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FINAL PROJECT REPORT

WATER USE IMPLICATIONS OF CALIFORNIA'S FUTURE TRANSPORTATION FUELS

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

It is essential for policy makers to understand how meeting California's future petroleum fuel, biofuel, and electricity demands will affect water consumption. The 'water-energy nexus' is an effective framework to integrate the transition to low-carbon transportation technologies with water resource management. Using this approach, scenarios were developed that reflect probable future developments in climate, energy and water policies.

Projections indicate that by 2030, California's low-carbon energy transition will increase non-petroleum energy use in transportation, while in-state oil consumption will decrease. This reduction, if exports do not increase, can potentially mitigate increasing water use for oil production and refining. Overall, the researchers estimate that meeting the state's long-term climate goals and adopting smart water policies can reduce today's freshwater consumption from oil and electricity uses by 60 percent in 2030.

Since the majority of biofuels consumed in California are imported, the analysis of biofuel water use takes a national scope. Differences in agronomic crop-water budgets are compared between an increased biofuel production scenario supported by policies that incentivize biofuels and a business-as-usual scenario with no incentives once existing ones end. Increased biofuel production shifts overall agricultural land use patterns and management practices. While changes in the average water intensities of biofuels from corn and soybean and total agricultural irrigation requirements are found to be quite small, increasing total acreage for biofuel feedstock may lead to reductions in groundwater recharge in certain regions.

Effective strategies for mitigating the water use impacts of providing energy vary across supply chains. For oil and gas production, legislative and technical means may mandate using water of minimal sufficient quality. For refineries and power plants, regulatory standards may serve to incentivize siting in regions with access to low-grade water resources.

Keywords: California, transportation, AB 32, water use, lifecycle analysis, energy-economic modeling, energy-water nexus, Renewable Fuels Standard, Low Carbon Fuel Standard, crop-water modeling.

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EXECUTIVE SUMMARY

Introduction

Interdependencies between water and energy resources are emerging as a key resource management concern for governments, non-governmental organizations (NGOs), and industries at local, regional, national and even multi-national levels. For a successful transition to low-carbon fuels and technologies that meet future energy demands together with effective water resource management requires an understanding of regionally appropriate water-energy interactions.

California has built a water management infrastructure that is among the most sophisticated, extensive, and energy-intensive in the world. Approximately 19 percent of the state's electricity and 30 percent of its non-power plant natural gas is used to store, convey, conserve, and treat water and wastewater. Across all sectors, many energy technologies critical for mitigating climate change will require substantial quantities of water, and may also have impacts on water quality. The California Air Resources Board in its latest Climate Change Scoping Plan, a blueprint for California climate policy to 2030, recognizes the necessity for integrated energy and water conservation management strategies.

Purpose

Transportation accounts for the largest share of California's greenhouse gas (GHG) emissions, and still relies overwhelmingly (about 93 percent) on petroleum products. As California progresses toward meeting its 2020 GHG reduction commitment and its 2030 target towards the 2050 goal (reducing GHG emissions 80 percent below the 1990 level), transportation energy sources will shift to alternative fuel sources that could include biofuels, natural gas, electricity, and hydrogen. These pathways require different types and quantity of water use per unit delivered energy than gasoline and other petroleum-derived fuels. Understanding these differences is essential to recognize how California's policies for water, energy and climate intersect. In this report, the authors seek to answer the following questions: What are the impacts on water use to meet California's transportation fuel use demand in 2030? What are the ranges of water use impacts that might result from different water management scenarios? What are the location distributions of these potential impacts within California that might occur? What are the most effective strategies to mitigate the water use impacts of providing energy for different fuel pathways?

Methods

This analysis addresses in-state and out of state water use impacts from California's future anticipated transportation energy demand. Within California, the analysis considers local and temporal dimensions, as well as the water type consumed and the fate of consumed water. The researchers aggregated volumes of water consumed for each climate and water management scenario including the magnitude and likely regions of greatest impact. Volumes of water used across all transportation energy supply chains were inventoried, delineating between water source *types* (freshwater, recycled water, brackish water, irrigation, etc.) and *fates* (injection of produced water into class II wells, storage in lined holding ponds for cooling water for electricity, runoff and groundwater infiltration for agricultural/biofuels water use, etc.).

To compare policy choices, the analysis adopted a scenario-based approach, using the results from two energy-economic models (*California-TIMES* and the *Biofuels Environmental Policy Analysis Model - BEPAM*) to quantify the impacts of water use associated with energy transitions. Four scenarios were constructed for probable future developments in energy and water in two dimensions: climate policy (a '*Reference*' scenario and a '*Deep GHG*' emissions reduction scenario), and water policy (based on '*Baseline*' current water use patterns versus a '*Smart*' more aggressive regulatory regime for water use). Under the *Reference* scenario, California continues to achieve GHG mitigation targets to meet its 2020 target, but no new policies were adopted beyond 2020. In the *Deep GHG* scenario, GHG emissions are reduced through 2050 with the goal of reducing emissions to 80 percent of 1990 levels by that year.

This analysis considers the main current and future energy supply chains for transportation: petroleum, biofuels, and electricity. The two main metrics of water use that are used to evaluate water consumption are (1) ***total water consumption***, typically reported as the volume of water of a given type (e.g. freshwater, recycled water, degraded water) consumed over an entire year, and (2) ***water use intensity***, which is the water consumed by a process per unit (energy) output, such as liters/megawatt-hour.

The trends in California's water use for petroleum production are traced by analyzing data from a detailed, well- and field-level database, and project these forward to estimate future water use for oil production in the state to meet in-state demand (that is, assuming no increase in exports).

Since most biofuels consumed in California are imported, the researchers used a national perspective for water use impacts of biofuels. The Biofuels Environmental and Policy Analysis Model was used to project cropping patterns and crop management across the contiguous U.S. under two hypothetical national policies: a modified Renewable Fuel Standard (M-RFS2) and a national Low Carbon Fuel Standard (N-LCFS), to compare a range of possible water uses given different feedstock mixes and different incentives.

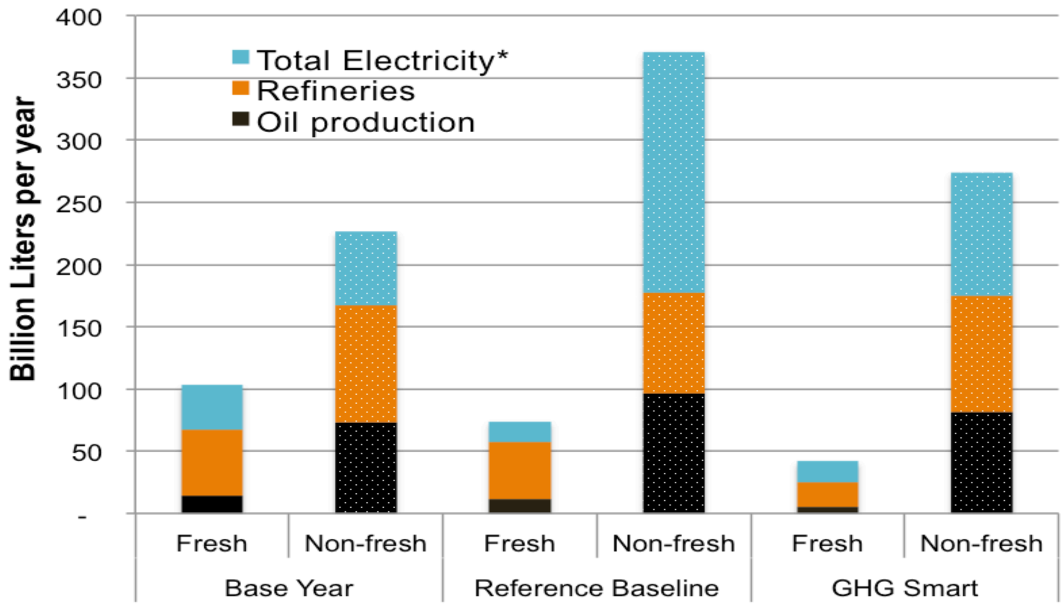
Current water use of electricity generation is used in combination with the likely amount and mix of electricity generation from California-TIMES economic model projected for 2030 to estimate the volumes of water (by source and type) under each of the four scenarios.

Finally, based upon a thorough literature review on the current impacts of water use from domestic production in shale/tight oil and gas, the water use of natural gas and oil produced in other states and countries for consumption by California's transport sector is estimated.

Results

The scenarios estimate that California's current and continuing low-carbon energy transition in the transportation sector will significantly increase non-petroleum energy use. At the same time, oil consumption decreases from 13 percent (*Reference*) or 23 percent (*Deep GHG*). The increased reliance on biofuels, natural gas, and electricity, together with reduced oil production in California, can have significant water use and quality impacts. The net changes in water use from the scenarios addressing the low-carbon energy transition in the transportation sector are shown in Figure ES.1. This Figure shows the projected total consumptive water use in 2030 for the *Reference* + *Baseline* water management scenario and the *Deep GHG* + *Smart* water use scenario, respectively. Water volumes are broken into *fresh* and *non-fresh* (i.e. recycled, degraded, and waste) water types, incurred in-state, by energy supply chain. The base year varies by supply chain (oil is 2012 and electricity is 2008).

Figure ES.1: Projected Water Consumptive Use for Transportation in 2030.



*Net out-of-state water consumption incurred due to energy supply imports is not included.

Petroleum Fuels

In-state oil consumption, currently at 290 billion liters, is projected to decline by 14 percent in the *Reference* scenario, or by 23 percent in the *Deep GHG* scenario. This is based upon assuming that reductions in California's oil consumption means reduced in-state production, while exports will remain the same as in the base year. While there is a reduction in oil consumption, in-state gross water injection is projected to increase by 14 percent in the *Reference* scenario (330 billion liters; but decrease by 4 percent by 2030 in the *Deep GHG* scenario 279 billion liters). Net freshwater consumption for oil extraction, currently at 14 billion liters, decreases 18 percent (*Reference* + *Baseline* water use scenario) or 35 percent (*Deep GHG* + *Smart* water use scenario).

Net freshwater consumption for oil extraction, currently at 14 billion liters, decreases under the *Reference* + *Baseline* water use scenario (11.4 billion liters) or, less significantly under the *Deep GHG* + *Smart* water use scenario (4.9 billion liters). Total (net) water use for oil extraction is estimated to increase from 87.5 billion liters currently to 105 billion liters under the *Reference* scenario, or increase slightly to 88.5 billion liters in the *Deep GHG* scenario.

As the volume of petroleum-based fuels consumed in California declines, total water consumption by refineries within California also decreases from 147 billion liters in 2012 under the *Reference* scenario (126 billion liters) and under in the *Deep GHG* scenario (118 billion liters).

As in the case of oil production, significant opportunities exist for refineries to substitute freshwater use with recycled water.

Electricity Generation

By 2030, California may witness substantial increases in the consumption of water for electricity generation compared to the 2008 level. Some of the renewable energy technologies (for example, geothermal, concentrating solar power), as well as the greater capacity of natural gas combined cycled power plants, will consume more water than the present generation mix.

Total water consumption for electricity generation increases from 95 billion liters in the base year (2008) to 116 billion liters under the *Deep GHG* scenario to 210 billion liters under the *Reference* scenario. Substantial increases in the consumptive water use for electricity generation in general, and dramatic increases in the water use attributable to electricity demand in transport, are likely to be widely distributed across the state. Transportation accounts for 0.4% of total in-state electricity generation in the base year, and 1.2% and 1.5% in the Reference and Deep GHG scenarios, respectively, in 2030. While certain regions and watersheds may face tradeoffs in accommodating water use for new power plants, it is also possible that the wide range of regions suitable for renewable power generation technologies and distributed power generation may add to system resiliency.

Biofuels.

For both policy scenarios – the policy similar to the Renewable Fuels Standard policy (M-RFS2) and a National Low Carbon Fuel Standard (N-LCFS), similar to California's LCFS – result in shifts to cellulosic feedstocks (*miscanthus,* and switchgrass). This will result nationwide in an increase in irrigation requirements by almost 1 percent under the M-RFS2 scenario, while these requirements decrease by 2 percent in the LCFS and RFS2.

On a more regional basis, where these feedstocks displace irrigated row crops, such as in some Southern and Midwestern states, net irrigation water demand will be reduced. On net, nationwide use of irrigation decreases slightly under the M-RFS2, and even more under the N-LCFS scenario.

Less water enters the water table under newly cropped areas, with less recharge into groundwater and surface water stocks throughout the watershed. The largest decreases in groundwater infiltration occur in areas such as northern Kansas and southern Nebraska where corn acreage increases dramatically under both scenarios. Reductions in groundwater infiltration are more moderate across most of the rest of the country, with the net nationwide effect a reduction in groundwater infiltration of 1 percent under the RFS2, and 4.6 percent under the N-LCFS.

Somewhat counter intuitively, net irrigation volumes decrease east of the Mississippi in both scenarios. Decreases in irrigation requirements by row crops being displaced by switchgrass and miscanthus over lands that require less irrigation per acre and where water is relatively abundant are offset by substantial increases in irrigation in the states west of the Mississippi

In certain regions of the South and the Midwest, policies promoting biofuel development may trigger significant alterations in crop-water use. Both policies, however, overall lead to greater water consumption, at the expense of groundwater recharge to refill groundwater aquifers and ground and surface water stocks.

Conclusions

As shown in Figure ES.1, there is a decline in the use of fresh water, as electricity generation, oil production, and refining operations substitute growing overall water requirements with non-fresh water sources. Taking all of the effects together, meeting the State's 2020 climate target (*Reference* scenario) can reduce absolute fresh water consumption by 28% in 2030 from today's level. Meeting the 2050 climate goal (*Deep GHG* scenario) can further reduce fresh water use by another 7 percent. And by adopting policies to shift to non-fresh water sources, fresh water use drops by another 25 percent. This totals 60 percent or 61 billion liters per year in water savings in electricity generation, refineries, and oil production compared to today's level.

Achieving the 2050 emission reduction targets under the *Deep GHG* scenario will require greater reliance upon distributed generation, including installation of new natural gas plants and renewables (which include some geothermal, as well as technologies with very low consumptive water requirements, like wind, solar PV, and tidal power). The overall result of increased electrification is increased water consumption for electricity generation across a wide geographic area, but the shift to certain renewables with very low water use intensity mitigates the consumptive need for water substantially. Regulations to incentivize or otherwise mandate water acquisition from, e.g., recycled or degraded sources may be beneficial toward this end, and are indeed legislated in the state's forward-looking water use legislation.

A climate policy that cuts transportation emissions will reduce the state's petroleum use, alleviating the increase in net water consumption in oil production and water sent to evaporation ponds and disposed to surface water. Moreover, decreased oil consumption translates to lower water consumption for oil refining. Increased consumption of freshwater for oil production and electricity generation across a wide geographic area can be effectively managed with *Smart* water management that shifts water use from higher quality freshwater to lower quality water types such as degraded and recycled water. Water resource tradeoffs occur at the local (or watershed) scale, making it necessary to model energy supply infrastructure at as high spatial resolution as feasible. Water use intensities disaggregated by water *source*, *type*, and *fate* can provide ranges of projected water use, serving as useful metrics for water management planning.

National policies promoting the production of biofuels may notably reduce water availability in the Midwest and in regions along the Mississippi and Missouri River basins, due to increased cropping and reductions in groundwater recharge. While irrigation water use decreases east of the Mississippi, biofuel policies may lead to increases in irrigated land areas in regions where water resources are scarce and are currently being exploited in an unsustainable manner, for example over the Ogallala Aquifer.

This analysis can serve as a foundation for two prongs of potential further investigation. First, potential 'hotspots' – regions where energy supply chains may exacerbate or contribute to water resource scarcity or water quality impacts – should be more carefully analyzed in detailed case studies. Case studies may adopt a range of methodologies, and, depending on their scope and purpose, they may adopt modeling, environmental impact assessments, stakeholder feedback, or a mix of these and other approaches. The second investigation that would build on the methodology adopted here is an integrated modeling framework that considers the constraints of water resource availability on future energy development. This enhancement can lead to a more comprehensive and optimized view of future energy systems from water constraints and substantial reductions in GHG emissions.

CHAPTER 1: Introduction

1.1 Management, Modeling, and Planning for the Water-Energy Nexus

Access to infrastructure providing water services (including, *inter alia*, sanitation, irrigation, and provision of clean drinking water) and energy services (such as lighting, heating, and transport) are among the key determinants of human health and well-being (Guo, Wu et al. 2011). Interdependencies between water and energy resources are emerging as a core concern of resource management at all levels (local, city, state, regional, national and even international in some regions of the world). The need to integrate planning to promote technologies that meet future energy needs and at the same time to allocate water resources efficiently requires an understanding of regionally appropriate water-energy nexus impact assessments. Throughout the world, the water-energy nexus is increasingly invoked in the context of very real and foreboding societal challenges such as poverty, security, climate change, and environmental degradation.

The nexus also offers an important planning challenge through which to formulate viable strategies to meet future energy demand while reducing the vulnerabilities of climate change and water sustainability. A lack of recognition of the need for the integrated solutions and proper tools can be counterproductive to resource management goals viewed in isolation, and may eventually become intractable. But policy makers are beginning to realize that ways to coordinate policy and behavior that explicitly recognize the nexus interactions must be found.

This study analyzes the potential water use impacts of future transportation fuels given various scenarios of projected transportation fuel use demand. This report focuses on water use and, to a lesser extent, water quality impacts incurred at key stages of supply chains for California's current and future energy pathways for transportation. This is the first step towards a more holistic and comprehensive water-energy analytic modeling framework that incorporates the bidirectional impacts between energy and water: future water availability at local and regional scales can also significantly constrain future development of energy supplies. An integrated framework that considers how best to manage future energy supplies and demand given water resource availability and impacts should be the eventual aim in terms of methodology applied for this type of research (Jolliet, Margni et al. 2003, Rosenbaum, Bachmann et al. 2008, Bayart, Bulle et al. 2010, Johnson, Zhang et al. 2011, Davies, Kyle et al. 2012, Jordaan 2012). Further, it is necessary to characterize impacts of water use in the local (ideally watershed level) context.

To appropriately understand all the impacts of water use, accounting must consider both other human (e.g. industrial, agricultural, and residential) and ecological uses, as well as hydrologic features. Further, analysis must contextualize water abstraction and quality alterations in the broader picture of trade flows of food, energy services, and products that require 'virtual' water to produce.

1.1.1 Federal and State Water Laws

Federal. The energy sector must comply with the two main federal policies regulating water: the Clean Water Act (CWA) of 1972 and the Safe Drinking Water Act (SWDA) of 1974. The SDWA mandates minimum water quality standards for all drinking water sources (2010). Although all activities related to fossil fuel extraction, processing and refining must comply with both the SDWA and the CWA, the Energy Policy Act of 2005 contains a clause exempting mandatory disclosure of underground injection of fracking chemicals, with the exception of diesel, from the SDWA (Congress 2005). There is some confusion about whether hydraulic fracturing (often referred to as 'fracking') activities have been 'exempted' from regulation under the SDWA. As demonstrated by Chesapeake Energy's record-breaking settlement totaling nearly $10 million (AP 2013), the exemption does not in fact prevent the EPA from pursuing litigation on other impacts (as in the Chesapeake Energy case, which targeted water quality impacts resulting from well construction and material transport, rather than those of injecting fracking chemicals) and disclosure requirements under the SDWA. An in-depth report on the legal, safety, and other ramifications of the Energy Policy Act exemption of fracking brines can be found in Tiemann and Vann (2013).

The CWA mandates that water released into surface water bodies must meet specific minimum quality standards. It regulates point source and non-point source emissions and requires entities emitting wastewater to obtain a National Pollutant Discharge Elimination System (NPDES) permit to do so . The CWA affects water use decisions across all energy supply chains by: (1) incentivizing wastewater treatment to standards that enable water recycling; (2) requiring a permit for recycled water use for irrigation, and; (3) providing resources and funding to local water districts (Alliance 2008).

California. The 2009 Water Conservation Act (Senate Bill x7-7) established an aggressive schedule for reducing per capita municipal and agricultural water use by 20 percent by 2020. In addition to this landmark legislation, California is implementing several other measures to promote water use efficiency, recycling, and conservation across all major sectors of the economy. Certain elements of California water policy affect the use of water for energy supply chains, and these are outlined here.

The Porter-Cologne Water Quality Control Act (SWRCB 2013) devolves day-to-day oversight of all water quality regulation to nine Regional Water Quality Control Boards. All operations with the potential to discharge into state surface and groundwater stocks are required under Porter-Cologne to: (1) maintain records on and report wastewater discharge events, and assist in inspections by State or Regional Boards; and (2) should contamination occur, cease and desist in discharging waste, (3) fund or conduct analysis and implementation of cost-effective and thorough measures to cleanup and/or abate the pollution – including remediation of closed operations such as mining sites, and, (4) in the case of judicial ruling of infringement of (state or federal) water quality laws, pay civil penalties. Electricity generation operations fall under the jurisdiction of the Act, and although oil, gas, and geothermal injection operations are to be reported to the California EPA's Division of Oil, Gas, and Geothermal Resources (DOGGR), they are also are subject to Porter-Cologne.

Another key water use mandate is a series of Assembly Bills beginning in 1991 requiring local water districts to implement policies and invest in infrastructure to meet ambitious targets for growing volumes of recycled water use. California's Water Code has a unique definition for recycled water, stating that it is "water which, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would not otherwise occur." (CA Water Code: 13050-13051). In 2012, the state legislated a mandatory increase in the use of recycled/storm water by 1.5/0.5 million acre-feet per year (AF/yr) by 2020, and 2.5/1 million AF/yr by 2030, respectively (California AB 2398 - Section 13560 of the State Water Code). To put these volumes in context, note that California's total freshwater withdrawal in 2005 was around 40 million AFY according to USGS water use statistics (Kenny, Barber et al. 2009). The focus on use of recycled water will be especially high in coastal areas where such water is considered "new water" in the state water plan (CA-DWR 2009) i.e., water from a previously untapped resource. Nevertheless, this is an ambitious mandate as it requires a more than twice recent historical rate of recycling water infrastructure growth of 40,000 AF/yr (WaterReuse_California 2012) and would require infrastructure growth to enable recycled water use. In fact similar goals set by previous legislation have not been met.[1]

Further, due to the extreme water scarcity in certain regions of California, in 2006 the State Water Resources Control Board (SWRCB) moved to consider *brackish* water, defined as water containing Total Dissolved Solids (TDS) concentrations between 1000-3000 mg/L, as "suitable, or potentially suitable, for municipal or domestic water supply." However, local water boards do have the power to deem groundwater sources meeting the TDS levels unsuitable, and forgo their use (Resolution 88-63, 2006). Sections 13510 and 13551 of the State Water Code prohibit the use of "…water from any source of quality suitable for potable domestic use for non-potable uses, including …industrial… uses, if suitable recycled water is available…" given conditions set forth in section 13550. These conditions take into account the quality and cost of water, the potential for public health impacts, the effects on downstream water rights, beneficial uses, and biological resources (O'Hagan and Monsen 1999, CA-DWR 2009).

Finally, Senate Bill 4 (Pavley 2013) requires permitting, thirty-day advance public notice, and issuance of environmental impact reports (EIR) by 2015, for well stimulation activities (including secondary and tertiary oil production, as well as hydraulic fracturing) in the state.

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[1] A similar act passed in 1991 set ambitious goals for ramping up the use of recycled water, but these targets weren't met, primarily because the statewide quotas could not be easily implemented and devolved at local levels – local agencies therefore often opted to follow the spirit, if not the strict regulatory letter, of the law, and adopted policies according to local priorities (Alliance, 2008). Increasingly, however, local agencies are recognizing that recycled water is both cheaper and more reliable than most other water supply options. In contrast to previous goals, the 2012 recycling targets are binding, but should not entail rate increases to domestic water users, as infrastructure for making use of recycled water are generally the least-cost options for additional supply. Moreover, in addition to certain cost advantages, recycled water is more reliable than other sources, as supplies may remain constant during droughts and as operators using recycled water are exempt from water use restrictions (Alliance, C. S. (2008). "The Role of Recycled Water in Energy Efficiency and Greenhouse Gas Reduction.")

Future legislation on fossil fuel development is likely, given the amount of public attention to issues like fracking in the state, and the potential development of the Monterey Shale. Various other regulatory regimes that affect specific energy pathways (e.g. petroleum production, electricity generation, biofuels production) are discussed in greater detail in the relevant sections on energy supply chains.

1.1.2 California's Global Warming Solutions Act - Assembly Bill 32

California's "Global Warming Solutions Act" (Assembly Bill 32, or AB 32) mandated that measures be developed to reduce the state's greenhouse gas (GHG) emissions to 1990 levels (427 MMT CO_{2e}) by 2020 (ARB 2006). It further expressed the goal of continuing post-2020 with (currently non-binding) abatement efforts targeting a subsequent 80% reduction from 1990 level by 2050. This target was set in line with emission rates that, if implemented globally, were deemed necessary to avoid high risks of dangerous impacts from climate change. Strategies to achieve the emissions reductions comprise both market-based mechanisms and various technology standards and mandates, including a cap-and-trade program, the Low Carbon Fuel Standard (LCFS), and policies targeting specific sectors including transportation, building, agriculture and non-energy sectors (CARB 2009). A recent comprehensive review study shows that a wide-range of scenarios can meet the state's 2050 goal, though there are significant variations in the mix and the contributions of specific technologies (Morrison, Eggert et al. 2014).

1.2 Water Use Implications of California's Future Transport Fuels

The single largest contributor to emissions in California is the transportation sector, accounting for 45% of total emissions (CARB 2013).[2] In 2012, California's transportation fuel consumption is comprised of 95% products of petroleum, of which 72% is petroleum gasoline and diesel. The remaining fractions include 3.6% fuel ethanol and biodiesel; 1.1% natural gas, and 0.09% electricity (Figure 1.1).

California currently produces about 200 million barrels of oil a year, about 30% of the oil it consumes (Department of Conservation 2013). The rest is imported from other states (20-30%) and foreign countries (40-50%). All petroleum is refined within California into petroleum gasoline to meet state-level regulatory levels: California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB), diesel (Ultra Low Sulfur Diesel, ULSD), and other petroleum products. As of 2013, there were sixteen refineries operating in California capable of producing CARB diesel and/or gasoline, with a combined operable capacity of 1.95 million barrels (MMbbl) per calendar day (EIA 2013e).

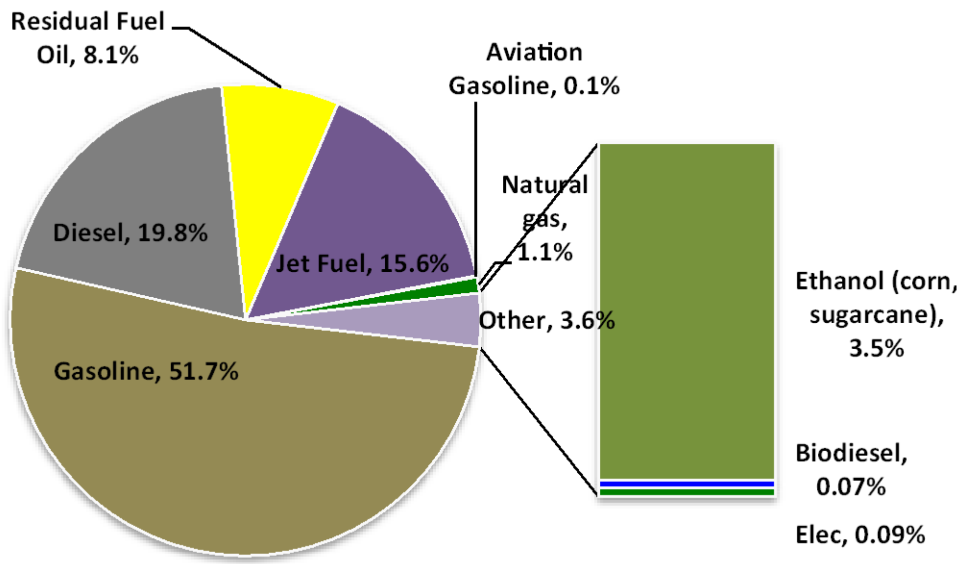
The exploitation of vast reserves of oil in the Monterey Shale in California could potentially produce as much as 15.5 billion barrels of oil (U.S. EIA 2011), which would have huge local

[2] Transportation emissions are primarily in-state emissions (77.8%), while the other 22.2% – 51.4 million metric tons CO_2 equivalent – comes from domestic and international aviation and international marine bunker fuel use. These emissions are reported but not included in the state emission inventory.

water use and water quality impacts. In its 2014 update, however, the EIA reduced its estimates of recoverable oil from the Monterey to only 600 million barrels, far below the 2012 estimate of 13.7 billion barrels of oil (EIA, 2012a). At the same time, as California implements climate policies to reduce GHG emissions from all sectors, transportation fuel uses could significantly shift to alternative fuel sources that include more use of biofuels, natural gas, electricity, and hydrogen (McCollum, Yang et al. 2012, Wei, Nelson et al. 2012, Greenblatt 2013, Morrison, Eggert et al. 2014). Many of these pathways have higher water use intensity than petroleum and gasoline (Webber 2007), King and Webber (2008), (King and Webber 2008, Harto, Meyers et al. 2010, Mishra and Yeh 2010). Many energy technologies critical for climate change mitigation, with a mid- to long-term deployment range, will require substantial quantities of water, and can have impacts on water quality (Macknick, Sattler et al. 2012, Madden, Lewis et al. 2013). Such technologies include concentrated solar power (CSP) (Norwood and Kammen 2012), enhanced geothermal systems (EGS) (Mishra, Glassley et al. 2011), crop-based biofuels (Fingerman, Torn et al. 2010, Mishra and Yeh 2011, UNEP 2011), hydrogen produced via electrolysis pathways, and carbon capture and sequestration (CCS). Additionally, abundant and economical yet water-intensive fossil resources, such as shale gas and shale/tight oil, gas-to-liquid (GTL), and even coal-to-liquid (CTL), have been and will continue to be expanded despite their substantial GHG emissions. These technologies' water requirements create conflicts and management trade-offs, especially in water-scarce regions such as California (Bayart, Bulle et al. 2010, Yates and Miller 2013).

However, significant opportunities exist to minimize the water intensity of future transportation fuels through judicious selection and locating/sourcing of fuels feedstock, production technologies, and demand management. Wind and solar photovoltaic (PV) technologies have a considerably lower lifecycle water consumption intensity (per kWh) than most thermoelectric electric generation plants (Davies, Kyle et al. 2012). Even with thermal power plants, dry cooling system can significantly reduce water withdrawals and consumption. Biofuels produced from waste materials also require very little water. Most of the water measures included in the 2014 Scoping Plan focused on the GHG emission benefits derived from reduced energy use, and the emission benefits are reflected in those sectors (CARB 2014). Nevertheless, significant synergies in energy and water management can be achieved through combined policies in promoting energy efficiency, water conservation, renewable or waste-based energy pathways (e.g. solar and wind energy, waste-based biofuels), and technology (e.g. dry cooling technology). Scenarios are developed in the next section to highlight these synergies, as well as the consequences of lack of coordination between energy and water management.

Figure1.1: California's Transportation Energy Consumption in 2012 (3479 PJ).



Source: EIA (2012b).

1.3 Scenarios

This report explores the water use implications of four 'bounding cases' that illustrate California's potential future transportation energy-water portfolios along two axes (GHG mitigation vs. water use intensity). Each axis is represented by 'low' versus 'high' at either end of the axis. Water use intensity (WUI) is defined as the net consumptive water use per unit energy produced or converted, for a single stage or across the entire lifecycle. Water and energy use are reported in the International system (SI) of units, with water reported in volumetric units (liters), and energy in joules and megawatt-hours.

2020 GHG emission goals and *Baseline* WUI: California is already committed to meet its 2020 GHG reduction target and its likely to succeed, thus the *Reference* scenario is one that meets California's 2020 GHG emission reduction target and future WUI of technology in each transportation fuel pathway will continue the current trend;

2020 GHG emission goals and '*Smart*' water use (Low WUI): represents the transportation fuel mix meeting 2020 GHG goals, with the WUI of transportation fuel pathways decreasing due to aggressive and forward-thinking planning and management in water use and water impacts. This scenario substitutes recycled water for freshwater;

Low-GHG emissions and *Baseline* WUI: represents the transportation fuel mix contributing to the longer-term 2050 GHG goals (i.e. greater GHG emission reductions beyond the 2020 requirement), with the WUI of transportation fuel pathways continuing at historical baseline trends due to lack of planning and management in water use and water impacts;

Low-GHG emissions and *'Smart'* water use (Low WUI): represents the transportation fuel mix contributing to the longer-term 2050 GHG goals, with careful planning and, to the extent possible, siting of low-carbon, low-water intensities of transportation fuel pathways to reduce overall water use and water impacts inside California as well as outside the state.

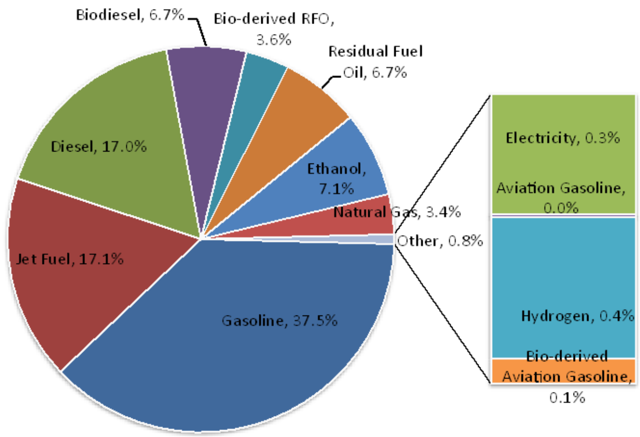
The four bounding scenarios represent possible trends of transportation fuel use and their water use and water impacts in California (and to a lesser extent federally and globally) in 2030 given energy and climate policies and technology advancement/investment possibilities. These scenarios are summarized in Table 1.1. The total energy requirements for transportation decrease relative to 2012 by 14% under the *Reference* scenario, and by 26% under the *Deep GHG* scenario. Interestingly, the fraction of transport energy coming from petroleum-based fuels decreases from 95% in the base year to 78% under both climate mitigation scenarios.

This report is structured as follows. Section 2 reviews methodologies for characterizing lifecycle water use of fuel pathways, and present the methods in calculating water use lifecycle analysis. Section 3 applies these methods, to estimate the current WUI values, as well as water sources and fates, of California's transportation energy pathways. The WUI and water use is projected for each of the four scenarios in 2030 in Section 4. Chapter 4 examines the spatial distribution of water use impacts within the state, as well as the aggregated statewide water impacts. The total aggregated impacts for the state are discussed in Section 5. The final Section discusses the implications of the results and proposes future research directions.

Table 1.1: Scenario Analysis of Water Use Impacts of Future Transport Pathways in 2030.

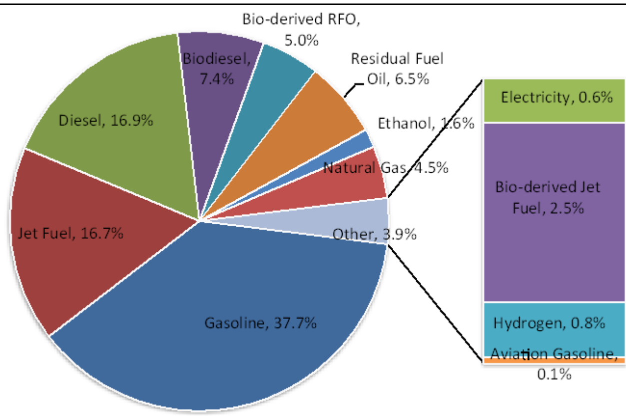
GHG Mitigation Level	Water Use Intensity (WUI) / Water Use Management	
2020 GHG Emission Goals (Reference)	The WUI of each transportation pathway follows recent historical trends (or remains constant), water sourced primarily from freshwater; **Oil & Gas**: increased reliance on recycled and produced water for secondary production and fracking. **Biofuels:** meet the federal biofuel program (M-RFS2) target. **Electricity:** All new power plants have either dry cooling or hybrid cooling technologies.	Low WUI *Water 'Smart'*
	Oil & Gas: Large share of unconventional oil resources – Monterey Shale oil, Canadian oil sands; **Biofuels:** limited food-crop based biofuels from corn and soybean (BEPAM BAU scenario); **Electricity:** Dominance of wet recirculating cooling technologies.	High WUI *'Baseline'*
2050 GHG Emission Goals (Deep GHG)	**Oil & Gas**: increased reliance on recycled and produced water for secondary production and fracking. **Biofuels**: meet the federal biofuel program (M-RFS2) target, as well as a federal Low Carbon Fuel Standard (LCFS); **Electricity**: high share of renewable electricity from wind and geothermal; All new power plants have either dry cooling or hybrid cooling technologies.	Low WUI *Water 'Smart'*
	Oil & Gas: Large share of unconventional oil resources – Monterey Shale, Canadian oil sands; **Biofuels**: meet the federal biofuel program (M-RFS2) target, as well as a federal Low Carbon Fuel Standard (LCFS); **Electricity**: Dominance of wet recirculating cooling technologies.	High WUI *'Baseline'*

2020 GHG Emission Goals (Reference):



Total = 3830 PJ; non-petroleum = 21.7%

2050 GHG Emission Goals (Deep GHG):



Total = 3420 PJ; non-petroleum = 22.2%

Total transportation energy use in 2012 was 3479 PJ. Bio-RFO is bio-derived residue fuel oil

CHAPTER 2:
Lifecycle Water Use Intensity of Transport Fuels

2.1 Analytic Framework and Fuel Types Considered

Lifecycle analysis (LCA) is a method that has developed over the past half century to examine the environmental impacts of products, production systems, and more recently, policies (Guinee, Heijungs et al. 2010). One example of the use of LCA as a tool that informs policy is in measuring the environmental impacts of transportation fuels. LCA methods have shown that vehicle tailpipe emissions account for roughly 80% of lifecycle GHG emissions from conventional gasoline but effectively zero percent from electricity or hydrogen; instead, in the case of these alternative energy sources, most of the emissions occur upstream (GREET 2010). The water use impacts of current and future transportation fuels occur mostly upstream during feedstock production stages, such in gas extraction or cultivation in the case of biofuels, refining in the case of fossil fuels, and in conversion stages (Webber 2007, King and Webber 2008, King and Webber 2008, Harto, Meyers et al. 2010, Mishra and Yeh 2010). Therefore, developing a transparent and consistent framework for measuring the lifecycle impacts of water use for transportation fuels is critically important for future policy planning and management.

This analysis does not include all possible future transportation fuel pathways, but focuses on the following selected feedstock/fuel pathways:

- **Petroleum fuels (gasoline, diesel, and other petroleum products):** includes conventional and unconventional extraction of oil, with more detailed analysis for California and using average numbers for Alaska, and the rest of the world. Conventional sources include primary, secondary, and tertiary technologies in California. Unconventional sources include Canadian oil sands, and vertical and horizontal fracking of unconventional oil in tight and shale formations. Only onshore oil production is considered, as offshore projects do not entail direct tradeoffs with other water users.

- **Biofuels**: includes food-based biofuel feedstock (corn and soy), energy crops (switchgrass and miscanthus), and biofuel production from wastes and agricultural residue. The *marginal* impacts of biofuels is assessed, taking into account potential land use change and changes in agricultural patterns and management across the U.S. given federal policy (the modified Renewable Fuel Standard, M-RFS2) and the potential extension of California's Low Carbon Fuel Standard (LCFS) to the national level.

- **Electricity:** includes all current and possible future sources of electricity generation in California: nuclear (light water reactors), coal steam (from imports), biomass, integrated gasification combined cycle (IGCC), geothermal (binary plant and flash), solar (photovoltaic, and thermal), wind, and natural gas (natural gas combined cycle [NGCC], steam boiler and combustion turbine [CT].

- **Natural Gas:** includes conventional and unconventional gas. Unconventional extraction methods considered include vertical and horizontal fracking in tight and shale formations.

2.1.1 Water use LCA across Four Energy Pathways

Methods in water use LCA (WULCA) have matured much over the past decade – they have incorporated methods from *water footprinting* (Gerbens-Leenes, Hoekstra et al. 2009, Hoekstra, Chapagain et al. 2009, Berger and Finkbeiner 2010, Scown, Horvath et al. 2011) and an emerging recognition of the need to link water inventories and impact assessments to hydrological modeling (Gheewala, Berndes et al. 2011, Jewitt and Kunz 2011). Section 2.2, reviews the current consensus and unresolved issues in WULCA. Figure 2.1 shows a schematic diagram of water use of different fuel pathways throughout the corresponding production chains and the portions of lifecycle that are considered in this analysis.

Figure 2.1: System Boundaries for Water Use Intensity of Future Transport Fuels.

Processes considered in the study are in black, those outside of the lifecycle boundary are in red.

This study builds on the outputs of two economic models, CA-TIMES and BEPAM, as the starting point. For most energy supply chains, California-specific and literature values for water use to estimate the water use intensity (WUI), which is defined as the net liters of water consumed per unit of energy, e.g. megajoule (MJ) or megawatt (MW), produced or converted, for a single stage or across the entire lifecycle .

The outputs of energy-economic models, which project under various scenarios the energy supply infrastructure and volumes of fossil fuels and electricity consumed in California (in the case of CA-TIMES), and national cropping patterns (in the case of BEPAM), are the starting point for estimating the water use in 2030. Table 2.1 shows the methods, assumptions and data sources used for each energy pathway, and outlines the sources and assumptions taken for projecting fuel and water use.

2.2 Projections of Water Use across Type, Source, Space and Time

This study combines available data sources with economic models to (1) *quantify and categorize current water use* and (2) *project water use in 2030*. The water use LCA analysis captures following dimensions:

Water type (source). Water sources can be disaggregated according to water quality (e.g. fresh, saline, degraded), storage type (e.g. green water or soil moisture, versus blue water or irrigation; and by surface versus groundwater sources), and modality of water use (i.e. consumption vs. withdrawals). The definitions vary by energy pathway, and the environmental impacts and economic tradeoffs vary by water type. Table 2.2 shows the breakdown of water *sources* and *fates* by energy pathway.

Water disposition (fate). Water used by the energy sector may ultimately be re-discharged into the immediate environment (as in the case of runoff and groundwater infiltration in growing biofuels feedstocks, or discharge into lakes and streams in the case of electricity generation with once-through cooling), evaporated (as in lined sumps and evaporation ponds in petroleum production), or re-injected into deep wells for disposal. The fate of water volumes used along energy supply chains may have environmental and economic consequences, particularly in cases where water quality has been substantially altered or compromised.

Table 2.1: Methodologies for Estimating Future Water Use Intensity by Energy Pathway.

Fuel	Water use intensity (WUI)	Projection of fuel use	Projection of fuel source	Projection of water use
Crude-derived fuels	California-specific and/or literature reviewed values for oil production. If needed, allocation o f water use to products is based on energy content.	CA-TIMES projections of petroleum-based liquid fuels demand.	California oil production: California Energy Commission (CEC) projections of low/high rates of gradual decline in future oil production; Domestic imports: EIA projections of shale oil production. International imports: Based on current proportions of imports from Alaska, Canada, and the rest of the world (ROW).	Literature review and regression analysis of California-specific technology- and water-use-intensity trends to estimate WUI of in-state and out-of-state crude oil extraction and refining.
Natural gas (NG)	Values for oil production based on literature review. When appropriate, allocation of water use to oil/gas products is based on energy content as a lower bound.	CA-TIMES estimates of NG use in transportation, as well as estimated water use from domestic conventional and shale gas production.	California gas production: oil/gas production estimates from the CEC; Domestic imports: EIA projections of Monetary Shale gas production domestic shale versus conventional gas production.	Literature review of water use intensity (WUI) ranges for traditional NG & shale gas.
Biofuels	The water use impacts are estimated with a process-based crop-water model with and without biofuel policies, using a partial-equilibrium model (BEPAM).	BEPAM projections of volumes and share of biofuels from first and second-generation feedstock under alternative biofuel/carbon policy scenarios.	CA-TIMES projections of in-state vs. out-of-state biomass feedstock. In-state biofuel mostly comes from wastes; out-of-state biofuel uses BEPAM scenario estimates of conventional and second-generation feedstock cultivation (including row crops, agricultural residues, and dedicated feedstocks).	Daily time step calculation of FAO 56 crop water balances to project water flows. Downscaled 10-kilometer resolution of cropping practices & land-use changes. Spatial analysis of soil type, cropping, & weather data (USGS, USDA, NCAR, etc.).
Electricity	California-specific and/or literature reviewed values for electric generation.	CA-TIMES estimates for electricity sources broken down by conversion technologies. Scenario-based projection of share of cooling technologies.	CA-TIMES estimates of total electricity production; the extent of in-state production comes from a separate ten-model comparison work (the California Climate Policy Modeling Dialogue).	WUI of generation based on review of EIA database & power plant licensing documents. Literature review to estimate volume and WUI of in-state and out-of-state feedstock extraction.

Table 2.2: Water Source and Disposition by Energy Pathway.

Pathway	Source	Disposition
Oil & gas production	• Produced; • Fresh (groundwater, domestic); • Waste (domestic waste, industrial waste). • Other (ocean, combination, and 'other' – i.e. unspecified);	• Evaporation ponds (line sump; percolation); • Injected into subsurface wells; • Sewer; • Surface.
Oil refining	• Degraded; • Fresh; • Potable.	• Other
Electricity	• Freshwater (slightly brackish water); • Degraded (degraded groundwater, degraded surface water); • Recycled; • Ocean.	• Evaporation; • Surface water.
Biofuels	• Irrigation (withdrawal, application losses, conveyance losses); • Rainwater.	• Evaporation & off-season transpiration; • Transpiration; • Groundwater infiltration; • Runoff.

Spatial location of water use in California. In 2005, 74% of the freshwater withdrawals were used for irrigation. Agriculture consumes more than 40% of California's freshwater, and from 52% (during a dry year) to 80% of the 'developed'[3] water supply (Hanson 2008). However, these averages mask substantial spatial heterogeneity: irrigation withdrawals may range from 1% to 99% of total water withdrawals by county (Kenny, Barber et al. 2009). Similarly, water scarcity is not uniformly distributed across California. About 75% of groundwater originates from north of Sacramento, while 80% of demand is in the southern part of California.

It is unknown how climate change may impact water stress in the future, though it will also likely alter precipitation patterns, with some areas becoming wetter and others becoming drier (IPCC 2007, McDonald, Green et al. 2011). Barnett et al. (2004) found that even with a conservative climate model, current demands on water resources in many parts of the West will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy (Barnett, Malone et al. 2004).

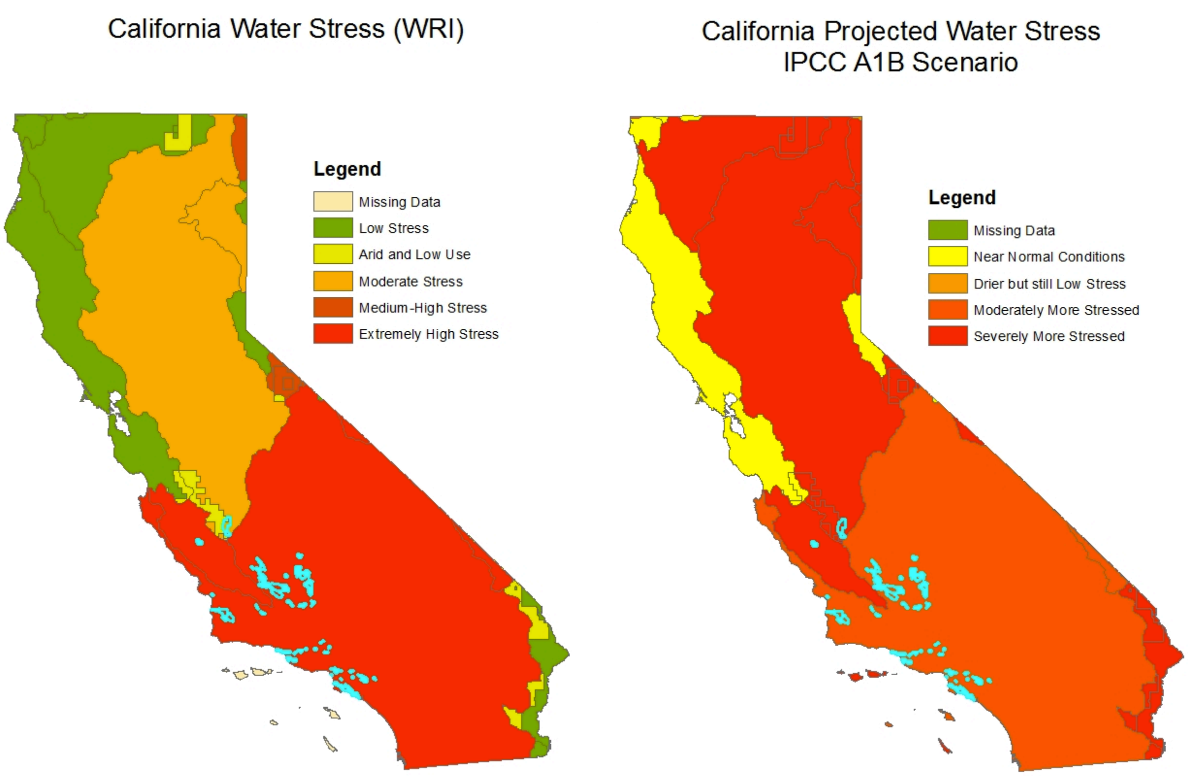
Figure 2.3 (left) below shows the current groundwater stress (groundwater withdrawal/recharge) is in Southern California. Spatially disaggregated water use analysis provides more meaningful information for planners and policymakers for making appropriate

[3] 'Developed' water includes water that requires infrastructure for delivery to economic uses, and thus excludes 'dedicated' water for environmental uses, as well direct agricultural usage of rainwater.

decisions (e.g. regarding technology and investment portfolio) in the context of tradeoffs between energy and water availability.

Temporal trends of water use in California. Water scarcity is projected to increase in California over time due to population growth, increased demand, and climate change (Draper, Jenkins et al. 2003, Tanaka, Zhu et al. 2006, Vicuna and Dracup 2007, Medellín-Azuara, Harou et al. 2008). As shown in Figure 2.3 (right), estimates by the Water Resources Institute (2009) suggest that the majority of California's 58 counties will be either moderately or severely stressed by 2025. Using an energy-economic model, total water use over time given population growth, increased demand, and climate/energy policies is taken into account. These are discussed in more detail in Section 4 of this report.

Figure 2.2: Projected Change in Groundwater Stress in California Due to Climate Change.



Current stress levels (left) and stress as projected in 2025 under the IPCC A1B Scenario (right).

Source: Reig, Shiao et al. (2013)

CHAPTER 3:
Lifecycle Water Intensity of Key Fuel Pathways

In this section, methods are detailed for estimating and allocating current net consumptive water use, or water use intensity of the four key energy supply chains serving California's transport demand. A review of the relevant literature estimating the water use intensity (WUI) and discussion of the water quality impacts of each of these supply chains follows. Methods and assumptions are outlined for tracking the water sources and fates of water volumes withdrawn and consumed. Analysis of current water use includes maps of energy production and processing (refining), together with volumes of water consumed or released, by type and disposition, respectively. In addition to WUI values, aggregate water use within California is reported, as well as water use incurred from imports of primary or processed energy resources.

3.1 Oil

3.1.1 Conventional Oil and Gas Resources

Conventional oil production entails some or all of the following operations, each of which may have water resource impacts: (1) construction of access roads, production and processing facilities; (2) producing power required for extraction and other processes; (3) producing the oil; (4) refining and upgrading operations (e.g. retorting, stabilization); (5) underground and surface-level mining and extraction operations (including dust control, equipment cleaning, etc.), and (6) holding, treatment, and discharge of produced water. In this study, the system boundary only includes power production (2), oil extraction (3), and refining (4) water use, which constitute the majority of the lifecycle water use of oil production (Gleick 1994, Mielke, Anadon et al. 2010). Also the disposition of produced water (6) is tracked.

Because oil and gas are often coproduced, despite the fact that drilling operations typically target one or the other resource, depending on the profitability at the time of well construction and initial production. In cases where oil and gas are coproduced, WUI is reported in terms of liters water per energy (e.g. GJ) extracted.

3.1.2 Water Use for Oil Extraction in California

California oil production has been declining since its peak in 1985. In 2009, California had 52,186 wells that produced approximately 197.5 million barrels (MMbbl) of crude oil (DOGGR 2012). In 2012, California was the third largest oil producing state in the U.S. (ranked after Texas and North Dakota and before Alaska), producing 196.3 MMbbl of oil (EIA 2013b). Although production has been declining, the EIA estimates that there are still 3,005 MMbbl of proven reserves in the state as of 2011 (EIA 2013a). Water use is a critical input to the petroleum production process, from extraction to refining. Water resources are severely constrained in California, and competition for water has become intense (Hanak, Lund et al. 2011).

Conventional oil is recovered either by primary, secondary, or tertiary recovery techniques. Suitable recovery technologies vary depending on a number of factors, including the field geology and the well age. The water intensity of petroleum extraction and refining varies greatly by type of recovery technology but the literature has not explicitly estimated water use associated with oil and gas extraction in California. Tracking historical trends and projecting potential future oil & gas water use is particularly important in light of possible water conflicts with agricultural and domestic use, especially with the recorded trends of high water use for diminishing oil return. A deeper understanding of spatial and temporal variation in water use intensity is needed to correctly predict potential water conflicts in California.

In petroleum production, water is injected into oil and gas wells and water is produced along with oil and gas. The produced water is either re-injected into the oil & gas wells for additional recovery, discharged in disposal pools, or, in specific cases, returned to the watershed for use by other sectors. The produced water, which is highly saline and contains a wide variety of inorganic ions, toxins, heavy metals, and naturally occurring radioactive materials (NORMs)[4], poses a variety of environmental problems, including migratory bird mortality and off-gassing of evaporation ponds (Thoma 2009). On the other hand, there are many potential "beneficial uses" of produced water – where the later term is a catch-all for recycling of produced water for crop irrigation, livestock watering, stream flow augmentation, and municipal and industrial uses (Shaffer, Arias Chavez et al. 2013) – – for instance, certain oil production operations in Kern county treat produced water so that it can be reused for irrigation. However, there is evidence of health and ecological impacts of surface water disposal of produced water (Shaffer, Arias Chavez et al. 2013, Shariq 2013), and so recycling for 'beneficial uses' should be carefully regulated and monitored to ensure that risks are minimized.

Literature Estimates of WUI by Technology

Water use intensity (WUI) is defined as the total net consumptive use of water volumes (typically in barrels or liters) injected to recover one unit (typically reported in either energy or volumetric units, e.g. MJ or liters, respectively) of oil (and/or gas if gas is co-produced with oil extraction). Primary recovery uses the natural pressure of the oil well to bring crude oil to the surface. Primary extraction is the dominant recovery technology for off-shore recovery, which in turn constitutes 20% of total recovery in the U.S. in 2012 (EIA 2013a), though off-shore wells may be either primary or secondary (Bibars and Hanafy).

The volume of water injected for tertiary recovery (EOR) is highly variable, and dependent on technology and location/geology (Table 3.1). Water use intensity may be as low as 1.9 liters of

[4] Concentrations of produced water vary by geological formation, water treatment technology, and extraction technology. Christie (2012) identifies and analyses the environmental impacts of common constituents of produced water, which include the following: inorganic ions (which contribute to high salinity levels – including sodium, chloride, calcium, magnesium, potassium, sulfate, bromide, bicarbonate, and iodide); heavy metals (barium, cadmium, chromium, copper, lead, mercury, nickel, silver and zinc, as well as traces of other metals including aluminum, boron, iron, lithium, manganese, selenium, and strontium); volatile organic compounds, and radioactive isotopes (e.g. radium, barium).

water per liter of oil (L/L) recovered with forward combustion[5] technology, or as high as 343 L/L with micellar polymer injection[6] technology (Gleick 1994, Wu, Mintz et al. 2009). The estimated WUI of CO_2 injection technologies vary from 4.3 L/L (Barry 2007), 13 L/L (Royce, Kaplan et al. 1984) to 24.7 L/L (Gleick 1994), though the range typically cited in the literature is 8.7- 24.7 L/L of oil recovered (Gleick 1994, King and Webber 2008, Wu, Mintz et al. 2009, Scown, Horvath et al. 2011).

Table 3.1: Water Use Intensity of Conventional Oil Production by Technology.

Type of extraction	WUI (L water/L oil)	Source	Notes
Primary	1.4	Gleick (1994)	
Secondary	8.6	Bush and Helander (1968)	
Tertiary (EOR)			
Steam	5.4	Gleick (1994)	
	4.1 - 168	Brandt (2010); Kovscek (2012)	For year 2006, estimates used to quantify CO_2 emissions
Cyclic steam	1.1 - 85	Brandt (2010); Kovscek (2012)	For year 2006, estimates used to quantify CO_2 emissions
CO_2	13	Royce (1984)	Survey of 14 oil companies
	24.7	Gleick (1994)	
	4.3	Barry (2007)	Shell's Denver City project (1988-1998 average)
Caustic	3.87	Gleick (1994)	
Forward combustion	1.93	Gleick (1994)	
Other	8.7	Gleick (1994)	
Micellar polymer injection	343.17	Gleick (1994)	Not currently practiced in U.S.

Water Use of California Oil and Gas Extraction

To assess current water use and project future use of petroleum production in California, detailed, California-specific data are used to depict a temporal and spatial picture of water use and water disposition for oil production in California from 1999 to 2012. The majority of data

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[5] Forward combustion technology, or in-situ combustion, is a process by which air is injected or air and water are co-injected into the reservoir. The oil is ignited to reduce viscosity, and is driven upwards by the combination of the gas drive from the combustion gases, a steam drive and a water drive. This process is also called fire flooding.

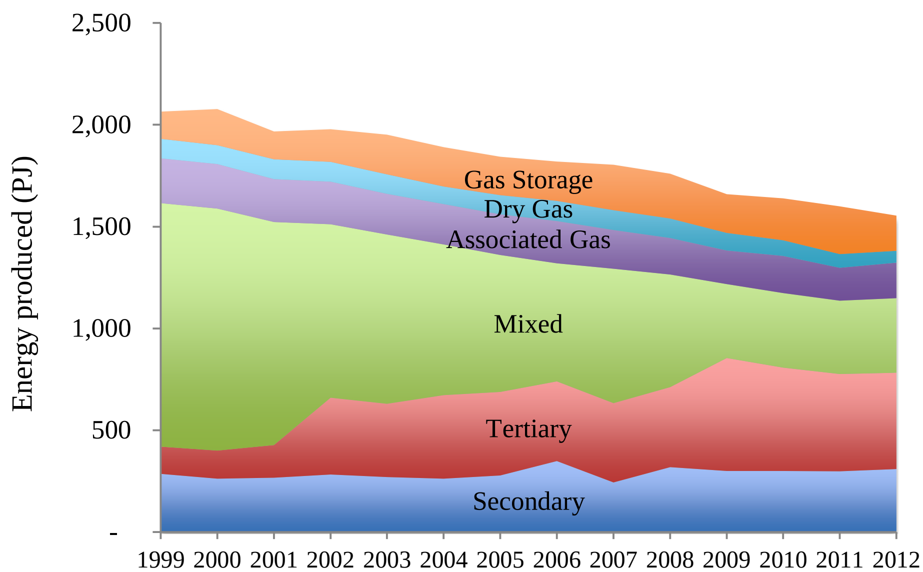
[6] Micellar polymer injection comprises four separate injection phases; a pre-flush, micro-emulsion, an injection of polymer solution to increase viscosity, and a final brine injection (Donaldson et al. 1989).

comes from Department of Oil, Gas, and Geothermal Resources (DOGGR) of the California Department of Conservation.

DOGGR collects data on the state's oil and gas production (DOGGR 2013b),[7] water injection (DOGGR 2013a), and disposition of water (DOGGR 2013b). The production database provides the estimated volumes of oil, gas, and produced water generated on a monthly basis by O&G wells within the state. The data is sorted by well type (including oil, gas and dry gas production) and includes information on the disposition of produced water, including injection into ground wells, sewer systems, and ground water disposal. Of the oil recovered in California, the vast majority was produced in wells classified as oil and gas wells in 2012 (Figure 3.1). A small percentage was produced in wells classified as dry (unassociated) gas. For the purposes of this analysis examining WUI of oil extraction, only wells classified as oil or oil and gas wells are included.

The use of tertiary production has drastically increased in California's oil fields over the past decade (from 7.9% in 1999 to 39.3% in 2012) to become the dominant method of production in 2012. The DOGGR database classifies between secondary extraction (water flooding), and the two dominant tertiary technologies: steam flooding and cyclic steam. Figure 3.1 shows the overall oil and gas production by production (or storage) and technology type from 1999-2012.

Figure 3.1: Oil and Gas Production (and Storage) by Technology Type in California.



Source: DOGGR (2013b).

[7] ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/

Roughly 47% of the gas produced in 2012 in California was generated in wells that coproduce oil and gas (Table 3.2). Natural gas produced from an oil & gas well is captured on site as flaring is prohibited in California. The produced natural gas is then marketed, or in the case of tertiary production, first used on site for steam production, after which unused gas is sold on the market (Brandt 2011). The median value of natural gas to oil produced is 0.013 MJ gas/MJ oil and the production-weighted average was 0.74 MJ natural gas/MJ oil in 2012. To properly attribute net water use to oil and gas, water use is allocated to oil only (upper bound for WUI) and oil & gas production (lower bound for WUI) by extraction technology. More detailed discussion of the methodology can be found in Appendix C.

Table 3.2: Oil and Gas Production by Well Type in 2012.

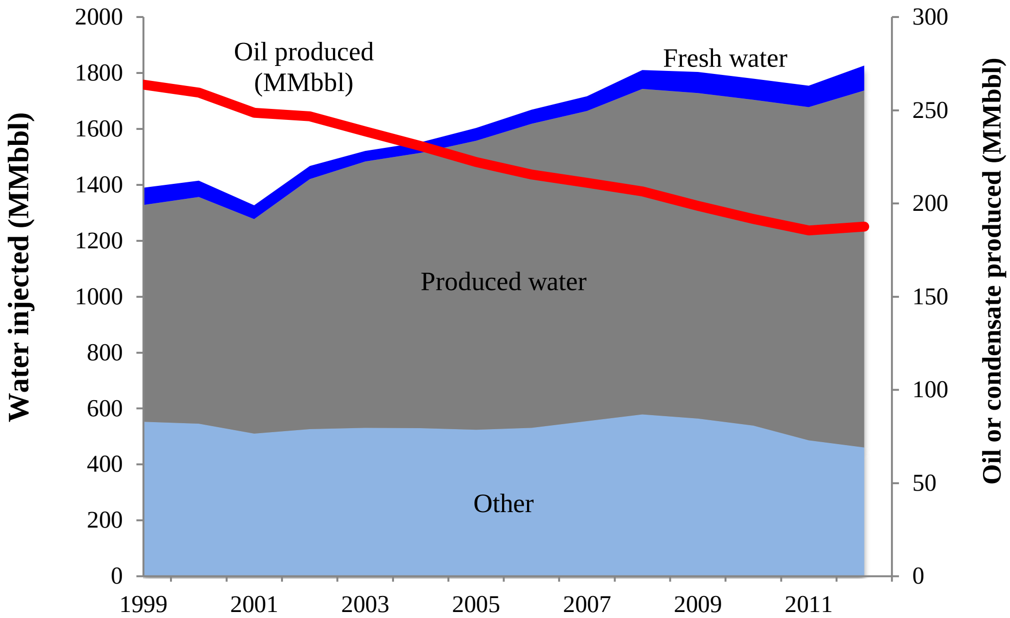
Fuel produced	Oil and gas wells	Dry gas wells
Oil (barrels)	196,084,435	67,293
Gas (million cubic feet)	186,623,730	53,519,190

Source: DOGGR (2013b).

Water Injection

The overall trend in water use for oil production is pronounced. While oil production has decreased from 1999-2012, water injection of every type has increased (Figures 3.2 and 3.3). Roughly 70% of injected water was injected into secondary wells in 2012, with the remainder attributed to tertiary wells. Freshwater injection has increased from 9.8 billion liters in 1999 to 14.3 billion liters in 2012 even as oil production (in oil and gas wells) has decreased from 41.9 billion liters (263.7 MMbbl) to 29.8 billion liters (187.6 MMbbl) (Figure 3.2). This translates to more than a doubling of the fresh water/oil ratio over three years – from 0.22 L of water / L oil in 1999 to 0.46 L/L in 2012.

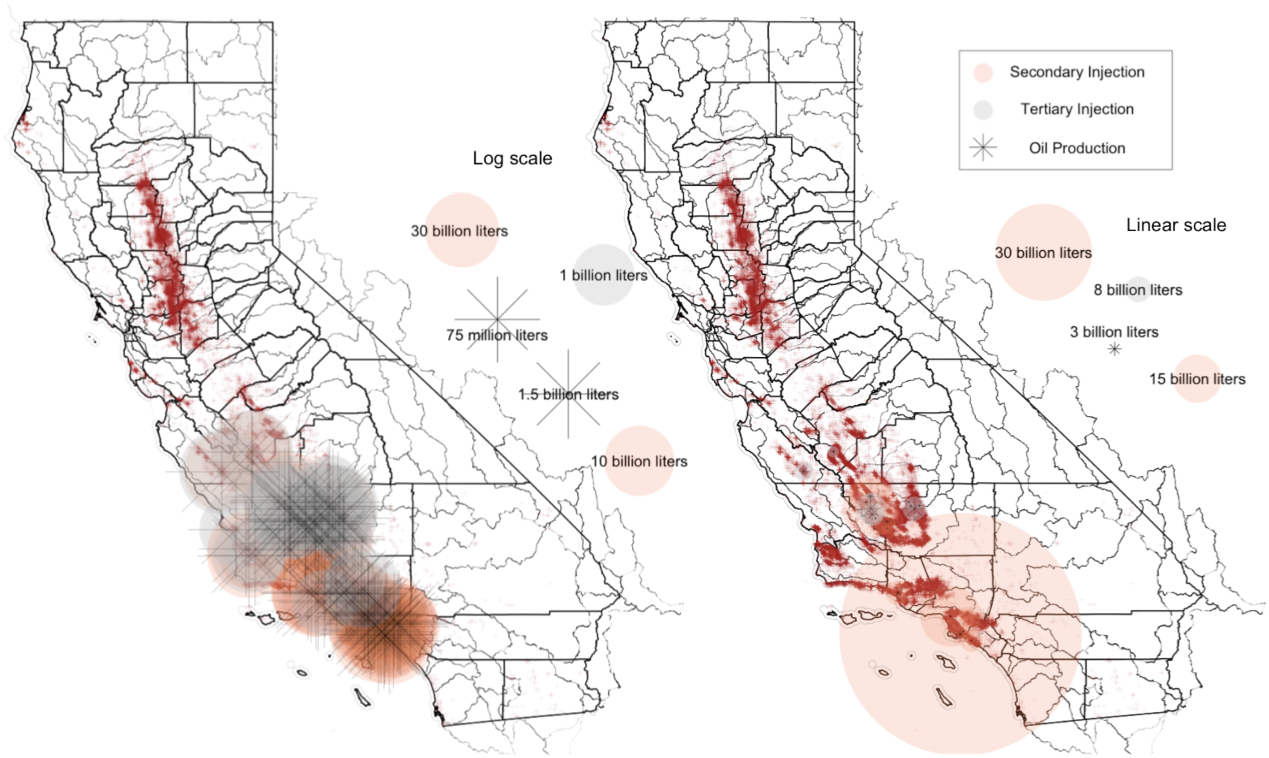
Figure 3.2: Water Injected by Type, and Oil or Condensate Produced in California.



Sources: (DOGGR 2013a, DOGGR 2013b)

A total of 215 billion liters (1,337 MMbbl) of water was injected into secondary wells in 2009: 3.5 billion liters of this was water classified as either groundwater or water from a water well and 1194 billion liters was produced water. In the same year, 75.4 billion liters of water was injected into tertiary wells: 10.9 billion liters was groundwater or water from a water well, and 32.4 billion liters was produced water. Figure 3.3 shows the spatial distribution of water injection by well type and oil production in 2012.

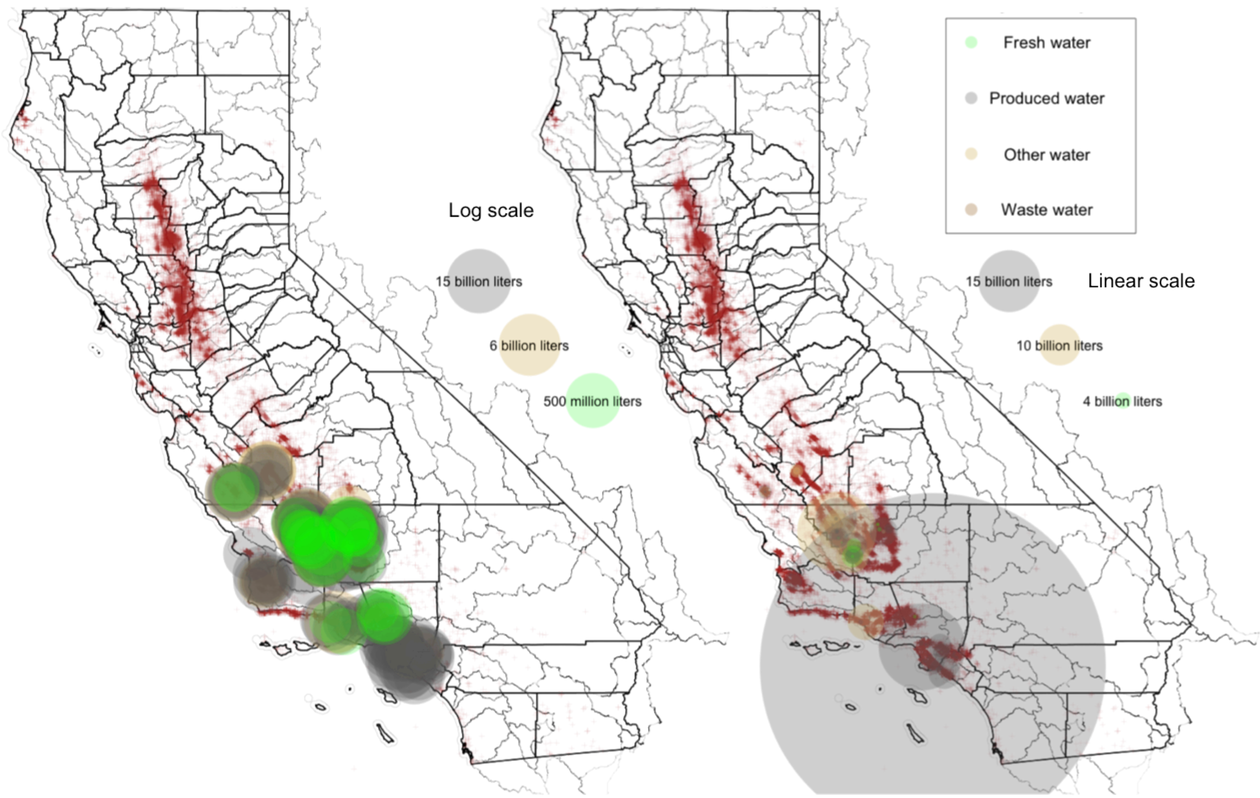
Figure 3.3: Gross Volumes of Water Injected into Oil Wells by Production Technology.



All volumes are for 2012. Gross water injection values are shown for secondary (orange) and tertiary (gray) production. The left-hand figure shows volumes in logarithmic scale, which is useful for visualizing volumes that are distributed over multiple orders of magnitude (as is the case with water injection and produced oil volumes). The right-hand figure shows the same information in a linear scale. Note that oil production volumes are plotted at one-quarter scale of water injection volumes. Dark-red fill indicates the locations of oil fields currently being produced in California.

Figure 3.4 shows total water injected in California by water type. The total water used has increased by 30% between 2009 and 1999 despite a 25% decrease in oil production. In 2009, 292 fields produced oil and gas in California, with the majority of oil production taking place in the Midway-Sunset, Belridge, South and Kern River fields. The types of water used include freshwater, saline water, water combined with chemicals, and 'other' types of water – a catchall category that includes mixed and unclassified sources.

Figure 3.4: Gross Volumes of Water Injected into Oil Wells by Water Type.

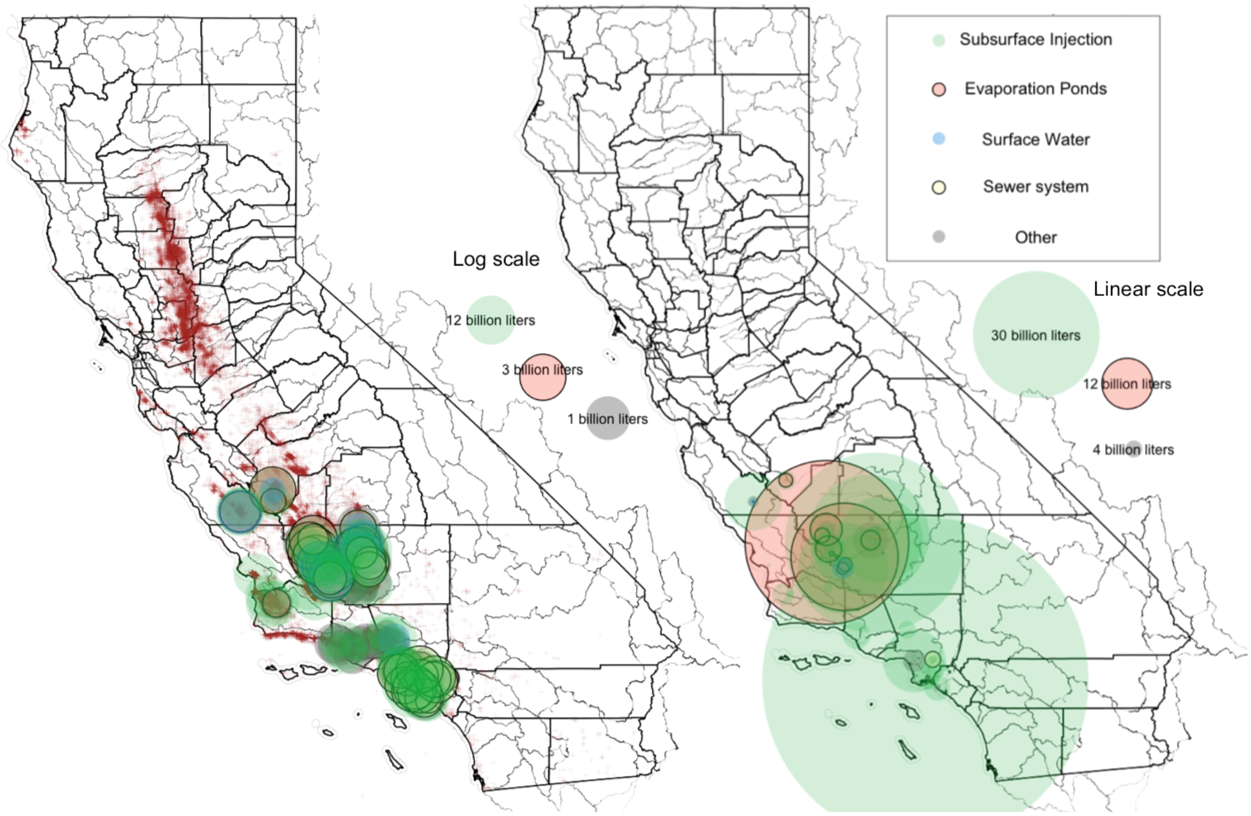


The left-hand figure shows volumes in logarithmic scale, which is useful for visualizing volumes that are distributed over multiple orders of magnitude (as is the case with water injection volumes). The right-hand figure shows the same information in a linear scale. Brown fill indicates the locations of oil fields currently being produced in California. All volumes shown are for 2012.

Water Disposition

Produced water is the water oil mixture extracted from oil wells in the recovery process. Crude oil and water are separated, and the produced water is then re-injected for additional oil recovery, sent to evaporation ponds, discharged to surface water or sewer systems, or injected into disposal wells. In 2012, the percentages were 65.2%, 21.5%, 2.0% and 1.5% for re-injection (for both production and disposal), evaporation, surface water, and sewer system disposal, respectively. Of water re-injected, 44.8% was re-injected into oil and gas wells as noted above, and 20.4% (92.6 billion liters of water) was disposed of in water disposal wells. The ratio of produced water to oil was 13.2 L water/L oil in 2012. Figure 3.5 shows the disposition of produced water in 2012 – a total of 435.7 billion liters of water was produced in that year.

Figure 3.5: Disposition of Produced Water from Oil Production in California.



Disposition (fate) of produced water for petroleum production in 2012. The left-hand figure shows volumes in logarithmic scale, which is useful for visualizing volumes that are distributed over multiple orders of magnitude (as is the case with water disposition). The majority (~65%) of produced water is reinjected into subsurface wells; 21.5% is sent to evaporation wells, 2.0% is released into surface water flows, and 1.5% is sent to sewer systems. Of water re-injected, 44.8% was re-injected into oil and gas wells, and 20.4% was disposed of in water disposal wells.

The WUI of California Oil Production

Water allocation for oil is conducted differently for secondary and tertiary production. For secondary extraction, or water flooding, net water use is either divided by total oil produced or allocated in proportion to the energy content of oil and gas produced. Tertiary technologies used in California oil fields include steam flooding and cyclic steam injection. In 2012, 70% of water injection in tertiary fields was for steam flooding, and 30% for cyclic steam. The water intensity of steam flooding and cyclic steam injection is calculated slightly differently. Both technologies use natural gas produced onsite or imported from elsewhere (if onsite production is insufficient) in cogeneration plants, and boil water to generate steam, which is then used to extract crude oil (Brandt 2011). The volume of natural gas required for steam generation to produce oil is therefore subtracted before allocating net water use to oil and gas produced. Table 3.4 summarizes the WUI of California's oil production in 2012 by production type and water type, providing the field-level mean, median, and 95th percentile gross injected water use intensity (WUI) and produced water intensity (PUI) for California's onshore oil production.

Table 3.3: Summary Statistics for WUI/PUI of California's Onshore Oil Production, 2012.

Type of extraction	Secondary	Tertiary	Mixed
Water use intensity (WUI)			
Fresh	**11.6**, (*1.6*), (35.6)	65, (*40*), (185)	**28**, (*27*), (52)
Produced	***353***, (*174*), (1167)	**41**, (*35*), (103)	**110**, (*51*), (373)
Waste	**--**, --, --	**--**, --, --	**1.4**, (*1.4*), (1.4)
Other/Mixed	**61**, (*21*), (223)	**30**, (*19*), (62)	**101**, (*80*), (235)
Total	**275**, (*189*), (1157)	**88**, (*95*), (193)	**197**, (*168*), (443)
			Produced water (PU)
Subsurface injection	**317**, (*179*), (948)	***354***, (*193*), (1120)	**303**, (*222*), (775)
Evaporation ponds	**74**, (*2.6*), (390)	**65**, (*29*), (240)	**103**, (*96*), (251)
Surface	**6.1**, (*0.7*), (31)	**8.7**, (*2.8*), (28.8)	**20**, (*1.3*), (70)
Sewer	**143**, (*15*), (552)	**0.32**, (*0.03*), (0.84)	**--**, --, --
Other	**57**, (*24*), (261)	**239**, (*67*), (1060)	**79**, (*41*), (280)
Total	**370**, (*269*), (1175)	**468**, (*317*), (1728)	**478**, (*396*), (793)

All units are in L/GJ. Mean values in bold, median values in (italics), 95th percentile values in (parentheses). Water use intensity (WUI) here refers to gross water injection volumes by water source type. All values are for only the population of fields that use the particular type of water (i.e. zero values are excluded in the distribution). Produced water use intensity (PUI) refers to water releases by disposition (fate).

As California oil fields age, more intensive methods are needed to recover remaining oil (Höök 2009). The number and proportion of EOR projects in California are both increasing (OIL & GASJ 2012a) and thus the WUI of oil extraction can be expected to increase as the split of extraction methods shifts from secondary to tertiary production in California. Regressions are fit on a field-by-field level using two functional forms: untransformed Ordinary Least Squares (OLS) and OLS based on a log-transformation of gross injected water volumes, against field age as the single independent variable. For further details, see Appendix C.

3.1.3 Refinery Water Use in California

The capacity of California's refineries decreased through the 1980s-1990s, followed by a slight uptick in capacity in the 2000s (Sheridan 2006). As of 2013, there were sixteen refineries operating in California, with an operable combined capacity of 1.95 MMbbl per calendar day (EIA 2013e). The California Energy Commission (CEC) estimates the state's refineries run on average at about 90-95% of capacity. The water required to refine crude oil varies by location and type of oil. The majority of water is used for cooling, with some additional volumes used for boiler feed, processing, sanitary services, and fire protection.

Recent studies estimate net water consumption WUI values of 1.0 to 1.9 liters of water to refine one liter of crude oil in the U.S., with a median value of 1.53 L/L (Gleick 1994, Buchan and Arena 2006, Wu, Mintz et al. 2009). The water used for refining is typically extracted from fresh surface water or fresh or degraded surface or groundwater sources, recycled water, or wastewater. Most refineries located in California have annual contracts with their respective counties allotting them a given volume of surface water in that year. For instance, the Valero refinery in Benicia is allocated 5.21 million gallons per day (1.9 billion gallons per year) by the city of Benicia (Benicia 2008). Several refineries, including BP's Carson refinery, have their own groundwater wells on site which supply 1.4 mgd of the total 4.1 required (CEC 2012). Groundwater is considered degraded if the salinity content is greater than 1000 ppm. Resolution No. 89-39 set 3000 mg/L as the maximum TDS concentration for a municipal or domestic water supply (CRWQCB 2013).

In total, California refineries used roughly 147 billion liters of water in 2012, which equates to approximately 1.1 liters of net consumptive water use per liter of refined crude (see Figure 3.6). The water use intensity of refineries ranged from 0.74 L water/L refined product (Valero, Benicia) to 1.41 L/L (ConocoPhillips 66, Wilmington). The range in water use Total freshwater use was 0.53 L/L with a maximum of 1.38 L/L (Shell, Martinez) and a minimum of no freshwater use for the Paramount Petroleum operations in Santa Maria. Table 3.4 shows the plant specific data, taken from various recent CEC and EIA reports and Environmental Impact Reviews.

Table 3.4: California's Operating Oil Refineries – Capacity and Water Use.

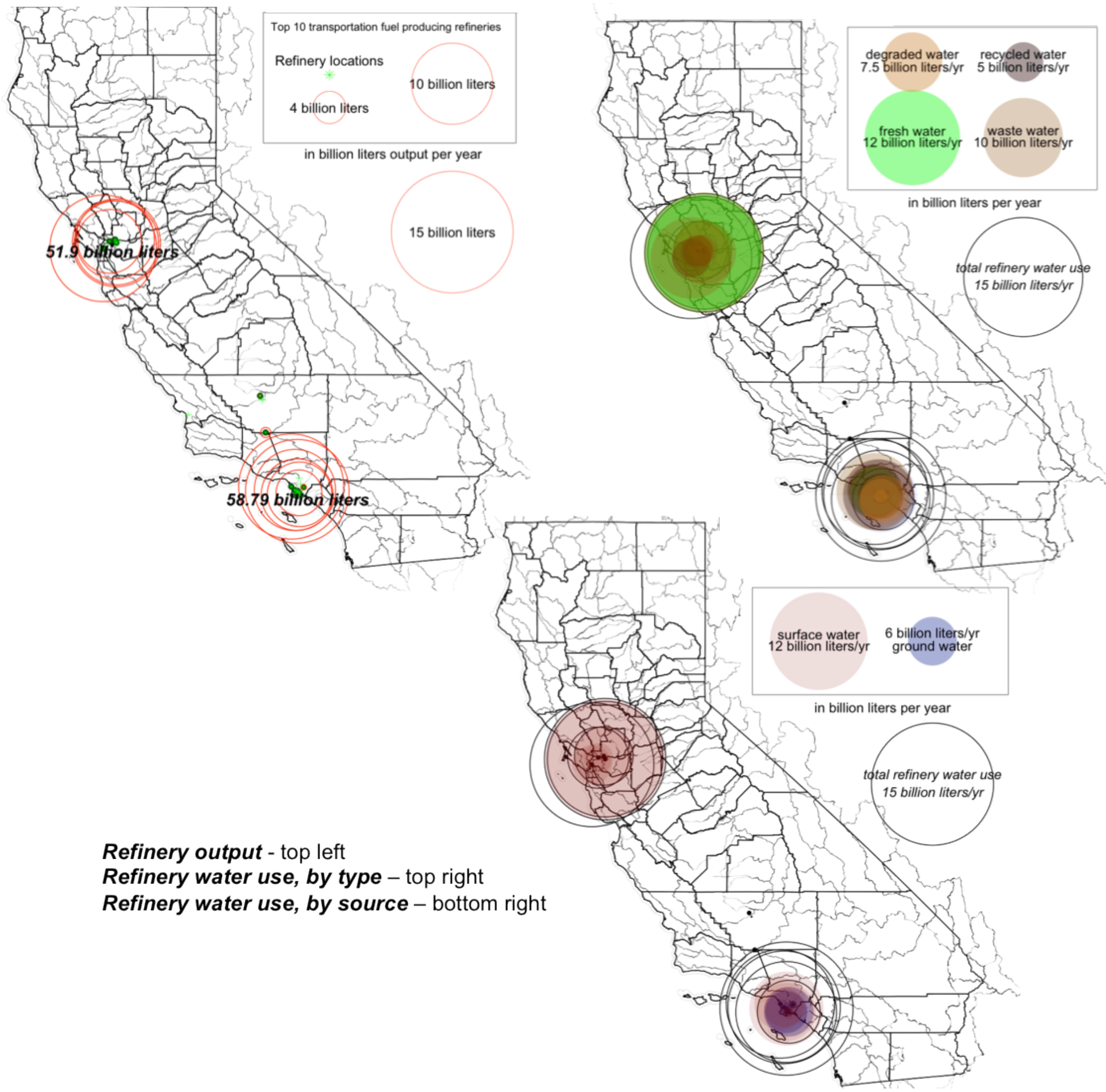
Refinery	Capacity (PJ/year)	Fresh	Recycled	Degraded	Waste
Chevron Refinery, Richmond	505	1.7	4.8	0	10.2
Conoco Phillips, Rodeo	304	3.6	3.9	0	4.2
Valero Benicia Refinery	374	7.2	0	0	3.5
Shell Oil Products US, Martinez Refinery	416	14.9	0	0	8
Tesoro Martinez / Rodeo	399	14.2	0	0	15.1
Chevron Refinery, El Segundo	498	6.4	6.9	0	9.7
ExxonMobil, Torrance	384	4.8	9	0	0
ConocoPhillips, Wilmington Refinery	339	0	0	5.2	0
BP West Coast, Carson	491	0	5.7	1.6	0
Tesoro Refining & Marketing Company	307	0	0	6.1	0
Paramount Petroleum, Paramount	26	0	0	0	0.4

Capacity is in petajoules per year, values are from 2013. Water use volumes are estimated abstractions from 2009-2013, in billion liters per year.

Data sources are various recent CEC and EIA reports and Environmental Impact Reviews.

Refineries in California are continually looking for recycled sources of water. For example, the Rodeo recycled project, to be completed in 2030, aims to provide 14 million liters of recycled water per day for use in its refining operations (i.e. boilers and cooling towers), thereby offsetting a substantial fraction (~70% of total water consumptive use) of freshwater use (EBMUD 2007).

Figure 3.6: Total Refined Product and Water Use by Source of California's Oil Refineries.



Total volumes of refined product (top), and water use by type (bottom left), and source (bottom right) at California's top ten refineries in 2012. Each ring represents a single refinery.

3.1.4 California's Imported Oil

Canadian Oil Sands

In 2012, California imported 2.265 billion liters (14.25 MMbbl) of oil from Canada, accounting for roughly 5% of all foreign sources imported that year (CEC 2012). Much of the crude oil produced in Canada comes from large deposits of oil sands. Oil Sands contain mixture of loose sand, clay, water, and dense and highly viscous form of petroleum, referred to as bitumen. Bitumen constitutes 10-12% of the rock composition by mass. The Canadian oil industry has rapidly expanded capacity to produce crude oil from oil sands in recent years, nearly tripling production from 33.4 million m^3 in 2000 to 101.5 million m^3 in 2012 (CAPP 2013). By 2035, as the production of conventional oil continues to decline, Canada's National Energy Board (NEB) expects 85% of total crude oil supply to come from bitumen (compared with 54% in 2010) (NEB 2011).

Water demand for oil sands mining is substantial. The most water-intensive processes in oil sands extraction are: (1) hot water washing of surface-mined oil sands and *in situ* deposits, which include (2) cyclical steam stimulation (CSS) and (3) steam-assisted gravity drainage (SAGD). Both CSS and SAGD use steam to soften the bitumen before extraction. As 80% of the steam used for oil extraction and processing is recycled, the water consumption of these processes is relatively low (Isaacs 2007). Steam-assisted gravity drainage (SAGD) tends to require lower injection pressures, resulting in lower steam/oil ratios and thus making it less water intensive.

Another highly water-intensive process in bitumen production is the transportation of raw oil sands to a bitumen extraction facility. Hydrotransport hot water (and sometimes caustic soda) is mixed with the mined oil sands to produce a slurry that can be pumped through a pipeline to the bitumen extraction facility. The hot water is added to process the bitumen, and the caustic soda aids in the separation process (Griffiths, Taylor et al. 2006). The oil/water slurry is then pumped into separation vessels in which the slurry settles into layers composed of bitumen froth, middlings, and sand and water, or tailings. The bitumen froth is skimmed off of the top and sent to froth treatment, the middlings are fed into a secondary separation vessel to undergo further separation, and the tailings are transported by pipeline to the tailings pond.

Tailings comprise coarse grains of sand, fine sand, clays, the water that was originally contained in the oil sands (called connate water), the hot water that was used in the extraction process (washing), and some residual bitumen. Depending on the quality of the oil sands being processed and the content of the bitumen and fines (small particles of silt and clay), 3-5 L of water are stored in tailings for every liter of bitumen. The resulting water is brackish and acutely toxic to aquatic biota due to high concentrations of organic acids leached from the bitumen during extraction (MacKinnon and Sethi 1993).

Under zero-discharge regulations, tailings are pumped from the extraction facility to tailings ponds where they are deposited and left to separate. Settling can take anywhere from decades to 150 years depending on the technologies and management used (Eckert, Masliyah et al. 1996). The result has been a continuous areal expansion of tailing ponds. By mid-2005, constructed area totaled over 70 square km (Dominski 2007) in Alberta, and the total volume of impounded tailings sludge (among all operators) exceeded 700 million cubic meters (Dominski 2007). Current reports indicate that as of 2011, the total surface area of all tailings ponds in the mineable area is 182 square kilometers excluding reclaimed course tailings (AESRD 2014).

Aggregate water volumes of water withdrawn and consumed, by source (recycled, saline, and fresh water) by the Athabasca oil sands development, together with a detailed documentation ad discussion of the environmental and ecological impacts, can be found in Griffiths, Taylor et al. (2006).

The WUI of Oil Sands Production

According to Kim, Hipel et al. (2013), around 85% of the water used for surface extraction (mining) is recycled water, as is roughly 90-95% of water to steam for *in situ* extraction. In estimating the WUI oil sands here, only the consumptive freshwater use is considered. Early studies estimated that the oil sands industry used an average of 4.8 liters of freshwater to produce 1 liter of bitumen oil (before upgrading) via surface mining in 1994 (Gleick 1994). In 2005, that estimate had dropped to 4 L/L including upgrading (Peachey and Eng 2005). Other estimates include a range of 3-5 L/L (Sawatsky 2004), and a point estimate of WUI of bitumen production, including upgrading, of 2.18 L/L in 2004 (Heidrick and Godin 2006, Isaacs 2007). Water consumption requirements for upgrading are less than 1 L/L (Peachey and Eng 2005). Overall, the water requirements for refining the synthetic crude produced from oil sands are comparable to those of conventional crude. The reduction in fresh water WUI can be attributed to increasing use of saline and recycled water sources.

As of 2013, based on data available from the Oil Sands Information Portal,[8] 2.2 liters of freshwater were required to produce one liter of synthetic crude oil (SCO) in 2012 by surface mining, whereas 1.3 liters of freshwater were required to produced one liter of synthetic crude by in situ processes in 2012 (AESRD 2014). For projects without integrated upgrading 0.3 liters of freshwater and 0.2 liters of brackish water were used to produce one liter of bitumen via in situ processes in 2013, and stand-alone upgrader projects required 0.4 liters of freshwater to produce a liter of synthetic crude in 2012 (AESRD 2014). Individual projects varied, and volumes as of 2011, are displayed in Table 3.5 (AESRD 2014, Development 2014, Pembina 2014).

To estimate the WUI of Canadian oil production overall, data were collected and analyzed by location and recovery method. The market shares of bitumen versus conventional production and surface mining and *in situ* technologies are taken from ERCB (2013).

[8] See: http://environment.alberta.ca/apps/osip/

Table 3.5: Freshwater Intensities of Oil Sands Extraction in Surface Mining Sites, 2011.

Company	Mine(s)	Liters freshwater/ Liters bitumen	Liters freshwater/ Liters SCO
Suncor Base Operations	Millennium Mine, Steepbank Mine, and Upgraders 1 and 2		1.7
Shell	Albian Sands Muskeg River Mine	2	
	Jackpine Mine	3.2	
Syncrude	Aurora North Mine	0.7	
	Mildred Lake Mine		2.6
CNRL	Horizon Mine		4.5

Sources:AESRD (2014), Development (2014), Pembina (2014)

Alaska

In 2012, California imported 12.1 billion liters of oil from Alaska, accounting for 11% of the oil consumed in California in that year. Alaska's oil production peaked in 1988 at about 117 billion liters (738 million barrels). In 2012, it was nearly 30.5 billion liters (192 million barrels), or about 8% of total U.S. production (EIA 2014). Since the completion of the Trans-Alaska Pipeline System from the North Slope of Alaska in 1977, about 97% of total Alaskan production has come from the North Slope. The remainder comes from Southern Alaska. In 2012, 30 billion liters (188.3 million barrels) were produced on the North Slope (98% of total production), and only 636 million liters (4 million barrels) were produced in Southern Alaska (EIA 2014).

There is little data available about the technology shares of production used in Alaska, however, in 2012, 17 of the 19 active fields in Alaska reported using enhanced oil recovery techniques. Data for Alaska's oil production is detailed in the Alaska Oil and Gas Conservation Commission (AOGCC 2014).[9] In 2012, fields using EOR injected 117 billion liters (980.8 million barrels) of water into oil wells, along with 9.2 billion liters (77.2 million barrels) of water into disposal wells, and 2,631,078,220 MMcf of gas into enhanced recovery projects. The total water use intensity of Alaskan oil production in 2012 was 2.8-3.7 L water/GJ energy and ranged from no net water consumption 8.3 L water/GJ oil at Prudhoe Bay Field (AOGCC 2014). The total produced water intensity (PWI) averaged 4.0 L water/L oil, with a range from no produced water to 21.4 L water/L oil. Approximately 99% of produced water in Alaska is re-injected for additional oil recovery (API 2000). To be consistent with the allocation approach that used for California, the net water use intensity of oil production (L water/ GJ) was calculated based on the following equation:[10]

Lower net WUI: $$\frac{Water\ Injected - (Produced\ Water - Water\ Disposed) \times 0.99}{Oil\ and\ Gas\ Produced}$$ (Equation 3.1)

[9] http://doa.alaska.gov/ogc/production/ProdArchives/parchiveindex.html

[10] Produced water re-use was cited as 99% in Alaska (API 2000).

Upper net WUI: $\frac{Water\ Injected - (Produced\ Water - Water\ Disposed) \times 0.99}{Oil\ Produced}$ (Equation 3.2)

Based on equations 3.1 and 3.2, the net WUI ranges from 1.4-5.8 L water/GJ. Fields with reported negative net WUI (Milne Point, McCarthur River, and Swanson River), or those that produced more water than could be injected, are excluded from the total average net WUI calculation.

Other Foreign Sources

Other foreign sources comprised 44%, or 41.6 billion liters (11 billion gallons), of California's petroleum supply in 2012 (CEC 2012). For the countries that export oil to California, very little data exist on the water intensity of petroleum extraction and refining. Moreover, it is difficult to project whether the WUI of foreign oil production might increase or decrease to 2030, as the two primary drivers of WUI will act in opposing directions. On the one hand, decreasing pressure in maturing oil fields will require either a shift from primary to secondary to tertiary techniques, or a shift toward greater injections of water, steam, or CO_2, in fields that use secondary and tertiary technologies. On the other hand, WUI may decrease as best management practices are disseminated and adopted worldwide, as better practices and technologies are developed, and as new oil fields are discovered. Most of California's imported crude from regions other than Canada and Alaska is expected to come from conventional crude oil and mature fields (Muggeridge, Cockin et al. 2014). This suggests that an increasing proportion of the crude imported to California may be well suited to use Enhanced oil recovery (EOR – which includes both secondary and tertiary technologies) in order to increase the recovery factor (RF) and oil production rate from these fields. Recent studies indicate that EOR may overtake other methods of oil production; however it may also become more efficient with time.

Due to the uncertainty as to future production methods, for imports from the rest of the world, the range of WUI used by the IEA (WEO 2012) was adopted. The IEA uses WUI estimates from Gleick (1994) and U.S. DOE (2006) to estimate ranges for refined conventional oil (primary) and refined EOR (including water flooding, CO_2 injection, steam injection, alkaline injection and in-situ combustion) or from 14-1000 (gallons/MMBTU). The WUI of primary oil production adopted by these sources ranges from 0.89 – 2.44 L/GJ, while the WUI of EOR techniques ranges much more widely, from 15.5 – 2770 L/GJ, but the upper bound estimates of this range are for rarely applied, highly water intensive technologies (e.g. micellar polymer production), and so the more realistic range of 15.5 – 1500 L/GJ (Table 3.2 gives these WUI values in L/L) is adopted.

Dal Ferro and Smith (2007) estimate current global produced water production at around 29.8 billion liters (250 million barrels) per day as compared with global oil production of around 12.7 billion liters (80 million barrels) per day. The resulting water to oil ratio is around 3:1 (Fakhru'l-Razi, Pendashteh et al. 2009). The global produced water intensity has risen over the past decade and continues to rise due to the maturation of oil fields (Khatib and Verbeek 2002, Dal Ferro and Smith 2007).

3.1.5 Fracking in California, Domestic Shale/Tight Oil, & the Monterey Shale

In this report, shale oil is defined to include tight oil, following the conventional EIA usage and adopting the terminology of a recent definitive report on domestic shale oil (Maugeri 2013).

Shale and tight oil resources are 'conventional' in the sense that they are light crudes with low sulfur content stored in 'unconventional' geological formations with low porosity and permeability (Maugeri 2013). The water use impacts and intensity of mining oil shale – unconventional heavy oil (kerogen) found in sedimentary rock – are reviewed in Appendix F.

As shale oil production has ramped up only in the past 2-3 years, no peer-reviewed published studies have yet emerged estimating the water use intensity of shale and tight oil. In light of this data limitation, as well as the similarity in technologies, processes, and geologies between shale/tight gas and shale/tight oil fracking,[11] the sole range of WUI values available is taken – 11.6-38.7 million m^3/MJ delivered, pipeline quality NG – reported for associated shale gas and oil (Goodwin, Carlson et al. 2012) to estimate the range of likely water use intensity (WUI) for shale and tight oil.

Prospects for Fracking the Monterey Shale

California's Monterey Shale formation stretches along the western half of California's Central Valley from just inland of San Francisco down to about 100 miles south of Bakersfield, and along the coast from North of Monterey to south of Los Angeles, spanning about 1,750 square miles. The formation spans nine counties in Southern California. Figure 3.7 shows the geographic extent of the Monterey Shale formation, and its overlap with nine counties in Southern California. In order of decreasing areal overlap, the counties coincident with the Monterey Shale play are: Kern, Kings, Santa Barbara, Los Angeles, Ventura, Orange, Fresno, San Luis Obispo, and Tulare.

The U.S. EIA projects that the U.S. has the potential by as early as 2017 to become the world's top oil producer, and could reach virtually complete self-sufficiency (97%) in supplying net energy demand of oil (EIA 2013). Until 2014, the U.S. EIA estimated that roughly 13.7 billion barrels of oil locked within the Monterey Shale (EIA 2012a) may be technically recoverable with new technologies. However, according to a recent article in the LA times[12], in its 2014 update, the EIA will reduce its estimate of currently recoverable oil to only 600 million barrels can be extracted from the Monterey.

Pepino (2014) uses the development of shale oil in the Bakken formation in North Dakota as a case study to explore the potential water use impacts of developing the Monterey Shale. She examines the economics and regulation of water sourcing in the Bakken, from 2006 to 2013, and compares the geology and water sources with those of Monterey. A map of competition for water in U.S. regions of current and potential shale energy development ranks California's resources as being located in regions of 'high' to 'extremely high' water risk, vis-à-vis the

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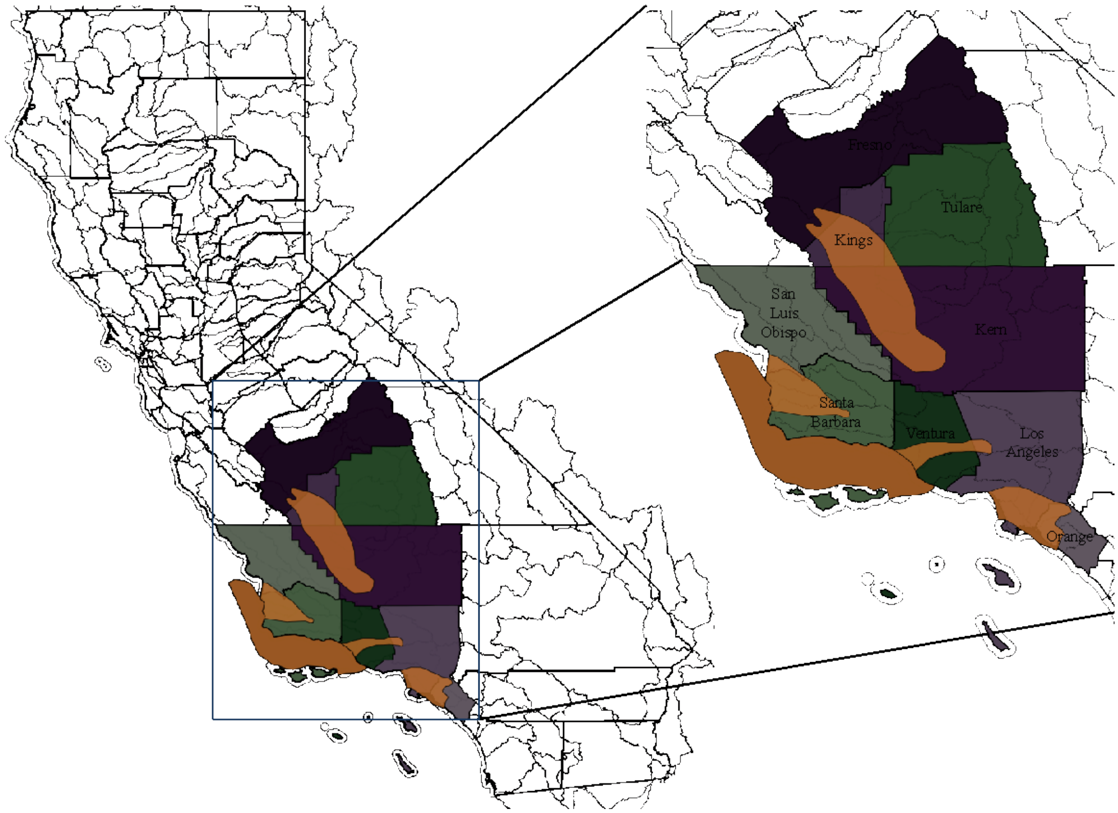
[11] The geology of shale and tight oil formations is similar to those in which shale and tight gas are produced. Thus, for WUI estimates of shale/tight oil, values from the two studies reviewed in the previous section on shale gas which consider coproduction of shale oil and gas were taken.

[12] See: "U.S. officials cut estimate of recoverable Monterey Shale oil by 96%." Louis Sahagun, LA Times, 5.21.2014, online at: http://www.latimes.com/business/la-fi-oil-20140521-story.html.

Bakken (itself also located in the arid state of North Dakota) being ranked as a region of only 'moderate' water risk (CERES 2014).[13]

Figure 3.7: Southern California Counties Coincident with the Monterey Shale Formation.



Nine counties are coincident with the Monterey Shale. The Monterey Shale itself is shown in brown.

If the Monterey Shale were to be exploited for oil after all, the source of water for hydraulic fracking jobs would depend on cost, access rights, and availability. Non-potable, recycled water is a potential source as it meets standards for evaporation and injection, however this would have to be purchased from municipal and private treatment plants. Further, releases of produced water would impact local water quality and availability. Absent regulations mandating volumes/percentages of recycled water use or economic incentivizes, water will likely be source from either the California State Water Project, or the Central Valley project (Pepino 2014), through competition for these water supplies with the state's $106 billion dollar agricultural industry (which makes up ~2% of the state's GDP) will be intense. Fractious political splits over environmental flows versus agricultural water use (e.g. salmon die off and the Delta smelt) have given way to litigation.

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[13] See: https://www.ceres.org/issues/water/shale-energy/shale-and-water-maps/hydraulic-fracturing-water-stress-water-demand-by-the-numbers

The complexity and relatively high porosity of California's geological formations increases the likelihood of water migration (Pepino 2014). It is likely that the WUI of fracking for shale oil would be slightly lower than in current developed fields (e.g., the Bakken field), as a consequence of the higher porosity in the Monterey facilitating absorption and storage of fracking fluid (Pepino 2014).

Moreover, the concern of induced seismicity is perhaps particularly relevant in California in light of the state's numerous active faults, as well as the recently established correlation between increased earthquake frequency and intensity and wastewater injection of flowback/produced water associated with fracking into Class II disposal wells (Ellsworth 2013). For a more detailed qualitative discussion of the potential water use impacts of developing the Monterey Shale, see Pepino (2014), and for detailed discussion of WULCA issues and hydraulic fracturing, see Appendix B (section B.2) of this report.

Fracking in California

While fracking has grown in recent years due to high economic returns and the ability to access previously unavailable shale plays, the practice has also increased the volume of freshwater required and wastewater produced to extract natural gas (Kiparsky and Hein 2013). Although hydraulic fracturing has been used in California for over 30 years, the technique has recently been considered by the industry for large-scale oil exploration activities (DOGGR 2013, Pepino 2014). For further discussion of water use trends and a comprehensive literature review of water use impacts of fracking in tight/shale formations for oil and natural gas, see sections 2.4.2-2.4.6 and Appendix B of this report. A brief summary of California's current regulations of fracking can be found in section 3.4.5 and in Kiparsky and Hein (2013).

To explore the current profile of fracking operations in California, two databases serve as key sources: the IHS International Exploration and Production database,[14] a private database, and *FracFocus* (GWPC and IOGCC 2014),[15] a voluntary disclosure website. IHS data includes annual oil, gas, and water production and water treatment data, as well as well information including the direction of the well (vertical, horizontal, or directional), the depth of the fracture, and the type(s) of additives and propping agents used in the well.

FracFocus is a national hydraulic fracturing chemical registry, managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Well identification (API) numbers reported in the *FracFocus* database were used to merge data with fracking wells in the IHS database. According to these data, there were 498 wells that used hydraulic fracturing techniques in 2012. Twenty-three of these specified gas as the primary product, and the remaining 475 primarily produced oil. In 2013, 436 wells used fracking techniques, all of which primarily produced oil. The majority of these wells were located in Kern County, with one in

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[14] http://www.ihs.com/products/oil-gas/ep-data/sets/international.aspx

[15] http://fracfocus.org/

Kings, two in Los Angeles and twelve located in Ventura County. Appendix C.3 further discusses the water quality impacts of fracking in California, focusing on the chemicals reported in the *FracFocus* database.

The majority of water, oil, and natural gas wells are drilled vertically. Vertical wells are most effective with rock units that have high permeability, where fluids can flow efficiently over long distances. Drilling at an angle other than vertical (i.e. 'directional' or 'horizontal' drilling), has been used to access reservoirs located directly below land holdings where drilling is impossible or forbidden. Also, horizontal drilling can increase the productivity in low permeability rocks by bring the well bore much closer to the source of the fluid. The majority of the wells in California identified as either vertical wells or directional wells (Table 3.6).

Table 3.6: California's Hydraulically Fractured Wells, by Type.

	Directional	Horizontal	Vertical
2012	147	40	189
2013	174	20	171

Number of hydraulically fractured wells operating in California in 2012 and 2013.

Source: IHS.

Oil and Gas Production by Hydraulic Fracturing in California

Fracked wells produced 11.7 and 13 petajoules (PJ) of oil, and 3.5 and 2.2 of gas, in 2012 and 2013. In both years, this accounted for only about 1-1.5 percent of the oil (and about 1% of the gas), produced statewide. Oil volumes produced range from 1 barrel (6.1 GJ) (such low volumes were produced in exploratory wells) to 44,800 barrels (274,000 GJ), with a median of 3,050 barrels and a mean of 5,360 barrels as of 2012. The amount of gas produced ranges from 1 million cubic feet (MCF) or 1.1 GJ to 356,000 GJ per well. Table 3.7 shows a summary of the methods and production of hydraulically fractured wells in California.

Water Use for Hydraulic Fracturing in California

According to voluntary reporting on *FracFocus*, hydraulic fracturing in California used a combined total of 232 million liters (61 million gallons) of water in 2012 and 179 million liters (47 million gallons) in 2013. As previously noted, this estimate is based on voluntary disclosures, and may not include wells that failed to produce oil or gas. The reported mean (median) volumes of water used per well (i.e. *w*ater *u*se per *w*ell or WUW) were 672 (350) thousand liters in 2012 and 498 (312) thousand liters in 2013 (Table 3.8).

Table 3.7: Oil & Gas Production by Hydraulic Fractured Wells.

Well Direction	Type	Fluid Type	Number of Wells	Oil (GJ)	Gas (GJ)
Directional	Acid	Acid	17	362,887	65,669
Directional	Flush	Water	2	4,773	153
Directional	Frac	NA	114	3,141,097	505,853
Directional	Frac	Fluid	18	660,515	80,930
Directional	Frac	Gel	3	28,998	3,567
Directional	Frac	Water	7	233,997	29,369
Directional	Frac	X-linkgel	139	3,406,282	847,574
Directional	Re-frac	NA	1	27,389	7,830
Directional	Re-frac	Fluid	1	1,181	-
Directional	*Total*	*Total*	283	7,867,119	1,540,944
Horizontal	Acid	Acid	3	246,229	17,058
Horizontal	Flush	Water	1	103,631	3,172
Horizontal	Frac	NA	14	1,309,735	120,280
Horizontal	Frac	Fluid	29	3,178,863	539,379
Horizontal	Frac	Gel	1	32,700	3,494
Horizontal	Frac	X-linkgel	10	991,896	111,463
Horizontal	Re-frac	Fluid	1	54,637	21,312
Horizontal	Re-frac	X-linkgel	1	112,229	16,623
Horizontal	*Total*	*Total*	54	6,029,920	832,780
Vertical	Acid	Acid	8	203,585	89,086
Vertical	Flush	Fluid	1	82,025	8,747
Vertical	Frac	NA	121	3,600,071	362,608
Vertical	Frac	Fluid	45	2,217,685	271,274
Vertical	Frac	Gel	1	33,710	8,211
Vertical	Frac	Water	4	107,217	6,640
Vertical	Frac	X-linkgel	136	3,040,629	506,745
Vertical	*Total*	*Total*	309	9,284,922	1,253,312

Oil and gas production in California's hydraulically fractured wells, by well direction, fracturing type, and fluid type, in 2012.

Sources: IHS, *FracFocus* (GWPC and IOGCC 2014).

Note that median water use for vertical and directional wells was much lower than that of horizontal wells (443-579 thousand liters versus 1,847 thousand liters in 2012). These estimates are much lower than water use estimates from Texas, where horizontal wells outnumber vertical ones. Nicot and Scanlon (2012) report a median of 10.6 / 4.5 million liters per well for horizontal / vertical wells in 2010 in the Barnett shale. Literature estimates for horizontal / vertical wells average 10 million / 1.5 million liters per hydraulic fracturing job, with up to eight fracking jobs potentially completable from a single well pad (Goodwin, Carlson et al. 2012, Nicot and Scanlon 2012, Murray 2013). However, as fracking wells age, they tend to use less water (Nicot and Scanlon 2012, Clark et al. 2013, Laurenzi and Jersey 2013), thus recent literature estimates consider varying time periods, and incorporate the estimated ultimate recovery of a well. Therefore, the lifetime water use intensity of California wells may be even lower than estimated here as these estimates rely upon only two years of data.

Table 3.8: Water Use per Well, by Well Direction.

Year	Well Direction	Number of wells	Median WUW	Mean WUW	Q95 WUW
2012	Directional	116	304	443	1,114
	Horizontal	34	1,403	1,847	4,132
	Vertical	152	362	579	1,129
2012	Total	302	350	672	1,945
2013	Directional	167	305	420	1,107
	Horizontal	20	1,508	1,486	2,153
	Vertical	157	292	449	1,053
2013	Total	344	312	498	1,494

Mean, median, & 95th percentile (Q95) ***w**ater **u**se per **w**ell* (WUW) for hydraulically fractured wells in California.

Source: FracFocus database (GWPC and IOGCC 2014) of voluntary disclosures.

California's lower WUW appears to result mainly from the predominance of vertical wells, which contrasts with the higher ratio of horizontal to vertical wells in other formations. Vertical wells have shorter treatment lengths; the average vertical depth in California was 1.6 km (5,149 feet) in 2012, and 1,3 km (4,138 feet) in 2013. Vertical wells reported shallower total depths than horizontal wells -- vertical wells reported an average of 1.35 km (4,431 feet) versus horizontal depths of 3.3 km (10,870 feet) in 2012. Shale formations in Texas are range from depths of 1.2–3.4 km (in the Eagle Ford Shale), 2.0 to 2.6 km (in the Barnett), and 3–4 km (in the Haynesville) (Nicot and Scanlon 2012).

The water use intensity (WUI) of California's hydraulically fractured wells is calculated by dividing total water injected by total energy produced. The WUI of the state's fracked wells was 18 / 14 L/GJ, in 2012, 2013, respectively. These estimates fall into the mid-range of recent literature estimates, which range from 3.6 L/GJ to 38.7 L/GJ (Goodwin, Carlson et al. 2012, Nicot and Scanlon 2012, Clark, Horner et al. 2013, Laurenzi and Jersey 2013, Murray 2013). The mean and median WUIs of the wells vary by well type (Table 3.9). Note that the WUI estimates for fracked well are lower than those for conventional oil production in California, for which the estimated net WUI of oil and gas produced in 2012 was 66 L/GJ.

Flowback/Produced Water

In California, the amount of water produced per well ranges from 84 gallons to 39 million gallons, translating to produced water ratios of 1 L/GJ-5,100 L/GJ in 2012 and 1.7 L/GJ-17,800 L/GJ in 2013. Table 3.10 shows the volumes of flowback/produced water per unit oil, and per unit total energy (i.e. oil and gas combined) in California's hydraulically fractured wells.

Table 3.9: Summary Statistics of Water Use Intensity of Fracking in California.

Year	Well Direction	Median WUI	Mean WUI	95th Percentile WUI
2012	Directional	18	84	158
	Horizontal	15	52	165
	Vertical	24	64	320
2013	Directional	11	48	58
	Horizontal	14	23	55
	Vertical	11	37	50

Median, mean, & 95^{th} percentile of ***w****ater* ***u****se* ***i****ntensity* (WUI – in L/GJ) of oil and gas production by hydraulic fracturing in California, in 2012 and 2013.

Sources: *FracFocus* (GWPC and IOGCC 2014) & IHS.

Table 3.10: Produced Water Intensity of Hydraulically Fractured Wells in California.

Year	Well Direction	Number of wells	Median (oil only)	Mean (oil only)	Q95 (oil only)	Median (total energy)	Mean (total energy)	Q95 (total energy)
2012	Directional	116	180	772	2,088	151	298	1,106
	Horizontal	34	80	165	659	69	135	493
	Vertical	152	101	243	800	89	186	509
2012	Total	302	125	447	1,182	102	225	680
2013	Directional	167	191	565	1,784	156	479	984
	Horizontal	20	136	176	247	118	127	177
	Vertical	157	120	290	925	93	229	674
2013	Total	344	149	417	1,078	129	348	737

Produced water volumes per unit oil and energy produced, in Liters/GJ.

3.2 Biofuels

In contrast to the other three energy supply chains (oil, natural gas, and electricity) treated in this study, the biofuels analysis takes a national scope. Under all CA-TIMES scenario projections, California will supply only very small quantities of crop-based biofuels. Certain crops sourced in-state, such as sugarbeets, castor, *camelina*, canola, safflower, or sorghum, can become biofuel feedstocks in the future, but in all likelihood, California's highly productive soils and climate, together with water scarcity, will continue to make it ideally suitable for producing high-value specialty crops (Kaffka, Williams et al. 2011, Kaffka 2013). Algal-based advanced biofuels are also a prospective feedstock for California, though certain economic barriers are still a major challenge for this biofuels pathway. For an overview of ongoing detailed spatial and economic modeling of potential biofuels production in California, see Kaffka (2013).

Though research results are not yet available, Kaffka and other researchers model the adoption of other promising bioenergy feedstock crops using the Bioenergy Crop Adoption Model, a model developed specifically for California. According to Kaffka (personal communication), winter annual oil seeds, energy (sugar) beets, sugar and energy cane, and grain are more suited to use for bioenergy feedstock in California than the dedicated feedstocks modeled here (miscanthus and switchgrass), due to their high yields and resource use efficiency, complementarity with existing cropping systems, and the simple technology required for their use as feedstocks. At the time of publication of this report, Kaffka's team is undertaking detailed analysis of current land use patterns across the state to test the likelihood that the above feedstock might be adopted. On the basis of outputs from this preliminary step, they then estimate economic effects, actual GHG reductions and fuel carbon intensity values.

No peer-reviewed studies have developed appropriate methods to estimate the water use impacts of municipal wastes and forest wastes used for biofuels production. Such impacts are likely to be very small, likely at least an order of magnitude smaller than those of growing dedicated feedstocks or even agricultural residues. In light of the scarcity of appropriate methods or literature and the small water use intensity of these pathways, the focus of this research is instead on national agricultural water use impacts of biofuels policies. Most of these impacts occur east of the Rockies, and they are concentrated primarily in the Frontier states and in regions adjacent to the Mississippi and Missouri Rivers.

3.2.1 Methods Overview

Most studies estimating the water use impacts of biofuels rely upon *attributional* lifecycle analysis (A-LCA) approaches (King and Webber 2008, Gerbens-Leenes, Hoekstra et al. 2009, Pfister, Bayer et al. 2011, Scown, Horvath et al. 2011), attributing liters of irrigation or evapotranspired water consumed per liter of biofuels produced to estimate the consumptive water use intensity of biofuels in liters per liter (or, when dealing with multiple liquid biofuel products or bioenergy, in liters/MJ). Allocating biofuel water use can be subjective especially when there are co-products (such as soybean meal and soybean oil) and the results are highly sensitive to the choice of allocation method and system boundary selected (Kaufman, Meier et al. 2010, Mishra and Yeh 2011). Further, biofuels water use should ideally be compared to baseline levels of evapotranspiration and contextualized in terms of water use versus alternative usages and environmental flows.

Nearly all previous studies, whether they use A-LCA or not, ignore some of the following important factors:

1. market-mediated (e.g. substitution & marginal) effects,
2. land use and (indirect) land use changes,
3. geographic heterogeneity, primarily in climate.

These three factors need to be taken into account to accurately reflect water use impacts of biofuel feedstock cultivation associated with large-scale biofuels production. As the majority of the water use impacts are incurred in the feedstock production phase (McKone and Enoch 2002, Chiu, Walseth et al. 2009, Wu, Mintz et al. 2009, Nicot and Scanlon 2012), this study focuses on the differences in agricultural water use among three scenarios, which all derive from the 2014 version of the Biofuels Environmental Policy Analysis Model used in Chen, Huang et al. (2014):

1. **BAU Scenario**: A counterfactual, or 'business-as-usual'. No policy is imposed; 2007 base year inputs match actual cropping patterns, but the blender's tax credit, mandated under the Renewable Fuels Standard, is discontinued immediately;
2. **Modified RFS2 (M-RFS2):** The Renewable Fuels Standard (RFS2) mandates, modified based on EIA's Annual Energy Outlook 2010 (RFS-AEO), which is modelled to achieve a reduction in cumulative domestic GHG emissions from 2007-2030 of 4.2% and;
3. **N-LCFS:** A national Low Carbon Fuel Standard (LCFS) is set at a level whereby it achieves the same level of domestic cumulative GHG reductions (4.2%) as in the RFS2 scenario over the period 2007-2030.

To address methodological shortcomings of previous studies estimating biofuel water use based on the estimates of the amount of water to grow biofuel feedstock (with some adjustment for water credits for co-products), this study makes the following methodological improvements over previous lifecycle inventory research estimating the water use impacts of biofuels:

- By adopting a consequential LCA approach based upon policy scenarios as modeled by a partial equilibrium economic model, *Biofuel and Environmental Policy Analysis Model* – BEPAM (Chen 2010), the problematic and subjective issues associated with assigning water use credits to co-products is circumvented. Further, as the model explicitly models price-quantity interactions (e.g. substitution and market-mediated effects), this analysis considers the interactions between water use change and LUC as results of agricultural crop substitution, agricultural land use expansion (as a result of new lands being brought into agricultural production for cultivation of biofuel feedstock [direct LUC] or displaced agricultural crops [indirect LUC]); and shifts on agricultural *LU intensity* (e.g. irrigated vs. rainfed land, till vs. no-till, single-cropping vs. rotations) that also affect the WUI of crop productions.
- The spatial data from the economic model (annual data at the county and Crop Reporting District scale), is downscaled to higher spatial resolution (~10 km) using a ten-year time series of cropping patterns from NASS (Han, Yang et al. 2012). Soil type (USDA accessed 6/9/2012) and daily meteorological data (NCAR accessed 9.14.2013) allow us to model the water impacts at the spatial resolution necessary to inform watershed-level management and planning.

- The FAO 56 (Allen, Pereira et al. 1998)[16] algorithms for estimating daily water balances were coded using *R* for each cropping pattern and across all three scenarios. This document provides in-depth qualitative considerations as well as computations necessary to compute daily crop-water balances using weather and soil data, together with agronomic data such as crop cultivar, water and soil management, and planting/harvesting dates.

The outputs of a partial equilibrium economic model – described in detail in Chen (2010) – were integrated with interpolated historical and future climate and high-resolution spatial data on soil and cropping patterns, and together these comprise the inputs to a process-based crop-soil-climate model. In this study, the latest BEPAM model version is used, as described Chen, Huang et al. (2014). This allows us to estimate differences in annual and seasonal green water (GW – directly from precipitation to soil) and blue water (BW – supplied by irrigation) use, as well as crop transpiration and soil-water flows (evaporation and off-season transpiration, runoff, and groundwater recharge).

Appendix D (D.1) provides further detail on the relevant policies (the RFS2 targets as projected in the EIA AEO 2010 and the national N-LCFS); assumptions and methods of the BEPAM modeling framework; data sources, assumptions, and methods of the modeling undertaken to derive and compare water use under each of the above three scenarios.

3.2.2 Data Sources & Methodology

The Biofuel and Environmental Policy Analysis Model

BEPAM is a stylized dynamic multi-market, multi-period model of the food/feed and fuel sectors. Geographic resolution and scope are highly detailed for the contiguous U.S., with base-year calibrated yield resolution at the county level (and sensitive to crop management including irrigation and tillage practices) and variable acreage resolution at the Crop Reporting District (CRD).[17] A detailed discussion of the model structure, input data, and assumptions is provided in Appendix D (D.2 and D.3).

Crop-Water Modeling

The analysis models crop water balances across (1) twelve row crops: corn, soybean, wheat (durum, winter, and spring varieties), rice, sorghum, oats (spring and fall), barley (spring and fall), cotton, peanuts, sugarbeets, sugarcane, and corn silage; (2) five biofuel feedstocks: corn, corn stover, wheat straw, and the dedicated cellulosic feedstock switchgrass and miscanthus, and; (3) other (marginal, idle, or non-cropped) land use categories: idle cropland, and cropland

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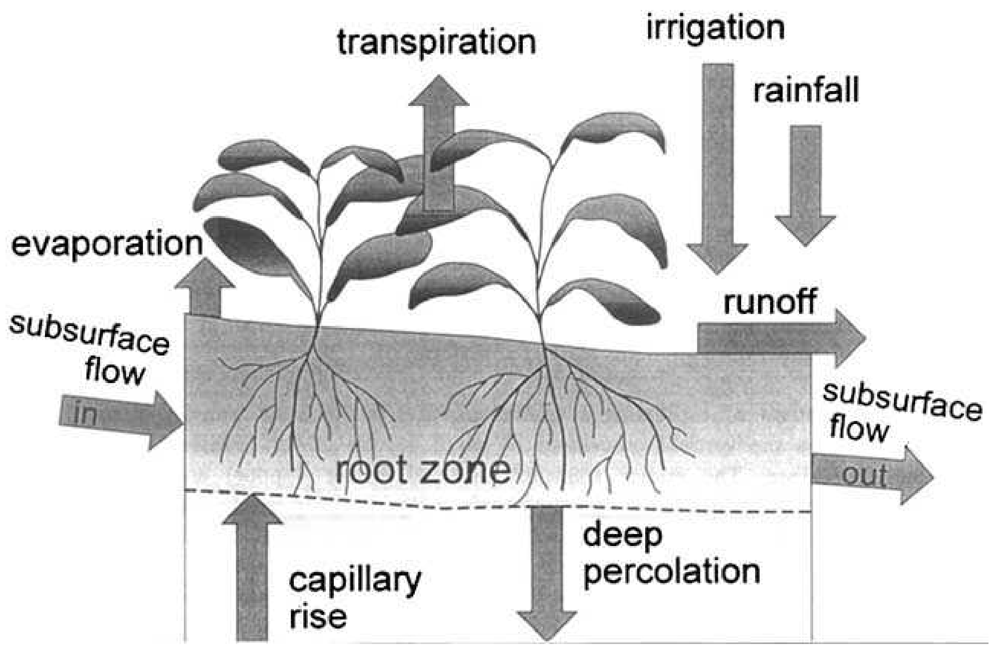
[16] Document 56, first published by the Food and Agriculture Organization of the United Nations (FAO) in 1998, and then updated in 2006, is titled, "*Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*."

[17] A CRD is an aggregation of typically 6-10 counties and is the basic unit of agricultural census data aggregation.

pasture. Calculating crop-water balances of non-cropped land is necessary in order to account for shifts on the extensive margin – as cropland comes into and goes out of production across scenarios, a counterfactual water use profile is needed for all land that is cropped in the other scenarios. Water balances for *idle land* and *cropland pasture*[18] are needed in particular to measure the change in water use balances resulting from conversion of marginal or uncropped land types to cultivation of dedicated biofuel feedstocks.

The daily water balances for all the cropping patterns and natural/managed land use types (e.g. cropland pasture, idle cropland, fallow cropland in the off-season) were estimated using the methods detailed in FAO 56, "*Guidelines for computing crop water requirements.*" (Han, Yang et al. 2012). Figure 3.8, taken from the aforementioned document, shows the water flows at the interface between soil, crop, and the atmosphere, considered by the water balance algorithm (note that subsurface in- and outflows are not considered by the crop water balance algorithms).

Figure 3.8: Water Flows between Soil, Crops, and the Atmosphere.



Source: FAO 56, "*Guidelines for computing crop water requirements.*" (Han, Yang et al. 2012).

Water use balances reported here are summed over the entire year, and reported as one of the following five types:

- **Transpiration** – the evaporation of water through the stomata of the leaves of the crop. Transpiration is reported here only for the crop being modeled, and is reported separately from evaporation because it is directly correlated with yields

[18] Both these categories of land are designations based on NASS survey categories. Both are modeled as perennial land cover with relatively low Kcb (crop water use coefficient) values.

and can be thought of as 'useful' (in the biological and broader economic sense) water consumption.

- **Evaporation and Off-Season ('weed') Transpiration**: Evaporation refers to water vaporized from the soil, which then reenters the atmosphere and is no longer available to plants. The rate of soil evaporation is dependent upon climatic conditions (temperature, humidity, wind speed, incident solar radiation), as well as soil characteristics, tillage, canopy cover, and plant growth stage and morphology. Transpiration during the fallow season (i.e. from weeds or other plants that are not directly converted into food, feed, feedstock, or other products of economic value) is added to evaporation and these are reported together.

- **Runoff**: surface runoff may occur following heavy rainfall, particularly in cases where the soil is completely saturated, has met or is close to its maximum water holding capacity (field capacity), or because rainfall exceeds the infiltration rate.

- **Groundwater infiltration**: water percolation into the deep subsoil then infiltrates into subsurface soil and rock. This water may then recharge local streams via lateral flows, replenish groundwater aquifers, or eventually flow into surface water reservoirs.

- **Irrigation**: for each crop, irrigation volumes were calibrated to survey reported state-level irrigation intensities, and total irrigated acreage per state was set to match these volumes.

Calculations consider irrigation scheduling, water stress, and crop-water balance estimation in the fallow season. For more details see Appendix D. Table 4 in this appendix lists the *csv* files giving the parameter values adopted in the analysis, together with a brief explanation of their meaning in the analysis. Full year balances are reported, and transpiration is reported as only the productive transpiration of the row crop or biofuel feedstock. Transpiration of the primary crop grown for food, feed, and/or as a feedstock is reported as there is a direct correlation in any given region and for any given variety between the transpiration and yield of the agricultural product (i.e. harvest). Off-season (weed) transpiration is reported together with evaporation, in consideration of the fact that weeds have no direct economic value. It should be noted that the dual crop-efficient slightly overestimates transpiration, as it counts some amount of evaporation occurring on the plant stem/leaf system as transpiration. Note as well that irrigation volumes are initially calculated as volumes provided to the crop.

Daily water balances as calculated by Penman-Monteith were validated in three ways. A description of the first two validation procedures – (1) comparison with an independent estimate that uses an algorithm applied to satellite-derived high resolution daily geophysical data and (2) detailed investigation of two study sites in California; as well as consulting crop ecology texts as a 'reality-check' are detailed in the following section. The third validation procedure, wherein consumptive (attributional) water use estimates for cultivation of key feedstocks (i.e. corn, stover, straw, switchgrass, and miscanthus) were compared against literature values, is detailed in section 4 of this report.

3.2.3 Base Year Water Balances and Water Use for Biofuels Feedstock Production

Here the methods are outlined for first overlaying land use and water balances, by cropping practice, and then aggregating water balances across crops to derive a full water balance for any given year and scenario modeled by BEPAM. Then some of the results for the base year (2008) are presented. This serves as a baseline even as it offers a brief introduction to water balances in agricultural systems, and of how to interpret the results. In 2008, approximately 37 billion liters of corn ethanol were produced domestically (Chen 2010).

The steps in deriving an aggregate crop-water balance for any given year and scenario are:

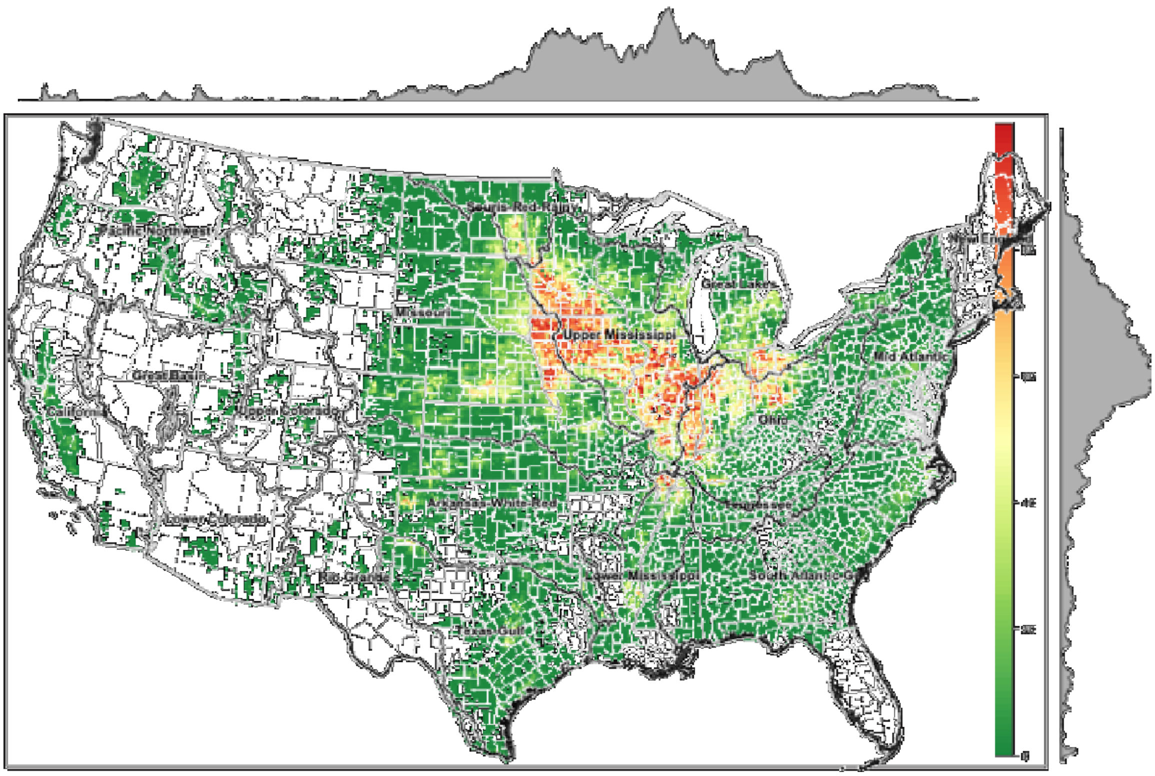
1. Allocate land areas to management practices;
2. Overlay water balances, by management practice;
3. Aggregate water balances for each crop;
4. For crops that are irrigated, calibrate irrigation (per-acre and total irrigation) to state-level survey data (NASS 2008), for each crop.
5. Validate modeled evapotranspiration (ET) for all crops against an 8-day average satellite-data and algorithm derived (i.e. also modeled) measure of ET (Mu, Zhao et al. 2011) at key locations for each crop. Detailed validation of ET against literature and field-tested values was done for irrigated crops in California, given the fact that the above-cited MODIS algorithm (Mu, Zhao et al. 2011) does not seem to model effects of irrigation well.
6. Aggregate water balances across all crops and uncropped (marginal, idle) land.

The above process is illustrated using the example of corn areas (for steps 1-5), and then for all row crops (step 6) in the base year (2008).

Allocate Land Areas

The first step is to normalize and allocate land areas cropped with a given crop as measured by satellite images (Han, Yang et al. 2012) to management practices as given in any year and scenario (see Appendix D for details). These land areas are then aggregated to include all cropping practices. Figure 3.9 shows the example of this aggregation for corn in the base year. Most of the corn is produced by rainfed farming in the Cornbelt and Midwest (e.g. Iowa, Illinois, Indiana, Ohio, Missouri) with limited areas of irrigated corn in the Midwest, Frontier, and Southern and Western states (e.g. Nebraska, Kansas, Texas, and Arkansas). Less than 1% of the irrigated corn production in 2008 came from California, and so less the state accounted for production of less than a quarter of one percent of grain corn (NASS 2008).

Figure 3.9: Land Area Cropped in Corn in 2008 as a Percentage of Total Land Cover.



Plots along the x- and y-axes indicate the marginal distributions decomposed along latitude and longitude lines of cropped area along latitude/longitude. Water Resource Regions (WRRs), the most basic hydrologic divisions at the U.S. national level, are labelled.

For every ~10 km cell in which a given management practice is applied, soil and daily weather inputs are used to derive the per hectare water balance. These per hectare water balances are then overlaid with the land use as in Figure 3.9 (i.e. scaled by the number of hectares in a given 10 km grid cell) to derive the total water balance for a given cropping practice, for any year / scenario modeled by BEPAM.

Water Balance Overlay by Management Practice

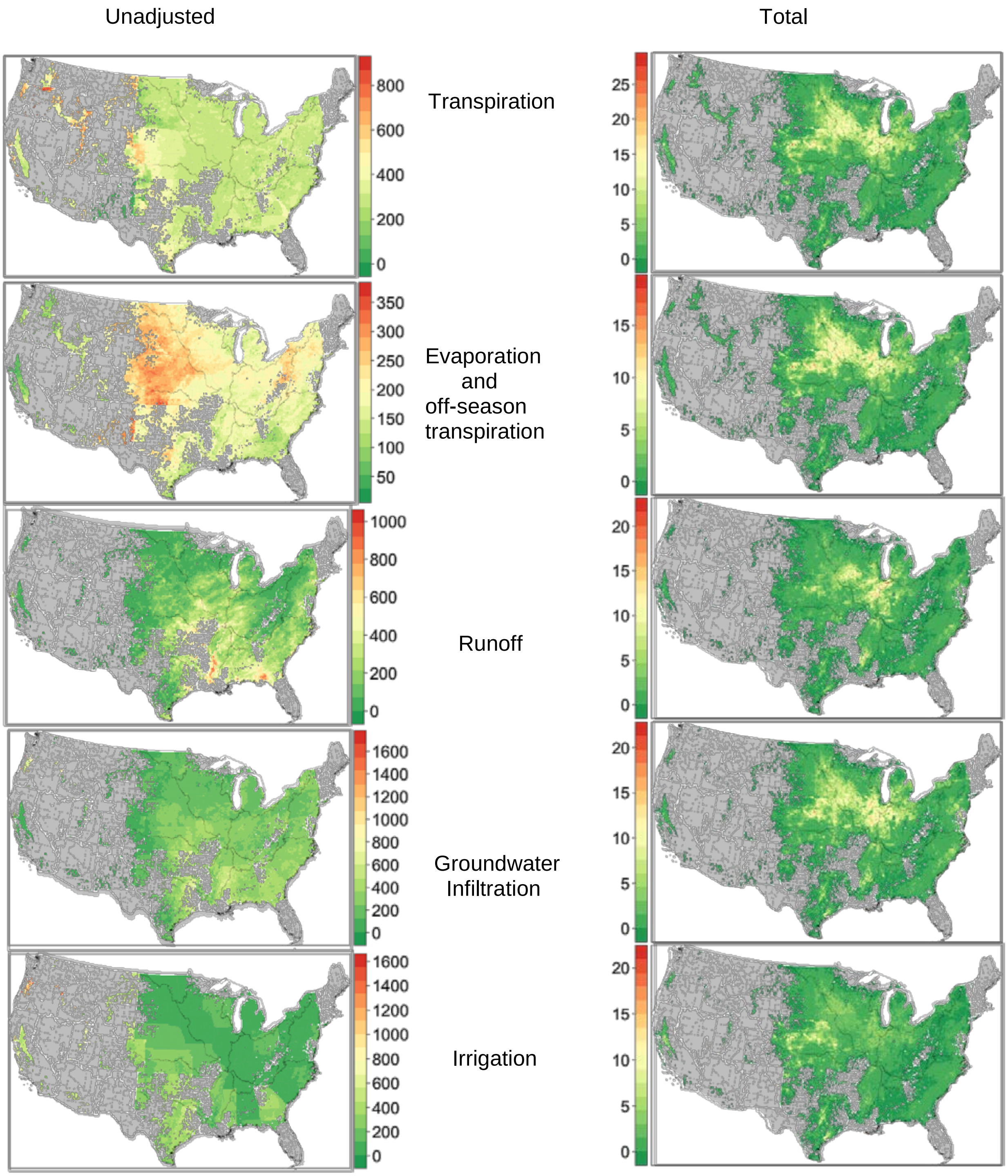
These *total* water balances are then aggregated across all cropping practices for a given crop. Figure 3.10 shows the *unadjusted* water balance (left - in annual millimeters) and *total* water balances (right - in ***thousand*** annual acre-feet), for corn, in 2008, across the contiguous U.S.

The water balances on the left of Figure 3.10 show the *unadjusted* average water balances (in mm) in each modeled pixel, while those along the right are multiplied by the total number of acres cropped (in corn, in this example) in each of the 10 km grid cells (i.e. Figure 3.9, scaled in acres per 10 km rather than percent land area), and also converted from mm to acre-feet. Both ways of visualizing the water balances provide valuable information. For instance, the figures on the left show that average *unadjusted* (i.e. non-areal) transpiration (and hence, by proxy, potential yield) are highest in the Northwest, Frontier States, and California's Central Valley, while the corresponding *total* transpiration map on the right shows that actual corn cropping occurs, as stated above, primarily in the Midwest and Cornbelt.

Similarly, as might be expected, unadjusted evaporation and off-season transpiration is greatest in the Frontier States, and Southern and Western states, but total evaporation and off-season transpiration over cropped corn land occurs primarily in those regions where the most corn is grown. Perhaps the most interesting pair of maps is for irrigation – as shown above, these agree well with survey estimates for both statewide irrigation volumes (actually given in acre-feet/acre in the Farm and Ranch Irrigation Survey – FRIS 2008) and are calibrated to match the statewide total irrigated acres, and show that the majority of irrigated corn is grown in Nebraska and other Frontier States (NASS 2008).

In order to see the geographic differences in intensity (i.e. agronomic water balance irrespective of cropped area), as well as the total (aggregate) impact – as weighted by total land use modeled in a given grid cell, it is useful for validation and reporting of water balances to visualize the unadjusted water balances (in mm) as aggregated across the eighteen Water Resource Regions (WRR – or HUC2 divisions) which span the contiguous U.S. Figure 3.11 shows the *average* water balances for corn (all management practices) in 2008 (in mm), by WRR, together with a background map with labeled Water Resource Regions.

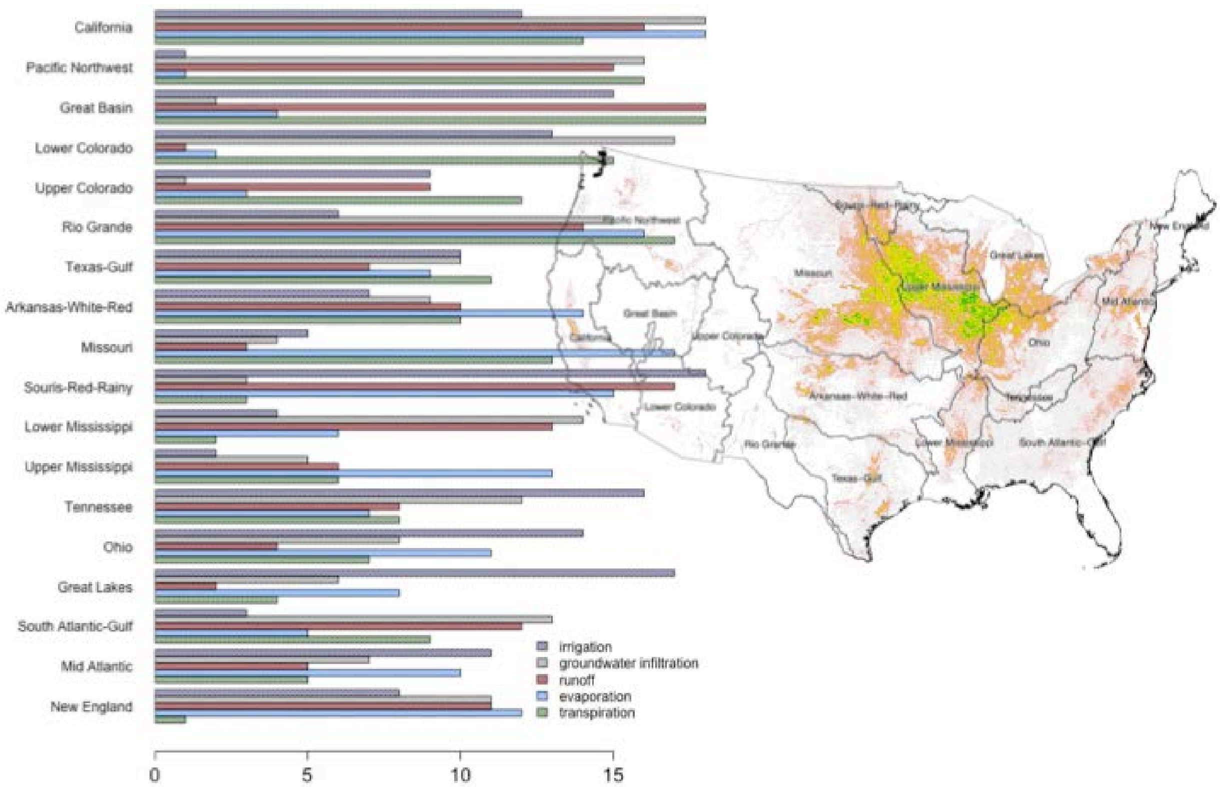
Figure 3.10: *Unadjusted* and *Total* Water Balances in Thousand Acre-Feet per Year for Corn in 2008.



Another useful visualization shows the distribution of unadjusted water balances (in mm) in each WRR. Figure 3.12 shows this distribution in each of the eighteen WRRs. In very general terms, the variability is a function the area cropped in a given cropping pattern (in this case corn) and the climatic variation over this cropped region. Abrupt cutoffs in the distribution are explained by the fact that cropped areas often run along geographic and climatic boundaries.

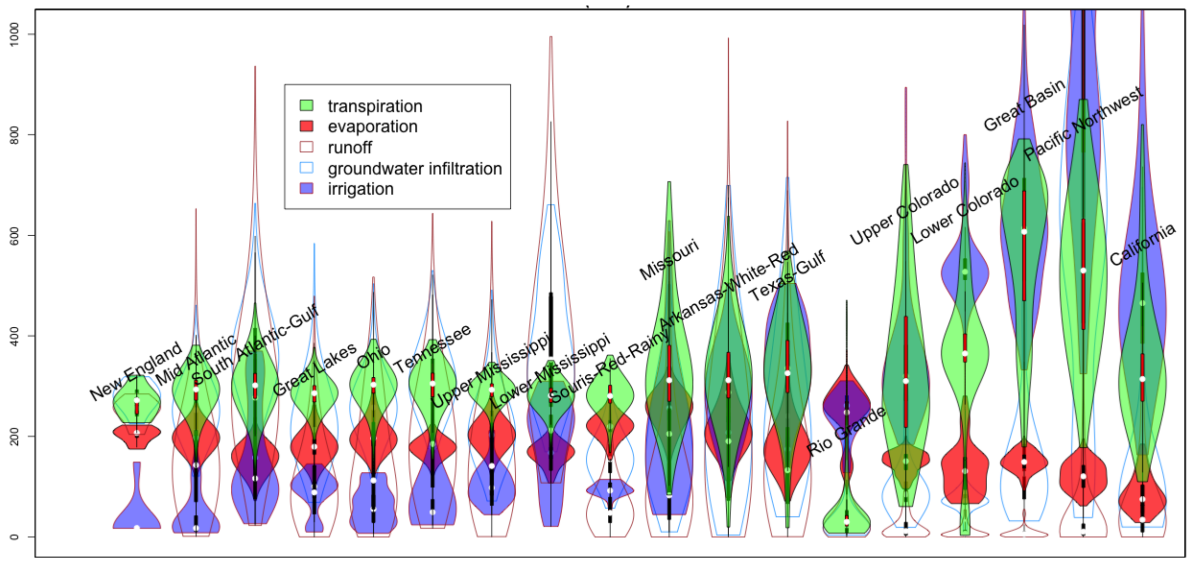
More specifically in the case of corn illustrated below, the median (unadjusted) transpiration is highest in the West (Great Basin, California, and Pacific Northwest), and these regions also receive the greatest volumes of irrigation per acre. Runoff levels are highest in the South (Arkansas-White-Red, Texas-Gulf, and Lower Mississippi), and in the Upper Mississippi. Irrigation volumes in the Northeast and Cornbelt are lowest, and indeed include a majority of land areas that are rainfed (i.e. without irrigation).

Figure 3.11. Average Water Balances for Corn in Each Water Resource Region, 2008.



Average water balances in the eighteen Water Resource Regions (HUC 2), in mm. The map shows the boundaries of the Water Resource Regions, together with land cropped in corn.

Figure 3.12: The Distribution of Water Balances by Water Resource Region, 2008.



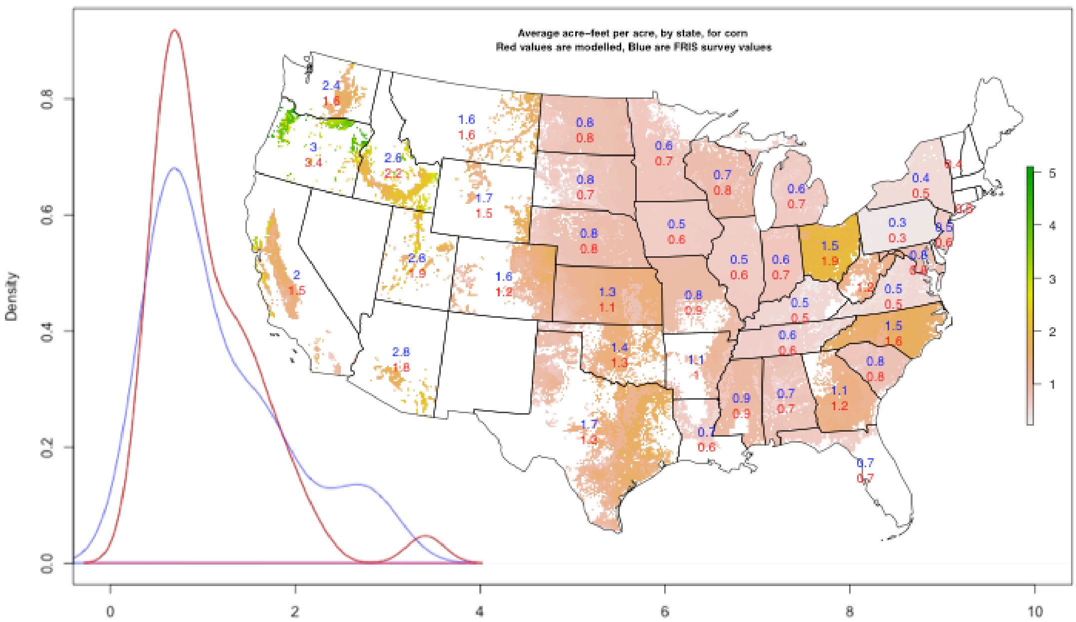
Average water balances in each of eighteen Water Resource Regions (HUC 2). Units are millimeters per year. A violin plot is equivalent to a boxplot, but instead of merely providing discrete summary statistics (e.g. mean, median, quintiles, min/max), it shows the full distribution. Within each violin plot is the box plot showing the median (white dot), 50% range (black box), and 25/75% range (lines).Irrigation in the Pacific Northwest peaks at 1555 mm per year.

Irrigation Calibration

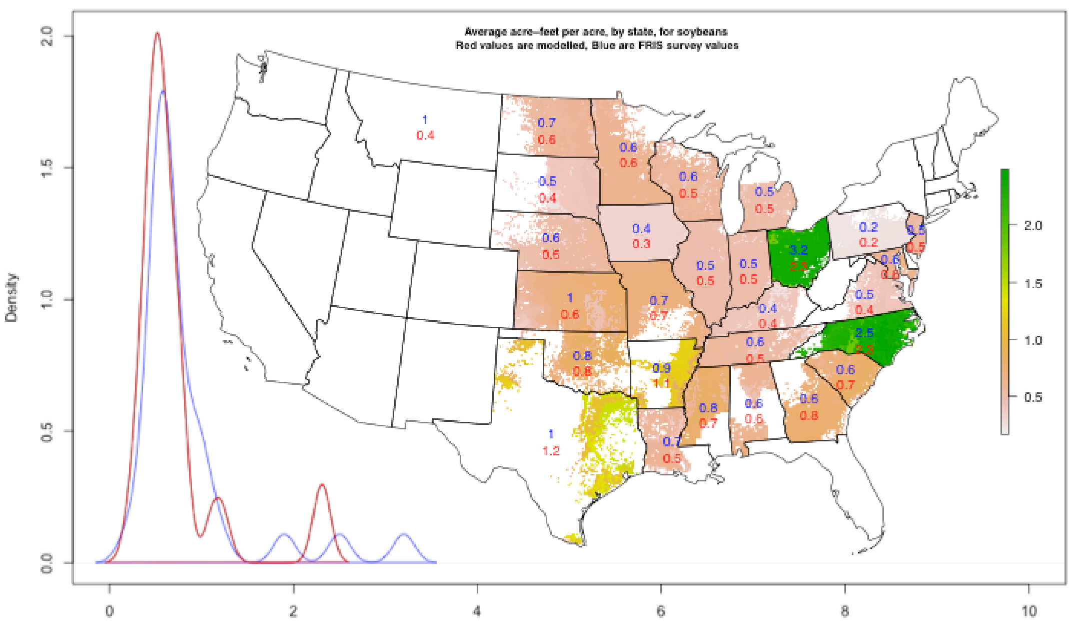
The irrigation rules were calibrated to match the total irrigated acreage reported in 2008, and to approximate the average state-by-state volumes of irrigation (in acre-feet per acre) for each crop. The volumes of irrigation for each crop matched state-level survey data with a great degree of fidelity. Figure 3.13. shows density plots and maps of the state-level distribution of average irrigation intensities (acre-feet per acre), as reported in survey (NASS 2008) in blue, and the modeled irrigation water intensities in red, for the four crops that constitute the greatest acreage: corn, soybeans, winter wheat, and alfalfa/hay.

Figure 3.13: Modeled versus State-survey Reported Irrigation by State.

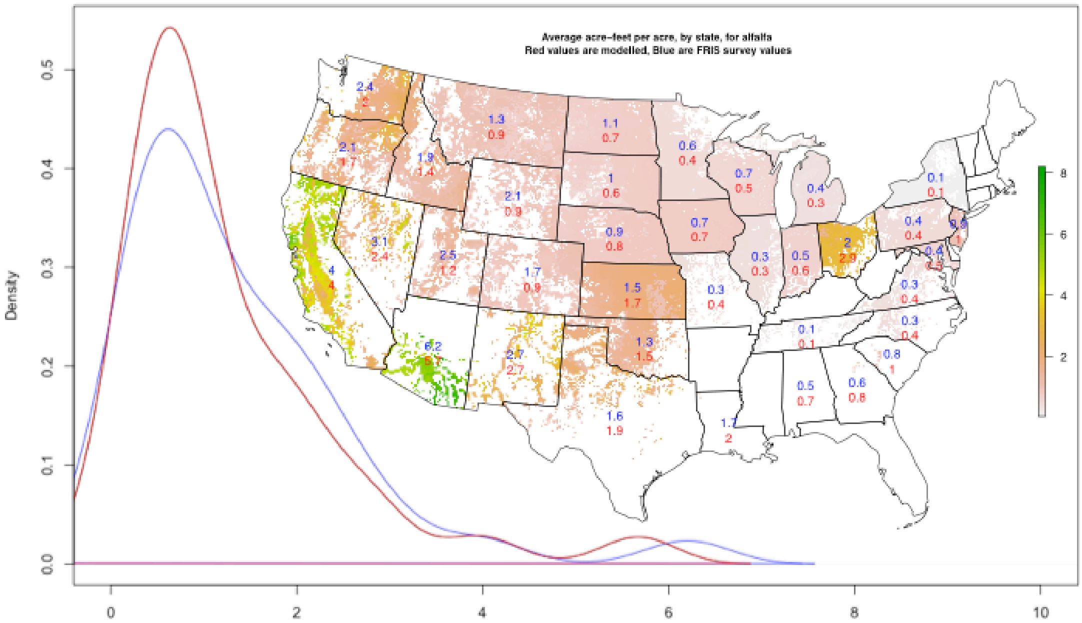
Corn



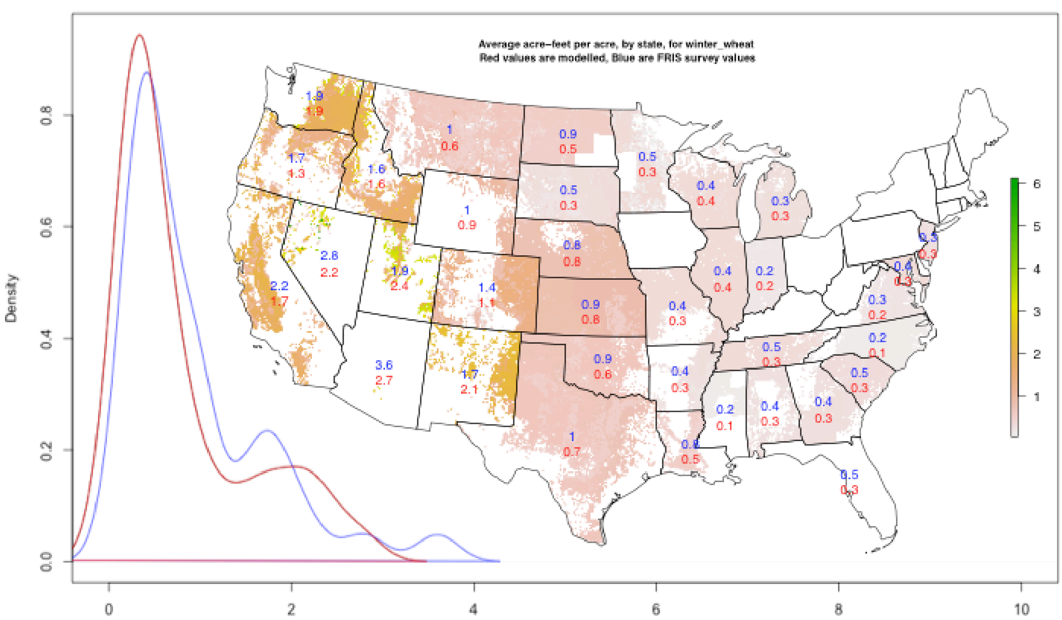
Soybeans



Alfalfa/Hay



Winter wheat

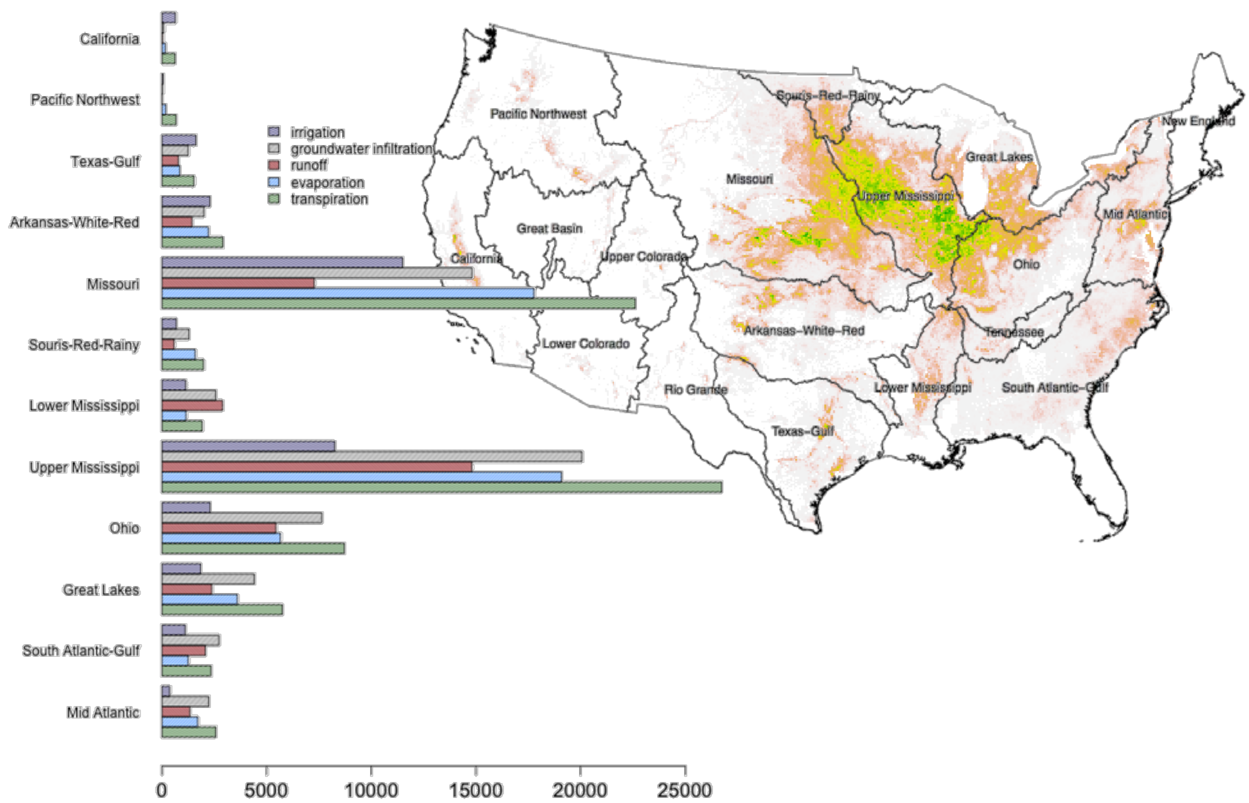


Irrigation water volume intensity (in acre-feet per acre) for corn, syobeans, winter wheat, and alfalfa/hay, in 2008. ***Modelled*** volumes are shown in red numbers and lines, and ***survey reported*** values are in blue numbers and lines). Total irrigated areas are set to match the survey reported acreages for each state.

For any given crop, the total water balances over all hectares cropped can be aggregated at any level of spatial resolution (i.e. by Water Resource Region, State, CRD, or county). Figure 3.14 shows such an aggregation at the Water Resource Region (HUC2) level for corn.

Figures 3.14 shows that total water balances correspond to the regions where corn is grown – primarily the Upper Mississippi and Missouri Water Resource Regions. Transpiration and evaporation and off-season transpiration volumes associated with corn cultivation are high in these regions. Most non-consumptive water use returns via the water table to surface water (via lateral flow), or recharges ground water stocks. Runoff fractions in these regions are moderate, in contrast to the Lower Mississippi water resource region, where runoff is high. Finally, irrigation volumes are greatest in the Missouri and (western) Upper Mississippi HUC2 region, where most irrigated corn is grown.

Figure 3.14: *Total* Water Balances for Corn in 2008 by Water Resource Region.



Average *total* water balances for corn in each of eighteen Water Resource Regions (HUC 2). The map shows the extent of the Water Resource Regions. Units are thousand acre-feet in each WRR per year.

Validation of Modeled Evapotranspiration

Two methods were used to validate modeled crop-water balances. First, for each of the row crops modeled, key locations were identified across the contiguous U.S. where the cropped area (per 10 km grid cell) were the highest in each of the eighteen Water Resource Regions. At each of these locations, daily modeled evaporation and transpiration were summed for the fallow preseason, growing season, and fallow postseason, and input weather, soil, and crop characteristics (e.g. rooting depth, soil coverage fraction, etc.) were extracted. The input parameters (e.g. derived reference evapotranspiration or ET_o, the dual crop coefficient, Kcb, irrigation volumes, soil water infiltration, etc.) were inspected on a case-by-case basis to verify that the relationships matched the daily algorithms prescribed in the FAO 56 manual (Allen, Pereira et al. 1998). Appendix D gives further details on the validation process.

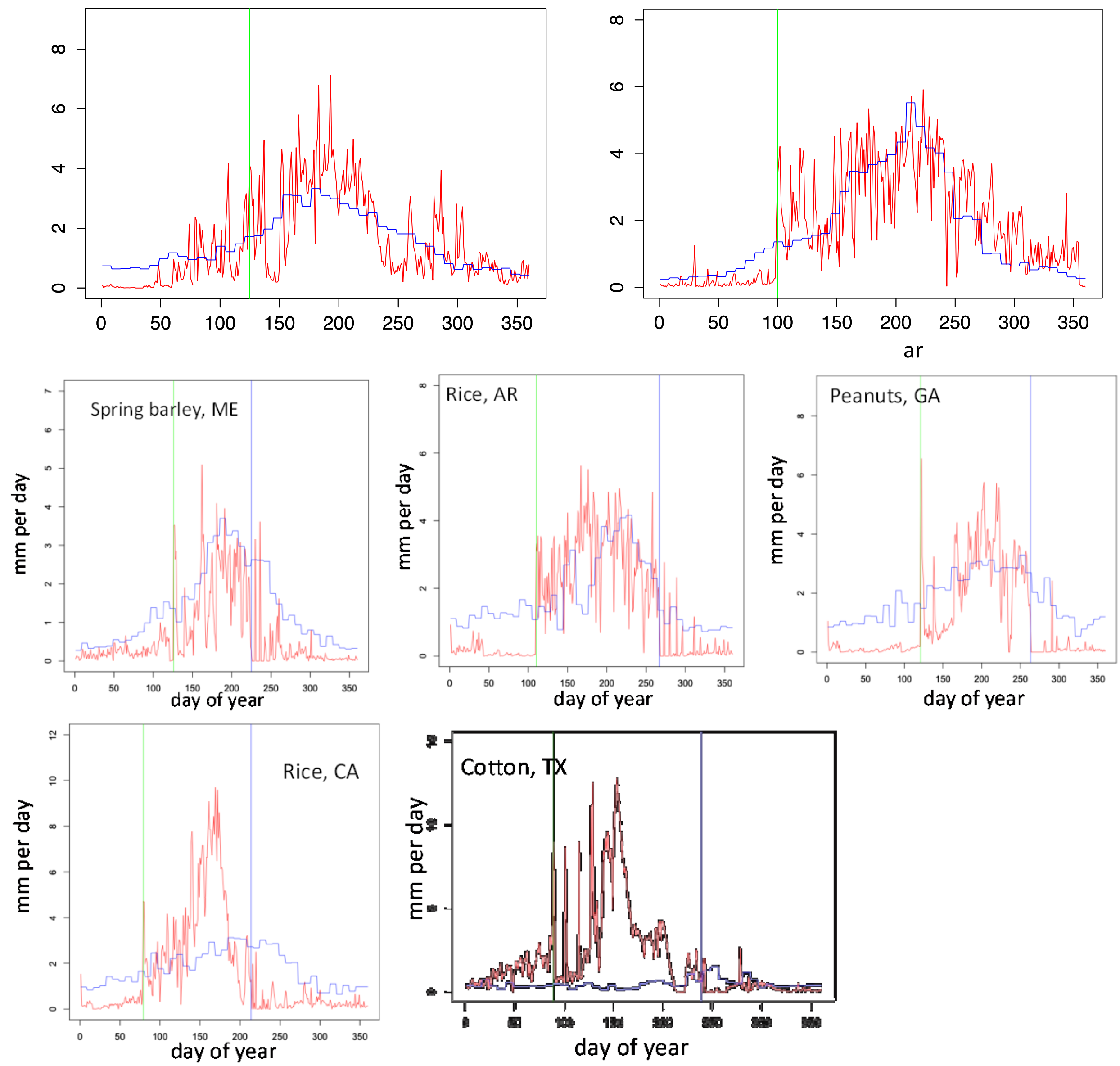
The next step in validating was to compare daily evapotranspiration (ET) against an established algorithm that uses MODIS satellite data to model average eight-day actual ET at ~1 km resolution – the MODIS 16 ET data product (Mu, Zhao et al. 2011). In most instances, the models matched with fairly high fidelity, but in cases of (likely irrigated) agriculture in the western U.S., the model developed for this report yields substantially higher ET estimates during the growing season than the algorithm relying solely on satellite data. In such cases, online texts and crop ecology textbooks were consulted, with the primary focus on California agricultural water balances. The ET estimated process-based crop water model (i.e. the one developed for this report) is in fact much closer to ET values reported in such texts. The researchers attribute the large discrepancy to the fact that the satellite-based algorithm does not incorporate irrigation water use and that the geophysical data sources used may not have high enough fidelity to monitor the effects of irrigation on crop-soil-atmospheric water interactions.

Figure 3.15 shows the outputs of the daily process-based crop water model (in red) as compared with the MODIS 16 algorithm (in blue). The growing season is indicated by the green (planting date) and blue (harvesting date) lines. Modeled ET is shown for a selection of crops grown in various states, and the final row of figures (bottom) shows that the MODIS 16 data product apparently fails to register actual ET for irrigated cotton (TX) and rice (CA).

On the basis of daily water balances like those shown in Figure 3.15, planting and harvesting dates were adjusted in some (Eastern and Midwestern) states, and for some crops (especially hay/alfalfa), to better match MODIS 16 outputs.

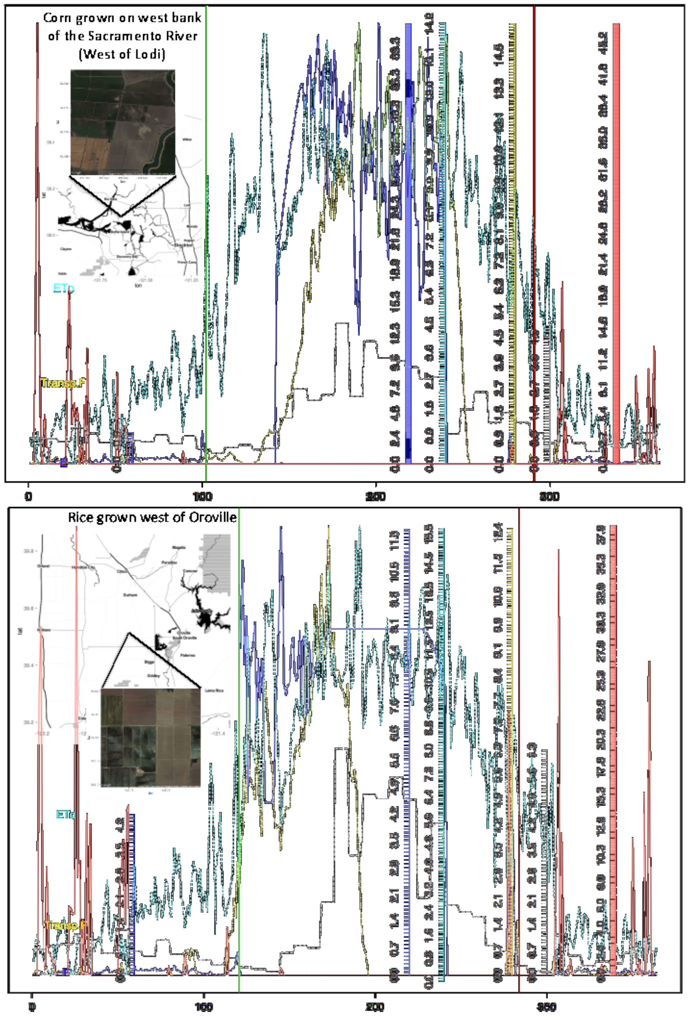
Two detailed case studies were used to further calibrate and verify the crop-water balance algorithm. Two locations in California where corn and rice were cropped in 2008 were used to 'ground-truth' the algorithm and to refine the daily ET calculations to match actual ET. For these two locations detailed investigation of all input parameters (weather, soil and crop parameters, and derived daily water flows, including irrigation) were calibrated until values reasonably approximated textbook reported ET values for crops grown in these regions. Figure 3.16 shows a sample of parameters and gives the locations of these two validation locations.

Figure 3.15 : Modeled Daily Evapotranspiration for Various Crops.



The outputs of the daily process-based crop water model used in this report are shown in red. These are compared with the ouputs of the MODIS 16 algorithm (in **blue**). The growing season is indicated by the green (planting date) and blue (harvesting date) lines. The final row of figures (bottom) shows that the MODIS 16 data product apparently fails to register ET in a region of irrigated rice (left) & cotton (right).

Figure 3.16: Validation Sites of Corn and Rice Water Balances in California.

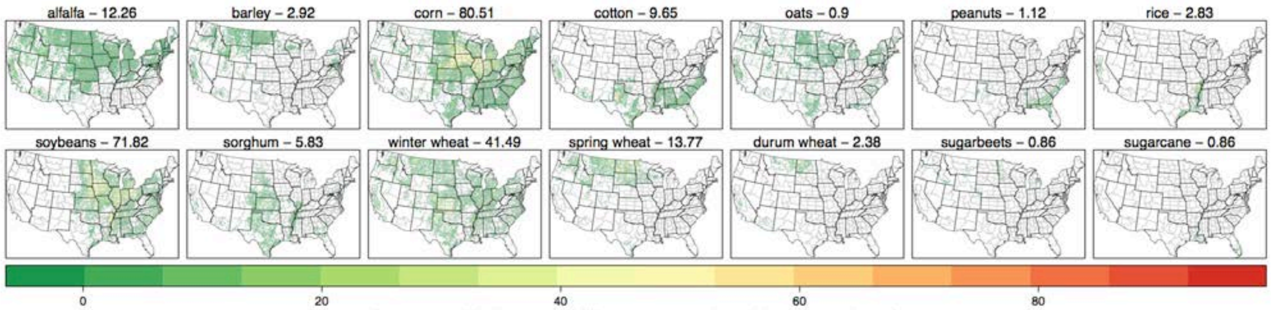


Detailed validation of the process-based crop-water model was performed using the two above sites: corn grown west of Lodi and rice grown west of Oroville, California.

Aggregation of Water Balances

Finally, water balances are aggregated ***across all crops*** in a given scenario/year combination. Figure 3.17 shows the areal coverage of all crops modeled in BEPAM, as downscaled according to the Cropland Data Layer, in the base year (2008). Values to the right of each crop give the total acreage (million acres).

Figure 3.17: Areal Coverage of Row Crops in the Base Year.



Areas cropped in the base year (2008) in crops modelled by BEPAM. The values to the right of each crop indicate the total area cropped, in million acres, for that crop. The color scale ranges from 0-100%, and shows the percentage of total land cropped in a given crop per 10 km grid cell. Note that the figure shows only alfalfa – not land cropped in other kinds of hay – tame, small grain, and wild hay (these were included in the analysis but not mapped above).

Figure 3.18 shows the resulting water balance across all crops modeled in BEPAM in 2008, aggregated at the coarsest level of resolution (by Water Resource Region), in thousand acre-feet per year. The accompanying map shows the total areas cropped in the row crops modeled by BEPAM – note that the majority of cropping (and hence crop-associated transpiration, evaporation, etc.) occurs in the Missouri, Upper and Lower Mississippi, Ohio, and Souris-Red-Rainy Water Resource Regions. Figure 3.19 maps the same five categories of crop-water use for all row crops in the base year, again in thousand acre-feet per year.

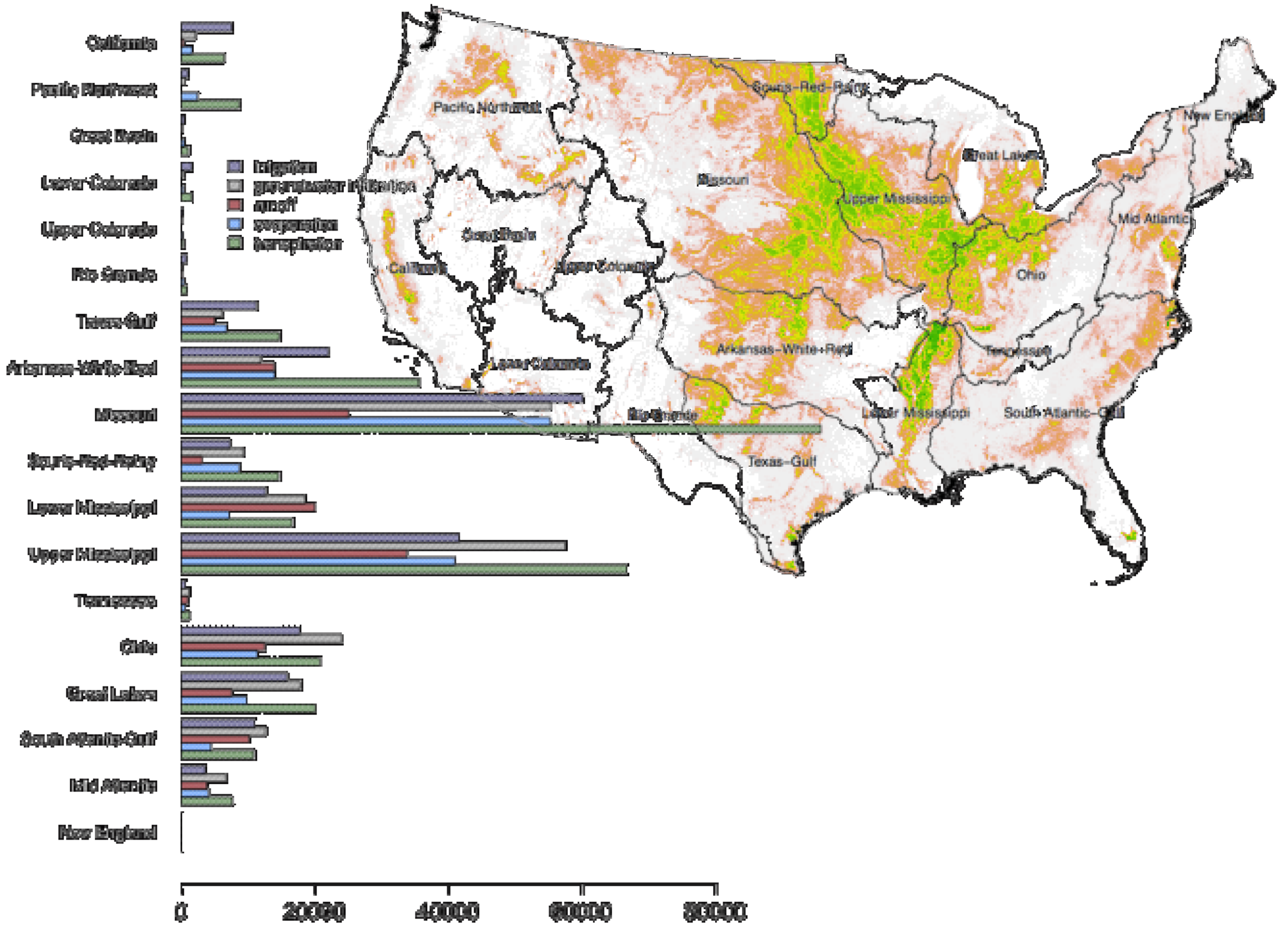
Calculating Changes in Water Balances in Future Years between Scenarios

Total water balances can then be aggregated at the Water Resource Region (WRR, or HUC 2) level. Figures 3.18 and 3.19 below show the total water balances, by WRR, and mapped at full resolution, for the base year.

Additional steps are needed to compare water balances across scenarios in future years. To compare across scenarios (as in Section 4.3), the following additional steps are necessary:

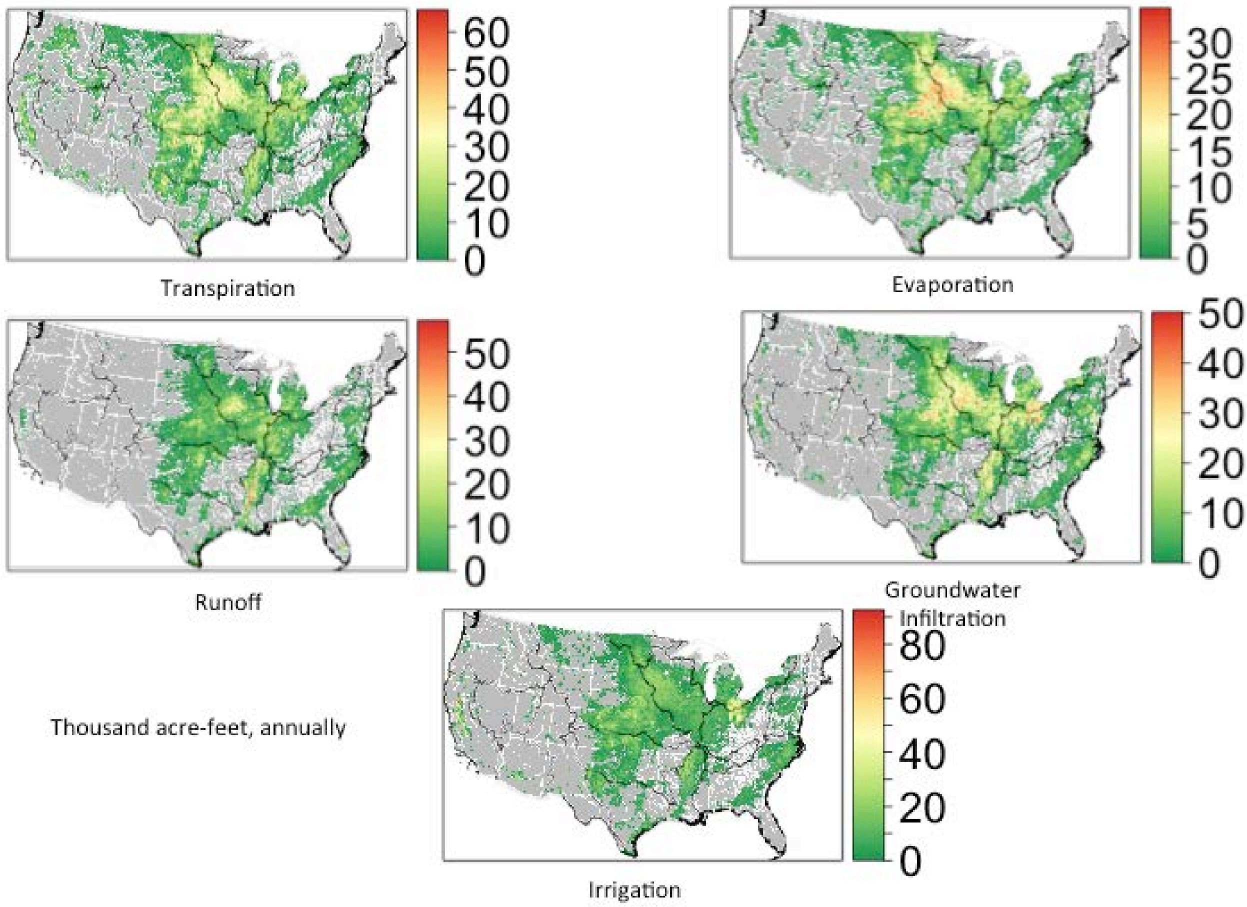
1. Calculate water balances for *idle cropland* and *cropland pasture* (there will be changes in crop water balances when these lands are displaced by dedicated biofuel feedstocks, i.e. switchgrass and miscanthus);
2. Calculate water balances for cropped land that is displaced between the BAU (counterfactual) and a given policy scenario (to account for cropped land including in only one of two scenarios being compared). This is achieved by taking the weighted average water balance across all row crops in a given scenario as a 'representative cropped land' water balance, and adding it to the aggregate crop water balance when comparing between scenarios.

Figure 3.18: Water Balances across All 16 BEPAM Crops in 2008 by Water Resource Region.



Average *total* water balances in each of eighteen Water Resource Regions (HUC 2). The map shows the extent of the Water Resource Regions, and areas cropped in the base year. Units are thousand acre-feet in each WRR per year.

Figure 3.19: Water Balances across All Sixteen Crops Modeled in BEPAM in 2008.

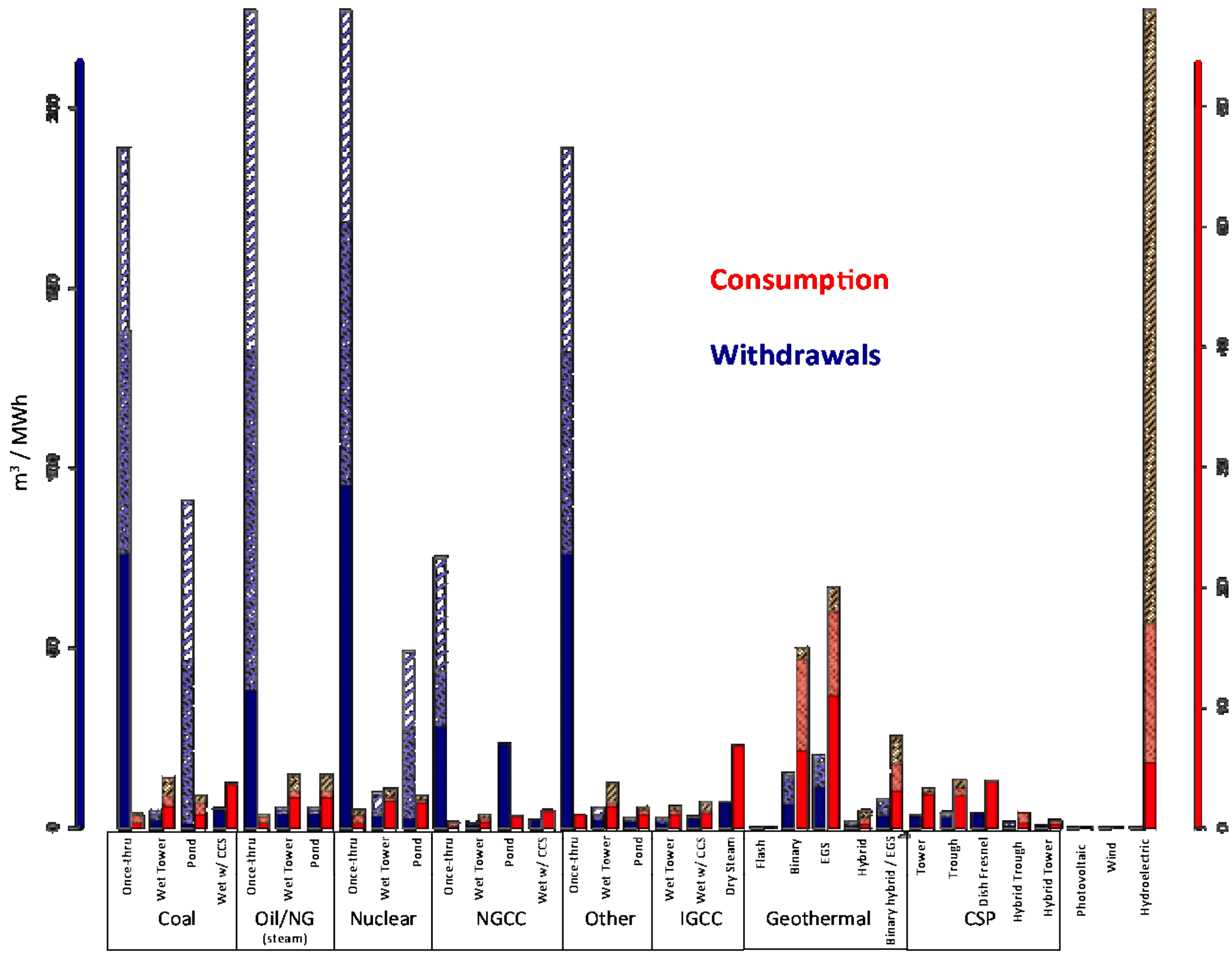


Water balances across all sixteen row crops modelled in BEPAM, in the base year (2008). Units are thousand acre-feet per year for each grid cell.

3.3 Electricity

Water use for electricity generation has been well characterized for a range of technologies, including thermoelectric generation (e.g. fossil fuels, nuclear), and renewable technologies. Figure 3.21 shows the considerable variation in operational phase water withdrawal and consumption intensities across and within fuel technologies. While much of the variation in thermoelectric power can be explained by cooling system technologies, other drivers, such as plant age, operational and thermal efficiency, cooling system age and water source, plant location, diurnal and seasonal temperature variations, wind speeds, and humidity levels, also impact the withdrawal and consumptive water use intensity of electricity generation.

Figure 3.20: Water Use for Electricity Generation by Technology & Fuel.



Operational phase water use of electricity generation. Red bars show consumptive water use intensity (left axis), and blue bars show withdrawal intensity (right axis). Low estimates in solid, median in double-hatched, and high estimates in single-hatched bars.

Source: Macknick, Newmark et al. (2011).

More recent work (Macknick, Newmark et al. 2012) has narrowed these ranges through identifying data and methodological inconsistencies in state and federal datasets (Meldrum, Nettles-Anderson et al. 2013), and clarified the operational, siting, and technological drivers of water use differences. However, despite the large variability, certain trends relevant to a transition to low-carbon electricity supply chains are readily apparent and robust: Concentrating Solar Power (CSP) and enhanced geothermal systems (EGS) have among the highest consumptive water use intensities of all technologies. Installing carbon capture and sequestration (CCS) systems also incurs a substantial decline in efficiency and greater than proportional increase in WUI. On the other hand, non-thermal renewable power generation, such as photovoltaics and wind power, have the lowest consumptive WUI.

3.3.1 Data Sources

The WUI of electricity generation is estimated by water source/type (freshwater, treated recycled water, degraded water, ocean, or estuary water). Estimates are derived for water consumption and withdrawals for once-through cooling (OTC) plants using seawater, and other renewable technologies based on three sources:

CEC Siting Cases. The CEC website contains applications for certification by various power plants since 1996 and the corresponding CEC Staff Assessments (CEC 2013). These applications and assessments provide records of water withdrawal and consumption estimates broken down by type of use (cooling tower, inlet fogging, domestic use, boiler steam, solar panel cleaning, etc.). The documents also provide water sources and the likely quality/functionality categories, as well as the presence or absence of zero liquid discharge (ZLD) facilities. ZLD systems ensure that a plant's wastewater output is disposed of within the plant boundaries and is not released for downstream use.

CEC Water use Information. The CEC has collected actual water use data for power plants greater than 20 megawatt (MW) capacity disaggregated by source and quality of water for 2010 (CEC 2012). No information is provided on the source of the underlying data, nor on the authors of this document. In cases where there is a disagreement, actual water use intensities reported in this document are considered more reliable than the previous source.

EIA Forms 860 and 923. Plants report water use information to the EIA along with other performance information. The statistics for 2008 were summarized in a study commissioned by the Union of Concerned Scientists or UCS (Averyt, Fisher et al. 2011). The nationwide water use intensities for various feedstocks, and conversion and cooling technologies were summarized by researchers from the National Renewable Energy Laboratory (Macknick, Newmark et al. 2012).

The analysis of plant-level water intensities for California plants using natural gas are broadly similar to the intensities reported by Macknick, Newmark et al. (2012). However, estimates differ from this study due to two key aspects unique to the state's power plants. First, many natural gas power plants in California use ZLD either in the form of evaporation ponds or as advanced reverse osmosis systems. In either case, the blowdown water is not released back for downstream reuse. The implication of ZLD technology for this study methodology is that all water withdrawn is consumed. Second, unlike other plants using OTC throughout the rest of the country, which largely depend upon freshwater, all of California's plants using OTC source water from the ocean and/or estuaries. Since California-based OTC plants use water sources with high salt concentrations, which are not usable by agricultural, industrial, or residential sectors, water consumption (evaporation) by such plants in the volumetric inventory of water use is not included.

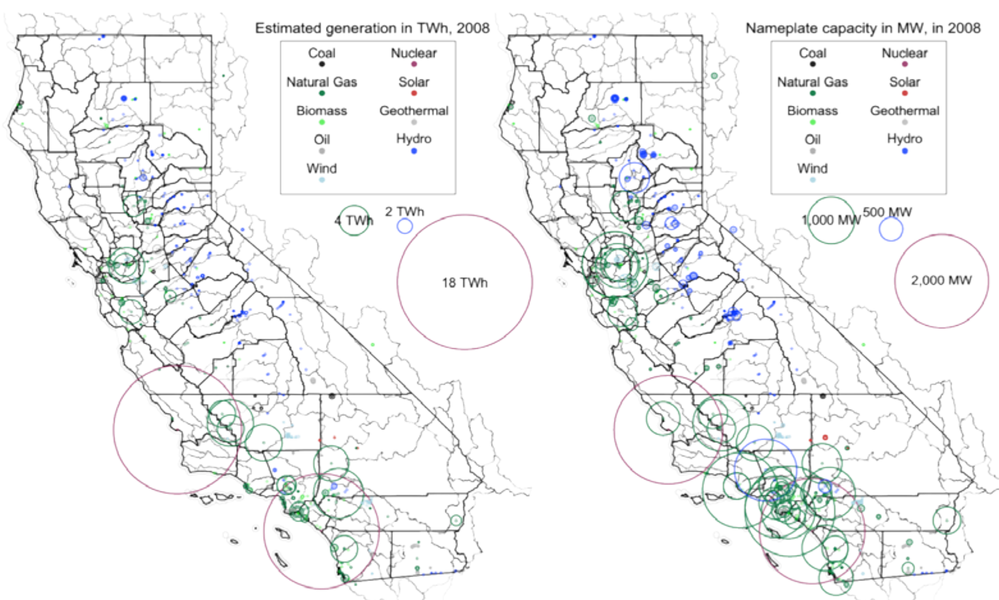
Other studies. For geothermal power plants, the geothermal water-use model developed by Mishra, Glassley et al. (2011) is used to derive water requirements. The model disaggregates water use by type/source: freshwater, degraded/recycled water, and geothermal fluid, the last of which has a high salt concentration (not unlike ocean or estuary water) and hence has limited or no alternative uses. Depending upon local geological conditions, such fluids may have high concentrations of salts—chlorides, sulfates and bicarbonates; and dissolved gases like ammonia and methane (Mishra, Glassley et al. 2011). Thus, geothermal fluid, since it is not accessible for any environmental or economic function (in contrast to the water types considered – e.g. freshwater, recycled, and degraded water), is likewise excluded from the reported WUI volumes.

Appendix E describes in detail the assumptions and data sources for estimating water use intensities, and summarizes the WUI values adopted for the base year and for the 2030 projections of water withdrawn and consumed.

3.3.2 Baseline Water Use

Figure 3.22 shows the estimated generation of California's major (> 20 MWh) power plants in 2008 based on EPA data, as summarized by the UCS study (Averyt, Fisher et al. 2011). Note that the San Onofre Nuclear plant permanently retired its units in 2013, and the state's other nuclear plant at Diablo Canyon is set to close by 2025.

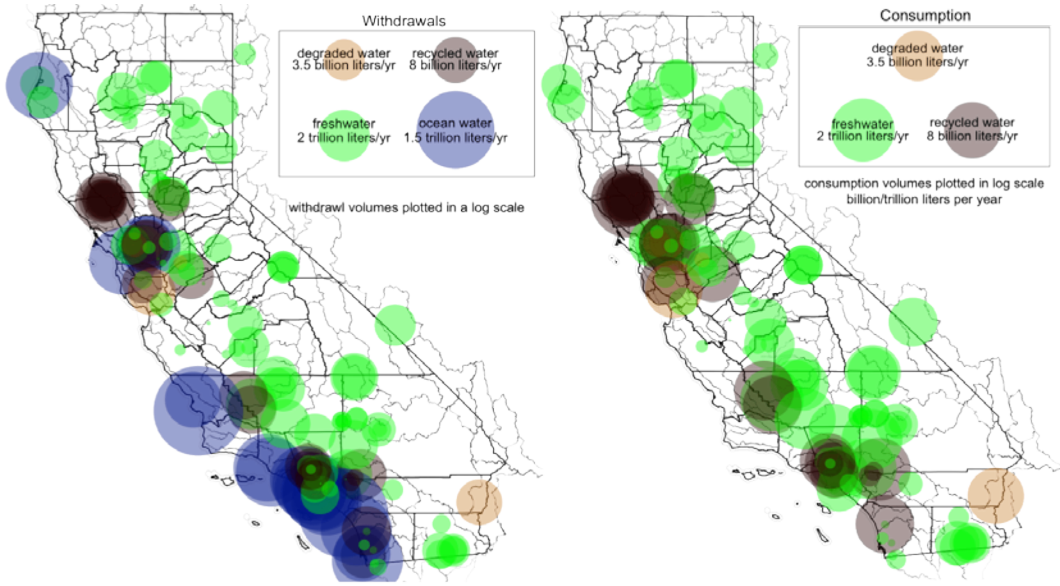
Figure 3.21: Electricity Generation & Nameplate Capacity in California, 2008.



Estimated electricity generation (TWh) (left), and nameplate capacity (MW) (right) of California's power plants, by plant type in 2008.

Figure 3.23 shows the estimated water withdrawn (top) and consumed (bottom) by these plants in the same year, by water type. The estimates are based on a detailed literature review of water use intensities and sources – See Section 3.4.1 and Appendix E.

Figure 3.22: Water Use of Major Electricity Generation Facilities in California, 2008.



Water withdrawals (left) and consumption (right) by water type (degraded, recycled, ocean, and freshwater). All volumes are plotted on a log scale.

3.3.3 California's Regulations on Water Use for Electricity Generation

Various water laws in California control the following three distinct but closely related aspects of power plant cooling:

a) ***Sources*** of water for cooling and process use;

b) ***Volumes*** of water *withdrawal* and *consumption* and consequently the choice of cooling technologies;

c) ***Fate/disposition*** of discharge of power plant effluent, including cooling tower blowdown.

Sources of Cooling Water

The State Water Resources Control Board's "Water Quality Control Policy on the Use and Disposal of Inland Waters Used for Power Plant Cooling – Resolution No. 75-58" (CA-SWRCB 1975) encourages the use of alternative sources of cooling water and/or the use of alternative cooling technology. The above resolution states that "…the source of power plant cooling water should come from the following sources in this order of priority depending on site specifics such as environmental, technical and economic feasibility consideration: (1) wastewater being discharged to the ocean, (2) ocean, (3) brackish water from natural sources or irrigation return flow, (4) inland wastewaters of low TDS, and (5) other inland waters."

As detailed in section 1 of this report, sections 13510 and 13551 of the State Water Code prohibit the use of "…water from any source of quality suitable for potable domestic use for non-potable uses, including …industrial… uses, if suitable recycled water is available…" given conditions set forth in section 13550. These conditions take into account the quality and cost of water, the potential for public health impacts, the effects on downstream water rights, beneficial uses, and biological resources (O'Hagan and Monsen 1999, CA-DWR 2009). Further, Section 13560 establishes the goal of increasing the use of recycled water in the state over 2002 levels by at least 1 million acre-feet per year (AFY) by 2020 and by at least 2 Million AFY by 2030. Both of these laws will impact water sourcing from electricity generation.

The CEC in its 2003 IEPR adopted a policy pursuant to SWCRB Resolution 75-58, indicating that approval of fresh water sources for power plant cooling would only be acceptable if alternative water supply sources are economically unsound or environmentally undesirable.

Nearly all power plants approved since 2000 use wet (recirculating) cooling technology and plan to use treated recycled water for cooling purposes, with five key exceptions (three NGCC plants and two solar thermal facilities) – *La Paloma* and *Pastoria* (both in Kern County) (1,048 MW and 750 MW), the *High Desert Power Project* in San Bernardino County (720 MW), and the *Beacon* and *Rice* parabolic trough power plants in Mojave Desert.

Some of the solar power plants in Mojave Desert plan to use slightly brackish groundwater (>1000 mg/L of salt content). SWRCB Resolution No. 88-63 (as modified by 2006-008) considers slight brackish water (<3000 mg/L or ppm) as "...suitable, or potentially suitable, for municipal or domestic water supply and should be so designated by the Regional Boards..." (SWRCB 2006). As a result, it is not expected such brackish water to be used by new power plants if recycled water is available. The solar power plants planning to use brackish groundwater – parabolic trough solar plants like Abengoa, Blythe, Rice, etc. – were required to provide economic justification for not using recycled water. The most common rationale came in the form of detailed documentation of the substantial investments that would be required to build and maintain long pipelines for supply from distant municipality water treatment plants.

Cooling Technology

The above-mentioned Resolution No. 75-58 also encourages the use of advanced cooling technologies like dry cooling or hybrid (wet/dry) cooling to reduce the volume of cooling water consumption. Siting cases of power plants approved with wet recirculating cooling "…should include an analysis of the cost and water use associated with the use of alternative cooling facilities employing dry, or wet/dry modes of operation…"

Despite the legal provisions encouraging use of dry or hybrid cooling, siting cases included only seven large (>50 MW) power plant projects in California with dry cooling (in total comprising a total combined rated capacity of around 1,000 MW), and none with hybrid cooling. The low shares of dry cooling are attributable to the higher capital and operating costs, and lower capacity, in particular during peak summer months. Analysis for the CEC (Maulbetsch and DiFilippo 2006) indicates that dry cooling in a new 500 MW NGCC power plant increased plant capital project cost by about 5% to 15% (US$ 8-27 million), and reduced annual generation by 1-2%, relative to wet recirculating cooling. Overall impact on revenues ranged from 1-2% of total revenue – this translates to an "effective cost" of saved water from

$3.40 to $6.00 per 1,000 gallons. This cost compares to more typical costs for industrial and residential uses ranging from $1.00 to $2.50 per 1,000 gallons. A similar analysis by NREL for solar thermal power plants estimated a capital cost penalty of 2% and annual generation penalty of 5% to shift from wet to dry cooling under the desert conditions of the Mojave Desert (Turchi, Wagner et al. 2010).

Five of the seven power plant projects with dry cooling are solar thermal (approved and under construction as of early 2013) – such facilities still require large volumes of water for panel washing, dust suppression, and auxiliary equipment cooling. This is based on a review of CEC Staff Assessment Reports of power plant siting cases since 2000. The review of assessment reports of these projects by CEC staff indicated that consumptive water requirements are around 85-108 gallons/MWh – this is around one-half the water use intensity of wet-cooled NGCC power plants.[19]

A large number of nuclear and natural gas plants in California use OTC facilities. In 2008, plants using OTC were responsible for 19% of electricity generated in California (56 TWh out of a total 300 TWh) (Vidaver, Ringer et al. 2009). The share has decreased since then partly due to the closure of one of the two nuclear power plants (San Onofre, Los Angeles in 2013) as well as the closure of multiple aging NG-power OTC plants like the Potrero Plant in San Francisco. Based on recent policy initiatives to phase-out once-through cooling in the state due to environmental concerns (SWRCB 2008), all plants with OTC are likely to be shut down or adopt alternative cooling technologies by 2030 (CCEF 2011). Under the CA-TIMES scenarios used in this analysis, all nuclear was phased out by 2030.

Discharge of Power Plant Effluent

The state water code places restrictions on disposal of cooling tower blowdown water. "…The discharge to land disposal sites of blowdown waters from inland power plant cooling facilities shall be prohibited except to salt sinks or to lined facilities approved by the Regional and State Boards for the reception of such wastes…". These restrictions largely emerge from the Porter-Cologne Water Quality Control Act of 1967 (Federal Clean Water Act).

Table 3.11 summarizes the water intensity numbers assumed in this study. Water requirements for coal power plants are not included in this table below. Water requirements and sources for such plants in the base year are based on Averyt, Fisher et al. (2011). Coal plants are assumed to be retired before 2030 based on CA-TIMES forecasts.

Most of the projects listed on the CEC Siting Cases website are equipped with zero-liquid discharge (ZLD) systems - which consist of either an advanced energy-intensive reverse osmosis system (as in the case of the Walnut Creek Energy Center in LA County) or a simple evaporation pond. Some plants, like the La Paloma in Kern County, take advantage of nearby

[19] The water consumption intensity of solar thermal (parabolic trough) plants with wet cooling is around 900-1000 gallons/MWh.

crude oil operations to discharge blowdown and wastewater into deep injection wells. For such plants, all water withdrawn is consumed. In other words, the water withdrawal and consumption intensities are same. The above regulations guide the allocation of cooling technologies and water source/type in the 2030 projections, discussed in detail in section 4.4.

Table 3.11: Assumed Water Withdrawal and Consumption Intensities (Liters/MWh)

Fuel	Technology	Cooling System	Withdrawal	Consumption
Natural Gas	Combined Cycle	Tower	806	806
		Dry	38	38
		Hybrid	79	79
	Combined Cycle & CCS	Tower	1,544	1,544
	Combustion Turbine	NA	284	227
Solar	Parabolic Trough	Tower	2,775	2,775
		Dry	382	382
	Power Tower	Dry	167	167
	Photovoltaic	NA	4	4
Geothermal	Hydrothermal (150 ^{0}C, Binary)	Tower	9,993	9,842
		Dry	4	4
		Hybrid	1,401	1,363
	Hydrothermal (200 ^{0}C, Flash)	Tower	0	0
	Hydrothermal (Dry Steam)	NA	2,006	2,006
	EGS (150 ^{0}C, Binary)	Tower	12,075	11,924
		Dry	2,355	2,355
		Hybrid	3,596	3,596
	EGS (200 ^{0}C, Flash)	Tower	0	0
Biomass	Combustion Turbine	NA	8	8
	Steam Turbine	Tower	2,627	2,101
		Dry	8	8
	Combined Cycle	Tower	874	700
		Dry	4	4
		Hybrid	235	235
Wind	NA	NA	0	0

3.4 Natural Gas

3.4.1 Conventional Drilling

The majority of water used in conventional (vertical) drilling of non-associated dry gas is for constructing the wellpad, drilling the well, preparing the borehole, and setting the casings. There are few studies that aid in estimating the consumptive WUI of conventional drilling, and many of these studies use aggregated estimates and were conducted prior to the domestic shale gas revolution. Three studies – U.S. DOE (2006), Goodwin, Carlson et al. (2012), and Clark, Horner et al. (2013) – estimate a WUI ranging from 5.4 liters/GJ (U.S. national average); 21.6-55.9 liters/GJ (Wattenberg shale gas from Colorado); and 9.3-9.45 liters/GJ (Texas average), respectively. The disparity between the second estimate and the other two may be a function of geology, and reflect real variability in WUI among formations.

3.4.2 Fracking for Shale/Tight Gas Resources

The combined use of two extraction technologies, hydraulic fracturing and directional drilling, has ushered in an era of inexpensive and rapid production of natural gas (and oil) from 'unconventional' sources – primarily sedimentary deposits of shale and tight oil and gas – in the United States (Gregory, Vidic et al. 2011). By the end of 2012, roughly 40% of gas produced domestically used the combination of these two technologies (Nicot, Scanlon et al. 2014). Here the combination of these two technologies – horizontal drilling and hydraulic fracturing – is referred to as 'fracking'.

The combined natural gas extraction process begins with the vertical drilling of a well to the depth of the source rock. Directional drilling then allows operators to angle the wellbore, typically horizontal to the ground surface, from a single well pad to reach rock formations typically 1-2 kilometers distance from the original well pad. The well is then hydraulically fractured ('fracked'), which injects pressurized water mixed with a slurry of specialized chemicals (which varies by well/field geology and operator) into rock formations through the wellbore to induce small rock fractures and thereby allow increased flow rates of natural gas into the well. While fracking has increased in recent years due to high economic returns and the ability to access previously unavailable plays, the practice has also increased the volume of freshwater required and wastewater produced to extract natural gas (Kiparsky and Hein 2013).

The water used for hydraulic fracturing is combined with more than 750 chemicals, including a mixture of proppants, scale inhibitors and surfactants, known to range from benign to toxic (Colborn, Kwiatkowski et al. 2011). While the chemical additives amount to between 2 percent-5 percent of the injected liquid by volume, hydraulic fracturing is a water-intensive process, so aggregate volumes of additives can also be large. Just how much water is needed to hydraulically fracture a well varies widely depending on the geology of the formation, the concentration and form of oil/gas deposits in the play, and, in the case of horizontal wells, the horizontal length of perforated pipelines. However, on average, vertical wells use 1,500 cubic meters of water to hydraulically fracture while horizontal wells use an average of 10,000 cubic meters per fracture, with up to eight fractures able to be completed from a single well pad (Goodwin, Carlson et al. 2012, Nicot and Scanlon 2012, Murray 2013). In the Marcellus formation, a wide variation – anywhere from 10-70 percent – of total injected water resurfaces as wastewater (Olmstead, Muehlenbachs et al. 2013). A range of 30-70% flowback or produced water is typical for estimates of produced water (GWPC 2013), with proportions depending primarily on the geology of the formation, well characteristics, and well age. Sources of water for initial drilling include freshwater withdrawn from permitted surface water bodies or purchased from public water suppliers, along with approximately 10% recycled wastewater from previous hydraulic fracturing operations.

It is worth noting that the majority (~95%) of water used in fracking occurs in the hydraulic fracturing stage, thus requiring a substantial volume of water over a short period, particularly during the development of a new field (Goodwin, Carlson et al. 2014). Further, water use occurs before recovering any gas/oil resource, and in some instances fracking fails to produce any natural gas and oil.

3.4.3 Literature Estimates of WUI of Shale and Tight Oil and Gas

The WUI of conventional and shale oil and gas extraction is defined as net water consumed per megajoules of petroleum or processed natural gas. The net water consumption is equal to the water volume used – primarily in drilling and hydraulic fracturing, – to produce fossil fuel energy resources minus the volumes of flowback water and produced waters that are in some cases directly reused or treated and recycled into the production stream. To the extent possible, WUI volumes are disaggregated by water source type, both for water use incurred inside California and for out-of-state water use of imported natural gas and petroleum.

The WUI for shale gas fracking is highly variable, and depends on the following factors: formation geology, EUR, and state-level regulation (which determines proportions of flowback/produced water reused and recycled). Figure 3.23 shows the range of recent literature estimates for consumptive water use intensity (WUI) of shale/tight gas and oil/gas resources, as well as for conventional (vertical) drilling. All figures show the WUI in liters consumed per megajoules gas, and in many cases, for the coproduction of petroleum and natural gas, in MJ of converted energy products.

The literature definition of consumptive water use, i.e. the net water consumed to produce shale gas & oil, is followed, and potential environmental impacts (e.g. induced seismicity) of reinjection of flowback/produced water are not analyzed in depth. For a brief summary of the EPA definitions and regulations governing water reinjection, see the section titled "Oil and Gas injection wells" in Appendix B.

Across the range of the studies reviewed, estimates of consumptive WUI of shale oil and gas extraction have been shown to be most sensitive to the following parameters:

- Estimated ultimate recovery (EUR)
- Total volume of fracturing fluid per fracking event
- Proportion of flowback/produced water reused and/or recycled
- Assumptions regarding the number of wells per drilling pad

Clark, Horner et al. (2013) find that WUI estimates are most sensitive to values adopted for the EUR and the total volume of fracturing fluid per fracking event – Four other studies (Nicot and Scanlon 2012, Laurenzi and Jersey 2013, Goodwin, Carlson et al. 2014, Nicot, Scanlon et al. 2014) also estimate and explicitly consider the sensitivity of WUI to EUR assumptions. Another key determinant of net WUI is the proportion of flowback or produced water reused and/or recycled. Directly reusing, or first treating and then recycling flowback or produced water volumes, is a way of substituting for freshwater use and thus reducing net WUI. Some formations (e.g. the Marcellus and Eagle Ford) are characterized by lower volumes of flowback (produced water immediately following hydraulic fracturing) and produced water, and so have higher net WUI than other formations (Nicot, Scanlon et al. 2014).

An operator's choice of whether and how much to reuse/recycle and then reinject of produced water is a function of technology, geology, and state-level regulations. For example, Pennsylvania's regulations prohibiting water injection into deep water wells have driven a shift from trucking increasing volumes of produced water to treatment facilities or out of state, to reuse and recycling in the Marcellus Shale. However, fresh water consumption still constitutes approximately 90% of total water use in fracking (Nicot, Scanlon et al. 2014) and reuse/recycling of flowback/produced water remains only a minor proportion of water use in other formations, and in general ranks below municipal water use in priority, and accounts for only 5% of net water consumption (Nicot, Scanlon et al. 2014). A further estimated 3% of water consumed comes from brackish sources. Certain operators, such as Apache Corporation, which operates in the Permian Basin plays in Texas, have developed economically viable operations and technologies to eliminate their use of freshwater entirely, by switching to degraded and brackish water sources for initial frack jobs, and reusing/recycling flowback and produced water for subsequent ones.[20] The degree to which these innovations may be applicable in other fields remains to be seen, as does the question of whether Apache's operational and technological advances will continue to be viable as wells age, and the level of total dissolved solids (TDS) in produced water increases (Goodwin, Carlson et al. 2014). Current ranges of fresh water use recorded in the peer-reviewed scientific literature range from 100 to 80 percent (i.e. reuse and recycling of produced and flowback water range from zero to 20 percent), with the exception of the Marcellus Shale, where operators recycle up to 95 percent of the flowback/produced water.

Four studies (Clark, Horner et al. 2013, Laurenzi and Jersey 2013, Murray 2013, Nicot, Scanlon et al. 2014) report and account for reuse and recycling rates. Laurenzi and Jersey (2013) show that assumptions regarding the number of wells per drilling pad (which typically ranges from about 6-20) influences the estimated WUI for Marcellus Shale gas, as the actual recycling rate depends directly upon this number.

Nicot, Scanlon et al. (2014) conducted a detailed inventory with a decade of quality-checked data on water use, reuse/recycling, and disposal for the Barnett Shale formation of Texas. As such, this study represents the best available LCA inventories for tracing water use in shale gas operations. In the decade-long time series data, the study finds a clear downward trend in WUI with well age, which they term the "WB ratio" (defined as the volume of flowback/ produced water per hydraulic fracturing event. They find that this ratio declines over well lifetime, but eventually stabilizes at a constant value. This implies decreasing WUI as wells age. Goodwin, Carlson et al. (2014) report exhaustive summary statistics of the water use of the sample of wells they use to estimate the WUI of oil & gas fracking operations conducted by Noble Energy Inc. in the Wattenberg field of Northeast Colorado. This study does not find evidence for a decreasing WUI as wells age in the Wattenberg.

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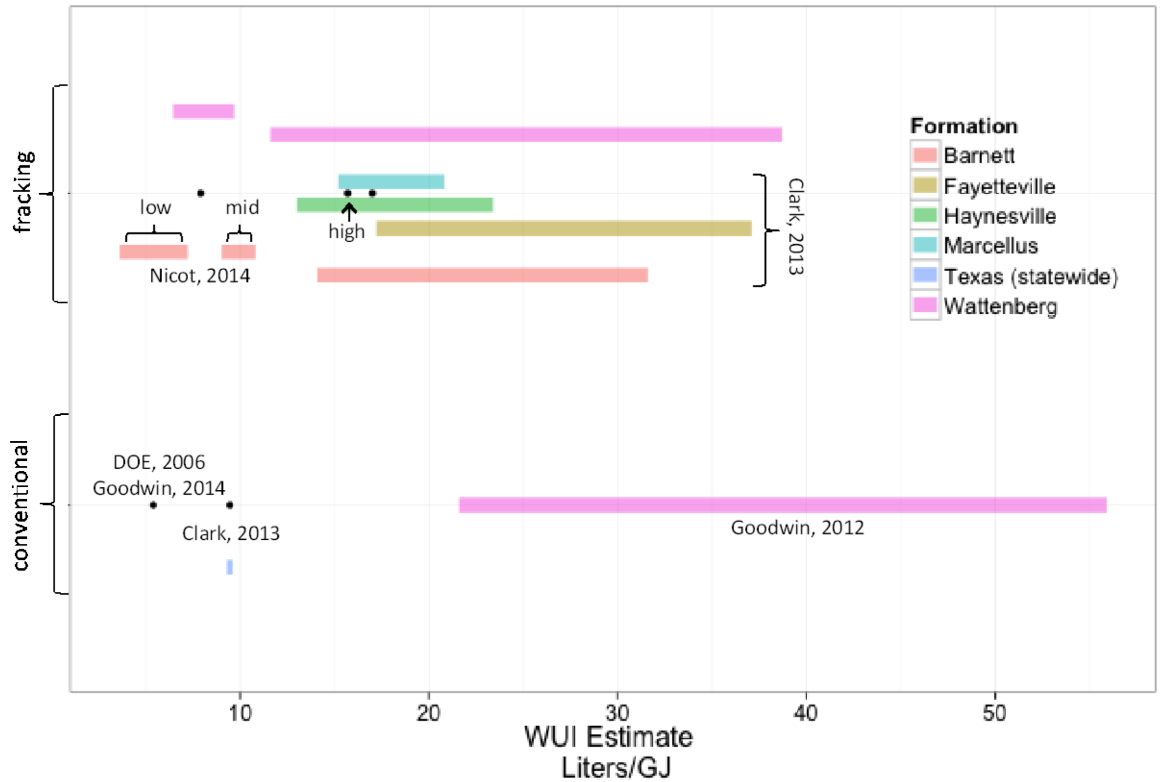
[20] See: http://www.energybiz.com/article/14/05/usa-hydraulic-fracturing-technology-evolves-and-improves

Figure 3.23: WUI Estimates of Conventional Recovery and Fracking for Shale/Tight Oil & Gas.



The most in-depth study is by Nicot, Scanlon et al. (2014) (in orange), wherein 'high' indicates the mean WUI to date; 'mid' the WUI for wells that have been in production for greater than six years, and 'low' is the asymptote of decreasing WUI trends as extrapolated to the EUR of wells.

Note that while all of the studies estimate fracking water use per well, only four studies – Goodwin, Carlson et al. (2012), Clark, Horner et al. (2013), Laurenzi and Jersey (2013) and Nicot and Scanlon (2012) further estimate water use of drilling operations, and report water consumption on an energy basis (i.e. by WUI). These studies further provide well-level and total MJ water use estimates for background processes – including cement manufacturing, drilling, diesel for truck imports of water, and mining of proppant materials – which together account for roughly one-eighth to one-quarter of shale gas fracking water use.

It is also worth emphasizing that it is likely that none of the studies discussed above and outlined in Table 1 in the appendix is entirely representative of the actual distribution of WUI and other water use activities for hydraulic fracturing across the geological formation. Not only are many studies using proprietary data, provided voluntarily to *FracFocus* or the researchers themselves, but there is no independent reporting of water use by wells fractured that fail to produce any natural gas at all (Goodwin, Carlson et al. 2012). Thus, the studies reviewed here may suffer from selection bias to the extent that more advanced operators are more willing to disclose their practices, and that the proportion of water used in constructing and fracturing non-producing wells has not been recorded or estimated by any study to date.

In summary, the peer-reviewed literature on the WUI and water quality impacts of fracking is sparse but increasing. Further discussion of the methodological and data limitations that prohibit comprehensive understanding of the water use impacts of fracking, as well as proposals to address these limitations, can be found in Appendix B (B.3).

Given the relative novelty of fracking and the yet-unsettled debate as to how the WUI of this technique compares with vertical drilling of conventional non-associated 'dry' gas, the full range of literature WUI estimate for both fracking and for conventional vertical drilling is adopted. Further, in light of the lack of any peer-reviewed studies estimating the WUI of shale oil (see Section 3.2.5), WUI values are taken based on current estimates of the WUI of shale oil & gas. Table 3.12 shows the estimates adopted in this study for each technology, which include a range and a 'best-guess' point estimate.

Table 3.12: Values Adopted for WUI of Conventional Gas and Shale/Tight Oil & Gas.

Resource (technology)	Point estimate (L/GJ)	Range (L/GJ)
Shale gas (fracking)	10	3.6 - 37.1
Shale/tight oil (fracking)	24	11.6 - 38.7
Conventional gas (non-associated, vertical drilling)	28	5.4 - 55.9

Clark, Horner et al. (2013) compare the WUI of shale gas fracking with conventional natural gas production, and find that shale gas fracking has a higher WUI than conventional unassociated gas. However, there is evidence (see Table 3.12 and Table 1 in the appendix, as well as recent industry reports)[21] that WUI for shale and conventional gas is comparable or may even be lower than for conventional natural gas – despite the fact that greater volumes of water are need for the fracturing event, a single fracking event produces substantially more gas than conventionally drilled vertical wells.

3.4.4 Water Sources for Horizontal Hydraulic Fracturing

Very little data exist on the sources of water for fracking, due to the fragmented nature of the industry and dynamic nature of water contracts. The majority of water used in hydraulic fracturing is freshwater (Nicot, Scanlon et al. 2014), sourced from surface and groundwater stocks as nearby the wells as permitted by regulations and climate – in arid regions, the proportion of groundwater used is generally higher, as surface water reserves are more scarce (Nicot, Scanlon et al. 2014).

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[21]See, for instance: http://www.platts.com/latest-news/natural-gas/houston/marcellus-shale-wells-produce-less-wastewater-21124720. Also the most recent peer-reviewed paper (Nicot, Scanlon et al. 2014) estimates that HHF uses less net consumptive water than vertical drilling for dry associated gas.

Transportation costs may account for the majority of water acquisition charges. In the Bakken formation, despite the fact that water purchasing costs are highly variable, dedicated use of recycled water and recycling of produced water is still not economically viable, and oil producers have begun to rely increasingly upon groundwater sources due to difficulties in obtaining rights and access to surface water sources (Pepino 2014).

Wastewater is handled differently depending on state regulations and the geology of the formation being exploited. Typically 90-95% of wastewater is disposed of in deep underground injection wells. Recent work corroborates the strong correlation between injection of large volumes of wastewater deep underground and large earthquakes, and posits a well-understood mechanism (namely, higher fluid pressures weaken a preexisting fault) by which injection may induce large earthquakes under certain geological conditions (Ellsworth 2013, van der Elst, Savage et al. 2013). However, treated wastewater can also be released into surface water bodies and sometimes reused for beneficial purposes. In dry states such as California, the potential for reuse is gaining attention (Kiparsky and Hein 2013).

3.4.5 Regulation and Prospects for Technological/Operational Improvements

Environmental Protection Agency Commissions Study, Revisits Rules

In 2011, the EPA drafted a plan to commission research on the impacts of hydraulic fracturing on drinking water resources (EPA 2011). Research is to be conducted on how the following aspects of fracturing might impact drinking water resources (in terms of both quantity and quality):

1. Water *acquisition* – impacts of large volume withdrawals of surface and groundwater;
2. Fracking *chemicals* – potential impacts of their contaminating the drinking water supply;
3. *Injection* – potential impacts and likelihood of injected water contaminating aquifers;
1. *Flowback* and *produced water* - potential impacts and likelihood of contamination in the immediate vicinity of the well;
2. Wastewater treatment and wastewater disposal – potential impacts and contamination.

The first peer-reviewed results of studies solicited and funded by the 2011 EPA plan have been released.[22] In addition to the suite of studies examining the potential impact of hydraulic fracturing on surface and ground water supplies, the EPA is currently developing and drafting proposed rules to amend the Effluent Limitation Guidelines. The Oil and Gas Extraction Category (40 CFR Part 435) of these guidelines were released in November 2014.[23]

[22] These are available at: http://www2.epa.gov/hfstudy/published-scientific-papers

[23] These are available at: http://water.epa.gov/scitech/wastetech/guide/oilandgas/

California Passes Senate Bill 4

In late 2013, California passed SB 4 (Pavley, 2013), state-level regulations over water stimulation technologies in fossil fuel production (including secondary and tertiary well stimulation, and hydraulic fracking). Previous to this legislation, the relevant regulatory agency, the California State EPA Division of Oil, Gas, and Geothermal Resources (DOGGR) did not have information on where or how many wells had been hydraulically fracturing in California.

Senate Bill 4 mandates that the chemical composition of water in groundwater wells in the proximity of oil wells be tested, and mandates that partial lists of fracking chemicals be made available to the public (lists including proprietary chemicals are to be provided to DOGGR and will be made available to health professionals in the case of an incident). It further mandates that DOGGR oversee permitting, drilling, and abandonment of all stimulated wells. Further regulatory guidelines are to be established by DOGGR over the coming two years.

Together with the State Water Control Board and Regional Water Quality Control Boards, DOGGR will evaluate contamination risks and the degree of water resource supply constraints facing scale-up of fracturing in the state. Finally, the bill commissions an independent study into the environmental, ecological, and economic impacts of fracking, and allows a forum for public comment. Most provisions of the bill went into effect on January 1, 2014, and DOGGR is targeting requiring full Environmental Impact Reports for all well stimulation activities by as early as January 1, 2015.

CHAPTER 4: Energy and Water Use Projections

In this section, the results of the water use analysis for the four scenarios in 2030 are presented. The four scenarios – Reference 2020 GHG emission goals and *Baseline* vs. '*Smart*' water use; and low-GHG emissions and *Baseline* vs. *Smart* water use – were described in Section 1.3. The projected water uses are summarized in tables showing the aggregate water use by water *type* within California; and visualized spatially as maps of net water consumption (WUI) by source *type* and *fate* (when available). For water use associated with fuel production to meet California's demand but taking place in regions outside of California, ranges or point values are applied to calculate overall water use – these volumes are also reported in tabular format, broken down by *region* and/or water source *type* whenever possible. Finally, the results are contextualized by comparing in-state water use to county-level withdrawal data from the most recent national water use survey (USGS 2005) to calculate the percentage contribution of net *consumptive* water use for fuel production as compared to the total *withdrawals*.

4.1 Oil

The projected water use associated with petroleum fuel production in 2030 is reported separately for in-state production and imported oil (disaggregating imports from Alaska, Canada, domestic shale oil, and the ***r***est ***o***f ***w***orld).

Projections and Sources of Petroleum Production

Projections of fuel consumption by California's transport sector are based on the Spring 2014 results of an energy-economic model, California-TIMES model (Yang, Yeh et al. 2014), projecting future transportation fuel use under the 2020 climate target and a low-carbon scenario that achieves 80 percent emission reduction below the 1990 level by 2050.

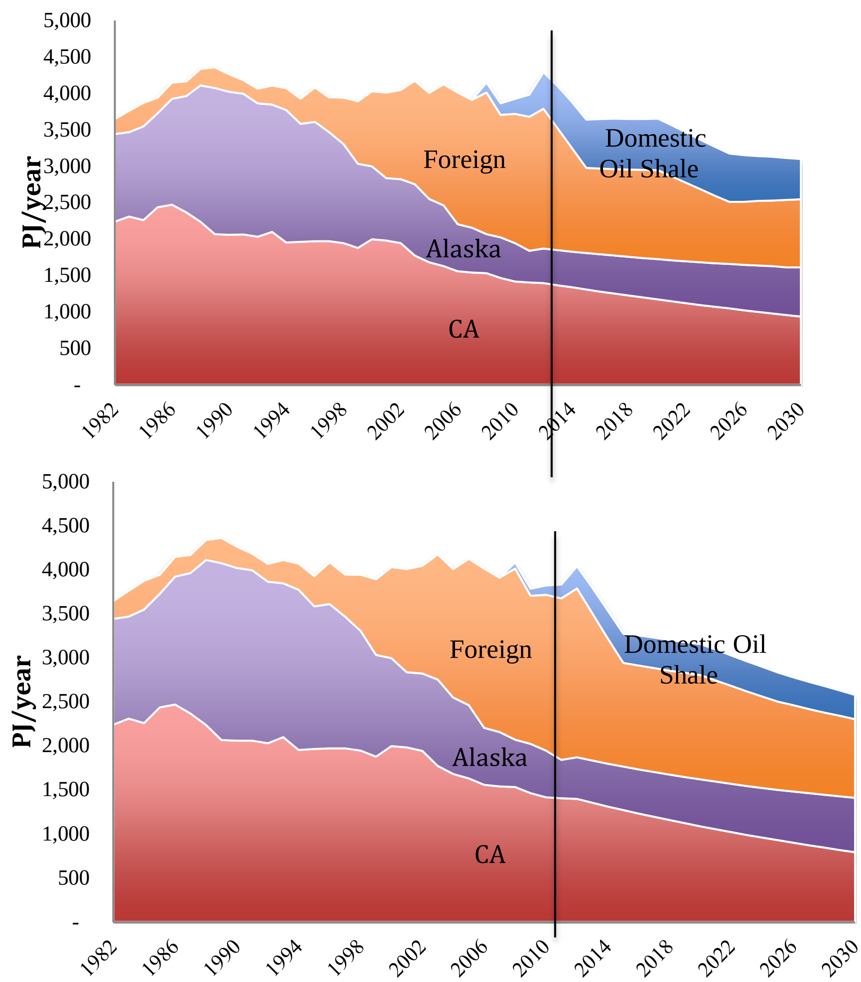
Current crude oil production is classified as being sourced from one of four categories – in-state production, Alaska, domestic oil shale (tight oil), and other foreign sources – according to CEC historical datasets on crude sources.[24] The projections from the most recent Transportation Energy Forecasts and Analyses for the biannual Integrated Energy Policy Report (CEC 2009, 2011, 2013), serve to create an upper and lower bound for the rate of decrease of California's production serving its own consumption of transportation fuel; under the *Deep GHG* scenario CA's production declines by 3.1% annually, and under the *Reference* scenario by 2.2% annually. Alaskan sources are projected to increase by 1.5% (Deep GHG scenario) and 2% (*Reference* scenario) annually. For the *Reference* scenario, domestic shale (tight) oil production matches 2013 projections from the EIA, while in the *Deep GHG* scenario only half of the volumes projected by the EIA are produced (EIA 2013)[25], an estimate that seems reasonable in light of independent

[24] See: http://energyalmanac.ca.gov/petroleum/statistics/2012_foreign_crude_sources.html

[25] See: http://www.eia.gov/forecasts/aeo/MT_liquidfuels.cfm#tight_oil

assessments of the ultimate estimated recovered of shale gas and oil wells (Hughes 2013). California's proportional consumption of the nation's crude-derived transportation energy is taken from the EIA (2011), and it is assumed that the proportion of crude used in California relative to the rest of the nation remains at 2011 levels in both the *Reference* and *Deep GHG* scenarios.[26] The resulting schedule of Petajoules of crude produced to serve the California transportation sector is shown below in Figure 4.1. Each of these sources, in turn, is assigned a range of WUI estimates, based upon projections of the recovery technologies used.

Figure 4.1: Crude Use by Source, *Reference* (Top) and *Deep GHG* (Bottom) Projections to 2030.



Petajoules of crude used for tranportation by source, in the *Reference* (top) and *Deep GHG* (bottom) scenarios. Data through 2012 are historical, 2013 through 2030 projections based on the average annual declines in California's in-state production reported in the latest IPER report (CEC 2013). See text for assumptions on rates of domestic oil shale development, Alaskan oil development, and foreign sources.

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[26] http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_btu_tra.html

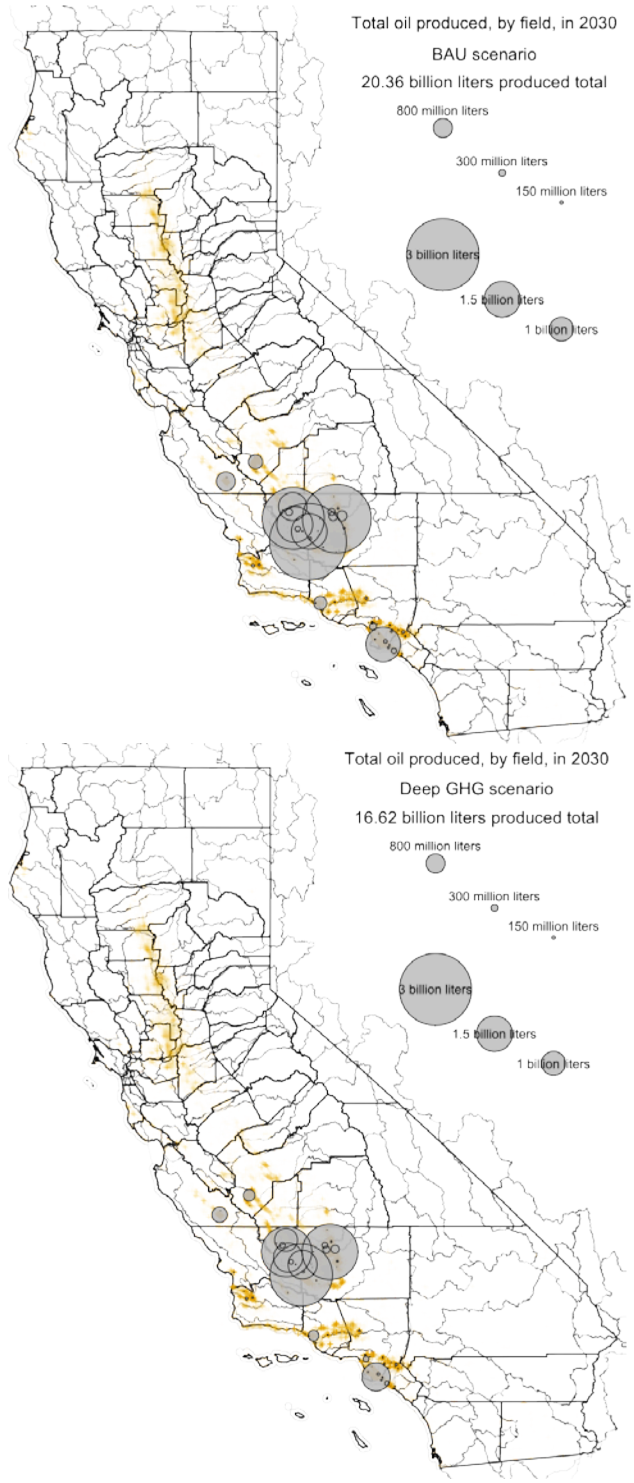
4.1.1 Water Use Projections for California Oil Production

As discussed in Section 3.2.3, CEC projections of annual percentage change in statewide oil production are used to allocate in-state production in the *Reference* and *Deep GHG* scenarios, using the 2.2% and 3.1% annual decline, respectively (CEC 2013). These are then applied equally across all water-injecting oil and gas fields. Figure 4.2 gives a spatial representation of oil production in California under the *Reference* and *Deep GHG* scenarios.

As outlined in Section 3.2.1, (with further details in Appendix C) regressions are fit on a field-by-field level using two functional forms: untransformed Ordinary Least Squares (OLS) and OLS based on a log-transformation of gross consumptive WUI, against field age as the single independent variable. Table 4.1 shows the gross water injection volumes (in billion liters) in California in 2030. The *Reference* scenario uses substantially more water than the *Deep GHG* as a result of higher oil production volumes. It also shows the summary statistics, across all fields, of gross water injection intensity (liters injected per liter oil produced), that results from the regression analysis.

After projecting gross water injections on a field-by-field basis, volumes of injected water are disaggregated by type, assuming (1) constant ratios among water type for the *Baseline* water use scenario, or (2) a reduction of freshwater use by 50%, to be substituted by produced (recycled) water, in the *Smart* water use scenario. Projected volumes of gross water injection volumes, by water type injected, are shown in Figure 4.3, however, a single figure shows the spatial distribution of water use in a single scenario, as the differences are so small that they are difficult to visualize. Table 4.2 shows the projected volumes of water injection under both GHG abatement scenarios (*Reference* and *Deep GHG*).

Figure 4.2: Petroleum Produced in California in 2030, Reference and Deep GHG Scenario.



Total petroleum produced (billion liters) by field in the Reference (left) & Deep GHG scenario (right). The light brown shows the location and extent of California's currently produced oil fields.

Table 4.1: Summary of Projected Gross Water Injection Volumes and Injection Intensity.

Summary Statistic	Gross water use (2012)	Gross water use (2030 Reference)	Gross water use (2030 Deep GHG)	Gross Water Injection Intensity (in 2030 in L/L)
Sum	290.5	332.2	271.1	*Max*: 125
Mean	3.8	4.3	3.5	16.3
Median	0.3	0.3	0.3	7.2
Standard deviation	10.8	13.0	10.7	23.7

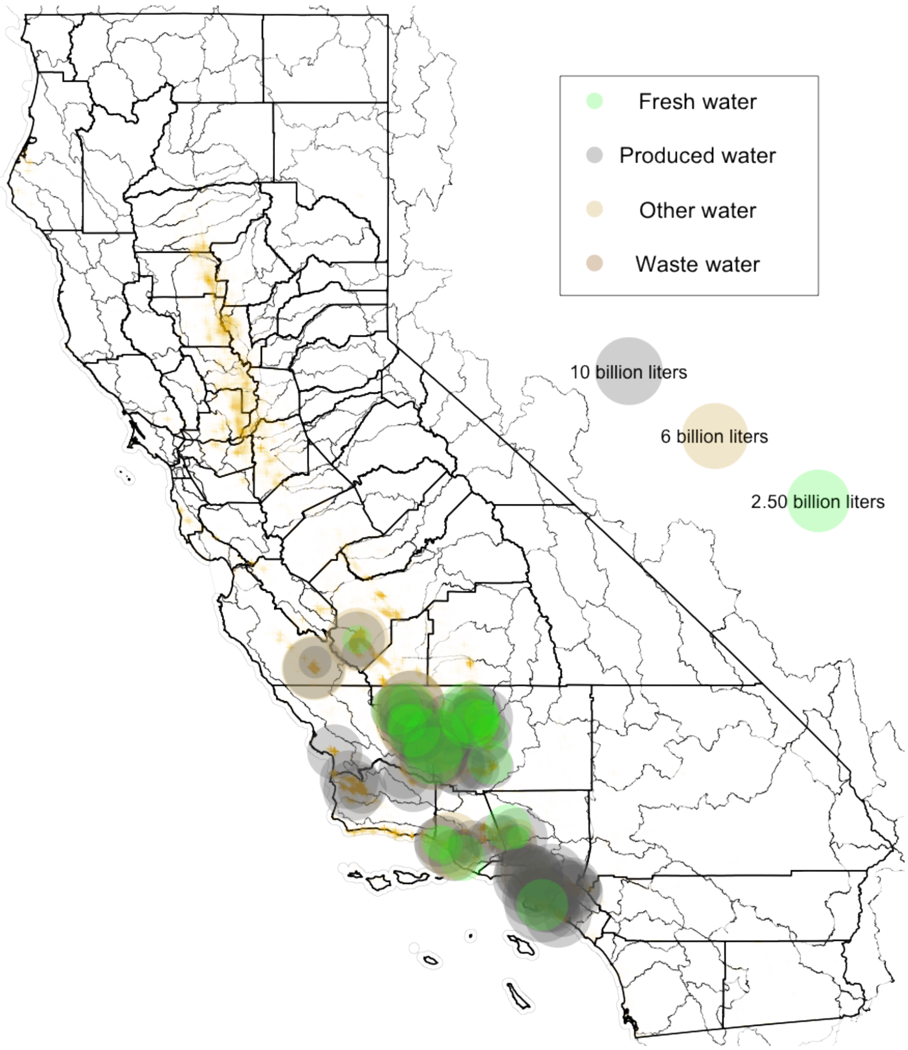
The middle three columns give gross water injected in billion liters (including all water source types). The right-most column provides field-level summary statistics of projected gross water injection intensity, in 2030, in L water injected / L oil produced (including all water source types) The maximum of that distribution (125 L/L) gives an indication of the lognormal distribution of the projected gross WUI. Gross injected water intensity is the same in both climate abatement scenarios (*Reference* & *Deep GHG*). Water source types & proportions of reinjected produced water are assumed to vary in the *Baseline* & *Smart* water use scenarios (see text for details).

Table 4.2: Projected Water Injection Volumes in 2030 by Scenario and Water Type.

Water Type	Secondary	Tertiary	Mixed	Total
Reference scenario				
Fresh	8.9	6.8	1.9	17.6
Produced	249	33.6	43.1	326
Waste	-	-	-	-
Other	12.3	24.6	107	144
Deep GHG scenario				
Fresh	7.3	5.5	1.5	14.3
Produced	203	27.4	35.2	266
Waste	-	-	-	-
Other	10.1	20.1	87.5	118

All water volumes are in billion liters. The table shows the projected volumes water of each category (fresh, produced, wastewater, and ‘other’) by field type (secondary, tertiary, mixed); and the total volumes of water injected, by water category.

Figure 4.3: Projected Water Injected for Conventional Oil Production in California in 2030.



Gross water injection in billion liters, in the 2030 projection. Differences among the four scenarios are not large enough to distinguish visually in the maps, but are summarized in Table 4.2. The light brown color shows the location and extent of California's currently produced oil fields.

Note that it is difficult to estimate the amount of freshwater that will be used in 2030 for oil production. The proportion of more freshwater-intensive technologies, such as tertiary recovery, has been increasing since 1999 and may continue to increase, driving up freshwater use. On the other hand, technological change may enable reuse/recycling, and then reinjection of greater volumes of produced water, even in tertiary production wells. The has been the case with secondary extraction technologies, which as of 2012, inject almost exclusively produced water to stimulate further oil production.

4.1.2 Water Impacts Oil Production – Imported Oil

Alberta's Oil Sands

Canada's oil production comes from conventional sources, as well as bitumen deposits (oil sands). The share of production from oil sands is 55% in 2012, but it is projected to increase (ERCB 2013). In 2012, bitumen production was 52% *in situ*, 48% surface mining. Roughly 80% of the bitumen still in place is considered well suited for in situ production, and only the remaining 20% for surfa.ce mining. In 2035, oil sands are projected to account for nearly 86% of Canada's production, compared with 57% in 2012 (ERCB 2013). Projections by the ERCB estimate 63% of oil sands production in 2030 will come from *in situ*, and 37% surface mining (ERCB 2013, NEB 2013).

Oil sands projections and production method splits for *in situ* versus surface mining proportions are from ERCB (2013). Based on the literature review (see preceding paragraph and section 3.2.3), the WUI of synthetic crude oil (SCO) is assumed to be 1.3 and 2.2 liters of freshwater per liter produced oil, for *in-situ* production and surface mining, respectively (AESRD 2014, GOA 2014). Finally, it is assumed that the proportion of foreign oil coming from Canada remains constant in 2030, at 5% of total foreign oil, or 2.3% of California's consumption. This results in an assumed 46.8 PJ of petroleum produced in the Canadian oil sands and consumed by California in 2030 in the *Reference* scenario, and 44.6 PJ in the *Deep GHG* scenario. In the *Smart* water use scenario, it is further assumed that regulatory pressure drives a recycling/reuse of freshwater resources, and decreases total water use by 25%. This results in a range of net water use of between 1,482 million liters (*Smart* water use, *Deep GHG* scenario) and 2,074 million liters (*Baseline* water use, *Reference* scenario) in 2030 (Table 4.3).

Table 4.3: Estimated Net Water Use in Millions of Liters for Producing Canadian Oil Sands in 2030 by Scenario.

Water use scenario	*Reference*	*Deep GHG*
Baseline	2,074	1,976
Smart	1,555	1,482

Alaska's North Slope

In 2012, California imported 12.1 billion liters of oil from Alaska, accounting for 11% of the oil consumed in California in that year. Alaskan sources are projected to increase by 1.5% (Deep GHG scenario) and 2% (Reference scenario) annually. This results in 674 PJ of Alaskan petroleum consumed by California in the *Reference* scenario, and 617 PJ in the *Deep GHG* scenario, in 2030. Given the dearth of information about trends in water use, the 2012 average WUI values (reported in section 3.2.3) are assumed to remain constant to project the amount of water necessary to produce oil imported to California in 2030. The midpoint of the WUI intensity estimates derived from data on fields in Alaska's North Slope (4.7 L/GJ) is taken, a range that results from allocating the considerable volumes of natural gas liquids (1.9 L/GJ), and assuming that they are all sold/marketed, to not allocating any water use (7.5 L/GJ). As in the case of Alberta's oil sands, in the *Smart* water use scenario it is assumed that regulations spur recycling/reuse that achieves a 25% reduction in net water use. For the *Reference* scenario, 2,378-3,171 million liters of water is consumed, and in the *Deep GHG* scenario 2,177-2,902 million liters of water is consumed in the *Smart* and *Baseline* water use scenarios respectively (Table 4.4).

Table 4.4: Estimated Net Water Use in Millions of Liters for Producing Alaskan Oil in 2030 by Scenario.

Water use scenario	*Reference*	*Deep GHG*
Baseline	3,171	2,902
Smart	2,378	2,177

Domestic Shale Oil

The projections of domestic shale oil development for the *Reference* scenario are from AEO 2013 *reference case* projections (EIA 2013c). For the *Deep GHG* scenario, these development projections are cut in half. Proportional shares of domestic shale oil to California are allocated based on the state's 2011 split of petroleum-derived liquid transportation fuels in relation to the entire U.S., as estimated by the EIA (2011).[27] The resulting allocation of petroleum to California is 276 PJ in the *Reference* and 552 PJ in the *Deep GHG* scenario.

Next, the relevant WUI ranges (discussed in Section 3.4, see Table 3.12) are applied, using the lower range of values (low-median) in the *Smart* water use scenario, and the upper range (median-high) in the *Baseline* water use scenario. Finally, water use is allocated according to water source *type*, assuming the current split (~95% freshwater; ~5% recycled water) for the *Baseline* water use scenario, and a 50-50 split, spurred by aggressive regulation, in the *Smart* water use scenario (note that this estimate is more optimistic than is the case for conventional oil, as the capacity to reuse/recycle water for fracking seems greater). Table 4.5 shows total net consumptive water use incurred by California's imports of domestic shale oil for transportation. In aggregating consumptive water use of energy resource imports across energy supply chains (in section 5), the midpoints of these ranges are reported.

[27] See Table C8. Transportation Sector Energy Consumption Estimates, 2011 (Trillion Btu). Available at: http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_btu_tra.html

Table 4.5. Estimated Water Use in Millions of Liters for U.S. Shale Oil for CA Transport in 2030 by Scenario.

	Reference Smart	Reference Baseline	Deep GHG Smart	Deep GHG Baseline
Recycled water	3,202 - 6,624	662 - 1,068	1,602 - 3,314	331 - 534
Freshwater	3,202 - 6,624	12,586 - 20,294	1,602 - 3,314	6,297 - 10,154
Total	**(6,403 - 13,238)**	**(13,248 - 21,362)**	**(3,204 - 6,629)**	**(6,629 - 10,689)**

Estimated range of total water use in 2030, by Scenario, for domestic oil shale imports to California for use in the transportation sector. Based on WUI from the literature and assumptions (documented in the preceding paragraph) regarding water sources.

Other Foreign Sources

In 2030, petroleum imported from other sources are projected to make up 28% of the total oil consumed in California in the *Reference*, and 30% in the *Deep GHG* scenario. The range of WUI values discussed in section 3 (1.4–24.7 L water/L oil) is used to project net consumptive water use from these *r*est *o*f *w*orld (ROW) sources. For each technology type, in the *Smart* water use scenarios, the lower end of the literature-cited WUI range is used, based on the assumption that stronger international regulatory regimes drive global dissemination of best practices. For the *Baseline* water use scenario, median literature-cited WUI values are taken. In the *Reference* scenario, 936 PJ of oil is imported from ROW sources, while in the *Deep GHG* scenario, 893 PJ of oil is imported from ROW to supply California's transportation demand. As in the case of Alaska and Canada, in the "*Smart*" water use scenario, it is assumed that regulation drives a 25% reduction in net freshwater use. Technology splits are based on the authors' "best-guess" estimates. Table 4.6 shows the technology splits, assumed WUI values, and derived water use, under each of the four scenarios, for oil imported for California's transport sector from the ROW.

Table 4.6: Water Use and Assumed WUI Values for Foreign Oil Production, by Scenario.

Technology	Fraction	WUI (in L/L)	
		Smart	***Baseline***
Primary	40%	1.4	1.4
Secondary	40%	8.6	8.6
Tertiary - steam	15%	4.1	5.4
Tertiary - cyclic steam	4%	1.1	43
Tertiary - CO_2	1%	4.3	24.7
Total imports (in PJ)			
Reference		936	
Deep GHG		893	
Total water use (million liters)			
Reference *Baseline*			164,896
Reference *Smart*			85,805
Deep GHG *Baseline*			141,338
Deep GHG *Smart*			73,547

Estimated total water use in 2030, by scenario, for oil imported from the *r*est *o*f the *w*orld, for California's transport demand. All water volumes are in million liters, oil imports are in PJ. Technology-specific WUI values are taken as the median value (in the *Baseline* water use scenario) and as the lowest value (in the *Smart* water use scenario) of literature sources. See preceding paragraph for further assumptions.

4.1.3 Projections of Refinery Water Use in California in 2030

Under the *Reference* / *Deep GHG* scenario, according to CA-TIMES model results, demand for crude oil for transport drops from 3,479 PJ in 2012 to 2,996 / 2,664 PJ in 2030. This translates to a reduction of approximately 86% / 76.5% of the 2012 refining requirements in 2030. Assuming in the *Baseline* water scenario that proportions of water consumed, by water type, remain constant with 2012 levels and under the *Smart* water management scenario that by 2030, it is feasible to source 50% of freshwater requirements using recycled water, Table 4.7 shows the consumptive water requirements to supply California's petroleum-derived transportation fuels.

Table 4.7: Projected Consumptive Water Use by California's Refineries in 2030.

	Reference Smart	Reference Baseline	Deep GHG Smart	Deep GHG Baseline
Freshwater	22.6	45.2	20.9	41.7
Recycled water	48.4	25.9	45.9	25.0
Degraded water	10.9	10.9	10.1	10.1
Waste water	43.7	43.7	40.3	40.3
Total	***125.6***	***125.6***	***117.2***	***117.2***

Estimated range of total water use in 2030 by Scenario, for California refineries in refining crude oil for in-state transport demand. In billion liters. Based on WUI as derived from 2009-2013 refinery sitting cases, and CEC and EIA sources, and from assumptions (documented in the preceding paragraph) regarding water sources.

4.1.4 Oil – Assumptions and Limitations

In the above allocation, it is assumed that all oil produced in California is consumed in-state. While this is not the case, it is a close approximation to actual practices; in fact, some percentage of California's petroleum is exported. The result is that an overestimation of water use within California serving California's transportation demand, and (likely to a lesser extent) underestimate net water consumption of imported petroleum. The magnitude of these impacts resulting from this misattribution is minor, and is likely far less than the uncertainty and variability of WUI values.

4.2 Biofuels

4.2.1 Metrics of Water Balance Change

The differences among the three policy scenarios (BAU or counterfactual, Modified RFS2 or M-RFS2, and N-LCFS) are analyzed, at high resolution (~10 kilometers), and at the CRD and regional scales, across the following metrics:

- Crop area expansion (in thousand hectares & by percentage change), including prime & marginal lands.
- Total water ***withdrawals*** and ***consumption*** at these scales, by source in two categories:
    - Irrigation, or 'blue water' (BW), and
    - rainwater/soil moisture , or 'green water' (GW).

Total water withdrawals and consumption are then estimated across these three categories at the level of Water Resource Regions (WRRs) and States.

As this method entails aggregating differentials in water use by crop, across scenario, absolute and differential water flow rates over given areas (mm^3/acre) can also be estimated, for the cropping and fallow seasons, as well as on an annual basis, of the following key water flows: (i) *irrigation* (withdrawn & consumed); (ii) *evaporation and off-season transpiration*; (iii) *transpiration*; (iv) *runoff*, and; (v) *groundwater infiltration*, all of which are measured in mm^3/acre (intensity); acre-feet per 10 kilometer (aggregate difference); and percentage difference between scenarios, over the relevant time period.

To compare this scenario-based or consequential analysis with previous studies, consumptive green water (GW) use (total evaporation & transpiration), as well as irrigation or blue water (BW) consumption, is estimated in the base year and for each of the policy scenarios in 2030. The modeled volumes of runoff and groundwater infiltration are also reported for each feedstock to biofuel product pathway. As with the other energy supply chains considered, these volumes are reported as consumptive water use intensity (WUI) values, in liters of water per final MJ of biofuel energy product. The range of derived water use estimates for feedstock cultivation fit well within the range of previously reported estimates, although the increased spatial and daily/seasonal and off-season temporal resolution represent a substantial improvement in terms of resolution and comprehensiveness over previous estimates.

Biofuels Produced in Each of the BEPAM Scenarios

In the year 2030 in the BAU (no-policy counterfactual), 15.9 billion liters (about 514 PJ) of biofuels are produced, which is in fact less than current annual production volumes. In 2030, the M-RFS2 requires an additional 138 billion liters, for a total of 154.15 billion liters (3.336 EJ) of biofuels production. In contrast, the N-LCFS requires only 132.5 billion liters (2.95 EJ) of (lower carbon intensity) biofuels be produced. Table 4.8 shows the breakdown of production in 2030, by feedstock. Here the primary concern is agricultural feedstocks, as these have the greatest water use impacts. In the base year (2008), approximately 15.2 billion liters of corn ethanol were produced domestically.

Note that the feedstocks *not* shown in bold italic (i.e. waste grease, forest waste, and pulpwood,) will require water use for production and processing. However, to the author's knowledge, either no LCA research exists from which to estimate consumptive WUI (e.g. wastes) for feedstock generation and collection; allocation methods are unclear (e.g. all waste feedstocks); or total water use impacts are assumed to be minor, and negligible compared to those of the agricultural and dedicated feedstocks (e.g. pulpwood). The major omissions in water use inventories are likely to originate from ignoring forest waste, which in the M-RFS2 and N-LCFS scenarios account for 6.3 and 3.38 billion liters of liquid biofuels produced, respectively.

Table 4.8: Biofuels Produced in Each of the Three BEPAM Scenarios in 2030.

Feedstock	BAU	M-RFS2	LCFS
Corn ethanol	***14.6***	***56.8***	***26.1***
Cellulosic	***-***	***83.5***	***93.2***
DDGS oil	***0.65***	***2.53***	***1.16***
Biodiesel	***0.65***	***3.42***	***4.9***
Soy oil diesel	***-***	***0.54***	***-***
Waste grease	-	0.35	0.35
Forest waste	-	6.30	3.38
Pulpwood	-	0.69	-
Total	**14.59**	**154.13**	**129.09**

Billion liters of liquid biofuels for transportation produced in 2030, by feedstock. Agricultural feedstocks, including dedicated feedstocks and agricultural residues, are shown in bold italic.

Key Drivers of Water Balance Differences among Scenarios

Changes in water balance are a function of a few key drivers:

- ***Land use change*** (LUC), which includes:
    - Shifts on the *extensive* margin (*substitution* – changing crops / cropping patterns, and *expansion* – bringing new land into cultivation, including marginal land for dedicated biofuel feedstocks, and shifting areas of cropping among crops or of any given crop).
    - Shifts on the *intensive* margin (e.g. irrigated vs. rainfed land, till vs. no-till, single-cropping vs. rotations).
    - Cultivation of dedicated feedstocks on marginal land.
- ***Crop characteristics***, of which the following are key:
    - *Length of growing season* – dedicated feedstocks (switchgrass and miscanthus), by virtue of being perennials, have a substantially longer growing season than staple row crops, such as corn, soy, and wheat. However, other crops grown as silage, such as alfalfa/hay, or may be cultivated with the practice of rotation or cover cropping, may reduce fallow season evaporation, runoff, and groundwater infiltration.
    - *Water use efficiency* (Kcb value) – Switchgrass and miscanthus have been selected and breed to enhance their already high water use efficiency (typically measured as biomass growth per unit water transpired). Other crops differ in their ability to accumulate biomass or harvestable biomass per unit water use.
    - *Rooting profile* – crops differ not only in terms of speed and depth of root growth, but also in terms of the efficacy with which they extract water from the soil (p value).

4.2.2 Land Use Changes

As compared with the BAU (no-policy) scenario, in 2030, 6.54 million additional acres are brought into production for crops and biofuels in the M-RFS2 scenario, representing an increase of about 2% percent over the 295 million acres produced in the no-policy scenario. In the N-LCFS, 16.61 million additional acres are brought into production (up about 6 percent from the no-policy scenario). Table 4.9 shows the acres cropped by each crop considered by BEPAM in 2030 under each of the biofuels policy scenarios (the BAU or no-policy counterfactual, the M-RFS2, and the N-LCFS), as well as the percent change in area cropped from the no-policy counterfactual.

Table 4.9: Areas Cropped, by Crop in Each of the Three Biofuel Policy Scenarios.

Crop	BAU	RFS	Δ	LCFS	Δ
Fall barley	0.17	0.17	2%	0.17	3%
Durum wheat	2.57	2.62	2%	2.62	2%
Sugarcane	0.87	0.84	-3%	0.86	-1%
Peanuts	1.23	1.23	0%	1.18	-4%
Sugarbeets	1.38	1.36	-1%	1.38	1%
Spring oats	1.53	1.63	6%	1.56	2%
Fall oats	2.52	2.47	-2%	2.44	-3%
Rice	2.77	2.62	-5%	2.71	-2%
Spring barley	3.86	3.66	-5%	3.80	-2%
Silage	5.63	5.42	-4%	5.51	-2%
Sorghum	7.21	6.81	-6%	6.38	-11%
Cotton	8.70	8.43	-3%	8.28	-5%
Spring wheat	10.65	8.03	-25%	9.18	-14%
Winter wheat	***45.05***	***43.42***	***-4%***	***38.97***	***-13%***
Alfalfa/hay	***56.76***	***56.03***	***-1%***	***53.98***	***-5%***
Corn	***71.30***	***89.51***	***26%***	***75.37***	***6%***
Soybeans	***73.02***	***62.65***	***-14%***	***67.11***	***-8%***
Switchgrass		0.05		3.80	
regular cropland		0.05		1.07	
marginal land				2.73	
Miscanthus		4.80		26.52	
regular cropland		1.06		13.61	
marginal land		3.74		12.92	
Total Acreage	***295.214***	***301.75***	***2%***	***311.82***	***6%***

Units are million acres. Crops shown in increasing order by cropped acreage. Switchgrass and miscanthus displace prime cropland and marginal land in the policy scenarios. Delta values show the change in acreage relative to the BAU (no-policy) scenario. Positive delta values (increases over the BAU scenario) are shown in red.

As shown in Table 4.9, in the M-RFS2 scenario, the most substantial LUC effects come from increased cropping of corn, which displaces other crops (primarily soybeans, but also alfalfa/hay, winter wheat, spring wheat, etc.). In the N-LCFS scenario, cultivation of switchgrass and miscanthus displaces all row crops, and most significantly results in shifts away from winter wheat, soybeans, alfalfa/hay, sorghum, and spring wheat. Notably, the N-LCFS also incentivizes extensive increases in corn cropping – the scenario leads to nearly a doubling of corn ethanol production in 2030 relative to the BAU.

According to market forces, agricultural practices are shifted among till/no-till/or rotating conventional and no-till techniques and between rainfed and irrigated cropping. Together with the fact that cultivation of biofuels on regular (prime) cropland in the Lower Mississippi, across swathes of the south, and in the Eastern-Central Cornbelt displace crops which are (in part) irrigated, differences in irrigated area are particularly relevant in light of the somewhat counterintuitive results that both policy scenarios (M-RFS2 and N-LCFS) require *less* net irrigation in these regions than the counterfactual scenario. Table 4.10 shows the changes in irrigated land areas, by crop, both in terms of total acres cropped in each scenario, and in terms of percentage change. As actual irrigation volumes are then a function of these changes in irrigated land areas together with crop-, soil-, and weather-specific criteria, these signs are suggestive, but in cases where the net impact on irrigation volumes is ambiguous, a -/+ or +/- indicates the likely, but not necessarily determinate direction of irrigation volumetric change (i.e. likely decrease and likely increase, respectively).

Table 4.10: Changes in Irrigation in Each of the Three Biofuel Policy Scenarios.

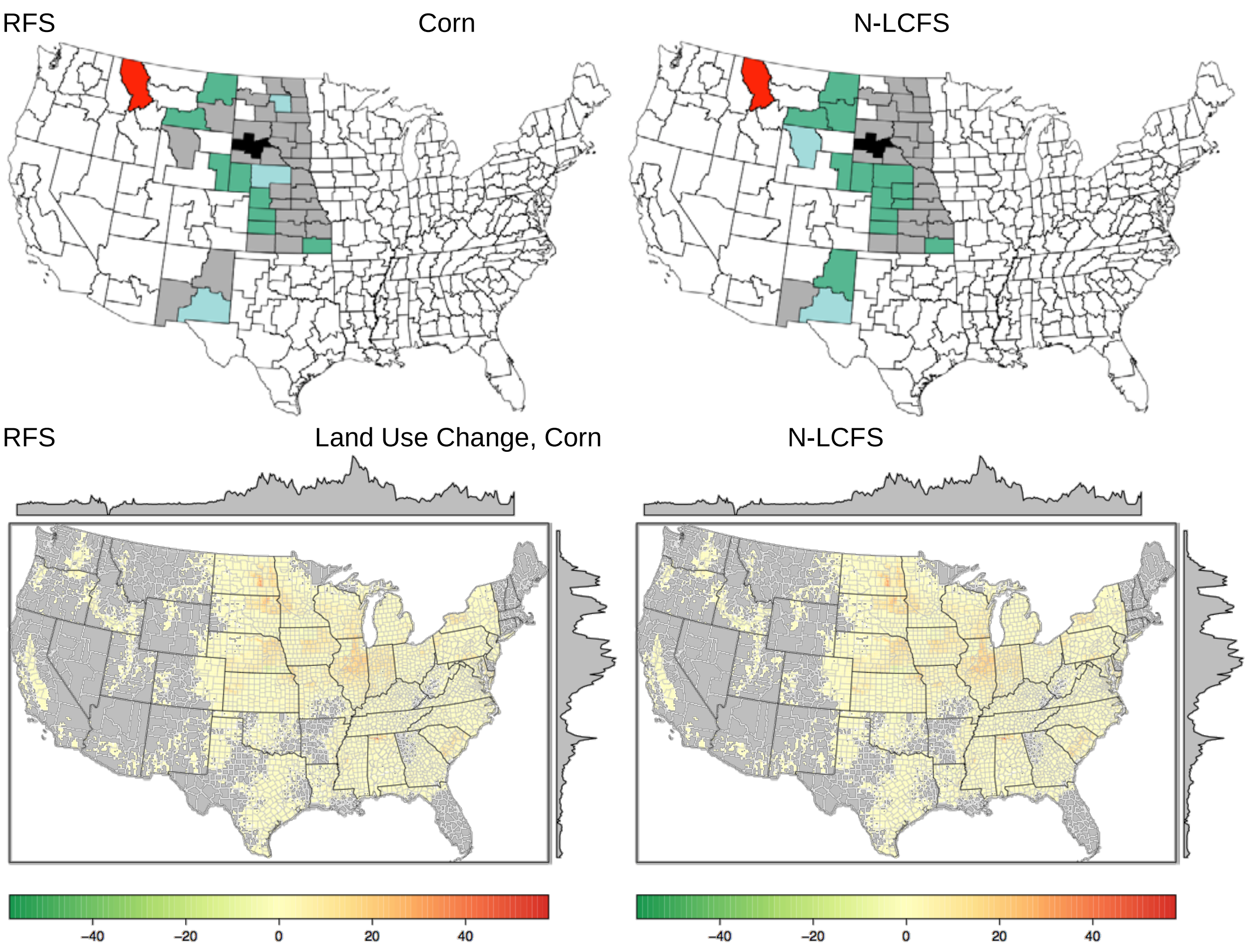
Crop	BAU	RFS	Δ	LCFS	Δ
Corn	8.11	9.02	11%	8.68	7%
Soybeans	4.76	3.68	-23%	4.20	-12%
Wheat (spring & winter)	4.40	4.51	3%	4.51	3%
Cotton	3.60	3.45	-4%	3.52	-2%
Alfalfa	3.41	3.31	-3%	3.37	-1%
Rice	2.77	2.62	-5%	2.71	-2%
Sorghum	1.04	1.01	-3%	1.03	0%
Spring barley	1.07	1.10	3%	1.07	0%
Silage	0.41	0.37	-9%	0.39	-6%
Spring oats	0.05	0.06	12%	0.05	2%
Peanuts	0.19	0.21	11%	0.19	0%

The signs show whether signs show whether ***total*** irrigated land area irrigated, as well as percentage increases (+) or decreases (-) relative to the BAU scenario (i.e. whether total irrigated land increases or decreases). Note that the actual effect on irrigation volumes is ambiguous (as it is also a function of the specific crop, weather, and soil. Positive delta values (increases over the BAU scenario) are shown in red.

Figure 4.4 shows the differences among the scenarios in terms of irrigated acreage for the four key crops: corn, soybeans, alfalfa/hay, and wheat (winter wheat and spring wheat are both irrigated). It contextualizes these changes in irrigated land by also showing the differences in total land cropped relative to the no-policy counterfactual. Dramatic increases (ranging from 10-40% of total land) in areas cropped in corn occur in both scenarios in regions of North and South Dakota, Nebraska, Iowa, and Illinois. Similarly dramatic increases in areas cropped in soybeans take place in North Dakota and Kansas, but these are moderated by decreases through the rest of the Midwest.

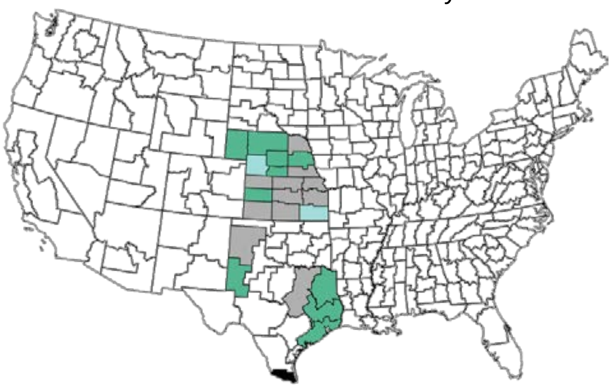
Figure 4.4: Changes in Area Irrigated in the RFS & N-LCFS Relative to the BAU in 2030.

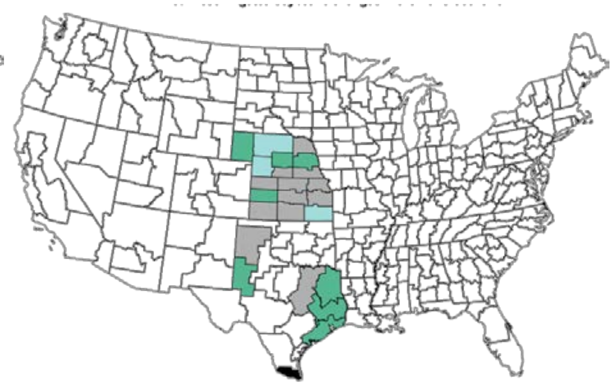
Black - 'gone'/no longer cropped; Red - 'new'/not cropped in the BAU, but cropped in the policy scenario; Grey - 'no change' in irrigated acreage; Green - negative change in irrigated area; Blue - positive change.



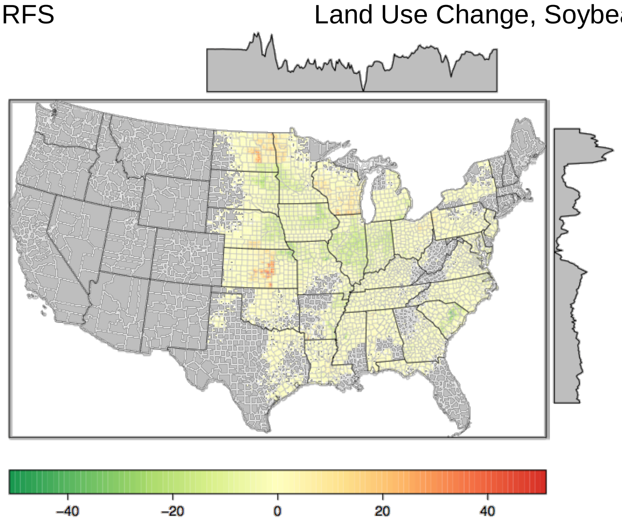
Black - 'gone'/no longer cropped; Red - 'new'/not cropped in the BAU, but cropped in the policy scenario; Grey - 'no change' in irrigated acreage; Green - negative change in irrigated area; Blue - positive change.

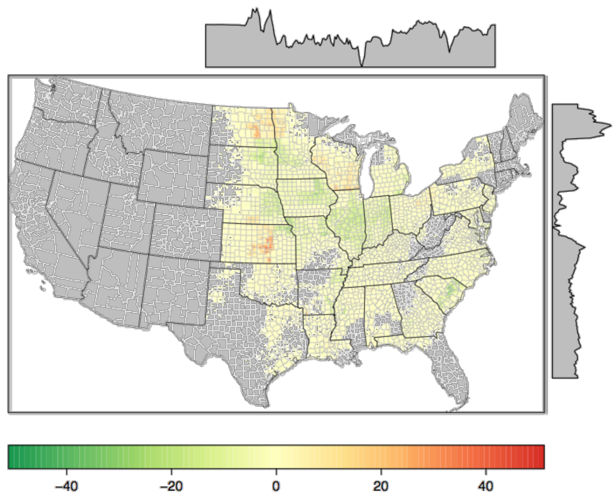
RFS Soybeans N-LCFS





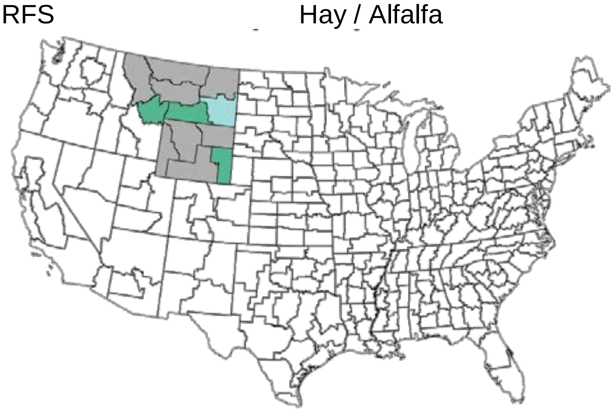
RFS Land Use Change, Soybeans N-LCFS

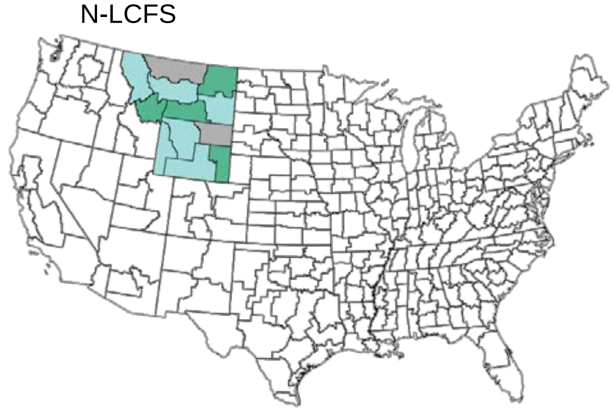




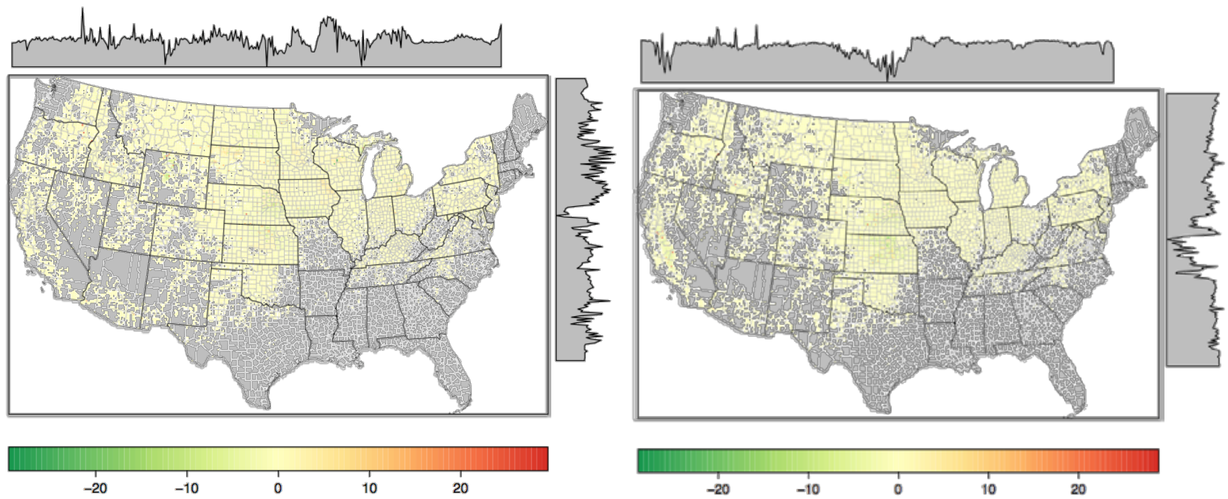
Black - 'gone'/no longer cropped; Red - 'new'/not cropped in the BAU, but cropped in the policy scenario; Grey - 'no change' in irrigated acreage; Green - negative change in irrigated area; Blue - positive change.

RFS Hay / Alfalfa N-LCFS



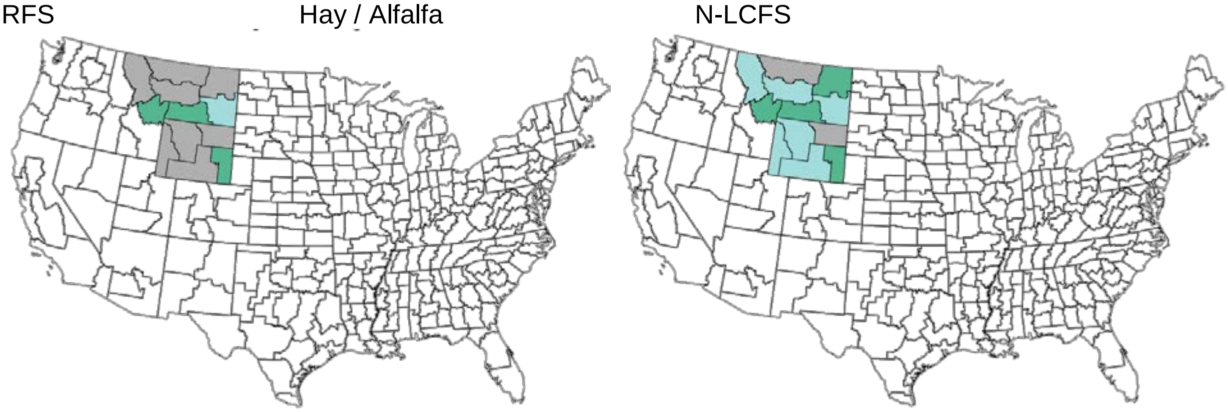


RFS Land Use Change, Hay / Alfalfa N-LCFS

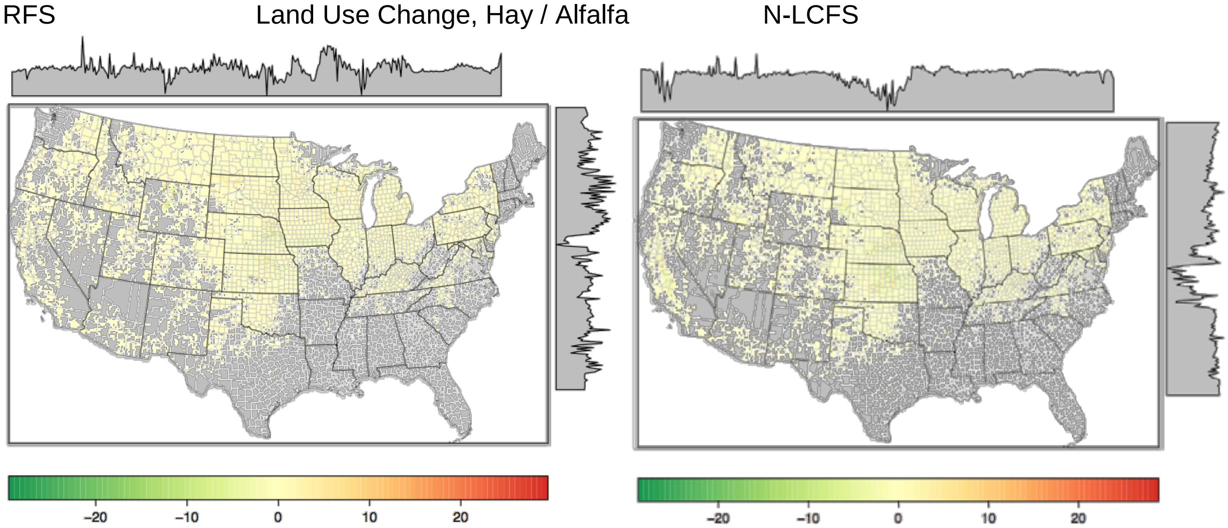


Black - 'gone'/no longer cropped; Red - 'new'/not cropped in the BAU, but cropped in the policy scenario; Grey - 'no change' in irrigated acreage; Green - negative change in irrigated area; Blue - positive change.

RFS Hay / Alfalfa N-LCFS



RFS Land Use Change, Hay / Alfalfa N-LCFS



Black - 'gone'/no longer cropped; Red - 'new'/not cropped in the BAU, but cropped in the policy scenario; Grey - 'no change' in irrigated acreage; Green - negative change in irrigated area; Blue - positive change.

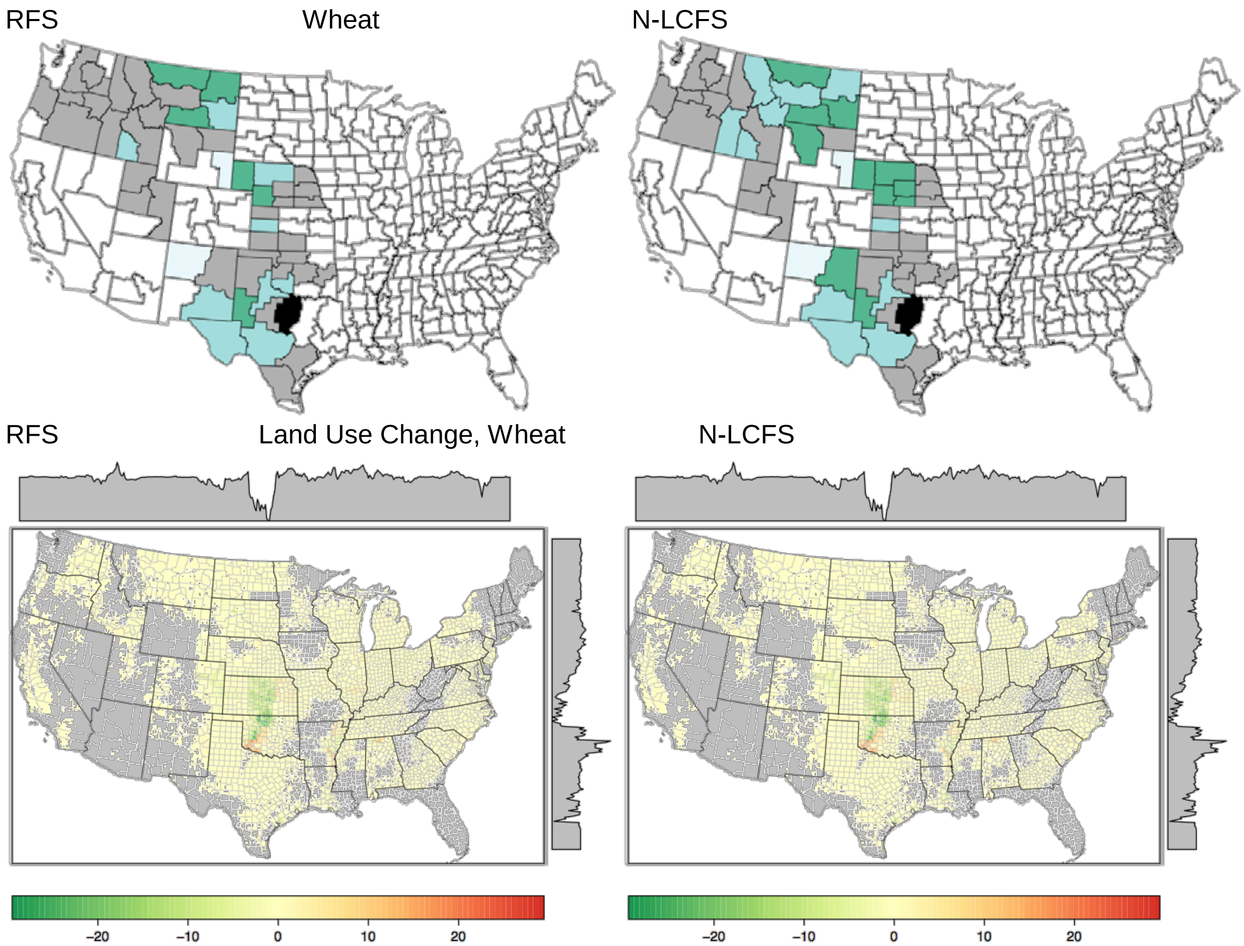
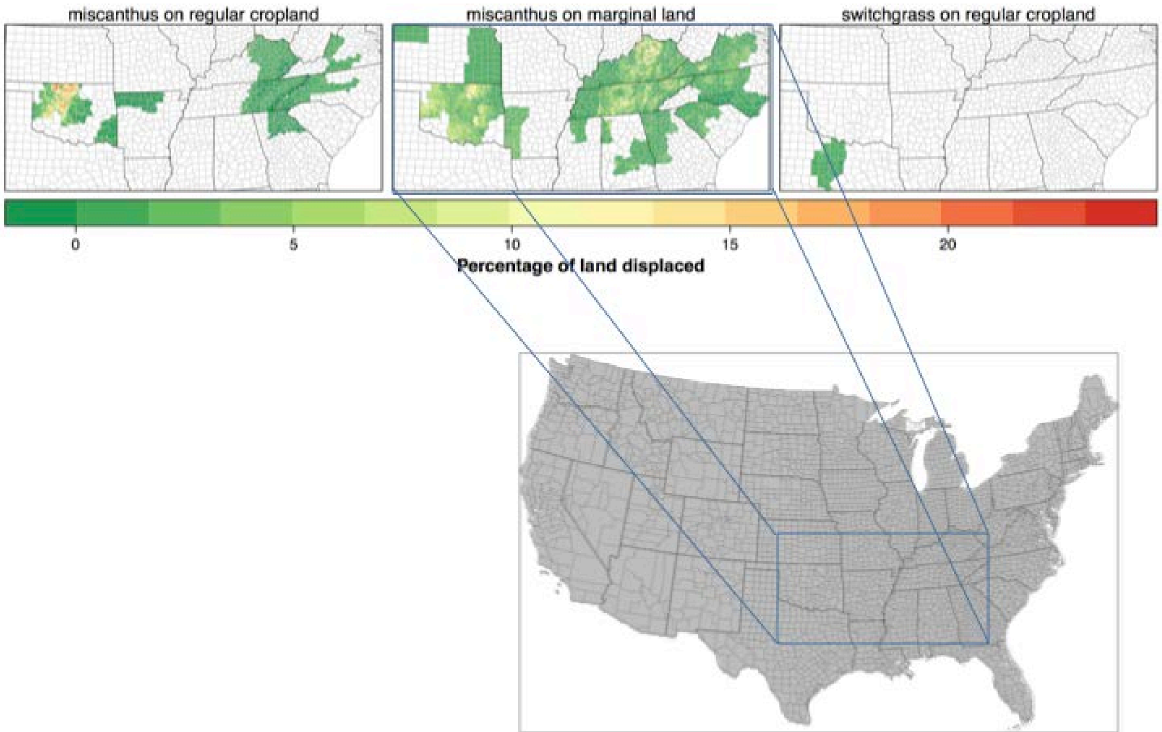


Figure 4.5 shows the percentage of land cropped in miscanthus and switchgrass in the RFS, by the type of land they displace, namely regular cropland, and marginal land. In the RFS scenario, switchgrass is grown only on marginal land, while the majority of miscanthus is grown on marginal land.

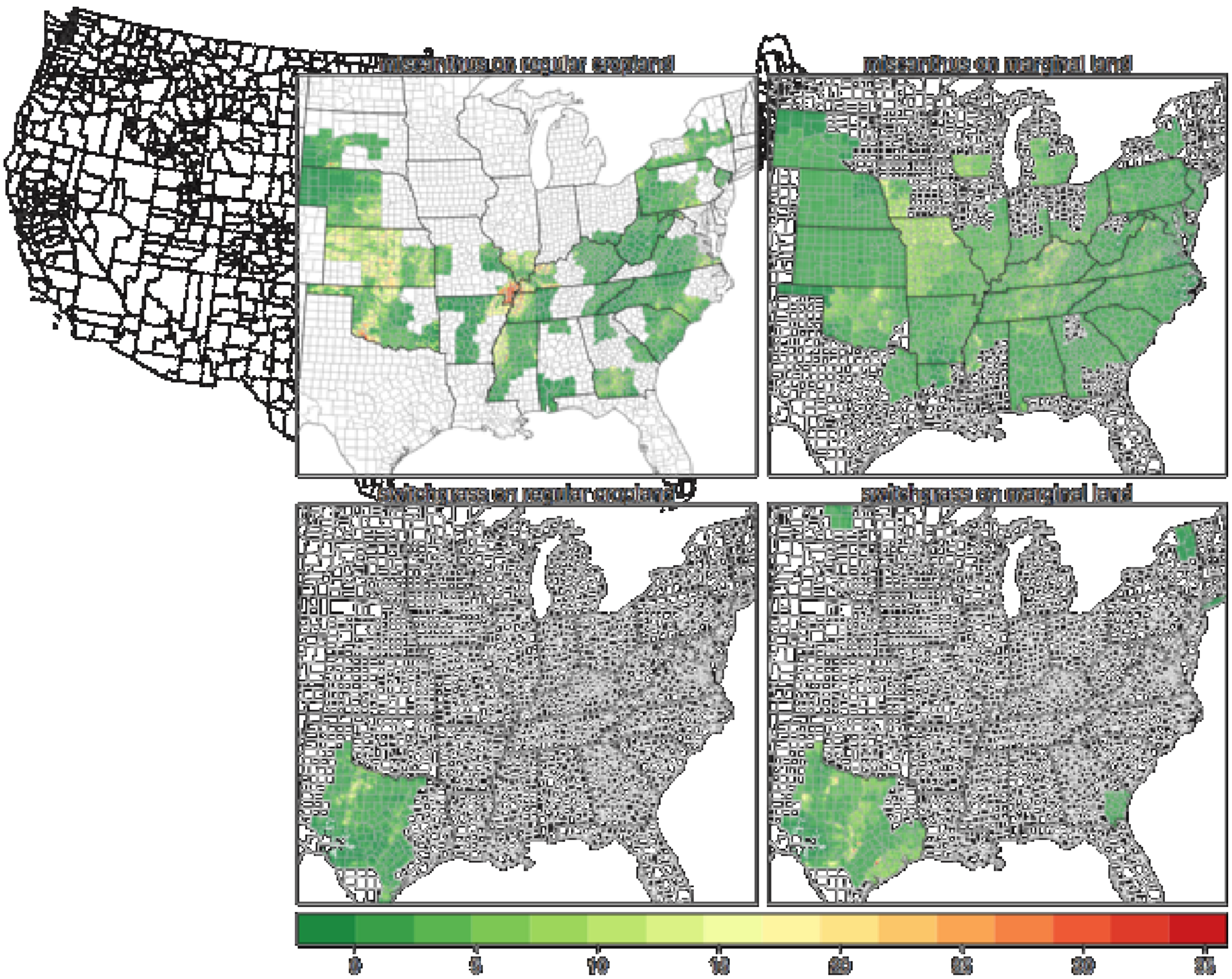
Figure 4.5: Percent of Land Cropped in Dedicated Feedstocks in the RFS Scenario.



Percentage of regular cropland and marginal land cropped in dedicated feedstocks in the RFS.

Figure 4.6 shows the percentage of land cropped in miscanthus and switchgrass in the N-LCFS scenario, again by the type of land they displace, namely regular (prime) cropland (left), and marginal land (right). About half of miscanthus is cropped on prime cropland, thus displacing row crops. In addition, both dedicated feedstocks for cellulosic ethanol (miscanthus and switchgrass) are also grown on marginal land, indeed most switchgrass is cropped on marginal land. Generally speaking, the water balance impacts of the displacement are opposite in these two cases: when the perennials displace row crops, the result is a decrease in evaporation and off-season transpiration, runoff, and groundwater infiltration, and an increase in transpiration. When they displace (unharvested) perennials that have grown for many years on marginal land, the results, while less pronounced, are increases in evaporation and off-season transpiration, runoff, and groundwater infiltration, at the expense of transpiration.

Figure 4.6: Percent of Land Cropped in Dedicated Feedstocks in the N-LCFS Scenario.



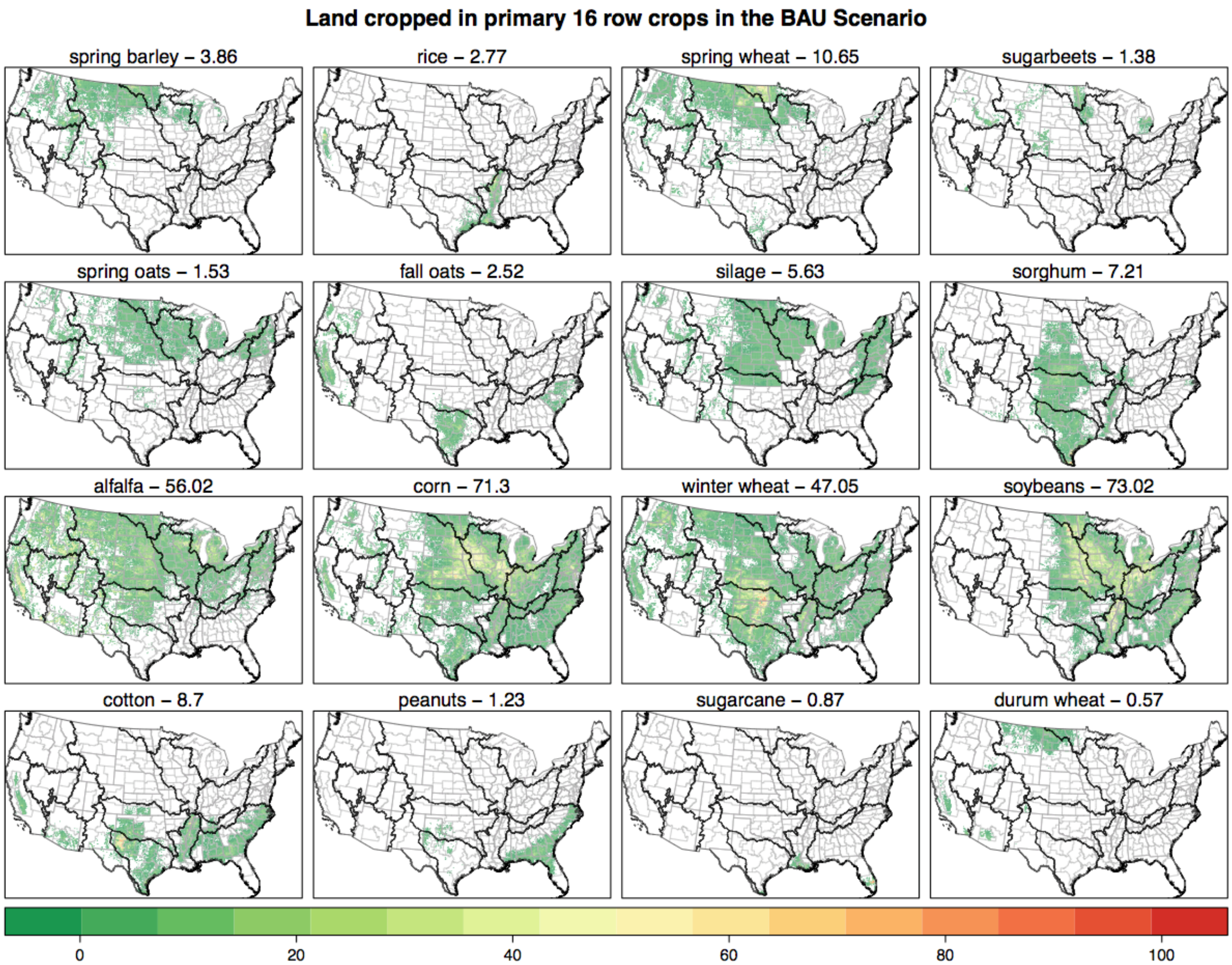
Cropping patterns of dedicated feedstocks explain much of the changes in the N-LCFS+RFS water balances. Values refer to the percentage of total area cropped per 10 km grid cell in ***miscanthus*** (top), and ***switchgrass*** (bottom). “Regular” cropland refers to the case where crops are displaced by cultivation of biofuels feedstocks – , while marginal land types do not displace land available for growing row crops.

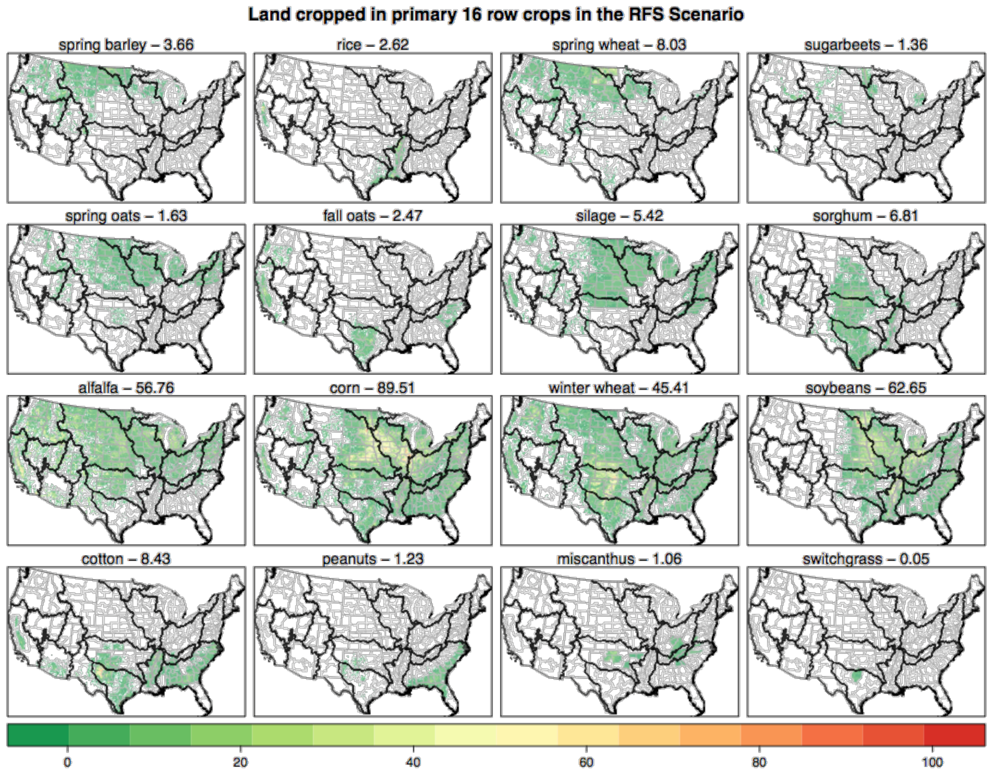
Aggregated Land Use Changes

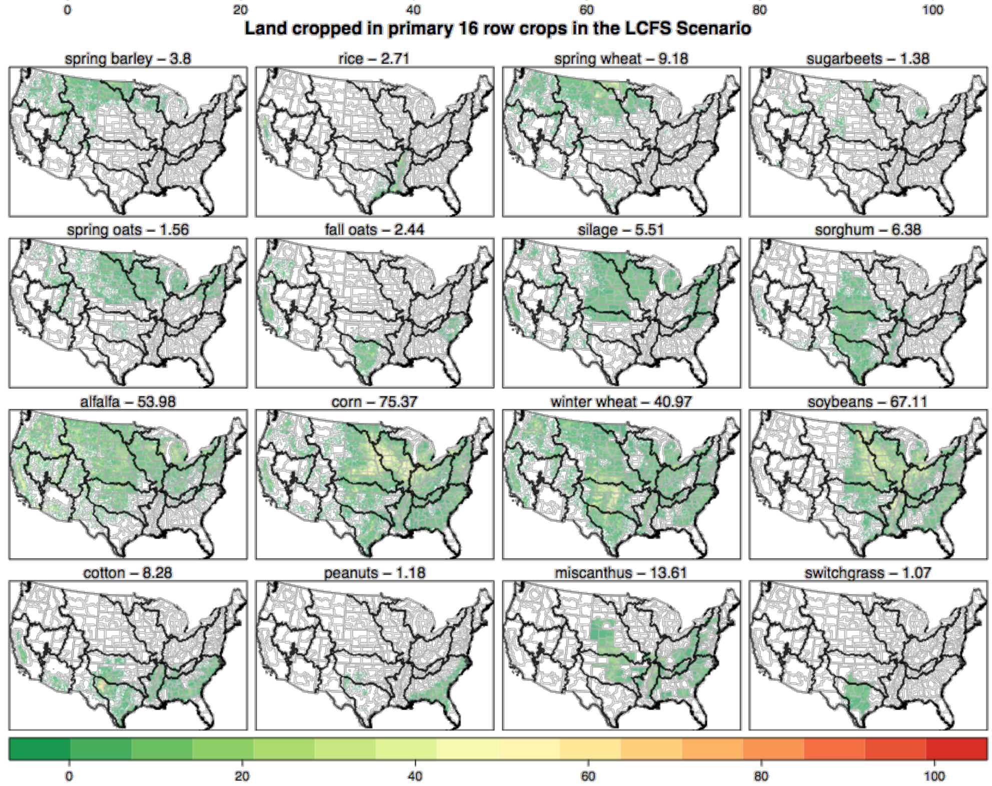
Figure 4.7 shows the land cropped in the sixteen major row crops modeled in BEPAM in the BAU (top), RFS (middle), and N-LCFS (bottom) scenarios, respectively. Values to the right of each crop show the total cropped area for that crop in million acres.

In addition to showing the spatial extent of each crop, the maps show which crops are displaced by switchgrass and miscanthus – these include corn, winter wheat, soybeans, alfalfa/hay, cotton, and peanuts, among others. Some proportion of land cropped in many of these crops is irrigated, even in the South and Midwest where dedicated biofuel feedstocks may displace them. Since all cultivation of switchgrass and miscanthus is necessarily rainfed, this implies a decrease in net irrigation requirements in regions where land displaced by these crops will be cropped with these dedicated biofuel feedstocks. Note that crops with the least cropped area are not shown: fall barley is not shown in the BAU, and fall barley, sugarcane, and durum wheat are all not shown in the RFS and N-LCFS scenarios – the latter two having been replaced to show regular cropland areas cropped in switchgrass and miscanthus.

Figure 4.7: Areas Cropped, by Crop, in Each of the Three BEPAM Policy Scenarios.







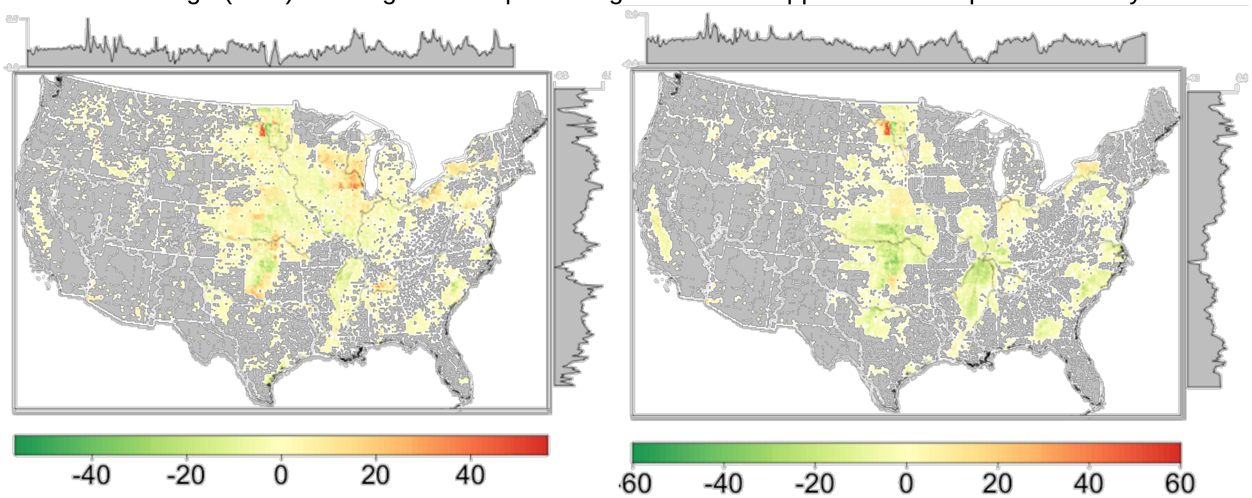
Acreage cropped, by crop, in each of the three BEPAM policy scenarios. Note that crops with the least cropped area are not shown: fall barley is not shown in the BAU, and fall barley, sugarcane, and durum wheat are all not shown in the RFS2 and N-LCFS scenarios – the latter two having been replaced to show regular cropland areas cropped in switchgrass and miscanthus.

Figure 4.8 show the aggregated land use change across all row crops in the RFS scenario (left) and the N-LCFS scenario (right), relative to the BAU (no-policy) scenario, in 2030. The top maps show net changes in cropped area across all row crops alone – before considering additional cropping of switchgrass and miscanthus. The bottom maps show the aggregated LUC in RFS and N-LCFS across row crops, also incorporating only the land use changes incurred by cultivation of switchgrass and miscanthus on regular (prime) cropland. Comparing the maps within a column shows the displacement of row crops in each of the scenario.

Figure 4.8: Land Use Changes in the RFS and N-LCFS Scenarios in 2030.

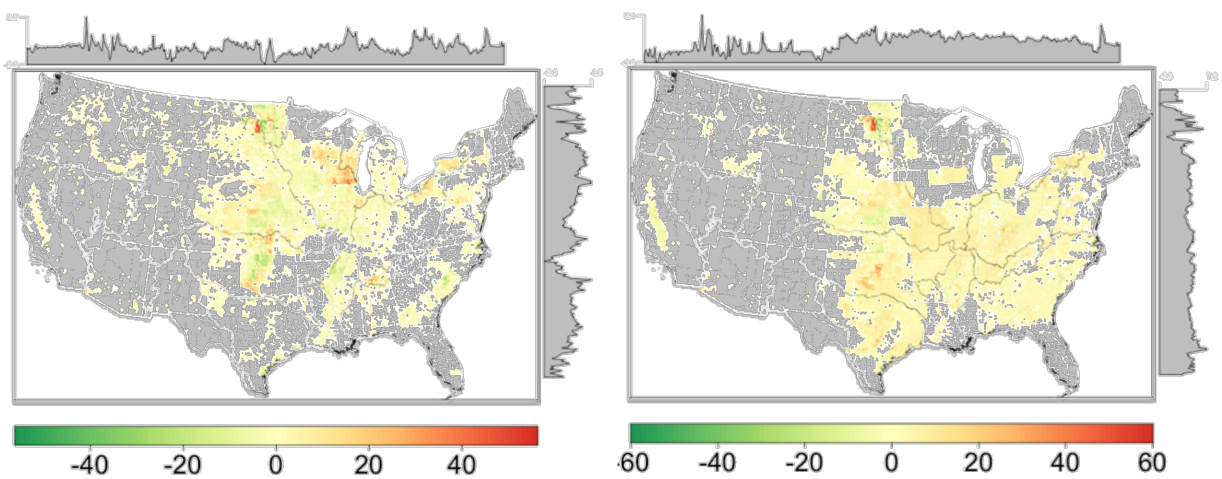
RFS N-LCFS

Land Use Change (LUC) – changes in the percentage of areas cropped in row crops modeled by BEPAM



RFS N-LCFS

Land Use Change (LUC) – changes in the percentage of areas cropped in row crops modeled by BEPAM, plus additional regular (prime) cropland cropped in switchgrass and miscanthus



All changes are in given in percentage of total area per grid cell.

Under the M-RFS2, the median/mean agricultural extensification per 10 km grid cell is an increase in 0.97% / 1.27% of land, or about 240 / 339 acres per grid cell (this figure does not include cells in which there was no increase or decrease in cropped land, but does include the additional cropland cultivated in switchgrass & miscanthus). The range of land use change (LUC) per grid cell was far greater – the minimum/maximum LUC was a decrease/increase in cropped land of -49% / +56%. Under the N-LCFS, the corresponding median/mean LUC per 10 km grid cell is nearly double that of the RFS, the increases were 2.19% / 2.68% of land, or about 541 / 662 acres per grid cell. The range of LUC per grid cell was similar to that in the M-RFS2 – the minimum/maximum LUC was a decrease/increase in cropped land of -49% / +60%. Both policy scenarios lead to increases in cropped area, primarily in the Upper and Lower Mississippi, Ohio, Great Lakes, and Tennessee Water Resource Regions. Under the RFS, there are patches of decreased acreage in some of these regions, but unambiguous expansion of cropped area in the western Cornbelt and northeastern stretches of the Upper Mississippi. Under the N-LCFS, increases in cropped area is spread over much of the eastern U.S. Consideration of these LUC patterns is an important element in analyzing the changes in water balances among scenarios. The above maps play an important role in interpreting the water balance changes, which is the next topic.

4.2.3 Water Use Intensity by Feedstock-Product Pathway (Attributional WUI)

Allocation of corn-based ethanol, as well as cellulosic ethanol from dedicated feedstocks (i.e. switchgrass and miscanthus) is straightforward. The water use for cultivating these feedstocks, as well as for wheat straw, corn stover, and soybeans, for the production of biofuels, will be shown as consumptive WUI values (for each of the five water balances) in standardized SI units (L/MJ). In this analysis the simplifying assumption adopted is that biomass was diverted to biofuels in proportion to harvest, irrespective of region of cultivation[28]; despite the fact that corn ethanol and soybean biodiesel feedstocks are typically sourced from regions in the Midwest and Cornbelt, given variations in corn prices and costs of transporting feedstocks by rail/truck (Suh, Suh et al. 2011).

Figures 4.9 and 4.10 show the water use intensity, in liters of water per megajoule of final energy product of the main feedstock to product biofuel pathways assumed to dominate biofuel production in 2030 in the BEPAM model. The figures show the intensity of net 'green water' consumptive use (i.e. the sum of water volumes transpired and evaporated), as well as the total consumptive 'blue water' or irrigation water use, where water consumption is assumed to equal the modeled water root application (no attempt was made to differentiate between water

[28] Hence, the actual distribution of allocational water use is likely to be closer to the range of WUI values given for those regions, and thus have a lower median irrigation (blue water use) requirement than the values reported below, which reflect the entire distribution across the contiguous U.S. Also not that in the case of corn ethanol, an allocation factor of approximately one-third could be adopted, as this would be consistent with the BEPAM model assumptions, to account for DDGS co-product credits. Thus, reducing the WUI by one-third would result in blue- / green-water WUI roughly consistent with studies that allocate DDGS credits.

withdrawal and consumption, as the efficiencies are high and model uncertainty and other assumptions would dominate). Also shown is the modeled annual runoff (this includes runoff over the cropping season as well as the fallow season, as well as evaporation) for each crop.

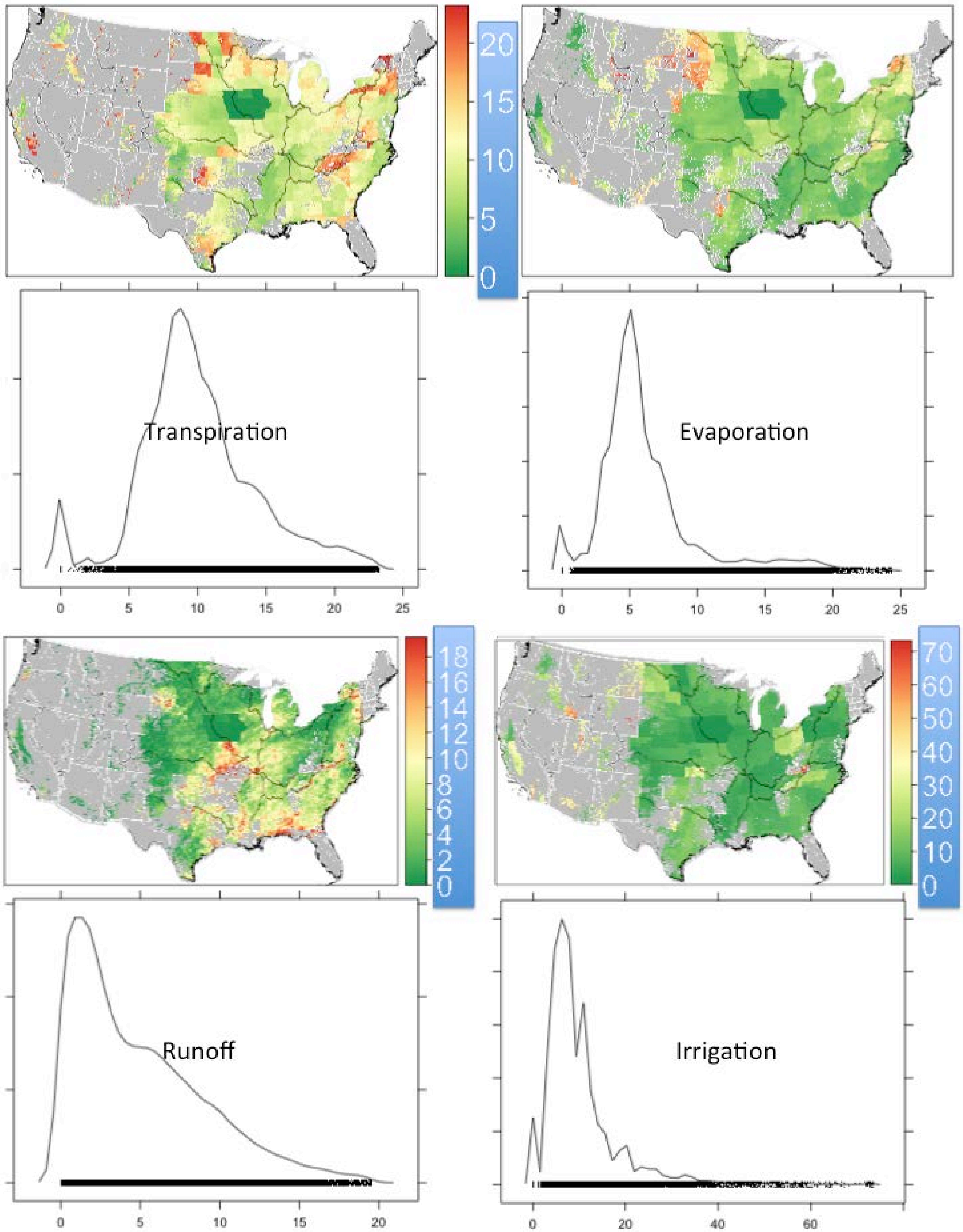
in contrast with previous estimates, these map the modeled WUI by region, resulting in a high resolution distribution of WUI across the contiguous U.S. Furthermore, the daily-crop water modeling allows for disaggregation of water use, for instance for the growing season versus over the entire year.

4.2.4 Water Balance Changes between Scenarios

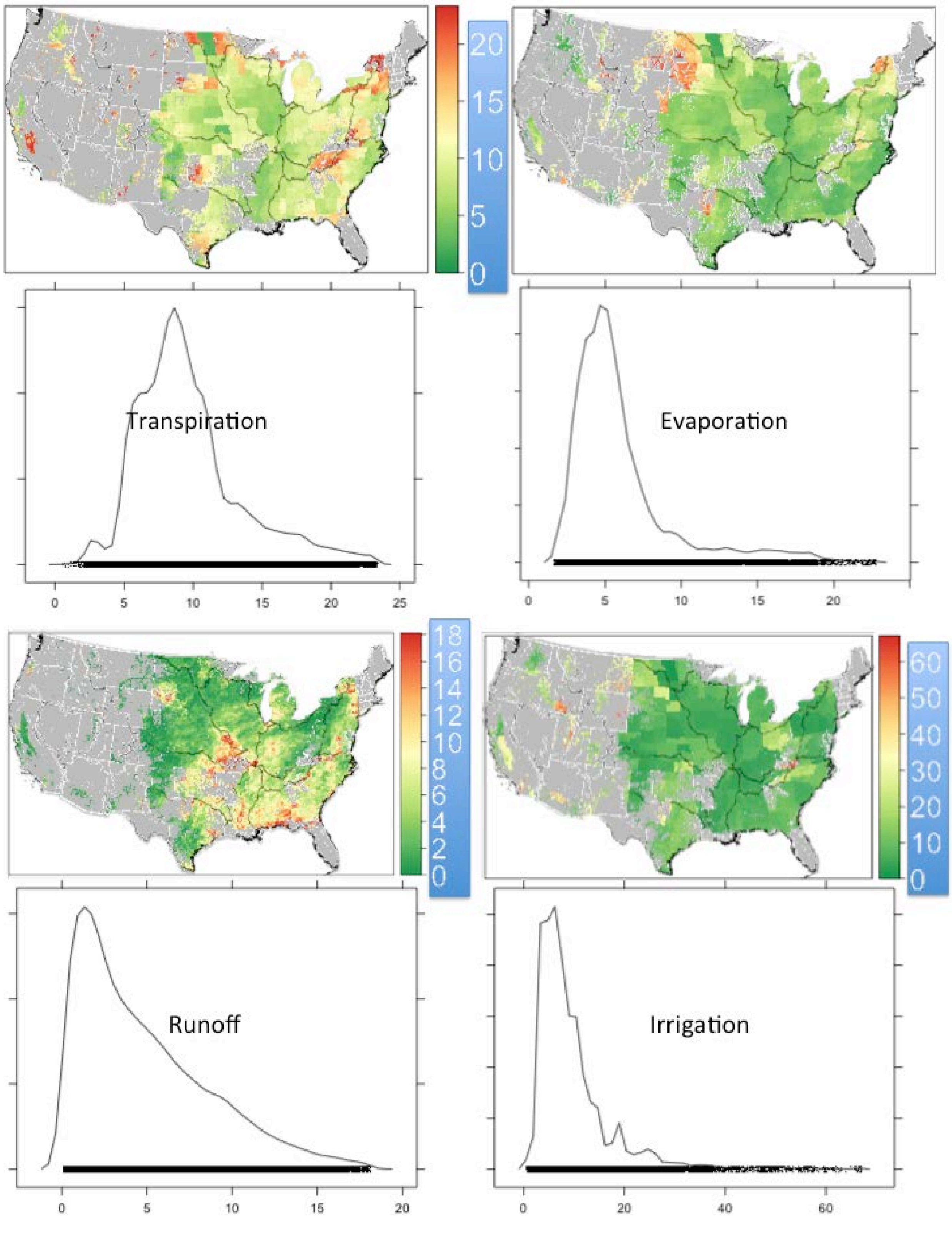
Table 4.12 gives a tabular overview of the nation-wide water balance changes for all 10 km grid cells in which water balances change among biofuel policy scenarios. All changes in agronomic water balances are in annual thousand cubic meters per 10 km grid, except for the total water balance changes, which are the net changes across the contiguous U.S. in million cubic meters. The six-figure summary statistics apply to all grid cells in which the water balance change in 2030 in the given policy scenario (with the M-RFS2 shown above, and the N-LCFS below). Note that while there are particular localities that undergo dramatic shifts in agronomic water balances (as evidenced by the minimum and maximum values), yet the magnitude of change across most 10 km grid cells is moderate. This results from the moderating impact of economic decisions on water use differences across scenarios, which is the primary mechanism for mediating the water use impacts of biofuel production and explains the differences in WUI as estimated in his study compared to results from LCA studies.

Figure 4.9: Water Use Intensity of Cultivation – Corn to Ethanol.

BAU Scenario – Transpiration (top left) and Evaporation (top right) / Runoff (bottom left) and Irrigation (bottom right). All WUI values are in Liters (water use) per MJ final energy product (ethanol).



RFS2 Scenario – Transpiration (top left) and Evaporation (top right) / Runoff (bottom left) and Irrigation (bottom right). All WUI values are in Liters (water use) per MJ final energy product (ethanol).



LCFS Scenario – Transpiration (top left) and Evaporation (top right) / Runoff (bottom left) and Irrigation (bottom right). All WUI values are in Liters (water use) per MJ final energy product (ethanol).

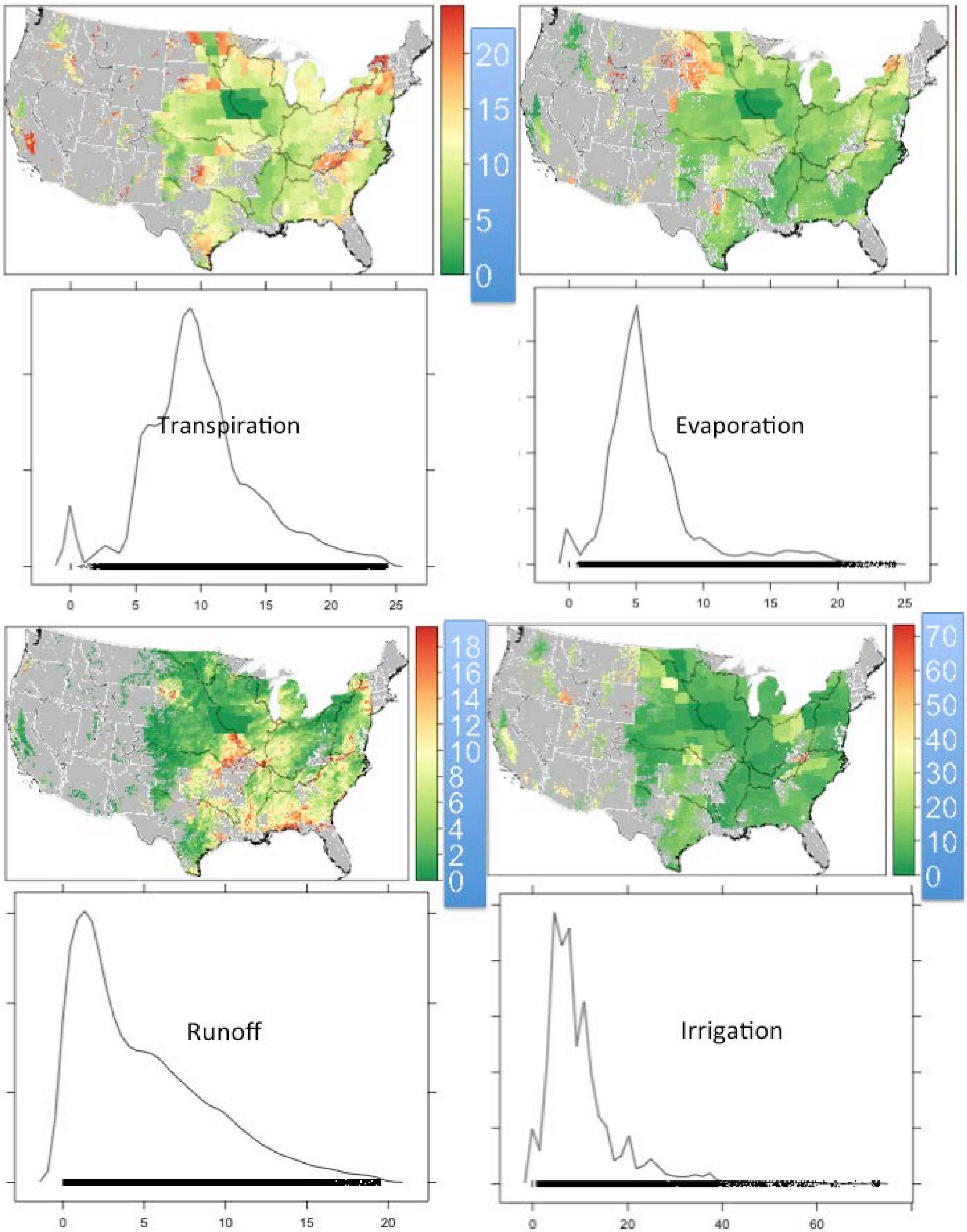
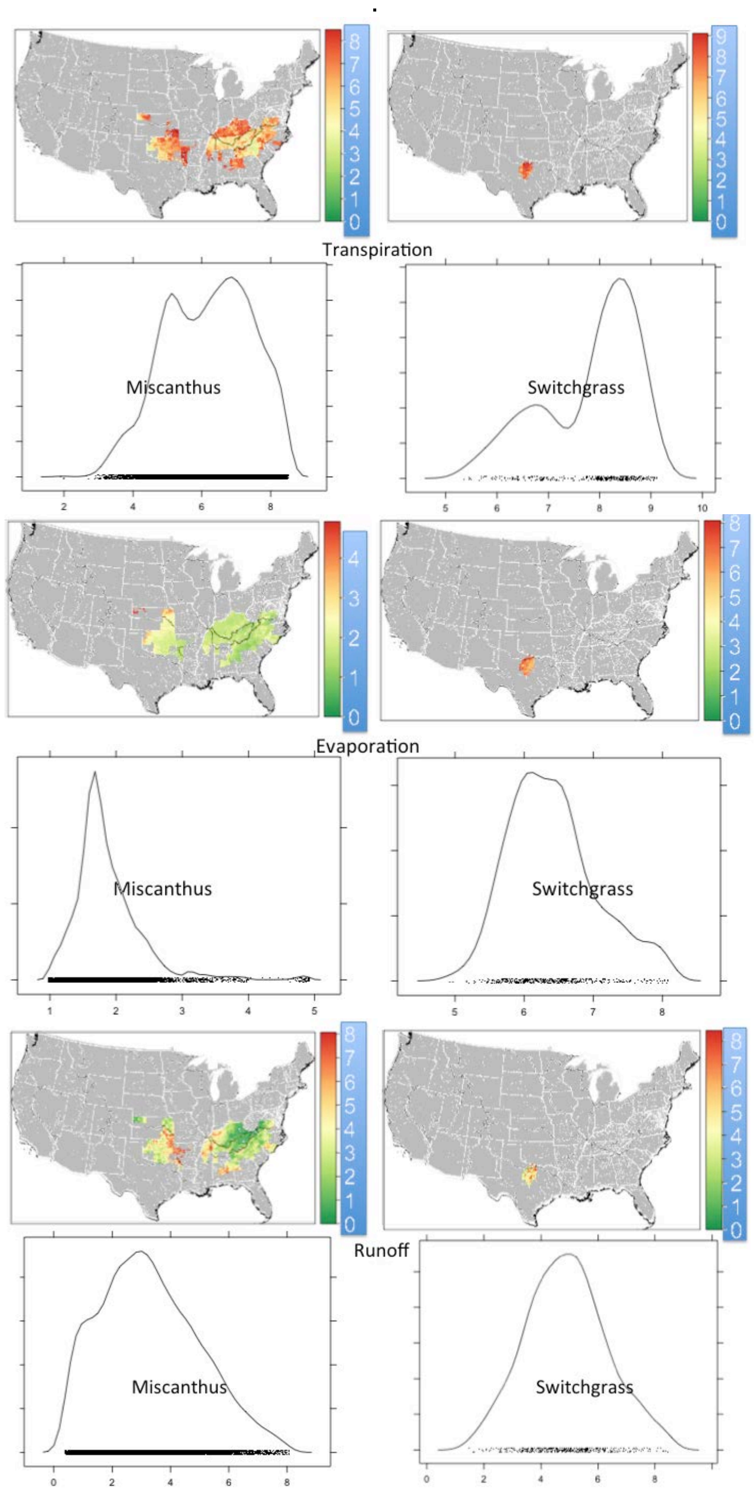
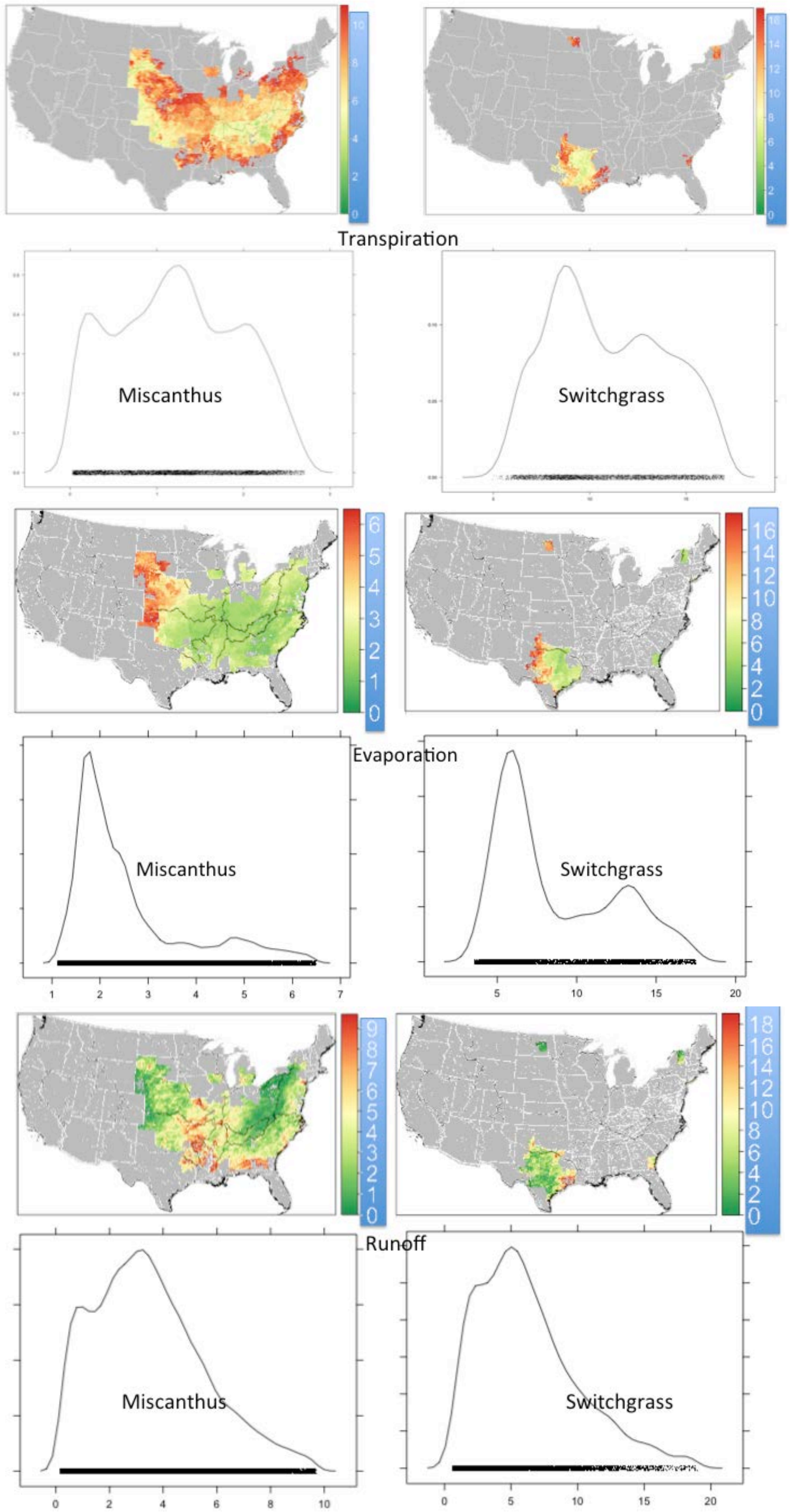


Figure 4.10: Water Use Intensity of Dedicated Feedstocks to Cellulosic Ethanol.



All WUI values in Liters per MJ final energy product (ethanol). RFS Scenario – Miscanthus is shown on the left, Switchgrass on the right. Water Use Intensity includes: _green water use_: ***Transpiration*** (top panels); ***Evaporation*** (mid panels). Runoff volumes are shown also (bottom panels). Dedicated feedstocks are cultivated without irrigation

LCFS Scenario – Miscanthus is shown on the left, Switchgrass on the right. Water Use Intensity includes: _green water use_: ***Transpiration*** (top panels); ***Evaporation*** (mid panels).Runoff volumes are shown also (bottom panels). Dedicated feedstocks are cultivated without irrigation.



All WUI values in Liters per MJ final energy product (ethanol).

These attributional WUI values fit well within the range of the literature reported values for green water (GW) and blue water (BW) consumptive use associated with feedstock cultivation as reported in the LCA literature.

Table 0.11: Summary Statistics of Water Balance Changes among Biofuels Scenarios.

M-RFS2 in 2030					
	Transpiration Δ	Evaporation and off-season transpiration Δ	Runoff Δ	Groundwater Infiltration Δ	Irrigation Δ
Mean	176	-14.6	-1.4	-184	17
Total	***1,000 (0.5%)***	***-830 (-0.9%)***	***-80 (-0.1%)***	***-1,050 (-1%)***	***960 (0.9%)***

LCFS in 2030					
	Transpiration Δ	Evaporation and off-season transpiration Δ	Runoff Δ	Groundwater Infiltration Δ	Irrigation Δ
Mean	125	-10.6	10.6	-46	-2.4
Total	***7,230 (3.7%)***	***-616 (-0.7%)***	***764 (1%)***	***-4,670 (-4.6%)***	***-2,700 (-2%)***

Summary of changes in water balances under the M-RFS2 (top) and N-LCFS (bottom), relative to the counterfactual no-policy scenario, at the national level, across only those 10 km grid cells that undergo changes in cropping practices, in ***acre-feet*** per year. Net changes as a percent of total water budgets nationwide are shown in ***bold parentheses***. Total changes (Δ) are *ne*t changes in each category, summed across the entire contiguous U.S., in ***thousand acre-feet*** per year.

Spatial Patterns of Water Balance Change

Before turning to the analysis of the impacts of the M-RFS2 and N-LCFS policy regimes in terms of smaller geographic units (i.e. by Water Resource Region and by State), it is useful to map the changes in water balances to examine the *patterns* of resultant changes at a fine spatial scale. Although it may be argued that 10 km grid cells are in fact too fine a geographic scale for analysis of prospective changes in crop-water balances under hypothetic biofuel policy scenarios, certain larger patches of net water balance impacts stand out as areas of concern.

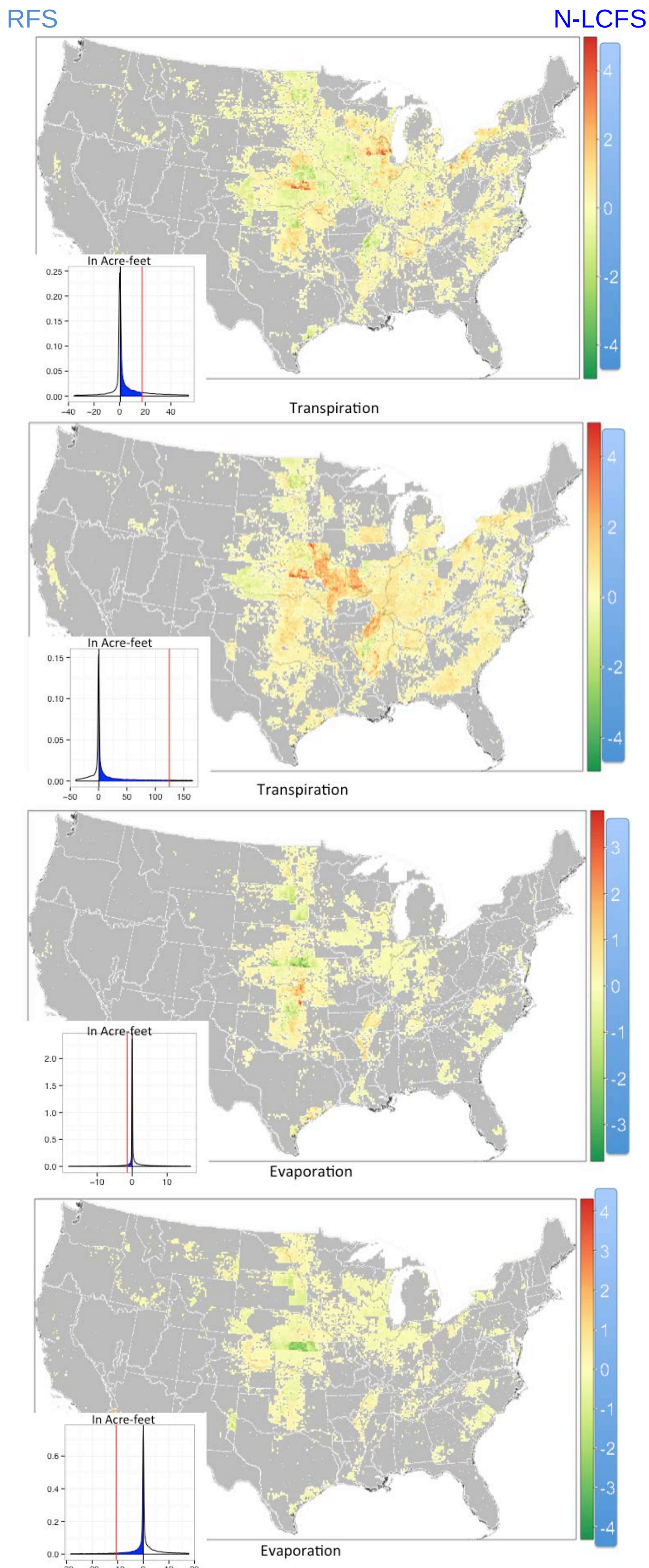
Water Balance Changes in the M-RFS2 Scenario

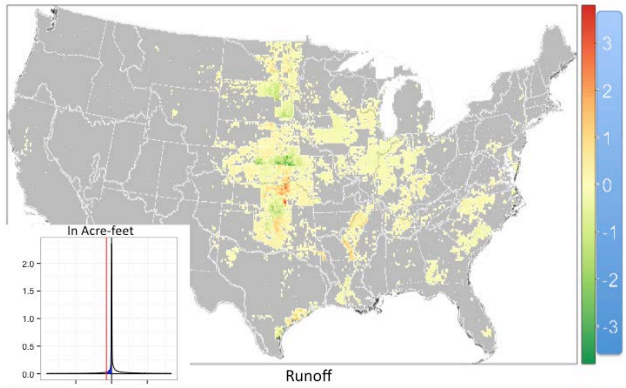
Figure 4.11 maps the national water balance changes that result from implementing the M-RFS2 scenario (left) and the N-LCFS scenario (right) relative to the BAU (no-policy) scenario. Each water balance map is plotted on a separate scale, where the unit for all maps is thousand acre-feet. Additionally, an inset density plot shows the mean (red) and median (black) change for each of the five categories of crop-water flow: transpiration, evaporation and off-season transpiration, runoff, groundwater infiltration, and irrigation. In the insets, the units are acre-feet.

Examination of these two figures reveals a number of general trends. In the RFS, increased cropping of corn in a few concentrated regions (mainly in Wisconsin, and in Southern Nebraska / Northern Kansas), leads to radically increased transpiration in those regions. But slight decreases in transpired water volumes are experienced throughout much of the rest of the Eastern U.S. The net effect is a moderate increase of about 20 acre-feet per 10 km grid cell in transpired water on average. In the N-LCFS, by contrast, transpired water volumes increase more notably across nearly the entire Eastern seaboard. As dedicated biofuels feedstocks (switchgrass and miscanthus) are grown on formerly uncropped prime and marginal lands, they consume (transpire) considerable volumes of water. This is accompanied by a slight decrease in transpired water in swathes of the Frontier States (in the Missouri and Soucis-Red-Rainy water resource regions), in both scenario. In the M-RFS2, transpiration increases are driven by dramatic increase in land brought into cultivation (in corn and soy), while in the N-LCFS the increases are mainly due to the displacement of row crops by switchgrass.

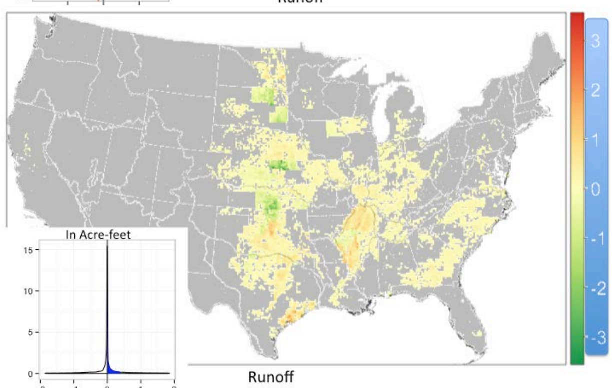
Total volumes of ***evaporation and off-season transpiration*** decrease slightly in the RFS scenario, and more notably in the N-LCFS scenario. The major change is in the region of Northern Kansas, which is intensively cropped in rainfed and irrigated corn. Evaporation and transpiration are often reported as ***evapotranspiration***, and this is treated in the case of biofuels water use as consumptive 'green water' (GW) use.

Figure 4.11: Total Water Balance Changes between the RFS and the No-Policy Scenario.

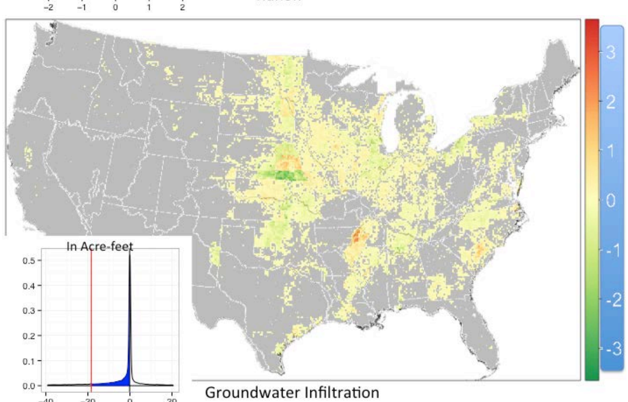




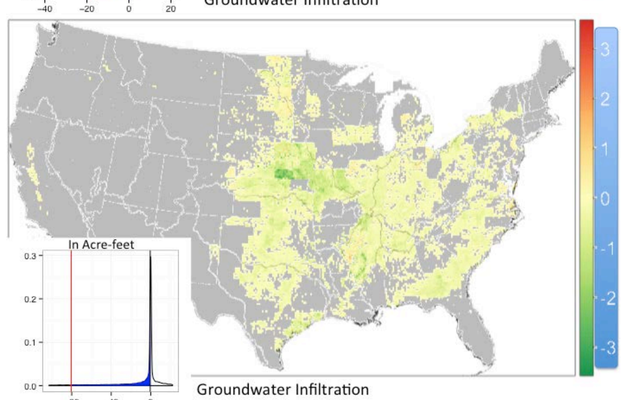
Runoff



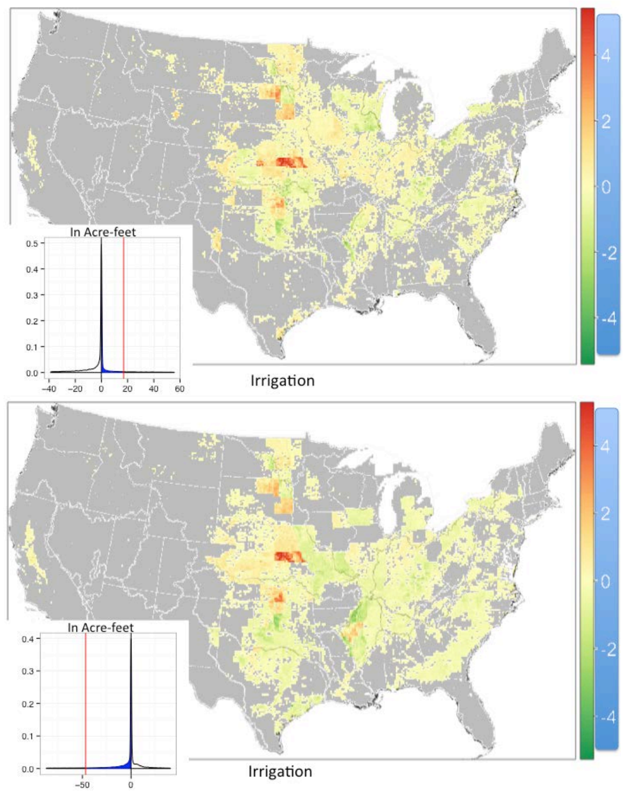
Runoff



Groundwater Infiltration



Groundwater Infiltration



Water balance changes *in thousand acre-feet* in the M-RFS2 and N-LCFS versus a counterfactual no-policy scenario. Inset distributions show the median (black line) & mean (red line) in *acre-feet*. Note that changes over most grid cells are quite small, but that the overall distribution of change is in all cases quite wide.

Changes in net volumes of ***runoff*** are very minor under both scenarios, but in both scenarios a region centered in Kansas experiences net decreases in runoff with increased planting of switchgrass and miscanthus on regular cropland, which displaces crops with shorter growing seasons (and hence with longer fallow seasons). In the N-LCFS scenario, runoff increases notably as a result of agricultural extensification in regions adjoining the Lower Mississippi – as dedicated biofuel feedstocks, are grown on previously uncropped (marginal) land, the capability of soil to retain heavy rainfall is compromised, and, during the fallow season, runoff levels over bare soil increases. Such impacts on runoff may lend credit to concerns that the M-RFS2, and even more the N-LCFS by incentivizing extensification of cropping (even of perennial feedstocks), has or may in the future continue to exacerbate nitrogen and phosphorus nutrient loading into the Mississippi and Missouri Rivers, thus contributing to eutrophication and 'dead zones' in the Gulf of Mexico. The casual connections between increased runoff as modeled by a simplified crop-water model, nutrient loading of extreme runoff events, and such large-scale ecological phenomena are well beyond the scope of this analysis, nevertheless the increases in runoff modeled under the combined economic and crop-water model do support such claims as to the environmental impacts of biofuels policies.

Against a backdrop of widespread, but moderate, net decreases in ***groundwater infiltration*** under the RFS scenario, and the aforementioned heavily cropped regions in Kansas with dramatic decreases in groundwater infiltration, are concentrated patches with increases in groundwater infiltration (e.g. in Southern Nebraska and Eastern Tennessee). In the N-LCFS scenario, with the exception of the region of Kansas which experiences a decrease in groundwater infiltration, the rest of the country sees a widespread but moderate decrease in groundwater infiltration, which is the result of increased cropping. The net effect is a decrease in groundwater recharge that is more notable in the N-LCFS scenario than under the RFS. As mentioned previously, the increased production of biomass for all purposes (i.e. to satisfy food, feedstock, nutritional, and other commercial needs, as well as biofuels) necessarily entails net increases in consumptive water use (or, equivalently, in evapotranspiration). The corollary is that net groundwater recharge (i.e. infiltration) decreases; less water enters the water table under cropped areas, and thus this implies less recharge into groundwater and surface water stocks throughout the watershed. Hydrologic modeling is beyond the scope of this treatment, but decreases in groundwater infiltration nevertheless translate indirectly to reduced ground- and surface water stocks at the local/regional watershed scale.

Patterns in ***irrigation*** water use are similar under both policy scenarios, with the most dramatic increase in irrigation water use occurring in where Kansas, Nebraska, and Colorado border on one another, but also in North and South Dakota. This is the result of expansion (in the RFS) and displacement (in the N-LCFS) of corn to these Western Cornbelt / Frontier regions, and an increase in irrigated corn cultivation. At the same time, some regions in the Eastern U.S. require less irrigation under the RFS, with changing patterns of cropping and with displacement of (partially irrigated) row crops by switchgrass and miscanthus. The net effect is an increase in irrigation water use, particularly in regions where water supplies are scarce, under the RFS.

Perhaps somewhat counterintuitively, net irrigation volumes decrease under the N-LCFS scenario. To some degree, this is explained by the model assumption that it will not prove economically favorable to irrigate dedicated feedstocks (switchgrass and miscanthus). However, the net decrease in irrigation water uses occur (in both scenarios) largely as a result of displacement of row crops by dedicated biofuel feedstocks, and increases in irrigation water use occur in both scenarios in the Western stretches of the Cornbelt and in arid Frontier States where water resources are more scarce.

In summary, water balance differences tend to be concentrated in distinct regions corresponding to dramatic shifts in cropping patterns. In the case of M-RFS2, increases in transpiration at the expense of groundwater infiltration are most pronounced over regions of the country where formerly idle cropland is cultivated in corn. Similarly, runoff increases most dramatically in regions, which shift to tilling corn and soil.

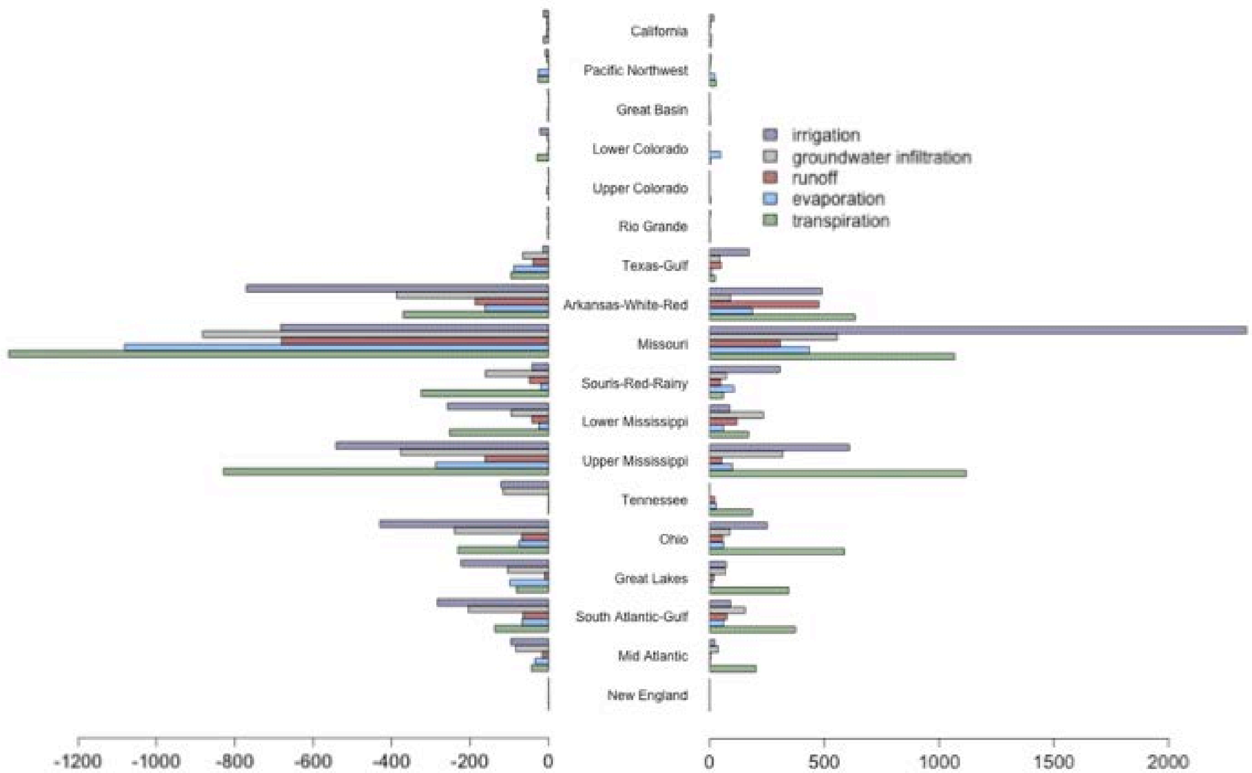
Note also that the differences include positive and negative changes within a single water resource region (WRR). For this reason, when changes are aggregated at the WRR level, all positive changes and all negative changes are summed and reported separately, in addition to reporting the net changes in water balances by WRR. This regional accounting of water balance changes is discussed in further detail below.

Water Use by Water Resources Region

Water Balance Changes in the Renewable Fuels Standard (M-RFS2) Scenario

Figure 4.12 shows the impacts of the M-RFS2 on water balances, where positive and negative changes are summed separately (i.e. total *positive* and total *negative* changes are derived without summing changes of opposite sign to get *net* changes).

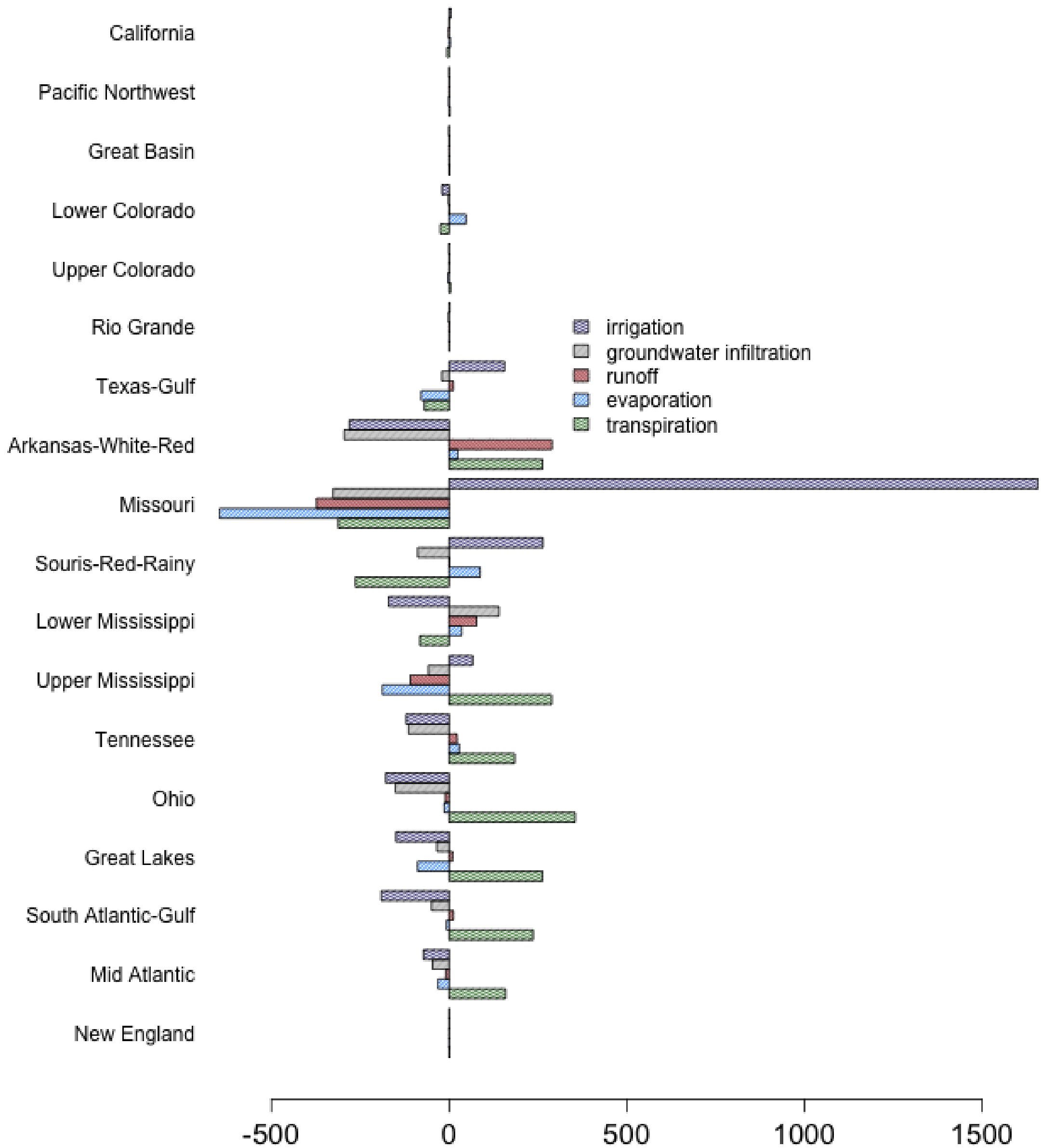
Figure 4.12: *Total* Water Balance Changes under the M-RFS2 by Water Resource Region.



Positive and negative changes are summed separately within each region to account for differences of opposite direction within a single WRR. Units are *thousand* acre-feet change from the no-policy scenario.

The impacts on agronomic water balances of the M-RFS2 scenarios are localized primarily in the Ohio, Missouri, Great Lakes, Arkansas-Red-White, South Atlantic Gulf, and Lower and Upper Mississippi Water Resource Regions (WRRs). In the Missouri, Souris-Red-Rainy, Lower Mississippi, and Texas Gulf regions, decreases in transpiration are greater than increases, and hence, as shown in Figure 4.13, the net change in transpiration water use is negative. In all other regions more transpiration occurs. As discussed previously, increases in transpiration are counterbalanced by decreases in groundwater recharge (and to a far lesser extent, by changes in evaporation and off-season transpiration). Decreases in irrigation and concomitant increases in transpired water across many of the Eastern, Midwestern, and Southern states (in the Upper Mississippi, Arkansas-Red-White, Tennessee, Ohio, Great Lakes, & South Atlantic Gulf) are the result of certain (rainfed) row crops displacing others, and of miscanthus / switchgrass displacing row crops.

Figure 4.13: *Net* Water Balance Changes in the M-RFS2 by Water Resource Region.



Positive & negative changes are summed such that they mediate total water balance changes for a given agronomic fate within each WRR. Units are *thousand* acre-feet change from the no-policy scenario.

Figure 4.13 shows that the majority of changes between the RFS and the counterfactual (no-policy) scenario occur east of the Rockies – very few changes occur in the western States. Despite the notable increase in irrigation in the Missouri and (to a lesser extent) in the Souris-Red-Rainy WRRs, transpiration actually decreases in these regions. The only explanation for these shifts is that irrigated corn (and other row crops) is displacing row crops with longer growing seasons and/or higher total annual transpiration quantities. This may be an indication of the diminishing marginal returns to irrigated corn cultivation in the Western Cornbelt and in Frontier States. Minor changes also occur in the Lower Mississippi, Souris-Red-Rainy, and Texas-Gulf WRRs.

Despite the fact that the changes in runoff and evaporation (where the latter also includes off-season transpiration) are smaller than those of transpiration and groundwater infiltration, these changes can nevertheless be of great significance in terms of ecology and hydrology. Increased evaporation equates to less (biologically and economically) productive water use. Increased runoff, particularly if runoff events are concentrated over short time periods (i.e. in extreme precipitation events), can lead to nutrient loading, which can then cause eutrophication and hypoxia.

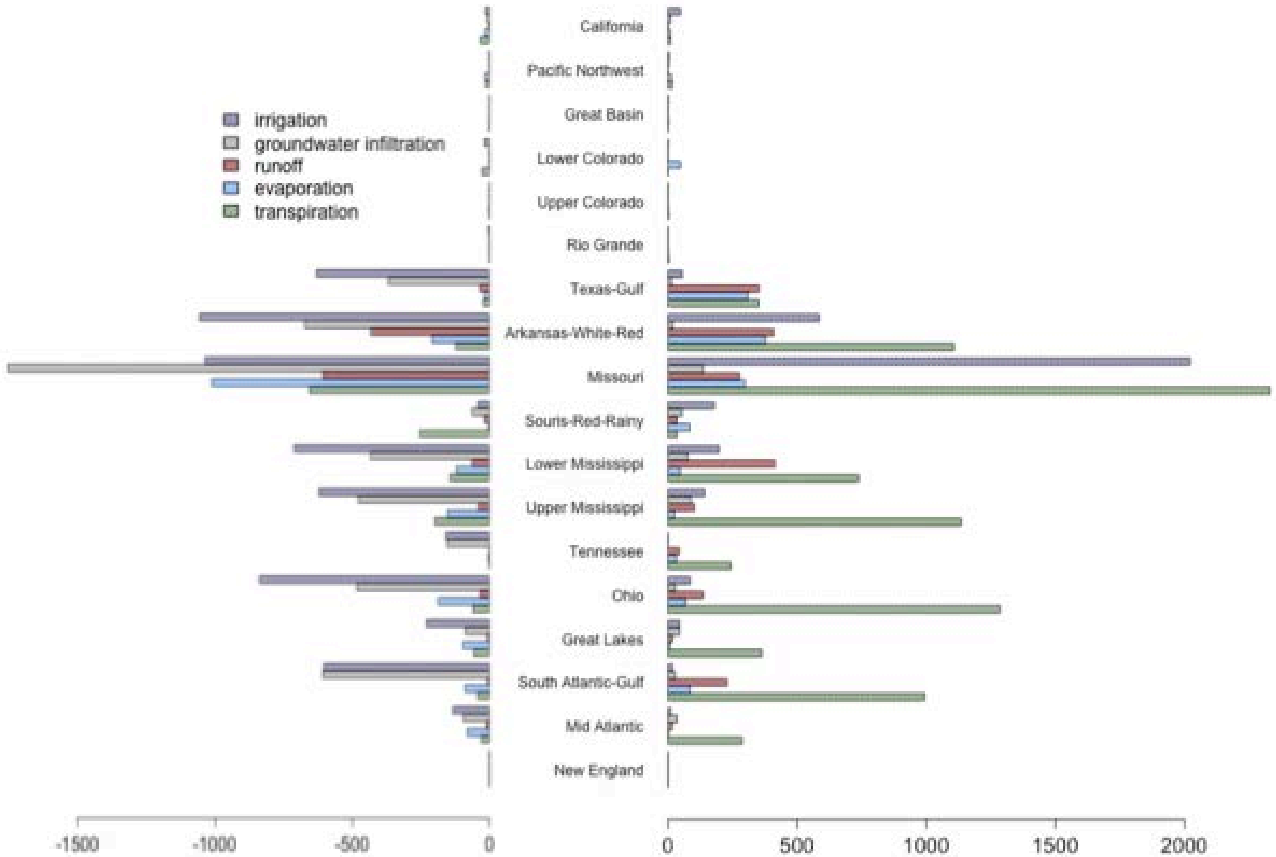
The counterintuitive but nevertheless logical implication that the RFS may lead to less net irrigation water use in eastern states, and that the N-LCFS may lead to an overall net decrease in irrigation water use nationwide, then a counterfactual no-policy scenario contradicts previous LCA literature. Traditionally, LCA methods estimate the irrigation water requirements for growing corn, which may be used as a feedstock for ethanol or other biofuel products – that is, traditionally LCA methods are allocational; as was done in this report in section 4.2.3. Since such irrigation water requirements are certainly variable positive volumes in the case of any irrigated corn crop, these studies assign a positive value of irrigation water use to biofuels such as corn ethanol. In contrast to these methods, this study finds that by shifting the cropping decisions of farmers according to more favorable economics for corn, (to a lesser extent) dedicated feedstocks, biofuels policies such as the M-RFS2 or the N-LCFS may actually lead to a net decrease in irrigation at a national scale, albeit the patterns of change may lead to increases in some regions and depend on changes in cropping practices at the regional level. By incentivizing a more dramatic shift to rainfed dedicated feedstocks, the net decrease in irrigation water use under the N-LCFS scenario is greater than it is under the M-RFS2.

Water Balance Changes in the Federal N-LCFS Scenario

Figure 4.14 shows the impacts of the N-LCFS on WRR water balances, again with positive and negative changes are summed separately. The first point to note about the changes under the N-LCFS is that, while the same general qualitative patterns emerge as under the M-RFS2 (i.e. increases in transpiration and decreases in irrigation, offset by decreasing groundwater infiltration, in the Missouri, Arkansas-White-Red, and Texas-Gulf WRRs), the geographic range of changes is broader (i.e. changes occur in more WRRs, over wider land areas), and the direction of change less ambiguous – transpiration increases nearly everywhere across the Eastern U.S. – the differences in water balances are quite minor in the California, Pacific Northwest, Great Basin, Lower Colorado, and Rio Grande WRRs. Runoff increases in these regions as well, most notably in the Upper and Lower Mississippi, and South Atlantic-Gulf WRRs. This results from wide scale conversion of 'marginal' cropland, i.e. previous uncropped grassland and pasture (which is covered by perennials), by switchgrass and miscanthus.

In contrast to the changes under M-RFS2, here the water balance changes as compared to the counterfactual no-policy BAU are spread more evenly over all the WRRs – although most of the changes are occurring in the Missouri WRR, here changes are notable also in the Ohio, Lower and Upper Mississippi, Arkansas-White-Red, South Atlantic-Gulf, Texas-Gulf, Souris-Red-Rainy, Mid-Atlantic, Great Lakes, and Tennessee Water Resource Regions.

Figure 4.14: *Total* Water Balance Changes under the N-LCFS by Water Resource Region.

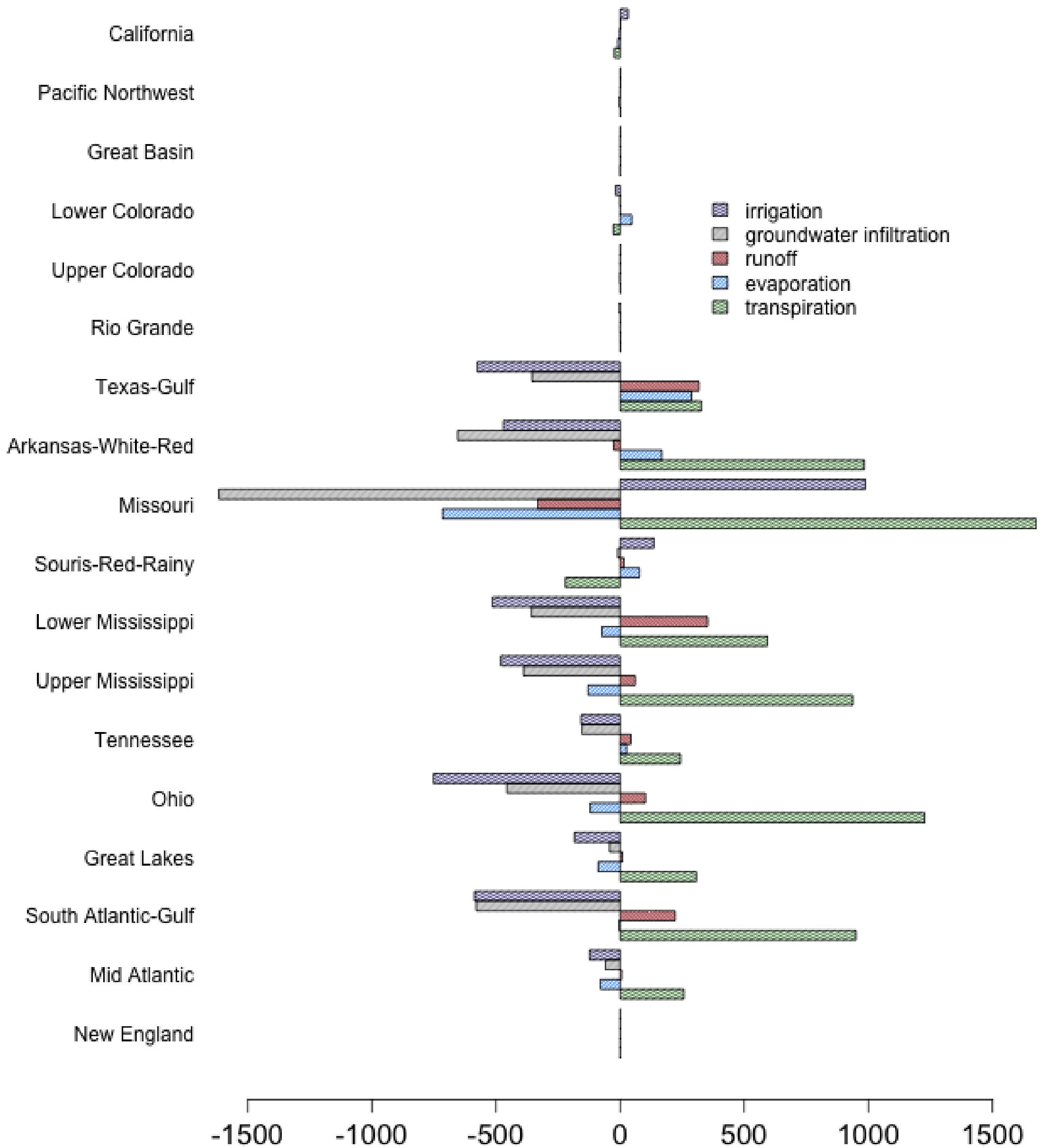


Positive and negative changes are summed separately within each region to account for differences of opposite direction within a single WRR. Units are *thousand* acre-feet change from the no-policy scenario.

Reductions in irrigation water used in the N-LCFS are more pronounced than those in the RFS, but similar in terms of spatial patterns. Less irrigation water is used across most of the Midwest other eastern states. Reduction in irrigation occurs primarily across the Missouri WRR, but also in the Arkansas-White-Red, Upper and Lower Mississippi, and Ohio Water Resource Regions.

Once again, it is informative to graph the net changes by WRR. Figure 4.15 shows the *net* water balance changes in the N-LCFS scenario, relative to the no-policy scenario. The main difference between the N-LCFS scenario and the RFS scenario is the clear trend throughout much of the Eastern U.S.: the additional cultivation of switchgrass and miscanthus on prime cropland and on marginal (formerly idle cropland and cropland pasture), leads to increased transpiration and increase (post-harvest) runoff, with commensurate decreases in evaporation and off-season transpiration, and groundwater infiltration. This pattern is evident in the Lower and Upper Mississippi, Ohio, Great Lakes, and Midatlantic. Runoff changes are more ambiguous (i.e. the net effect is a decrease in runoff) in Missouri and the Arkansas-White-Red Water Resource Regions.

Figure 4.15: *Net* Water Balance Changes under the N-LCFS by Water Resource Region.



Positive & negative changes are summed to a *net* water balance changes for a given agronomic fate within each WRR. Units are *thousand* acre-feet change from the no-policy scenario.

In summary, both policy scenarios lead to greater transpiration (i.e. biologically and economically useful water consumption), at the expense of groundwater recharge to refill groundwater aquifers ground- and surface water stocks. The reduction in groundwater infiltration is roughly 4.6 times as pronounced in the N-LCFS scenario than in the RFS, (equivalently, increases in evapotranspiration or "green water use" are greater under N-LCFS than in the RFS), which means that the N-LCFS can be expected to consume more water, leaving less for environmental and other alternative uses, than the N-LCFS. Somewhat counterintuitively, and contrary to previous allocational LCA studies, this scenario-based methodology finds that both policy scenarios lead to a reduction in irrigation water requirements over the Eastern U.S., but this is counterbalanced by increased acreage in (at least partially) irrigated row crops, and primarily corn, in the Western Cornbelt and Frontier States. Indeed, the N-LCFS as modeled leads to a net decrease in irrigation water use, nationally.

4.3 Electricity

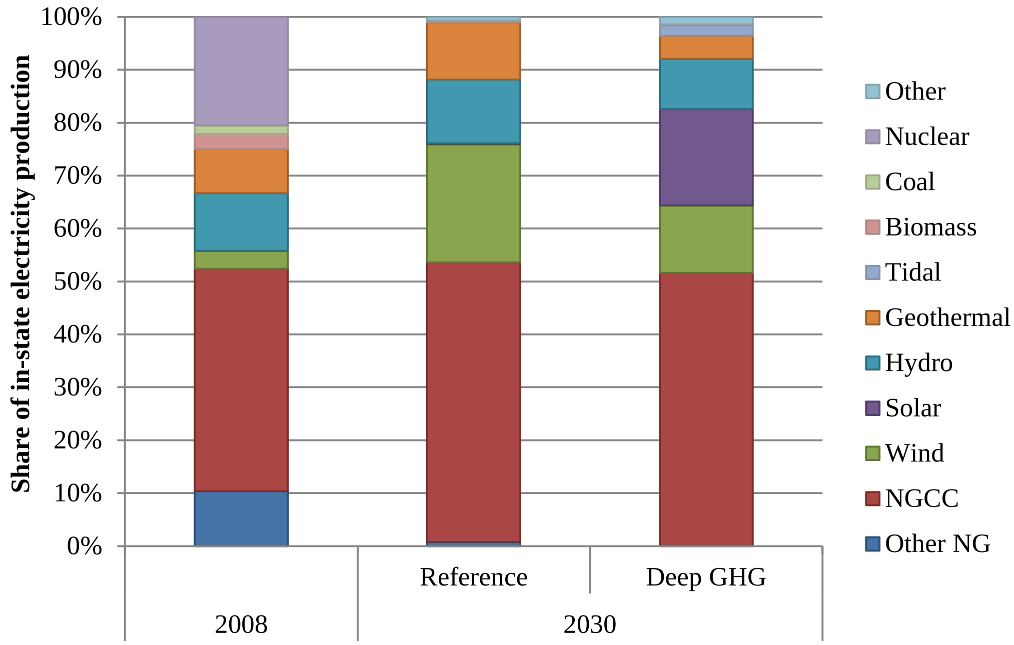
4.3.1 Electricity Generation Portfolios

The CA-TIMES forecasts of electricity generation in 2030 for the *Reference* and *Deep GHG* policy scenario are the basis of the electricity analysis. Forecasts are disaggregated based on feedstock (natural gas, nuclear, coal, and renewables like wind, solar, geothermal, etc.); and conversion technologies (i.e. Rankine, Brayton, and Combined Cycle for natural gas power plants). The analysis assumes that 20% of the electricity is imported in both future scenarios (Morrison, Eggert et al. 2014), and allocate the imports equally across all feedstock and conversion technologies.

The hour-of-day and seasonal variation in demand for electricity are not considered. Instead, the economy-wide annual average share of different feedstocks/technologies is adopted, and it is assumed these are representative of electricity use by the transportation sector. The impact of this assumption on resulting water use estimates for California's transportation sector by 2030 is quite limited given that electricity is a very small proportion of overall transportation energy.

Figure 4.16 gives the projected share of various power plant technologies in the *Reference* and *Deep GHG* scenarios. In the *Reference* scenario, in-state electricity production increases dramatically from around 158 TWh (in 2008) to 261 TWh. In the *Deep GHG* scenario, there is an even greater degree of economy-wide electrification, which results in a doubling of electricity generation, to around 329 TWh.

Figure 4.16: Share of Electricity Generation Technologies in the Base Year and 2030.



Electricity production does not include electricity generated by co-generation plants.

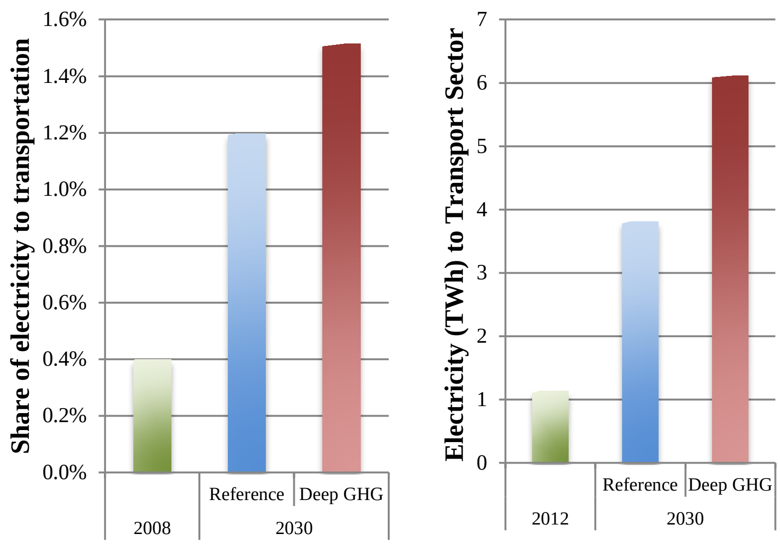
The following enumerates the salient aspects of CA-TIMES projections of electricity produced in 2030 under the *Reference* and *Deep GHG* scenarios:

- NGCC accounts for the largest share of electricity production in both scenarios. The share increases from 42% in 2008 to around 53% in 2030 in both the *Reference* and *Deep GHG* scenario.
- Electricity from wind resources is projected to grow at the fastest rate of all technology types. The share of electricity from wind grows from around 3% in 2008 to around 13%-22% in 2030.
- In the *Reference* scenario, generation by geothermal more than doubles (geothermal is necessary in this scenario to meet RPS mandates). In the Deep GHG scenario, by contrast, geothermal power increases only 10%. This is particularly relevant to projected water use, as geothermal power has among the higher water use intensity (WUI) of all electricity generation technologies.
- In both scenarios, electricity from nuclear power plants is phased out before 2030. Further, Carbon Capture and Sequestration (CCS) is assumed to not become viable in this time frame, due to political/technical/economic hurdles.
- In the Deep GHG scenario, Solar PV and tidal resources each make up a sizable proportion of total electricity generation (about 18% and 2%, respectively). The

WUI of both of these technologies is quite low, and tidal power uses no fresh water for operations.

- Electricity consumption by the transportation sector grows from less than 1 TWh (0.31% of total in-state electricity generated) in 2008 to 3.8 GWh (in the *Reference* scenario, or 1.2% of total generation) or to 6.1 TWh (*Deep GHG* scenario, at 1.5% of total generation) in 2030 (Figure 4.17).

Figure 4.17: Electricity Consumption by the Transport Sector: Share (Left) and TWh (Right).



Total electricity use is 310 TWh in the *Reference* and 475 TWh in the *Deep GHG* scenario.

4.3.2 Electricity Cooling Technologies

The CA-TIMES output does not disaggregate power plants based on cooling technologies. Some simplifying assumptions about the share of cooling technologies for each feedstock/ conversion technology pathway are adopted. These assumptions are detailed in Appendix E.

The share of electricity pathways varies only between GHG mitigation scenarios (*Reference* and *Deep GHG*), and not by the current study's assumptions concerning the water dimension (i.e. *Baseline* versus *Smart* water use). Water availability and pricing is likely to influence power plant siting decisions as well as choice of cooling technology and water source/type (Table 4.12).

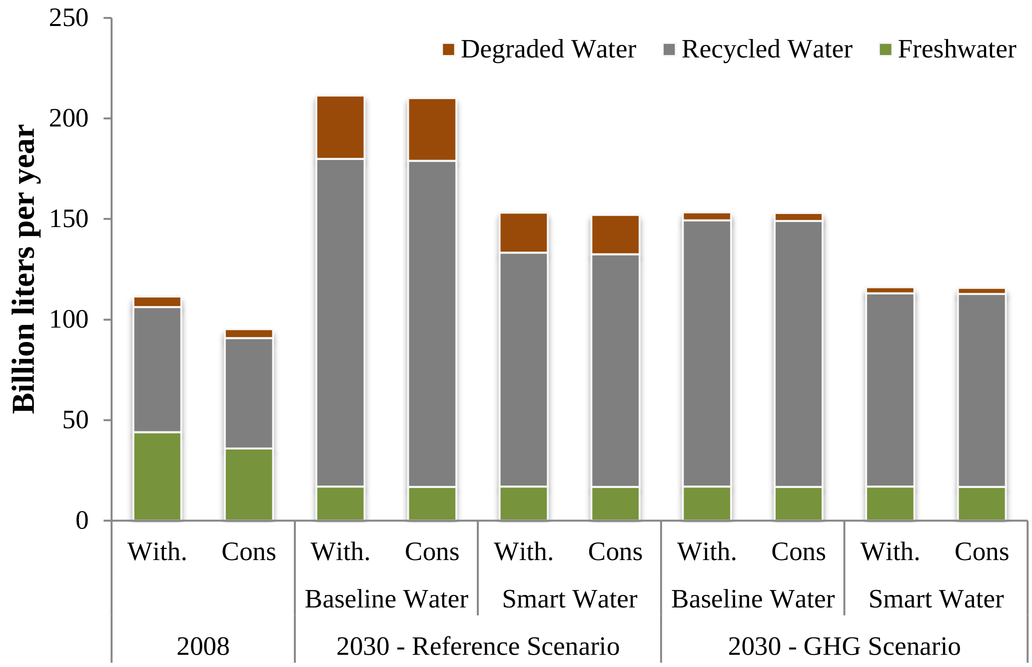
Table 4.12: Water Type & Cooling Technology Assumptions for Electricity Generation.

	Baseline water use scenario (High WUI)	**Smart water use scenario** (Low WUI)
Water source/type	• All new power plants will primarily use recycled treated water (67%) and to some extent degraded water (33%). • All existing once-through cooling plants power plants will close by 2030 except for the Diablo Canyon Nuclear Power Plant – as a result ocean water use will be restricted to this plant in 2030. • Water required for sustenance of dry steam resources (Geysers) will be recycled water. For sustenance / heat mining of flash and EGS resources – 50% recycled and 50% degraded resources.	Same as in the Baseline water use scenario.
Cooling technology	• For Geothermal – Binary (ORC) plants, 65% of capacity is wet cooled while 35% is dry cooled – this is the current ratio in California. All flash power plants will be wet cooled. • New nuclear capacity is assumed to have wet recirculating cooling. • All other new power plants: 75% of capacity will be wet recirculating cooling, while remaining 25% will be dry cooled.	• New power plant capacity will have equal shares of wet recirculating, dry and hybrid cooling. Hybrid cooling will be designed to consume 10% of recirculating. All flash geothermal plants will have wet cooling. • New nuclear capacity is assumed to have wet recirculating cooling.
Zero Liquid Discharge (ZLD)	• All new power plants will be equipped with reverse osmosis systems to minimize water use. • Also, new power plants cannot discharge blowdown to canals or rivers given stringent water quality norms. Power plants regions with in dry weather conditions (as in southeastern California) will be equipped with evaporation ponds; others will have advanced reverse osmosis systems (due to constraints in land availability).	Same as in the *Baseline* water use scenario.

4.3.3 Aggregate Water Use Demand Forecasts

Based on above electricity generation projections from CA-TIMES and the assumptions adopted regarding cooling technologies and share of electricity imports, the statewide aggregate demand for water by the electricity sector is shown in Figure 4.18. Fresh water consumption is cut roughly in half, as a result of strict regulation – OTC plants are gradually phased out, as are many of the in-state power plants that rely upon fresh water. In contrast, recycled and degraded water use increases from around 94 billion liters in 2008 to around 135-193 billion liters in the *Reference* scenario in 2030, depending on how aggressive water management targets electricity generation (as modeled by the *Baseline* versus *Smart* water management scenario. In the *Deep GHG* scenario, increases in '*non-fresh*' (i.e. recycled and degraded) water use are more moderate. Despite greater overall electrification, the portfolio of technologies in the *Deep GHG* scenario is less reliant on water-intensive technologies (primarily geothermal, and so 'non-fresh' water use increases by only 20%-60% (to 99-136 billion liters).

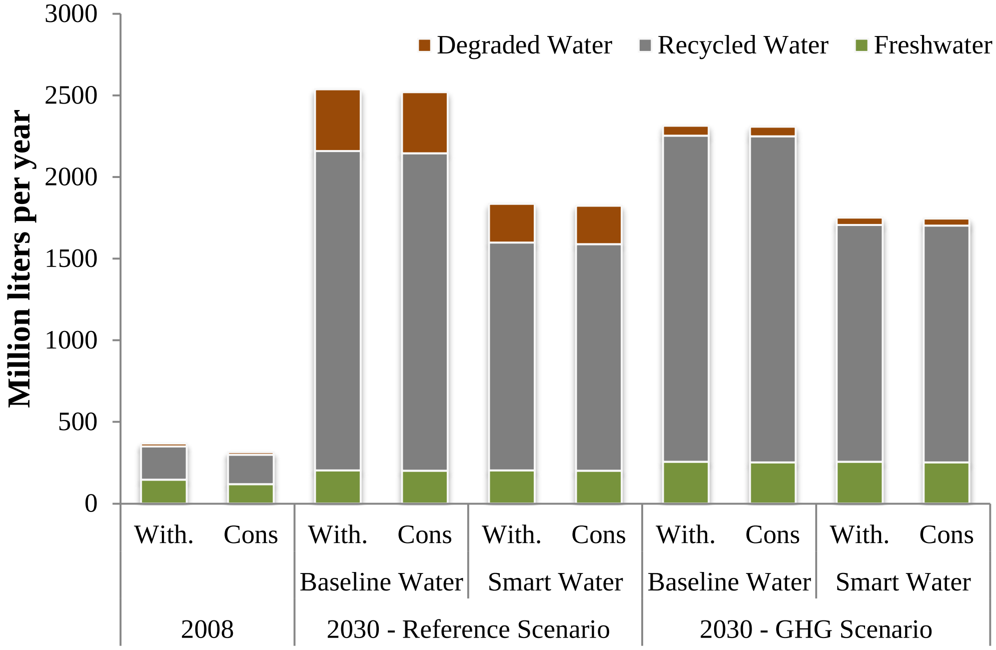
Figure 4.18: Water Withdrawal and Consumption for Electricity Generation in California.



The *Deep GHG* scenario requires substantially more water primarily as a result of increased adoption geothermal and nuclear power, both of which have high consumptive WUI values. Ocean water use for once-through cooling (OTC) plants, and water demand by co-generation plants are not included.

Considering only the share of electricity consumed by the transportation sector, total (fresh plus 'non-fresh') water consumption attributable to the transportation sector increases from around 381 million liters in the base year to 1.8-2.5 billion liters in 2030 in the *Reference* and 1.75-2.3 billion liters in the *Deep GHG* scenario (Figure 4.19).

Figure 4.19: Water Use for Electricity Attributable to the Transport Sector.



4.3.4 Spatial Analysis

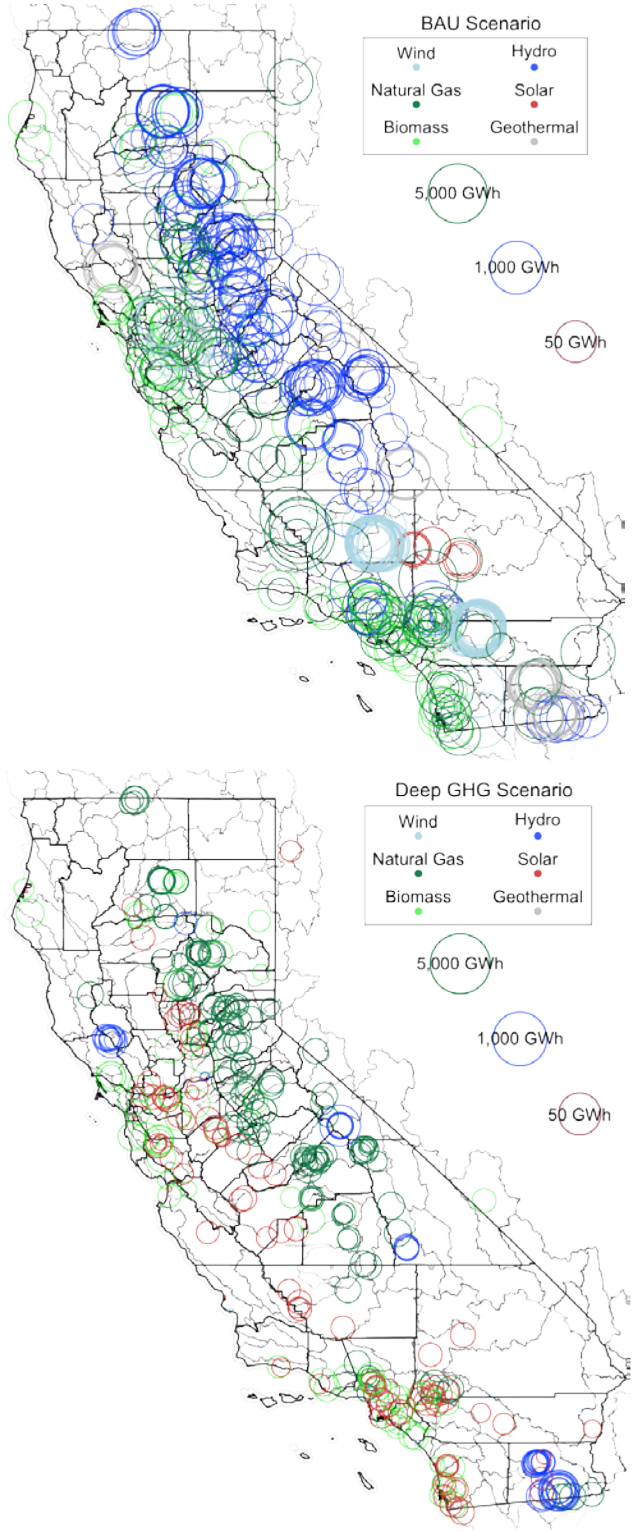
Some general simplifying assumptions about power plant locations are taken in determining likely water source s and cooling technologies. Power plant capacity for any given technology grows around current locations on a *pro-rata* basis, except in the following instances:

All once-through cooling (OTC) plants are phased out;

Geothermal electricity generation from dry steam is assumed to remain at the same level in 2030 as in 2008;

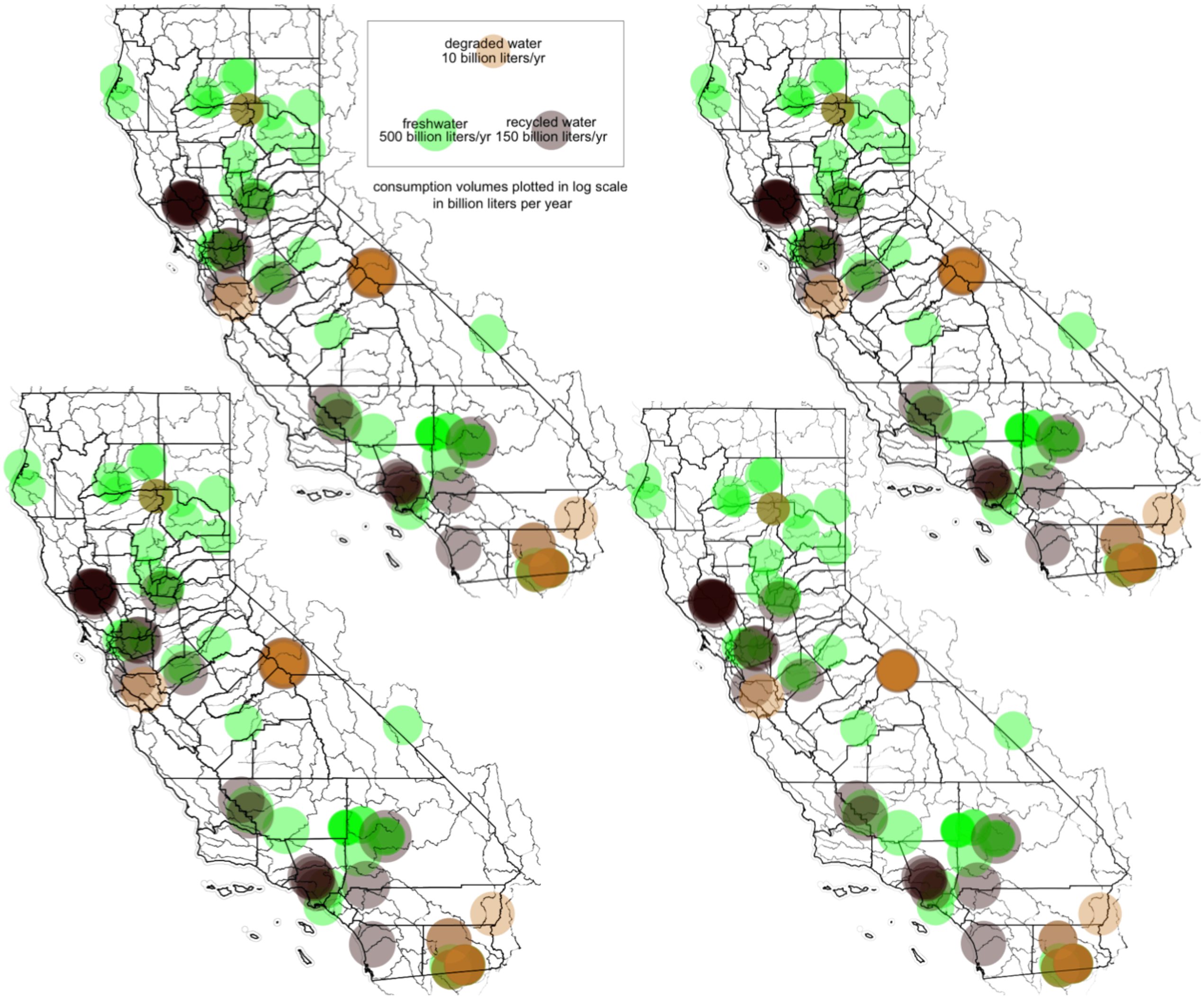
The figures on the following three pages show the locations of power generation within the state, by plant type, in both the *Reference* and *Deep GHG* scenario (Figure 4.20); and the resultant volumes of water consumed (Figure 4.21), by water type, and again in both climate abatement scenarios.

Figure 4.20: Electricity Generation by Plant Type in Each of the GHG Abatement Scenarios.



Electricity generation (GWh) in the *Reference* (left), and *Deep GHG* (right) scenarios.

Figure 4.21: Water Consumption by Water Source Type in Each of the Four Scenarios.



Water consumption (MG/yr) in *Reference Baseline* water use (top left), *Reference Smart* water use (top right), *Deep GHG Baseline* water use (bottom left), & *Deep GHG Smart* water use scenarios (bottom right). Note that all water volumes are in a single log scale.

4.4 Natural Gas

Natural gas (NG) can be used for transportation either directly as liquid or gaseous fuels in compressed natural gas (CNG) engine or liquefied natural gas (LNG) engine vehicle or trucks. It can also be combusted in power plant to generate electricity that goes in electric vehicles. The water implications of these two pathways are discussed separately below. The projections of total natural gas (NG) used directly in the transportation sector, as well as gas used for electricity generation, are based on CA-TIMES scenarios (Yang et al., 2014).

4.4.1 Natural Gas Used Directly by California's Transport Sector

According to CA-TIMES scenarios, 128 PJ of NG are used directly in transportation in the *Reference*, and 153 PJ are used in the *Deep GHG* scenario in 2030 for medium- and heavy-duty trucks. It is assumed that natural gas is imported from other U.S. states, and disaggregate between conventional dry gas and gas produced via horizontal hydraulic fracturing based on AEO 2013 *reference case* projections (EIA 2013c). By these projections, about 70% of domestic natural gas will be produced via fracking, 12.5% by conventional onshore drilling (including both associated and non-associated), and 17.5% using other methods (e.g. offshore production, coalbed methane) in 2030.

Literature cited WUI ranges (discussed in section 3.4.3, see Table 3.12) are applied, using the lower range of values (low-median) in the *Smart* water use scenario, and the upper range (median-high) in the *Baseline* water use scenario. Finally, water use is allocated according to water source *type*, assuming the current split (~95% freshwater; ~5% recycled water) for the *Baseline* water use scenario, and a 50-50 split, spurred by aggressive regulation, in the *Smart* water use scenario. Table 4.14 shows total net consumptive water use incurred by direct use in each of the four scenarios. Natural gas for use directly in transport is assumed to be primarily imported. For aggregating water use volumes (section 5), midpoints of these ranges are used.

Table 4.13: Estimated Water Use for Natural Gas Used Directly in Transport by Scenario.

	Reference Smart	***Reference Baseline***	***Deep GHG Smart***	***Deep GHG Baseline***
Fracking				
Recycled	112 - 313	31 - 117	213 - 593	59 - 219
Fresh	112 - 313	580 - 2201	213 - 593	1126 - 4178
Conventional				
Recycled	52 - 156	16 - 31	98 - 298	29 - 59
Fresh	52 - 156	298 - 395	98 - 298	566 - 1128
Total	***328 - 938***	***925 - 2744***	***623 - 1782***	***1780 - 5584***
Recycled	164 - 469	47 - 149	311 - 891	88 - 278
Fresh	164 - 469	878 - 2595	311 - 891	1692 - 5306

Range of water use for natural gas imports, in million liters per year, based on literature-cited WUI and assumptions regarding water sources (see text).

4.4.2 Natural Gas for Electricity Used in Transportation

The magnitude of the difference in the volumes of natural gas used in transportation between the base year and the future scenarios is not very large: in the *Reference* climate mitigation scenario it grows by 7% and in the *Deep GHG* scenario by 33%. Far more important is the aggressiveness of the state's water policies; as in other production pathways, it is assumed that an increased proportion of water abstracted for natural gas production (both in California and from imports) uses recycled water, and that by mandating greater use of produced water reuse/recycling, the WUI of natural gas production diminishes to the lower realms of the current range (see the preceding paragraph for detailed assumptions). Table 4.15 shows the range of water used in-state and for natural gas imports used to generate electricity and attributable to California's transport sector.

Table 4.14: Estimated Water Use for Electricity in Transport Coming from Natural Gas, 2030.

	Imports of Natural Gas for electricity				In-state production		
	2012	***Smart*** water	***Baseline*** water		***2012***	***Smart***	***Baseline***
Fracking							
Recycled water	0.3 - 1.2	0.3 - 1.3	0.4 - 1.6		1.7 - 6.3	1.8 - 6.8	2.3 - 8.3
Freshwater	6.3 - 23.4	6.8 - 25.2	8.3 - 31		32 - 120	34.4 - 129	42.4 - 159
Conventional							
Recycled water	0.9 - 1.9	1 - 2	1.2 - 2.5		4.7 - 9.5	5.1 - 10.2	6.2 - 12.6
Freshwater	17.6 - 35	18.9 - 37.6	23.3 - 46.4		90 - 180	96.7 - 193.5	119.3 - 238.5
Total	**(25 - 62)**	**(26.9 - 66.6)**	**(33.1 - 82.2)**		**(129 - 315)**	**(139 - 339)**	**(171 – 418)**

Range of water use for natural gas in-state production and imports, in million liters per year, used in NGCC plants to generate electricity that then goes to meet California's demands in electric transport, in 2008 and 2030. Note that the difference in volumes of natural gas used for electricity between the *Reference* and *Deep GHG* scenario is not substantial enough to lead to changes in net consumptive water use. Estimates are based on literature-cited WUI and assumptions regarding water sources (see text).

4.4.3 Natural Gas – Assumptions and Limitations

The analysis here relies upon studies that have only begun to quantify the variables that determine volumes of water use needed for fracking. However, the most recent studies make clear the fact that lower levels of recycling/reuse of produced water that are the current industry norm do, at least, imply that significant water savings (in terms of net water use) could be realized by regulations or other measures incentivizing reinjection of produced water in refracturing or initial completion of collocated wells. Peer-reviewed literature on the WUI and other water use impacts of hydraulic fracturing is scarce but can be expected to grow rapidly in the coming few years. The results of EPA-commissioned research on the water use impacts of domestic hydraulic fracturing will begin to be released and published in the latter half of 2014. Statistical analyses are already beginning to discern the impact of state-level regulations, differences among geological formations, water sourcing, disposal practices, and reuse/recycling of produced water for repeated hydraulic fracturing. To this, detailed empirical geological and hydrological studies will soon add a much-needed level of sophistication to our understanding of the water use impacts of hydraulic fracturing.

CHAPTER 5: Total Transport Sector Water Use

In this section, water volumes used in-state are aggregated across all energy supply pathways, by water source *type*. This allows us to create a spatial inventory and to report aggregate volumes of net consumptive water use incurred by California's transport sector in 2030, across all four bounding scenarios. Next, these water volumes are contextualized in two ways: first by comparing the aggregated projected water use with base year water use, and then by comparing them with water *withdrawal* volumes at the county-level, as estimated by the USGS in 2005. This latter comparison is necessarily approximate; as it compares projected consumptive water use under four scenarios in 2030, disaggregated by water source *type*, with *withdrawal* estimates of freshwater (and no further distinctions for recycled, degraded, or produced water) for 2005. Examining the water use in the context of 2005 withdrawals offers a glimpse of the potential water use futures implied by various climate mitigation and water management scenarios.

5.1 Aggregated Water Use across Transport Energy Supply Pathways

Table 5.1 shows the aggregate volumes of net consumptive water use incurred within California (in ***bold***), and for oil/natural gas imported from out of state (reported in *italics parentheses*) as projected in each of the four scenarios across all California-specific supply chains (i.e. oil, natural gas, and electricity), by water source *type*.

Table 5.1: Total Water Consumptive Use in the Base Year by Energy Supply Chain.

Energy Pathway	**Within California**						*Imports (all water types)*
	Fresh	**Recycled**	**Degraded**	**Waste**	**Produced**	**Other**	
Electricity	35,820 **143**	54,957 **220**	4,385 **18**	**-**	**-**	**-**	*19,032* *76*
Oil production	**14,090**	**-**	**-**	**14**	**202,953**	**73,204**	*321,171*
Refineries	**52,820**	**30,235**	**12,832**	**51,141**	**-**	**-**	-
Natural gas	**211**	**11**	**-**	**-**	-	-	*43*

Units are **million liters** per year. Values in ***bold*** are for water use impacts incurred within the state of California, those reported in *italics* (in the final column) are for net *out-of-state* water consumption incurred by prodution of energy supply imports – all import water volumes are assumed to be freshwater (i.e. <1000 ppm TDS), but not further classified by water type. Note that the base year varies by supply chain, so the volumes are not entirely consistent; electricity data are for 2008, oil and gas data and refinery data are for 2012. Gross produced water volumes are shown here, all other volumes are net consumptive use. Natural gas is used both directly in transport and as a feedstock for electricity production.

Table 5.2 shows the same information (i.e. water consumptive use, by water type and by energy supply chain) as projected for the year 2030, and for each of the scenarios. Again, it reports water use impacts incurred both within state (reported in **bold**) and as a result of transport energy supply chains that import energy resources from out-of-state (reported in the final column, in *italics*). The delta values (Δ) show the change, as a multiplier, in the given scenario of the preceding water volume relative to the base year.

5.2 Spatial Analysis

For consumptive water use within state, volumes of projected water use in each of the four scenarios are spatially aggregated by water source type and across all supply chains. The figures below show these aggregated water use estimates at original spatial resolution. In section 5.3, these estimates are aggregated at the county-level for comparison with 2005 freshwater withdrawals, as reported by the USGS (2005).

Figure 5.1 shows the consumptive water use – and, for oil, gross produced water volumes –, aggregated across all energy supply chains (i.e. electricity, refineries, and oil production), in the base year. The map designates water type by color, and energy supply chain by symbols (i.e. outlines for refineries, crosshairs for electricity generation, and no additional demarcation for oil production). The left-hand map is on a logarithmic scale, and the right-hand map is on a linear scale. The log-scale map is useful for visualizing all the regions and types of water use across all supply chains throughout the state, and the linear scale makes it clear that by far the greatest water use impacts statewide are incurred by oil production and refining, the latter of which uses large volumes of fresh, degraded, and recycled water.

Figure 5.2, which extends to the following page, shows the same information – net consumptive water use and gross produced water volumes, aggregated across energy supply chains, as projected in 2030 for each of the policy scenarios. Water volumes are given in billion liters, in both log (on the left-hand side) and linear (right-hand maps) scale.

The maps show that achieving the 2050 emission reduction targets under the *Deep GHG* scenario will require reliance upon distributed generation, including peaking natural gas plants and renewables (which include Concentrating Solar Power and geothermal, *inter alia*). The result is increased consumption of freshwater for electricity generation across a wide geographic area. Regulations to incentivize or otherwise require water acquisition from e.g. recycled or degraded sources may be beneficial toward this end, and though the implication is an expansion of water consumption for transportation in particular and for the energy sector more broadly, the distribution of water consumption may also add to system resilience.

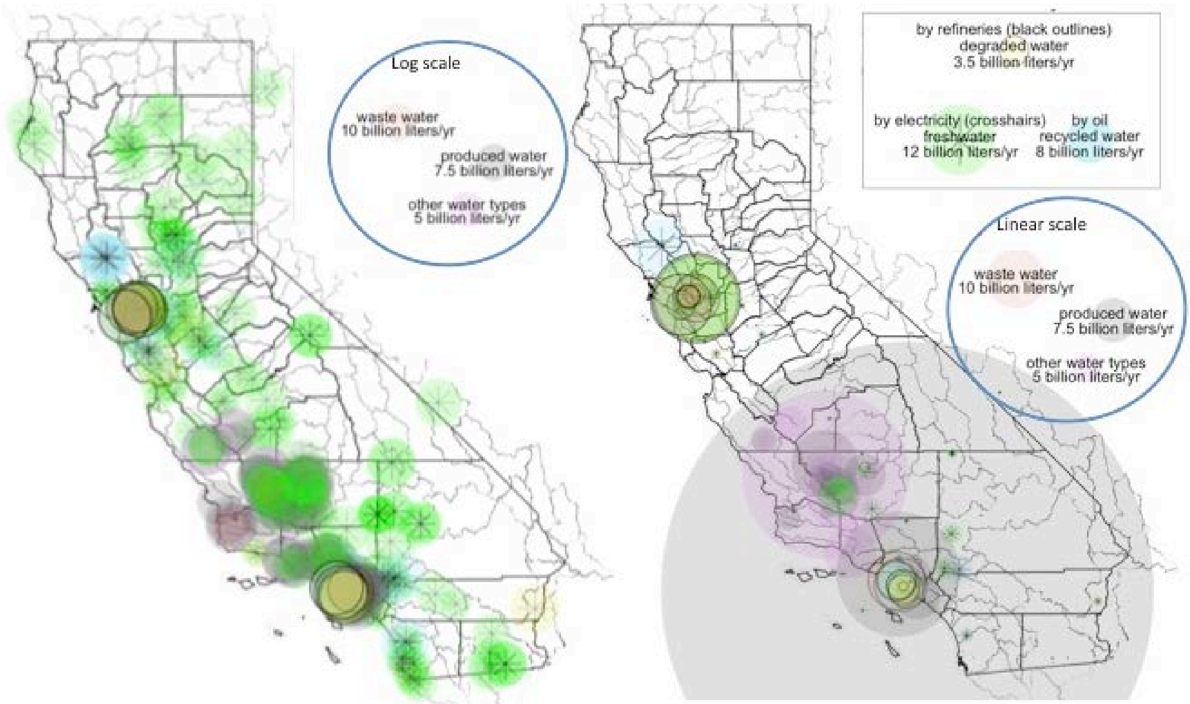
In contrast to electricity usage, a climate policy that cuts transport emissions will require the state to wean itself off of crude-derived fuels. As such, the *Deep GHG* scenario can alleviate the increasing net water consumption and produced water requirements for oil production seen in the *Reference* case (these are a consequence of the increasing water use intensity and produced water intensity of California’s on-shore oil fields, as discussed in sections 3.1 and 4.1).

Table 5.2: Projected Water Consumption for Transport by Scenario & Energy Supply Chain.

Pathway	Fresh	Δ	Recycled[&]	Δ	Degraded	Δ	Waste	Δ	Produced (gross)	Δ	Other types	Δ	Imports[+]	Δ
Reference Baseline[#]														
Oil production	11,000	0.8	-	-	-	-	-	-	225,000	1.1	93,000	1.3	164,000	0.5
Refineries	45,000	0.9	26,000	0.9	11,000	0.9	44,000	0.9	-	-	-	-	-	-
Total electricity	17,000	0.5	162,000	3.0	31,000	7.1	-	-	-	-	-	-	42,000	2.2
Natural gas	230	1.1	10	1.1	-	-	-	-	-	-	-	-	1,880	43.7
Reference Smart														
Oil production	6,000	0.4	6,000	-	-	-	-	-	225,000	1.1	93,000	1.3	87,000	0.3
Refineries	23,000	0.4	48,000	1.5	11,000	0.9	44,000	0.9	-	-	-	-	-	-
Total electricity	17,000	0.5	116,000	2.1	20,000	4.5	-	-	-	-	-	-	31,000	1.6
Natural gas	120	1.4	120	6.3	-	-	-	-	-	-	-	-	680	15.8
Deep GHG Baseline														
Oil production	10,000	0.7	-	-	-	-	-	-	191,000	0.9	79,000	1.1	139,000	0.4
Refineries	42,000	0.8	25,000	0.8	10,000	0.8	40,000	0.8	-	-	-	-	-	-
Total electricity	17,000	0.5	132,000	2.4	4,000	0.9	-	-	-	-	-	-	31,000	1.6
Natural gas	280	1.3	10	1.3	-	-	-	-	-	-	-	-		87.0
Deep GHG Smart														
Oil production	5,000	0.3	5,000	-	-	-	-	-	191,000	0.9	79,000	1.1	74,000	0.2
Refineries	21,000	0.4	46,000	1.2	10,000	0.8	40,000	0.8	-	-	-	-	-	-
Total electricity	17,000	0.5	96,000	1.7	3,000	0.7	-	-	-	-	-	-	23,000	1.2
Natural gas	150	0.7	150	13.3	-	-	-	-	-	-	-	-		29.3

Units are million liters per year. Delta values (Δ) indicate x-fold difference from the base year. Except for gross produced water, all volumes are net consumptive use. Boxes in **red** are for increases in consumptive water use, whereas boxes in green are decreases. [&] California's Water Code for the definition of recycled water is taken: "water which, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would not otherwise occur." Here it includes treated waste water from municipality, industrial sources, and produced water from oil fields for oil production. [+] Imports are the net *out-of-state* water consumption incurred due to energy supply imports. [*] This includes water use of total in-state electricity generation (*) allocated to transportation, which is 0.4% in the base year, and estimated at 1.2 % and 1.51% in the *Reference* and *Deep GHG* scenarios, respectively, in 2030.

Figure 5.1: Aggregated Water Use Impacts of Transport in the Base Year, by Pathway.



Note that the base year varies by supply chain, so the volumes are not entirely consistent; electricity data are for 2008, oil and gas data and refinery data are for 2012. Units are billion liters per year. All volumes are plotted on a single log scale (left), and on a single linear scale (right).

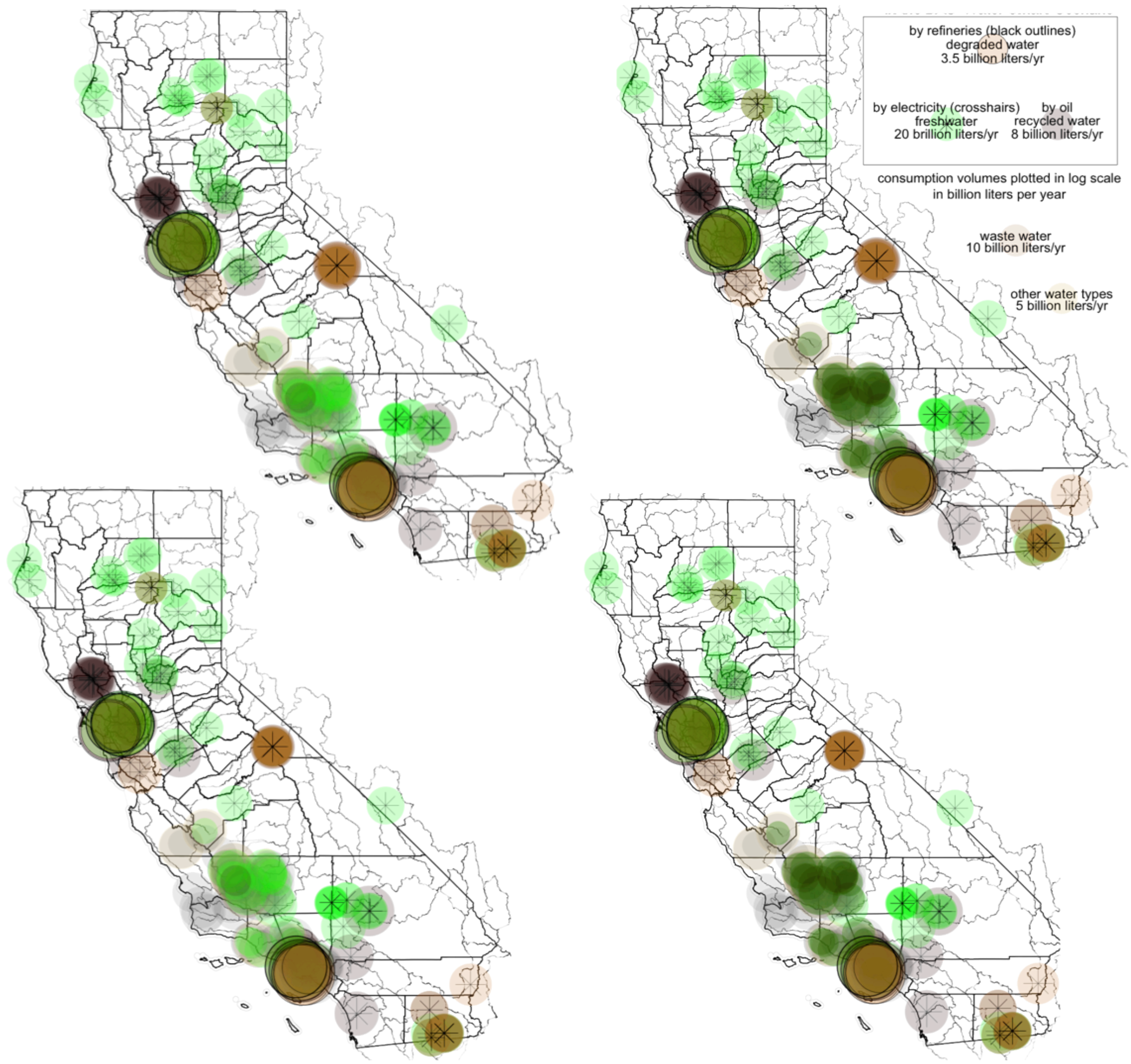
Moreover, decreased oil consumption under both the *Reference* and *Deep GHG* scenario translates to lower water consumption for oil refining. As with electricity, regulations mandating or incentivizing the use of lower quality (e.g. recycled or degraded) water sources may mitigate water use impacts of oil production and refining, as shown by contrasting the *Baseline* and *Smart* water use scenarios under both climate policy cases.

5.3 Sectoral Water Withdrawals in California at a County Level

The USGS provides county-level estimates of water withdrawals for the year 2005, by sector usage (USGS 2005). Here those key outputs of that dataset that is most relevant in terms of providing context for the volumes of net water consumption incurred by the transport sector in 2030 are treated and maps. Three caveats should be noted in making this comparison:

1) The USGS maps show ***withdrawals***, and the estimates are for net ***consumptive*** water use. In the cases of recirculating thermoelectricity power and water use for petroleum and natural gas production, as well as refinery water use, the definitions are nearly identical. In the case of irrigation for biofuels and agricultural crops, the difference is negligible, as delivery irrigation efficiencies are very high in California. Moreover, the distinction is not very important in California, as this analysis assumes that biofuels feedstocks within California are primarily from municipal solid waste and other non-agricultural sources.

Figure 5.2: Projected Water Use Impacts in California in 2030 by Scenario.



Units are billion liters per year. All volumes are plotted on a single log scale. Scenarios are in the following order: *Reference Baseline* water use (top); *Reference Smart* water use (second row); *Deep GHG Baseline* water use (third row); *Deep GHG Smart* water use (bottom).

The USGS tracks only *fresh* (<1000 ppm) and *saline* (>1000 ppm) water withdrawals. This analysis distinguishes among many *types* of water sources, each with a range of functionality and implied economic costs and tradeoffs.

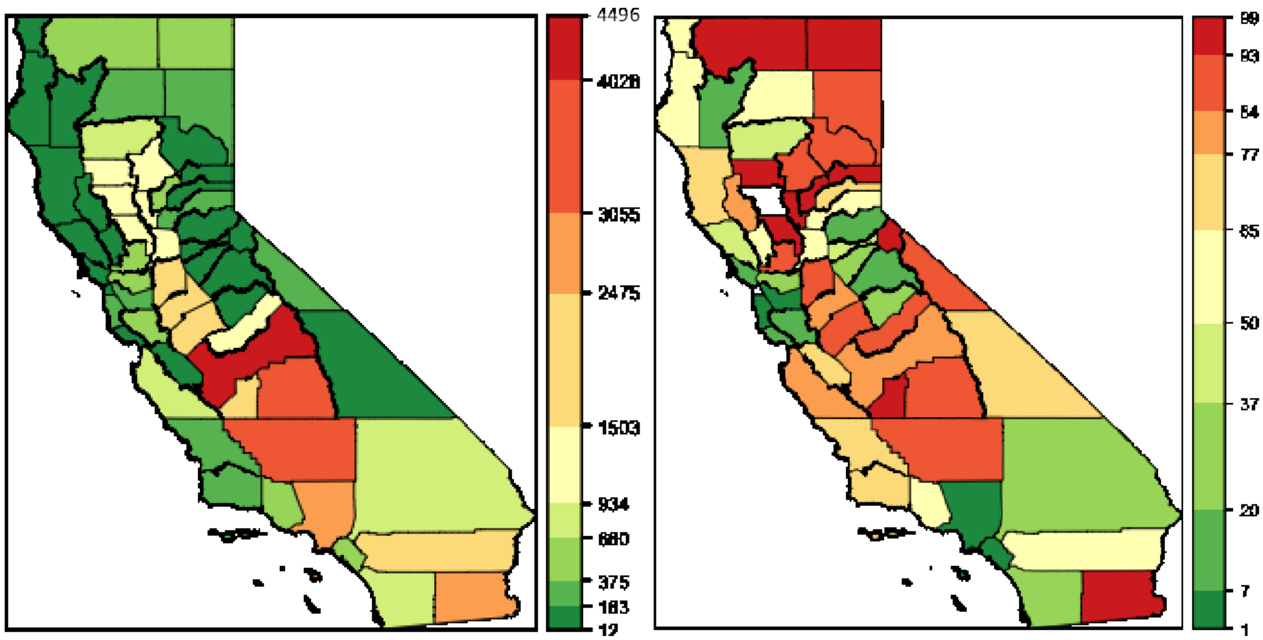
The USGS maps are for the 2005, and the projections are for 2030. In addition to the likely demand-side impacts across all sectors of a growing population, climate change may impact the distribution and availability of water.

With these caveats in mind, it is useful to contextualize the aggregated volumes of water consumed for energy supply chains serving California's transport demand by comparing these to the UGSG survey data.

I. Freshwater Withdrawals are Primarily Irrigation for Agriculture

First, it is worth emphasizing that there is not a very strong correlation between total population and total freshwater use, at the county level. Indeed, the Pearson coefficient between these two variables is only R = 0.31. However, as the majority of water withdrawals are incurred by the agricultural sector, a much stronger correlation can be seen between total freshwater withdrawals and total agricultural irrigation water use (R = 0.926). Indeed, as shown in Figure 5.3, the majority of total freshwater withdrawals are for irrigation.

Figure 5.3: Total Freshwater Withdrawals and Irrigation Withdrawals.

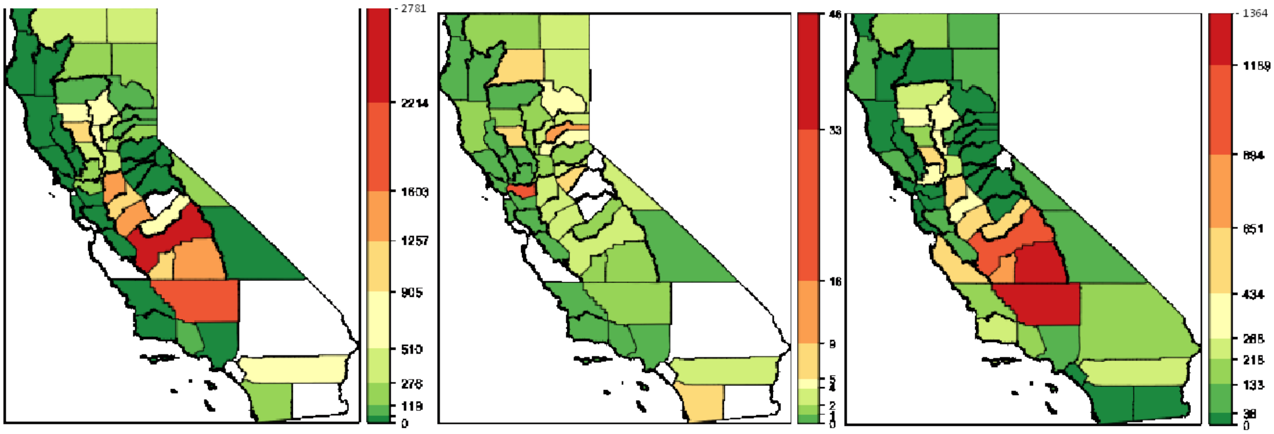


Total estimated total freshwater withdrawals, by county, in billion liters/year (left), and the percentage thereof that is used for irrigation (right), in 2005. The Pearson coefficient between irrigation surface and groundwater freshwater withdrawals is R = 0.926.

Source: USGS (2005)

Figure 5.4 shows the USGS estimates of surface and groundwater freshwater withdrawals in 2005. Interestingly, volumes of surface water withdrawals for irrigation exceed those of groundwater withdrawals by an average of 2.5 times (but with a median multiple of only about 0.5). The multiple of surface over groundwater withdrawals is shown in the middle map of Figure 5.4. The USGS categorizes other uses of water withdrawals at the county level into the following classes: public supply/domestic, industrial, livestock, aquaculture, mining, and thermoelectric power generation. These sectors constitute the remaining fractions of freshwater withdrawal. For the present study's purposes, the last two categories (mining and thermoelectric power generation) are relevant – below maps show total freshwater use by these sectors, as well as the proportions of surface- and groundwater stocks of fresh water withdrawn by these two energy supply sectors.

Figure 5.4: Irrigation Withdrawals in billion liters/year in 2005.



Total county-level irrigation: freshwater surface water (left) and groundwater (right) withdrawals in 2005, in billion liters/year. The middle map shows the multiplier of surface/groundwater irrigation freshwater withdrawals. White counties indicate that no data was available in the survey. The Pearson coefficient between irrigation surface and groundwater freshwater withdrawals is R = 0.688.

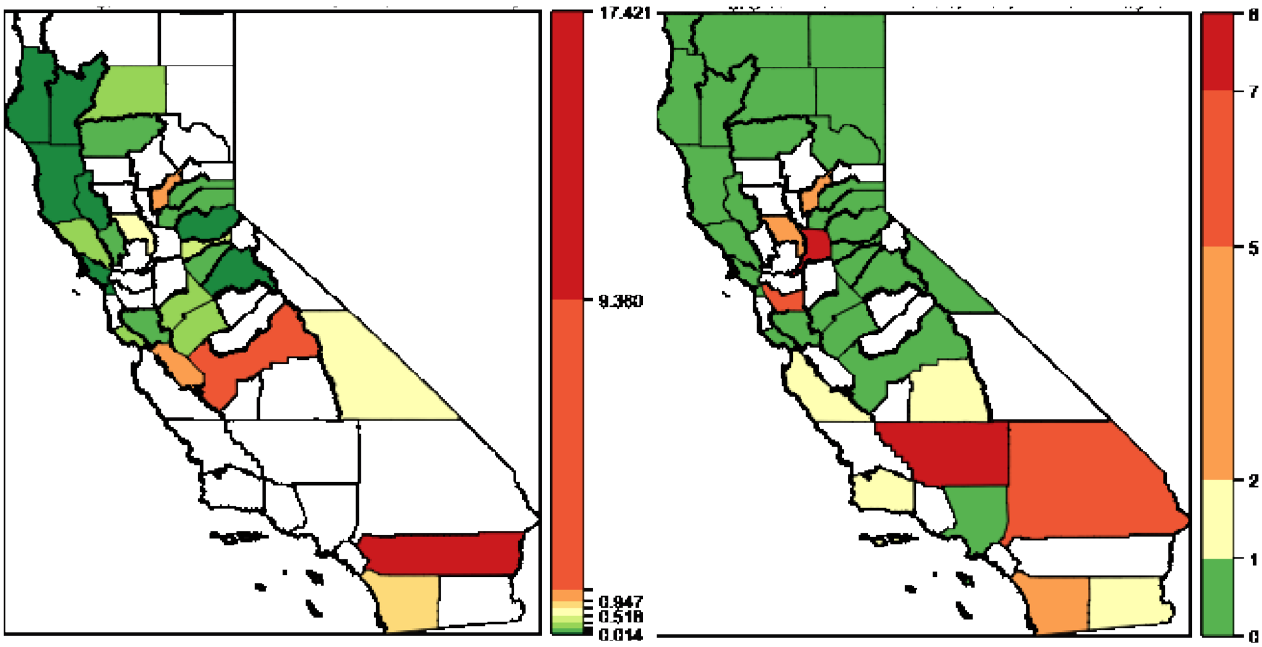
Source: USGS (2005).

II. *Freshwater Withdrawals by Mining Operations and Electricity Generation*

The mining water withdrawal category for the UGSG 2005 county-level data include withdrawal for both fuel and nonfuel mining, where the latter includes water use for the extraction of ores, minerals, stones, sand, and gravel, and the former includes fossil fuel production (i.e. petroleum and natural gas in the case of California). Thus, only a subset of water used in mining can be attributed to coal and natural gas. The estimates adopted here, covered in section 3.1 and based on the DOGGR databases, are both far more accurate and have a higher resolution (i.e. at the well level, and aggregated from monthly to annual data). Figure 5.5 shows the volumes of fresh water withdrawn, by county, for mining operations. The left-hand figure shows surface water withdrawals, and the right-hand figure shows groundwater withdrawals. Again, it is worth emphasizing that mining operations as classified by the USGS include both fuels and nonfuel mining, and so only a fraction of the water withdrawn is likely taken for oil and gas production.

The older, once-through cooling (OTC) power plants, which are located along the coast, exclusively withdraw considerable volumes of saline water, while power plants with recirculating cooling take in fresh water (i.e. water with <1000 ppm TDS), as shown in the same figure (bottom row, in billion gallons/year). Of these estimates, only the freshwater is of consequence in terms of having natural resource (as opposed to environmental) impacts.

Figure 5.5: Freshwater Withdrawals for Fuels and Non-fuels Mining, by County.

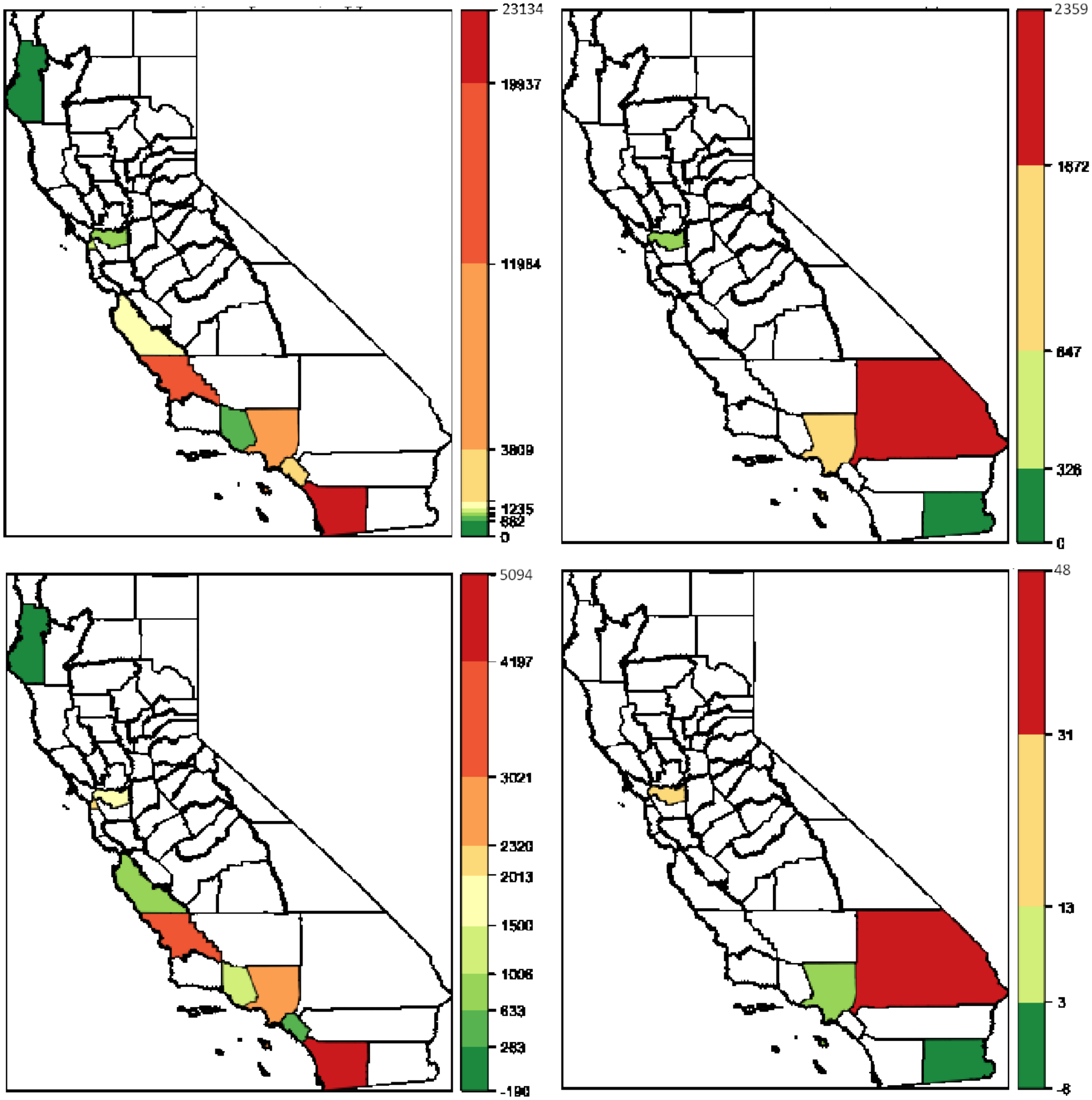


Fresh surface water (left) and groundwater (right) withdrawals by mining in 2005, in billion liters/year. “Mining” as categorized by the USGS includes both fuels and nonfuels mining, and thus overestimates total water withdrawals for oil and natural gas production.

Source: USGS 2005.

Figure 5.6 shows the estimated power generation in GWh, by OTC (left), & recirculating cooling (right) thermoelectric power plants, at a county level (top row). It also shows, on the bottom row, the saline water withdrawn by OTC thermal power plants (left), and total freshwater withdrawals (effectively the same as total consumption) by recirculating power plants (right), in billion liters/year. For the current study’s purposes in cataloguing only the fresh water use of transport energy supply chains, the right-hand figures are relevant (i.e., ocean water withdrawals are not counted).

Figure 5.6: Thermoelectric Power Generation and Water Withdrawals in 2005.



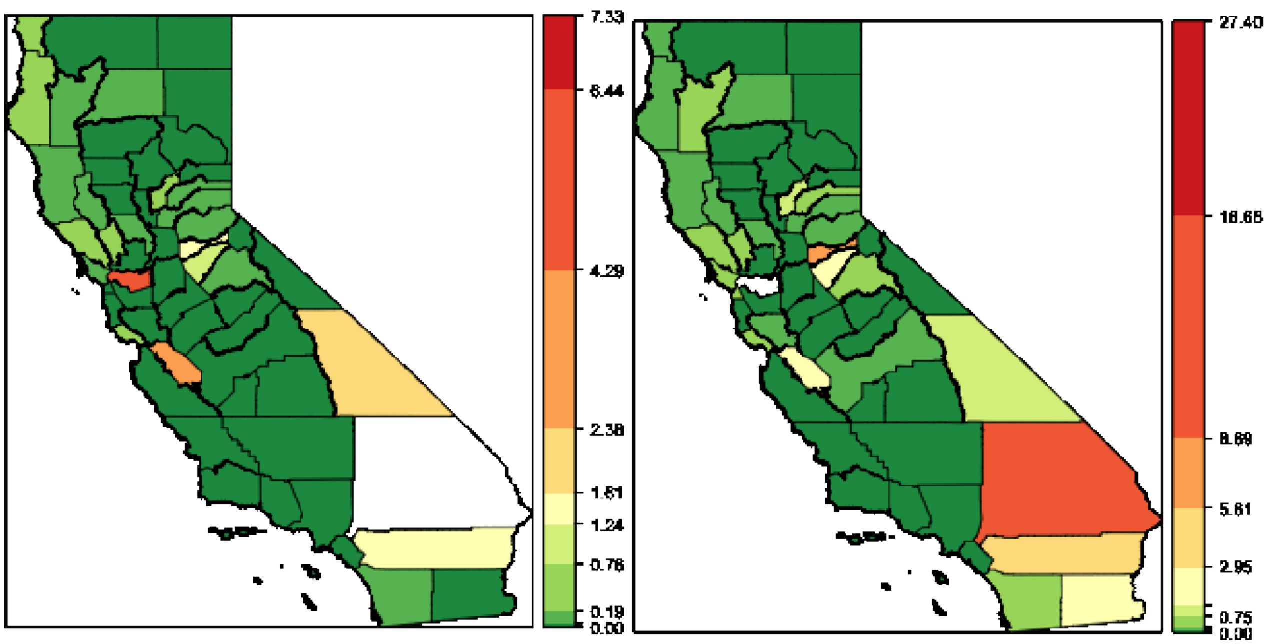
Top row: estimated power generation (GWh), by OTC (left), & recirculating (right) thermoelectric power plants, at a county level. Bottom row: saline water withdrawn by OTC thermal power plants (left), and total freshwater withdrawals (effectively the same as total consumption) by recirculating power plants (right), in billion liters/year.

Source: USGS (2005).

III. Upper Limit of Freshwater Withdrawals for Energy Generation in 2005.

By summing the freshwater withdrawals of mining and electricity generation, then dividing by the total freshwater withdrawals, a consistent estimate of the upper bound of total water withdrawals in 2005, using only data from the USGS survey, is derived. Figure 5.7 shows the fraction of water withdrawn by both mining and electricity generation of total water withdrawals. These upper-bound percentages can be contrasted with the estimated fraction of ***consumptive*** water use in the base year as estimated for oil, natural gas, and electricity, using the methods detailed above. Water use can also be calculated for each of the above transport energy supply chains under each of the four scenarios in 2030, using the methods documented in section 4. Next, these lower-bound estimates are presented. There are multiple reasons for us to think of the following percentages as lower-bounds; first, they are fractions of net *consumption* over total *withdrawals*, and second, they represent only that portion of electricity servicing transportation demand.

Figure 5.7: Upper-bound Estimate of Freshwater Withdrawal by Energy Supply Sector.



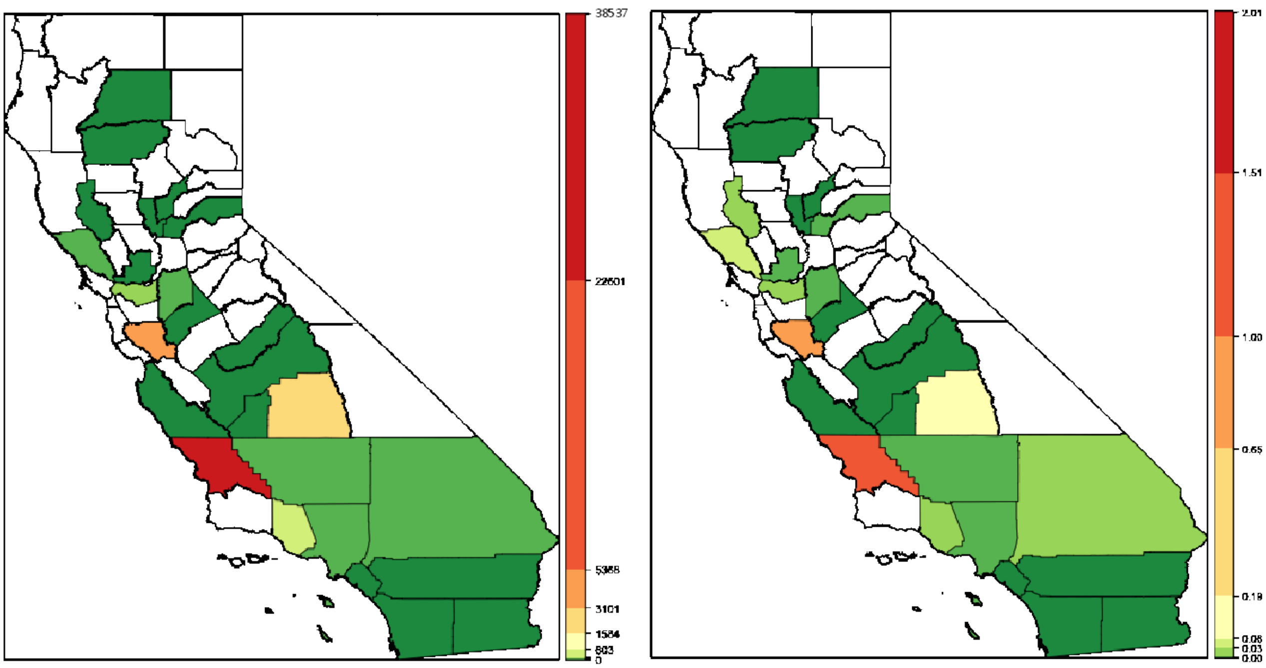
Percentage of freshwater surface water (left) and groundwater (right) withdrawals by the energy supply sector (mining plus recirculating thermoelectric power plants) in 2005, in billion liters/year. Estimates represent an upper bound, as “mining” includes both fuels and nonfuels operations.

IV. Lower Limit of Freshwater Withdrawals (Net Consumptive Use) for Energy Generation.

In exactly the same fashion, the fraction of freshwater consumption by energy supply chains in the base year may be calculated by aggregating the volumes of water used (see Figure 5.1 above), by water quality/type, for each county.

Figure 5.8 aggregates these volumes across all three types, and expresses the total volumes as a fraction of county-level freshwater withdrawals, as reported in the USGS 2005 census. In the base year, consumptive use of high quality (though not necessarily potable) fresh water dominates, and use of recycled and degraded water in energy supply chains represents less than 1% of total use. This can be seen as representing a great opportunity for sourcing water from degraded sources, or for coordinating infrastructure to make use of recycled water. Also note that percentages in Figure 5.8 are increase dramatically in certain counties as compared with the base year. However, it is important to qualify these tiny percentages, in that (1) they aggregate across water types not classified by USGS, (2) they represent county-level averages, and (2) they are consumptive use and not (just) withdrawal.

Figure 5.8: Aggregate Base Year Water Consumption & Percentage of Total Withdrawals.



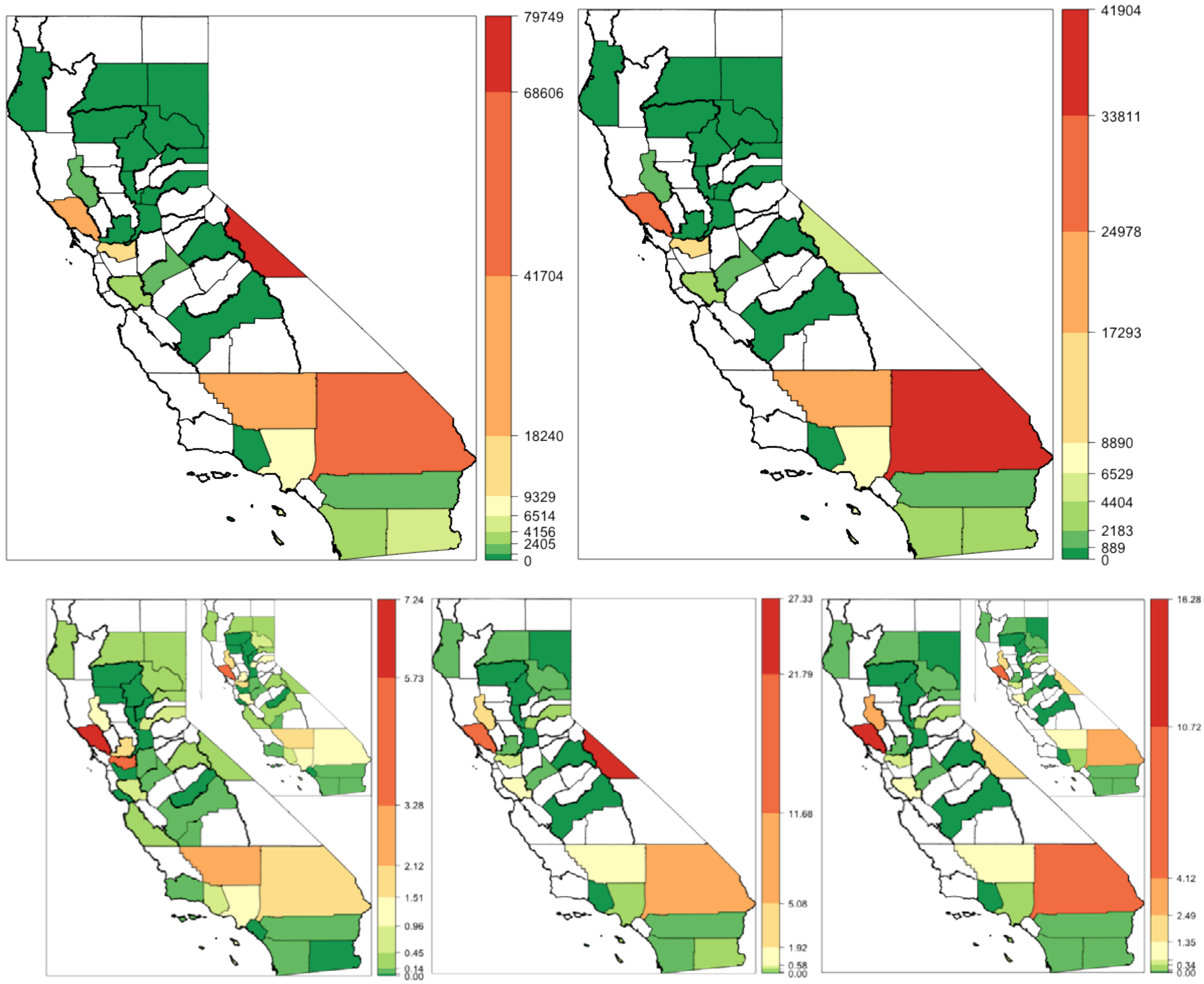
Total aggregate water consumption across all water types (fresh, recycled, degraded, and waste water) incurred for California's transportation demand, in millions of liters (left); and the percentage of total net consumptive use out of all freshwater withdrawals as estimated by the USGS in 2005 (right). Note that the base year varies by supply chain, so the volumes are not entirely consistent.

V. Fractional Net Consumptive Use for Energy Generation in the Future – "Hotspots".

Figure 5.10 repeats the aggregation of in-state consumptive water use across all supply chains serving California's transport energy demand, and across all water types, for each of the four climate abatement/water management scenarios. It shows the percentage of 2005 water withdrawals represented by 2030 net consumptive water use for transportation energy, in the *Reference* (left) and *Deep GHG* climate scenarios (right); as differences in aggregate water consumption between the *Baseline* and *Smart* water management scenarios were very small within a given climate scenario, they are not shown. However it is important to note that the primary impact of *Smart* water management will be to substitute consumptive water use of high quality with lower quality (i.e. recycled or degraded) water types.

The key message conveyed by these maps is that, regardless of whether the state continues to achieve its aggressive GHG reduction goals after 2020 (*Deep GHG* scenario) or not (*Reference* scenario) consumptive water use and water impacts incurred by the energy sector in general and the supply chains providing for California's transportation sector in particular will continue to grow, and may increase for certain counties county-level by as much as threefold.

Figure 5.9: Percentage of 2005 Withdrawals by Projected Water Consumption, by Scenario.



<u>Top:</u> Aggregated net consumptive water use for transportation energy in the *Reference* (left) and *Deep GHG* (right) scenarios in 2030, in million liters annually. *<u>Bottom</u>*: Aggregated net consumptive water use for transportation energy divided by 2005 total freshwater withdrawals, as reported at the county level by the USGS. In the base year (left), and for each of the two climate scenarios: the *Reference* scenario (middle) and the *Deep GHG* scenario (right).

Smart water policies may mitigate the impacts by driving use of lower quality water, incentivizing reinjection or reuse/recycling (as in Kern county) of produced water, or even by siting certain facilities (e.g. power plants) in regions where the tradeoffs of water consumption is less acute. The policy impacts of this research, as well as future research needs, are discussed in the following section.

CHAPTER 6: Discussion

In this section, the implications of the total in-state and out-of-state estimated volumetric consumptive use of water detailed in the previous section is presented. Various technological and policy alternatives to mitigate water use and its impacts are proposed. For certain supply chains, the choice of fuel and technology may be an effective lever to use to reduce water use, for others, appropriate siting may be the most cost-effective measure, and for others, substituting lower quality water sources for freshwater may pose a viable option.

After discussing the policy implications of the results, as well as assumptions and limitations of the methods adopted here, the cutting edge of academic research at the water-energy nexus is outlined. This frontier highlights the importance of linking energy, water, climate, and economic models to generate optimal strategies, and applying these models to challenges and choices at the local and regional levels.

6.1 Oil and Gas

6.1.1 Fracking

Concerns over water volumes consumed by fracking are particularly acute in states where water scarcity is already cause for public concern and the reality or potential for rapid expansion of oil and gas operations may represent yet another source of competition for limited water resources. With discussions of exploiting the Monterey Shale reserves via horizontal hydraulic fracturing, California joins a long list of states (including Colorado, Texas, Wyoming, Oklahoma, and Kansas) where the new technology may lead to tradeoffs and even disputes among the agricultural, industrial, residential, and energy sectors in allocating water.[29]

In any case, in terms of WUI across a fuel supply chain, water consumption volumes extracted in the production and refining of natural gas are dwarfed by withdrawal (in the case of OTC), and consumption (in the case of recirculating technologies) in the electricity generation stage, regardless of whether the gas is extracted via vertical drilling or fracking (Clark, Horner et al. 2013).

Already contentious battles of water will likely become all the more acrimonious as California's population grows and under the projected impacts of climate change on the frequency and intensity of precipitation, and on rising sea levels leading in some coastal regions to saltwater intrusion of groundwater.

[29] Despite the fact that water volumes consumed by HHF operations typically represent only a fraction of a percent of statewide water use, even in the dry states listed above, watershed/county level impacts and competition among end uses are likely to be more pronounced.

In a state where agricultural production and processing make up roughly 2 percent of the state's GDP, and tourism generates upwards of $106 billion in spending and employs 917,000, competition for scarce water resources from the energy supply sector will have substantial economic impacts. For a state concerned with sustainability and conserving its natural resources for future generations, it is now time to instrumentalize the realization that integrated planning of energy and water resources is the only rational and effective way management strategy.

6.2 Biofuels

The analysis of biofuels modeled potential changes in agronomic water use resulting from changes in agricultural patterns and management in the U.S. under two policy scenarios: a revised *Renewable Fuel Standard* scenario, and a national *Low Carbon Fuel Standard* modeled after California's policy.

By altering the economic landscape of domestic agriculture, alternative national biofuels policies lead to different cropping patterns. These direct and indirect land use changes lead to altered patterns of agronomic water use. Cropping over larger land areas implies a net national increase in transpiration under any biofuels policy. Counterintuitively, to the extent that biofuels policies promote cropping of dedicated feedstocks and these are grown in rainfed conditions, biofuels policies may actually lead to a net national ***decrease*** in irrigation water volumes across the Eastern U.S. At the same time, however, by driving agricultural extensification in the Western Cornbelt and across Frontier States, biofuels policies are likely to drive increased irrigation water use in arid states where water supplies are scarce.

Both policy scenarios lead to an increase in total cropped land. The revised RFS increases cropped land by roughly two percent over the 295 million acres, while the N-LCFS is projected to lead to an increase of approximately six percent – in this case primarily a result of switchgrass and miscanthus displacing row crops and being grown on marginal lands. The net result of increased acreage cropped in dedicated biofuels feedstock and row crops nationwide is an increase in transpiration of economic crops, and a corresponding decrease in groundwater infiltration. On net, under the revised RFS, the result is a very slight decrease in runoff, whereas the N-LCFS leads to a more substantial increase in runoff. However, as with irrigation, the spatial patterns of change in runoff matter – and these spatial patterns are a primary subject of this report's investigation.

In summary, by increasing total cropped land area, biofuels policies also consume more water and lead to reductions in groundwater recharge over large swathes of agricultural lands in the Cornbelt and Midwest. Hence, both policy scenarios lead to greater transpiration (i.e. biologically and economically useful water consumption), at the expense of groundwater recharge to refill groundwater aquifers ground- and surface water stocks.

Aside from incentivizing the production of greater volumes (and with a greater total energy content) of lower carbon biofuels, the N-LCFS may lead to greater reductions in irrigation water use. These results add further support to the growing body of evidence that biofuels and other climate policies that offer economic incentives in direct proportion to carbon emission reductions and other measurable and verifiable environmental benefits perform in most cases better than simple mandates or targets.

6.3 Electricity

Based on the electricity generation projections under CA-TIMES for the *Reference* and *Deep GHG* scenarios, and assumptions about cooling technologies and share of electricity imports, water withdrawal (fresh, recycled and degraded) for statewide electricity demand increases from around 95 billion liters in 2005 to around 210 billion liters in the *Reference* scenario in 2030 (more than doubling) and to 152 billion liters in GHG Scenario (increasing by about 60%). In the *Smart* water use scenario, water withdrawal decreases by around 20-30% in 2030 compared to the *Baseline* water scenario.

With the electrification of the transportation section, the share of water consumption attributable to electricity demand for in-state transport increases dramatically, by a factor of three in the *Reference* scenario, and by nearly a factor of four in the *Deep GHG* scenario.

Substantial increases in the consumptive water use for electricity generation in general, and dramatic increases in the water use attributable to electricity demand in transport, are likely to be widely distributed across the state. While certain regions and watersheds may face tradeoffs in accommodating water use for new power plants, it is also possible that the wide range of regions suitable for renewable power generation technologies and distributed power generation may add to system resiliency.

6.4 Policy Insights and Potential Future Research Extensions

This section summarizes the cutting edge of modeling at the water-energy nexus. After briefly reviewing attempts by Integrated Assessment models (which typically link engineering-energy systems with economic and environmental dynamics and attempt to model long-time scales (e.g. decades to centuries), at global to national scope), modeling platforms that soft-link geographically explicit water and energy models are presented, and recent research is reviewed that uses these models to conduct case-studies examining the repercussions of optimizing for economically and environmentally viable outcomes under water and energy constraints.

One of the most direct insights that can be drawn from this analysis is in identifying regions of potential concern in terms of tradeoffs or scarcity of water resources. For instance, the research identifies California's Inland Empire and the Central Valley as regions where energy demand may exacerbate already acute water scarcity.

Similarly, policies promoting the production of biofuels may significantly reduce water availability in the Midwest, Cornbelt, and in scattered regions along the Mississippi and Missouri River basins, and further lead to increased runoff. But to identify particular regions and watershed where the tradeoffs between supplying energy and water might be most acute requires more targeted modeling using different methods which consider a more limited geographic scope and a more restricted set of variables or considerations. Furthermore, detailed hydrologic modeling would be required to determine the landscape scale impacts of changing cropping patterns on hydrologic budgets, water availability, and water quality.

6.4.1 Case Studies and Siting Scenarios to Explore California-Specific Impacts

This analysis can serve as a foundation for two prongs of potential further investigation. First, once potential 'hotspots' – regions where energy supply chains may exacerbate or contribute to water resource scarcity or water quality impacts – have been identified, basic input parameters under various policy scenarios may be used to bound the likely water use impacts (e.g. in terms of rates/volumes of water withdrawal/consumption, or degradation). These can become the basis for detailed case studies, which might incorporate economic, hydrologic, and even political and social dimensions. Case studies may adopt a range of methodologies, and, depending on their scope and purpose, they may adopt modeling, environmental impact assessments, stakeholder feedback, or a mix of these and other approaches.

Certain new tools, such as the recently completed LEAP-WEAP platform[30], developed by the Stockholm Environment Institute, may be ideal models for exploring the tradeoffs and interactions between electricity generation, agriculture, and (e.g. agricultural and municipal) water supply sectors. Modeling platforms that consider the dynamic interactions between economic and engineering components of energy and water supply are ideal if certain large-scale projects, such as developing the Monterey Shale for oil, building large CSP facilities in the Central Valley, come again to be considered. Siting scenarios for in-state biorefineries, geothermal power, and in-state non-agricultural feedstocks, may also benefit from economic-engineering models. Section 6.4.3 outlines research using LEAP-WEAP and similar platforms to examine the tradeoffs and impacts of pricing, scarcity, and timing on integrated resource management problems at the water-energy nexus.

6.4.2 Cutting-Edge Research at the Water-Energy Nexus

This study is *unidirectional* in that it analyzes the potential water use impacts of future transportation fuels *given* various scenarios of projected transportation fuel use demand. This is only the first step towards a more holistic and comprehensive water-energy analytic framework that is bidirectional: future water availability at local and regional scales can also significantly constrain future development of energy supplies. An integrated framework that considers how best to manage future energy supplies and demand *given* water resource availability and impacts should be the gold standard for this type of research (Jolliet, Margni et al. 2003, Rosenbaum, Bachmann et al. 2008, Bayart, Bulle et al. 2010, Johnson, Zhang et al. 2011, Davies, Kyle et al. 2012, Jordaan 2012). Further, it is necessary to characterize impacts of water use both in the local (ideally watershed level) context – accounting for other human (e.g. industrial, agricultural, and residential) and ecological uses, as well as hydrologic features to appropriately understand the impacts – and in the context of trade flows of food, energy services, and products that require 'virtual' water to produce.

Recent research proves the need to analyze the *bidirectional* interdependencies between water and energy, often in the context of other resource and environmental/ecological impacts such as

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[30] For a policy brief describing the capabilities of the LEAP-WEAP platform, see: http://www.sei-international.org/publications?pid=2149.

climate, food, and land. This research shows how integrated modeling and systems-level analysis are necessary to capture the constraints and synergies imposed by water availability on energy production and provision, and vice-versa – yielding insights and reaching conclusions that are distinct from those afforded by optimization of a single resource or criterion (e.g. efficiency, cost). Furthermore, these research projects point to the need to model at both local and global scales: water and energy both provide services that vary in space and time, but also are integral to and embodied in goods and services that are traded globally. This report focuses on water use and, to a lesser extent, water quality impacts incurred in various keys stages of supply chains for California's current and future energy pathways for transportation.

Thus, the second kind of investigation that would build upon the methodology adopted here is a truly integrated modeling framework. In contrast to the current approach of using the outputs of energy-economic models as the basis for estimating (the differences among) water use impacts of various policy scenarios, a handful of studies (which necessarily consider a more geographically restricted scope than e.g. all of California) have begun to 'soft-link' hydrologic and energy models, and in certain cases even to incorporate dynamics of economics and climate change. Such an approach, which considers the interactions among energy, economics, water resources, and climate, leads to qualitatively and quantitatively difference answers from a 'fragmented' modeling of only one or two of these considerations (e.g. energy-economic modeling). Though it risks leading to opaque and difficult to interpret results, integrated modeling represents the methodological frontier of science- and data-based integrated resource management and policy.

Integrated Assessment Models (IAMs) at the Water-Energy Nexus

Integrated assessment (IA) models such as Pacific Northwest National Laboratory's (PNNL) Global Change Assessment Model (GCAM) and the MESSAGE model at the International Institute for Applied Systems Analysis (IIASA) have only very recently begun to incorporate water use implications of growing population, energy supplies, and economic activity (Davies, Kyle et al. 2012, Hejazi, Edmonds et al. 2012, Hejazi, Edmonds et al. 2013, Kyle, Davies et al. 2013). A sophisticated baseline and various scenarios projecting water use for energy has been incorporated into GCAM (including *direct* primary stages such as production, mining, and crop cultivation; intermediate stages like transportation and distribution; secondary stages like electricity generation; and certain other conversion losses along the energy supply chain) (Davies, Kyle et al. 2012, Kyle, Davies et al. 2013). Similar work to incorporate water withdrawal volumes and consumptive use is ongoing at IIASA with their MESSAGE model, also at the national scale. While these efforts are a useful first step toward quantifying the potential water use impacts of transitioning to renewable energy sources, the coarse geographic and temporal resolution limits the degree to which water availability constraints and economic tradeoffs of water use can be modeled with much realism. Efforts to downscale the results and/or link them to hydrologic models may be the next logical step in using the outputs of IA models to inform policy and planning at the water-energy nexus.

Soft-Linked Hydrologic and Energy Models Enable Case Studies at Regional and Local Scale

A research initiative based at the KTH Royal Institute of Technology's Division of Energy Systems Analysis has developed soft-linkages across various models and datasets to integrate and iteratively solve for interactions among *C*limate, *L*and-use, *E*nergy, and *W*ater *S*ystems. The KTH team uses the recently integrated water-energy modeling platforms the Water Evaluation and Planning model (WEAP) (Yates, Sieber et al. 2005) and the Long range Energy Planning system (LEAP) (Lazarus, Heaps et al. 1997), together with GIS-based analysis using downscaled spatial temperature and precipitation projections from climate mosaic models, and IIASA/FAO Agro-Ecological Zones (AEZ) (Fischer, Nachtergaele et al. 2012). The CLEWS research identified tradeoffs, synergies, and constraints imposed by water and energy in both an extremely poor country (Burkina Faso), and an upper-middle income island nation (Mauritius). In both cases, they found that policies informed by isolated modeling of a single resource system (i.e. energy, water, agriculture) and without considering mutual constraints, "could become both incoherent and counterproductive. (Hermann, Welsch et al. 2012)"

In the case of Burkina Faso (Hermann, Welsch et al. 2012), an impoverished, landlocked African country with a rapidly growing population that is primarily dependent on subsistence and small-scale agriculture, on traditional biomass (wood) for energy (primarily cooking), low access to electricity (15%), and no known reserves of hydrocarbons, the challenge is to shift to modern energy infrastructure while improving access to energy services. The CLEWS modeling leads to the insight that targeted, intensive cultivation of food and commodity crops (e.g. sugarcane and cotton seed oil), together with introduction of Jatropha as a biofuel feedstock on marginal land in zones of high rainfall and ready access to surface- and groundwater will enable an economically beneficial transition from traditional to modern biomass (thereby reducing energy products imports even while supporting health and human development goals). Agricultural intensification will further minimize deforestation and thus reduce net carbon emissions.

The key lesson from the CLEWS modeling exercise is that by incorporating feedbacks and constraints among energy, economics, water, and land, the integrated assessment model comes to substantially different conclusions and policies than isolated resource optimization models, and so provides a more appropriate, holistic framework for managing multiple scarce resources.

6.4.3 Overview of Policy Insights

A number of broader policy insights emerge from this analysis. In terms of mitigating the water use impacts of providing energy, certain strategies may prove more effective for some supply chains, while completely different strategies are more appropriate for others. For instance, in the case of oil and natural gas production, legislative and technical means may be sought to source water of the 'lowest' potentially usable quality (e.g. wastewater, recycled, or degraded water). In the case of oil refineries and electricity generation, minimum regulatory standards or pricing may be designed to incentivize siting in regions with easy access to such low-grade water resources, or alternatively in regions where water scarcity or alternative water uses are not great concerns. Of course, such siting decisions must also be properly balanced against competing economic and operational considerations (e.g. transport accessibility and distance to markets/consumers). For yet other supply chains, such as biofuels feedstocks, the constraints imposed by water scarcity and societal and/or economic costs of water consumption may make certain technologies with lower water use efficiencies a better choice than technologies that would have been adopted otherwise. In this instance, 'sustainability certification' standards or other economic instruments that incentivize certain practices or operations with higher water use efficiency, or which restrict operations in a certain region to not exceed certain maximum scale thresholds, may prove most effective in keeping water use impacts in check.

Uncertainties and Other Caveats

The results of the analysis conducted here are necessarily limited in terms of precision and accuracy, and yet a number of assumptions were needed to reach them. The models used incorporate with the maximum sensible degree of technical detail and data resolution our understanding of the technological and economic causal mechanisms that drive energy supply chains. Using the output of these models, as well as assumptions based on expert knowledge as to potential future decisions and trends (e.g. siting cases for power plants, existing laws on cooling water technologies and water sourcing), it is possible to construct fairly detailed scenarios of future water use throughout the state. However, projections are necessarily reported with some degree of uncertainty – often the results are reported in terms of ranges of values and at a lower spatial resolution than desirable, e.g. for hydrologic modeling. Obviously, no one can predict with certainty where future facilities, such as refineries and power plants, will be built. Once built, the capacity at which they will operate is further beholden to complex economic and social forces that are, by their very nature, impossible to forecast with much certainty, particularly over many decades. Moreover, while continual development of existing technologies and invention of new and unforeseeable technologies are the dependable fruits of our legal and economic systems, it is impossible to project with any great certainty the rate at which technology may reduce or altogether obviate the need to withdraw, consume, or pollute water volumes to obtain and process oil, or to generate electricity.

Further, despite every effort to regionalize the analysis, further work remains to be done to investigate and thoroughly characterize the hydrologic and economic impacts of water management and energy generation portfolios at the resolution of individual and neighboring watersheds.

GLOSSARY

Term	Definition
AEO	Annual Energy Outlook
AF	Acre-feet
BEPAM	Biofuels Environmental Policy Analysis Model
bgge	Billion gallons of gasoline equivalent
CARB	California Air Resources Board
CARBOB	California Reformulated Gasoline Blendstock for Oxygenate Blending
CA-TIMES	California-TIMES, MARKAL economic model
CEC	California Energy Commission
CRD	Crop Reporting District
CSP	Concentrated Solar Power
DOGGR	California State EPA Division of Oil, Gas, and Geothermal Resources
EIR	Environmental impact report
EOR	Enhanced oil recovery
ETo	Reference evapotranspiration
FAO	United Nations Food and Agriculture Organization
FRIS	Farm and Ranch Irrigation Survey
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle analysis
LCFS	Low Carbon Fuel Standard
LEAP	Long-range Energy Alternatives Planning
LUC	Land use change
MMbbl	Million barrels
NASS	The USDA National Agricultural Statistics Service
OTC	Once-through cooling
PJ	Peta Joule is equal to one quadrillion (10^{15}) joules.
PV	Photovoltaic solar
RAW	Readily available water
R&D	Research and development
RPS	Renewable Portfolio Standard
M-RFS2	Renewable Fuel Standards Mandate (M – modified second version)

SWRCB	(California) State Water Resources Control Board
TDS	Total dissolved solids
WEAP	Water Evaluation and Planning (model)
WCI	Western Climate Initiative
WUI	Water use intensity
WWR	Water resource region
WWT	Wastewater treatment
USDA	U.S. Department of Agriculture
ULSD	Ultra low sulfur diesel
U.S. DOE	U.S. Department of Energy
U.S. EIA	U.S. Energy Information Administration
U.S. EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
ZLD	Zero liquid discharge

REFERENCES

AESRD (2014). Alberta Environment and Sustainable Resource Development Oil Sands Information Portal. A. E. S. R. Development.

Aldhous, P. (2012). "Drilling into the Unknown." New Scientist **213**(2849): 8-10.

Allen, R. G., L. S. Pereira, D. Raes and M. Smith (1998). "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56." FAO, Rome 300: 6541.

Alliance, C. S. (2008). "The Role of Recycled Water in Energy Efficiency and Greenhouse Gas Reduction."

AOGCC (2014). Production Data Archives Alaska Oil and Gas Conservation Commission, Department of Administration.

AP (2013). "Chesapeake Energy agrees to settle W.Va. case."

API (2000). Overview of Exploration and Production Waste Volumes and Waste Management Practices in the United States. prepared by ICF Consulting for the American Petroleum Institute.

ARB (2006). "Assembly Bill 32: Global Warming Solutions Act."

Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers and S. Tellinghuisen (2011). Freshwater use by U.S. power plants: Electricity's thirst for a precious resource - A report of the energy and Water in a Warming World initiative. Cambridge, MA, Union of Concerned Scientists.

Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers and S. Tellinghuisen (2011). Freshwater use by US power plants: Electricity's thirst for a precious resource, Union of Concerned Scientists Cambridge, MA.

Barbier, E. (2002). "Geothermal energy technology and current status: an overview." Renewable and Sustainable Energy Reviews **6**(1): 3-65.

Barnett, T., R. Malone, W. Pennell, D. Stammer, B. Semtner and W. Washington (2004). "The effects of climate change on water resources in the west: introduction and overview." Climatic Change **62**(1-3): 1-11.

Bartis, J. T., T. LaTourrette, L. Dixon, D. Peterson and G. Cecchine (2005). Oil shale development in the United States: Prospects and policy issues, Rand Corporation.

Bayart, J.-B., C. Bulle, L. Deschênes, M. Margni, S. Pfister, F. Vince and A. Koehler (2010). "A framework for assessing off-stream freshwater use in LCA." The International Journal of Life Cycle Assessment **15**(5): 439-453.

Benicia (2008). Valero Improvement Project: Addendum to VIP EIR. City of Benicia, City of Benicia.

Berger, M. and M. Finkbeiner (2010). "Water footprinting: How to address water use in life cycle assessment?" Sustainability **2**(4): 919-944.

Berger, M. and M. Finkbeiner (2012). "Methodological Challenges in Volumetric and Impact‐Oriented Water Footprints." Journal of Industrial Ecology.

Berndes, G. (2002). "Bioenergy and water--the implications of large-scale bioenergy production for water use and supply." Global Environmental Change **12**(4): 253-271.

Bibars, O. A. and H. H. Hanafy Waterflood Strategy - Challenges and Innovations, Society of Petroleum Engineers.

Bonnet, J.-F. and D. Lorne (2009). Water and Biofuels in 2030: Water Impacts of French Biofuel Development at the 2030 Time Horizon, N°19/2009. Les cahiers du CLIP, 2009. 98 p.

Boulay, A.-M., C. Bouchard, C. Bulle, L. Deschênes and M. Margni (2011). "Categorizing water for LCA inventory." The International Journal of Life Cycle Assessment **16**(7): 639-651.

Boulay, A.-M., C. c. Bulle, J.-B. Bayart, L. Deschênes and M. Margni (2011). "Regional characterization of freshwater use in LCA: modeling direct impacts on human health." Environmental science & technology **45**(20): 8948-8957.

Brandt, A. R. (2011). "Oil depletion and the energy efficiency of oil production: The case of California." Sustainability **3**(10): 1833-1854.

Buchan, M. and B. Arena (2006). Water and the refinery—an introduction to growing issues impacting refinery water use. American Institute of Chemical Engineers (AIChE) Chicago symposium, Oct.

CA-DWR (2009). California Water Plan - Update 2009. Sacramento, CA, CA Department of Water Resources

CA-DWR (2009). California Water Plan Update (Update 2009). Sacramento, CA, CA Department of Water Resources.

CA-SWRCB (1975). Water Quality Control Policy on the Use and Disposal of Inland Waters used for Powerplant Cooling. C. S. W. R. C. Board. Sacramento, CA. **Order No. 75-58**.

CAPP (2013). Statistical Handbook for Canada's Upstream Petroleum Industry.

CARB (2009). "AB 32 Climate Change Scoping Plan Document.".

CARB (2013). California's Greenhouse Gas Inventory by Sector & Activity. Sixth Edition: 2000 to 2011, California Air Resources Board.

CARB (2013). "Climate Change Scoping Plan, First Update, Discussion Draft for Public Review and Comment."

CARB (2014). Proposed First Update to the Climate Change Scoping Plan: Building on the Framework, California Air Resources Board.

CCEF (2011). One-Through Cooling Phase-out. Sacramento, CA, California Clean Energy Future: 5.

CEC (2009). "2009 Integrated Energy Policy Report."

CEC (2011). "2011 Integrated Energy Policy Report."

CEC (2012). 2012 Monthly Receipts of Crude Oil by Source. California Energy Commission.

CEC (2012). Water Factor 2010, California Energy Commission.

CEC (2012). Watson Cogeneration Steam and Electric Reliability Project, California Energy Commission.

CEC (2013). "2013 Integrated Energy Policy Report."

CEC (2013). Energy Facility Status: Power Plant Projects Since 1996. Sacramento, CA, California Energy Commission.

CERES (2014). "Hydraulic Fracturing & Water Stress: Water Demand by the Numbers; Shareholder, Lender & operator Guide to Water Sourcing."

Chapagain, A. K. and S. Orr (2009). "An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes." Journal of Environmental Management **90**: 1219-1228.

Chen, X. (2010). A dynamic analysis of US biofuels policy impact on land use, greenhouse gas emissions and social welfare, University of Illinois.

Chen, X., H. Huang and M. Khanna (2012). "Land-Use And Greenhouse Gas Implications Of Biofuels: Role Of Technology And Policy." Climate Change Economics **3**(03).

Chen, X., H. Huang, M. Khanna and H. Onal (2012). "Alternative transportation fuel standards: Welfare effects and climate benefits." Energy Biosciences Institute Working Paper). Urbana: University of Illinois at Urbana-Champaign. Available on the World Wide Web: http://papers.ssrn.com/sol3/papers.cfm.

Chen, X., H. Huang, M. Khanna and H. Önal (2014). "Alternative Transportation Fuel Standards: Economic Effects and Climate Benefits." Journal of Environmental Economics and Management.

Chen, X., H. Huang, M. Khanna and H. Önal (2014). "Alternative transportation fuel standards: Welfare effects and climate benefits." Journal of Environmental Economics and Management **67**(3): 241-257.

Chen, X. and M. Khanna (2012). "The market-mediated effects of low carbon fuel policies." AgBioForum.

Chen, X., M. Khanna, H. Huang and H. Önal (2012). "Meeting the Mandate for Biofuels: Implications for Land Use, Food, and Fuel Prices."

Chen, X. and H. Onal (2012). "An Economic Analysis of the Future US Biofuel Industry, Facility Location, and Supply Chain Network." Facility Location, and Supply Chain Network (June 14, 2012).

Chiu, Y.-W., B. Walseth and S. Suh (2009). "Water embodied in bioethanol in the United States." Environmental Science & Technology **43**(8): 2688-2692.

Clark, C., A. Burnham, C. Harto and R. Horner (2012). "Hydraulic Fracturing and Shale Gas Production: Technology, Impacts, and Policy." Argonne National Laboratory.

Clark, C. E., R. M. Horner and C. B. Harto (2013). "Life Cycle Water Consumption for Shale Gas and Conventional Natural Gas." Environmental science & technology **47**(20): 11829-11836.

Colborn, T., C. Kwiatkowski, K. Schultz and M. Bachran (2011). "Natural gas operations from a public health perspective." Human and Ecological Risk Assessment: An International Journal **17**(5): 1039-1056.

Congress, U. (2005). "Energy policy act of 2005." Public Law **109**(58): 42.

Congress, U. (2005). "Energy Policy Act of 2005." Public Law **109**: 58.

Congress, U. (2007). "Energy independence and security act of 2007." Public Law **2**.

Cooley, H., K. Donnelly, N. Ross and P. Luu (2012). "Hydraulic fracturing and water resources: Separating the frack from the fiction." Pacific Institute. June.

CRWQCB (2013). Updated Waste Discharge Requirements and Rescission of Order No. 94-070. California Regional Water Quality Control Board: San Francisco Bay Region.

Dal Ferro, B. and M. Smith (2007). "Global onshore and offshore water production." Exploration & production–oil & gas review: 34-36.

Davies, E. G., P. Kyle and J. A. Edmonds (2012). "An integrated assessment of global and regional water demands for electricity generation to 2095." Advances in Water Resources.

DeMeo, E. A. and J. F. Galdo (1997). Renewable Energy Technology Characterizations. Washington, D.C. and Palo Alto, CA, Electric Power Research Institute (EPRI) and U.S. Department of Energy.

Department of Conservation (2013). 2012 Preliminary Report of California Oil and Gas Production Statistics Natural Resources Agency, State of California.

Development, A. E. S. R. (2014). Alberta Environment and Sustainable Resource Development Oil Sands Information Portal. A. E. S. R. Development.

DiPippo, R. (2004). "Second law assessment of binary plants generating power from low-temperature geothermal fluids." Geothermics **33**(5): 565-586.

DiPippo, R. (2008). Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impacts, Butterworth-Heinemann.

DiPippo, R. (2009). Inyo County Coso/Hay Ranch DEIR Comments**:** 9.

DOE (2009). Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation (Report to Congress). Washington, DC, U.S. Department of Energy.

DOE, U. (2006). "Energy demands on water resources: Report to Congress on the interdependency of energy and water." Washington, DC: US Department of Energy.

DOGGR (2013). "Hydraulic Fracturing in California.".

DOGGR (2013a). Monthly Injection Database. California Department of Oil Gas and Geothermal Resources (DOGGR), California Department of Oil Gas and Geothermal Resources (DOGGR).

DOGGR (2013b). Montly Production Database. California Department of Oil Gas and Geothermal Resources, California Department of Oil Gas and Geothermal Resources.

Dominguez-Faus, R., S. E. Powers, J. G. Burken and P. J. Alvarez (2009). "The water footprint of biofuels: A drink or drive issue?" Environmental Science & Technology **43**(9): 3005-3010.

Dominski, M. (2007). Surface mined oil sand: tailings practices, performance, and projections. Alberta Energy and Utilities Board. Proceedings of the 3rd International Heavy Oil Conference.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund and R. E. Howitt (2003). "Economic-engineering optimization for California water management." Journal of water resources planning and management **129**(3): 155-164.

Duchane, D. V. (1996). Progress in making hot dry rock geothermal energy a viable renewable energy resource for America in the 21st century. Energy Conversion Engineering Conference, 1996. IECEC 96., Proceedings of the 31st Intersociety, IEEE.

EBMUD (2007). Rodeo Recycled Water Project. Bay Area Integrated Water Management Plan East Bay Municiple Utilities District.

Eckert, W. F., J. H. Masliyah, M. R. Gray and P. M. Fedorak (1996). "Prediction of sedimentation and consolidation of fine tails." AIChE journal **42**(4): 960-972.

Ecoinvent (2013). Ecoinvent Database, Ecoinvent.

Ehrenberg, R. (2012). "The facts behind the frack: Scientists weigh in on the hydraulic fracturing debate." Science News **182**(5): 20-25.

EIA (2012a). "Annual Energy Outlook."

EIA (2012b). "State Energy Data System (SEDS)."

EIA (2013). "Annual Energy Outlook."

EIA (2013a). Crude Oil Proved Reserves, Reserves Changes, and Production, Energy Information Administration.

EIA (2013b). Petroleum Supply Annual and Petroleum Supply Monthly reports, Energy Information Administration.

EIA (2013c). Annual Energy Outlook 2013, EIA

EIA (2013d). "Weekly Petroleum Report, January 8, 2013."

EIA (2013e). "Number and Capacity of Petroleum Refineries."

EIA (2014). Crude Oil Production. U. S. E. I. Administration.

EIA, A. (2013). Early Release Overview, Release Date: December 5, 2012, Report Number: DOE/EIA-0383ER (2013).

EIA, U. (2011). "Annual energy outlook 2011 with projections to 2035." Washington DC: Energy Information Administration, United States Department of Energy.

El-Houjeiri, H. M., A. R. Brandt and J. E. Duffy (2013). "Open-source LCA tool for estimating greenhouse gas emissions from crude oil production using field characteristics." Environmental science & technology **47**(11): 5998-6006.

Ellsworth, W. L. (2013). "Injection-induced earthquakes." Science **341**(6142).

EPA (2008). "Clean Water Act."

EPA (2010). Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, US Environmental Protection Agency Washington, DC.

EPA (2010). "Safe Drinking Water Act." Atomic Energy Act, Occupational Safety and Health Act, Toxic Substance Control Act, Clean.

EPA (2011). "Draft Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water."

EPA (2012). "Underground Injection Control (UIC) program."

ERCB (2013). "Alberta's Energy Reserves 2012 and Supply/Demand Outlook 2013-2022."

Fakhru'l-Razi, A., A. Pendashteh, L. C. Abdullah, D. R. A. Biak, S. S. Madaeni and Z. Z. Abidin (2009). "Review of technologies for oil and gas produced water treatment." Journal of Hazardous Materials **170**(2): 530-551.

Fan, Y., H. Li and G. Miguez-Macho (2013). "Global patterns of groundwater table depth." Science **339**(6122): 940-943.

Fingerman, K., M. Torn, M. O'Hare and D. Kammen (2010). "Accounting for the water impacts of ethanol production." Environmental Research Letters **5**(1): 014020.

Fischer, G., F. Nachtergaele, S. Prieler, E. Teixeira, G. Tóth, H. van Velthuizen, L. Verelst and D. Wiberg (2012). "Global Agro-Ecological Zones (GAEZ v3. 0)–Model Documentation." International Institute for Applied systems Analysis (IIASA), Laxenburg. Rome, Italy: Austria and the Food and Agriculture Organization of the United Nations (FAO).

GAO (2011). Impacts of Potential Oil Shale Development on Water Resources. G. A. Office.

Gerbens-Leenes, P., A. Hoekstra and T. Van der Meer (2009). "The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply." Ecological economics **68**(4): 1052-1060.

Gerbens-Leenes, P. W., A. Y. Hoekstra and T. H. van der Meer (2008). "The water footprint of bioenergy." Proceedings of National Academy of Science **106**(25): 10219-10223.

Gheewala, S. H., G. Berndes and G. Jewitt (2011). "The bioenergy and water nexus." Biofuels, Bioproducts and Biorefining **5**(4): 353-360.

Gleeson, T. and Y. Wada (2013). "Assessing regional groundwater stress for nations using multiple data sources with the groundwater footprint." Environmental Research Letters **8**(4): 044010.

Gleick, P. H. (1994). "Water and Energy." Annual Review of Energy and the Environment **19**(1): 267-299.

GOA (2014). "Oil Sands Information Portal." Government of Alberta.

Goodwin, S., K. Carlson, C. Douglas and K. Knox (2012). "Life cycle analysis of water use and intensity of oil and gas recovery in Wattenberg field, Colo." Oil & Gas Journal.

Goodwin, S., K. H. Carlson, K. Knox, C. Douglas and L. Rein (2014). "Water Intensity Assessment of Shale Gas Resources in the Wattenberg Field in Northeastern Colorado." Environmental science & technology.

Greenblatt, J. (2013). Estimating Policy-Driven Greenhouse Gas Emissions Trajectories in California: The California Greenhouse Gas Inventory Spreadsheet (GHGIS) Mode, Lawrence Berkeley National Laboratory.

GREET (2010). Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Argonne, IL, Argonne National Laboratory.

Gregorio, D., S. Saiz, M. Gjerde, P. Isorena, A. Laputz, F. Roddy and S. Vassey (2008). Scoping Document: Water Quality Control Policy on the Use of Coastal and Estuarine Waters For Power Plant Cooling. Sacramento, CA, State Water Resources Control Board; California Environmental Protection Agency.

Gregory, K. B., R. D. Vidic and D. A. Dzombak (2011). "Water management challenges associated with the production of shale gas by hydraulic fracturing." Elements **7**(3): 181-186.

Griffiths, M., A. Taylor and D. Woynillowicz (2006). "Troubled Waters, Troubling Trends." Technology Options to Reduce Water Use in Oil and Oil Sands Development in Alberta.

Grubert, E. A., F. C. Beach and M. E. Webber (2012). "Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal-and natural gas-fired electricity." Environmental Research Letters **7**(4): 045801.

Guinee, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall and T. Rydberg (2010). "Life Cycle Assessment: Past, Present, and Future†." Environmental science & technology **45**(1): 90-96.

Guo, J. J., J. Y. Wu and R. Z. Wang (2011). "A new approach to energy consumption prediction of domestic heat pump water heater based on grey system theory." Energy and Buildings **43**(6): 1273-1279.

GWPC (2013). "Hydraulic Fracturing Water Usage." Groundwater Protection Council & Interstate Oil and Gas Compact Commission.

GWPC and IOGCC (2014). FracFocus Chemical Disclosure Registry, Ground Water Protection Council,

Interstate Oil and Gas Compact Commission.

Han, W., Z. Yang, L. Di and R. Mueller (2012). "CropScape: A Web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support." Computers and Electronics in Agriculture **84**: 111-123.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle and B. Thompson (2011). Managing California's Water: From Conflict to Reconciliation San Francisco, CA, Public Policy Institute of California.

Hanson, B. (2008). "Irrigation of Agricultural Crops in California." Presentation to the ARB sustainability working group.

Harto, C., R. Meyers and E. Williams (2010). "Life cycle water use of low-carbon transport fuels." Energy Policy **38**(9): 4933-4944.

Hedman, B., D. Ken, E. Wong and A. Hampson (2012). Combined Heat and Power: 2011 ‐ 2030 Market Assessment, ICF International Inc. for California Energy Commission.

Heidrick, T. and M. Godin (2006). Oil sands research and development, Alberta Energy, Oil Sands Development.

Hejazi, M., J. Edmonds and V. Chaturvedi (2012). "Global Irrigation Demand–A Holistic Approach." Irrigat Drainage Sys Eng **1**: e106.

Hejazi, M., J. Edmonds, V. Chaturvedi, E. Davies and J. Eom (2013). "Scenarios of global municipal water-use demand projections over the 21st century." Hydrological Sciences Journal(ahead-of-print): 1-20.

Hermann, S., M. Welsch, R. E. Segerstrom, M. I. Howells, C. Young, T. Alfstad, H. H. Rogner and P. Steduto (2012). Climate, land, energy and water (CLEW) interlinkages in Burkina Faso: An analysis of agricultural intensification and bioenergy production. Natural Resources Forum, Wiley Online Library.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya and M. M. Mekonnen (2009). "Water footprint manual: State of the art 2009."

Hoekstra, A. Y. and P. Hung (2002). "Virtual water trade." A quantification of virtual water flows between nations in relation to international crop trade. Value of water research report series(11): 166.

Höök, M. (2009). Depletion and decline curve analysis in crude oil production, Uppsala University.

Hopkins, K. (2013). ". California's Energy Future: An Overview." The Monterey Shale & California's Economic Future: 7.

Huang, H., M. Khanna and X. Yang (2011). Cost of Maintaining CRP in Presence of Biofuels. 2011 Annual Meeting, July 24-26, 2011, Pittsburgh, Pennsylvania, Agricultural and Applied Economics Association.

Hughes, J. D. (2013). "Energy: A reality check on the shale revolution." Nature **494**(7437): 307-308.

IPCC (2007). Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, Cambridge University Press.

Isaacs, E. (2007). "The Canadian Oil Sands in the Context of the Global Energy Demand, 17th Convocation of the International Council of Academies of Engineering and Technological Sciences." Tokyo, Japan.

Iwanaga, T., S. El Sawah and A. Jakeman (2013). "Design and implementation of a Web-based groundwater data management system." Mathematics and Computers in Simulation **93**: 164-174.

IWMI (2007). Comprehensive Assessment of Water Management in Agriculture. London, Earthscan.

Jaffe, A. (2014). "personal communication with Kate Tiedeman."

Jain, A. K., M. Khanna, M. Erickson and H. Huang (2010). "An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States." GCB Bioenergy **2**(5): 217-234.

Jewitt, G. and R. Kunz (2011). "The impact of biofuel feedstock production on water resources: a developing country perspective." Biofuels, Bioproducts and Biorefining **5**(4): 387-398.

Jin, S. and G. Feng (2013). "Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002–2012." Global and Planetary Change **106**: 20-30.

Johnson, B., Z. Zhang, M. Velleux and P. Julien (2011). "Development of a Distributed Watershed Contaminant Transport, Transformation, and Fate (CTT&F) Sub-model." Soil and Sediment Contamination: An International Journal **20**(6): 702-721.

Jolliet, O., M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer and R. Rosenbaum (2003). "IMPACT 2002+: A new life cycle impact assessment methodology." The International Journal of Life Cycle Assessment **8**(6): 324-330.

Jordaan, S. M. (2012). "Land and Water Impacts of Oil Sands Production in Alberta." Environ Sci Technol **46**(7): 3611-3617.

Kaffka, S. R. and M. W. Jenner. 2010. Biofuels and Biodiversity in California: Scenarios of Biofuel Production**.** California Energy Commission. Publication number: CEC-500-2013-048. http://www.energy.ca.gov/2013publications/CEC-500-2013-048/CEC-500-2013-048.pdf

Kaffka, S., R. Williams, J. Zhang and M. Jenner (2011). "Prospects for Agricultural Feedstocks for Biofuels in California." Presentation Sept. 22, 2011. http://www.energy.ca.gov/2010-ALT-1/documents/2011-09-22_forum/presentations/Mark_Jenner_Biomass_Collaborative.pdf.

Kanoğlu, M. and Y. A. Çengel (1999). "Economic evaluation of geothermal power generation, heating, and cooling." Energy **24**(6): 501-509.

Kaufman, A. S., P. J. Meier, J. C. Sinistore and D. J. Reinemann (2010). "Applying life-cycle assessment to low carbon fuel standards—How allocation choices influence carbon intensity for renewable transportation fuels." Energy Policy **38**(9): 5229-5241.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace and M. A. Maupin (2009). Estimated use of water in the United States in 2005, US Geological Survey Reston, VA.

Khanna, M., X. Chen, H. Huang and H. Önal (2011). "Supply of cellulosic biofuel feedstocks and regional production pattern." American Journal of Agricultural Economics **93**(2): 473-480.

Khanna, M. and D. Zilberman (2012). "Modeling The Land-Use And Greenhouse-Gas Implications Of Biofuels." Climate Change Economics **3**(03).

Khatib, Z. and P. Verbeek (2002). Water to value-produced water management for sustainable field development of mature and green fields. SPE International Conference on Health Safety and Environment in Oil and Gas Exploration and Production, Society of Petroleum Engineers.

Kim, Y. J., K. W. Hipel and C. W. Bowman (2013). "Water security problems in Canada's oil sands." Canadian Water Resources Journal **38**(1): 61-72.

King, C. W. and M. E. Webber (2008). "The water intensity of the plugged-in automotive economy." Environmental Science & Technology **42**(12): 4305-4311.

King, C. W. and M. E. Webber (2008). "Water intensity of transportation." Environmental Science & Technology **42**(21): 7866-7872.

Kiparsky, M. and J. F. Hein (2013). "Regulation of Hydraulic Fracturing in California." Regulation.

Kounina, A., M. Margni, J.-B. Bayart, A.-M. Boulay, M. Berger, C. Bulle, R. Frischknecht, A. Koehler, L. M. i Canals and M. Motoshita (2012). "Review of methods addressing freshwater use in life cycle inventory and impact assessment." The International Journal of Life Cycle Assessment: 1-15.

Kyle, P., E. G. Davies, J. J. Dooley, S. J. Smith, L. E. Clarke, J. A. Edmonds and M. Hejazi (2013). "Influence of climate change mitigation technology on global demands of water for electricity generation." International Journal of Greenhouse Gas Control **13**: 112-123.

Laurenzi, I. J. and G. R. Jersey (2013). "Life Cycle Greenhouse Gas Emissions and Freshwater Consumption of Marcellus Shale Gas." Environmental science & technology **47**(9): 4896-4903.

Lazarus, M., C. Heaps and P. Raskin (1997). "LEAP Long-range energy alternatives planning system." Stockholm Environmental Institute, Boston, Massachusetts.

Lemoine, D. M., R. J. Plevin, A. S. Cohn, A. D. Jones, A. R. Brandt, S. E. Vergara and D. M. Kammen (2010). "The climate impacts of bioenergy systems depend on market and regulatory policy contexts." Environmental science & technology **44**(19): 7347-7350.

MacKinnon, M. and A. Sethi (1993). A comparison of the physical and chemical properties of the tailings ponds at the Syncrude and Suncor oil sands plants. Proceedings of Our Petroleum Future Conference, Alberta Oil Sands Technology and Research Authority (AOSTRA), Edmonton, Alta.

Macknick, J., R. Newmark, G. Heath and K. Hallett (2011). "A review of operational water consumption and withdrawal factors for electricity generating technologies." Contract **303**: 275-3000.

Macknick, J., R. Newmark, G. Heath and K. Hallett (2012). "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature." Environmental Research Letters **7**(4): 045802.

Macknick, J., S. Sattler, K. Averyt, S. Clemmer and J. Rogers (2012). "The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050." Environmental Research Letters **7**(4): 045803.

Madden, N., A. Lewis and M. Davis (2013). "Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature." Environmental Research Letters **8**(3): 035006.

Matek, B. (2013). 2013 Annual US Geothermal Power Production and Development Report. Washington, D.C. , Geothermal Energy Association.

Maugeri, L. (2013). "The shale oil boom: a US phenomenon." Harvard Kennedy School.

Maulbetsch, J. S. and M. N. DiFilippo (2006). "Cost and value of water use at combined cycle power plants." Rep. CEC-500-2006-034 Prepared for the California Energy Commission Public Interest Energy Research (PIER) Program, Maulbetsch Consulting, Menlo Park, CA.

Maulbetsch, J. S. and M. N. DiFilippo (2006). Cost and Value of Water Use at Combined-Cycle Power Plants. PIER Energy-Related Environmental Research. Sacramento, California, California Energy Commission.

McCollum, D., C. Yang, S. Yeh and J. Ogden (2012). "Deep greenhouse gas reduction scenarios for California - Strategic implications from the CA-TIMES energy-economic systems model." Energy Strategy Reviews **1**(1): 19-32.

McDonald, R. I., P. Green, D. Balk, B. M. Fekete, C. Revenga, M. Todd and M. Montgomery (2011). "Urban growth, climate change, and freshwater availability." Proceedings of the National Academy of Sciences **108**(15): 6312-6317.

McKone, T. and K. Enoch (2002). CalTOX (registered trademark), A multimedia total exposure model spreadsheet user's guide. Version 4.0 (Beta), Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Medellín-Azuara, J., J. J. Harou, M. A. Olivares, K. Madani, J. R. Lund, R. E. Howitt, S. K. Tanaka, M. W. Jenkins and T. Zhu (2008). "Adaptability and adaptations of California’s water supply system to dry climate warming." Climatic Change **87**(1): 75-90.

Meldrum, J., S. Nettles-Anderson, G. Heath and J. Macknick (2013). "Life cycle water use for electricity generation: A review and harmonization of literature estimates." Environmental Research Letters **8**(1): 015031.

Michaelides, E. and J. Ryder (1992). "The influence of seasonal and daily temperature fluctuations on the work produced by geothermal power plants." International journal of energy systems **12**(2): 68-72.

Mielke, E., L. D. Anadon and V. Narayanamurti (2010). "Water consumption of energy resource extraction, processing, and conversion." Cambridge, MA: Belfer Center for Science and International Affairs, Harvard Kennedy School.

Mishra, G. and S. Yeh (2010). Analysis of Lifecycle Water Requirements of Transportation Fuels: Corn-based Ethanol Model Description. Research Report UCD-ITS-RR-10-12. Davis, CA, Institute of Transportation Studies, University of California, Davis.

Mishra, G. S., W. E. Glassley and S. Yeh (2010). Analysis of Lifecycle Water Requirements of Energy & Transportation Fuels: Electricity from Geothermal Resources - Model Description. Davis, CA, University of California Davis.

Mishra, G. S., W. E. Glassley and S. Yeh (2011). "Realizing the geothermal electricity potential—water use and consequences." Environmental Research Letters **6**(3): 034023.

Mishra, G. S. and S. Yeh (2011). "Life cycle water consumption and withdrawal requirements of ethanol from corn grain and residues." Environmental science & technology **45**(10): 4563-4569.

Mishra, G. S. and S. Yeh (2011). "Life cycle water consumption and withdrawal requirements of ethanol from corn grain and residues." Environ Sci Technol **45**(10): 4563-4569.

Morrison, G., A. Eggert, S. Yeh, R. Isaac and C. Zapata (2014). "Summary of California Climate Policy Modeling Forum." Institute of Transportation Studies, University of California, Davis.

Morrison, G., A. Eggert, S. Yeh, R. Isaac and C. B. Zapata (2014). Summary of California Climate Policy Modeling Forum, Institute of Transportation Studies, University of California, Davis.

Mu, Q., M. Zhao and S. W. Running (2011). "Improvements to a MODIS global terrestrial evapotranspiration algorithm." Remote Sensing of Environment **115**(8): 1781-1800.

Muggeridge, A., A. Cockin, K. Webb, H. Frampton, I. Collins, T. Moulds and P. Salino (2014). "Recovery rates, enhanced oil recovery and technological limits." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **372**(2006): 20120320.

Murphy, H. D., R. Drake, J. Tester and G. Zyvoloski (1984). Economics of a conceptual 75 MW Hot Dry Rock geothermal electric power station, Los Alamos National Lab., NM (USA); Massachusetts Inst. of Tech., Cambridge (USA).

Murray, K. E. (2013). "State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, USA." Environmental science & technology.

NASS, U. (2007). "Census of agriculture." US Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

NASS, U. (2008). "Farm and ranch irrigation survey." US Department of Agriculture, National Agricultural Statistics Service.

NASS, U. (2010). "Field Crops: Usual Planting and Harvesting Dates." **Agricultural Handbook Number 628**.

NCAR (accessed 9.14.2013). Dataset number 512.0. Research Data Archive (RDA).

NEB (2011). Canada's Energy Future: Energy Supply and Demand Projections to 2035, National Energy Board.

NEB (2013). "Canada's Energy Future: Energy Supply and Demand Projections to 2035.".

Newell, R. G. and D. Raimi (2014). "Implications of shale gas development for climate change." Environmental science & technology.

Nicot, J.-P. and B. R. Scanlon (2012). "Water use for shale-gas production in Texas, US." Environmental science & technology **46**(6): 3580-3586.

Nicot, J.-P., B. R. Scanlon, R. C. Reedy and R. A. Costley (2014). "Source and Fate of Hydraulic Fracturing Water in the Barnett Shale: A Historical Perspective." Environmental Science & Technology.

Norwood, Z. and D. Kammen (2012). "Life cycle analysis of distributed concentrating solar combined heat and power: economics, global warming potential and water." Environmental Research Letters **7**(4): 044016.

NOSA. (2012). "Fact Sheet - Oil Shale and Water." from http://www.oilshaleassoc.org/documents/Fact-Sheet-Water-2012.pdf.

O'Hagan, J. and N. Monsen (1999). Delta Energy Center: Final Staff Assessment (Part 2 -Soil & Water Resources). Sacramento, CA, California Energy Commission.

O&GJ (2012a). 2012 worldwide EOR survey, Oil and Gas Journal**:** GENERAL INTEREST; SPECIAL REPORT; Pg. 57.

Olmstead, S. M., L. A. Muehlenbachs, J.-S. Shih, Z. Chu and A. J. Krupnick (2013). "Shale gas development impacts on surface water quality in Pennsylvania." Proceedings of the National Academy of Sciences.

Onishi, N. (2013). Fracking Tests Ties Between California 'Oil and Ag' Interests. New York TImes.

Outlook, A. E. (2010). "Energy Information Administration." United States.

Pavley, F. (2005). "AB 1007 (Pavley)." Assembly Bill 2005.

Pavley, F. (2013). "Senate Bill 4 -- Chapter 313."

PE_International (2013). GaBi Software Version 3.

Peachey, B. and P. Eng (2005). "Strategic Needs for Energy Related Water Use Technologies: Water and the EnergyINet." New Paradigm Engineering: 34-36.

Pembina. (2014). "Oilsands 101: Water Impacts." from http://www.pembina.org/oil-sands/os101/water.

Pepino, C. J. (2014). "Water Resources Needed to Hydraulically Fracture California's Monterey Shale for Oil."

Pfister, S., P. Bayer, A. Koehler and S. Hellweg (2011). "Environmental impacts of water use in global crop production: hotspots and trade-offs with land use." Environmental science & technology **45**(13): 5761-5768.

Pfister, S., A. Koehler and S. Hellweg (2009). "Assessing the environmental impacts of freshwater consumption in LCA." Environmental science & technology **43**(11): 4098-4104.

Pfister, S., A. Koehler and S. Hellweg (2009). "Assessing the Environmental Impacts of Freshwater Consumption in LCA." Environmental Science & Technology.

Pfister, S. and B. G. Ridoutt (2013). "Water Footprint: Pitfalls on Common Ground." Environmental science & technology.

Plevin, R. J., M. A. Delucchi and F. Creutzig (2013). "Using Attributional Life Cycle Assessment to Estimate Climate‐Change Mitigation Benefits Misleads Policy Makers." Journal of Industrial Ecology.

Reig, P., T. Shiao and F. Gassert (2013). "Aquedcut Water Risk Framework." World Resources Institute.

Ridoutt, B. G. and S. Pfister (2010). "A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity." Global Environmental Change **20**(1): 113-120.

Ridoutt, B. G. and S. Pfister (2010). "A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity." Global Environmental Change **20**: 113-120.

Rosenbaum, R. K., T. M. Bachmann, L. S. Gold, M. A. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H. F. Larsen, M. MacLeod and M. Margni (2008). "USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment." The International Journal of Life Cycle Assessment **13**(7): 532-546.

Royce, B., E. Kaplan, M. Garrell and T. M. Geffen (1984). "Enhanced oil recovery water requirements." Minerals and the Environment **6**(2): 44-53.

Sanyal, S. K. and S. L. Enedy (2011). Fifty Years of Power Generation at the Geysers Geothermal Field, California - The Lessons Learned. Thirty-Sixth Workshop on Geothermal Reservoir Engineering. Stanford, California.

Sawatsky, L. (2004). "Improved Stewardship of Water Resources that are Entrusted to Oil Sands Mine." (Golder Associates).

Schaible, G. (2013). "USDA Economic Research Service-Documentation."

Schreiber, R. P. (2013). The National Ground Water Monitoring Network Data Portal: From Pilot to Production. 2013 NGWA Summit—The National and International Conference on Groundwater, Ngwa.

Scown, C. D., A. Horvath and T. E. McKone (2011). "Water Footprint of U.S. Transportation Fuels." Environmental Science & Technology **45**(7): 2541-2553.

Scown, C. D., A. Horvath and T. E. McKone (2011). "Water Footprint of U.S. Transportation Fuels." Environ Sci Technol **45**(7): 2541-2553.

Scown, C. D., A. Horvath and T. E. McKone (2011). "Water footprint of US transportation fuels." Environmental science & technology **45**(7): 2541-2553.

Shaffer, D. L., L. H. Arias Chavez, M. Ben-Sasson, S. Romero-Vargas Castrillón, N. Y. Yip and M. Elimelech (2013). "Desalination and reuse of high-salinity shale gas produced water: drivers, technologies, and future directions." Environmental science & technology **47**(17): 9569-9583.

Shariq, L. (2013). "Uncertainties associated with the reuse of treated hydraulic fracturing wastewater for crop irrigation." Environmental science & technology **47**(6): 2435-2436.

Sheridan, M. (2006). "California Crude Oil Production and Imports." Sacramento: California Energy Commission.

Suh, K., S. Suh and T. Smith (2011). "Implications of corn prices on water footprints of bioethanol." Bioresource technology **102**(7): 4747-4754.

SWRCB (2006). Adoption of Policy Entitled "Source of Drinking Water.". C. S. W. R. C. Board. Sacramento, CA. **Resolution No. 88-63 (as revised by Resolution No. 2006-0008).**

SWRCB (2008). Scoping Document: Water Quality Control Policy on the Use of Coastal and Estuarine Waters For Power Plant Cooling. Sacramento, CA, State Water Resources Control Board, California Environmental Protection Agency.

SWRCB (2013). "Porter-Cologne Water Quality Control Act ".

Tanaka, S., T. Zhu, J. Lund, R. Howitt, M. Jenkins, M. Pulido, M. Tauber, R. Ritzema and I. Ferreira (2006). "Climate Warming and Water Management Adaptation for California." Climatic Change **76**(3-4): 361-387.

Tao, Y., S. Zhang, Y.-g. Zhu and P. Christie (2009). "Uptake and acropetal translocation of polycyclic aromatic hydrocarbons by wheat (Triticum aestivum L.) grown in field-contaminated soil." Environmental science & technology **43**(10): 3556-3560.

Tester, J. W., B. Anderson, A. Batchelor, D. Blackwell, R. DiPippo, E. Drake, J. Garnish, B. Livesay, M. Moore and K. Nichols (2006). "The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century." Massachusetts Institute of Technology.

Thoma, E. (2009). Measurement of Emissions from Produced Water Ponds: Upstream Oil and Gas Study #1, Environmental Protection Agency.

Thornton, P., T. MM, B. Mayer, N. Wilhelmi, Y. Wei and R. Cook (2012). "Daymet: Daily surface weather on a 1 km grid for North America,1980 - 2012. Acquired." **Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.**

Tiemann, M. and A. Vann (2013). "Hydaulic Fracturing and Safe Drinking Water Act Regulatory Issues." Congressional Research Service(R41760).

Turchi, C. S., M. J. Wagner and C. F. Kutscher (2010). Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses, National Renewable Energy Laboratory**:** 108.

U.S. EIA (2011). Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays, U.S. Energy Information Administration, U.S. Department of Energy.

UNEP (2011). The Bioenergy and Water Nexus. Paris, United Nationa Environment Programme.

USDA (accessed 6/9/2012). "U.S. General Soil Map (STATSGO2)."

USGS (2005). "USGS Water Use Data for USA."

van der Elst, N. J., H. M. Savage, K. M. Keranen and G. A. Abers (2013). "Enhanced remote earthquake triggering at fluid-injection sites in the midwestern United States." Science **341**(6142): 164-167.

Vicuna, S. and J. Dracup (2007). "The evolution of climate change impact studies on hydrology and water resources in California." Climatic Change **82**(3-4): 327-350.

Vidaver, D., M. Ringer, M. Nyberg, D. Metz and C. Leni (2009). The Role of Aging and Once-Through-Cooled Power Plants in California—An Update. Sacramento, CA, California Energy Commission.

Wang, M. (2009). "GREET 1.8 c." Argonne National Laboratory.

WaterReuse_California (2012). "Benefits of AB 2398 (Hueso)."

WBCSD (2013). Global Water Tool, World Business Council for Sustainable Development.

Webber, M. E. (2007). "The water intensity of the transitional hydrogen economy." Environmental Research Letters **2**(3): 034007.

Wei, M., J. H. Nelson, M. Ting and C. Yang (2012). California’s Carbon Challenge: Scenarios for Achieving 80% Emissions Reduction in 2050, Lawrence Berkeley National Laboratory.

WEO, I. (2012). "World Energy Outlook 2012." International Energy Agency. Paris.

Williams, C., M. Reed, R. Mariner, J. DeAngelo and S. Galanis Jr (2008). "Assessment of moderate-and high-temperature geothermal resources of the United States." US Geological Survey fact sheet **3082**(4).

Williams, C. F., M. J. Reed and R. H. Mariner (2008). "A review of methods applied by the US Geological Survey in the assessment of identified geothermal resources." US Geological Survey Open-File Report **1296**: 27.

Wu, M., M. Mintz, M. Wang and S. Arora (2009). "Water consumption in the production of ethanol and petroleum gasoline." Environmental Management **44**(5): 981-997.

Wu, M., M. Mintz, M. Wang and S. Arora (2009). "Water consumption in the production of ethanol and petroleum gasoline." Environ Management **44**(5): 981-997.

Yang, C., S. Yeh and e. al. (2014). "Modeling Optimal Transition Pathways to a Low Carbon Economy in California: California TIMES (CA-TIMES) Model." A Final Report Submitted to the California Air Resources Board, Institute of Transportation Studies, University of California, Davis.

Yates, D. and K. A. Miller (2013). "Integrated decision support for energy/water planning in California and the Southwest." The International Journal of Climate Change: Impacts and Responses **4**(1): 49-63.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee (2005). "WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1: Model Characteristics." Water International **30**(4): 487-500.

Yeh, S., G. Berndes, G. S. Mishra, S. P. Wani, A. Elia Neto, S. Suh, L. Karlberg, J. Heinke and K. K. Garg (2011). "Evaluation of water use for bioenergy at different scales." Biofuels, Bioproducts and Biorefining **5**(4): 361-374.

APPENDICES

Appendix A: Water Use LCA – Methodological Debates & Frontiers

Appendix B: Further Details on Water Use of Hydraulic Fracturing

Appendix C: Oil Production in California

Appendix D: Biofuels – Scenarios, Data Sources, and Assumptions

Appendix E: Estimating the Water Use of Electricity Generation in California

Appendix F: Water Use Impacts of Exploiting Oil Shale (Kerogen)

Appendix G: Water Use Impacts of Developing the Monterey Shale

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