these shares are likely to continue to grow. However, if new technologies gain widespread acceptance, they could dramatically alter water use. For example, implementation of down-hole oil-water separation technology could eliminate produced water (PW) which in turn could require either more

[3] WDG requires less steam for drying, thereby reducing water use. The major advantage of WDG, however, is in energy savings.
[4] In 2005, half of U.S. crude oil production used water flooding (EIA 2007b).

freshwater or less (if PW that remains down-hole increases well pressures). Impacts of new technology on net water use remain to be seen.

Alternative water sources for oil recovery have been explored to displace groundwater. Using primarily desalinated seawater for injection, Saudi Arabian oil wells consume only about 3 to 6 gal of water/gal gasoline.

In contrast to E&P, oil refining consumes relatively small amounts of water, from 0.5 to 2.5 gals per gal of crude oil processed. Water management is practiced industry-wide and water recycling and reuse are in-place at many existing and most new projects. Combining oil E&P and refining, producing a gal of gasoline from conventional crude in Saudi Arabia or in the U.S. can consume as little as 2.8 or as much as 6.6 gals of water.

Gasoline from Canadian Oil Sands

Oil sands are deposits of bitumen[5] in combination with clay, sand, and water. 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 five gals of freshwater (primarily surface water from the Athabasca River) to produce a gal of synthetic crude oil. The two dominant in-situ technologies, steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), require large quantities of steam for bitumen recovery. Utilizing extensive recycling to lower water use, recovery operations require 1.3 gal to 5.0 gal of water to produce a gal of bitumen. From E&P to refining, a total of 2.6 to 6.2 gal of water is needed to produce a gal of gasoline from oil sands.

Issues

Each fuel lifecycle presents a unique pattern of opportunities and challenges related to its consumptive water use. There are, however, a number of common issues. Consumptive water use by all lifecycles considered in this study raises issues of sustainability; has the potential to affect water quality and land degradation; and involves some measure of ecosystem disruption. For the most part, these issues apply primarily to feedstock production. For example, aquifer depletion may be exacerbated as a result of irrigation water demands for corn growing or injection water needs for conventional or oil sands-based crude oil recovery. Fuel processing tends to be less water-intensive, due to a combination of integrated operations and more extensive water recycling and reuse.

Cumulative impacts are 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 as examined in this study, is particularly applicable to questions of sustainability, and none more so than with respect to water resources.

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[5] Bitumen is a heavy, black viscous oil that must be rigorously treated to upgrade it into crude oil before it can be processed in a refinery.

Conclusions

This analysis found that consumptive water use for feedstock and fuel production varies considerably by region, type of feedstock, soil and climactic condition, and production technology for bioethanol; and 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. A summary of consumptive water use for the fuels analyzed in this study is presented in Table S-2.

Our analysis indicates that conservation measures to reduce consumptive water use are needed to achieve sustainable bioethanol and gasoline production. Improved water management is needed for corn irrigation, particularly in those areas where water is scarce. Cellulosic feedstocks may need to be grown in their native habitat to reduce or eliminate irrigation. Groundwater use and management is especially critical in arid regions, and in locations with high concentrations of biofuel or oil production facilities.

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. For cellulosic ethanol facilities, a process optimized for water use should be encouraged. Finally, the use of produced water re-injection for oil recovery should be increased.

**Table S-2. Consumptive Freshwater Use for Ethanol and Petroleum Gasoline Production**

| Fuel (feedstock) | Net water consumed[a] | Major factors affecting water use |
|---|---|---|
| Corn ethanol | 10–324 gal/gal ethanol[d] | Regional variation caused by irrigation requirements due to climate and soil types |
| Switchgrass ethanol | 1.0 –9.8 gal/gal ethanol[d] | Production technology |
| Gasoline (U.S. conventional crude)[b] | 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)[c] | 2.6–6.2 gal/gal gasoline | Geologic formation, production technology |

[a] In gal of water per gal of fuel specified.
[b] PADD II, III and V combined.
[c] Including thermal recovery, upgrading and refining.
[d] All water used in ethanol conversion is allocated to the ethanol product.

# 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. And, the 2007 *Energy Independence and Security Act* (EISA) is committing this country to produce 36 billion gal of renewable fuels by 2022 — 16 billion gal of cellulosic ethanol, 15 billion gal of corn ethanol and 5 billion gal 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 U.S. is importing more unconventional crude oil, much of it derived from Canadian oil sands, and extracting a growing share of domestic crude using secondary and tertiary recovery technologies on existing onshore wells.[6] All three of these fuel pathways — ethanol from biological feedstocks, gasoline from oil sands, and gasoline from secondary recovery technologies in oil 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. 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 gal of ethanol in the United States?
- How much water is consumed to produce a gal 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?

## 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.

[6] Canada has stepped up production of bitumen to more than 1 million barrels per day (CAPP 2007).

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,[7] 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 evapotranspiration (see below) from plants. Precipitation is only included insofar as it affects the need for irrigation, the primary focus of this analysis.

Transpiration accounts for the movement of water within plants and the loss of water vapor through stomata[8] 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 evapotranspiration is called consumptive or net water use because it cannot be reused for another purpose in the immediate vicinity (NAS 2007). This study focuses on consumptive water use from irrigation. It does not estimate crop ET directly, but instead examines net irrigation water use for given feedstocks at an aggregate level.

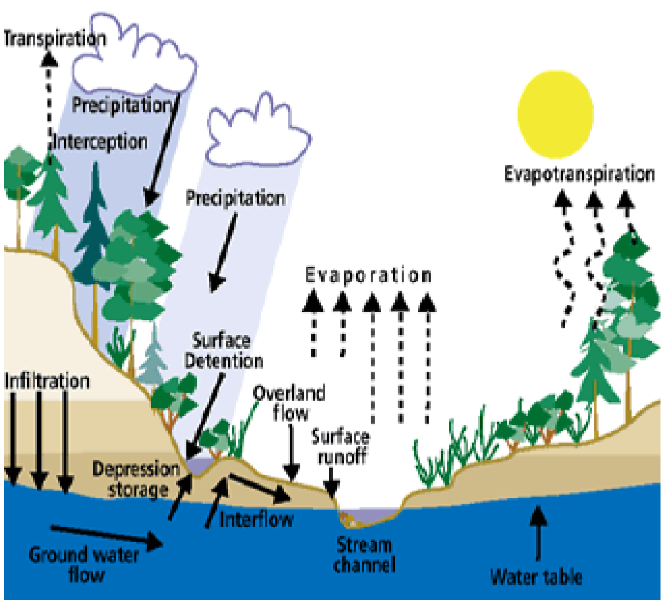


**Figure 1. Hydrologic cycle (Allen 2007, used with permission)**

Freshwater is withdrawn from surface water or groundwater to support agricultural operations, industrial processes or 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.

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7 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.

8 Stomata are minute orifices or slits in the epidermis of leaves, stems, etc., through which gases are exchanged.

Historically, biofuels have been produced from grain-based crops with water supplied by precipitation and/or irrigation. The agriculture sector is a significant water user, especially for irrigation. Almost 60 percent of the world's freshwater withdrawals are used for irrigation. In the U.S., 42 percent of freshwater withdrawals from 1960 to 1995 were for agriculture (USGS 2007). Approximately 70 percent of the water withdrawn (primarily for irrigation) in the U.S. agricultural sector is consumed. Although recent data are not available, the ratio of consumption to total withdrawals for the agricultural sector may have stabilized since 1985 (Figure 2). The rest (30 percent) is returned to the water body. In the end, 85 percent of U.S. freshwater consumption is attributable to agricultural activities.

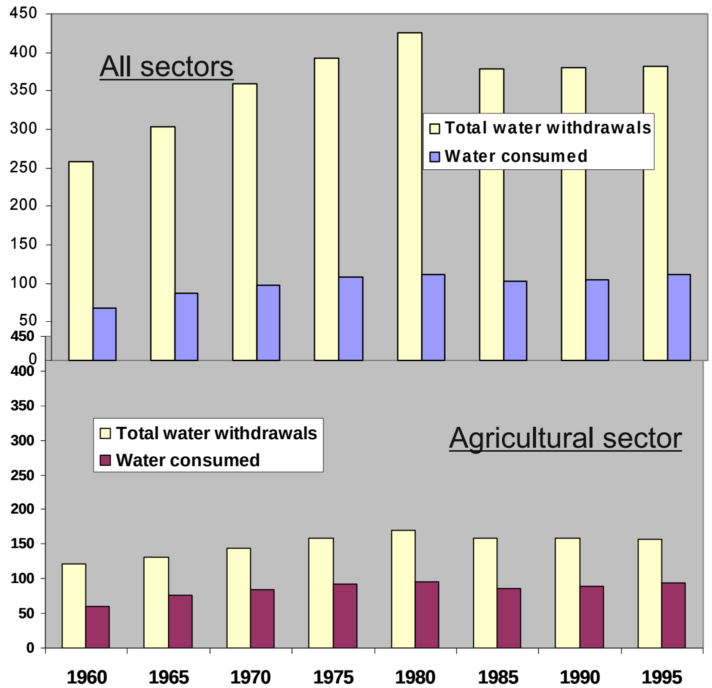



**Figure 2. U.S. Freshwater Withdrawals and Consumption, All Sectors and Agricultural Sector, 1960–1995 (million acre-ft/yr, USGS 2007)**

As reported in the Census of Agriculture and the Farm and Ranch Irrigation Survey, irrigated acreage has increased steadily since 1900, from less than 10 million acres to nearly 60 million acres (USDA 2007). However, the amount of water applied per acre has decreased from 25 inches in the 1970s, to 20 inches today (Gollehon 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 (Pellegrino et al. 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.

Today, agricultural residues, dedicated energy crops, forest wood residues 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, 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.

## 1.2 Water Use in Crude Oil Recovery

As domestic crude oil production declined in the last 30 years (EIA–AER 2008), the U.S. 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 percent 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–AER 2008). Table 1 provides an overview of U.S. crude oil production and net imports.

**Table 1. U.S. Crude Oil Supply (EIA 2007b; EIA-AER 2008)**

| | Domestic Production | | Imports | | | | | | | Total Supply |
|---|---|---|---|---|---|---|---|---|---|---|
| | Onshore | Offshore | Algeria | Nigeria | Saudi Arabia | Venezuela | Canada[a] | Mexico | Others[b] | |
| 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] Includes oil sands production, 1.1 million bbl/d.
[b] 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 percent 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 exploration and production (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 lifecycle analysis (LCA).[9] Using this approach, water consumption is estimated by lifecycle stage: feedstock production (or farming, in the case of biofuel), feedstock transportation, fuel production, fuel transportation, and fuel utilization. Among lifecycle 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 lifecycle steps — feedstock production and fuel processing/production — for (a) ethanol from corn, (b) cellulosic ethanol from switchgrass, (c) gasoline from domestic and imported conventional crude oil, and (d) 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 Office of Biomass Programs of the U.S. Department of Energy (DOE). Collaborators include Energetics, Inc., the National Renewable Energy Laboratory (NREL), and Argonne National Laboratory (Argonne). For that effort, Energetics (Pellegrino et al. 2007) is focusing on national water resource impacts of the future feedstock production scenarios in the "billion-ton" study sponsored by the U.S. Department of Agriculture (USDA) and DOE (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, and petroleum recovery and refining.

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

- Feedstock production (including irrigation for biofuel feedstocks)
  - Corn
  - Switchgrass
  - Conventional crude: United States and Saudi Arabian
  - Unconventional crude: Canadian oil sands

[9] 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.

- Ethanol production
  - Corn dry mill
  - Cellulosic biorefinery: biochemical (BC), thermochemical (TC) gasification to mixed alcohols, and a hybrid syngas-to-ethanol process
- 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 lifecycle stages. Beyond this, our 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 energy independence goals.

# 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, production process and technology; and summarize results by relevant parameter.

## 2.1 Data Collection and Processing

In order to focus on the products and processes most likely to affect water consumption, representative feedstocks, fuel pathways and regions were specified for each liquid fuel and used to target the data search. The feedstocks and fuel pathways included in this analysis are 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 and groundwater and production of "produced water" (PW) in oilfield operations) are collected by state, this 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 Petroleum Administration for Defense District (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 lifecycle 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 gal of water consumed per gal of product fuel. This analysis is intended to derive unit estimates of water consumed by major fuel production lifecycle 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)<br>USDA Farm and Ranch Irrigation Survey (1998, 2003)[a]<br>USGS database (1985–1995)[b]<br>USDA–ARS Corn Dry Mill Model (USDA–ARS 2006)<br>USDA Ethanol Plant Survey (Shapouri and Gallagher 2005)<br>Keeney and Muller (2006)<br>Pellegrino et al. (2007)<br>Wu (2008)[c] |
| Cellulosic | Ethanol | NREL report (Aden et al. 2002)<br>Pellegrino et al. (2007)<br>Phillips et al. (2007) |
| Conventional crude | Gasoline | DOE Report to Congress (2006)<br>$CH_2M$ Hill (2003)<br>Petroleum company publications (Shell, Suncor, Syncrude 2007)<br>Gleick (1994)<br>Royce et al. (1984)<br>Ellis et al. (1998)<br>Buchan and Arena (2006)<br>Bush and Helander (1968) |
| Oil sands | Gasoline | Peachey (2005)<br>Suncor (2007)<br>Syncrude (2007)<br>Isaacs (2005 and 2007)<br>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 Renewable Fuels Association (RFA) in 2007.

## 2.2 System Boundaries and Water Balance

As illustrated in Figure 3, this study defines consumptive or net 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 input and output. Total input water includes freshwater, saline groundwater and recycled water. Total output water includes water losses (consumption) and recycled water. Water losses can be in liquid (wastewater) or gaseous form (vapor). ***Freshwater 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*** occurs through ET, evaporation, discharge, disposal, and by the incorporation of water into products. ***Water recycle*** is the throughput that is reused in the system. Examples include irrigation run-off returned to the water body or for groundwater recharge, produced water re-injection for crude oil and oil sands production, boiler condensate reuse as process water, and treated process water reuse as cooling make-up. Freshwater use for sanitation, equipment cleaning, fire protection, and drinking water are not considered in this study.

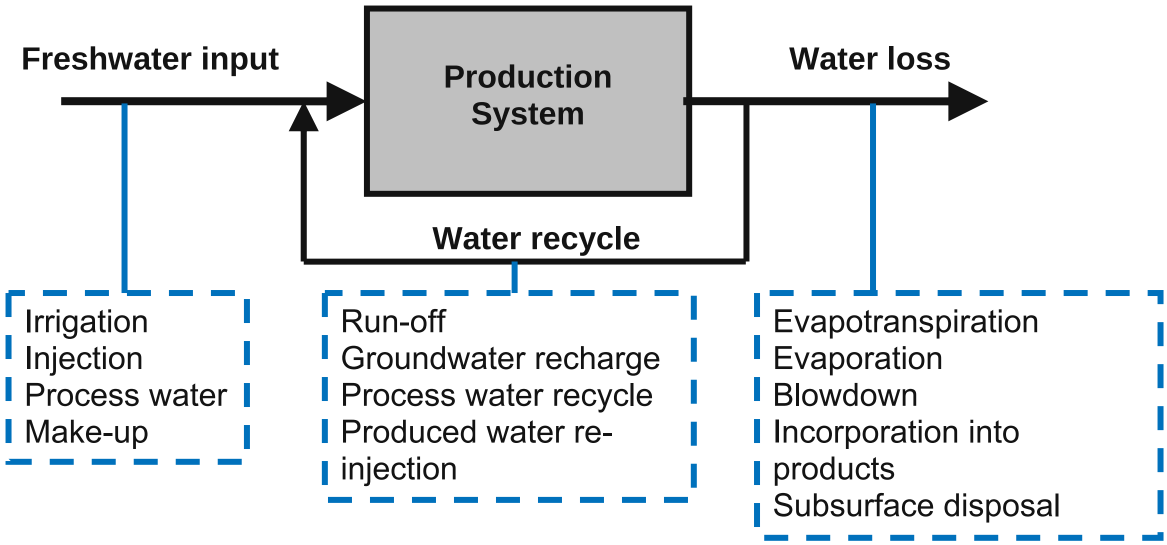



**Figure 3. System Boundary, Water Inputs, Outputs, and Losses of a Conceptual Fuel Production System**

Ethanol production plants and oil refineries have well-defined system boundaries and water use 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 corn field to surface water or groundwater in its watershed, or injection water flow into a single well) are not readily available across the U.S. Thus, we examine feedstock production on a macro scale (i.e. total water inputs and outputs in a region over time), 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 4 (a), 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.[10] 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 water loss from soil percolation, ET, and absorption to the crop (Figure 4 (a)).

In an oil field, freshwater and a portion of produced water are introduced through an injection well. Produced water lifted from the production well includes 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 —

[10] Since precipitation is not within the system, it is shown as a dashed input.

injection water is retained in the formation into which it is injected — and that disposal wells to which some produced water is pumped are outside the system boundary. Given this assumption, 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 4 (b) illustrates this equivalence. Figure 5 depicts the physical arrangement of extraction and injection wells in a typical oil field.

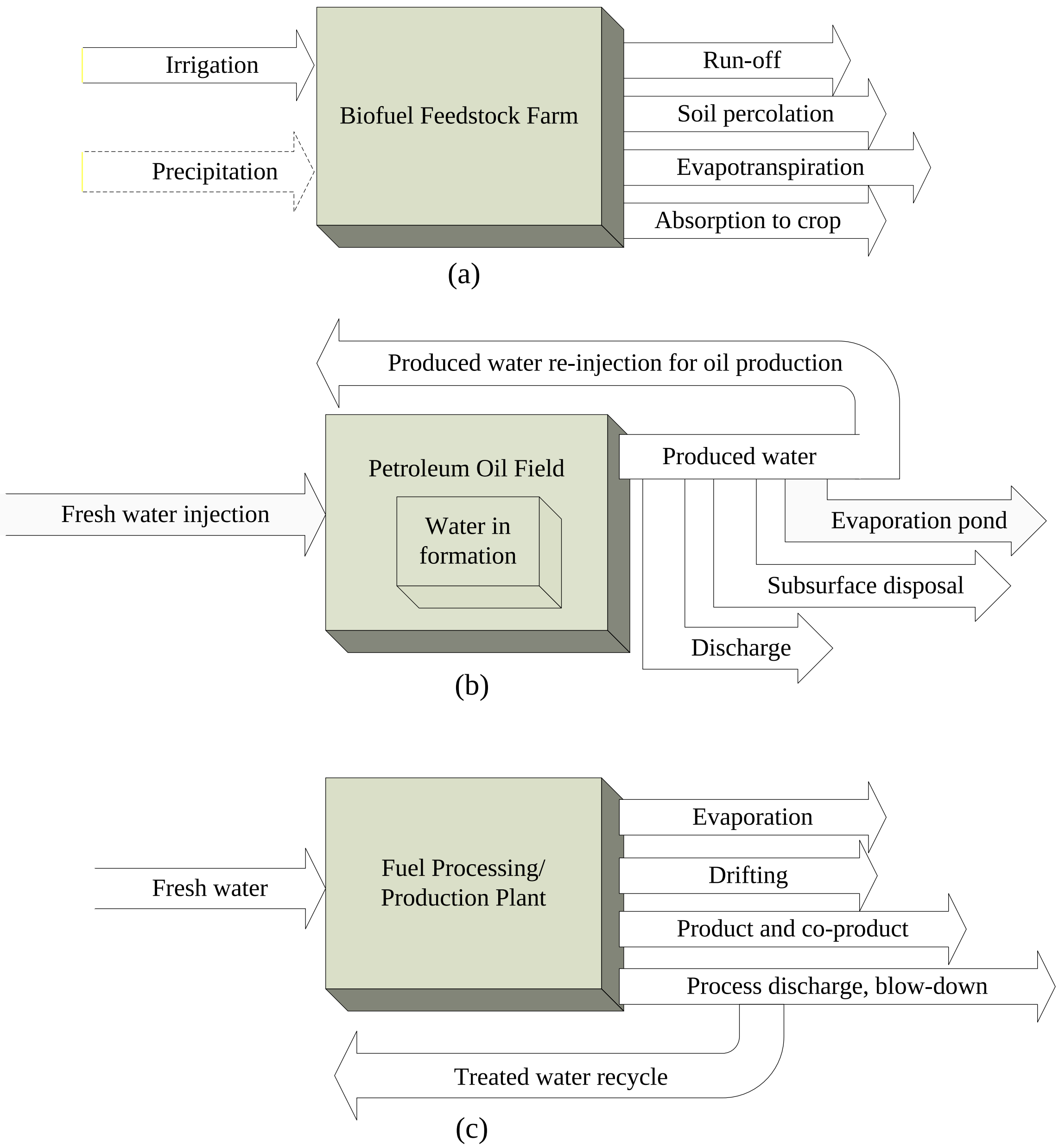



**Figure 4. Water Inputs and Outputs for (a) Biofuel Feedstock Production; (b) Petroleum Oil Production; and (c) Ethanol Production/Oil Refining**

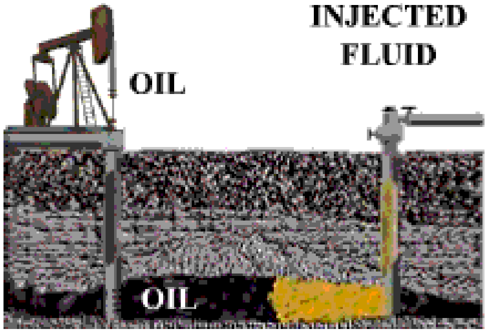



**Figure 5. A Typical Onshore Oil Field**

As shown in Figure 4 (c), consumptive water use in the fuel production process includes water loss through evaporation, drifting, incorporation into products and co-products, blow-down, and process water discharge. The specific analysis procedure for each fuel is detailed in Sections 3–4.

## 3. Ethanol

Corn growing tends to consume significantly more water than growing the feedstocks to produce cellulosic ethanol. But conversion of corn to ethanol tends to consume less water than conversion of cellulosic feedstocks to ethanol. The following discussion highlights these differences.

### 3.1 Corn Ethanol

Corn production and net 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 88 percent of corn production (USDA–NASS) and 95 percent of ethanol production in the U.S. (RFA 2007). USDA farm production regions are shown in Figure 6.

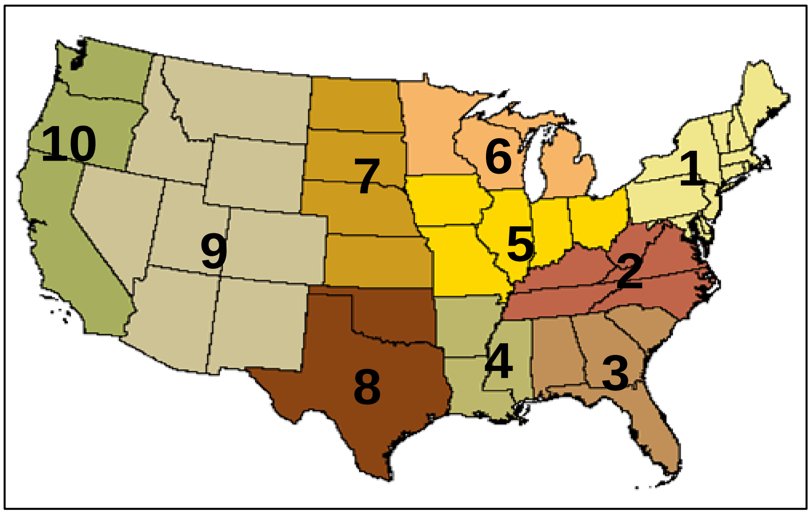



**Figure 6. USDA Farm Production Regions (Adapted from Pellegrino et al. 2007)**

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 percent 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.), although the actual amount varies with type of soil, weather, etc.

### 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 (USDA–NASS 2007).This region receives an average of only 22 inches of rainfall per year. By contrast, Regions 5 and 6 receive 16 and 8 inches more rain, respectively (Table 3).

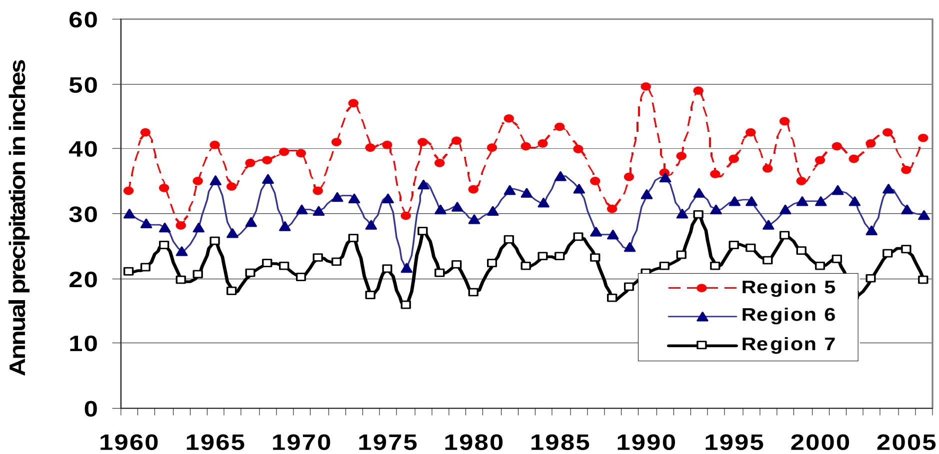



**Figure 7. Annual Precipitation in USDA Regions 5, 6 and 7 (USGS 2007)**

**Table 3. Average Annual Precipitation[a] by Corn-Growing Region (Pellegrino et al. 2007)**

| 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.

In areas where water demand exceeds that available from soil moisture and precipitation, irrigation must be applied. Nationally, irrigation application rates vary significantly, from 0.4 to 2.3 acre-ft per acre of corn (USDA 2003). Even in the Corn Belt, there are significant differences in irrigation rates (Figure 8). Irrigation can be as little as

0.57–0.58 ft[11] as in Regions 5 and 6 or as much as 1.2 ft as in Region 7 (Figure 8). For this study, the percent of corn grown with irrigation is used to weight state totals to account for differences in production and irrigation rates.

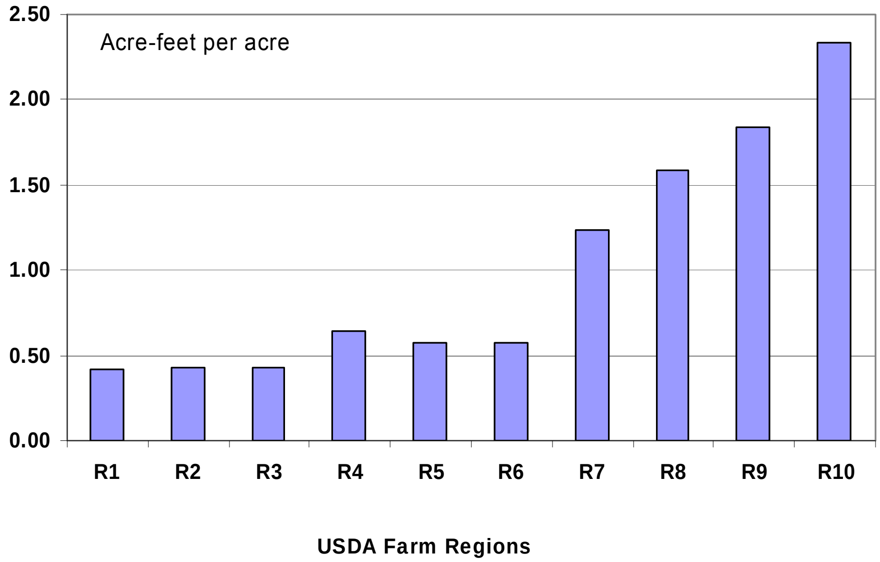



**Figure 8. Corn Irrigation Water Use by USDA Region (USDA 2003)**

Regardless of crop type, Figure 9 shows that only 14 percent of total water withdrawals by all sectors in the East-Central Region (including USDA Regions 5 and 6) are for irrigation, as compared with 64 percent in the Northern Plains (USDA Region 7). This is not surprising since irrigation in a given area is highly dependent on regional conditions. In the U.S., most water withdrawals (86 percent) and irrigated acres (75 percent) are in the 17 co-terminous western states (USGS 2007). The amount of water applied for irrigation in these states accounts for 88 percent of total U.S. irrigation water (USDA 2003). Irrigated acreage in these states typically receives less than 20 inches per year precipitation and cannot support crops without supplemental water.

It is also worth noting that because of soil and climactic differences, feedstock crops may have different water requirements when grown in different regions. For example, corn generally uses less water than soybeans in Pacific and Mountain regions, while the two crops require similar amounts of water when grown in North Central and Eastern regions. By contrast, corn grown in the Northern and Southern Plains states generally requires more water per acre than soybeans (NRC 2007).

[11] Acre-ft per acre.

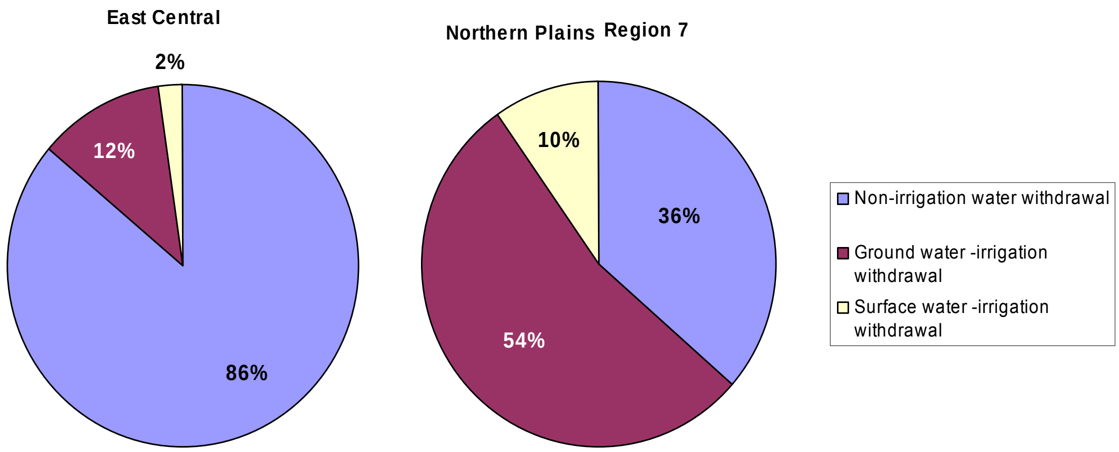



**Figure 9. Distribution of Water Withdrawals for Irrigation and Non-Irrigation Uses in Corn Belt Regions (USDA 2003)**

In order to estimate national average rates of water use, we calculate the percent of irrigated corn acreage for each state (USDA 2003). On average, 13 percent of harvested corn acreage is irrigated in the 12 major corn-producing states: Iowa, Indiana, Illinois, Kentucky, Missouri, Minnesota, Wisconsin, Michigan, North Dakota, South Dakota, Nebraska and Kansas (Wu, Wang and Huo 2006). In Region 7, Nebraska relies heavily (61 percent) on irrigation for growing corn (Table 4), as does the western part of Kansas. This compares with much more modest irrigation rates in Michigan, Missouri (9 percent each) and the other corn-producing states in the three regions (between 0.7 percent and 5.5 percent). On average, 43.1 percent of corn-growing acres require irrigation in Region 7, as compared with 2.4 percent in Region 5 and 3.9 percent in Region 6.

**Table 4. Irrigation by State and Major Corn-Producing Region (USDA 2003)**

| State | USDA Farm Region | Irrigated Acres | Harvested Acres | Percent of Acreage Irrigated | |
|---|---|---|---|---|---|
| | | | | State Average (%) | Regional Average[a] |
| IA | 5 | 86,261 | 11,761,392 | 0.7 | |
| IL | 5 | 211,167 | 10,742,787 | 2.0 | |
| IN | 5 | 180,305 | 5,123,291 | 3.5 | |
| MO | 5 | 246,315 | 2,677,491 | 9.2 | **Region 5: 2.4%** |
| MN | 6 | 178,457 | 6,556,082 | 2.7 | |
| WI | 6 | 83,602 | 2,862,031 | 2.9 | |
| MI | 6 | 180,261 | 2,007,021 | 9.0 | **Region 6: 3.9%** |
| SD | 7 | 123,229 | 3,165,190 | 3.9 | |
| ND | 7 | 54,445 | 991,390 | 5.5 | |
| KS | 7 | 1,346,807 | 2,494,179 | 54.0 | |
| NB | 7 | 4,505,579 | 7,344,715 | 61.3 | **Region 7: 43.1%** |
| **Cornbelt Average** | | **7,196,428** | **55,725,569** | **12.9** | |

[a] Weighted by harvested acreage of each state in the region.

Typically, 70 percent of irrigation water is incorporated into the crop. The bulk of this water is subsequently lost to the system as a result of ET, soil percolation and crop absorption. The remaining 30 percent returns to surface or groundwater via runoff and groundwater recharge (USGS 2007). Using this proportion, producing one bushel of corn in Region 7 consumes 865 gal 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 19 and 38 gal per bushel, respectively. In all three regions, most of the water used for irrigation is withdrawn from groundwater aquifers. In the U.S., 77 percent of the irrigation water used for corn is from such aquifers; the remaining 23 percent comes from surface water (USDA 2003).

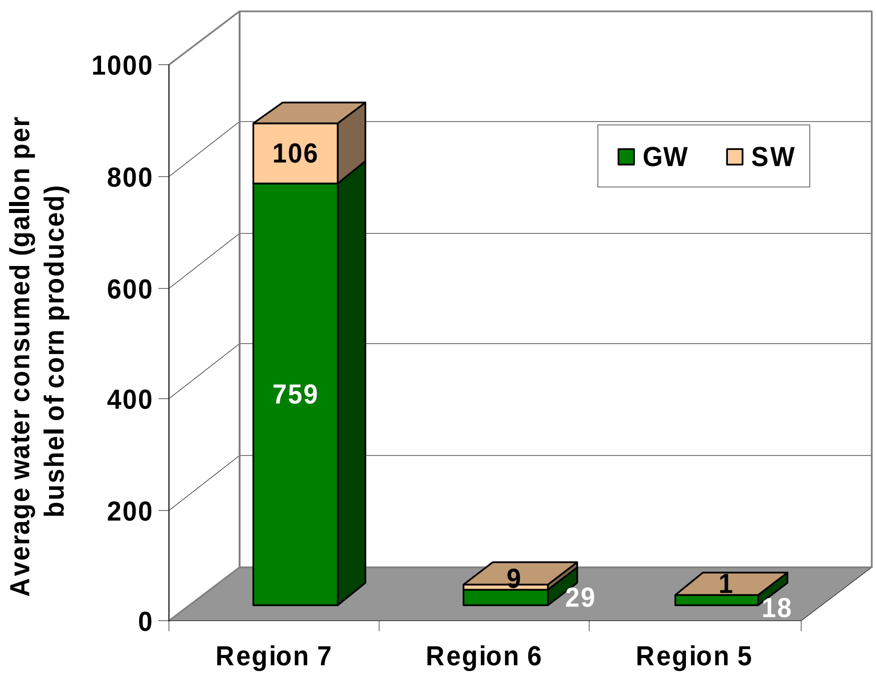



**Figure 10. Net Consumption of Ground and Surface Water for Corn Irrigation (USDA 2003)**

According to the USDA Farm and Ranch Irrigation Surveys, irrigation practices have changed in recent years (USDA 1998 and 2003). As shown in Figure 11, less groundwater was consumed for corn irrigation in 2003 than in 1998 for most regions. However, groundwater irrigation increased 38 percent in Region 7 and 8 percent in Regions 5 and 6 between those years. Expanded corn acreage is the major factor behind this increase — corn ethanol production nearly doubled between 1998 and 2003 (RFA 2007). Some of this increase can also be attributed to changes in precipitation. As shown in Figure 7, while Region 5 received average precipitation in both years, Regions 6 and 7 were dryer in 2003 than in 1998.[12]

Although Region 7 accounts for 55 percent of the groundwater consumed for corn growing in the U.S. (Figure 12), it produces only a fifth of all U.S. corn. Region 5 (Iowa,

[12] Region 7 received 27 inches of rain in 1998 but only 20 inches in 2003.

Illinois, Indiana, Ohio, Missouri) is a near mirror image — it consumes only 3 percent of U.S. groundwater irrigation for corn, but grows 52 percent of the crop. Figure 12 compares shares of corn production and groundwater consumptive use among the three regions in 2003 (USDA 2003; USDA–NASS 2007). Together, the three regions accounted for 60 percent of total U.S. groundwater irrigation and 8.5 percent of total U.S. river water irrigation for corn growing while producing 88 percent of the U.S. corn crop in that year (Figure 13).

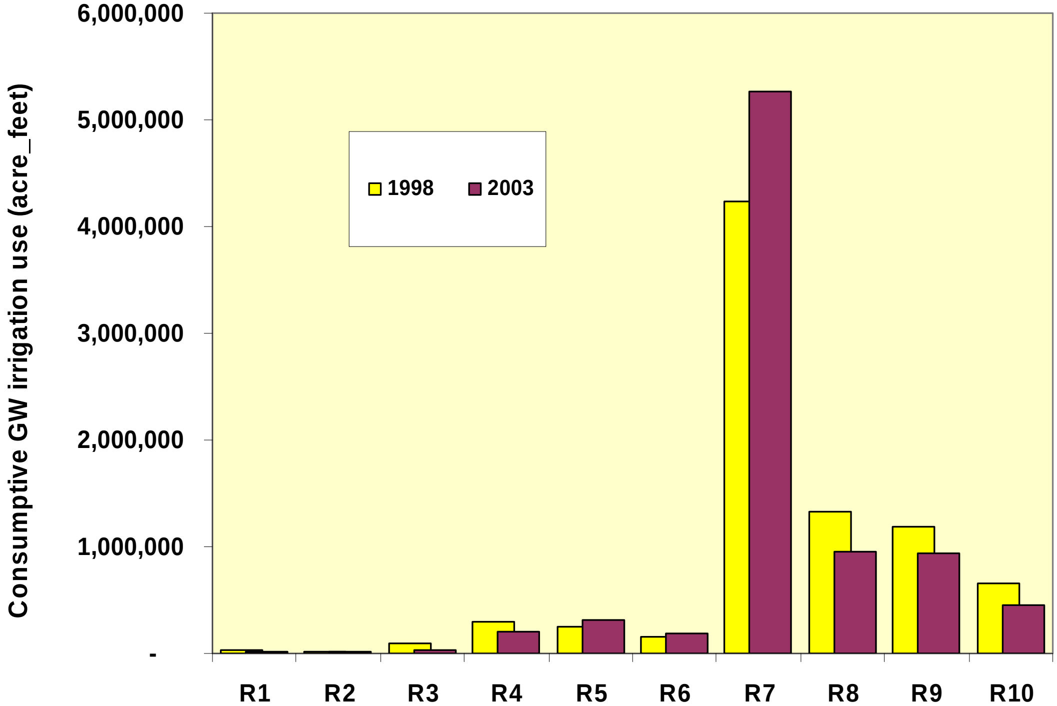



**Figure 11. Groundwater Consumed for Corn Irrigation by USDA Region, 1998 and 2003 (USDA 2003). Multiply acre_ft value by 325760 to obtain gallons.**

### 3.1.2 Corn Ethanol Production

Ethanol production requires water for grinding, liquefaction, fermentation, separation, and drying processes. 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 estimate average water consumption for the existing stock of dry mill plants (in which the corn is dry ground, cooked and fermented). The total water use is then weighted by the ethanol production.

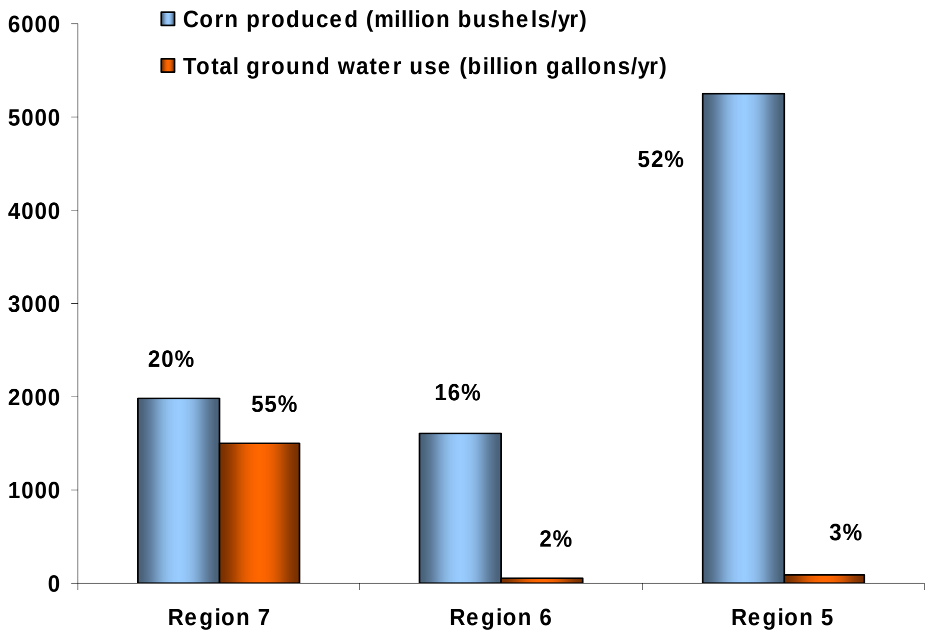



**Figure 12. 2003 Corn Production and Net Groundwater Use, USDA Regions 5, 6 and 7 (USDA–NASS 2007)**

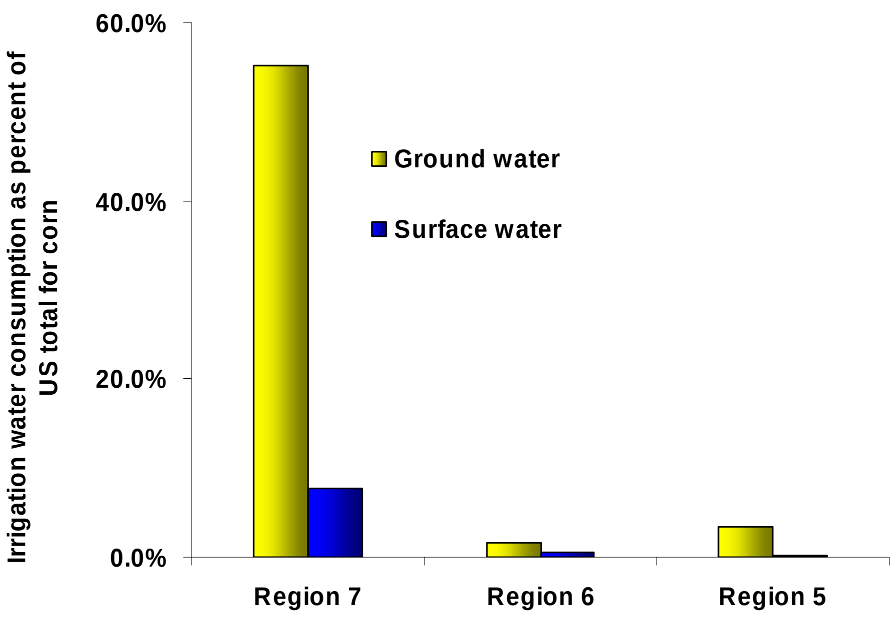



**Figure 13. Water Consumed for Corn Irrigation by Source, USDA Regions 5, 6 and 7 (USDA 2003)**

Figure 14 illustrates the water system of a typical dry mill plant. Following the corn-growing portion of the ethanol lifecycle (discussed in Section 3.1.1 above), corn is harvested and transported to ethanol plants for conversion. Water is consumed 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, dried distillers grains with solubles (DDGS), which may be considered another water loss.[13] 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. 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 5 percent boiler make-up water rate, USDA's corn dry mill model estimates that a fairly new dry mill corn ethanol plant without process optimization consumes approximately 3 gal (25–26 lbs) of water for every gal of ethanol produced (USDA 2007; McAloon 2008). As shown in Figure 15, the cooling tower and dryer account for the majority (53 percent and 42 percent, respectively) of this water.

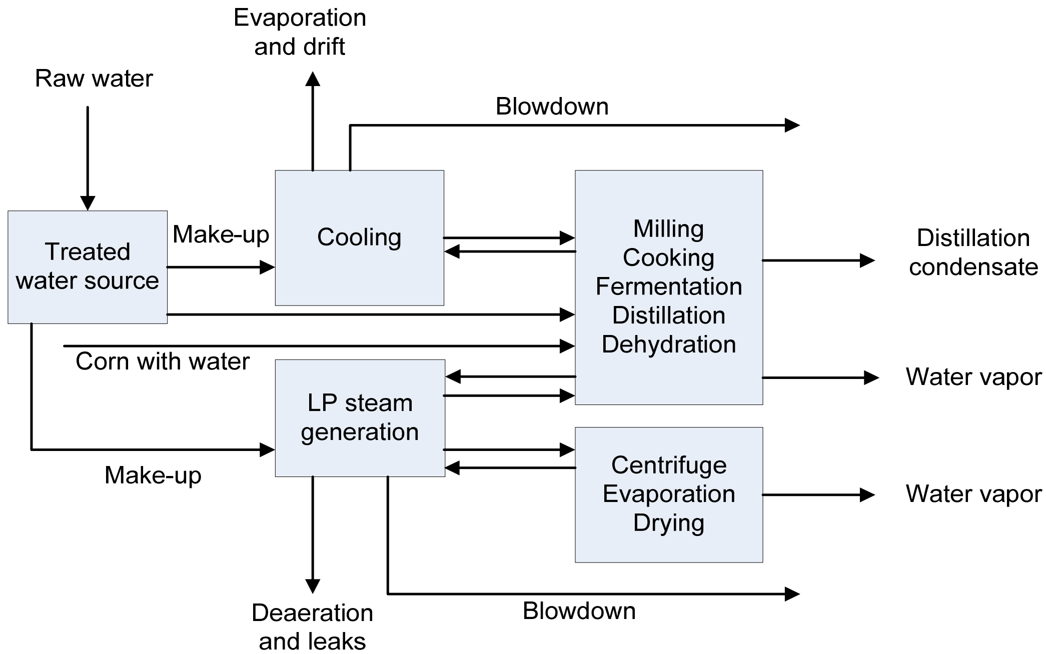



**Figure 14. Water System in a Typical Dry Mill Ethanol Plant**

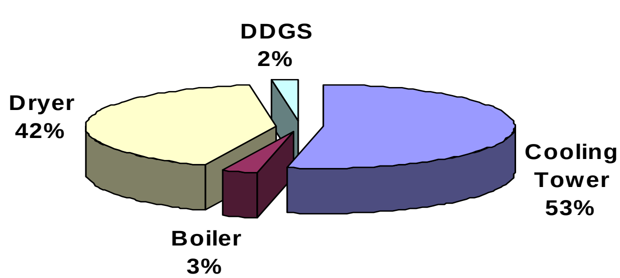



**Figure 15. Breakdown of Water Consumed in Ethanol Production Via Corn Dry Milling (USDA Dry Mill Model)**

[13] All water use in ethanol conversion in allocated to the ethanol product.

This is significantly less than earlier estimates. Shapouri and Gallagher (2005) report that older dry mill ethanol plants use up to 11 gal of water per gal of ethanol, and Phillips et al. (2007) report that in 1998 the average dry mill consumed 5.8 gal of water per gal of corn ethanol produced. The downward trend is also documented in a comprehensive database maintained by the State of Minnesota (Keeney and Muller 2006) which shows a 21 percent reduction in water use by corn ethanol plants from 1998 to 2005, with an annual reduction rate of 3 percent (Figure 16). A similar trend is shown nationally in Figure 17.

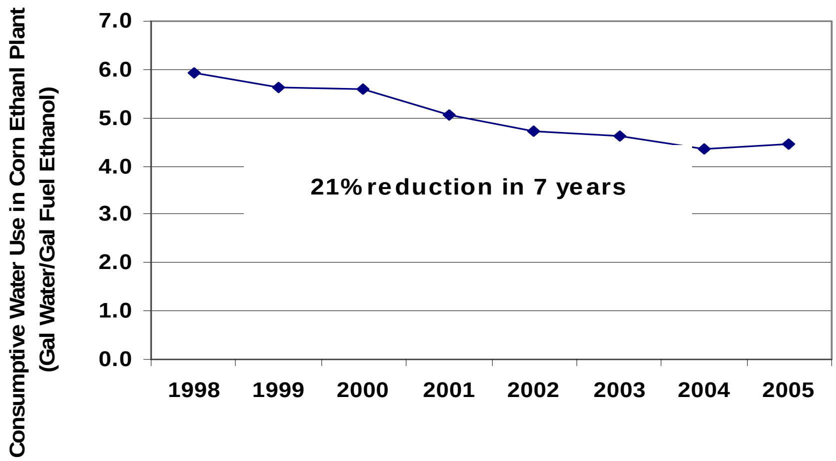



**Figure 16. Consumptive Water Use in Minnesota Dry Mill Corn Ethanol Plants, 1998-2005 (Keeney and Muller 2006)**

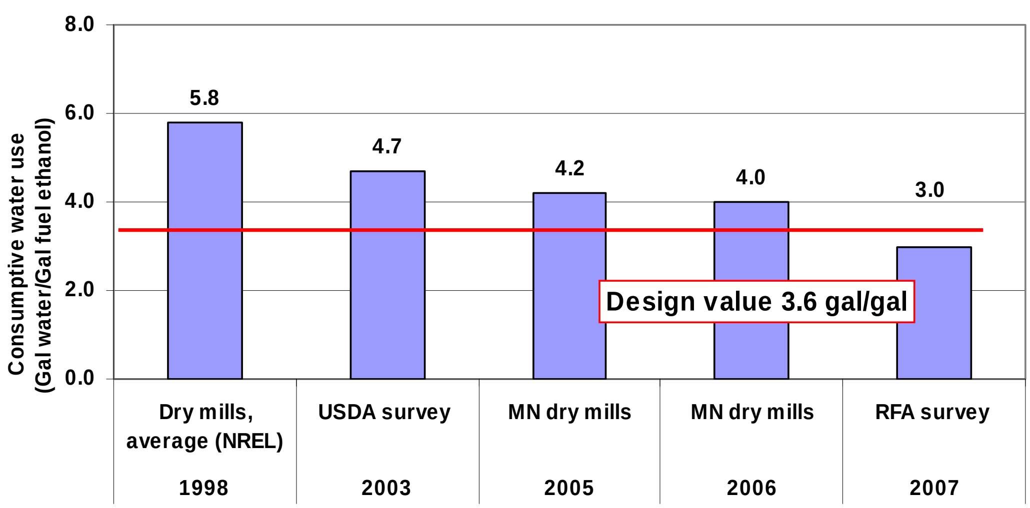



**Figure 17. Average Consumptive Water Use in Existing Corn Dry Mill Ethanol Plants**

With improved equipment and energy efficient design, water use in newly-built ethanol plants appears to be declining further. An analysis of the latest survey conducted by the Renewable Fuels Association (RFA) reveals that freshwater consumption in existing dry mill plants has declined to 3.0 gal per gal of ethanol produced, in a production-weighted average, a significant drop of 48 percent in less than 10 years (Wu 2008). This 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. Water use can be minimized further through process optimization, capturing more of the water vapor from the dryer, further reducing 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 Consumptive Water Use in Major Steps of the Corn Ethanol Lifecycle

Figure 18 graphically shows average water inputs and consumption to produce a bushel of corn in USDA Regions 5, 6 and 7. As noted previously, approximately 70 percent of input water is consumed via ET, soil percolation and absorption. The remaining 30 percent becomes surface run-off and groundwater recharge which may be available for re-use as irrigation water (For additional discussion of groundwater recharge, see Section 5.1).

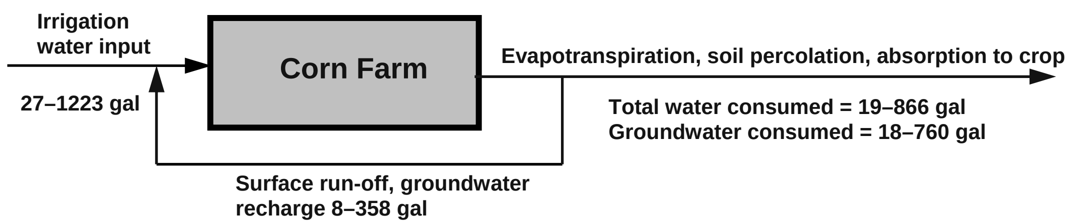



**Figure 18. Water Input and Consumption to Produce One Bushel of Corn in USDA Regions 5, 6 and 7 (USDA 2003; USGS 1995)**

Figure 19 illustrates average water input and consumption to produce a gal 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. Note that all water use is allocated to ethanol production (For additional discussion of co-product allocations, see Section 6.2.2).

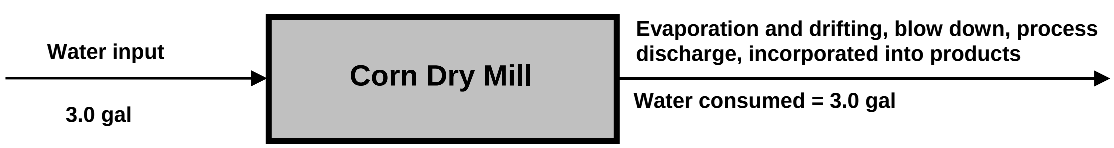



**Figure 19. Water Input and Consumption of an Average Corn Dry Mill Producing One Gal of Fuel Ethanol (RFA 2007)**

Based on average consumption of 3.0 gal of water/gal of corn ethanol produced in a dry mill plant, average irrigation water use for corn farming in USDA Regions 5, 6 and 7 (Figure 8), and dry mill ethanol yields of 2.7 gal per bushel, we estimate total consumptive water use for 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 one gal of corn-based ethanol consumes a net of 10 to 17 gal of freshwater when the corn is grown in Regions 5 and 6, as compared with 324 gal when the corn is grown in Region 7.

**Table 5. Consumptive Groundwater and Surface Water Use from Corn Farming to Ethanol Production in Regions 5, 6 and 7 (gal water/gal denatured ethanol produced)**

| USDA Regions | Region 5 | Region 6 | Region 7 |
|---|---|---|---|
| *Share of U.S. ethanol production capacity (%)*[a] | *52* | *14* | *30* |
| *Share of U.S. corn production (%)* | *52* | *16* | *20* |
| Corn irrigation, groundwater | 6.7 | 10.7 | 281.2 |
| Corn irrigation, surface water | 0.4 | 3.2 | 39.4 |
| Ethanol production[c] | 3.0 | 3.0 | 3.0 |
| Total[b] | 10.0 | 16.8 | 323.6 |

[a] Based on 2006 ethanol production capacity in operation (RFA 2007).
[b] Allocates all water use to ethanol production.
[c] Production weighted average.

As with corn production, U.S. corn ethanol production is concentrated in the same three regions (Regions 5, 6 and 7). Together, these regions account for 95 percent of ethanol production and 88 percent of corn production (RFA 2007). Among the three, Region 7 grows 20 percent of the corn (Figure 12), yet produces 30 percent of the ethanol (Table 5). Accounting for the largest share of corn and ethanol production (52 percent), Region 5 uses the least amount of freshwater.

## 3.2 Cellulosic Ethanol

Cellulosic ethanol can be produced from a variety of sources including perennial grasses, forest wood residues, short-rotation woody crops and agricultural residues. 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

Cultivated cellulosic feedstocks include dedicated energy crops like perennial grasses, forest wood residues, and agricultural crop residues (e.g., corn stover, wheat straw, rice hulls, cotton gin, etc.). Irrigation requirements for these feedstocks depend on the type and origin of the feedstocks, the climate in which they are grown and soil conditions. Switchgrass and other perennial grasses are deep-rooted and efficient in their use of nutrients and water, and thus tend to be relatively drought tolerant. In its native habitat, switchgrass yields of 4.5 to 8 dry tons per acre (Downing et al. 1995; Ocumpaugh et al. 2002; Taliaferro 2002) are possible without irrigation. Although irrigation could increase yield, it may not be sufficient to offset the additional cost (e.g., for water, pumping and energy). If switchgrass were grown in regions where it is not native (e.g., certain parts of the northwestern U.S.) 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

Commercial-scale cellulosic ethanol plants and biorefineries are still at an early stage in development. Ethanol can be produced from switchgrass via several processes:

- Biochemical conversion (BC) using enzyme hydrolysis and fermentation,
- Thermochemical conversion (TC) using gasification and catalytic synthesis,
- Thermochemical conversion using pyrolysis and catalytic synthesis, or
- A hybrid approach combining 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. Gasification consumes relatively little water. The BC process requires more water for additional pretreatment steps to break down the cellulosics. With current technology, producing one gal of cellulosic ethanol via a BC process (such as dilute acid pretreatment followed by enzymatic hydrolysis) consumes 9.8 gal of water (Wallace 2007). With increased ethanol yield, it is estimated that consumptive water use can be reduced to 5.9 gal (Aden 2002). By comparison, an optimized TC gasification process requires only 1.9 gal of water to produce a gal of fuel ethanol (Phillips et al. 2007).[14]

Numerous efforts are underway to reduce water intensity. 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 to increase water recycling and reuse. And, developers are pursuing novel processes, including syngas-to-ethanol using a hybrid approach which combines gasification with syngas fermentation to produce ethanol. The freshwater requirement for this latter process is claimed to be less than one gal for each gal of ethanol produced (Coskata 2008).

[14] Ethanol, methanol, butanol and pentanol from a mixed-alcohol thermochemical process.

### 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-based cellulosic ethanol consumes only the water needed for conversion via BC, TC or hybrid processes. As shown in Table 6, production of a gal of cellulosic ethanol consumes 1.9–9.8 gal of water. Figure 20 displays these data in an input output format.

**Table 6. Water Use for Switchgrass-Based Ethanol Production**

| Process | Average water use (gal/gal) | Reference |
|---|---|---|
| Biochemical | | |
| Current technology | 9.8 | Wallace (2007) |
| Advanced technology | 5.9 | Aden et al. (2002) |
| Thermochemical | 1.9 | Phillips et al. (2007) |
| Hybrid (Syngas fermentation-to-ethanol) | 1.0 | Coskata (2008) |

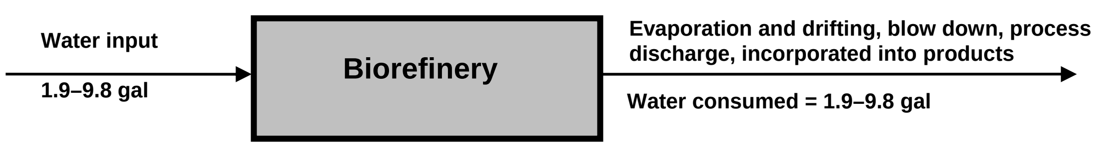



**Figure 20. Water Input and Consumption for a Biorefinery Producing One Gal of Cellulosic Ethanol**

From a lifecycle perspective, switchgrass consumes a minimal amount of water relative to most sources of corn ethanol. As compared to Table 5, cellulosic ethanol produced from switchgrass via a BC process (Table 6) consumes nearly as much water (9.8 gal) as ethanol produced from corn grown in Region 5 (10.0 gal). However, cellulosic ethanol produced from switchgrass via a thermochemical process requires 80 percent less water.

# 4. Gasoline

Petroleum gasoline production can consume substantial quantities of water, especially for crude oil recovery. As a general rule, however, the gasoline lifecycle is less water intensive than the corn ethanol lifecycle. Nonetheless, 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 impact of different types and sources of crude oil on average water use, we examine water consumption in the major lifecycle stages for conventional crude (from domestic onshore wells and a major Saudi Arabian field) and unconventional crude oil sands. Conventional crude, primarily pentanes and heavier hydrocarbons, is a refining feedstock. Oil sands generally must be upgraded via hydrogen addition or coking before becoming a refining feedstock.

## 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 Petroleum Administration for Defense Districts (PADDs), these regions represent 90 percent of U.S. domestic onshore crude oil production and 81 percent of U.S. refinery output (EIA 2007d). Shown in Figure 21, these regions are:

– PADD II (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, Ohio, Kentucky, Tennessee),
– PADD III (Texas, New Mexico, Arkansas, Louisiana, Mississippi, and Alabama),
– PADD V (California, Arizona, Nevada, Oregon, and Washington).


**Figure 21. Petroleum Administration for Defense Districts**

Consumptive water use is estimated for each of these PADDs. In crude oil recovery, consumptive water use is largely injection water that cannot be recycled and reused (Figure 4b). Recovery can be accomplished via several technologies which have different water requirements. Thus, in order to estimate average water use for crude recovery, technology-specific water intensities (i.e., water injection requirements) must be estimated and coupled with market shares to calculate technology-weighted injection water requirements (gal/gal). Then, the amount of produced water (PW)[15] re-injected into the formation must be estimated and subtracted from the total. Figure 22 illustrates the approach. Equations 1 and 2 describe the calculations.

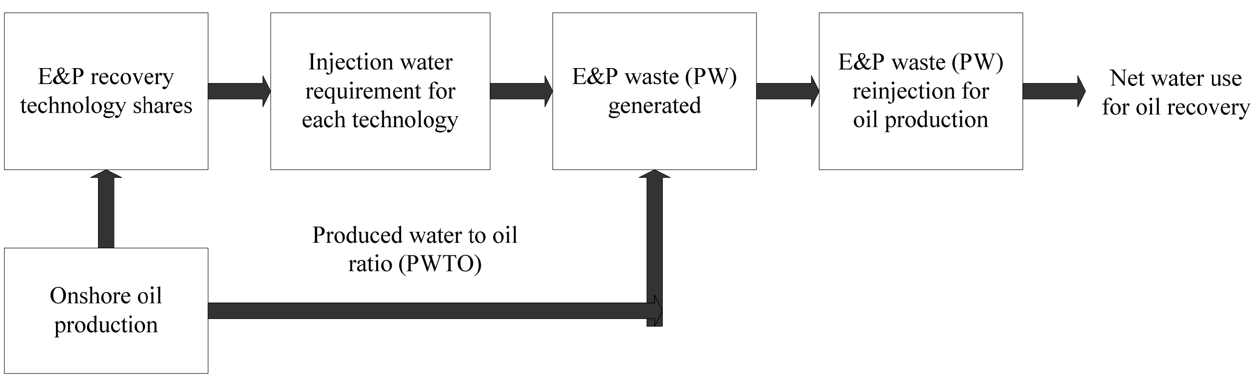



**Figure 22. Calculation Logic of Net Water Use for Crude Oil Recovery**

[15] Also known as E&P waste.

Once the contribution from each technology is estimated, injection water is calculated as a technology-weighted average. Next, the ratio of PW to oil recovery (PWTO) is calculated for each region. Then, the product of produced water (PW) and the share of PW that is re-injected for oil recovery is subtracted from this total. Both PW and the re-injection share are obtained from PADD data. The remainder is net water use for crude oil recovery (see Equation 2).

$$\begin{array}{c} \textbf{Total oil} \\ \textbf{production} \\ \textbf{(gal oil)} \end{array} \times \begin{array}{c} \textbf{Technology} \\ \textbf{share (\%)} \\ \text{Tech. 1} \\ \text{Tech. 2} \\ \text{Tech. 3} \\ \ldots\ldots \\ \text{Tech. n} \end{array} \times \begin{array}{c} \textbf{Injection water} \\ \textbf{required (gal/gal oil)} \\ \text{Tech. 1} \\ \text{Tech. 2} \\ \text{Tech. 3} \\ \ldots\ldots \\ \text{Tech. n} \end{array} \Longrightarrow \begin{array}{c} \textbf{Technology weighted} \\ \textbf{injection water} \\ \textbf{requirement} \\ \textbf{(gal/gal)} \end{array} \quad \ldots \text{[Equation 1]}$$

$$\begin{array}{c} \textbf{Technology weighted} \\ \textbf{injection water} \\ \textbf{requirement} \\ \textbf{(gal/gal oil)} \end{array} - \begin{array}{c} \textbf{Produced} \\ \textbf{water} \\ \textbf{generated} \\ \textbf{(gal/gal oil)} \end{array} \times \begin{array}{c} \textbf{\% of produced water} \\ \textbf{re-injected for oil} \\ \textbf{production} \end{array} = \begin{array}{c} \textbf{Net water use} \\ \textbf{for oil E\&P} \\ \textbf{(gal/gal oil)} \end{array} \quad \ldots \text{[Equation 2]}$$

### 4.1.2 Imported Conventional Crude Oil

As was shown in Table 1, the U.S. imports over two-thirds of its crude oil supply. Excluding Canada, from which unconventional sources represent an increasing share of imports, Saudi Arabia accounts for the largest share. Saudi fields tend to be younger. Since publically available national data for Saudi Arabia is very limited, for this analysis, data on a typical Saudi field are used to represent the average water intensity of Saudi crude oil imported to the U.S.

### 4.1.3 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 intensity 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 stated above, net water use for oil production is determined for each region, as well as for the total U.S. Because regional technology shares are not readily available, regional water usage is estimated using national technology shares (i.e., assuming similar market shares for each region of interest) and intensity, but with regional PW generation and re-injection estimates.

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

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 produced water (PW), saline groundwater and freshwater are also used. 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 23 shows the 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. However, not until the tertiary recovery phase did produced water exceed injection water. Among tertiary recovery technologies, $CO_2$ injection has attracted growing interest since it has the added benefit of $CO_2$ sequestration.

Onshore wells currently account for 67 percent of domestic oil production, the bulk of that via secondary recovery (Table 7). Although the consensus is that most offshore wells use primary recovery, no technology-specific data are publicly available on offshore recovery technologies. For this analysis we assume all offshore production is via primary recovery.

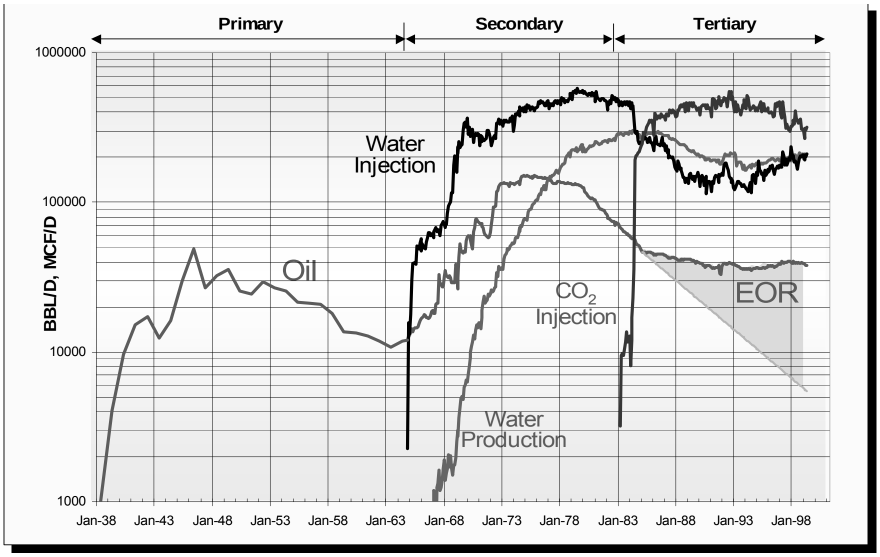



**Figure 23. Water Injection, Oil and Water Production in Primary, Secondary and Tertiary Recovery, Shell Denver City Project (Barry 2007. Used with permission)**

Figure 24 shows the resulting distributions of onshore, offshore and total domestic oil production by recovery technology. Half of total production is estimated to come from secondary water flooding, 13 percent from EOR and 38 percent from primary recovery (although less than 5 percent of onshore production uses primary recovery).

**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) | Onshore recovery technology share (%) |
|---|---|---|---|---|
| Primary | 1940 | 37[d] | 228[e] | 6.6 |
| Secondary (water flooding) | 2589 | 50[b] | 2589 | 74.7 |
| Tertiary (EOR) | 649[c] | 13 | 649 | 18.7 |
| Total | 5178 | 100 | 3466 | 100.0 |

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

Figure 25 provides a breakdown of onshore U.S. oil 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 percent of total EOR (O&GJ 2006).

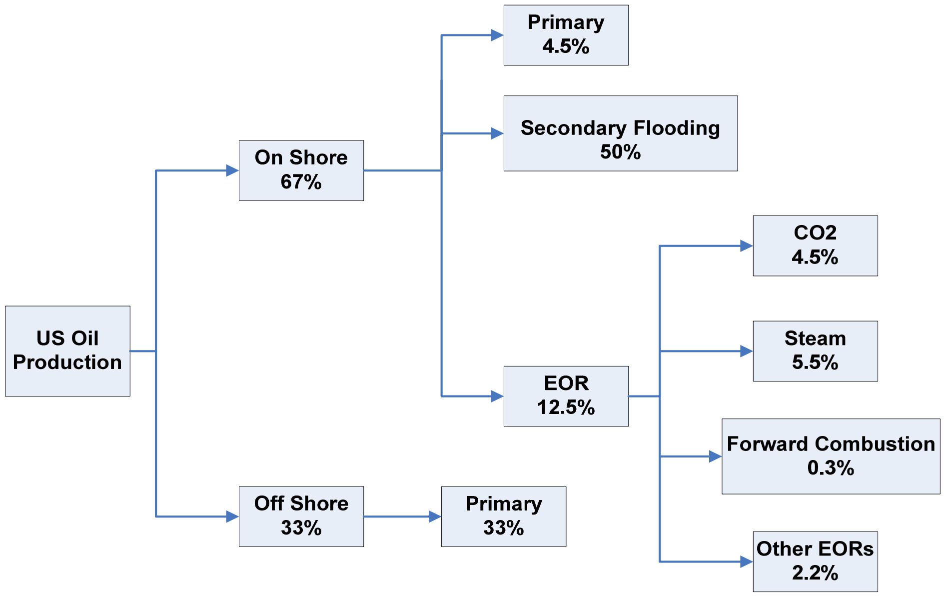



**Figure 24. Technology Shares for Onshore and Offshore U.S. Crude Oil Recovery (EIA 2007b; O&GJ 2006)**

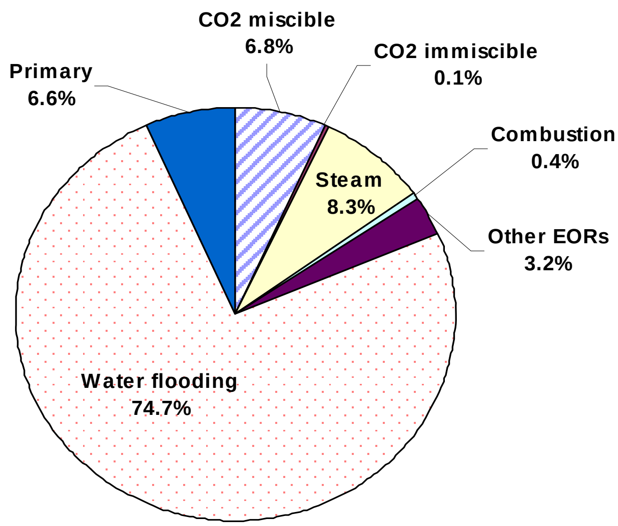



**Figure 25. Onshore US Crude Oil Recovery by Technology (EIA 2007b; O&GJ 2006)**

Injection water requirements vary with recovery technology. Primary recovery requires an average of only 0.21gal of freshwater/gal 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, the formation in which it is located and the region. Based on their analysis of the history of 80 U.S. secondary wells, Bush and Helander (1968) show that over their water-flooding lifetime, an average of 8.6 gal of water is injected to recover a gal 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 gal per gal 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 reported water use of 13 gal of injection water per gal of crude oil recovered (Royce 1984). In the early 1990s, Gleick reported 24.7 gal/gal recovered (Gleick 1994). 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 23, above). 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 gal per gal 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.

**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 underway (O&GJ 2006).

Based on the share of production (Table 7) and water intensity (i.e., the amount of water injected per unit of oil produced) of each recovery technology (Table 8), total injection water use for domestic onshore production is estimated according to Equation 1 above.

As of 2005, domestic onshore recovery operations required 1,171 million gal of injection water to produce 146 million gal of conventional crude oil (Table 9). Technology-weighted average water injection was 8.0 gal of water/gal of crude. This estimate does not include treated PW injected for oil recovery, which are discussed in Section 4.2.2. Secondary water flooding is responsible for 79.7 percent of injection water use in U.S. onshore oil production (Figure 26). Although micellar-polymer-based recovery currently consumes relatively large amounts of water, there are no active projects employing this technology in the United States (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 the technology, there are significant variations in injection water required for oil recovery from region to region. For example, Texas Oil and Gas District 8 and 8A at West Texas injected 12.7-14.7 gal of water to recover a gal 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**

| | **Oil Production** | | **Water Injection** | | |
|---|---|---|---|---|---|
| **Recovery Technology** | **(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] 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.

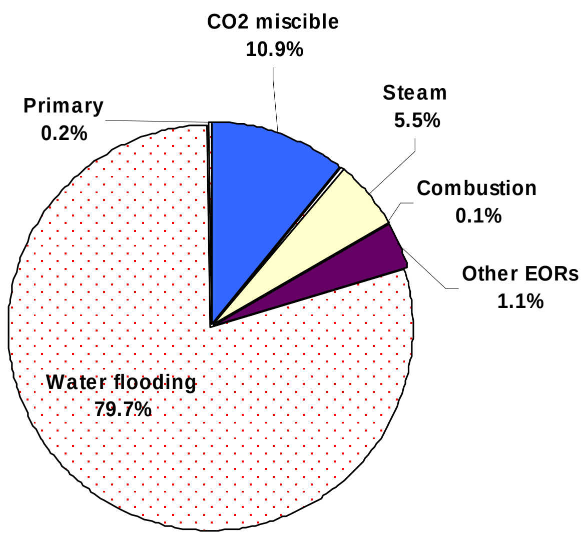



**Figure 26. Injection Water Use by Crude Oil Recovery Technology, U.S. Onshore**

### 4.2.2 Produced Water Re-Injection for Oil Recovery

Whether occurring naturally in the formation itself or due to water injection, produced water (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 of 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 to a separate injection well, 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.[16] 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 bbl of produced water were generated at U.S. onshore operations (API 2000). Worldwide, 77 billion bbl of water were produced from oil wells in 1999 (Khatib and Verbeek 2003). As shown in Figure 23, the amount of produced water generally increases over the life of secondary recovery in a conventional oil well. In terms of output, the ratio of produced water-to-oil (PWTO) increased by 1.2 bbl/bbl from 1985 to 1995 for the entire country (API 2000). Since then, an independent estimate by Veil et al. (2004) suggests that the ratio increased an additional 2.0 bbl/bbl 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, 1985, 1995 and 2002**

| | **Produced Water (1000 bbl)[a]** | **Oil Production (1000 bbl)[b]** | **PWTO Ratio** |
|---|---|---|---|
| 1985 | 20,608,505 | 3,274,553 | 6.3 |
| 1995 | 17,922,200 | 2,394,268 | 7.5 |
| 2002 | *Not available* | *Not available* | 9.5[c] |

[a] API 2000.
[b] EIA 2008a.
[c] Veil 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 study, 71 percent of the produced water from oilfield operations in the United States is re-injected into the

[16] For the vast majority of U.S. onshore locations, PW must be lifted, handled and pumped to acceptable disposal sites.

reservoir. As shown in Figure 27, only about a quarter of PW is discharged or injected to subsurface disposal wells.

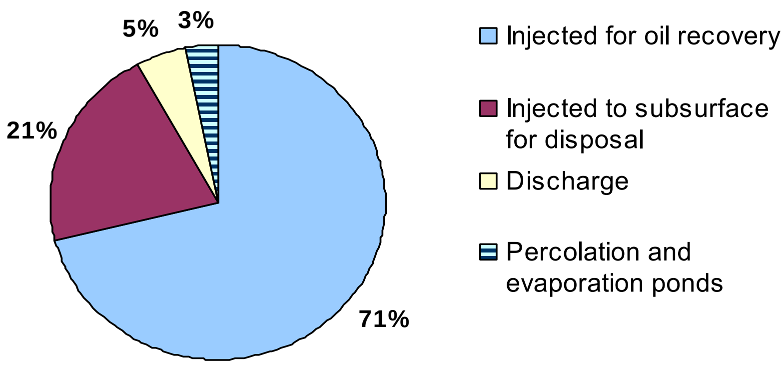



**Figure 27. Fate of Produced Water from U.S. Oil Recovery (API 2000)**

Our estimate of the technology-weighted average quantity of injection water required for domestic onshore production (8.0 gal per gal of crude) was presented (Table 9) and discussed in Section 4.2.1 above. That estimate reflects the calculation logic laid out in Figure 22 and Equation 1 above. Assuming a national average PWTO ratio of 9.5 gal of PW per gal of crude and that 71 percent of PW is re-injected for oil recovery, national net water consumption is estimated to be 1.3 gal/gal of crude from U.S. onshore operations.

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), PWTO is about 1.0-1.2 gal of PW per gal of crude in the Texas Oil and Gas Districts 8 and 8a, as compared to the average ratio in PADDIII, 10.9. This low ratio reflects local hydrology. As discussed in Section 4.2.1., the low PW yield could not meet the injection water demand of 12.7-14.7 gal per gal of oil in these two districts. In fact, fresh water as well as large amount of saline/brackish water from underground aquifer was used for oil recovery.

Indeed, for individual wells that employ diligent water management, less water-demanding recovery technologies, and while water quality allow, it is conceivable that 100 percent of PW can be re-injected for oil recovery and net water consumption could approach zero (Figure 23). The constraint to increased PW recycling and reuse is the associated cost for lifting and water treatment as compared with employing other competing technologies. For example, in newly developed down-hole separation technology, oil and water are separated below the surface, potentially reducing produced water volume by as much as 97 percent (API 2007) and cutting water management costs. If this technology were widely adopted, less PW could be available for re-injection. On the other hand, less injection water may be needed because down-hole separation keeps PW in the formation therefore maintains oil reservoir pressure. This tradeoff is an open question in oil field water management. It is entirely possible that one technology will be preferable for one application but not for another. The choice will depend on local and regional conditions.

### 4.2.3 Regional Water Use

Like biofuel feedstock production, crude oil production depends on local and regional water availability. Three PADD regions (PADDs II, III and V) account for the bulk of total and onshore crude production in the U.S. As shown in Table 11, PADD III accounts for more than 43 percent of domestic onshore oil production, while PADD V accounts for one-third. Well productivity varies considerably among the three regions. Although PADDs 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 with less than a tenth of the wells.

**Table 11. U.S. Oil Production and Producing Wells by PADD Region, 2005**

| PADD Region | Total Production[b] (000 bbl/d) | Onshore Production (000 bbl/d)[b] | Percent of U.S. Onshore Production | Number of Production Wells[a] | 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] World Oil 2007.
[b] EIA 2008a.

Table 12 presents regional PWTO ratios for 1995 and 2002. Clearly, the range of PWTO widens over the years (from 3.3–11.3 in 1995 to 3.4–14.7 in 2002) and Region 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 12. PWTO Ratios[a] by PADD Region**

| PADD Region | PWTO in 1995[b] | PWTO in 2002[c] |
|---|---|---|
| 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] PWTO = gal of produced water per gal of crude oil.
[b] API 2000.
[c] 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 percent) followed by PADDs IV and V; PADDs II and III re-inject about half of the PW generated. Using equations 1 and 2 above, net water needed for injection in the three regions (PADDs II, III and V) is calculated in Table 13. Because regional data on production by recovery technology are not available, national estimates (see Table 9) are used.

**Table 13. Net Injection Water Use for Onshore Domestic Crude Production**

| PADD Region | Technology-Weighted Average Injection Water Use (gal/gal)[a] | Produced Water-to-Oil Ratio[b] | 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 | *none* |
| 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 | *none* |
| 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.

As discussed in Section 4.2.1, injection water use for various recovery technologies (see Table 9) was used to derive a national technology-weighted estimate of injection water per unit of oil produced. This estimate served as the starting point for deriving regional estimates. State estimates of PW and crude produced (Veil et al. 2004) were summed to yield regional estimates and PWTO averages. Subtracting PW re-injection by PADD region yielded regional net water use as shown in Table 13.

A net of 2.1–5.4 gal of water is required to produce one gal of crude oil in PADDs II, III and V. According to TX Railroad Commission, the net freshwater injection for oil recovery in TX Oil and Gas District 8 and 8a is about 2 gal per gal 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. As shown in Table 13, PWTO and the degree of produced water re-injection for oil recovery also have significant effects on net water use. 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 for injection is critical to reducing net water use. For example, if PW re-injection in PADD V were to increase from current levels (76 percent) to 99 percent, it could cut water use to 4.7 gal/gal; a similar change in PW re-injection in PADDs II and III (from 52% and 53% currently to 80 percent) could result in net zero water usage. Although PADD I and PADD IV have net zero water use per unit of oil recovered, their oil production shares are small (~10 percent, Table 11). In contrast, PADDs II, III and V together account for 90 percent of onshore crude oil production (Figure 28). Reducing net water use in these regions could have a much greater national impact.

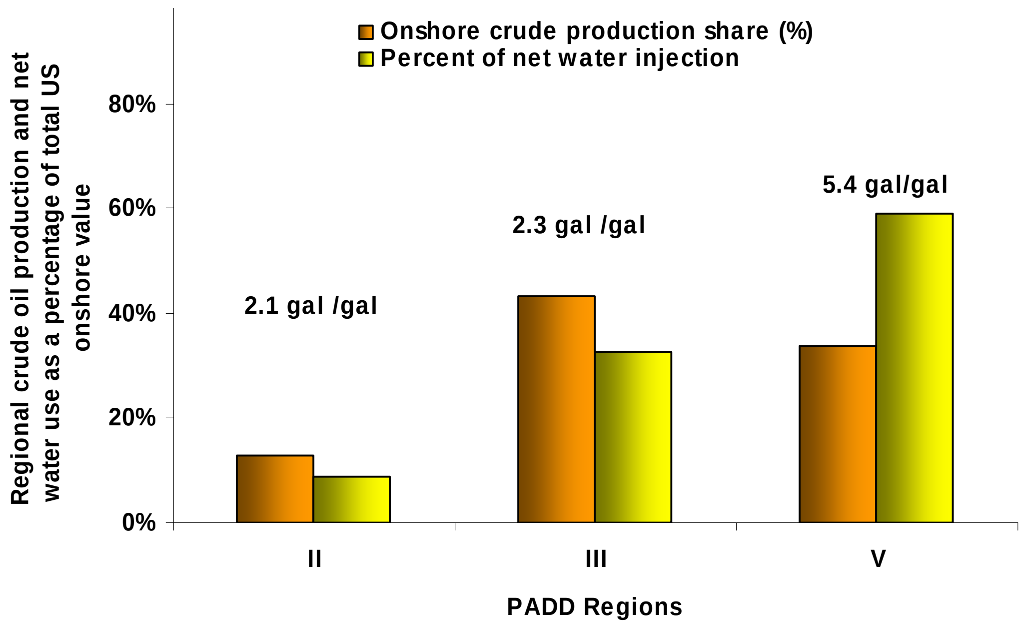



**Figure 28. Onshore Oil Production and Water Use for Major U.S. Oil-Producing Regions**

### 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 and do not require large quantities of injection water to maintain pressure. Nevertheless, scarce rainfall and a lack of surface water make water supply a serious problem. Oil production consumes the Saudi's most valuable water resource — groundwater contained in seven major aquifers and for which little recharge occurs.

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. 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 percent reduction). During the six-year period from 1999 to 2004, oil and water production, water injection 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), roughly 7 million bbl/d of treated seawater was injected to produce 5 million bbl/d of crude (or 1.4 gal water/gal oil) currently (Durham 2005). Today, the PWTO ratio is about 0.39 (SUSRIS 2004) for Saudi operation, as compared with average of 9.5 for U.S. onshore production. It is reported that this 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). Although data on reuse and recycling of produced water are not available, as a general rule little produced water from Saudi oil production is available for re-injection.

For this study, we use a range of net water use assumptions, from 1.4 gal/gal (Durham 2005) to 4.6 gal/gal, 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 U.S. imported 1.6 million bbl/d of Canadian crude oil (10.5 percent of its supply) in 2005. Much of that crude was produced from oil sands. In 2004, the Energy Information Administration (EIA) and the O&GJ formally recognized Canadian oil sands as proven oil reserves, moving Canada from 21$^{st}$ to 2$^{nd}$ place among oil-rich nations (Figure 29).


**Figure 29 Oil Reserves by Country as of December 2004 (O&GJ 2004)**

Of Canada’s 179 billion bbl of proven reserves, 175 are contained in oil sands (O&GJ 2004). 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 percent of Canadian crude oil production) in 2006 (Table 14). This growth has been spurred by increased demand for transportation fuels, particularly in the U.S., 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.[17] 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 2008). 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.

**Table 14. Canadian Crude Oil Production by Source, 2005 and 2006 (CAPP 2008a; CAPP 2008b)**

| Source, Year and 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 | |

Oil sands are composed of sand, silt and clay, water, and about 10–12 percent crude bitumen, a thick, tar-like substance containing high levels of sulfur and nitrogen compounds (Alberta Energy 2004). As compared with petroleum, producing gasoline from oil sands typically requires an additional processing step following extraction. In this step, oil sands are upgraded into synthetic crude oil which is then refined into products like gasoline and diesel oil. Upgrading may occur in integrated, onsite operations as part of surface mining, or offsite, if pipelines are available to transport the bitumen and a diluent is added to improve its viscosity.

[17] 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 typically recovered by open-pit or surface mining of relatively shallow deposits,[18] or by thermal in situ techniques for deeper deposits. Surface mining accounted for 59 percent of Canadian oil sands-based crude oil production in 2006 (up from 56 percent in 2005) while in situ extraction accounted for 41 percent. In situ operations are expected to dominate future oil sands recovery operations.

<u>Surface Mining</u>

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 (commonly called the Athabasca deposit), includes all of Canada's surface-minable reserves as well as 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 percent of Canada's remaining oil sands reserves are amenable to surface mining (CAPP 2008c) which recovers about 90 percent of the oil in the deposit (NEB 2004). Figure 30 provides a general overview of surface or open-pit mining processes. Land disruption 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), a paste-like substance remaining after long-term settling in the tailing pond.

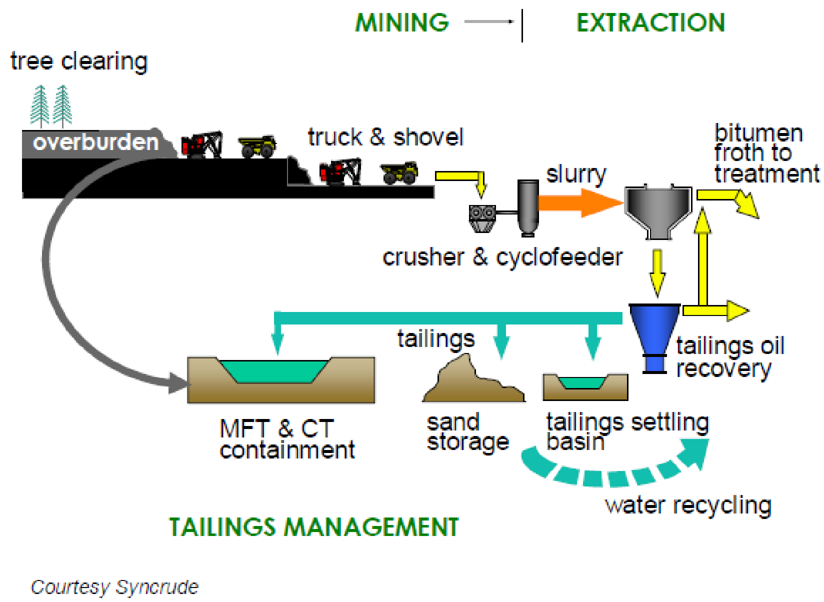



**Figure 30. Major Steps in Oil Sands Recovery by Surface Mining (Flint 2005)**

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

Figure 31, a generic diagram of oil sands mining and upgrading operations, provides additional detail on the material flows (Masliyah et al. 2004). As shown in the figure, feed ore (consisting of solids, bitumen, salts and rock) is transported to an extraction plant where it is separated into recovered bitumen, bitumen froth (60 percent bitumen, 30 percent water and 10 percent fine solids) and tailings. A solvent-diluted treatment process extracts the bitumen, recovers solvents, and rejects residual water and solids from the froth (Flint 2005). Tailings from extraction and froth treatment are sent to solid storage and tailings ponds for dewatering (which in time provides additional recycled process water) and for settling of fine solids.

There are two major options for reducing water use in extraction and upgrading from surface mining. If naphtha (produced from upgrading) is used for froth treatment, over 98 percent of the bitumen can be recovered, but residual water and solids pass into the bitumen stream creating downstream problems in upgrading operations, and increasing water use and intensity. If a paraffinic solvent is used for froth treatment, residual water and solids can be reduced, thereby averting these problems, but hydrocarbon yield tends to decline (Flint 2005).

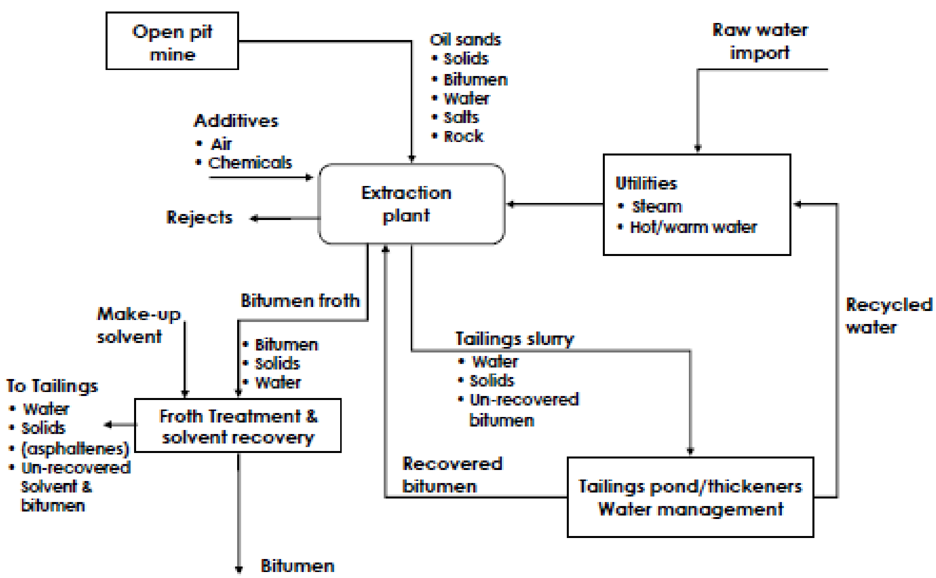



**Figure 31. Process Steps in Surface Mining of Oil Sands (Flint 2006, adapted from Masliyah et al. 2004)**

In Situ Recovery

Approximately 82 percent of Canada's oil sands reserves are only recoverable via processes that extract the bitumen without removing the rock matrix from its bed (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, pumping it to the surface, and (if necessary) mixing it with a diluent so that it is fluid enough to flow through a pipeline. The two 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 32, CSS involves cycling or intermittent injection of high pressure steam into the reservoir at single injector/producer wells. During a soak phase, between injection and production, additional steam may be injected. Although CSS is a mature technology that was originally limited to vertical wells, combinations of vertical and horizontal wells are now used (Flint 2005).

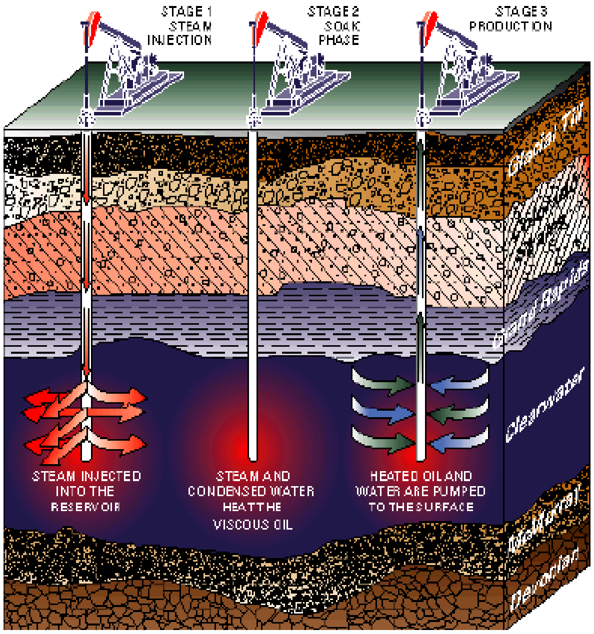



**Figure 32. Cyclic Steam Stimulation (CSS) Is a Staged Technique Using Vertical Injection and Production Wells (Flint 2005)**

Figure 33 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 — pairs of horizontal wells up to 1,000 meters long are drilled horizontally into the reservoir — and continued advances in that technology are likely to extend its applicability and reduce its cost.

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 less costly 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 percent of the bitumen in the ore, in situ methods have somewhat lower recovery rates. SAGD reportedly can recover 60–80 percent of the bitumen in the reservoir (Woynillowicz et al. 2005), while CSS can recover approximately 20-35 percent with typical steam/oil ratios of 3 to 4 (Flint 2005).

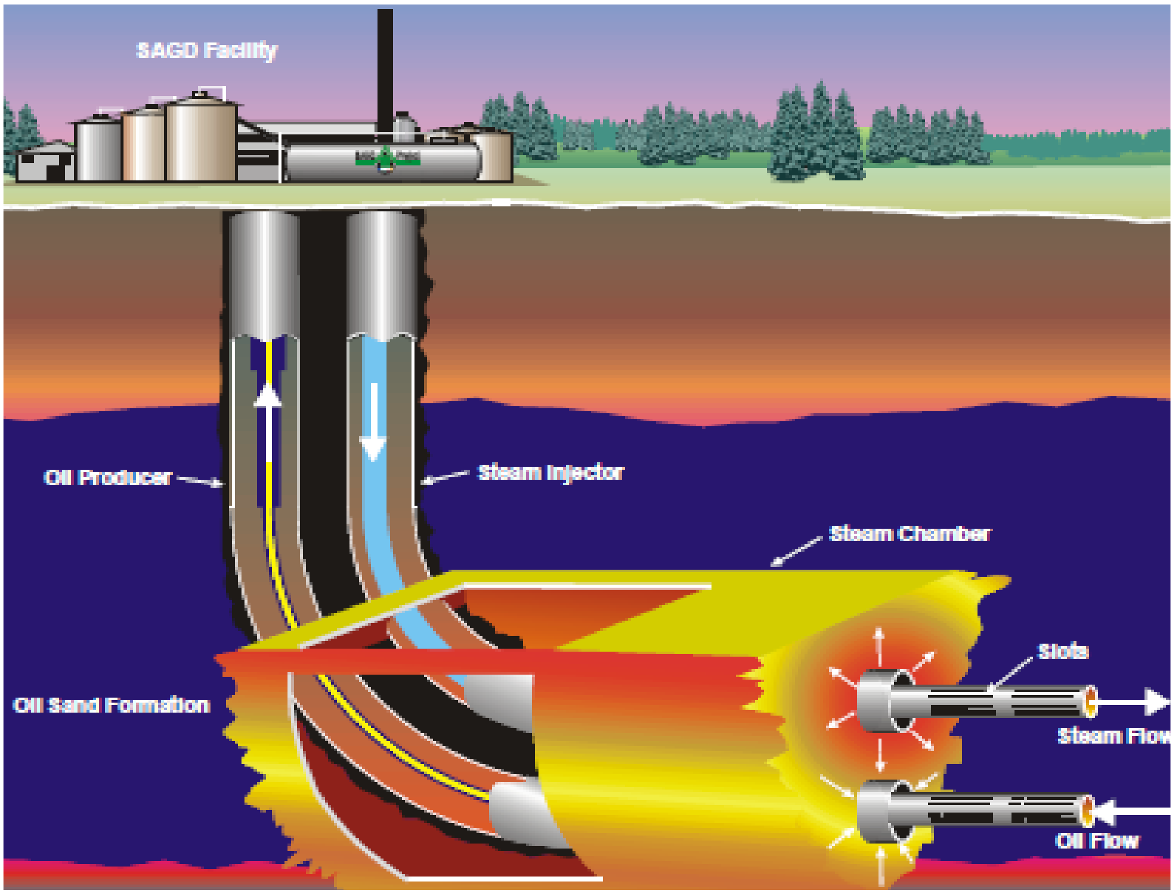



**Figure 33. Steam-Assisted Gravity Drainage (SAGD) Uses Pairs of Injection and Production Wells (Flint 2005)**

<u>Technology Shares</u>

Isaacs (2007) estimates that 16.3 percent of in situ production is via SAGD (Athabasca), 19.0 percent via CCS (Cold Lake), and 1 percent via multi-scheme techniques (Peace River), and that synthetic crude oil recovered via in situ processes accounts for 36.3 percent of Canadian crude oil production. By contrast, CAPP (2008b) data indicate that in situ recovery accounted for 44.4 percent of production in 2005 (Table 14). Using CAPP's share for in situ recovery and Isaacs' shares for recovery technologies, we estimate technology-specific shares for in situ production in 2005 (Table 15).

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

| Location and Recovery Method | Bitumen Recovery Technology | Share of Oil Sands Crude Production (%) | Net water use[d] (gal/gal oil sands) | |
|---|---|---|---|---|
| | | | Recovery | Upgrading |
| Athabasca – Mining | Shovel and truck | 55.6[b] | 4.0[a] | – |
| Athabasca – In Situ | SAGD[e] | 22.0[c] | 0.3 | 1.0 |
| Cold Lake – In Situ | CSS[e] | 21.2[c] | 1.2 | 1.0 |
| Peace River – In Situ | Multi-scheme | 1.2[c] | 4.0 | 1.0 |

[a] Including water recycle and bitumen upgrade.
[b] CAPP 2008b, Table 14.
[c] Isaacs 2007.
[d] Surface mining net water use: Isaacs 2007; Peachey 2005; Heidrick and Godin 2006. SAGD, CSS and multi-scheme net water use: Gatens 2007.
[e] SAGD = steam-assisted gravity drainage; CSS = cyclic steam stimulation.

As with conventional oil, oil sands recovery technology has a major effect on water consumption (Table 15). Surface mining and multi-scheme techniques[19] 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 project — is particularly problematic since the water used in the extraction plant (Figure 30) is withdrawn 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, the oil sands industry used an average of 4.8 gal of freshwater to produce a gal of oil (before upgrading) in1994 when operations were concentrated in Fort McMurray and recovery was via surface mining. By 2005, that average had dropped to 4 gal/gal including upgrading and water recycle and reuse (Peachey 2005). More recently, Heidrick and Godin (2006) as well as Isaacs (2007) report that water intensity in Alberta is 2.18 gal/gal including upgrading. For our estimate, we use Peachey's industry average (4.0 gal/gal) which is shown in Table 15.

Table 15 also provides water intensity (net water use) by recovery technology. Although both SAGD and CSS are steam intensive, their net water use is relatively low since over 80 percent 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 at several oil sands surface mining projects. Cold water flooding is comparable to conventional water flooding in secondary oil recovery. This technique reduces the high energy cost associated with oil sands mining, but might increase freshwater consumption unless alternative sources such as saline water is used (Griffiths et al. 2006).

### 4.4.2 Oil Sands Upgrading

Today, most surface-mined oil sands are upgraded to synthetic or "refining-ready" crude oil in Northern Alberta, as part of integrated operations that also separate bitumen from

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

the feedstock ore. Since the thick crude oil is deficient in hydrogen, upgrading requires hydrogenation (typically obtained by reforming natural gas, although some projects gasify coal, coke or asphaltene, a by-product of the upgrading process) or coking to convert it to an acceptable refining feedstock.

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 is already migrating toward Edmonton. In 2003, Shell added an upgrader to its refinery at Scotford, just northeast of Edmonton. Eight other upgraders (including an expansion to Scotford) with a combined capacity to upgrade almost two million b/d into synthetic crude oil are now in various stages of planning or construction. Known as “Upgrader Alley”, this area may contain over 40 percent of Alberta’s upgrading capacity within the next decade (Griffiths and Dyer 2008).

Unlike surface-mined oil sands upgraded to synthetic crude oil, bitumen recovered via in situ processes historically has been transported by pipeline to refineries, mostly in the U.S. (CAPP 2008c). As shown in Table 15, upgrading requires less than 1 gal of water/gal of crude (Peachey 2005).

## 4.5 Refining

Figure 34 illustrates the water system of a typical North American oil refinery. Most water use is for steam production, cooling, and process needs. According to $CH_2$MHill (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 percent of refinery water consumption (Figure 35).

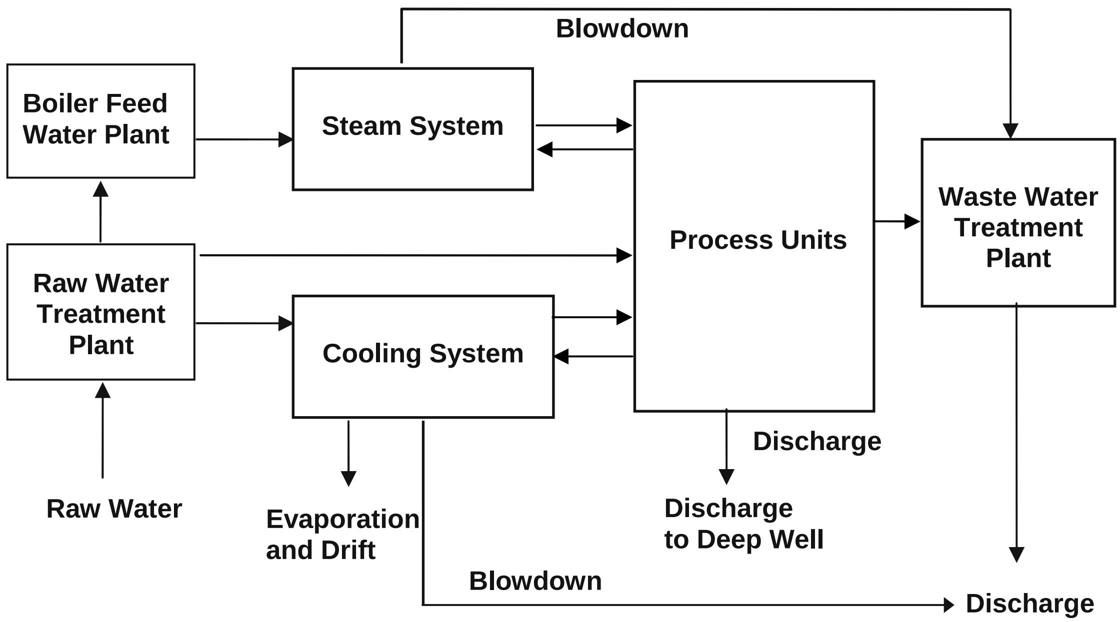
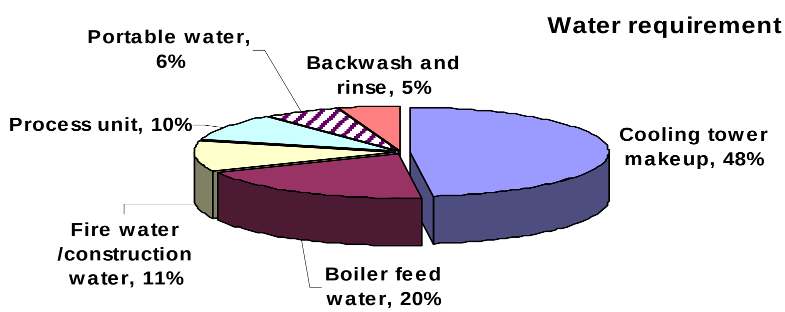



**Figure 34. Water System in a Typical North American Refinery (adapted from CH2MHill 2003)**



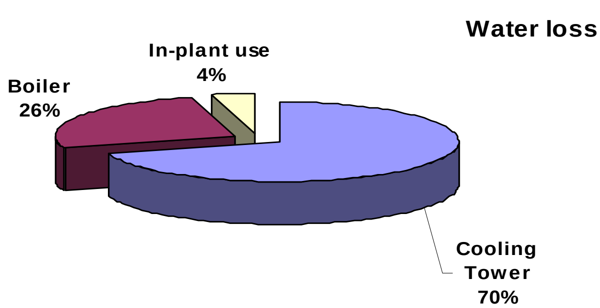




**Figure 35. Water Requirements and Losses in a Typical Refinery ($CH_2$MHill 2003)**

Water scarcity is a perennial issue in certain U.S. regions, such as notoriously drought-prone West Texas and the West Coast, where water management is already a fact of life. Worldwide, in response to growing demand for oil products, refining capacity is expanding. Globally, water reuse in oil refining is expected to rise 350 percent from 2004 to 2015 (Buchan and Arena 2006). 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 percent of global refining capacity may be in water-scarce regions (NAS 2005; Buchan and Arena 2006).

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 percent of steam condensate is recovered in well-maintained and newer refineries around the world, as compared with only 30 percent recovery in older refineries (Seneviratne 2007). Wastewater recycling and reuse is also becoming increasingly common. At Chevron's El Segundo refinery, nearly 80 percent 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 (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.

Based on estimates from 1994 to 2006 (Gleick 1994; Ellis et al. 1998; Buchan and Arena 2006), processing a gal of crude oil in U.S. refineries consumes 0.5 to 2.5 gal of water (Figure 36). On average, 1.53 gal of water is consumed for each gal of crude. Because of yield gain during crude processing (i.e., 42 gal of crude generate 44.6 gal of refined product), consumptive water use can also be expressed as 1.4 gal of water per gal of refined product.

The synthetic crude oil produced from oil sands upgrading 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 gal of water per gal of synthetic crude oil (after upgrading).

## 4.6 Consumptive Water Use in Major Steps of the Gasoline Lifecycle

### 4.6.1 Conventional Petroleum to Gasoline Lifecycle

As indicated above, 90 percent of U.S. onshore oil production consumes from 2.1 to 5.4 gal of water for each gal of crude oil recovered (Tables 13). Together with an average of 1.5 gal/gal consumed for refining, a total of 3.6–7.0 gal of water is required to produce/process a gal of crude oil in the three major PADD regions (PADDs II, III and V). Similarly, for Saudi Arabian crude, 2.9–6.2 gal of water are consumed for each gal of crude oil produced. Table 16 presents a summary of consumptive water use during the major steps of the conventional petroleum gasoline lifecycle. Results are expressed in terms of both gal/gal of crude oil and gal/gal of gasoline. Net injection water use is calculated and regional shares are estimated from estimates of crude oil production (Table 11), injection water use, and PW re-injection (Table 13).

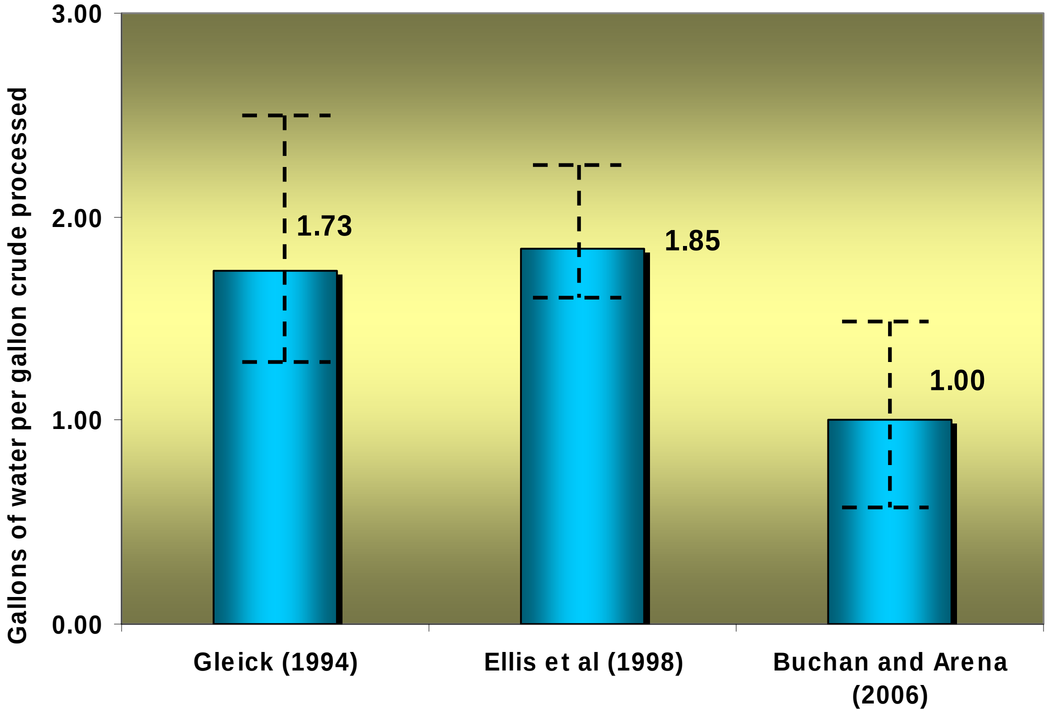



**Figure 36. Estimates of Net Water use in U.S. Refineries (gal water/gal crude)**

Figure 37 illustrates the water flows in crude oil recovery from conventional sources and oil refining. The range of values reported in the literature for input water, water reuse/recycling and consumption is shown, as well as consumed water disposition.

**Table 16. Net Water Use 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 U.S. (%)[d] | 12.8 | 43.2 | 33.6 | |
| Share of gasoline production in U.S. (%)[e] | 20.7 | 42.4 | 18.2 | |
| Share of injection water use for crude recovery in U.S.[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 percent (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.

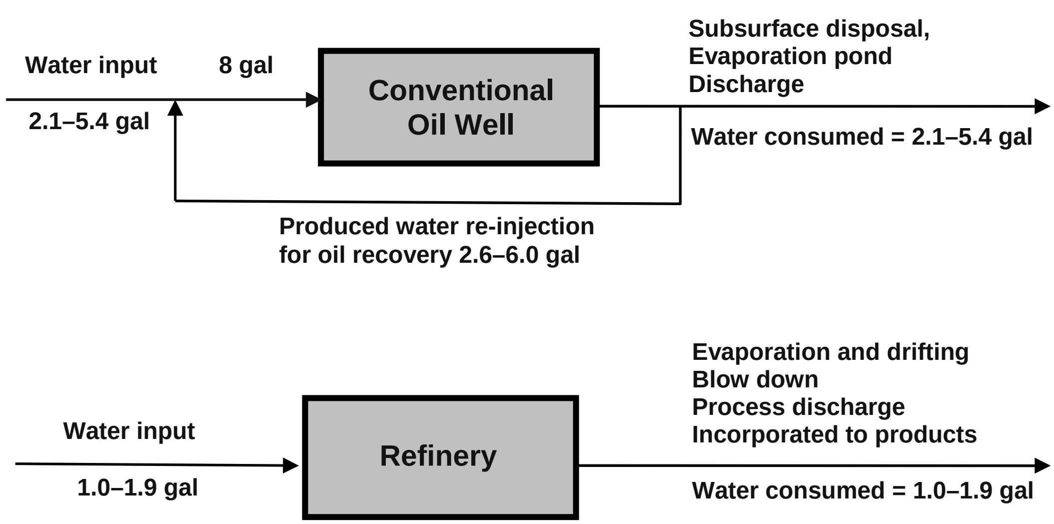



**Figure 37. Water Flows in U.S. Oil Production and Refining**

### 4.6.2 Oil Sands to Gasoline Lifecycle

It takes 2.8–6.5 gal of water to produce a gal of crude from Canadian oil sands (Table 17). Using reported shares and water intensity by production technology, we find that 56 percent of oil sands-based crude is produced using 6.5 gal of water per gal of bitumen.

**Table 17. Net Water Use from Crude Recovery to Refining, Canadian Oil Sands-Based Gasoline**

| | **Surface Mining (Athabasca)** | **In Situ Recovery** | | |
|---|---|---|---|---|
| | | **SAGD (Athabasca)** | **CSS (Cold Lake)** | **Multi-Scheme (Peace River)** |
| Mining and upgrading [a]<br>(gal water/gal bitumen) | 4.0 | 1.3 | 2.2 | 5.0 |
| Refining [b]<br>(gal water/gal bitumen) | 1.5 | 1.5 | 1.5 | 1.5 |
| Total water use<br>(gal water/gal bitumen)<br>(gal water/gal gasoline) | <br>5.5<br>5.2 | <br>2.8<br>2.6 | <br>3.7<br>3.5 | <br>6.5<br>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 38 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.

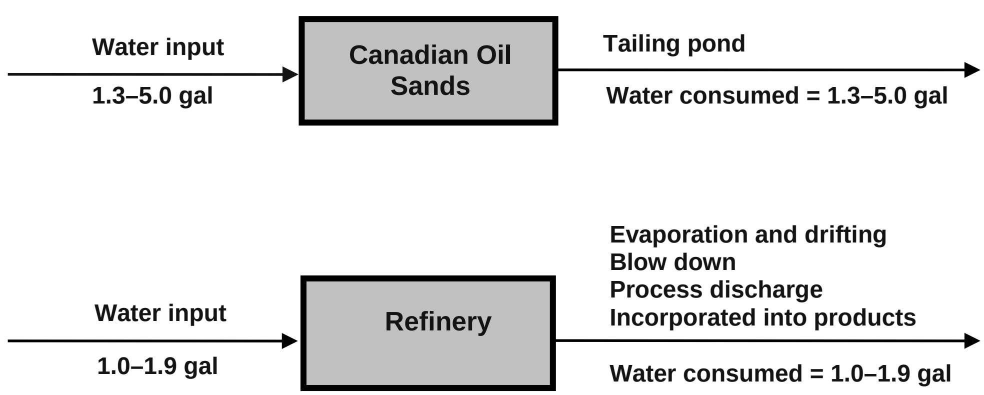



**Figure 38. Water Input and Consumption for Bitumen Production and Refining to Produce One Gallon of Synthetic Crude Oil from Canadian Oil Sands**

Figure 39 presents the share of oil sands-derived crude oil production by location and recovery technology, along with our estimates of total water use for recovery (including upgrading) by location and recovery technology. Viewed in this light, surface mining in

Athabasca is clearly water intensive (since Athabasca produces 56 percent of oil sands-derived crude yet consumes 78 percent of the water used for production). By contrast, in situ recovery using SAGD at Athabasca uses the least water relative to its share of oil sands-derived crude production.

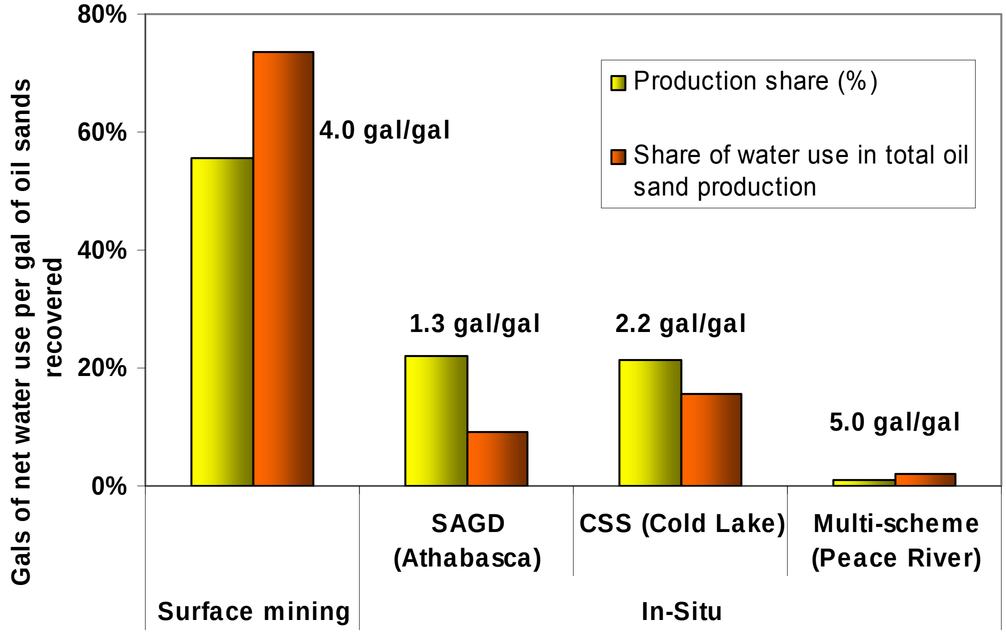



**Figure 39. Shares of Synthetic Crude Oil Production and Net Water Use from Bitumen Recovery Through Crude Production by Recovery Technology (Gatens 2007; CAPP 2008a; CAPP 2008b)**

## 5. Additional Issues

The issue of sustainability involves a complex interplay of local, regional and global actions over time utilizing 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 net 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 lifecycles) differ with respect to sustainability. By themselves, even projects with relatively high net 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 net 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. 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 — and their effect on petroleum gasoline, oil sands-based gasoline, corn ethanol and cellulosic ethanol lifecycles.

A related issue is the "lock-in" of water intensity associated with current technologies in the 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. This is a perennial problem in commercializing advanced technologies.

### 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 and feed production, urban development, power generation, crude oil recovery, 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. Aquifer depletion is perhaps the most serious water-related impact of energy development. Historically, aquifer depletion has been more closely associated with agricultural activities; but the production of fossil fuel feedstocks could potentially impact 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 use their allocations or risk losing them 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 and PADD V. However, the entire issue of water rights and allocations is beyond the scope of this effort.

### 5.1.1 Agriculture and Biofuel Feedstock

In agriculture, it is not unusual for groundwater withdrawals to exceed recharging during periods of peak water demand or unusually dry spells. But when pumping continually exceeds recharging over a sustained period, the water level and saturated thickness of the aquifer will decline. Portions of 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 illustrate this effect. About 20 percent of U.S. irrigated farmland overlies this aquifer, and about 30 percent 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, as a result, water levels have dropped more than 100 ft (from predevelopment levels) in places where irrigation pumping is most intense. As shown in Figure 40, water levels have dropped most precipitously in West Texas, and parts of western Kansas and the Oklahoma panhandle.

Compare to Figure 6, Midwest corn-growing regions barely overlap with the problematic regions of the High Plains aquifer (West Texas, West Kansas, and Oklahoma Panhandle in Figure 40). Current corn produced for ethanol accounts for a fraction of the crop production (wheat, corn, soy, sorghums, etc.) from the entire High Plains. Nevertheless, this is a particularly critical issue with respect to future feedstock development. Expansion of existing feedstock or planning of large-scale feedstock in the water-stressed regions of High Plains should be thoroughly examined.

According to the USGS (1996):

> *Water conservation methods and secondary recovery of capillary water are among some of the alternatives that are being explored to solve the water-supply problems in the High Plains of Texas*.

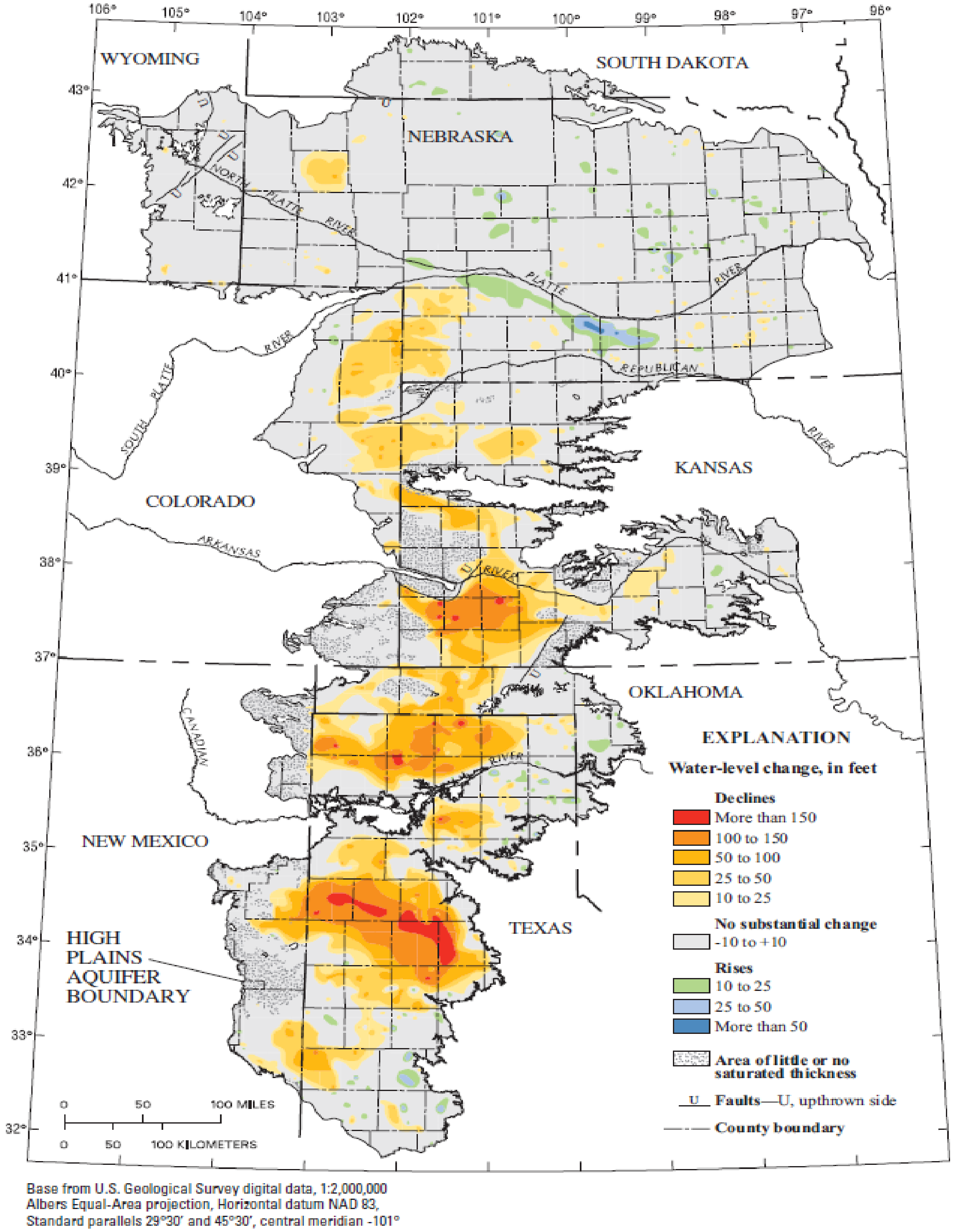



**Figure 40. Water Level Changes in the High Plains Aquifer, Predevelopment to 2005 (McGuire 2006).**

### 5.1.2 Conventional Crude Oil

As stated above, oil recovery can also impact 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. The extent of any deficit, however, will depend on the health of the aquifer itself (which in turn depends on the density and intensity of all water-consuming uses, including oil recovery operations, in the watershed).

### 5.1.3 Oil Sands

Surface mining of oil sands typically disrupts groundwater flow, but most of the water used in the process itself comes from surface water (See Sec. 6.1.1).

In situ recovery is more likely to affect aquifers. Some researchers suspect that the voids created by oil sands extraction may trap groundwater flow, thereby disrupting the natural process of aquifer recharging. The likelihood of this effect and its long-term impact are not known. Likewise, certain efforts (chief among them is the increasing use of injection water from deep saline aquifers) to reduce net fresh water use may have uncertain long-term impacts on underground water systems.

## 5.2 Soil Erosion

Any activity that alters the land has the potential to promote soil erosion. In agriculture, continued planting of a single crop (monoculture), 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.

Native perennials are a key exception to cautions against monoculture since their deep root systems make them less susceptible to drought and better able to hold the soil. Because of these important advantages, cellulosic ethanol feedstocks must be carefully selected. Some species may be better suited to one region; others to a different region. If cellulosic feedstocks are likely to come from crop residues, sustainable practices will be required to reduce the potential for soil erosion.

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

## 5.3 Water Quality

While this report focuses on the quantity of water required to produce fuels, the impact of fuel production on the quality of that water can never be ignored. Water discharged from feedstock and fuel production processes has a unique chemical profile that can have significant environmental impact. Fortunately, discharges are subject to strict emission standards that limit the impact of any single project. The bigger problem is the cumulative impact of many projects, particularly over time. Watersheds with concentrated fuel and feedstock production activities will tend to have greater water quality impacts than those with fewer such facilities, all else being equal. In other words, concentrating operations within a watershed may exacerbate impacts of many types of operations. The resulting impact may be greater than the sum of its parts. This is especially true for oil fields and oil sands operations.

The consideration of cumulative impacts has gained increasing traction as Canadian regulators and local officials grapple with a flood of applications to expand oil sands recovery and upgrading operations. Many of the same issues and concerns apply equally well to conventional oil recovery in the U.S. or overseas. In chronically dry and drought-prone regions, not only is water reuse and recycling critical, but developers must be especially vigilant at protecting limited sources of freshwater from contaminants.

Process waste streams may contain toxics and other contaminants. Liquid wastes from conventional oil recovery, oil sands recovery and upgrading, and oil refineries including tailings from surface mining (including sand storage, tailing ponds and settling basins) may contain highly toxic substances benzene, toluene, and xylene (BTX), arsenic, heavy metals, naphthenic acids, and various organic compounds. Their leakage to surface and groundwater could have devastating health effect and lasting environmental impact. The monitoring and control of waste are critical to preventing the migration of these substances into ground and surface waters.

Crops grown for ethanol feedstocks are not immune from water quality problems. Primarily due to fertilizer run-off from agricultural cropping land for the production of food, feed, and fuel, nitrate contamination has been found in the groundwater of certain parts of the U.S, and nitrogen and phosphorus also have been accumulating in surface waters, resulting in eutrophication downstream in the Mississippi River and the Gulf of Mexico.[20] Sound irrigation management and efficient irrigation is needed to reduce nitrogen and phosphorus run-off from agricultural lands to watersheds. Cellulosic biofuel feedstocks such as native perennials (e.g., switchgrass) tend to be more pest and disease resistant and require less nitrogen and phosphorous.

A promising strategy 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. A study is currently underway to examine scenarios of feedstock production using high-nutrient water sources. With careful planning, it may be possible to produce biofuel feedstocks requiring much less freshwater per unit of feedstock produced than currently.

[20] Eutrophication is the process whereby a body of water becomes rich in dissolved organic carbon and nutrients, thereby encouraging the growth of oxygen-depleting plant life such as algae blooms which in turn depletes dissolved oxygen in water and harms to other organisms. Eutrophication is responsible for "dead zones" in portions of the Gulf of Mexico and other water bodies.

## 5.4 Land Degradation

As mentioned in Section 4.4, land degradation is a key impact of oil sands development. Landscape change is typical, especially with surface mining. It is estimated that 2–2.5$m^3$ of tailing material are produced per bbl 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 mature fine tailings (MFT). On average, 1.5 bbl of MFT is generated per bbl of bitumen produced. The water discharged into the tailing ponds cannot be recycled because of the suspended sediments.

The tailing ponds/lakes have changed the landscape around the Athabasca deposit. Although plans have been developed to reclaim the land upon completion of oil sands recovery operations, there is considerable uncertainty about the lifetime of much of the waste (e.g., 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 will affect water quality.

Reclamation will involve restoring groundwater flows that were disrupted to de-water mine pits and prevent flooding. Undoing decades of watershed disruption will be a complex task.

## 5.5 Ecosystem Disruption

In open pit mining, removing the overburden and draining the mine pit typically destroys 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 restore carbon, was disturbed by currently operating oil sands mines in Athabasca Boreal region (Grant et al. 2008). Tailing ponds are toxic to marine organisms and already impact 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) impacts could include an increased susceptibility to certain pests or diseases or, the potential for the monoculture become an invasive species to other crops. These differences highlight the importance of considering regional conditions and sources in feedstock selection. Local soil, water and weather conditions, and feedstock characteristics and needs are critical.

## 5.6 Energy–Water Interdependence

As stated in DOE's Report to Congress (2006), "Water is an integral element of energy resource development and utilization." It is used directly in hydroelectric generation, for cooling and emissions scrubbing in thermoelectric generation and, as discussed above, as a key input to crude oil recovery and refining, to growing biofuel feedstock, and for ethanol production. Conversely, energy is consumed to power the infrastructure 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. In some areas, groundwater tables are dropping at an alarming rate (Figure 40). Meanwhile, new ecological water demands and climate change could reduce available freshwater supplies even more (DOE 2006). It is against this backdrop that we are examining consumptive water use in ethanol 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 lifecycle 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. Similar is true for petroleum crude recovery and refining. As with any average, there is considerable variation among individual projects, facilities, and the most noticeable being regions. There is also uncertainty in the underlying data and the mechanics of the calculations. These issues are discussed below.

## 6.1 Comparative Water Use

There are significant regional differences for biofuels. Net water use for ethanol production varies significantly in the U.S. major corn growing regions. As was shown in Table 5, producing a gal of corn ethanol can consume as little as 10.0 or as much as 324 gal 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 gal water per gal of ethanol (USDA region 5).

Similarly, switchgrass-based cellulosic ethanol production, when grown in its native habitat in U.S., can consume from 1.0 to 9.8 gal of water (Table 6), depending on process technology. This latter figure has dropped recently to 6.0 gal because of yield improvement.

Feedstocks rely largely on water from precipitation. Substantial variation on irrigation water use for corn ethanol in USDA regions 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 41 compares water use to produce a gal of gasoline from the conventional and non-conventional crude sources examined in this study. As shown in the figure, net use varies from less than 3 gal in Ghawar and Athabasca to nearly 7 gal in PADD V. 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, net water use is extremely variable. For ethanol production the key determinants are feedstock (corn or cellulosic) and the amount of irrigation water needed to generate acceptable yields. For gasoline production, the key determinants are the characteristics of the individual reservoir, the crude deposit itself, the recovery technology used, and the degree of produced water recycling.

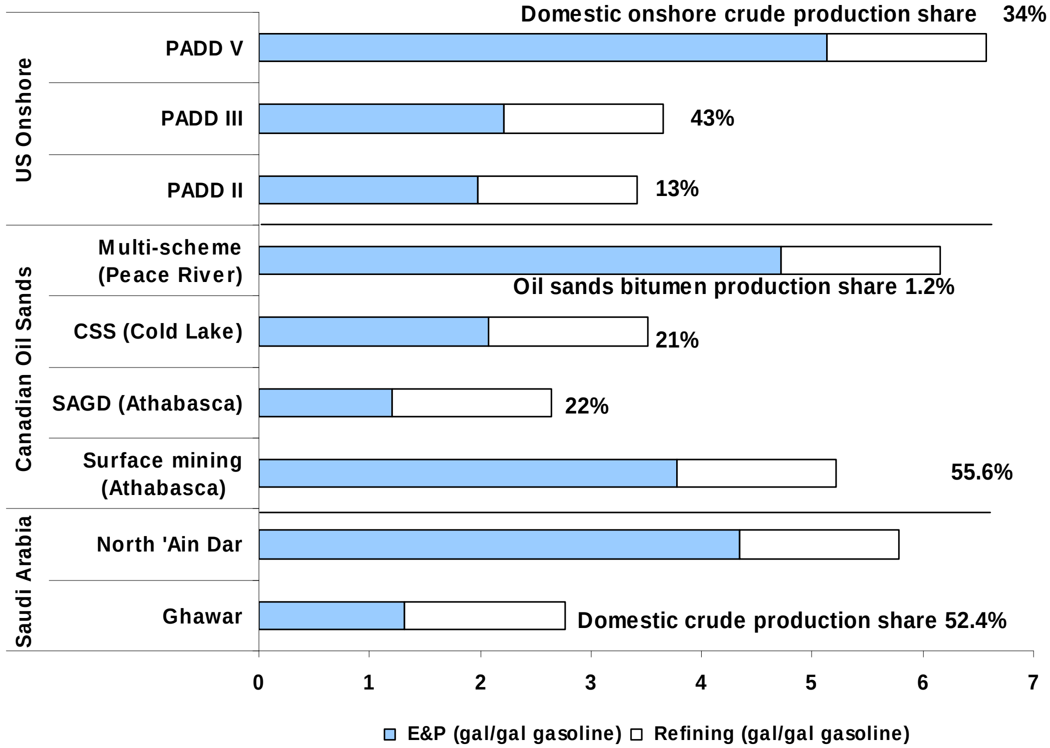



**Figure 41. Net Water Use for Gasoline Production from Conventional (U.S. and Saudi) and Non-Conventional Crude (Oil Sands) by Lifecycle Stage, Location and Recovery Method**

## 6.2 Limitations and Uncertainties

Production and consumption information scattered in a number of different databases and sources were assembled for this effort. While the resulting data are broad, they are far from complete. A number of 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 introduce additional uncertainties. Information on co-products is also incomplete, adding uncertainty to allocation decisions.

### 6.2.1 Data Gaps

Statistics compiled by 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 lifecycle stages contain more gaps than comparable data for ethanol lifecycle 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 water use may or may not be available for that year. Although irrigation and precipitation data are well-documented, USGS' efforts to document agricultural water withdrawals and consumption have been stalled for more than a decade. Thus, the ratio of consumption to water withdrawals for crop irrigation used in this analysis is based on the last available national survey, which was conducted in 1995. Since there are no data on water withdrawals and consumption for specific regions or waterways, regional ratios could not be estimated and used to examine regional differences.

- Aggregate reporting of oil recovery by technology. For domestic onshore crude oil E&P, neither state nor PADD production is reported by recovery technology. Thus, we applied national technology shares for our regional analyses. Likewise, international data rarely report production by recovery technology.

- PW from US 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. However, for this analysis, all PW was allocated to oil extraction.

- 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 several major energy companies was underway, but results were not yet available.

- 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

Domestic onshore conventional crude, Saudi Arabian conventional crude, and Canadian oil sands-derived crude together account for only 38 percent of U.S. crude oil supply (Table 1). However, these crudes present a broad range of water implications and, from the perspective of liquid fuel production in the U.S., account for 95 percent of current ethanol production and 81 percent of motor gasoline production.

### 6.2.3 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 U.S. (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.

A number of alternative methods have been developed to allocate co-product contributions to aggregates like energy use, greenhouse gas (GHG) emissions or criteria pollutant emissions. As of this writing, no such methods have been developed specifically for allocating net water use. The present effort is a major step forward in this regard.

The choice of allocation method is typically a major analytical issue in lifecycle analysis, not just from a purely conceptual standpoint, but 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 gal of gasoline.

For corn ethanol, Wang et al. (2008) estimated that 20-46% of total greenhouse gas burdens of the corn-to-ethanol cycle could be allocated to DGS. However, in this study, we allocate all water use for the cycle to the ethanol product.

## 6.3 Conclusions

Consumptive water use for biofuel feedstock and ethanol production varies considerably by growing region, type of feedstocks, soil characteristics, climactic condition, and production technology. There are significant regional differences, however, particularly for corn production. 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 lifecycle, 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 greater than 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 bioethanol and gasoline production. Improved water management and more efficient irrigation practices are needed for corn growing, particularly in those areas where water is scarce. Development of drought-resistant strains that maintain or increase corn yields are also desirable, as is an emphasis on cellulosic feedstocks grown in their native habitat (thereby minimizing irrigation requirements while achieving desirable feedstock yields). The use of produced water 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 system 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 is particularly true for areas overlying the High Plains aquifer, where there is growing competition for limited groundwater supplies and some new oil and gas projects and production facilities are proposed. In these regions improved irrigation management, increased treatment and recycling of process discharges, and reuse of produced water are being implemented not only to conserve scarce resources but also to 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 that consumptive 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 cause devastating environmental impacts. At the extreme, degraded water quality can also impact 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 can contain higher levels of TDS than irrigation water). A study is currently underway to investigate potential synergies from using contaminated groundwater for biofuels development.

Water quality is also process specific. Depending on feedstock and production process, discharges can have distinctive chemical profiles that affect downstream wastewater treatment needs, opportunities for treated wastewater recycling, and final solids disposal. Research is needed to determine 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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## Acronyms and Abbreviations

ANL: Argonne National Laboratory

API: American Petroleum Institute

bbl: barrel

bbl/d: barrel per day

BC: Biochemical conversion.

CAPP: Canadian Association of Petroleum Producers

$CO_2$: Carbon dioxide

CT: Consolidated tailings

CSS: Cyclic steam stimulation

DDGS: Distiller's dried grain and solubles

DOE: U.S. Department of Energy

E&P: Oil extraction and production

EIA: Energy Information Administration

EISA: Energy Independence and Security Act

EOR: Enhanced oil recovery

ft: feet

gal: gallons

gal/d: gallons per day

GAO: Government Accountability Office

GHG: Greenhouse gas

LCA: Lifecycle analysis

MFT: Mature fine tailings

mln: million

NAS: National Academy of Sciences

NASS: National Agricultural Statistics Service

NAWQA: National Water Quality Assessment Program

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

TDS: Total dissolved solids

TC: Thermochemical conversion

USDA: U.S. Department of Agriculture

USGS: U.S. Geological Survey

WDG: Wet distiller’s grain

WTW: Well-to-wheel

WWTP: Wastewater treatment plant