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China's Energy-Water Nexus in 2009 by Sankey Diagram

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We visualize water utilization in China from source to service and onward to destination, using a Sankey diagram to analyse the energy-water nexus at the national level. Among total water usage in China, about 53.4 % ultimately enters the atmosphere through evaporation and evapotranspiration; and 20.7 % and 6.4 % flows out to other countries or to salt basins, respectively. Only 0.4 % is re-used after sewage treatment and reclamation. The electricity required for water supply, treatment, utilization and post-use utilization comprised about 4–10 % of total national electricity consumption in 2009. Water used by energy-related industry represents an important contribution (about 14 %) of total water consumption and withdrawal in this country.

1. Introduction

Some recent studies have highlighted the energy-water nexus (particularly the coal-water nexus). For example, Ghelichzadeh et al. (2012) works for power-water cogeneration analysis, Opwis et al. (2012) analyses biogas generation from waste water while Uche et al. (2013) emphasizes the water-exergy nexus. Analysis of the water footprint of various economic activities has been pursued primarily using input-output models in particular. Kahrl and Roland-Holst (2008) traced relationships between energy and water resources through China's input-output table structure, drawing conclusions focused on the energy implications of water use. A similar study was made by Zhao et al. (2009), who also use input-output table. Guan and Hubacek (2007) analysed water consumption at inter-regional and Wang et al. (2009) analysed in district levels. Water witdrawl footprint of energy supply to cities was analyzed by Cohen (2014). However, challenges in quantification of the national water-energy nexus and visualization of inter-relations in policy analysis are rarely in the existing literature. Water withdrawals by various sectors from various regions of the world are analysed in Connor (2009) and Mukherji (2007). Researchers noticed, that in most of Asian countered, water consumption is largely agrarian, while North America and Europe withdraw more water for the industrial sectors. Industrial water use including power production accounts for 20 % of total worldwide water use while use in the residential sector uses only 10 % (Plappally 2012). However, as one of the largest economy in the world, China has unique water consumption characteristics. According to the authors' calculation based on data from CWRM (2010), water use of primary industry (excluding that of livestock) accounted for 62.4 % of total water use in China in 2009. This was followed by water use in secondary industries at 13.3 %, urban domestic use at 7.3 %, tertiary industry at 1.9 %, and all other sectors less than 2 %.
We analyse water flows from source to service and onward destinations for China, using a Sankey diagram as a visualization tool in this paper. In Section 2, we outline our methods for the Sankey diagram analysis. Section 3 provides a detailed description of the data used. In Section 4, we describe our results. Section 5 offers conclusions and directions for future work.

2. Methodology

2.1 Water Sankey diagram from source to service and destination

Sankey diagrams (Sankey, 2014) have been used for over a century for mapping energy flows. Many efforts have been made to map the energy-water nexus with these diagrams in Cullen and Allwood (2010).

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In the life cycle of an energy source, water is withdrawn and consumed. In the extraction, distribution, and end use of water resources, energy is consumed. The Sankey diagram can demonstrate the aforementioned complex inter-relationships if used properly.

2.2 Water-energy nexus

Water is withdrawn and consumed throughout the life cycle of an energy source. Energy is consumed in the extraction, distribution, and end use of water resources. In the water Sankey diagram, energy usage rates are assessed individually, as described in Section 3.

3. Water sources and consumption

3.1 Definition for water sources, usage and destination

Definitions are shown in Tables 1, 2 and 3, respectively.

Table 1: Definition of water source

Water source	Description
Surface water (inter-basin)	Water that is transferred inter-basins through long-distance conveyance projects (i.e. South-to-North Water Transfer Project (SNWTP))
Surface water (including recycled water, excluding inter-basin)	Renewable surface water that is available for use (excluding the above inter-basin surface water), and water that is treated and reused (wastewater).
Groundwater	Renewable groundwater resources
Ocean for desalination	Water is desalinated from ocean water

Table 2: Definition of water usage

Water usage	Description
Environment and ecology	Water that is physically distributed to rivers to maintain ecosystems (left in rivers is excluding).
Agriculture	Water that is used for irrigation purposes to produce crops/milk and meat products
Domestic	Water that is used in rural and urban residential housing units (households).
Commercial	Water that is used in commercial purpose, including water that is used in the sectors of trade, accommodation and catering, transport and communication, and society organizations.
Industrial	Manufacturing, processing and other industrial plant water uses, water for energy sector is excluding.
Energy sector	Water that is used for the power generation and supplying, and for the solid, liquid and gas fuel production and supplying

Table 3: Definition of water destinations

Water destination	Description
Atmosphere (Evaporation and evapotranspiration)	into atmosphere through evaporation and evapotranspiration finally
Outflow (Clean)	outflow to other countries or salt basin in clean quality
Out flow(Dirty)	outflow to other countries or salt basin in dirty quality
Percolation to groundwater	Water are percolated to groundwater
Recycled water	Water recycled from wastewater collection and treatment

3.2 Data on energy for water chain in China

Based on literatures review, we adopt energy intensity factors for specific water processes (see Table 4).

3.2.1 Water from inter-basin transfer projects

In 2009, 13,900 Mm^3 of water was supplied by inter-basin water transfer projects, representing 2.9 % of total surface water supply in China. The transferred water is mainly from the lower Yellow River, northward and southward to the Haihe and Huaihe River basins, respectively, and from the lower Yangtze River to the Huaihe River basin. This includes 4,500 Mm^3 transferred from the Yellow River to Haihe region, and 3,540 and 5,280 Mm^3 from the Yellow and Yangtze Rivers to the Huaihe basin, respectively. Among these top three inter-basin water transfer projects, the Yellow River-to-Haihe project is the only one to lift water stepwise, and it transferred about one-third of total inter-basin water in the country in 2009. It has a distance of about 390 km, and electricity consumption for this long distance conveyance is about 4.0 kWh. This assumes that the project has an electricity consumption rate per unit water transported (t-km) similar to a northern California state water project with energy consumption about 16,000 kWh/MG (6.56 kWh/ m^3) per about 400 mi conveyance (CEC, 2005).

Furthermore, we estimate that the average energy use for all water transferred from the inter-basin is about 1.6 kWh/t, assuming that other water-transfer projects are principally diverted projects and consume negligible energy.

Table 4: Average energy intensity for specific water processes in China [a]

Item	Energy intensity factor (kWh/t)
1. Energy for water withdraw	
To get inter-basin water	1.33
To get surface water (for non-agriculture use)	0.19
To get ground water	0.33
2. Energy for water used directly	
To treat water for industry and domestic direct use	0.24
To distribute water for industry and domestic direct use	0.18
3. Energy for water through centralized water company	
To treat water in water company	0.12
To distribute water from water company	0.12
4. Energy for water utilization	
Agriculture	0.58
Civil public and landscape	0.23
For urban domestic life	6.42
For rural domestic life	3.21
5. Energy for sewage	
Sewage collection	0.10
Sewage treatment	0.60

[a] Data sources are explained in Section 3.2.1 to 3.2.8

3.2.2 Surface water

Power is required to get surface water from rivers or lakes to factories for direct use, or to water plants for further treatment. According to Wang (2008), the electricity use rate is 0.19 kWh/m^3 of water supplied to non-agriculture use. In the agricultural use of surface water, energy consumed during its acquisition is calculated in the water utilization stage.

3.2.3 Ground water

About one-fifth of water in China comes from ground sources, and this increases in the north to one-third. According to the field survey and calculations of Wang et al. (2012), the energy use rate from groundwater pumping in all China was 0.33 kWh/m^3.

3.2.4 Recycled water

After wastewater is discharged and treated, it can be reclaimed for future use at an energy use rate of about 0.20 kWh/m^3, based on the average electricity rate reported by the U.S. Department of Energy (DOE, 2006) (800 kWh/million gallon, or 0.2 kWh/t).

3.2.5 Water desalination

Only a small fraction of water supply in China is from desalination projects, and the volume is about 30 Mt. According to Xie (2009), about 3.5 kWh of electricity is needed to obtain 1 t of potable water from sea water.

3.2.6 Water treatment and distribution

Once water is extracted, there are two pathways to treat it, depending on the purpose – direct use or through a centralized water treatment company. Only 0.004 kWh of electricity is required to treat 1 t of water before industrial or domestic use, with an energy use rate of 0.18 kWh per m^3 (Wang et al., 2012). However, there is up to 0.12 kWh (Cohen et al., 2004) of electricity needed to treat 1 t of water at a water company before it is distributed, with energy use rate 0.12 kWh. This is a low value for California, considering that the Chinese water supply system is relatively new, compact, and efficient (DOE, 2006).

3.2.7 Water utilization

We were unable to find any data on energy used during the water utilization phase at either the macro or micro level in China. We assume that agricultural water uses the combined sprinkler and furrow technology in the country, with energy usage rate 0.58 kWh per m^3 of water (WEF, 2010). Civil public and landscape water is considered using the booster pumping technology, with an energy use rate 0.23 kWh per m^3 of water. Tap and shower use accounts for most urban household water use, since washing machines using warm water or dishwashers are very uncommon. An energy use rate of 6.42 kWh/m^3 of water is associated with urban household utilization. In rural village households, the energy usage rate is set to half that of urban households (Hu et al., 2013).

3.2.8 Sewage collection and treatment

The wastewater treatment rate in Chinese cities was about 77 % in 2010 (NDRC, 2011), which is lower than the level (80 %) in Beijing (BWB, 2011). The electricity rates for water use based on Beijing case (Hu et al, 2013), in which about 0.1 kWh and 0.5 kWh of electricity are used to collect and treat 1 t of wastewater, respectively, similar to the U.S. situation (DOE, 2006).

4. Water consumption in energy flow circles

We calculated the water used in energy-related industries based on the following method – water amount used equal to the water use factor times energy output or energy conversion losses. We also disaggregated subsections (solid/liquid/gaseous fuel production, and electricity generation/supply) within the industrial sector, which we refer to as energy subsectors. Water used by other industries is designated as manufacturing use. As shown in Table 5 and explained below, we collected estimated water use factors based on expert opinion, governmental regulation, and a literature review. Based on specific energy output or throughput in China 2009, water use amounts for the energy subsectors were calculated.

Table 5: Water energy-use factors and results showing water used in energy production in China in 2009

Item	Factor [a]	Unit	Output amount	Unit	Water use (In Mm^3)
1.Water for fuel production					
Coal	23	m^3/t	3,300 [b]	Mt	75,900
Petroleum	2.2	m^3/t	388 [b]	Mt	850
Natural gas	0.262	L/m^3	89,470 [b]	Mm^3	20
2.Water for coal-electricity generation	2.45	L/kWh	2,982,800 [c]	GWh	7,310
3.Total energy production					84,080

[a] Sources: (Pan et al., 2012) for coal; (Mielke et al., 2010) for petroleum and NG; (CEC of China, 2011) for electricity.

[b] Source: (NBSC, 2011)

[c] Source: (CEC of China, 2011)

5. Results and discussion

Water from source to service and destination in China during 2009 is shown in Figure 1: energy-related subsectors are subtracted from industry. We find that most of the utilized water in the country ultimately enters the atmosphere via evaporation and evapotranspiration. About one-quarter of this water flows to other countries or to salt basins, mostly with clean quality. Only a small fraction of waste water is used after sewage treatment and reclamation, but 19.1 % of used water in China percolates to groundwater, which from a long-term perspective may also be used. Water has been considered as a key resource in energy production. About half of water use in the industrial sector is by the energy subsector, as shown in Table 6. About one-seventh of total water use in China is for energy production. Water used in coal mining and processing is the largest component of overall water supply for energy in the country.

When we consider the energy used for water consumed in agriculture and public environments, electricity for the water chain in China constituted about 10.2 % of total electricity consumption in 2009. The contribution of each water process to the total energy consumption in the water chain is calculated out: water supply and conveyance stage dominates this contribution (20 %), followed by post-use treatment (10 %). Moreover, if the energy of water utilization for agriculture and public environment is not included, the aforementioned ratio changes to about 4.3 %, roughly the same as in the U.S. About 4 % of U.S. power generation was used for “water supply and treatment”. (DOE, 2006). The subsector of coal electricity production and supply accounted for 1.23 % of total national freshwater consumption in 2009. The subsector of coal electricity production and supply represented about 12.3 % of total national water use.

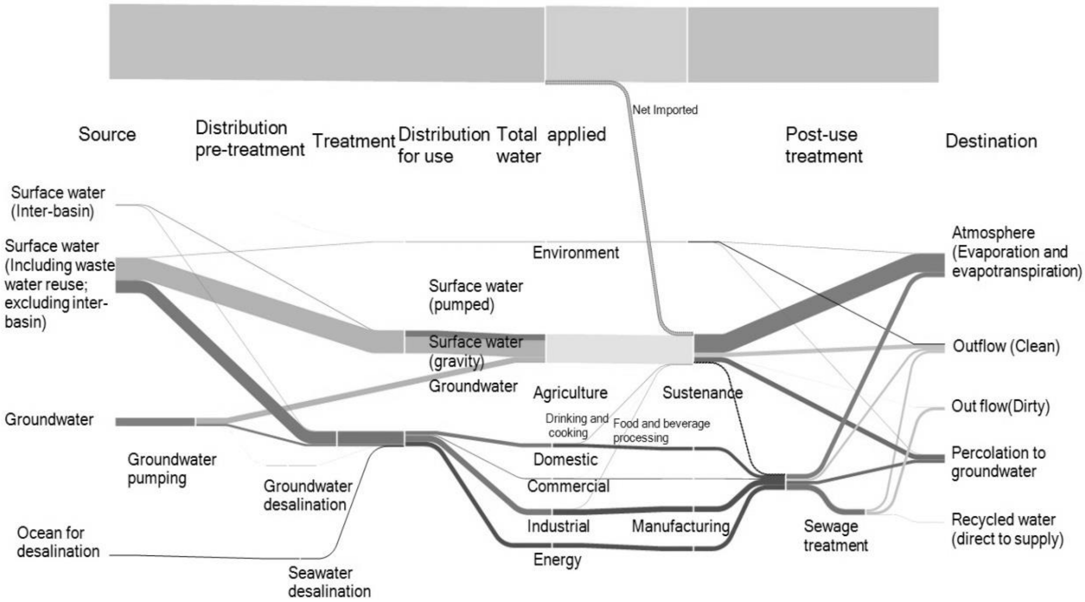

Figure 1: Water Sankey diagram for China in 2009 calculated and drawn by authors

Table 6: Water use for energy in industrial subsectors in China in 2009

Sub-sector	Water consumption (Mm^3)	Share of water for industry use	Share of total water use
1. Manufacture	58,490	41.03 %	9.81 %
2. Energy	84,080	58.97 %	14.11 %
2.1 Coal	75,90	53.24 %	12.73 %
2.2 Oil	850	0.60 %	0.14 %
2.3 NG	20	0.01 %	0.00 %
2.4 Coal electricity	7,310	5.13 %	1.23 %

Note: Water withdrawals for electricity subsector are about 10 times the water consumption for this subsector.

6. Concluding remarks

Based on China energy-water nexus analysis, the key concluding remarks are: A Sankey diagram is a good tool for showing water flow from source to service and destination, and can express the complex energy-water nexus inter-relationships. Electricity used in the Chinese water supply chain was about 4.3 % of the total national electricity consumption in 2009, which is in line with observations from other regions such as California in the United States. About 14.1 % of the total national water use was for energy production, and the electric power subsector consumed 2.5 % of the total national freshwater.

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