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Nationwide Water Availability Data for Energy-Water Modeling

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Abstract

The purpose of this effort is to explore where the availability of water could be a limiting factor in the siting of new electric power generation. To support this analysis, water availability is mapped at the county level for the conterminous United States (3109 counties). Five water sources are individually considered, including unappropriated surface water, unappropriated groundwater, appropriated water (western U.S. only), municipal wastewater and brackish groundwater. Also mapped is projected growth in non-thermoelectric consumptive water demand to 2035. Finally, the water availability metrics are accompanied by estimated costs associated with utilizing that particular supply of water. Ultimately these data sets are being developed for use in the National Renewable Energy Laboratories' (NREL) Regional Energy Deployment System (ReEDS) model, designed to investigate the likely deployment of new energy installations in the U.S., subject to a number of constraints, particularly water.

Contents

1.0 Introduction

There is a growing concern over the tight coupling between energy and water (e.g., DOE 2007). Specifically, significant water is used in the extraction, processing, and production of energy, while significant energy is required to extract, convey, treat, and store water. This energy-water nexus raises questions as to whether there is sufficient available water to meet future energy needs. Also of concern is the extent to which limited water availability will increase the demand for energy for desalination, wastewater reuse, and operation of water conserving technologies.

The most significant factor in the energy-water nexus is the use of water in thermoelectric power generation. In fact, thermoelectric power represents the largest water withdrawal in the United States, accounting for 41% of all fresh water withdrawals (Kenney et al., 2009). When seawater is considered, withdrawals increase to 48% of all water use in the U.S. Water consumption (that water that is withdrawn from a water body and never returned) follows a very different trend, accounting only for 3-4% of nationwide consumption (e.g., Tidwell et al. 2012). Agriculture accounts for the majority of consumptive water use, at a rate of about 81% of all consumption (Solley et al. 1995).

This water use is not uniformly distributed across the nation, rather varies strongly by location. For example, most agricultural irrigation occurs in the Western U.S. while thermoelectric consumption accounts for less than 1% of total consumption. Alternatively, irrigation is very limited in the East, while thermoelectric water consumption can account for over 25% of local consumption (Kenney et al., 2009). This variability in water use extends all the way down to the individual power plant. Water use, both withdrawal and consumption, are significantly influenced by such factors as the size of the plant, the type of cooling system, the fuel type, emissions controls and other factors (Macknick et al., 2012).

With growing demand for electricity comes the increased demand for water; however, how much water is a question of particular interest. A variety of estimates have been made over the years. In most cases water withdrawals are projected to only increase slightly (~1-2%) or decrease, largely due to the move away from open-loop cooling (NETL 2008; Feeley et al. 2008, Tidwell et al., 2012; Tidwell et al., 2013). Alternatively, consumptive use estimates have been projected to range from an increase of 35% to a minimal increase. This range in variation stems from differences in assumptions concerning the future fuel mix, required new capacity, and future emission controls. It is not just a matter of how much total water is likely to be required, but more importantly where the new power plants are likely to be located (Roy et al., 2012; Sovacool, 2009). In fact issues concerning the siting of new power plants and the availability of water have already been realized; specifically, construction of concentrating solar thermal power plant in Kingman, AZ was greatly delayed over water source issues (Adams-Ockrassa 2011); the State of California has established policies that prohibit the use of freshwater for any new electric power development (California Water Code, Section 13552); and, Nevada Energy abandoned a proposed plan for a 1,500MW coal-fired plant over water and environmental concerns (Woodall 2009).

The purpose of this effort is to explore where the availability of water could be a limiting factor in the siting of new electric power generation. To support this analysis, water availability is mapped at the county level for the conterminous United States (3109 counties). Five water sources are individually considered, including unappropriated surface water, unappropriated groundwater, appropriated water (western U.S. only), municipal wastewater and brackish groundwater. Also mapped is projected growth in non-thermoelectric consumptive water demand to 2035, to provide an indication of the competition over available water between the thermoelectric and non-thermoelectric sectors. Finally, the water availability metrics are accompanied by estimated costs associated with utilizing that particular supply of water.

Ultimately these data sets are being developed for use in the National Renewable Energy Laboratories' (NREL) Regional Energy Deployment System (ReEDS) model, designed to investigate the likely deployment of new energy installations in the U.S., subject to a number of constraints, with a high degree of spatial resolution. The model identifies the least-cost pathway to meet electricity demand, taking into consideration a variety of different generation technologies, transmission constraints, season demand variation, and renewable energy resource availability. With these water availability and cost data, power plant siting will now also be constrained by the availability of water within ReEDS. This effort leverages and extends current work funded by DOE's Office of Electricity to support the Western Electricity Coordinating Council and the Electric Reliability Council of Texas to integrate water into their long range transmission planning.[1] This project effectively extends the water availability analysis to the eastern half of the nation.

2.0 Methods

Availability, cost, and projected future demand for water are mapped for the 17-conterminous states in the western U.S. Specifically, water availability is mapped according to five unique sources including unappropriated surface water, unappropriated groundwater, appropriated surface/groundwater, municipal wastewater, and brackish groundwater. Associated costs to acquire, convey and treat the water, as necessary, for each of the five sources are also estimated. To complete the picture, competition for the available water supply is projected over the next 20 years.

2.1Water supply data

Unappropriated Surface Water

States exercise full authority in matters pertaining to off-stream water use. In the western states water is managed according to the doctrine of prior appropriation, which defines a system of

[1] http://energy.sandia.gov/?page_id=1741

priority where the first to make beneficial use of water has the first right to it in times of drought. Access to this water requires only a permit or water right issued by the state's water management agency. However, any new water development is allocated the most junior priority in the basin, thus delivery in times of drought may be limited. Whether water is available for new development depends on characteristics of the physical water supply, the water rights structure in relation to supply, and related instate compacts and international treaties. Additionally, navigational or environmental regulation may further limit allocation or timing of deliveries. Particularly in arid regions the states have estimated how much surface water is available for new development. Although the states have different terms for such water, here it is referred to it as unappropriated surface water.

For purposes of this analysis, state estimated unappropriated surface water values are adopted throughout the West. Estimates of available unappropriated surface water are based on years with normal streamflow. Although availabilities based on drought flows would yield a more dependable estimate for new development, such estimates were available only for a single state, Texas.

For the eastern states, environmental flow considerations are used to define unappropriated surface water availability. A widely used environmental standard in the U.S. (Reiser et al., 1989) is based on studies by Tennant (1976) which found streams maintain excellent to good ecosystem function when streamflows are maintained at levels of ≥60-30% of the annual average. For this study we adopt a conservative threshold of 50% to define unappropriated surface water. Thus for basins where estimates are not available directly from the states, unappropriated surface water, Q_{usw}, is calculated as:

$$Q_{usw}^{j} = 0.5 * \left(Q_{avg}^{j} + C^{j}\right) - C^{j}$$

where *j* designates the watershed, Q_{avg} is the long term annual average gauged streamflow, *C* is the total consumptive use of water upstream of the gauging point. Annual average streamflow data are taken from the National Hydrography Dataset (NHDPlus, 2005) while consumptive water use data are derived as discussed below.

Streamflow data are not readily available at the spatial resolution necessary for incorporation into the ReEDS model. Our approach included the use of long-term average data compiled by the USGS[2] as well as the NHDPlus Version 1[3] dataset to determine surface water availability based on stream gauge flow data in areas where long-term data was not available. This primarily included coastal areas where stream gage information in the USGS data was not available or influenced by tidal fluctuations.

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[2] Stewart et al. (2006) USGS Streamgages Linked to the Medium Resolution NHD http://water.usgs.gov/GIS/metadata/usgswrd/XML/streamgages.xml

[3] http://www.horizon-systems.com/NHDPlus/NHDPlusV1_home.php NOTE: NHDPlus Version 2 (most recent version) was not available when the water supply analysis was completed.

The 6-digit HUC, or "Accounting Unit" was used in this analysis as data from this resolution was available in both datasets. For inland watersheds, the USGS Average Daily Flow (in cfs) for the period of record available at the gauge is used as the amount of available surface water. For coastal watersheds, NHDPlus catchment files were joined with their associated flowline attributes. NREL supplied boundaries for Power Control Areas (PCAs) (136) which are disaggregated further into Resource Supply Regions (RSRs) (358). These were then overlain on each catchment. Then, for each PCA and RSR within that particular catchment, the incremental flow value within the flowline attribute table was summed to determine the contribution within that catchment. For coastal watersheds that had no up-stream contribution, this method was able to add an element of surface water availability where stream gages are not present. Where upstream contributions are known, an effort was made to add the contribution from the upstream gage to the sum of the incremental flow to the outlet point of the catchment.

Due to the different spatial resolution between the HUCs and RSRs, a spatial weighting calculation was made to apportion the water from the watershed to each RSR. This was done by apportioning a percentage of the water in each 6-digit HUC to each RSR as a function of total RSR area within that HUC. Results are presented in cfs for the 358 RSRs and also consolidated up to the 136 spatially aggregated PCAs. Figure 1 below shows the intersection between the 329 6-digit HUCs and the 358 RPRs (colored fill).

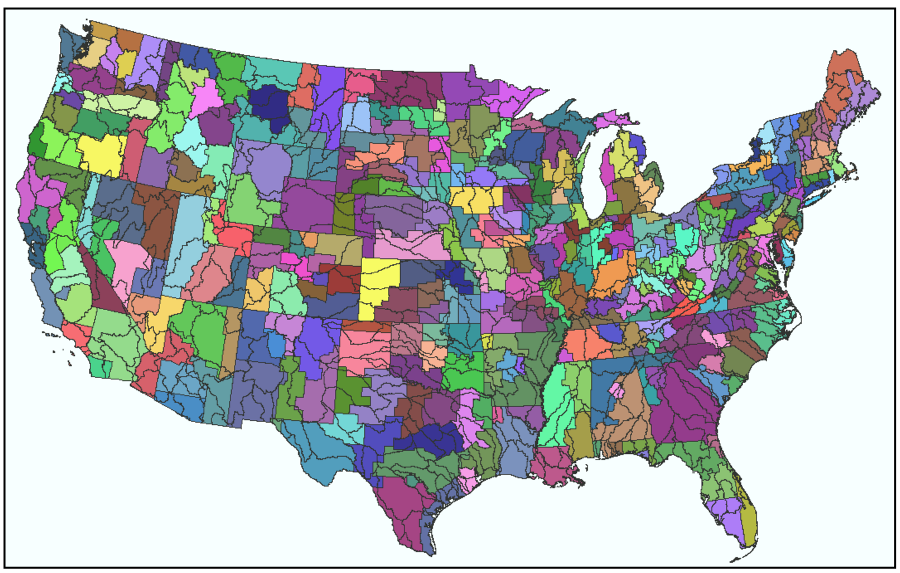

Figure 1. Intersection of RSRs and 6-digit HUCs. RSR boundaries are aggregated based on county boundaries and as evident in the figure, rarely follow the watershed boundaries.

Unappropriated Groundwater

States exercise full authority over the allocation of groundwater resources. Determining the availability of groundwater for future development is complicated by numerous factors including the manner with which groundwater is managed (e.g., strict prior appropriation, right of capture); the physical hydrology of the basin; degree of conjunctive management between surface and groundwater resources; allowable depletions, and a variety of other issues. Except in very limited cases, the states have not broadly estimated and published data on the availability of unappropriated groundwater.

Given the aforementioned complexity and relative lack of supporting data, a simple water balance approach is adopted to identify potable groundwater that is potentially available for development where state estimates were not available. That is, unappropriated groundwater is set equal to the difference between annual average recharge and annual groundwater pumping. Recharge rates are taken from the USGS (2003), which are derived from stream base flow statistics, while pumping rates are taken from state data where available or from USGS (Kenny et al., 2009) otherwise.

To account for unique groundwater management and/or aquifer characteristics, further restrictions on unappropriated groundwater availability are introduced. Specifically, availability is set to zero in watersheds located within state defined groundwater protection zones (where available, data was acquired directly from each Western state[4]). Groundwater availability is likewise set to zero in watersheds realizing significant groundwater depletions (historical groundwater declines exceeding 40 ft. as given by Reilly and others [2008]). Finally, groundwater availability is set equal to zero in any watershed that 10% or less of its land area is underlain by a principle aquifer (Reilly et al., 2008).

Brackish Groundwater

For this analysis brackish water availability is limited to resources no deeper than 2,500 feet and salinities below 10,000 total dissolved solids (TDS). Deeper, more concentrated resources would generally be very expensive to exploit.

Estimates of brackish groundwater resources across the western U.S. are very spotty. To cover this entire area requires the use of multiple sources of information. The best quality data are state estimated volumes of brackish groundwater that are potentially developable; however, this data is only available for Texas (LBG-Guyton Associates, 2003), New Mexico (Huff, 2004), and Arizona (McGavock, 2009). States limit exploitation of the resource by applying some type of allowable depletion rule. In this case it is assumed that only 25% of the resource can be depleted over a 100 year period of time (annual available water is determined by multiplying estimated total volume of brackish water by 0.0025).

[4] 'Western states' refers to 17 western states whose water availability and demand data was specifically gathered as part of the 'Energy and Water in the Western and Texas Interconnects' Project. These states include: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming.

The next best source of data is reported use of brackish groundwater as published by the USGS (Kenny et al., 2009). This does not provide a direct measure of available water, simply an indication that brackish water of developable quality is present. Conservatively we assume that double the existing use could be developed up to a maximum limit of 10 MGAL/D. Also assumed is that the minimum quantity available is 1 MGAL/D.

Finally, if a watershed has no brackish water volume estimate or brackish water use then the presence of brackish groundwater wells is used. The USGS maintains the National Water Information System (NWIS)[5] database which contains both historical and real-time data of groundwater well depth and quality (USGS, 2011). Where at least one well exists brackish water availability is set to 1 MGAL/D. To avoid brackish water that is in communication with potable streamflow, availability is set to zero when the average depth to brackish water is less than 50 ft. and the salinity is less than 3000 TDS.

Wastewater

Non-fresh water supplies offer important opportunities for new development. Municipal wastewater is rapidly being considered as an alternative source of water for new development, particularly in arid regions. Municipal wastewater discharge data is relatively consistently available throughout the U.S. The EPA publishes a pair of databases (Permit Compliance System [EPA, 2011][6], and Clean Watershed Needs Survey [EPA, 2008][7]) that provide information on the location, discharge, and level of treatment for most wastewater treatment plants in the U.S. Additionally, the USGS (Kenny et al., 2009) publishes municipal wastewater discharge values aggregated at the county level. These three sources of information are combined to provide a comprehensive view of current wastewater discharge across the West. Lastly, the projected growth in municipal wastewater discharge to 2030 is estimated (see future Water Demand section below) and added to the current discharge rates.

However, not all of this discharge is available for future use. A considerable fraction of wastewater discharge is currently re-used by industry, agriculture, and thermoelectric generation. Re-use estimates are determined both from the USGS (Kenny et al., 2009) data as well as the EPA databases (as they record the point of discharge, e.g., stream, agriculture, power plant and in some cases are designated as discharging to 'reuse'). These re-use estimates are subtracted from the projected discharge values.

In western states the availability of municipal wastewater must consider return flow credits. Those municipalities that discharge to perennial streams receive return flow credits for treated wastewater. This water is not available for new development as it is already being put to use downstream. Unfortunately, there are no comprehensive data on wastewater return flow credits.

[5] http://waterdata.usgs.gov/nwis
[6] http://www.epa.gov/enviro/facts/pcs-icis/search.html
[7] http://water.epa.gov/scitech/datait/databases/cwns/index.cfm

In efforts to identify plants that are likely credited for their return flows, those plants that directly discharge to a perennial stream are identified (point of discharge is identified in the databases noted above as being a stream with average flow of 10 cfs or more). These plants are excluded as a source of available municipal wastewater.

Appropriated Water

This source attempts to quantify water that could be made available for new development by abandonment and transfer of a water right. Only states that govern water according to the doctrine of prior appropriation, western states, issue transferrable water rights. As such, this water source only applied to western states, states west of the 100th meridian. Water transfers have traditionally involved sales of water rights off irrigated farm land to urban uses. The potential for such transfers is estimated based on the irrigated acreage in a given watershed that is devoted to low value agricultural production; specifically, irrigated hay and alfalfa. Data (irrigated acreage and water volume applied) are taken from the USDA's Agricultural Census (USDA, 2007). There is often resistance to large areas of irrigated agriculture being abandoned. As such, land abandonment is limited to 5% of the total irrigated acreage in the watershed. This limit is based on the state projected average decline in irrigated acreage across the western U.S.

For watersheds experiencing significant groundwater depletions (see unappropriated groundwater metric above) the available appropriated water is reduced by 50%. This is to account for the fact that some portion of future water rights abandonment is likely to be used to offset the groundwater depletion (Brown 1999).

2.2 Water demand data

Water demand data were acquired in one of two ways. For western states, data were collected directly from the state water management agency. For eastern states, water projections were estimated according to data available through the U.S. Geological survey. Details for both approaches are given below.

Western State Analysis

Water demand data for the western states was acquired largely come from the state's individual water plans and online databases. Water demands are distinguished according to current verses projected future demands; withdrawal verses consumptive use; and, the source water (e.g., surface water, groundwater, wastewater, saline/brackish water). Demands are also distinguished by use sector; specifically, municipal/industrial, thermoelectric, and agriculture.

Water demand projections vary by state in terms of spatial resolution, target dates, and categories of growth. All projected demands are mapped to the county level using an aerial or population weighting scheme. Projections were also uniformly adjusted to the year 2035. This was achieved through simple linear extrapolation between current use estimates and that projected at target dates beyond 2035. Although data were collected for all reported growth scenarios (e.g., high, medium and low), the medium growth projections are reported here.

Eastern State Analysis

Estimates of projected water demand in 2035 were determined using values of known water use (demand) from USGS county level data from 1995 to 2005[8]. The different categories included water use for the following: domestic and public water supply, industrial, mining, livestock and irrigation. For each category, the county FIPS code was analyzed using the 2005 code as the reference. As some county boundaries change, this was done to ensure that the projections are made on the most recent boundaries with water use data.

Domestic and public water supply is calculated for 1985, 1990, 1995, 200 and 2005 as the sum of both the Public Supply – total fresh water withdrawal and the Total Domestic Self Supplied water withdrawal in Mgal/d. From here, the following method was used to determine the 2035 water use: 1) calculate 2005 per capita water use in Mgal/d/person; 2) determine the per capita water use in 2035 by adding the 2005 per capita water use to the product of 30 (years between 2005 and 2035) the slope of the 1985 to 2005 per capita water use (each year's water supply in Mgal/d is first divided by the population); 3) a check is made 20% above and below the 2005 per capita water use and compared to the 2035 calculation. The resulting value is then constrained to that range if the 2035 calculated value falls outside of it; 4) the final result is then converted back to Mgal/d by multiplying by the projected 2035 population, which was determined by using the following equation: multiplying the 2005 population by e^(state specific 30-year growth rate x 30[years from 2005 to 2035]), where the state specific 30-year growth rate is determined from census data in 2000, projected to 2030 (for each state)[9]

Industrial water use is determined by calculating an intensity in $/gal. The following steps are made to determine the 2035 industrial water use: 1) For each state, the sum of the county industrial water use is determined; 2) The gross state product (GSP) in Million $ is needed for all analysis years, 1985, 1990, 1995, 2000 and 2005. Actual data is brought in from 2000 and 2005[10]. To get data from 1985, 1990 and 1995, a growth rate is calculated between 2000 and 2006 state population data[11], then extrapolated back starting in 2000 to estimate the GSP for those three years; 3) The state summed withdrawals are then divided by the state GSP for each year (1985 through 2005) to get a value in Mgal/Million $. Which is then used to determine a slope per state over the 1985 to 2005 time period; 4) The 2005 industrial water use in Mgal/d is divided by the 2005 *county derived* gross state product (which is determined by multiplying the 2005 county population by the 2005 GSP per capita[12]) to get a 2005 intensity value in Mgal/$; 5) A raw 2035 intensity value in gal/$ is calculated by adding this previously calculated value to the product of the slope and 30 (years between 2005 and 2035); 6) This value is then checked at 35% below or 20% above the 2005 intensity value. The resulting value is then constrained to that range if the 2035 calculation value falls outside of it; 7) The final result is then converted back to

[8] http://water.usgs.gov/watuse/

[9] http://www.census.gov/prod/1/pop/p25-1130/p251130.pdf

[10] http://www.bea.gov/regional/gsp/action.cfm

[11] http://www.bea.gov/regional/gsp/

[12] Sandia's EPWSim model was used to calculate the 2005 GSP per capital (Million USD/person)

MGAL/D by multiplying the 2035 GSP by county by the constrained value in (6). Any data where there are gaps for 2000 or 2005 in the historic published record are checked and the last reported value is brought in.

Both Mining and irrigation water use projections for 2035 are left at the same levels as 2005 as these sectors have seen little change since the 1970s (Kenney et al. 2009).

Livestock water use is calculated in a similar way as industrial water use, with the main exception that data from 2000 was not utilized as it is incomplete and 2005 data was not utilized as it contains aquaculture. This primarily impacts the slope calculation as described above in step 3 for determining industrial water use. Also, the raw intensity was calculated with 40 years instead of 30 as the starting year was 1995 instead of 2005.

2.3 Water Cost Data

Each of the five sources of water carry a very different cost associated with utilizing that particular supply. The interest here is to establish a consistent and comparable measure of cost to deliver water of potable quality to the point of use. As with water availability, costs are resolved at the county level. Considered are both capital and operating and maintenance (O&M) costs. Capital costs capture the purchase of water rights as well as the construction of groundwater wells, conveyance pipelines, and water treatment facilities, as necessary. All capital costs are amortized over a 30-yr horizon and assume a discount rate of 6%. O&M costs include expendables (e.g., chemicals, membranes), labor, waste disposal as well as the energy to lift, move and treat the water (assumed $0.35/kWh). Below, specifics unique to each source are discussed.

Unappropriated Surface Water

No costs are assigned to unappropriated surface water. It is recognized that there are costs associated with constructing intake structures and permitting. Such costs are not considered in part because of the wide range of variability across use types and location. More importantly, similar intake and permitting costs will be realized with all five sources of water, thus estimating these uncertain costs are of little value to this effort.

Unappropriated Groundwater

Estimated costs consider both capital and O&M costs to lift water for use. Capital costs for drilling are estimated along with electricity to lift water following the approach outlined in Watson and others (2003). Depth to groundwater is taken from USGS well log data (USGS, 2011) and averaged at the county level.

Appropriated Surface Water

Water rights transfer costs are based on historic data collected by the *Water Strategist* and its predecessor the *Water Intelligence Monthly* (Water Strategist, 2012). Costs are estimated by state because of the limited availability of data. Only transactions involving permanent transfers from agriculture to urban/industrial use are considered. Recorded transfers are averaged by year and by state and the average of the last 5 years used for purposes of this study. Data is only available for 12 western states: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, Washington, and Wyoming. No efforts are made to project how costs may vary in time given the wide range of factors and associated uncertainty that plays into the water transfers market.

Municipal Waste Water

Estimated costs consider expenses to lease the waste water from the municipality, convey the water to the new point of use, and to treat the waste water. Fees charged to lease treated waste water from the municipality were estimated based on the initial work of the Electric Power Research Institute (EPRI, 2008). Values reported in the EPRI report were verified and updated as necessary based on a review of fees published on line. As no geospatial or plant related trends were noted in the pricing an average of the reported fees was adopted for this study, which was calculated at $400 per acre-foot.

Conveyance of treated wastewater from the treatment plant to the point of use is a potentially important cost. Considered are both capital construction costs for a pipeline and O&M costs principally related to electricity for pumping. Associated costs calculations are consistent with Watson and others (2003). The key factor in this analysis is the distance between the treatment plant and point of use. Distance values are calculated as a function of the land use density around the existing treatment plant. Land use densities were calculated within a 5-mile buffer around all existing treatment plants with conveyance distances simply distributed according to a rank order of land density with low values given a conveyance distance of 1 mile and to the highest land use density given a distance of 5 miles.

It is assumed that all waste water must be treated to advanced standards before it can be re-used. This conservative assumption was adopted considering both realized improvements in downstream operations (e.g., increased cycles of use, reduced scaling, improved feed quality) and the current trend of regulation toward requiring advanced treatment (EPRI, 2008). Plants operating at primary or secondary treatment levels (EPA, 2008, 2011) are assumed to be upgraded to advanced standards. Capital construction costs are based on the analysis of Woods et al. (2012), which scale according to treatment plant throughput and original level of treatment. Associated O&M costs consider expenses for electricity, chemicals and labor.

Shallow Brackish Groundwater

Estimated costs consider both capital and O&M costs to capture and treat the brackish groundwater. Cost calculations follow standards outlined in the Desalting Handbook for Planners (Watson et al., 2003). Capital costs include expenses to drill and complete the necessary groundwater wells and construct a treatment plant utilizing reverse osmosis. Number of wells and treatment plant capital costs are based on the treated volume of water, which is assumed to be 5 Mgal/d. Other key design parameters include the depth of the brackish water and TDS. These data averaged at the county level, were estimated from the USGS brackish groundwater well logs (USGS, 2011). O&M costs capture expenses for labor, electricity, membranes and brine disposal.

3.0 Results

Water availability and cost data are mapped below. Our presentation begins with a review of the data at its highest resolution-the county level. Water availability, demand and cost data are mapped and discussed. Simple water budgets are constructed to help identify regions where water stress is likely to occur. Water availability metrics are also compared to the locations of existing thermoelectric power plants to indicate areas where their water use has a significant impact on water resources and alternatively where changes in electric generation practices could lead to valuable water savings. Finally, the data are aggregated at the Resource Supply Region (RSR) and Power Control Area (PCA) levels for use in the ReEDS model. A brief discussion of the data is given along with a presentation of the water supply curves developed to integrate the raw water data into ReEDS.

3.1 Water Availability

Water availability is mapped for the five unique sources of water for the conterminous United States at the county level (Figure 2). Water availability for all five sources is mapped using a consistent but non-linear scale. Counties marked in white designate regions with no availability for that source of water (or insufficient information to suggest a reliable supply in the case of brackish groundwater). A quick review of all five maps clearly reveals significant variability across the five sources of water as well as county-to-county variability within each source of water. The expressed variability is a function of the physical hydrology, water use characteristics, and water management practices unique to each county.

Availability of unappropriated surface water (Figure 2a), that water that only requires the issue of a right/permit from the state's water management agency to develop, is largely limited to the eastern U.S. Little to no unappropriated surface water is available in the West with the exception of western Colorado, southwestern Wyoming, western Oregon and the Dakotas. In total, 664 counties lack access to a developable unappropriated surface water source. It is interesting to note that much of the Northwest which is generally considered as having plentiful water resources, has been closed to new water appropriations by their respective water management agencies. Alternatively, unappropriated surface water is generally available in the East, largely due to limited water use for irrigation and a generally more humid climate.

Availability of unappropriated groundwater (Figure 2b) varies widely from coast-to-coast. Of particular note is the limited availability of groundwater throughout the Great Plains region, which is largely due to overexploitation (depletion) of this regional aquifer. Pockets of overexploitation are also seen in the Mid-West and far Northeast. Availability varies significantly in the West. This spatial variability largely reflects differences in the way the individual states manage their groundwater resources. California is noted as having no available groundwater for development because of policies precluding use of potable water for new thermoelectric development. In total 868 counties lack available unappropriated groundwater.

Appropriated water is that surface and groundwater which could be transferred from one use to another, generally involving the abandonment of irrigation with the transfer of water to the municipal or thermoelectric sector for use. As such, appropriated water only has meaning in the western states, where water use is regulated through a system of water rights. Availability of appropriated water is consistently distributed throughout the West (Figure 2c). Quantities likely to be transferred are relatively small, generally less than 5000 AF/yr. The greatest availability corresponds to regions with heavy irrigated agriculture including, southern Arizona, eastern Colorado, panhandle of Texas, central Washington, and the Snake River basin in Idaho. Again, appropriated water is excluded from new thermoelectric development in California.

Availability of municipal wastewater is sporadically distributed across the West (Figure 2d), while a significant improvement in availability is realized in the East reflecting the increased density of community water systems. In fact, wastewater has the best spatial coverage with only 579 counties lacking access. The highest availabilities are associated with large metropolitan areas such as along the southern coast of California, Tucson/Phoenix, Miami, New York City, Detroit, Chicago, and others.

Brackish groundwater is available throughout much of the West except in the far Northwest (Figure 2e). In contrast, brackish water is of limited availability throughout the Great Plains and almost non-existent in the East with 1731 counties lacking a verifiable supply of brackish water. The highest availabilities are noted in Arizona, New Mexico and Texas, where detailed brackish groundwater studies have been conducted. Thus mapped availability is more an indication of what we know and currently use rather than an indication of the actual resource in the ground.

3.2 Future Water Demand

Projected future demands for water (consumptive use) are mapped in Figure 2f. Mapped are new demands projected between 2005 and 2035. Demands are mapped at the same scale as water availability (Figures 2a-2e) but with the color scale reversed to distinguish high demands with hot colors. A noteworthy aspect of the map is the large regions with zero to negative projected future demands (white areas on map). These are regions where the state projects some level of abandonment of irrigation combined with limited rural population growth. While the states project little growth (or declines) in irrigated agriculture, healthy increases in the municipal and industrial sectors are expected. It follows that the largest growth is clustered around metropolitan areas. In the West there is also an apparent difference in projections among the states, e.g., compare the projected growth in South Dakota growth vs. the lack of projected growth in Nebraska and Kansas, which simply reflects differences in assumptions.

3.3 Water Cost

Water costs associated with each source of water except unappropriated surface water are mapped in Figure 3. In order to map all four costs comparably, a non-linear color scale was necessitated to capture the broad range in values. Note that costs were not calculated for watersheds where a particular supply of water was unavailable (watersheds mapped white).

Each water supply shows some degree of county-to-county variability. This variability is masked to some extent for the brackish and wastewater maps by the large bin sizes necessitated for the scale. Variability in cost for unappropriated groundwater largely corresponds with the average depth to groundwater. Appropriated water transfers are seen to be more costly in the Southwest where water supplies are most limited. Municipal wastewater costs tend to increase as the size of the wastewater treatment plant decreases and the level of treatment increases. Brackish water costs tend to increase as depth and TDS increases.

The most important feature of these maps is the significant variability across sources, particularly between fresh and non-fresh. Average costs for unappropriated groundwater runs $76/AF while appropriated water is estimated at $131/AF. Alternatively non-fresh supplies are considerably more expensive with municipal wastewater running $580/AF and brackish water $1882/AF. Historically, development has largely relied on inexpensive unappropriated water or transfers of appropriated water. The cost of water is likely to play a much more important role in planning and design of future development.

3.4 Water Budget

Comparison of water availability with projected future demand provides an indication of where future consumption will challenge available supplies unless measures are taken. To explore this issue available water sources (Figure 2a-2d) are aggregated and the projected future demand (Figure 2e) subtracted to yield a simple water budget at the county level across the conterminous U.S. Two budgets are constructed; one that only considers unappropriated surface/groundwater sources (Figure 4a) and a second that considers all five sources of available water (Figure 4b). The unappropriated water budget is constructed as these are generally the first supplies of water that are considered because they have the lowest utilization costs (see above).

As expected, unappropriated surface and groundwater supplies are unlikely to be sufficient to meet future demands throughout much of the West. This is indicated by the broad areas with negative water budget values, where projected future demand exceeds the available supply (areas mapped as white); particularly, New Mexico, Utah, Washington, Montana, Idaho, Nebraska, Texas, eastern Colorado and western Kansas. In total 679 counties have 2035 water demands that exceed the available unappropriated surface and groundwater supply. More importantly 131 of these counties are in the top 10% of fastest growing counties.

The picture improves considerably when all five water sources are considered (Figure 4b). Fortunately, appropriated, brackish, and municipal wastewater tend to be available in counties with limited or no unappropriated water supply. In fact, only 138 counties have insufficient supplies to meet 2035 demand when all five sources of water are considered. However, these watersheds tend to be associated with areas experiencing strong urban growth; specifically, 95 are associated with the top 10% of fastest growing counties.

3.5 Current Thermoelectric Water Use vs. Water Availability

Current water consumption by thermoelectric power generation is mapped against water availability. Specifically, power plants are paired by their respective water source and the availability of that particular source (e.g., surface water using power plants mapped with unappropriated water availability). Such comparisons provide a window into the potential for water related stress pertaining to thermoelectric operations in that county.

Figure 5a shows unappropriated surface water availability mapped at a county level with surface water using thermoelectric power plants superimposed. Note that the size of the plant symbol indicates the intensity of water consumption. From this map it is apparent that thermoelectric surface water use is largely concentrated in the East, with much of the development along major water ways and the Great Lakes. There are also a number of scattered surface water using plants in the West. One hundred sixty-three plants are noted to use more surface water than is available from an unappropriated water source with all but 17 of these plants located in western counties. This does not suggest that the plants do not have water to operate (they have secured rights or permits); rather, this simply suggests locations where surface water is of limited supply and thus the plants run the risk of water shortages in times of drought. Most plants in the West are used to drought and have sophisticated contingency plans in place to deal with reduced stream flows. Alternatively, these plants represent a potential source of water if the plant were to retrofit to a non-potable source of water or dry cooling or if the plant were to be retired (and replaced by a lower water intensity facility). The plants in California are not counted as limited surface water supply is policy driven rather than a physical constraint.

Similarly, groundwater using thermoelectric power plants are mapped with available unappropriated groundwater (Figure 5b). At first view it is apparent that fewer power plants depend on groundwater. These plants are relatively evenly distributed across the U.S. In total, sixty-seven plants are located in counties with limited groundwater availability, with 8 in the far East, 35 in the High Plains and 24 in the West. The majority of these plants are associated with counties experiencing significant groundwater overdraft (Reilly et al., 2008) and thus my face water shortage in the long term as groundwater levels recede. The plants in California are not counted as limited groundwater supply is policy driven rather than a physical constraint.

As a point of comparison, power plants using wastewater are plotted alongside unappropriated surface water (Figure 5c). The interest here is to explore the role of water availability on the siting of power plants using alternative water supplies. First, the limited number of power plants using wastewater is noteworthy. Roughly two-thirds of the plants are located in relatively water limited regions of the West. However, interestingly about a third are located in the East where water availability is less of an issue. Here it is likely that local issues or drought related impacts drove the decision to use wastewater.

The final review maps all freshwater using power plants on the projected demand for water (new water needs) between 2005 and 2035 (Figure 5d). The intention is to indicate those power plants located in counties with rapid growth and thus high competition over new water resources. These are location that might experience pressure to retire and/or retrofit to a non-potable source of water. A total of 74 plants are located in counties were projected growth exceeds 50,000 AF/yr. with 59 of the plants in the West.

3.6 Maps at the RSR and PCA Level

Water availability and cost metrics have also been mapped at the RSR and PCA levels which are used in the ReEDS model. Mapping was easily accomplished by aggregating counties into the RSR and PCA regions. Water availability metrics aggregated at the RSR level for the five water sources and projected future water demand are given in Figures 6a-f, while associated cost data are given in Figures 7a-d. Similarly water availability metrics at the PCA level are given in Figures 8a-e and cost metrics in Figures 9a-d.

Both the RSR and PCA maps faithfully reproduce the basic trends evident in the highest resolution data mapped at the county level (Figures 2 and 3). As expected, distinct smoothing is evident as the county level data is aggregated to the RSR and then to the PCA level. Also noted is that the low end values tend to be clipped as the resolution is decreased. This occurs as counties with little or zero availability are aggregated with counties with higher availability. Similar “clipping” is occurring at the upper end as well; however, we are much less concerned about areas with abundant water resources.

3.7 Supply Curves

Ultimately, the water availability and cost data is used by the ReEDS model in the form of a water supply curve. Specifically, the supply curve plots the quantity of water available at or below a given price. As an example, supply curves are developed for a few of the PCA regions. This is accomplished by plotting the cost verses cumulative supply (rank ordered by cost) for each source within the PCA region. Figure 10 provides curves for 6 PCA regions selected at random that are indicative of trends seen throughout the U.S. Inspection of the curves reveals significant disparity across the PCA regions. Regions 60 and 20 indicate relatively little availability of water overall with only limited supplies of expensive non-potable water. This is consistent with their locations in Texas and Montana, respectively. The other PCA regions are characterized by much more abundant unappropriated water, characteristic of their locations in the eastern U.S.

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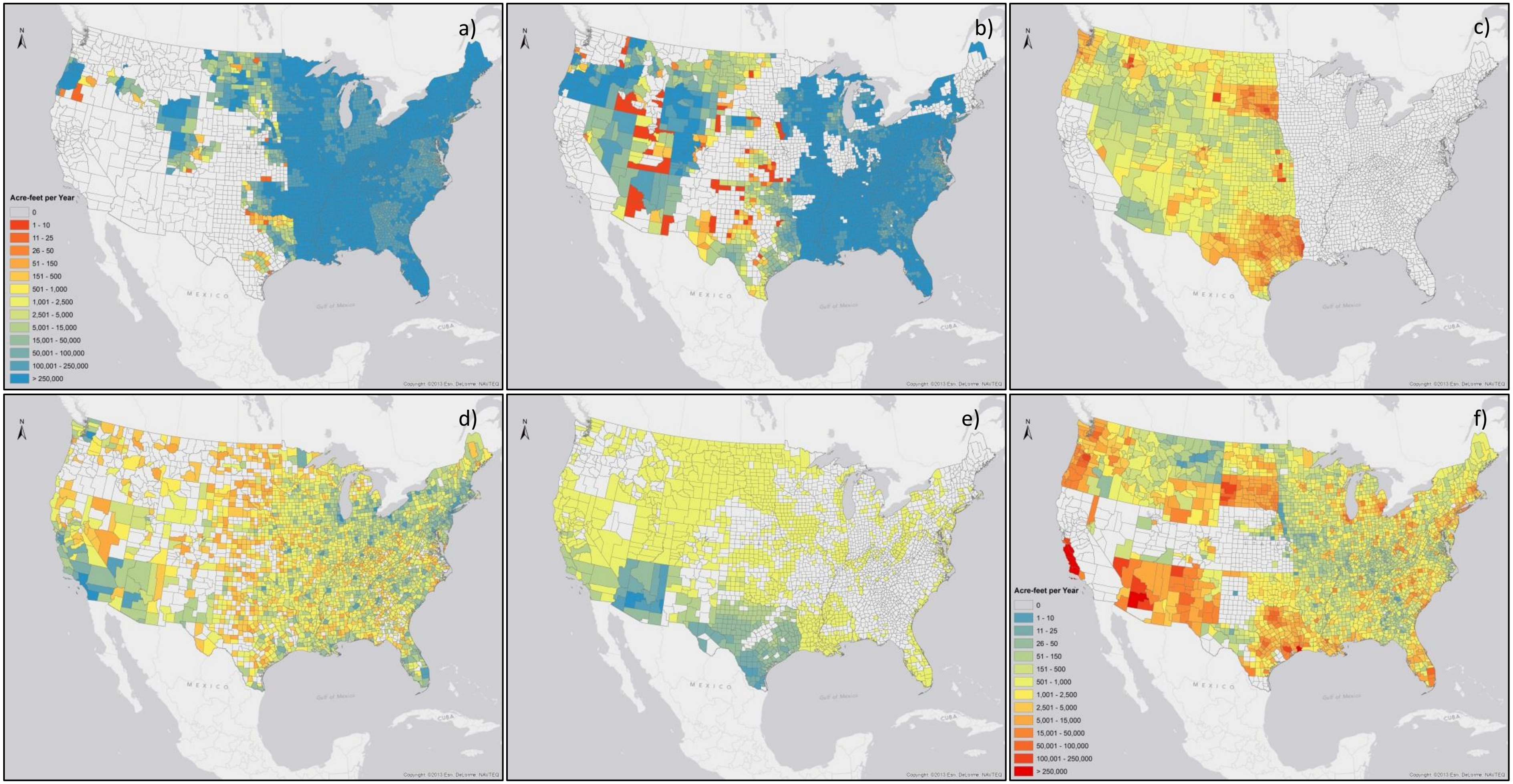

Figure 2. Water availability and future demand. Mapped are water availability metrics for a) unappropriated surface water, b) unappropriated groundwater, c) appropriated water, d) municipal wastewater, e) brackish groundwater, and f) projected increase in consumptive water use between 2005 and 2035. All metrics are mapped at the county level. All are mapped to a consistent non-linear color scale; however the color scheme is reversed between availability and demand (e.g., hot colors indicate limited availability or high demand).

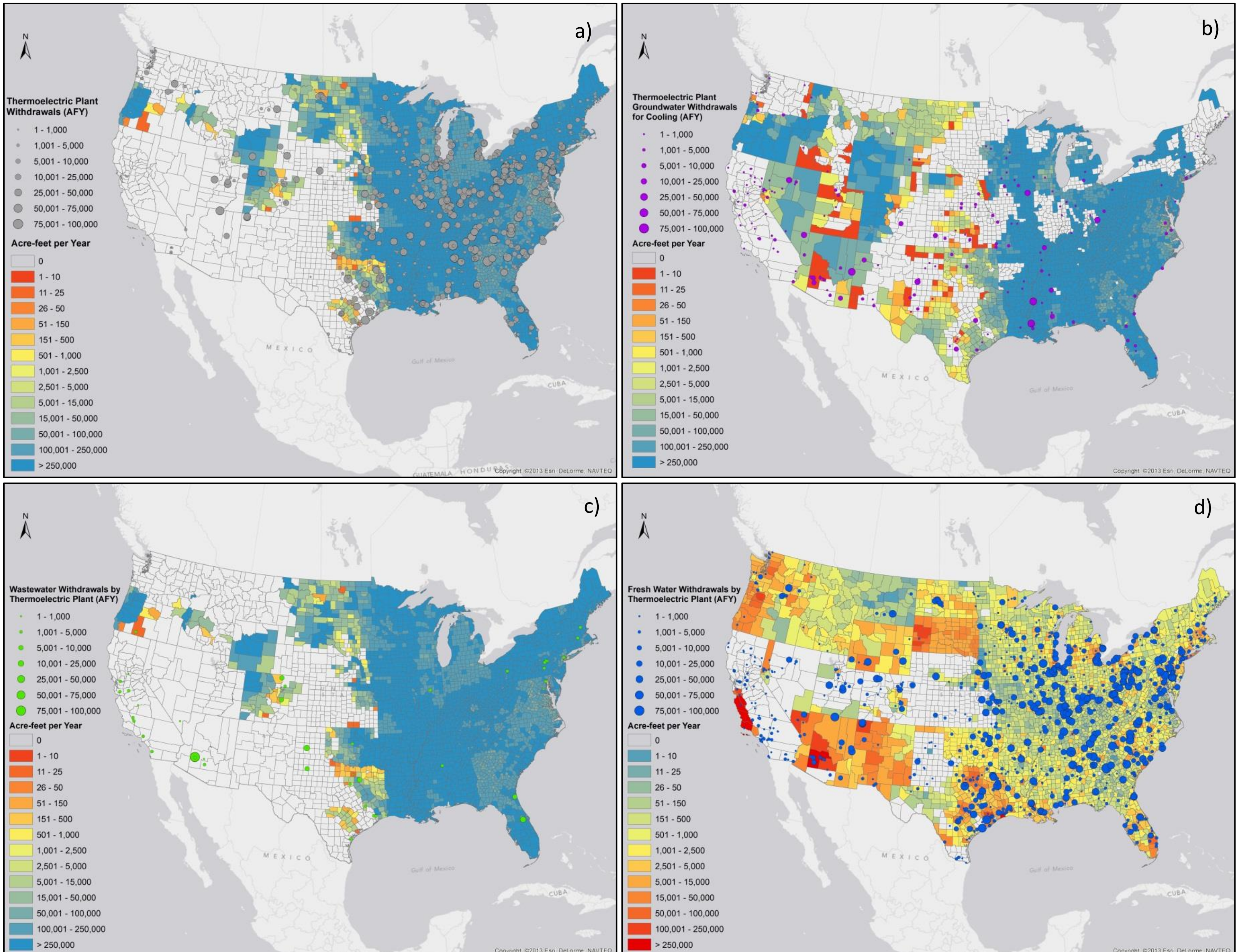

Figure 5. Water availability and future demand in relation to existing plants. Mapped are water availability metrics for a) unappropriated surface water and plants withdrawing surface water for cooling, b) unappropriated groundwater and plants withdrawing groundwater for cooling, c) unappropriated surface water and plants withdrawing municipal wastewater for cooling, d) new demand and plants withdrawing fresh water for cooling.

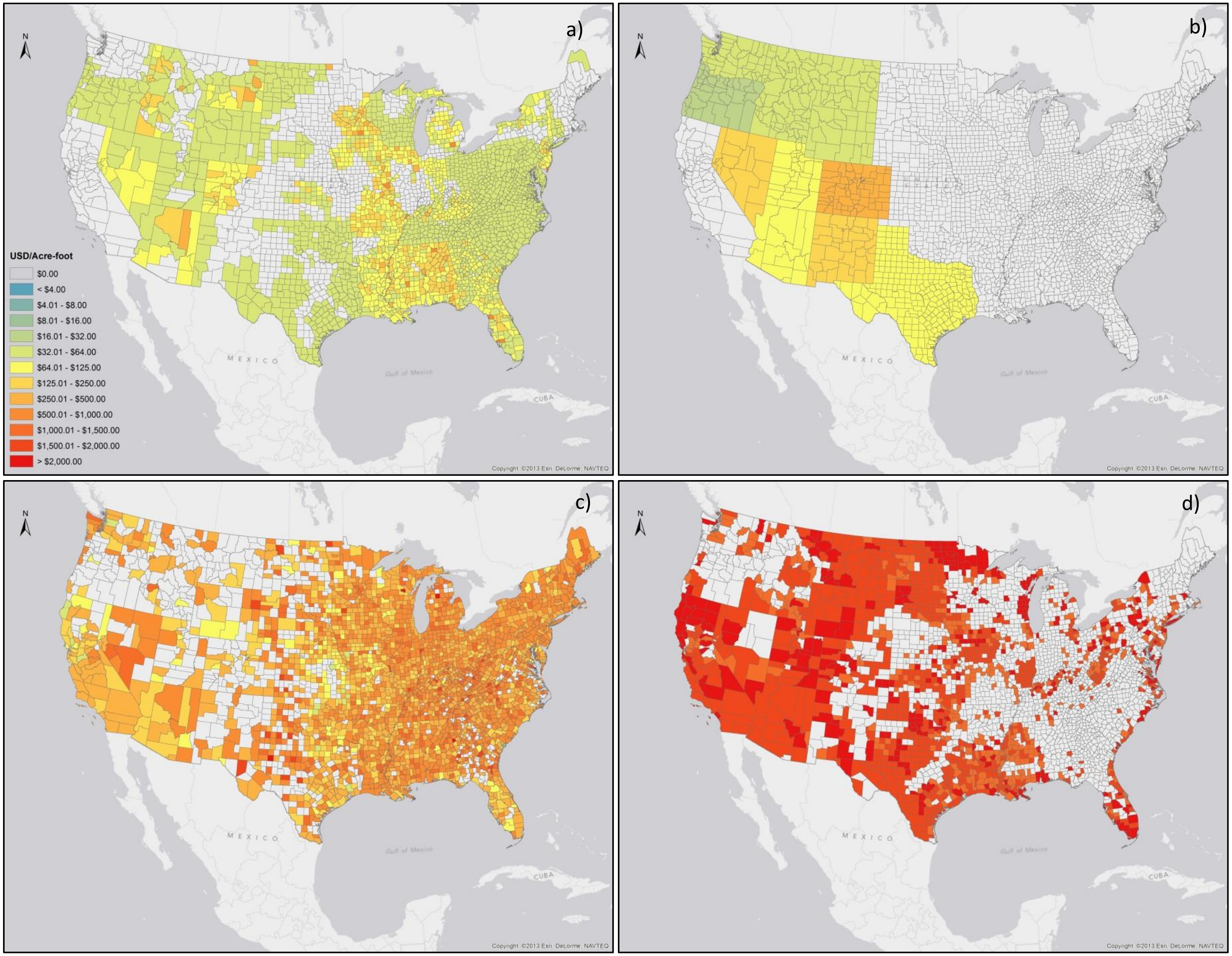

Figure 3. Water cost. Mapped are water cost metrics for a) unappropriated groundwater, b) appropriated water, c) municipal wastewater, and d) brackish groundwater. All metrics are mapped at the county level. All are mapped to a consistent non-linear color scale.

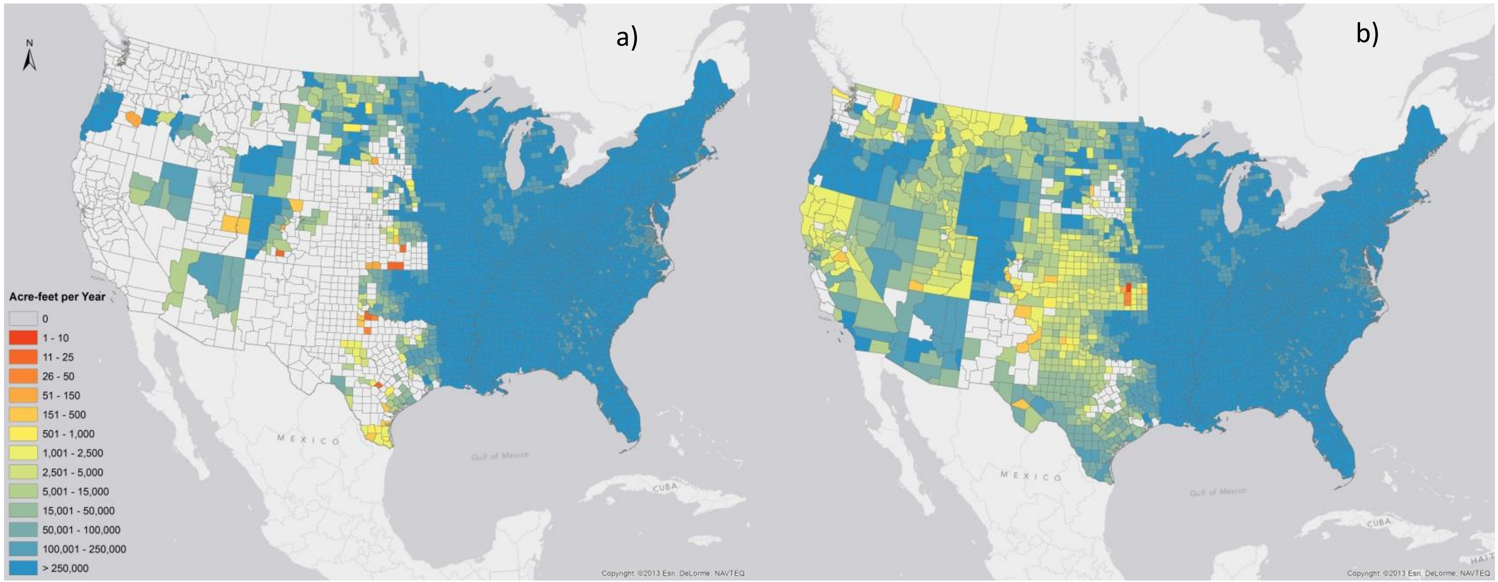

Figure 4. Availability – Demand in 2035. Mapped are a) unappropriated water sources – change in demand, 2035 and b) all water sources – change in demand, 2035. All metrics are mapped at the county level. All are mapped to a consistent non-linear color scale.

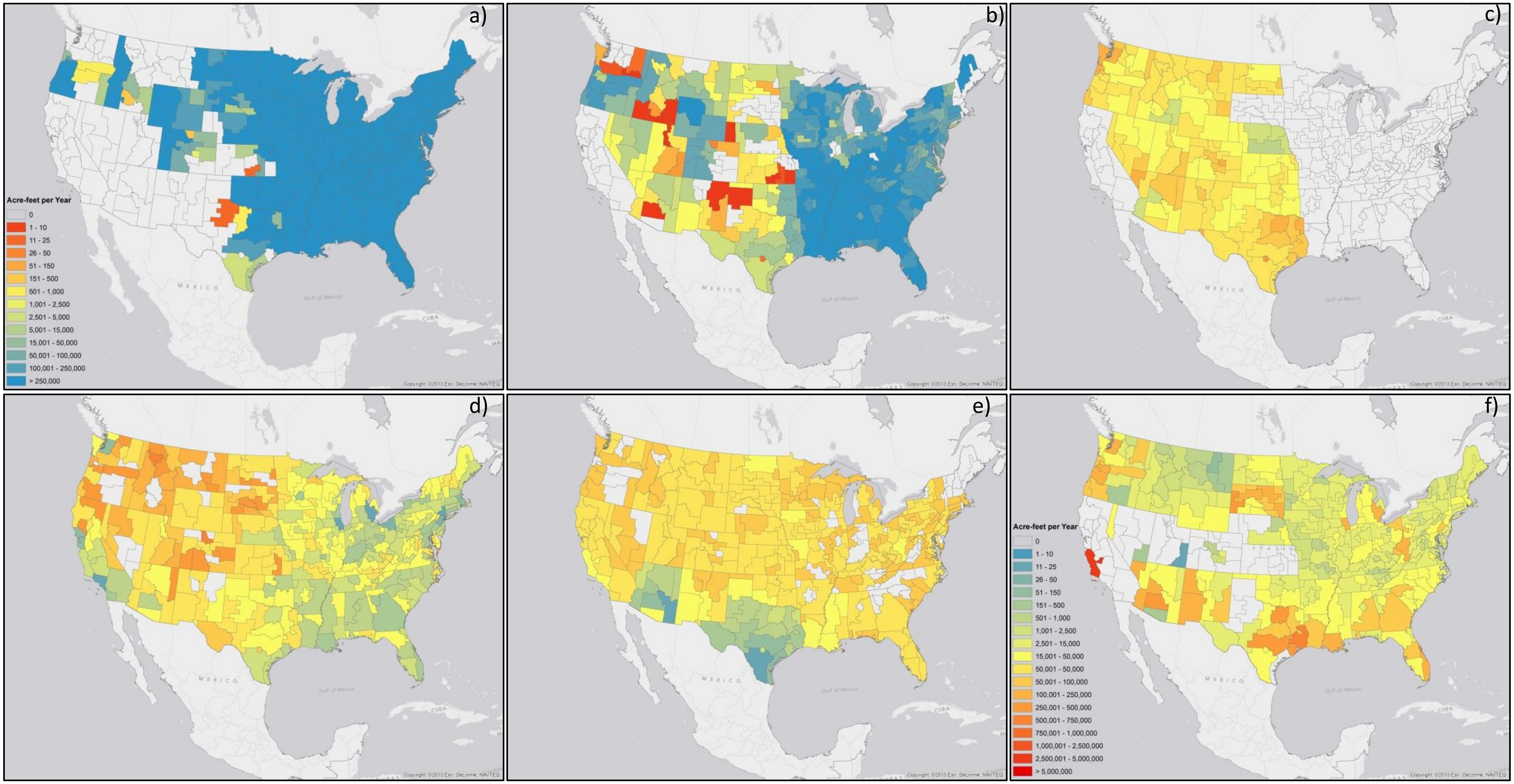

Figure 6. Water availability and future demand. Mapped are water availability metrics for a) unappropriated surface water, b) unappropriated groundwater, c) appropriated water, d) municipal wastewater, e) brackish groundwater, and f) projected increase in consumptive water use between 2005 and 2035. All metrics are mapped at the Resource Supply Region (RSR) level. All are mapped to a consistent non-linear color scale; however the color scheme is reversed between availability and demand (e.g., hot colors indicate limited availability or high demand).

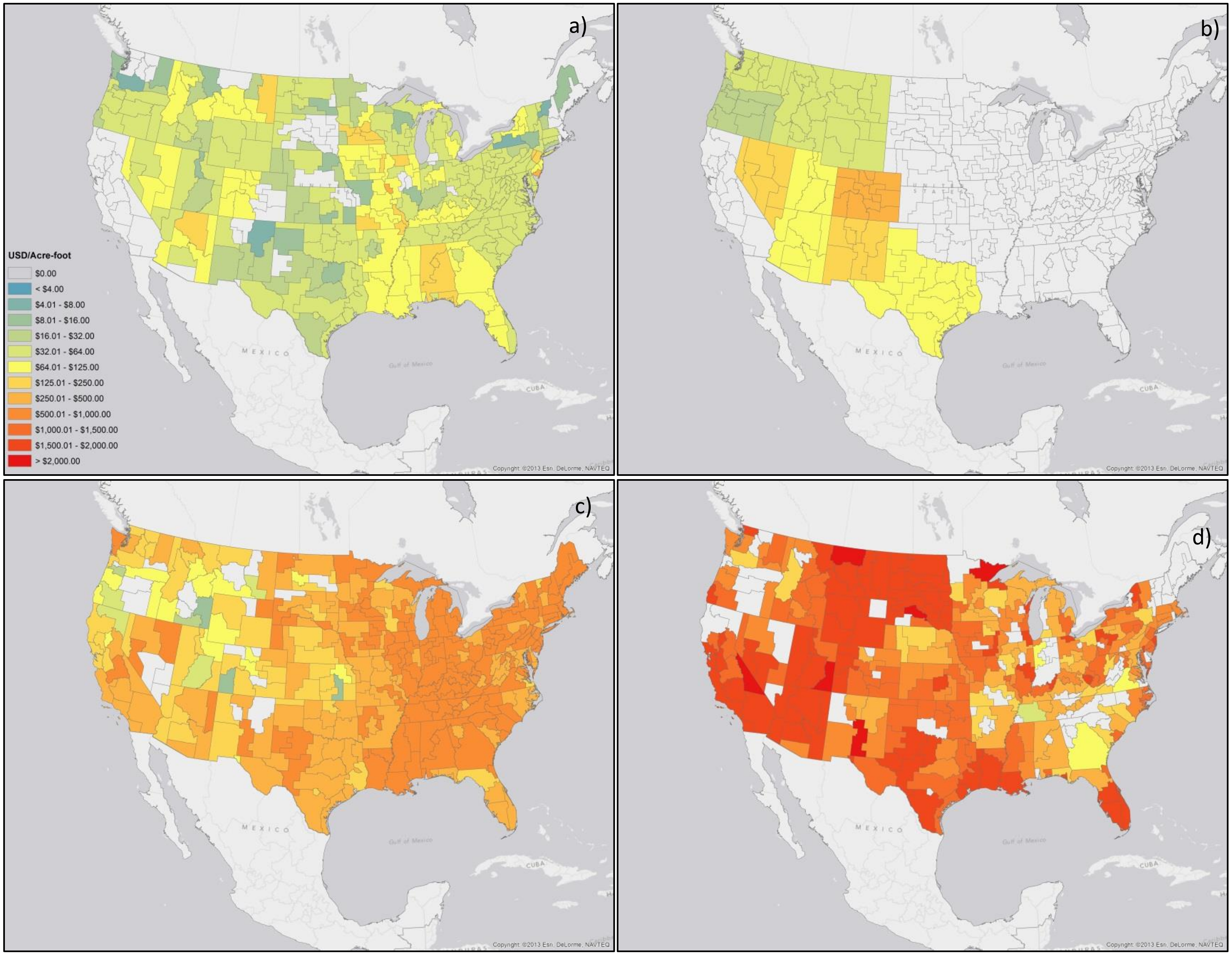

Figure 7. Water cost. Mapped are water cost metrics for a) unappropriated groundwater, b) appropriated water, c) municipal wastewater, and d) brackish groundwater. All metrics are mapped at the RSR. All are mapped to a consistent non-linear color scale.

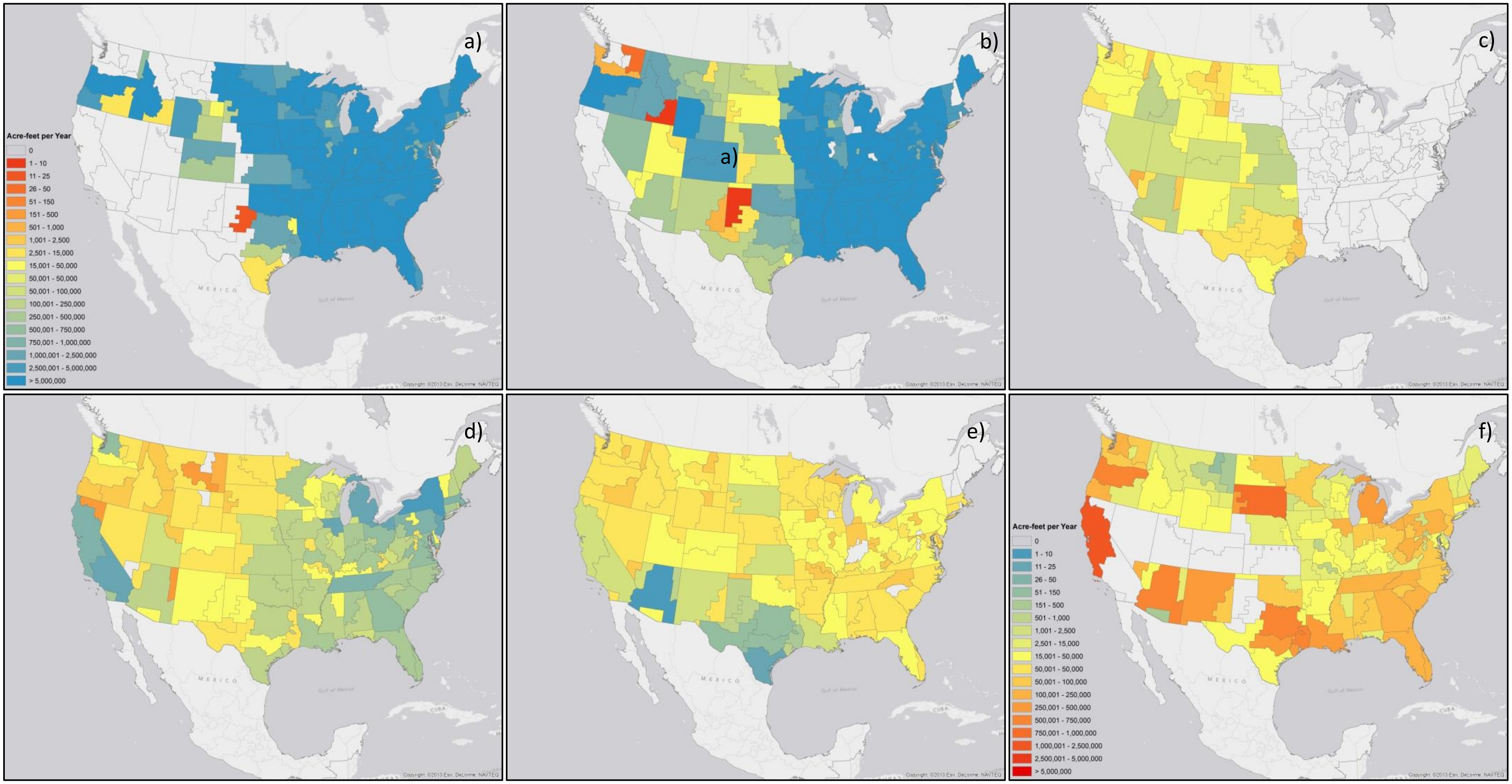

Figure 8. Water availability and future demand. Mapped are water availability metrics for a) unappropriated surface water, b) unappropriated groundwater, c) appropriated water, d) municipal wastewater, e) brackish groundwater, and f) projected increase in consumptive water use between 2005 and 2035. All metrics are mapped at the Power Control Area (PCA) level. All are mapped to a consistent non-linear color scale; however the color scheme is reversed between availability and demand (e.g., hot colors indicate limited availability or high demand).

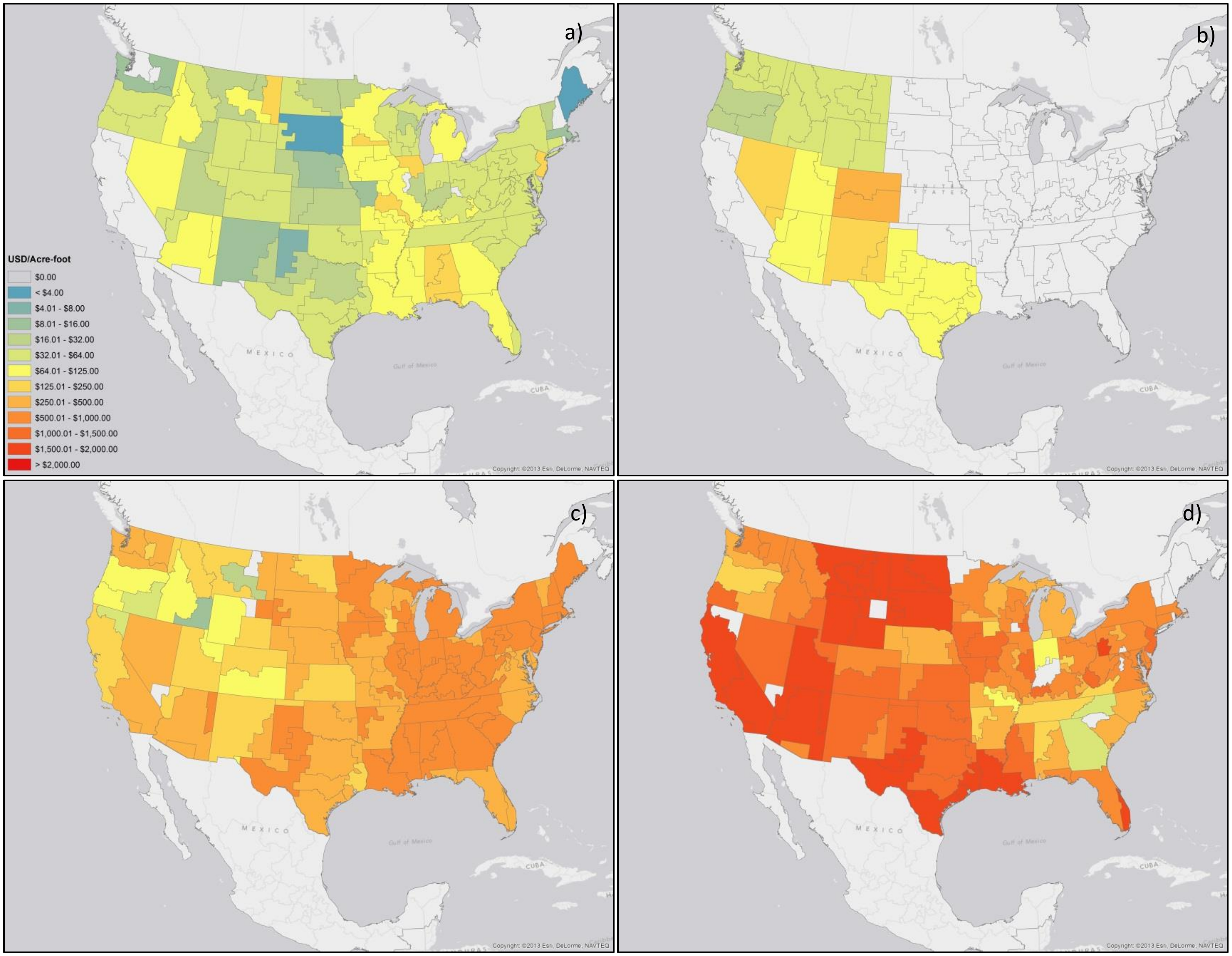

Figure 9. Water cost. Mapped are water cost metrics for a) unappropriated groundwater, b) appropriated water, c) municipal wastewater, and d) brackish groundwater. All metrics are mapped at the PCA. All are mapped to a consistent non-linear color scale.

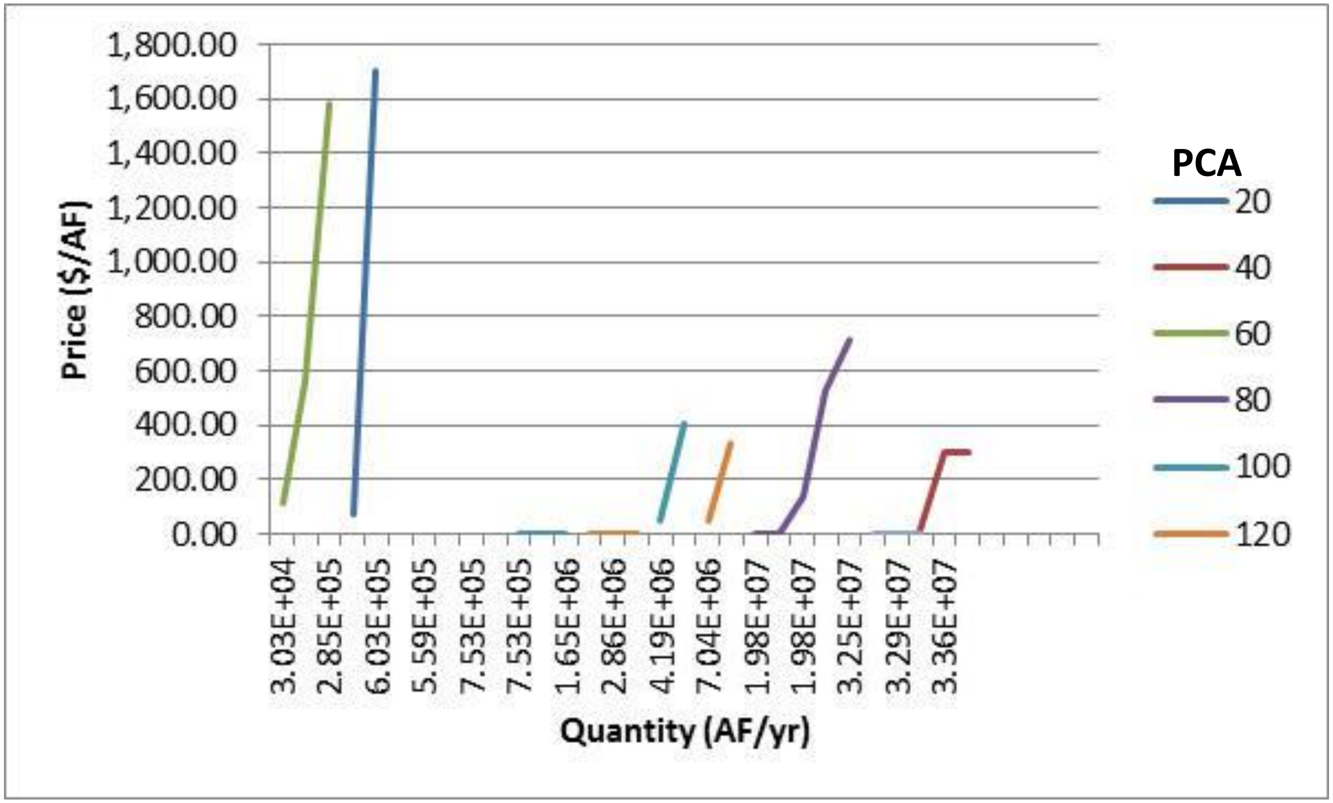

Figure 10. Cost curves showing the quantity of water available at a given price. Curves are shown for select PCA regions.

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