Use of the Life Cycle Methodology to Calculate Energy Consumption of Urban Water Cycle: A Case Study of Ordos City

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Abstract: Water resources and energy constitute two broad categories of resources required for social and economic development. The water-energy nexus has become a focus of research in recent years. Although water resources are closely related to energy systems, the processes involved remain incompletely understood due to the diversity and complexity of energy types, processes, and consumption sectors. This study aimed to accurately calculate the energy demand of water resources and to identify an effective method of improving the energy utilization efficiency of water. The life cycle of water resources was divided into five stages based on the life cycle methodology: (1) extraction, (2) purification, (3) transportation, (4) utilization, (5) sewage treatment. The quantity and characteristics of energy consumed in each stage were studied, and an equation to calculate energy consumption for each stage was proposed. Using the city of Ordos in Northwest China as an example, energy consumption of water resources from 2013 to 2017 was analyzed. The results showed that from 2013 to 2017, energy consumption and per unit energy consumption of water resources in Ordos decreased by 33.3% and 30.6% from $1.62 \times 10^8$ kWh to $1.08 \times 10^8$ kWh and from $10.11 \text{kWh} \cdot \text{m}^{-3}$ to $7.02 \text{kWh} \cdot \text{m}^{-3}$, respectively. The majority of energy consumption over the entire life cycle of water resources occurred during the utilization stage at a proportion of total energy consumed of ~95%. Use of water for thermal power generation was identified as the single largest consumer of energy and, therefore, has the greatest potential for energy saving.

Keywords: water–energy nexus; life cycle methodology; energy consumption of water; Ordos city

1. Introduction

Water resources and energy are resources that are essential for maintaining a productive human society [1–5]. Since water resources and energy are interdependent and closely related through processes such as material exchange, energy flow and information interaction, it is recognized that integrated management of water resources and energy is required [6–11]. The five stages of the water life cycle, namely extraction, purification, transportation, utilization, treatment and discharge, all consume energy. The amount of energy consumed by each stage of the life cycle varies due to their varying economic, technological and environmental conditions, which is an important component of the theory of the water–energy nexus: if there is a deficit of energy required for any stage of the water life cycle, the amount of water supply or consumption will in turn be affected [12–15]. Given the current context of global population growth, dwindling resources and deterioration of the ecological environment, the exploration of the quantitative relationships between water resources and energy resources is of
great significance. An improved understanding of these relationships can help identify an effective
method of improving energy efficiency of water resources to achieve sustainable development [16–22].

Although water resources and energy systems are closely related, the processes involved
remain incompletely understood due to the high diversity and complexity of water resources types,
flow processes and consumption sectors. Therefore, past studies on the relationships between water
and energy have mainly used a simple index method to estimate unit electricity consumption or fuel
consumption of water resources use [23], which may not be accurate. A variety of methods have been
applied to study the energy demand of different water resource types. Spang et al. [24] proposed
the Energy Intensity (EI) model in a study which used monitoring data to calculate the electricity
consumed by the water supply service system of a municipal area in California during the processes
of water extraction, transmission and utilization. The National Technical University of Athens developed
the Urban Water Optioneering Tool (UWOT) [25] based on a genetic algorithm, which was used to
calculate the energy demand of urban water supply equipment and evaluate measures to reduce
drinking water demand and the impact of the urban heat island effect. Baki et al. [25] used the UWOT
model to calculate the energy consumption of the Athens urban water supply system and discussed
the potential for the use of this tool in the strategic planning for urban sustainable development and
for efficient management of water resources and energy. The Water-Energy Sustainability Tool Web
(WESTWeb) was developed by the University of California based on the life cycle theory. The tool has
since been used to calculate the energy consumption and air pollutant emissions of a water supply
systems in California [26] and Nova Scotia [27] in the United States, where it was found that the
production of 1 million liters of water consumes ~5.4 GJ of energy.

While it is evident that many past studies focused on the energy consumption of water resources
use, the majority were not comprehensive or focused only on a single type of water resource or on a
single stage of the water resources life cycle. For example, Spang [24] and Baki [25] in a study of the
energy consumption of urban water systems did not consider that of water supply and water use
within farmland irrigation. In addition, while Stokes [26] analyzed the energy consumption of water
resources extraction, purification and transportation in California, the energy consumption of water
utilization was ignored.

The present study proposed a model to comprehensively calculate the energy demand of water
resources use for a specific region based on the life cycle methodology. Energy consumption of
each stage of the water resources life cycle was analyzed by focusing on the physical flow of water,
and equations for quantifying the energy consumption of each stage were given. Considering the
availability of data, taking the city of Ordos in Northwest China as an example, the energy consumption
of water resources was calculated for the period 2013 to 2017, and the trends in energy consumption
over time were analyzed and summarized, thereby providing a reference for improving the energy
efficiency of water resources and furthering understanding of the water-energy nexus.

2. Data and Methods

2.1. Study Area

The city of Ordos is located in the southwest region of the Inner Mongolia Autonomous Region,
China, covers an area of 87,000 km² and has a permanent population of 2.0687 million people. Ordos is
an important economic center and a key energy development area at a national level. The per capita
gross domestic product (GDP) of Ordos in 2017 was 235,200 yuan, the highest in China. Ordos has
a typical temperate continental arid and windy climate with low precipitation that is concentrated
in summer. At present, the total natural water resources in Ordos is estimated to be $2.96 \times 10^8$ m³,
of which surface water and groundwater resources are $1.31 \times 10^8$ m³ and $2.10 \times 10^8$ m³, respectively
(the repeated calculation amount of surface water and groundwater is $0.45 \times 10^8$ m³).
2.2. Data

The available data extending from 2013 to 2017 were used to calculate the energy consumption of the entire life cycle process of water resources in Ordos. The data were mainly sourced from the Ordos Water Resources Bulletin (2013–2017) [28], China Urban Water Supply Statistical Yearbook [29], China Urban Drainage Statistical Yearbook [30] and existing research results.

2.3. Methods

The concept of a life cycle was originally conceived within the biological sciences and referred to the developmental stages an organism experiences over its entire lifespan, including birth, development, maturity, aging and death. Later, the concept of a life cycle was introduced into social and economic sciences to describe the life cycle process of resources and products. Within this context, a life cycle can be understood as the sum of all stages of an object’s lifespan while being exploited for human benefit.

It should be noted that the water resources life cycle in the context of the present study has a different meaning to the natural water cycle (hydrological cycle). The water cycle refers to a continuous natural process by which water is circulated throughout the earth and the atmosphere through evaporation, condensation and precipitation. The natural water cycle is specifically manifested in different natural forms of water such as surface water, groundwater, soil water and atmospheric water, and these forms remain in an equilibrium and are not greatly changed by the influence of external factors. The life cycle of water resources in the context of the present study includes all aspects of human exploitation of water, and include water extraction, storage, purification, transportation, utilization, consumption, discharge back to nature and sewage reuse. The sum of these aspects of human exploitation can be regarded as a water resource life cycle from “birth to death”. The life cycle of water resources can also be called the “urban water cycle”. In comparison with the natural water cycle, the life cycle of urban water resources is a complex system incorporating societal, economic and environmental aspects, which include all interactions with energy during exploitation for human benefit. The life cycle of water resources starts from the extraction of water from a compartment of the natural water cycle (such as surface or groundwater) and ends with discharge or evaporation of water back into the natural water cycle or through recycling through advanced treatment [31–37].

Based on this concept of a life cycle methodology and the physical flow process of water resources, the entire life cycle of water resources can be categorized into five stages: (1) extraction, (2) purification, (3) transportation, (4) utilization and (5) sewage treatment. The present study calculated the energy consumption of each stage in the life cycle of water resources from 2013 to 2017, using the city of Ordos as an example. It should be specially pointed out here that the energy consumption in the process of urban water cycle we studied refers to the energy directly consumed in the process of urban water resources recycling, such as electricity for pumping, heating and so on, but does not include some indirect energy consumption in the process of urban water cycle, such as various chemicals used in the process of wastewater treatment.

2.3.1. Energy Consumption of the Water Extraction Stage

The different types of exploitable water resources include surface water, groundwater, rainwater, desalinated seawater and reclaimed water. The energy consumed during the reclaiming of water was calculated during the sewage treatment stage. The energy consumed during rainwater harvesting and desalination mainly relates to the power consumed by relevant equipment. Since there was no rainwater harvesting or desalination in Ordos over the period 2013–2017, these two categories of water extraction could be ignored in the present analysis.

Energy Consumption for Extracting Surface Water

The process of extraction of surface water can be divided into four broad engineering categories: (1) water storage, (2) water lifting, (3) water diversion and (4) inter-basin water transfers.
The energy consumed by water storage engineering mainly relates to mechanical energy lost during water conveyance due to overcoming resistance. The mechanical energy per unit mass of water lost during process of water conveyance is termed “head loss”, and includes head loss that occurs during conveyance and locally, with the latter usually being 5–10% of the former (5% in the current study paper [38]). Pumping stations consume power to overcome resistance. Since water diversion engineering usually uses natural gravity to transport water from a source to terminal users, the energy consumption of this category of water extraction can be neglected. The energy consumed by inter-basin water transfer engineering is the same as that of water storage engineering. Since no inter-basin water transfers were implemented in Ordos during the period 2013–2017, this category of surface water extraction was ignored in the present study.

The equations used for calculating the energy consumed during the extraction of surface water were as follows:

\[ e_{11} = \frac{m_1 g (h_f + h_j)}{3.6 \times 10^6 \times \beta_1} + \frac{m_2 g h_i}{3.6 \times 10^6 \times \beta_2} \]  

\[ h_f = i \times L \]  

\[ h_j = 5\% \times h_f \]

In Equations (1)–(3), \( e_{11} \) is the energy consumed through extracting surface water, \( m_1 \) and \( m_2 \) are the weights of water in water storage and pumping engineering, respectively (kg), \( g \) is the gravitational acceleration constant (N kg\(^{-1}\)), \( h_f \) is the head loss occurring along the conveyance path (m), \( h_i \) is the elevation to be overcome during the movement of water and was taken as the average surface elevation of Inner Mongolia [40] (\( h_1 = 260.98 \) m), \( i \) is head loss per unit pipe length (\( i = 0.00125 \) [40]), and \( L \) is the length of the pipeline section (\( L = 5 \) km) [40].

Energy Consumed through Extracting Groundwater

The principle used to calculate the energy consumed by extracting groundwater for urban consumption is the same as that for surface water extraction engineering. The head of a water pump needs to be considered within the extraction of groundwater for agricultural production, including static head, pumping drawdown, head loss of the below-ground well pipe, head loss of the above-ground irrigation pipe and outflow head. Wang et al. [41] proposed a linear correlation between the pump head and groundwater depth, as shown in Equation (5).

The equations for calculating the energy consumed during the extraction of groundwater are as follows:

\[ e_{12} = \frac{(m_3 h_d + m_4 H) g}{3.6 \times 10^6 \times \beta_3} \]  

\[ H = 0.906 h_d + 21.75 \]

In Equations (4) and (5), \( m_3 \) and \( m_4 \) are the weights of groundwater extracted for use in urban and rural areas, respectively (kg), \( h_d \) is the depth of underground water, taken as the average groundwater depth for Inner Mongolia [40] (\( h_d = 26.97 \) m), \( \beta_3 \) is the pump efficiency for extracting groundwater (\( \beta_3 = 95\% \)) [39], and \( H \) is the head of a water pump (m).

2.3.2. Energy Consumed during the Water Purification and Transportation Stages

The water purification process involves a series of operations implemented within a water treatment plant, including sedimentation filtration, sterilization and disinfection, and consumption of energy during water purification is mainly due to electric energy consumed by the operation of an electric mixer and sedimentation tank. The water transportation stage involves the conveyance of purified water to end users through the water reticulation system, with energy consumed mainly related to the electric energy required for the operation of a water tower, clean water tank, pump station and
other equipment used in the water reticulation system. Since it is difficult to calculate the specific energy consumption of each process during the purification and transportation stages, energy consumption was calculated by multiplying volumes of water purification and transportation by the corresponding unit power consumptions. The data required for the calculation were sourced from the China Urban Water Supply Statistical Yearbook (2013–2017) [29].

2.3.3. Energy Consumed during the Water Utilization Stage

The main uses of water resources can be broadly divided into four categories: (1) domestic water, (2) industrial water, (3) agricultural water and (4) ecological water. Among the categories, agricultural water mainly relates to water used for irrigation and rural livestock watering. The energy consumed during the extraction of surface water and groundwater was calculated during the water resource extraction process. Ecological water refers to the water resources used to maintain the normal development and relative stability of various ecological systems within a specific time and space, such as water for greening, water for rivers and lakes, etc. Since ecological water does not directly benefit the domestic and economic sectors and the energy consumed is negligible, the current study ignored the energy consumption of ecological water.

Energy Consumed during the Process of Domestic Water Use

Domestic water includes household water and public water. Energy consumed during the use of household water mainly includes heating energy consumed for domestic drinking water and bathing as well as mechanical energy consumed by domestic appliances such as washing machines and other equipment. Public domestic water includes drinking water, cleaning water and other basic domestic water and infrastructure water, and the energy consumed during the use of public water mainly relates to the conversion of electric energy into thermal energy or mechanical energy. Jiangshuan [40] found that the unit energy consumption of domestic water and public domestic water in Ordos is 12.62 kWh·m⁻³ and 11.6 kWh·m⁻³, respectively.

Energy Consumed during the Process of Industrial Water Use

Industrial water consumption can be divided into three broad categories, namely, (1) thermal power generation, (2) general industrial production and (3) domestic water consumption of employees working at a factory. The energy consumed through thermal power generation includes that for the heating of water in a boiler and for circulating cooling water. The energy consumed through general industrial production is mainly related to the circulating cooling system. Domestic water consumption by factory employees usually accounts for 5–10% of total industrial water consumption, was taken as 5% in the current study [40] and was calculated in a similar way to that for public domestic water consumption.

The equations used to calculate the energy consumed during industrial water consumption were as follows:

\[ e_{42} = e_{421} + e_{422} + e_{423} \]  (6)

\[ e_{421} = \frac{m_5 \times \Delta t \times c}{3.6 \times 10^6 \times \beta_4} + D \times \alpha \]  (7)

\[ e_{422} = \frac{W_i \times e_x}{\beta_5} \]  (8)

\[ e_{423} = 11.6 \times 5\% \times W_g \]  (9)

In Equations (6)–(9), \( e_{421} \), \( e_{422} \) and \( e_{423} \) are the energy amounts consumed through the use of water for thermal power generation, general industrial production and domestic consumption by factory employees, respectively (kWh); \( m_5 \) is the weight of boiler heating water (kg); \( \Delta t \) is the heating temperature (generally, water at 25 °C is heated to 400 °C; therefore, \( \Delta t = 375 \) °C); \( c \) is the specific
heat capacity of water \( c = 4.2 \text{kJ}\cdot\text{kg}\cdot\text{K}^{-1}\); \( \beta_4 \) is the water consumption efficiency of boiler heating \( (\beta_4 = 75\%) \) [39]; \( D \) is thermal power generation (kWh); \( \alpha \) is the power consumption rate of the water pump in the circulating cooling system \( (\alpha = 1.55\%) \) [42]; \( W_l \) is the quantity of water recycled in general industry \( (\text{m}^3) \); \( e_c \) is the power consumption of circulating 1 m\(^3\) water \( (e_c = 6.4 \text{kWh}\cdot\text{m}^3) \) [40]; \( \beta_5 \) is the operating efficiency of the circulating cooling system \( (\beta_5 = 50\%) \) [40]; and \( W_g \) is the total amount of industrial water \( (\text{m}^3) \).

2.3.4. Energy Consumed during Sewage Treatment

Wastewater treatment involves the collection and treatment of wastewater. Sewage treatment plants (STPs) can be broadly categorized into ordinary STPs and STPs that reclaim water. Wastewater includes domestic sewage, rainwater in contact with streets or highways and water contaminated by industry. There are various forms of wastewater treatment technology, including physical treatment, chemical treatment and biological treatment. The energy consumption intensity of each wastewater treatment technology is different. The sum of power consumption of all sewage treatment plants is taken as the total energy consumption of sewage treatment stage. The calculation of energy consumed during the sewage treatment process is similar to that for the purification process, and energy consumed is calculated by multiplying the quantity of sewage treated or water reclaimed by the corresponding unit power consumption. The data required for this analysis were obtained from the China Urban Drainage Statistical Yearbook (2013–2017) [30].

3. Results and Discussion

3.1. Energy Consumption Characteristics of Each Stage during the Life Cycle of Water Resources

The calculation results over the years were shown in Appendix A. The present study analyzed the energy consumption characteristics of each stage during the entire life cycle of water resources, using 2017 as an example (Table A5). In 2017, the total energy consumed through the entire life cycle of water resources in Ordos was \( 108 \times 10^8 \) kWh, approximately 18.24% of the total \( 592 \times 10^8 \) kWh of energy consumed in Ordos for that year. Figure 1 shows the breakdown of energy consumption among the different stages in the water resource life cycle. Figure 1 shows that energy consumed during the utilization of water accounted for the largest proportion of total energy consumed during the entire life cycle of water resources at 95.26%. The energy consumed by the water sector accounts for 3.12%, whereas the amounts of energy consumed by water transport, purification and sewage treatment are relatively small, collectively accounting for 1.62%. Energy consumed during the water consumption stage far outweighed the sum of energy consumption of all other stages, indicating that this stage has the highest potential for energy saving.

![Figure 1](image-url)
The different categories of water resources exploited during the water extraction stage include surface water, groundwater, rainwater and desalinated water. However, the city of Ordos only consumed surface water and groundwater in 2017. Figure 2 shows the breakdown of energy consumption during the extraction of these two categories of water resources for Ordos in 2017. Figure 2 shows that energy consumed during the extraction of surface water was approximately twice that for extracting groundwater, which was mainly due to the high ground elevation of Ordos, resulting in the need for more power consumption by surface water extraction engineering. In addition, since the quality of local surface water resources in Ordos is poor, there is limited surface water resources development potential, whereas groundwater resources are relatively rich. Therefore, to service the water requirements of social and economic development in Ordos, the degree of exploitation of deep groundwater in Ordos is continually increasing, which will consequently result in the increase in the proportion of energy consumed by groundwater extraction.

![Figure 2](https://via.placeholder.com/150)

**Figure 2.** Proportions of energy consumption for the extraction of two categories of water resources in the city of Ordos, China, in 2017.

Energy consumed during the water utilization stage includes that by industry and the domestic sector. The energy consumed by industry through the use of water can be broadly divided into that for thermal power generation, other general industrial uses and domestic water for factory employees. The energy consumed through the use of domestic water can be broadly divided into that consumed by residents and that consumed by the public sector. Figure 3 shows the breakdown of energy consumed through the use of water in Ordos in 2017. It is evident that thermal power generation accounted for the largest proportion of consumed energy, reaching 75.52%, followed by energy consumed by industrial production and the domestic sector, accounting for 13.34% and 8.42%, respectively. The amounts of energy consumed through the use of domestic water for factory employees and the public sector accounted for only 1.44% and 1.28%, respectively. Within the energy consumed through thermal power generation, the majority of energy was consumed by the boiler heating system, followed by the circulating cooling water system. Therefore, the highest potentials for energy saving within thermal power generation are through increasing the efficiency of boiler heating and optimizing the circulating cooling water system.

The per unit of water energy consumed of water resources can be obtained for each stage of the life cycle of water resources by dividing energy consumed by the corresponding water quantity. To facilitate an in-depth comparative analysis, the per unit of water resource energy consumed during water extraction was further divided into that for extraction of surface water and groundwater, and energy consumed for water consumption was further divided into that of industry and the domestic sector. Figure 4 shows the per unit of water resource energy consumed for each stage of the water resource life cycle. It is evident that the order of per unit water resource energy consumption among the different stages of the water resources life cycle can be ranked as industrial water > domestic water > surface water extraction > sewage treatment > transportation > purification > groundwater extraction. The amounts of per unit water resources energy consumed by industry and the domestic sector were much higher than those of the other water resources life cycle stages, indicating that these two stages have the highest potential for energy saving.
always used the majority of energy. Energy consumption of the extraction stage first increased from 10.11 kWh in 2013 to 3.66 kWh in 2015, following which it decreased to 3.38 kWh in 2017. The changes in energy consumed over each stage of the water resources life cycle can be ranked as industrial water > domestic water > surface water extraction > sewage treatment > transportation > purification > groundwater extraction. The different categories of water utilization in the city of Ordos, China, in 2017 are shown in Figure 2.

Figure 3. Proportions of energy consumption among the different categories of water utilization in the city of Ordos, China, in 2017.

Figure 4. Per unit water resources energy consumption among the different stages of the water resources life cycle in Ordos, China, in 2017.

3.2. Historical Trends in Energy Consumption through the Life Cycle of Water Resources

3.2.1. Characteristics of Energy Consumption during the Entire Life Cycle of Water Resources

Table 1 shows the water and energy consumed over the entire life cycle of water resources in Ordos for the period 2013–2017. Figure 5 shows clear year-by-year generally consistent declining trends in energy consumption and per unit water resources energy consumption in Ordos for 2013 to 2017. The year-by-year decline in total energy consumption in Ordos from $161.99 \times 10^8$ kWh to $108.07 \times 10^8$ kWh can be explained by a concurrent decline in total water extraction. An additional reason for the decline in total energy consumption is an improvement in the efficiency of energy consumption in each stage of the water resources life cycle. This reduction in total energy consumption of the water resources life cycle resulted in a monotonic reduction in per unit water resources energy consumption from $10.11$ kWh·m$^{-3}$ to $7.02$ kWh·m$^{-3}$. The changes in energy consumed over each stage of the water resources life cycle was analyzed in depth.

Table 2 shows the year-by-year energy and proportion of total energy consumed of each stage in the life cycle of water resources in Ordos. It is evident that the proportion of energy consumed during the utilization stage remained constant throughout each year at ~95%, and therefore, this stage always used the majority of energy. Energy consumption of the extraction stage first increased from $3.15 \times 10^8$ kWh in 2013 to $3.66 \times 10^8$ kWh in 2015, following which it decreased to $3.38 \times 10^8$ kWh in 2017. Although there was fluctuation in the energy consumption of the extraction stage, the proportion of total energy consumed during this stage increased monotonously from 1.94% to 3.12%, mainly...
because there was a year-by-year decrease in total energy consumption of the water resources life cycle. The proportions of total energy consumed during the purification and transportation stages remained below 1%, whereas that of the transportation stage consistently remained higher than that of the purification stage. The latter observation can be explained by unit energy consumption during the transportation stage in Ordos consistently being slightly higher than that in the purification stage over the period 2013–2017. In fact, there was no absolute relationship between the energy consumption of the transportation and purification stages, and the observation related to the operation efficiency of equipment used in the two stages. The sewage treatment stage consumed the lowest proportion of total energy consumed, and the efficiency of energy consumption of sewage treatment showed little change. However, the report 2014 Emission Reduction Task of Major Pollutants in Ordos City issued by the Ordos Environmental Protection Bureau stipulated the need for vigorous promotion of the construction of urban sewage treatment facilities, regeneration of water treatment systems and supporting pipe networks and the upgrading of existing facilities. The implementation of this policy resulted in a significant increase in the sewage treatment capacity of Ordos in 2014 from $0.24 \times 10^8$ m$^3$ to $>0.88 \times 10^8$ m$^3$, which resulted in energy consumption of sewage treatment showing a dramatic increase from $0.16 \times 10^8$ kWh in 2013 to $0.61 \times 10^8$ kWh in 2014, and the proportion of total energy consumed by this stage increased from 0.10% to >0.41%.

Table 1. Water and energy consumed over the entire life cycle of water resources.

| Year | Water Consumption ($10^8$ m$^3$) | Energy Consumption ($10^8$ kWh) | Unit Energy Consumption (kWh·m$^{-3}$) |
|------|-------------------------------|---------------------------------|-------------------------------------|
| 2013 | 16.02                         | 161.99                          | 10.11                               |
| 2014 | 15.70                         | 148.45                          | 9.46                                |
| 2015 | 15.68                         | 136.10                          | 8.68                                |
| 2016 | 15.66                         | 116.93                          | 7.47                                |
| 2017 | 15.40                         | 108.07                          | 7.02                                |

Figure 5. Year-by year changes in energy consumed during the life cycle of water resources in Ordos, China.

3.2.2. Changes in Energy Consumption during the Water Extraction Stage

Table 1 and Figure 6a show that although there is a year-by-year decline in total water extraction in Ordos, energy consumed during the water extraction stage fluctuated between $3.09 \times 10^8$ kWh and $3.66 \times 10^8$ kWh. At the same time, the ratio of energy consumption for surface water extraction to energy consumption of groundwater extraction remained relatively stable at 2:1.
Table 2. Energy consumption and proportion of total energy consumed for each stage of the life cycle of water resources in Ordos, China. (Dimension of energy consumption: 10^8 kWh).

| Year | Extraction | Proportion | Purification | Proportion | Transportation | Proportion | Utilization | Proportion | Sewage Treatment | Proportion |
|------|------------|------------|--------------|------------|----------------|------------|-------------|------------|----------------|------------|
| 2013 | 3.15       | 1.94       | 0.75         | 0.46       | 1.14           | 0.71       | 157         | 96.79      | 0.16           | 0.10       |
| 2014 | 3.09       | 2.08       | 0.78         | 0.52       | 1.15           | 0.78       | 143         | 96.21      | 0.61           | 0.41       |
| 2015 | 3.66       | 2.69       | 0.50         | 0.37       | 1.15           | 0.78       | 130         | 95.80      | 0.61           | 0.41       |
| 2016 | 3.55       | 3.04       | 0.73         | 0.62       | 0.95           | 0.70       | 111         | 94.88      | 0.67           | 0.62       |
| 2017 | 3.38       | 3.12       | 0.33         | 0.30       | 0.96           | 0.82       | 103         | 95.26      | 0.69           | 0.62       |

Figure 6b shows that changes in per unit surface water extraction energy consumed were relatively large, mainly due to changes to water extraction by engineering infrastructure for water storage, water lifting and water diversion. The amounts of water extracted by water storage engineering and water diversion engineering generally reduced between 2013 and 2017 from $1.45 \times 10^8$ m$^3$ to $0.60 \times 10^8$ m$^3$ and from $3.07 \times 10^8$ m$^3$ to $0.21 \times 10^8$ m$^3$, respectively, in 2017. In contrast, the amount of water extracted by water extraction engineering showed an initial increase from $2.72 \times 10^8$ m$^3$ to $3.30 \times 10^8$ m$^3$ followed by a decrease to $2.96 \times 10^8$ m$^3$.

The energy consumption of the per unit water storage, lifting and diversion engineering were $2.28 \times 10^{-5}$ kWh, $7.63 \times 10^{-4}$ kWh and negligible, respectively. Since the energy consumption of the per unit water of water lifting engineering was far greater than that of water storage engineering, the energy consumption of the per unit of surface water extraction engineering was mainly affected by water lifting engineering, showing an increasing trend followed by a decreasing trend. In contrast, there was little variation in energy consumption of the per unit underground water extraction, ranging from $0.12$ kWh·m$^{-3}$ to $0.13$ kWh·m$^{-3}$. Therefore, the energy consumption of the per unit water extraction stage was driven by that of surface water extraction, first showing an increase followed by a decrease.

Energy consumption of groundwater storage engineering was mainly affected by water pipeline materials, water delivery distance and pump efficiency, whereas energy consumption of water lifting engineering was mainly affected by water lifting height and pump efficiency. It is clear that effective approaches to reduce the energy consumption of the per unit water storage engineering, including the selection of material with a small head loss along the water transmission pipeline and the selection of an appropriate water transmission path to reduce transmission distance and improve pump efficiency of water storage engineering. In addition, an effective approach to reduce the energy consumption of the per unit water lifting engineering includes improving pump operation efficiency of water lifting engineering.

3.2.3. Year-by-Year Changes in Energy Consumption during the Water Utilization Stage

Figure 7 shows that energy consumption of the water utilization stage in Ordos decreased year-by-year from 2013 to 2017, from $156 \times 10^8$ kWh to $103 \times 10^8$ kWh. Energy consumption for thermal power generation showed a dramatic decrease from $138 \times 10^8$ kWh to $77.7 \times 10^8$ kWh, with the proportion of total energy consumption decreasing from 88.12% to 75.52%. Energy consumption of water for general industrial production and domestic water use increased slightly from $8.87 \times 10^8$ kWh to $13.7 \times 10^8$ kWh and from $6.15 \times 10^8$ kWh to $8.68 \times 10^8$ kWh, respectively, representing an increase in the proportion of total energy consumed of 5.65% to 13.34% and 3.92% to 8.43%, respectively. The energy consumed by domestic water use by factory employees and by the public sector showed little change, and the proportion of total energy of each category of water use remained at ~1%.
Table 2. Energy consumption and proportion of total energy consumed for each stage of the life cycle of water resources in Ordos, China. (Dimension of energy consumption: 10^8 kWh).

| Year | Extraction | Purification | Transportation | Utilization | Sewage Treatment |
|------|------------|--------------|----------------|-------------|-----------------|
| 2013 | 3.15       | 0.75         | 1.14           | 157         | 0.16            |
| 2014 | 2.08       | 0.46         | 0.71           | 96.79       | 0.10            |
| 2015 | 3.09       | 0.78         | 1.15           | 96.21       | 0.61            |
| 2016 | 2.08       | 0.52         | 0.78           | 95.80       | 0.41            |
| 2017 | 3.66       | 0.50         | 0.95           | 94.88       | 0.60            |

3.2.2. Changes in Energy Consumption during the Water Extraction Stage

Table 1 and Figure 6a show that although there is a year-by-year decline in total water extraction in Ordos, energy consumed during the water extraction stage fluctuated between 3.09 × 10^8 kWh and 3.66 × 10^8 kWh. At the same time, the ratio of energy consumption for surface water extraction to energy consumption of groundwater extraction remained relatively stable at 2:1.

![Figure 6a](image1.png)  
(a) Year-by-year change of energy consumption of the water extraction stage in Ordos, China. (a) Energy consumption of water extraction; (b) energy consumption of the per unit water.

The analysis showed that the thermal process consumed the highest proportion of energy, exceeding that of all other water consumption categories combined. Therefore, there is a high potential for energy saving within the thermal power water consumption process. The significant reduction in the energy consumed through the use of water in thermal power generation in Ordos is the main reason for a year-by-year reduction in total energy consumption of the water sector and also the main reason for a reduction in energy consumption of the entire life cycle of water resources in Ordos. The energy consumed during the use of water for thermal power generation includes that for operating the boiler and the circulating cooling system. The energy consumption of the per unit water of the boiler is ~583.33 kWh m⁻³, and it is mainly affected by the heating efficiency of the boiler.

Taking 2017 as an example, a reduction in energy consumed by water use in thermal power generation from 77.7 × 10^8 kWh to 76.8 × 10^8 kWh can be achieved by increasing the efficiency of boiler heating from 75% to 76%, which will lead to a reduction in total energy consumed over the entire water resources life cycle from 10.8 × 10^8 kWh to 10.7 × 10^8 kWh. In other words, an increase in the efficiency of boiler heating of 1% can lead to a reduction in total energy consumed over the entire life cycle of water resources by 0.8%, thereby indicating that energy consumed by boiler heating has a considerable influence on total energy consumption of the entire water resources life cycle. Therefore, improving the efficiency of water use within boiler heating is an effective approach to improve the energy consumption efficiency of the entire water resources life cycle.

3.2.4. Year-by-Year Changes in Energy Consumption of the per Unit Water of Each Stage in the Water Resources Life Cycle

Figure 8 shows that besides that of industrial water and domestic water, the energy consumption of the per unit water of the other stages of the water resources life cycle remained below 1 kWh m⁻³ all
year round and therefore had a negligible impact on energy consumption of the entire water resources life cycle. The energy consumption of the per unit water of industrial water decreased monotonously from 59.56 kWh·m⁻³ in 2013 to 36.48 kWh·m⁻³ in 2017, which directly resulted in a reduction in total energy consumption of water resource use. Industrial water use includes water for thermal power generation, general industrial production and domestic water use by factory employees. The present study showed that a reduction in energy consumed within the use of water in the boiler heating water stage of thermal power generation was the main reason for a reduction in the energy consumed during the entire water resources life cycle. From 2013 to 2017, there was a year-by-year reduction from 2013 to 2017 in water consumption within the thermal power industry within Ordos from $1.21 \times 10^8$ m³ to $0.63 \times 10^8$ m³, which resulted in a reduction in the energy consumed by boiler heating of water and a reduction in total energy consumption of the entire water resources life cycle. It is found that compared with 2013, total energy values consumed by the use of water resources and by the use of water in industry in 2017 were reduced by $55.5 \times 10^8$ kWh and $53.9 \times 10^8$ kWh, respectively, indicating that changes in energy consumption within industrial water consumption play an important role in changes in energy consumption of the water resources life cycle.

![Figure 7](image1.png)

**Figure 7.** Year-by-year changes in energy consumption of the water utilization stage in Ordos, China.

![Figure 8](image2.png)

**Figure 8.** Year-by-year changes in energy consumption of the per unit water of each stage of the water resources life cycle in Ordos, China.

The life cycle of water resources was divided into five stages based on the life cycle methodology: (1) extraction, (2) purification, (3) transportation, (4) utilization and (5) sewage treatment. The energy consumption characteristics and variation trend of water resources in Ordos city over the years have
been calculated and analyzed. In the past research, due to the limitation of data sources and discipline barriers, the research on energy consumption of water resources was often focused on one or two stages in the whole process of urban water cycle. This paper provides the calculation formula or method of energy consumption in each link of social water cycle process. These formulas and methods are applicable not only to other cities but also to calculation of energy consumption of water resources at the provincial, watershed and national scale. Through the calculation of this case, the energy consumption of each link in the process of social water cycle was analyzed, and the effective way to improve the energy utilization efficiency of water resources was found. This method can analyze and evaluate the history, current situation and future trend of energy consumption of water resources. At the same time, the calculation methods and ideas provided in this paper are not only applicable to the calculation of energy consumption of water resources but also can provide reference for the calculation of the mutual consumption of other resources, such as calculating the water consumption and change trend in the whole life cycle of different energy sources such as coal, oil and electricity, so as to find an effective way to reduce energy consumption.

4. Conclusions

The present study proposed a method to calculate energy consumption during the entire water resources life cycle, which addressed certain shortcomings of existing methods that focus on only one or several stages of the water resources life cycle. Year-by-year changes in energy consumed by each stage of the water resources life cycle were analyzed with the aim of reducing energy consumption through the use of water resources and of improving the efficiency of energy use. This method could be used to analyze and evaluate the historical, current and future trends in the energy consumption of water resources, can further enrich the basic theory of the water-energy nexus and can provide a basis for formulating water and energy planning strategies.

Year-by-year total energy consumption of the entire life cycle of water and the energy consumption of the per unit water over the period 2013–2017 in Ordos showed a decline, with a generally consistent downward trend. Energy consumed during the water utilization stage accounted for the largest proportion of total energy consumed, accounting for ~95% every year. Energy consumed by the extraction of water was the second highest and increased from 1.94% to 3.12%. The energy consumption values of other stages accounted for less than 1% of total energy consumed. It was found that energy consumed during the process of boiler water heating in the water consumption stage was the largest among any of the studied stages and that total energy consumption over the entire water resources life cycle can be reduced by ~0.8% by improving the efficiency of boiler water heating by 1%. Therefore, improving the efficiency of boiler water heating water can be an effective approach to improving energy consumption efficiency and reducing energy consumption over the entire water resources life cycle.

Potential exists for extending the present study by incorporating a comparison of the results of this paper that used the water resources life cycle methodology with results of studies which employed other methods. The focus of future research can be taken into account the impact of environmental factors. For example, life cycle methodology can be used to calculate the emissions of environmental pollutants in each stage of the life cycle of urban water resources, and probability estimation methodology can be used to study how to save the energy consumption of water resources as much as possible under the premise of ensuring the environmental sustainable development.

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Appendix A. The Year-by-Year Consumption of Energy by Utilization of Water Resources

Table A1. Energy consumed through the use of water in Ordos, China, for 2013 (dimension of water quantity: $10^8$ m$^3$; dimension of energy consumption: $10^8$ kWh; ditto below).

| Links        | Water Quantity | Energy Consumption | Classification | Water Quantity | Energy Consumption | Classification | Water Quantity | Energy Consumption |
|--------------|----------------|--------------------|----------------|----------------|--------------------|----------------|----------------|--------------------|
| Extraction   | 1600           | 3.15               | Total          |                |                    |                |                |                    |
|              |                |                    | Surface Water  | 724            | 2.11               |                |                |                    |
|              |                |                    | Storage        | 145            | 0.03               |                |                |                    |
|              |                |                    | Lifting        | 272            | 2.07               |                |                |                    |
|              |                |                    | Diversion      | 307            | 0                  |                |                |                    |
|              |                |                    | Interbasin Diversion | 0 | 0                  |                |                |                    |
|              |                |                    | for Urban      | 218            | 0.17               |                |                |                    |
|              |                |                    | for Agricultural | 644          | 0.87               |                |                |                    |
|              |                |                    | Desalination   | 0              | 0                  |                |                |                    |
|              |                |                    | Rainwater      | 0              | 0                  |                |                |                    |
|              |                |                    | Reclaimed Water| 15.7           | 0                  |                |                |                    |
| Purification | 183            | 0.75               |                |                |                    |                |                |                    |
| Transportation | 223           | 1.14               |                |                |                    |                |                |                    |
| Utilization  | 1600           | 157                | Total          |                |                    |                |                |                    |
|              |                |                    | Industry       | 249            | 148                |                |                |                    |
|              |                |                    | Thermal Power  | 121            | 138                |                |                |                    |
|              |                |                    | General Industrial | 115       | 8.87               |                |                |                    |
|              |                |                    | Employees      | 12.5           | 1.45               |                |                |                    |
|              |                |                    | Domestic       | 67.4           | 831                |                |                |                    |
|              |                |                    | Household      | 48.8           | 6.15               |                |                |                    |
|              |                |                    | Public         | 18.6           | 2.16               |                |                |                    |
|              |                |                    | Agriculture    | 123            | 0                  |                |                |                    |
|              |                |                    | Ecology        | 50.2           | 0                  |                |                |                    |
| Sewage Treatment | 24           | 0.16               | Total          |                |                    |                |                |                    |
| Treatment   |                |                    | Ordinary       | 82.4           | 0.035              |                |                |                    |
|              |                |                    | Reclaimed      | 15.7           | 0.13               |                |                |                    |

Note: In “circulating cooling”, the quantity of thermal power generated corresponding to water quantity, $10^8$ kWh.
**Table A2.** Energy consumed through the use of water in Ordos, China, for 2014.

| Links          | Water Quantity | Energy Consumption | Classification               | Water Quantity | Energy Consumption | Classification       | Water Quantity | Energy Consumption |
|----------------|----------------|--------------------|-------------------------------|----------------|--------------------|----------------------|----------------|-------------------|
| Extraction     | 1570           | 3.09               | Surface Water                 | 550            | 1.91               | Storage              | 55.9          | 0.013             |
|                |                |                    |                               |                |                    | Lifting              | 246           | 1.89              |
|                |                |                    |                               |                |                    | Diversion            | 248           | 0                 |
|                |                |                    |                               |                |                    | Interbasin Diversion | 0            | 0                 |
|                |                |                    | Groundwater                   | 960            | 1.18               | for Urban            | 201           | 0.16              |
|                |                |                    |                               |                |                    | for Agricultural     | 758           | 1.02              |
|                |                |                    | Desalination                  | 0              |                    |                      | 0             |                   |
|                |                |                    | Rainwater                     | 0              |                    |                      | 0             |                   |
|                |                |                    | Reclaimed Water               | 60.2           |                    |                      | 0             |                   |
| Purification   | 188            | 0.78               |                               |                |                    | Boiler Heating       | 19.1          | 111               |
| Transportation | 233            | 1.15               |                               |                |                    | Circulating Cooling  | 603 (10^6 kWh) | 9.35              |
|                |                |                    | Industry                      | 266            | 133                | General Industrial   | 146           | 11.2              |
|                |                |                    |                               |                |                    | Employees            | 13.3          | 1.54              |
|                |                |                    | Domestic                      | 75.4           | 9.39               | Household            | 62.4          | 7.88              |
|                |                |                    |                               |                |                    | Public               | 13            | 1.51              |
|                |                |                    | Agriculture                   | 1170           | 0                  |                      |               |                   |
|                |                |                    | Ecology                       | 55.4           | 0                  |                      |               |                   |
| Sewage Treatment | 88.4         | 0.61               | Ordinary                      | 28.2           | 0.11               |                      |               |                   |
|                |                |                    | Reclaimed                     | 60.2           | 0.49               |                      |               |                   |
| Total          |                | 148                |                               |                |                    |                      |               |                   |
## Table A3. Energy consumed through the use of water in Ordos, China, for 2015.

| Links                | Quantity | Energy Consumption |
|----------------------|----------|--------------------|
| Extraction           | 1570     | 3.66               |
|                      |          |                    |
| Surface Water        | 589      | 2.53               |
| Groundwater          | 921      | 1.14               |
| Desalination         | 0        | 0                  |
| Rainwater            | 0        | 0                  |
| Reclaimed Water      | 58.7     |                    |
| Purification         | 173      | 0.50               |
| Transportation       | 208      | 0.95               |
|                      |          |                    |
| Industry             | 248      | 121                |
| Domestic             | 75       | 9.36               |
| Agriculture          | 1180     | 0                  |
| Ecology              | 63.1     |                    |
|                      |          |                    |
| Sewage Treatment     | 85.7     | 0.60               |
|                      |          |                    |
| Total                | 136      |                    |

### Classification

| Classification       | Water Quantity | Energy Consumption |
|----------------------|----------------|--------------------|
| Storage              | 50.8           | 0.012              |
| Lifting              | 208            | 2.51               |
| Diversion            | 330            | 0                  |
| Interbasin Diversion | 0              | 0                  |
| Purification         | 173            | 0.50               |
| Circulating Cooling  | 639 (10^8 kWh)| 9.91               |
| General Industrial   | 142            | 10.9               |
| Employees            | 12.4           | 1.44               |
| Household            | 65.1           | 8.21               |
| Public               | 9.92           | 1.15               |
| Agriculture          | 1180           | 0                  |
| Ecology              | 63.1           |                    |
| Ordinary             | 27             | 0.12               |
| Reclaimed            | 58.7           | 0.48               |
Table A4. Energy consumed through the use of water in Ordos, China, for 2016.

| Links            | Water Quantity | Energy Consumption | Classification | Water Quantity | Energy Consumption | Classification      | Water Quantity | Energy Consumption | Classification      | Water Quantity | Energy Consumption |
|------------------|----------------|--------------------|----------------|----------------|--------------------|---------------------|----------------|--------------------|---------------------|----------------|---------------------|
| Extraction       | 1570           | 3.55               | Surface Water  | 591            | 2.45               | Storage             | 71.1           | 0.016              | Lifting             | 201            | 2.43                |
|                  |                |                    |                |                |                    | Diversion           | 318            | 0                  | Interbasin Diversion | 0             | 0                   |
|                  |                |                    | Groundwater    | 901            | 1.11               | for Urban           | 193            | 0.15               | for Agricultural    | 708            | 0.96                |
|                  |                |                    |                |                |                    | Desalination        | 0              | 0                  | Rainwater           | 0             | 0                   |
|                  |                |                    |                |                |                    | Reclaimed Water     | 74.3           |                    |                     |                |                     |
| Purification     | 173            | 0.73               |                |                |                    |                     |                |                    |                     |                |                     |
| Transportation   | 221            | 0.96               |                |                |                    |                     |                |                    |                     |                |                     |
| Utilization      | 1570           | 111                | Industry       | 260            | 101                | Thermal Power       | 72.6           | 86.1               | General Industrial  | 175            | 13.4                |
|                  |                |                    |                |                |                    | Employees           | 13             | 1.51               | Household           | 67.9           | 8.57                |
|                  |                |                    |                |                |                    | Public              | 11.2           | 1.29               |                     |                |                     |
|                  |                |                    | Agriculture    | 1140           | 0                  |                     |                |                    | Ecology             | 85.8           | 0                   |
|                  |                |                    |                |                |                    | Ordinary            | 33.2           | 0.14               | Reclaimed           | 74.3           | 0.61                |
|                  |                |                    |                |                |                    |                     |                |                    |                     |                |                     |
| Total            | 117            |                    |                |                |                    |                     |                |                    |                     |                |                     |
### Table A5. Energy consumed through the use of water in Ordos, China, for 2017.

| Links         | Water Quantity | Energy Consumption | Classification     | Water Quantity | Energy Consumption | Classification     | Water Quantity | Energy Consumption |
|---------------|----------------|--------------------|--------------------|----------------|--------------------|--------------------|----------------|--------------------|
| Extraction    | 1540           | 3.38               | Surface Water      | 565            | 2.27               |                     | Storage        | 59.7               | 0.014              |
|               |                |                    |                    |                |                    | Lifting            | 296            | 2.26               |
|               |                |                    |                    |                |                    | Diversion          | 209            | 0                  |
|               |                |                    |                    |                |                    | Interbasin Diversion | 0             | 0                  |
|               |                |                    | Groundwater        | 899            | 1.10               | for Urban          | 197            | 0.16               |
|               |                |                    |                    |                |                    | for Agricultural   | 702            | 0.95               |
|               |                |                    | Desalination       | 0              |                    | 0                  |                |                    |
|               |                |                    | Rainwater          | 0              |                    | 0                  |                |                    |
|               |                |                    | Reclaimed Water    | 75.3           |                    | 0                  |                |                    |
| Purification  | 174            | 0.33               |                    |                |                    |                    |                |                    |
| Transportation| 226            | 0.67               |                    |                |                    |                    |                |                    |
| Utilization   | 1540           | 103                | Industry           | 255            | $9.30 \times 10^8$ | Thermal Power      | 63.3           | 77.7               |
|               |                |                    |                    |                |                    | General Industrial | 179            | 13.7               |
|               |                |                    |                    |                |                    | Employees          | 12.7           | 1.48               |
|               |                |                    | Domestic           | 80.1           | $9.99 \times 10^8$ | Household          | 68.8           | 8.68               |
|               |                |                    |                    |                |                    | Public             | 11.3           | 1.31               |
|               |                |                    | Agriculture        | 1130           | 0                  |                    |                |                    |
| Sewage Treatment | 108         | 0.75               | Ecology            | 71.7           |                    |                    |                |                    |
|               |                |                    |                    |                |                    | Ordinary           | 33.2           | 0.13               |
|               |                |                    |                    |                |                    | Reclaimed          | 75.3           | 0.62               |
| Total         |                |                    |                    |                |                    |                    | 108            |                    |
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