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Mapping the Energy-Water Nexus around the Pacific Rim

Asia-Pacific Economic Cooperation's Energy Working Group

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Abstract

In 2010 global energy production was responsible for 15% of the world's water withdrawals, while 8% of energy consumption was used to deliver water services. Management of this energy-water nexus requires a clear understanding of these inter-related demands as well as their regional distribution. Toward this need the energy-water nexus was mapped for almost 12,000 watersheds distributed across the 21-economies comprising the Asia-Pacific Economic Cooperation. Water consumption for energy production was estimated for 9 different sectors including thermoelectric and hydroelectric power; energy extraction including coal, oil, natural gas, uranium and unconventional oil/gas; and, energy processing including oil and biofuels. Conversely, the energy consumed providing water services was mapped for three sectors, drinking water, wastewater and seawater desalination. These measures of resource consumption were put in context by drawing comparison with published measures of water risk. In total 792 watersheds were designated at energy-water risk; that is, where High to Extreme water stress was co-located with a basin where water was used in energy production. For six economies watersheds at energy-water risk represented half or more of all basins where water was used in energy production, while four additional economies exceeded 30%.

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Introduction

Energy production requires water, while water delivery requires energy. This important interplay has been gaining considerable interest in an international context. A few examples include energy and water as the theme of the 2014 World Water Day (UN 2014), with the corresponding World Water Development Report (WWAP 2014) devoted to exploring how water-related issues and choices impact energy and vice versa. The Water for Energy Framework was launched during the 6th World Water Forum in 2012 to provide a common language for defining the impacts of energy on water (EIP 2015). The World Economic Forum issued a report in 2014 to inform energy policy-makers on nexus issues (WEF 2014), while the World Bank initiated their Thirsty Energy program to support countries efforts to proactively manage energy and water together (WB 2013). And, for the first time the International Energy Agency (IEA) included analyses and projections of energy impacts on water in the World Energy Outlook (IEA 2012). Such interest is driven by the fact that both energy and water are at the top of the global development agenda (Malone 2014), yet significant policy gaps exist in managing this nexus.

The importance of the energy-water nexus is signaled by the intensity of the interaction. Specifically, in 2010 global water withdrawals for energy production were estimated to be 583 billion cubic meters (Bm^3) representing 15% of the world's total withdrawals, of which 66 Bm^3 were consumed (IEA 2012). The water sector was likewise thirsty for energy as 8% of energy consumption was used to lift, treat, and move water (WWAP 2014). Growing populations and economies threaten to intensify the energy-water nexus. By 2035, water withdrawals could increase by 20% and consumption by 85%, driven by a shift towards higher efficiency power plants with more advanced cooling systems (that reduce water withdrawals but increase consumption) and increased production of biofuel (IEA 2012). Given that 1.2 billion people currently live in areas with physical scarcity of water (UNDP 2007), there is an increasing risk of conflict between power generation, other water users and environmental considerations. Similarly, the demand for electricity by the water sector is increasing given the expanding utilization of non-traditional water sources and the move to service the world's 2.5 billion people who lack access to water sanitation and the 748 million that lack access to safe drinking water (WHO 2014).

Management of the nexus requires a clear understanding of the water used for energy production and the energy used to deliver water. Estimates at a global level have been developed by the IEA (2012) as noted above. However, the world is anything but uniform, characterized by strong regional differences in population, resource demand, resource endowment, type and extent of water and energy infrastructure, economics, and industrialization to name a few. These differences lead to variability in the energy-water nexus at the regional level. Recognizing this regionalization the World Water Development Report (WWAP 2014) explored the energy-water nexus across five different continental and sub-continental regions. A series of regional case studies appeared in a special issue of Ecology and Society (Hussey and Pittock 2012). Spang and others (2014) utilized existing national energy portfolio data to estimate the water consumption of energy production for over 150 countries. Additionally, there are a number of studies that focus on the energy-water nexus of an individual country (e.g., Cai et al. 2014; DOE 2014) or a specific aspect of the energy-water nexus in a particular country (Tidwell et al. 2013, Tidwell et al. 2014; Averyt et al. 2011).

In efforts to better inform the energy-water nexus dialogue, this paper builds on and extends the previously noted work in three important ways. First, water used in energy production is mapped across multiple economies and multiple use cases (e.g., thermoelectric power, fuel processing) at a subnational level to distinguish variability within economies. Second, the water used in energy production is put in context by drawing comparison with published measures of water risk (WRI 2015). Third, the energy used to lift, move and treat water is mapped across multiple economies and multiple use cases (e.g., wastewater services, desalination) at a subnational level. The analysis addresses the 21-member economies of the Asia-Pacific Economic Cooperation which are linked by shared geography and economy. The objective of the mapping is to quantify the energy-water nexus at a subnational level, pinpoint potential vulnerabilities, and identify opportunities for international collaboration.

Methods

Mapping of the energy-water nexus for the APEC member economies relied on publically available data. Given the breadth of analysis, many different data sources were required. In general production or capacity data at the plant-level were taken as the entry point for analysis. These production data were combined with average water/energy intensity values to estimate plant-level energy/water use. The plant-level values were then aggregated by watershed for 11,653 basins. The aggregate values were mapped using standard GIS software to facilitate visualization of trends and patterns. To help provide added context, the water for energy values were overlain on Aqueduct estimates of total water risk (WRI 2015). Below a detailed description of the calculations and assumptions associated with each energy and water use sector is given.

Water for Energy

Thermoelectric power: Water consumption estimates, PPQ_i, for individual power plants were largely lacking in the open literature. As such, usage values were estimated by multiplying power plant production P_i, by the water intensity, *WI*, of the power plant (cubic meters per mega-Watt-hour [m^3/MWh]):

$$PPQ_i = P_i * WI_f = C_i * CF_{p,f} * H * WI_f \tag{1}$$

where subscripts designate plant, *i*, and fuel, *f*. Also lacking in the open literature were production values for individual plants, except in the case for the United States (EIA 2015a). For all economies except the United States, electrical production was estimated by multiplying plant capacity, *C* (mega-Watt [MW]), plant capacity factor, *CF* (%), and hours in a year, *H* (Equation

1 where the subscript *p* designates the prime mover). Data on power plant characteristics were available through the IHS International Exploration and Production Database (IHS 2012); specifically, plant name, location (latitude and longitude), primary fuel, prime mover, and capacity. Capacity factors, which are the ratio of a plant's actual generation to its potential generation, were not available for individual plants. As such, capacity factors were set equal to averages for the United States power plant fleet (EIA 2015a) distinguished by fuel type and prime mover (Table 1). These plant level production values were then adjusted (by adjusting the capacity factor data) such that the total calculated electric power production (by fuel type and prime mover) equaled the reported production by APEC member economy (EIA 2015b).

Water intensity factors were taken from Macknick and others (2012), which were compiled from reported data in the open literature distinguished by fuel and cooling type (reproduced in Table 1). Power plant level information on cooling technology was not available (except for the United States, see Diehl et al. 2013) so factors for recirculating cooling were adopted. This resulted in inflated water consumption estimates for nuclear and coal facilities using open-loop cooling (2 to 3 times overestimation); however, open-loop cooling with freshwater accounts for a small part of generation capacity (e.g., 14% Russia, 12% Canada, 4% China and 0% Japan, see IEA 2012). To an even lesser extent overestimation of water consumption occurred for dry cooled systems, except for coal-fired plants in the Northern provinces in China where 127GW of new generation was reported to operate with dry-cooling technology (Yang et al. 2015) accounted for in this analysis.

As the primary concern is freshwater use, power plants located within 1.3 kilometers of the coast were excluded from the analysis as they were assumed to be cooled with seawater. Finally, water consumption for thermoelectric power generation estimated at the power plant level was aggregated to the watershed and APEC member economy levels.

<u>Fuel Extraction</u>: Water consumption estimates, FEQ_i, for individual energy plays/mines were calculated as:

$$FEQ_i = P_i * WI_f \tag{2}$$

where *P* is the production (mega-Joules per year [MJ/yr.]) and *WI* is the water intensity of the extraction process (m^3/MJ). Again, subscripts designate the play/mine, *i*, and fuel, *f*. Water intensity values were taken from Spang and others (2014) which were compiled from operational data in the open literature (reproduced in Table 1). Consumptive water use was estimated for conventional and unconventional oil and gas, coal, and uranium. Similar to water consumption for thermoelectric power, the play/mine level estimates were aggregated to the watershed and APEC member economy levels.

Information on individual conventional oil and gas plays was available through the IHS International Exploration and Production Database (IHS 2012), providing data on the name,

Table 1: Water consumption factors

Energy Process	Energy Source	Water Consumption Factor	Unit
Thermoelectric Power Generation*	Coal	2.60	m^3/MWh
	Natural Gas Steam	3.13	m^3/MWh
	Natural Gas Combined Cycle	0.77	m^3/MWh
	Nuclear	2.55	m^3/MWh
	Biopower	2.09	m^3/MWh
	Geothermal	1.91	m^3/MWh
Extraction**	Coal	0.043	m^3/GJ
	Conventional Oil	0.081	m^3/GJ
	Conventional Gas	0.004	m^3/GJ
	Uranium	0.033	m^3/GJ
	Unconventional Oil/Gas	0.017	m^3/GJ
Processing**	Oil	0.04	m^3/GJ
	Bioethanol	0.145	m^3/GJ
	Biodiesel	0.031	m^3/GJ

* Data reproduced from Macknick and others (2012), median values
** Data reproduced from Spang and others (2014), median values

location, and cumulative production since initiation of operations. Annual production of the play, P_i, was calculated as:

$$P_i = \frac{CP_i}{CP_c} * P_c \qquad (3)$$

where CP_i is the cumulative production of the play, CP_c is the cumulative production of the APEC member economy, and P_i is the annual production of the APEC member economy in 2012 (EIA 2015b). Offshore production is excluded from the analysis as utilization of sea water is assumed. A similar exercise was accomplished individually for conventional oil and conventional gas production.

Data on annual production of oil and gas from unconventional (shale) plays was available for the United States from EIA (2015c; 2015d). Canada and China are the only other APEC economies to produce unconventional oil and/or gas. Production data for these economies were taken from EIA (2015e).

Coal production data was available through the United States Geological Survey (2015); specifically, information concerning the name of the mine, its location, capacity and status. Annual production was estimated according to Equation 3 using international production data from EIA (2015b).

Uranium production data was limited to that available through the World Nuclear Association (2015). Production data by mine for 2014 was available for the world's top producers, including the APEC member economies, Canada, Australia, Russia, United States, and China.

Fuel Refining: Water consumption associated with the refining of oil, bioethanol and biodiesel was estimated at the plant-level and subsequently aggregated to the watershed and APEC member economy levels. Estimates were derived using Equation 2 with water intensity values taken from Spang and others (2014). For oil refineries, plant level information was available through the IHS International Exploration and Production Database (IHS 2012), including the name, location, status and capacity of the plant. Annual production was estimated according to Equation 3 with international production data at the APEC member economy level coming from EIA (2015b). The IHS database also provided information on bioethanol and biodiesel plant name and location, but lacked capacity information. For this case, bioethanol and biodiesel production at the APEC member economy level (EIA 2015b) was uniformly distributed over all active plants in that economy.

Water Risk

Water risk values were taken directly from the Aqueduct Water Risk Atlas (WRI 2015). These water risk values are based on a framework that includes 12 global indicators grouped into three categories of risk to yield one aggregate value (used here). The first risk category is the Water Quantity Risk that considers baseline water stress (ratio of withdrawals to available flow), inter-annual variability, seasonal variability, flood occurrence, drought severity, upstream storage and groundwater stress. The second category scores the Physical Water Quality Risk, measuring the return flow ratio and upstream protected land. The final category addresses Regulatory and Reputational Risk, treating media coverage, access to water and threaten amphibians. Together these measures provide a consistent and comprehensive measure of water risk. A complete description of the data collection, calculation, and mapping techniques are described in the Aqueduct Waster Risk Framework documents (Reig et al. 2013).

Energy for Water

Energy is used to lift, convey, treat and distribute water. Due to data limitations, energy used in the water sector was limited to drinking water, municipal wastewater, and desalination. Because there is very limited data at the individual plant level, energy use estimates were developed largely on population distributions and access to improved drinking water and sanitation services.

Drinking Water: Energy use to provide drinking water services, ED_w, was estimated at the watershed-level according to:

$$ED_w = \frac{Pop_w}{Pop_c} * A_c * DQ_c * EI_{ws} \quad (4)$$

where *Pop* is the population (people), *A* is the percentage of people with access to improved drinking water services, *DQ* is water withdrawal in the municipal sector (m^3/yr.) and *EI* is the energy intensity of drinking water services (MWh/m^3). Subscripts designate the APEC member economy, *c*, watershed, *w*, and water sector, *ws*. Population data was acquired from the Center for International Earth Science Information Network (CIESIN 2005) while the percentage of people with access to improved drinking water was taken from the Pacific Institute (2015). Water withdrawals by APEC member economy in the municipal sector were taken from AQUASTAT database (FAO 2014). Information on individual municipal drinking water systems was not available; as such, the energy intensity adopted was based on the United States average electricity consumed per cubic meter of delivered drinking water (6.41×10^{-4} MWh/m^3), including the energy to lift, convey, treat, store and distribute the water (EPRI 2013).

<u>Wastewater</u>: Energy use in the municipal wastewater sector was estimated in a similar fashion to that of drinking water (above). Calculation of energy use followed the formulation in Equation 4. Percentage of population connected to improved wastewater services was taken from the World Bank (WB 2015). Wastewater production by APEC member economy was taken from the AQUASTAT database (FAO 2014). Again, information on individual wastewater plants was not available, thus the energy intensity was based on the United States average electricity consumed per cubic meter of treated wastewater (6.78×10^{-4} MWh/m^3) taken from the work of EPRI (2013).

<u>Desalination</u>: Energy use for desalination plants, ES_p, was based on data for the 100 largest plants as of 2004 (Wangnick 2005). Data included location and capacity of the plant. Plant capacity, DSQ_i (million gallons per day), was then multiplied by an energy intensity factor based on averages for plants operating in the United States (EPRI 2013).

Results

The water consumed by energy production and the energy consumed to provide water services were mapped for 11,653 watersheds comprising the 21-APEC member economies. Below, results are given grouped first by water use for energy followed by a discussion of the energy use for water. In each case the analysis begins with a review of the watershed scale mapping and then progresses to the APEC member economy level. Water and energy use are then put in context by comparing them to an expression of water risk (WRI 2015).

Water for Energy

<u>Watershed</u>: Maps indicating the water consumed in energy production for each of the APEC economies were developed for eight different energy sectors. These sectors were organized into three groups, energy extraction (oil, natural gas, coal, uranium and unconventional oil/gas), energy processing (oil, biofuels), and thermoelectric power generation. In addition, hydropower was mapped by capacity given the difficulty of assigning water use to multipurpose reservoirs. Figure 1 shows a map of the water consumed for thermoelectric power generation while Figure 2

shows that for natural gas extraction. Maps for the other 7 sectors are provided in the supplemental file for this paper.

Three facts were quickly evident in comparing the maps. First, there was a big difference in the scales of water use between the 8 sectors. Natural gas extraction topped-out at 5 Mm^3/yr. and biofuel refining at 1 Mm^3/yr. In contrast, all other energy sectors topped-out at greater than 100 Mm^3/yr. Second, the number of impacted watersheds differed considerably. Thermoelectric power generation resulted in water consumption in 1211 watersheds in the APEC region, while natural gas extraction impacted 934, oil extraction 901, unconventional oil/gas 320, oil refining 279, biofuel refinement 258, coal extraction 168, and uranium 20 watersheds. There were 775 watersheds with some hydropower capacity. The third noteworthy feature was the very different spatial footprint of water consumption among the various sectors. For example, heavy consumption of water by thermoelectric power occurred in the eastern United States, China, Australia and western Russia, while in contrast, unconventional oil/gas extraction was limited largely to the United States and Canada.

In total 38.9 Bm^3/yr. of water was consumed in the energy sector across the APEC economies. Thermoelectric power generation was by far the largest consumer of water at 19.2 Bm^3/yr. or 49% of consumption (Figure 3). Coal extraction was the next largest consumer of water at 6.2 Bm^3/yr. or 15%. Other notable sectors included unconventional oil/gas at 5.3 Bm^3/yr. (14%), oil refining at 3.9 Bm^3/yr. (10%) and oil extraction at 3.7 Bm^3/yr. (9%). Energy production involving water use (including hydropower) occurred in 2495 watersheds (21%) in the APEC region.

<u>APEC Member Economy</u>: Water consumption estimated at the watershed level was aggregated to the APEC member economy level for each of the 8 energy sectors. The mix of water consumption across the eight energy sectors was graphed in Figure 4 for each of the 21 APEC economies. Note that the consumption of sea water for thermoelectric power generation and offshore oil and natural gas extraction are not included in these estimates. This figure indicates considerable variability in energy mix and thus water consumption profiles for the APEC economies. This variability reflects the difference in the geographic footprint of water use seen in the watershed maps (e.g., Figures 1-2). Thermoelectric power generation was the most important single sector across APEC member economies resulting in ≥ 40% of consumption in 15 economies and 60% in 10 APEC member economies. Refining of oil accounted for ≥ 25% of 7 economies energy sector water consumption, while oil extraction accounted for ≥ 35% of 3 APEC member economies water consumption.

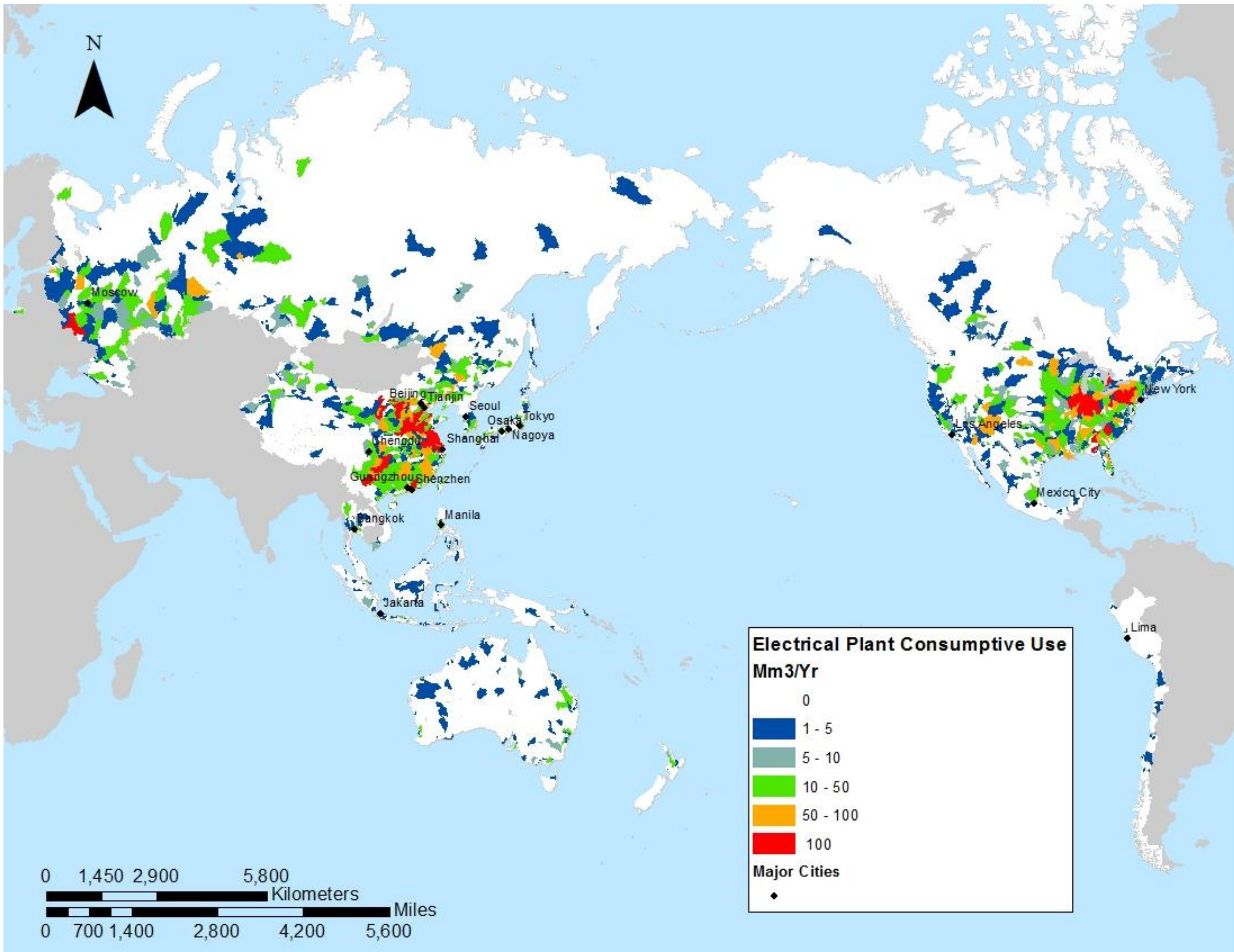

Figure 1: Water consumed for thermoelectric power generation in the 21-member economies of APEC. Data are mapped for almost 12,000 watersheds across this region.

A four order of magnitude difference in total water consumption for energy production was noted across the APEC economies (Figure 5). The United States registered the largest water consumption at 13.8 Bm^3/yr. followed by China at 13.6 Bm^3/yr., Canada at 1.8 Bm^3/yr. and Australia at 1.0 Bm^3/yr. In contrast, Brunei consumed only 1.5 Mm^3/yr. and Papua New Guinea 12.1 Mm^3/yr. On a per capita basis, Canada led with 59.1 m^3/person, followed by Australia with 56.1 m^3/person and the United States with 50 m^3/person. In contrast, eleven other APEC member economies had rates less than 6 m^3/person.

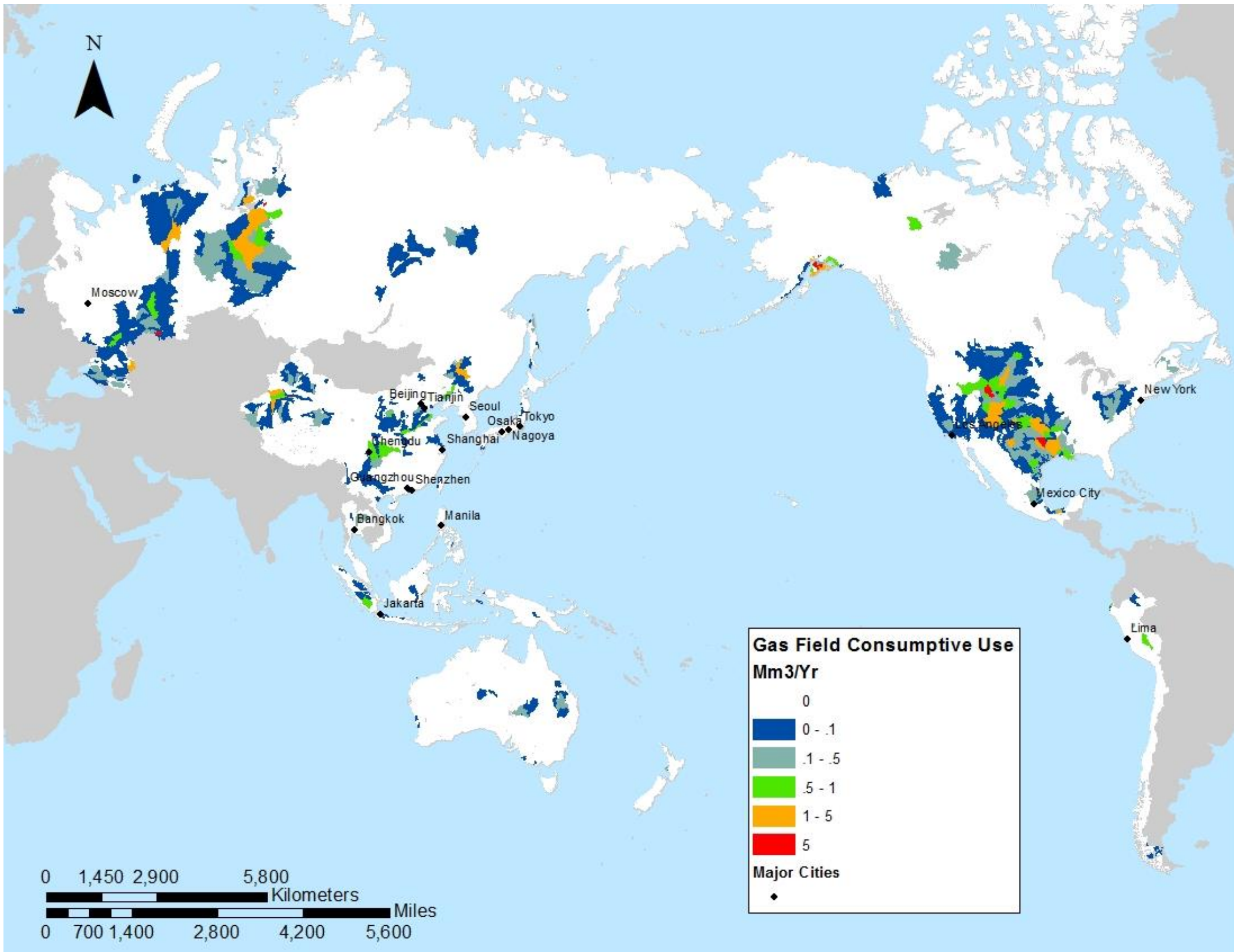

Figure 2: Water consumed for natural gas extraction in the 21-member economies of APEC.

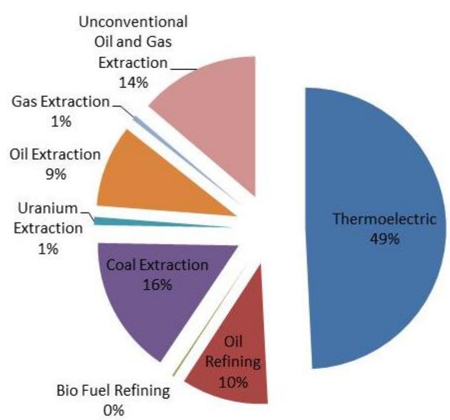

Figure 3. Percent water consumption by energy sector in the APEC region.

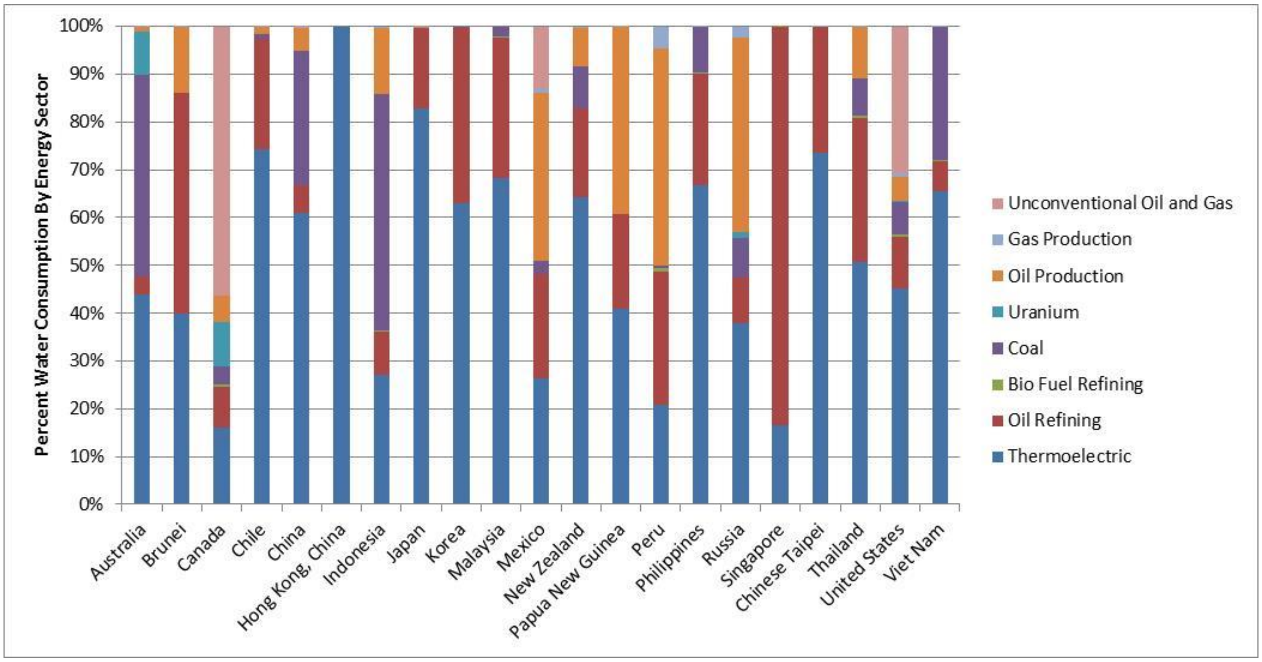

Figure 4. Distribution of water consumption across the eight energy sectors for each APEC member economy. Note that the consumption of sea water by thermoelectric generation and off-shore oil/natural gas extraction is not included.

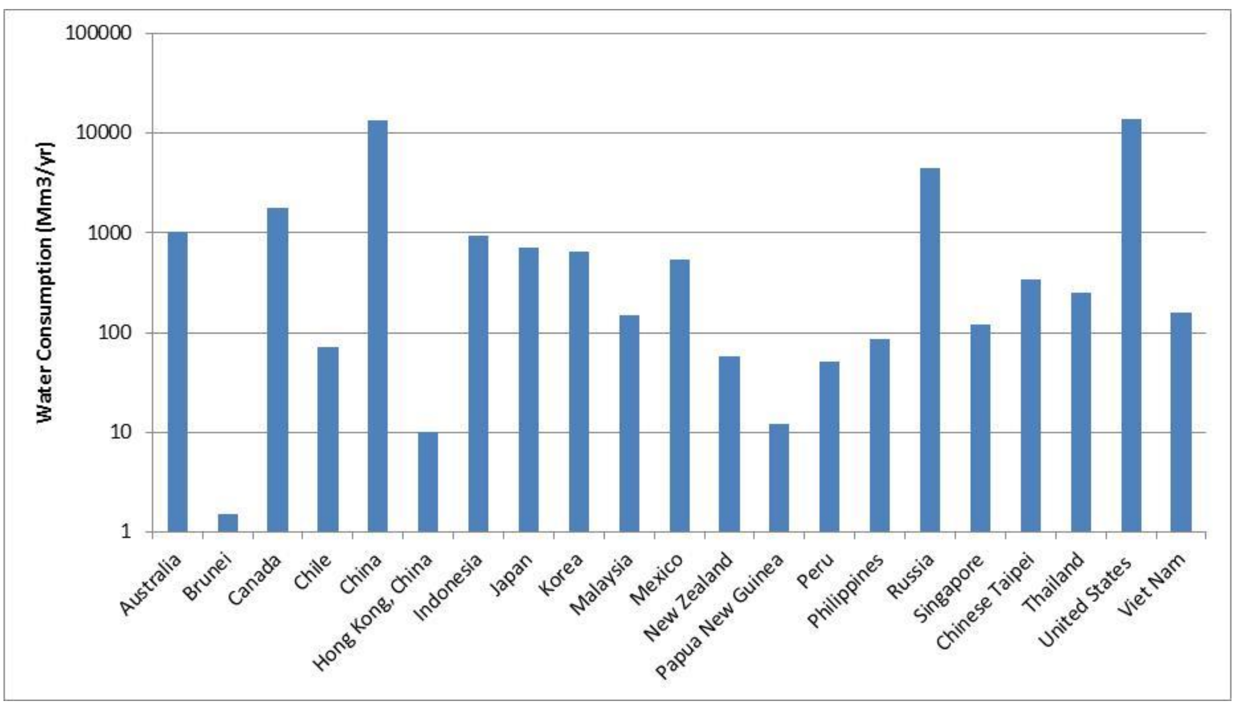

Figure 5. Energy related water consumption for each of the 21 APEC member economies.

Water Risk

Watershed: In Figure 6 the Aqueduct Water Risk metric was overlaid on the total water consumption for energy production data. Cross-hatched areas refer to watersheds designated with High to Extreme water risk. Figures 7 and 8, respectively, provide views of the same map but expanded around China and the United States. “Energy-Water Risk” was inferred where these maps intersect; that is, watersheds where water risk was High to Extreme and there was consumption of water for energy production. These watersheds at energy-water risk are locations where existing operations deserve extra attention and are also locations where expanding energy production will be problematic due to physical/institutional limitations on water supply.

Energy related water use was particularly heavy in the eastern portions of the United States, China and Australia, along with the western portions of Canada and Russia (Figure 6). High to Extreme water risk was concentrated in the western United States, northern China, western

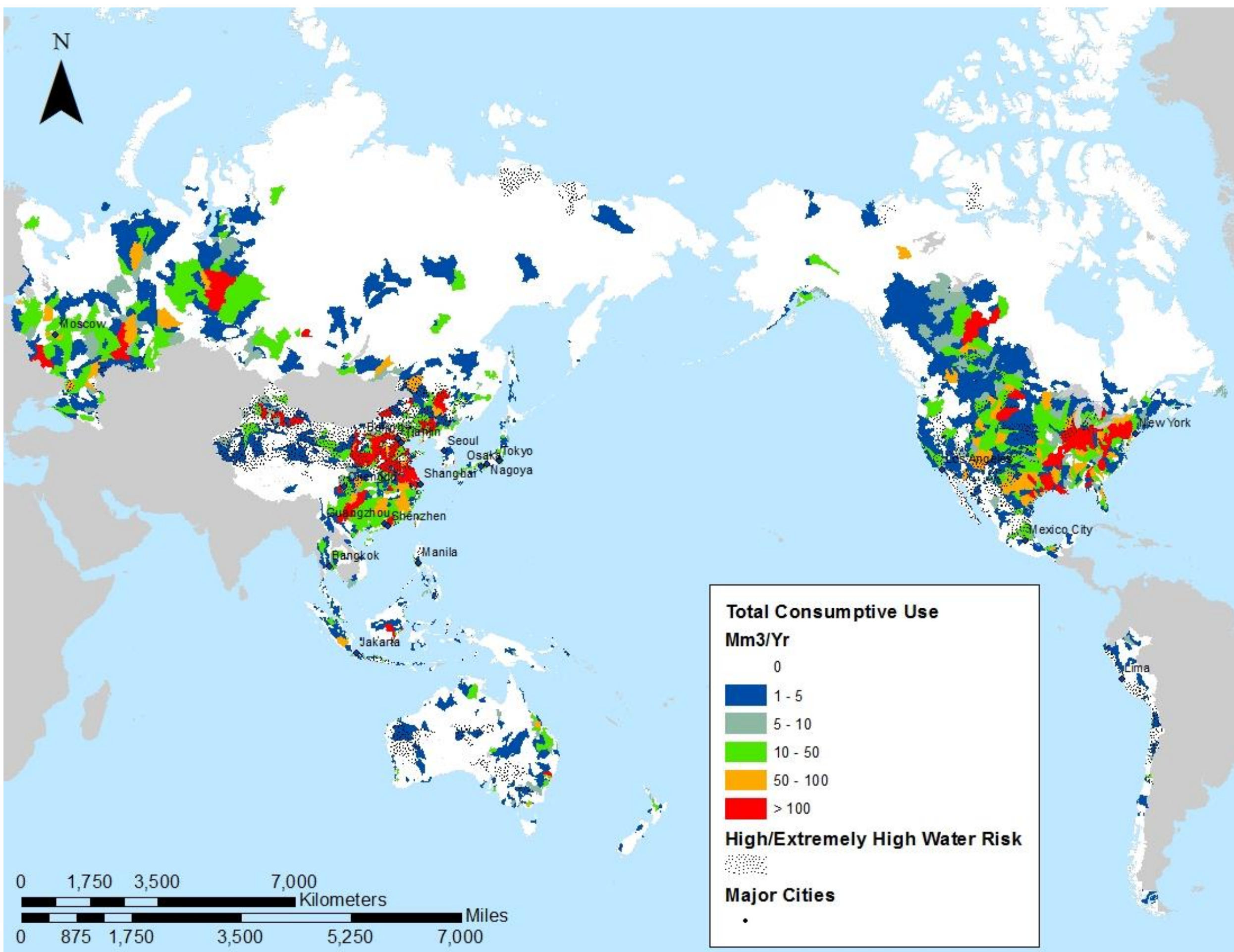

Figure 6: Total water consumption for energy production mapped over regional water risk (WRI 2015). Data are mapped for the 21-member economies of APEC for almost 12,000 watersheds across this region.

Australia and the extreme west coast of South America (Figure 6). In total 2330 watersheds in the APEC region (20%) were designated as High to Extreme water risk, while 782 of these watersheds (6.7%) also had some water use for energy production—thus defined as being at energy-water risk. The highest concentration of watersheds at energy-water risk was in northeastern China and the western United States. Thermoelectric power production contributed to energy-water risk in 437 watersheds, gas production in 337, oil extraction in 331, hydropower in 190, oil refining in 114 watersheds, biofuel refining in 105 watersheds, and natural gas extraction in 97 watersheds.

APEC Member Economy: There was significant disparity in water risk across the 21 APEC economies (Table 2). Nine economies had over 20% of their watersheds at High to Extreme water risk, with Korea at 61% being the highest. In contrast, nine of the remaining 12 economies had less than 10 % of their watersheds at High to Extreme water risk. These watersheds were found to be co-located with 782 watersheds where water was used in energy production, designated as being at energy-water risk. This is particularly concerning for several economics where watersheds at energy-water risk represent 50% or more of all basins where water is used in energy production; specifically, Hong Kong, China and Singapore (100% but only occupy a single watershed each), Korea (59%), China (54%), Peru (51%) and Chinese Taipei (50%). Four other economies exceed 30%, Philippines (45%), United States (37%), Chile (37%) and Mexico (31%).

Energy for Water

Watershed: Maps depicting the energy consumed to provide water services were compiled for the 21 APEC economies. Energy use for three different water sectors were mapped, including the energy consumed to deliver drinking water, to treat and dispose of wastewater and to operate desalination plants. Figure 6 shows the map of energy use for drinking water services, the other two maps are included in the supplemental file to this paper. As this estimate of energy use was strongly dependent on the population of the watershed, its footprint was dictated by population distribution, that is, high values are associated with urbanized areas. Although difficult to detect in the maps several economies have limited access to improved drinking water such as Papua New Guinea (40% access), Philippines (71%) and Peru (82%), resulting in overall reduced energy use. Similar results apply to wastewater services but with more dramatic differences in access. Data for desalination plants are limited to the largest 100 plants, which results in plants only in the United States, China, Australia, and Mexico, in each case located near the ocean.

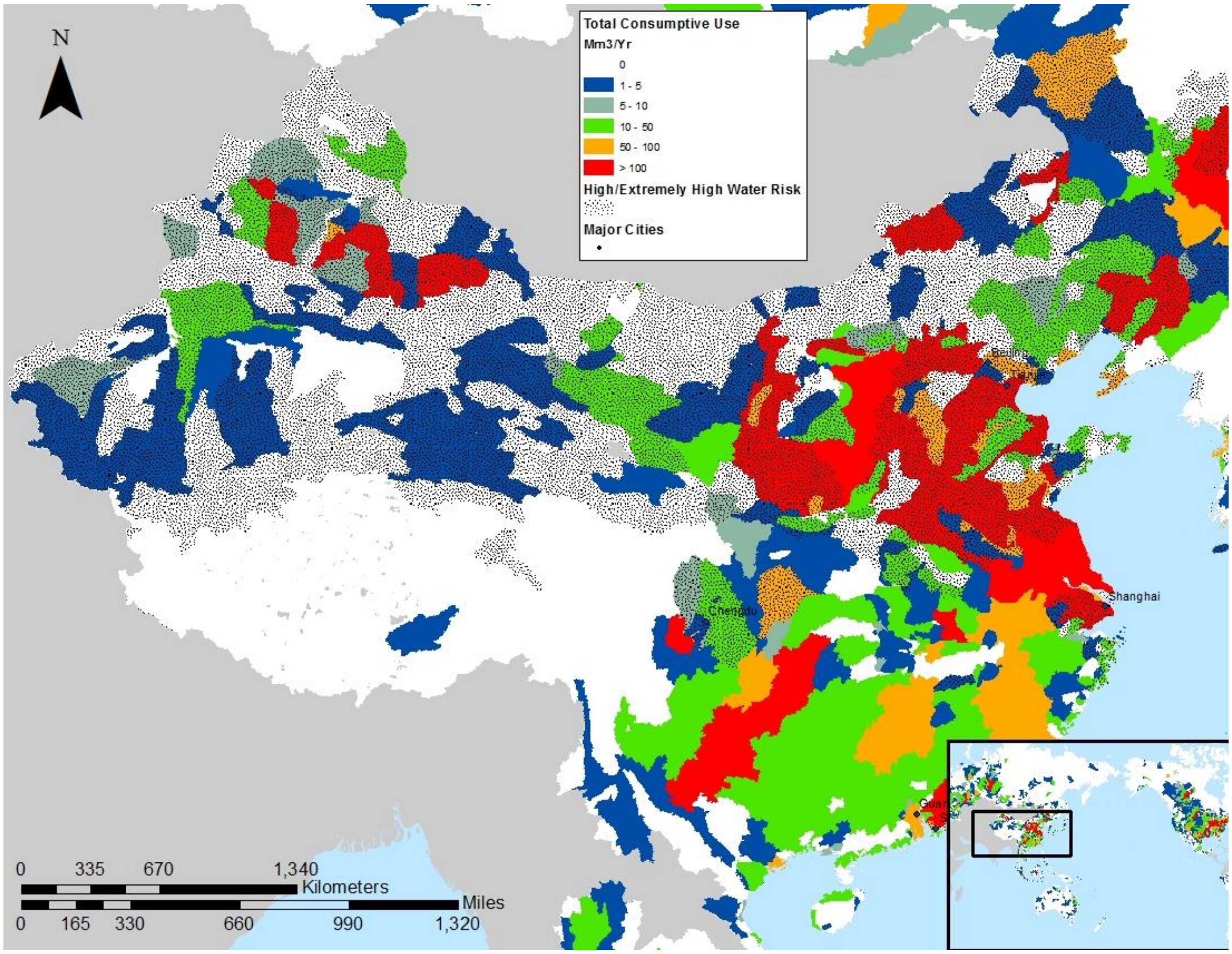

Figure 7: Total water consumption for energy production mapped over regional water risk (WRI 2015) focused on the China region.

Total energy consumption for water services in the APEC region was roughly 252 million mega-Watt-hours per year (MMWh/yr.). Energy consumption was relatively evenly split between drinking and wastewater at 135 MMWh/yr. and 111MMWh/yr., respectively, while electricity used for operating of desalination plants measured 4MMWh/yr. On average APEC members expend about 2.5% of their electricity production on water services.

APEC Member Economy: Energy used in providing water services estimated at the watershed level was aggregated to the APEC member economy level for each of the 3 water sectors (see Supplemental Material for data table). Energy for drinking and wastewater tracked each other relatively closely for each APEC member economy. Any variances were due to differences in access between drinking and wastewater. Energy use for desalination operations was limited to just 5 APEC member economies; however, this was largely an artifact of the availability of data which was limited to the world's largest 100 plants. Electricity for desalination tended to be one- to two-orders of magnitude less than that used in the drinking or wastewater sectors.

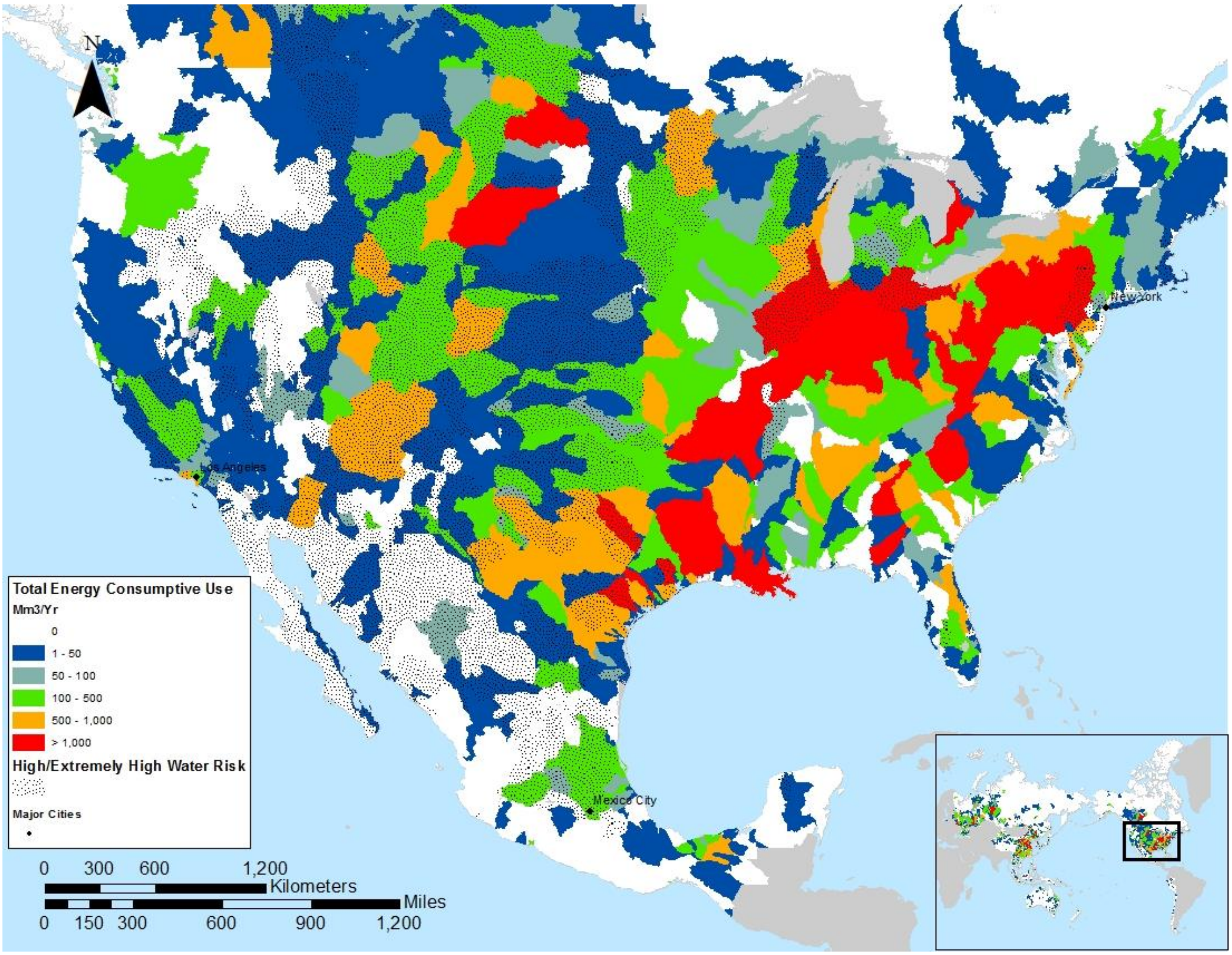

Figure 8: Total water consumption for energy production mapped over regional water risk (WRI 2015) focused on the United States region.

There was a large disparity in the total energy used to provide water services among the 21 economies. The range ran from a high of 74 MMWh/yr. for the United States to 0.055 MMWh/yr. for Papua New Guinea. In terms of the percent of total electricity production used in the water sector the Philippines had the highest at 4.8% and Viet Nam the least, 0.9%.

Megacities: Eighteen cities were identified with a population of ≥10M people in the APEC region (see cities listed in each of the Figures). These are locations of focused growth and thus significant demand for water and energy resources. Notable is the fact that eleven of these cities are located in watersheds with High to Extreme water risk. Also, all of the cities have some water use for energy production, in most cases resulting from 2 or more different energy sectors. Importantly, these cities are also associated with some of the highest energy requirements to provide water services (simply because of their large population).

Table 2. Watersheds at water risk and energy-water risk by APEC member economies

APEC member economies	Total Watersheds	Water Risk	Water Used in Energy Production	Energy-Water Risk	Percent Basins at Energy-Water Risk*
Australia	1362	207	155	41	0.26
Brunei	17	0	3	0	0.00
Canada	1486	46	187	35	0.19
Chile	268	103	38	14	0.37
China	1630	765	434	235	0.54
Hong Kong, China	1	1	1	1	1.00
Indonesia	865	80	126	26	0.21
Japan	240	55	108	18	0.17
Korea	63	39	22	13	0.59
Malaysia	237	9	35	3	0.09
Mexico	623	303	90	28	0.31
New Zealand	159	2	28	1	0.04
Papua New Guinea	152	7	10	2	0.20
Peru	216	95	35	18	0.51
Philippines	69	23	20	9	0.45
Russia	2294	106	314	31	0.10
Singapore	1	1	1	1	1.00
Chinese Taipei	35	13	18	9	0.50
Thailand	184	8	38	2	0.05
United States of America	1611	456	796	294	0.37
Viet Nam	135	11	35	1	0.03

*Percentage of basins at energy-water risk relative to the total number of basins where energy production requires water.

Discussion

The energy-water nexus has been mapped for 11,653 watersheds distributed across the 21 APEC economies. Water consumption for energy production was explored for 9 different sectors including thermoelectric and hydroelectric power; energy extraction including coal, oil, natural gas, uranium and unconventional oil/gas; and, energy processing including oil and biofuels. Conversely, the energy consumed while providing water services was mapped for three sectors, drinking water, wastewater and seawater desalination.

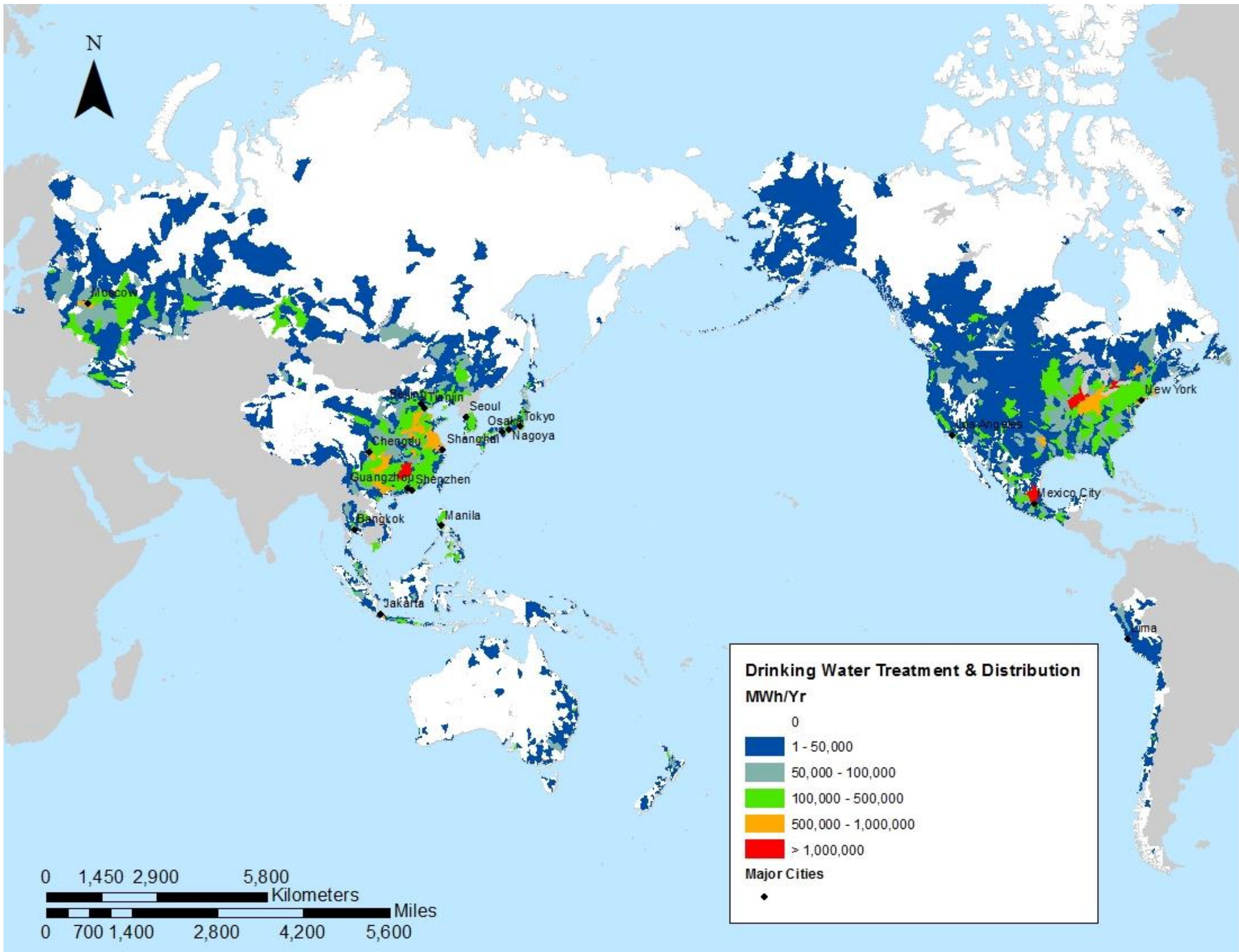

Figure 9: Energy used to provide drinking water services in the 21-member economies of APEC.

A significant challenge to this work was the availability of data, and these limitations must be appreciated when interpreting results. Across the multiple datasets used in the analysis, confidence is placed in information concerning location (e.g., of a mine or plant), type of feature (e.g., coal-fired vs. nuclear power plant) and capacity. Therefore, results related to the spatial distribution and texture (relative strength from one location to another) of resource use are viewed with a high level of confidence. Alternatively, confidence in the absolute values of water and energy consumption are much more suspect. This lower level of confidence is caused by a number of factors, including lack of installation specific production values; lack of details on installation characteristics such as type of cooling system or open pit vs. underground mining; and, utilization of water and energy intensity factors that represent broad industry averages while recognizing that individual plant operations often deviate significantly. A measure of control was exercised on these estimates by constraining energy production at the APEC member economy level to match reported data for which there is a high level of trust (EIA 2015b). Additionally, lack of data precluded estimation of water consumption for biofuel feedstock irrigation, which is viewed as an important limitation of this analysis.

Even in the face of these limitations important insights can still be gained from this analysis. The first is the importance of place in understanding the energy-water nexus. A review of the various maps (Figure 1-2 and 6-9) reveals significant granularity within each county; that is, a rich geospatial pattern of interdependent water and energy consumption. Also important is the fact that the pattern and density of consumption varies considerably across the various energy and water sectors. For example, the footprint of water consumption for coal extraction is very

different from that for thermoelectric power generation. There are a variety of factors at work that influence the noted patterns. In some cases the pattern is defined by the endowment of a resource such as with the case of coal, oil, natural gas, uranium and unconventional oil/gas extraction. Alternatively, thermoelectric power, drinking water and wastewater are strongly influenced by population trends, while energy processing and desalination trends reflect a blend of endowment, population and infrastructure. The fact that water used in energy production occurs in 2495 watershed is both beneficial in the sense that these demands are broadly distributed, but also means that issues of water and energy are colliding in many locations.

These distinctive geospatial trends suggest that different regions are faced with different energy-water challenges. This is the case whether the perspective is a watershed or APEC member economy. Some regions experience high water consumption for oil extraction, while other areas are characterized by high water consumption for biofuel processing, while still other areas have water demands across multiple energy sectors. The water risk footprint also varies by watershed, both in the way it is expressed (e.g., limited groundwater supply, instream flow requirements, high water use, drought prone) and its intensity (Low to Extreme). Overlap between these two sets produces yet another dimension of concern. Thus, steps taken to manage the energy-water nexus in one watershed may need to be very different than in a neighboring watershed.

Ultimately this work provides insight into the regional variability of the energy-water nexus. This is useful for a number of reasons. First, the analysis helps identify "hot-spots"; in particular, regions that have overlapping energy and water risks. In total 792 watersheds were designated at energy-water risk. For six economies these watersheds represented half or more of all basins where water was used in energy production. Four additional economies were at 30% or more. While such distinction does not necessarily mean the region is destined to fail, but rather attention to the co-management of energy and water is warranted. Second, the analysis provides insight for future development, providing quantitative information to help direct new development away from areas of intense use and high water risk. Finally, the analysis can help connect regions facing similar challenges and thus the opportunity for collaboration.

Future Activities

Several useful steps can be taken to build on this initial analysis. Among the first activities would be to improve the energy-water data collected as part of this analysis. Direct engagement with APEC member economy energy and water ministries would be needed to gather and verify all available data pertaining to electricity production, energy extraction, fuel processing, and water treatment. These data would be used to fill in missing information (to that gathered above) and to verify current data. Examples of missing information include electricity production, cooling type and water source for all thermoelectric power plants; production data by mine and play; and, oil and biofuel production by processing plant. Of particular interest would be data for estimating the water consumed by the irrigation of biofuel feedstocks. Together, such data would improve the analysis provided here, particularly the absolute values of water and energy use by watershed and APEC member economy.

With a solid understanding of the current state of the energy-water nexus throughout the APEC region, attention would focus on how the nexus might evolve in the future. Working with APEC member economy ministries, scenarios projecting alternative energy and water futures would be developed as a uniform basis for planning. Scenarios would consider such factors as climate variability, domestic and international policy, technology evolution, fuel prices and many others. Using the basic analysis established here, water use by energy production (across the 9 different sectors) and the energy use for water services (3 different sectors) would be estimated and compared to updated measures of water stress. This would help identify areas where expanding water and energy use could be problematic, “energy-water nexus hotspots”.

Where these hotspots are identified, measures to mitigate issues would be explored. A variety of measures are immediately available such as favoring construction of low water intensity electric power generation options (e.g., PV solar, natural gas combined cycle); siting of new water intensive development in regions with abundant water; managing the growing demand for water and energy; and capturing the energy in wastewater streams. There are also emerging technologies pertaining to power plant cooling and water treatment that could significantly alter the future character of the energy-water nexus. However, such measures must be considered in the broader context of cost, system reliability, environmental impacts and national security.

Supporting this analysis and planning would be a series of workshops and case studies. Workshops would be organized to help educate member economies on energy-water nexus issues, to jointly explore mitigating measures, and for networking of expertise and data. Such workshops would also provide a venue for identifying opportunities for collaboration across member economies; particularly, through engagement in co-benefitting case studies. Case studies would be designed to educate, test, and demonstrate the efficacy of measures for managing and mitigating the effects of the energy-water nexus. Case studies would include joint energy-water planning exercises as well as the demonstration of emerging technologies.

References

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. November.

Cai, B., Zhang, B., Bi, J. and Zhang, W., 2014. Energy's thirst for water in China, Environmental Science and Technology, 48, 11760-11768.

Center for International Earth Science Information Network (CIESIN), 2005. Gridded Population of the World Version 3 (GPWv3): Population Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (Downloaded 28 Sept 2015).

Diehl, T.H., Harris, M.A., Murphy, J.C., Hutson, S.S., and Ladd, D.E., 2013, Methods for estimating water consumption for thermoelectric power plants in the United States: U.S. Geological Survey Scientific Investigations Report 2013–5188, 78 p., http://dx.doi.org/10.3133/sir20135188.

DOE (U.S. Department of Energy), 2014. The Water-Energy Nexus: Challenges and Opportunities, June 2014. at: http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities

EIA (Energy Information Administration), 2015a. Form 923: Monthly and Annual Electric Power Data (Washington, DC: US EIA)

EIA (Energy Information Administration), 2015b. International Energy Statistics (Washington, DC: US EIA): at http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12

EIA (Energy Information Administration), 2015c. Shale Gas Production (Washington, DC: US EIA): at http://www.eia.gov/dnav/ng/ng_prod_shalegas_s1_a.htm

EIA (Energy Information Administration), 2015d. Drilling Productivity Report (Washington, DC: US EIA): http://www.eia.gov/petroleum/drilling/pdf/dpr-full.pdf

EIA (Energy Information Administration), 2015e. Shale Gas and Tight Oil are Commercially Produced in Just Four Countries (Washington, DC: US EIA): http://www.eia.gov/todayinenergy/detail.cfm?id=19991#

EIP, 2015. W4EF-Framework for evaluation and report of the energy impacts on water. http://www.eip-water.eu/W4EF

EPRI (Electric Power Research Institute), 2013. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*, Topical Report 3002001433; Electric Power Research Institute: Palo Alto, CA.

FAO (Food and Agriculture Organization of the United Nations), 2014. AQUASTAT database. http://www.fao.org/nr/water/aquastat/main/index.stm. Website accessed on[03/11/2014 18:8]

Hussey, K. and Pittock, J., 2012. The Energy-Water Nexus: Managing the Links between Energy and Water for a Sustainable Future, Ecology and Society, 17(1): 31.

IEA (International Energy Agency), 2012. World Energy Outlook. Chapter 17, Water for Energy.

IHS, 2012. IHS International Exploration and Production Database, see www.ihs.com/energy.

Macknick J., Newmark R., Heath G. and Hallett K. C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature, Environ. Res. Lett. 7 045802

Malone, D., 2014. Comments opening World Water Day, March 23, 2014; see http://ourworld.unu.edu/en/world-water-day-focus-on-the-water-energy-nexus

Pacific Institute, 2015. Update: Water Data, Table 3a and 3b: Access to Improved Drinking Water by Country, 1970-2008 & 2011.

Reig, P., Shiao, T. and Gassert, F., 2013. Aqueduct Water Risk Framework, Working Paper of the World Resources Institute, Washington, DC: January 2013, http://www.wri.org/publication/aqueduct-water-risk-framework.

Spang, E.S., Moomaw, W.R., Gallagher, K.S., Kirshen, P.H. and Marks, D.H., 2014. The water consumption of energy production: an international comparison, Environmental Research Letters, 9, 105002, 14pp.

Tidwell, V.C., Moreland, B. and Zemlick, K., 2014. Geographic footprint of electricity use for water services in the western U.S., *Environmental Science and Technology*, 48(15), 8897-8904. DOI: 10.1021/es5016845.

Tidwell, V.C., Malczynski, L.A., Kobos, P.H., G. Klise, E. Shuster, 2013. Potential impacts of electric power production utilizing natural gas, renewables and carbon capture and sequestration on U.S. freshwater resources, *Environmental Science and Technology*, 47 (15), pp 8940–8947, **DOI:** 10.1021/es3052284.

United Nations, 2014. UN Water: Water and Energy, http://www.unwater.org/topics/water-and-energy/en/.

UNDP, 2007. Human Development Report 2006. Coping with water scarcity. Challenge of the twenty-first century. UN-Water, FAO, 2007.

U.S. Geological Survey, 2015. Mineral Operations outside the United States, 2010: Virginia. Available online at: http://mrdata.usgs.gov/metadata/minfac.html

WB (The World Bank), 2015. World Development Indicators: Improved Sanitation Facilities, http://data.worldbank.org/indicator/SH.STA.ACSN

WB (The World Bank), 2013. Thirsty Energy: securing Energy in a Water-Constrained World, http://www.worldbank.org/en/topic/sustainabledevelopment/brief/water-energy-nexus

Wangnick/GWI. 2005. 2004 *Worldwide desalting plants inventory.* Global Water Intelligence. Oxford, England.

WEF (World Economic Forum), 2014. The Water-Energy Nexus: Strategic Considerations for Energy Policy-Makers, Global Agenda Council on Energy Security, May 2014.

WHO (World Health Organization), 2014. Investing in Water and Sanitation: Increasing Access, Reducing Inequalities. http://www.who.int/water_sanitation_health/publications/glaas_report_2014/en/

World Nuclear Association, 2015. World Uranium Mining Production. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/

WRI (World Resources Institute), 2015. Aqueduct Water Risk Atlas, available at: http://www.wri.org/applications/maps/aqueduct-atlas/#x=33.49&y=1.59&s=ws!20!28!c&t=waterrisk&w=def&g=0&i=BWS-16!WSV-4!SV-2!HFO-4!DRO-4!STOR-8!GW-8!WRI-4!ECOS-2!MC-4!WCG-8!ECOV-2!&tr=ind-1!prj-1&l=3&b=terrain&m=group

WWAP (United Nations World Water Assessment Programme), 2014. *The United Nations World Water Development Report 2014: Water and Energy*. Paris, UNESCO. http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2014-water-and-energy/

Yang, C-J, Sun, R. and Jackson, R.L., 2015. Air-cooled thermoelectric power in China and the United States, in review, available at: http://people.duke.edu/~cy42/Air-cooling.pdf

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