An Improved Emergy Analysis of the Environmental and Economic Benefits of Reclaimed Water Reuse System

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Abstract: Reclaimed water, a nontraditional water source, has become a desirable choice for meeting the increasing demand in areas with water shortages. However, the environmental and economic benefits of reclaimed water reuse systems (RWRSS) are unclear. Therefore, we conducted this study to assess the environmental performance of RWRSS based on emergy analysis. Notably, the emergy index system was improved by incorporating the environmental impacts of air emissions. The results show that the improved emergy indicator system was more rigorous than the traditional emergy index system. The environmental loading ratio and the emergy sustainability index of the studied system based on an improved emergy index system was 0.202 and 30.01, respectively. The environmental economic value was \(3.52 \times 10^{20}\) sej/y. The results show that the RWRSS has good sustainability, and high environmental and economic benefits. Compared with two other RWRSS (Scenario A in Zhengzhou City and Scenario B in Chongqing City) and one seawater desalination system (Scenario C in Qingdao City), it is found that RWRSS are preferred as a way to obtain water resources over seawater desalination under the same water quality conditions. It is also important to select an appropriate treatment process according to the raw water quality and reclaimed water use in the practical application.

Keywords: reclaimed water; environmental economic value; environmental performance; emergy analysis; emission impacts; Qingdao City

1. Introduction

Faced with the severe shortage of conventional water resources, governments are actively exploring alternative sources to obtain adequate freshwater resources. These efficient alternatives mainly include seawater desalination, reclaimed water reuse, and inter-basin water transfer [1]. Amongst them, reclaimed water has become the preferred strategy in many countries due to its stable supply and being less affected by climatic and seasonal changes [2–5]. According to statistics, global water reuse capacity has reached \(5.45 \times 10^{10}\) L per day (L/d) in 2015 [6,7]. The utilization rate of reclaimed water in developed countries such as the United States (US) and Israel has reached over 70%, while that in China is only about 10% [5,8,9].

Nowadays, reclaimed water is widely used in irrigation, municipal and environmental, and industrial applications [10–15]. In industrial reuse, two treatment steps are involved: (1) sewage treatment to remove suspended solids, and most dissolved organic and inorganic compounds; (2) further deep treatment of the sewage works effluent to industrial water quality [16–18]. It can be seen from The reuse of urban recycling water (China national standards) that the basic water quality indicators of reclaimed water for industrial use are more than those of other water purposes. In order to ensure the safety of industrial reuse, it is necessary to put forward higher treatment requirements for reclaimed water plants. Advanced purification technologies mainly include physical and chemical methods (coagulation, adsorption and filtration, etc.) [19], biological methods (biological filter,
membrane bioreactor, etc.) [20], membrane separation methods (ultrafiltration membrane, reverse osmosis, etc.) [21–23] and various coupling technologies. Hoinkis et al. (2012) found that MBR technology has great potential in industrial water reuse [24]. Liu et al. (2015) studied the incorporation of an activated carbon membrane bioreactor (MBR) into a pre-existing treatment process to meet the requirements of the advanced treatment of reclaimed water [25]. As regards the quality of reclaimed water, there are several concerns in relation to industrial reuse, including: (1) the components in reclaimed water may cause scaling, erosion, peeling, biological growth, etc.; (2) pathogenic microorganisms and chemical pollutants may affect human health during cooling water reuse [26,27]. Puckorius et al. (2013) suggested that the chloride in reclaimed water corrodes stainless steel and mild steel, while ammonia corrodes copper and copper alloy more severely [28]. Walker et al. (2013) found that reclaimed water with excess hardness could reduce the heat transfer efficiency of cooling system components [29]. As an integral part of urban water management, in addition to the above treatment technology and water quality, the environmental and economic benefits of reclaimed water are also essential. However, the sustainability and the environmental economic value (Ve) of RWRSs are unclear. Therefore, it is necessary to assess the Ve and the sustainability of reclaimed water reuse.

Emergy analysis, one of the most useful ecologically conscious tools, can convert the input and output of the system into a unified unit (sej) to analyze the environmental performance of systems [30,31]. Recently, emergy analysis has been used in agriculture, industry, urban, and ecosystem services [32–37]. In particular, Yang et al. (2017) conducted an emergy analysis to assess the Ve and sustainability of a constructed rapid infiltration system [38]. Some studies have also suggested that emergy analysis has defects, such as the insufficient consideration of pollutant emission impacts [39–41]. Therefore, emission impacts are integrated into improved emergy indices in this study.

We conducted this study to perform an emergy analysis of RWRS in Huangdao District, Qingdao City, China. The main objectives are: (1) to improve the evaluation system of Ve based on the improved emergy indices; (2) to make an environmental account of RWRSs through improved indicators; (3) to provide a new means of combining economic methods and ecological methods for the accounting of the environmental economic value of systems.

2. Study Site

In 1999, the wastewater reuse project was first established at the Haipo River Wastewater Treatment Plant in Qingdao City. The government of Qingdao gradually began to pay attention to the use of recycled water. The influent of wastewater reuse projects is mainly related to the effluent remaining after the secondary treatment of urban domestic sewage and industrial wastewater treatment. After treatment, the reclaimed water is mainly used as industrial water and municipal water. The Lianwan River sewage treatment plant is located in Qingdao Huangdao District, and is mainly used to treat industrial and domestic sewage from Huangdao, Xin’an, Lingzhushan Street Office. The treatment processes are “coagulation + continuous flow sand filter” or “deep well aeration activated sludge process”. The effluent quality meets the level A standard of “Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant”. Reclaimed water treatment plant A, with an area of 18,600 m$^2$, is located in the south of the Lianwan River sewage treatment plant. This plant is mainly used for the further deep purification of the outer drainage of the Lianwan River Sewage Treatment Plant. The reclaimed water treatment approaches include: (1) “Equalization + high efficiency sedimentation tank + ultrafiltration + reverse osmosis”—the reclaimed water treatment process; (2) “Activated carbon adsorption + flocculation precipitation”—the concentrated water treatment process; (3) “plate frame press filter”—the sludge dewatering treatment process (Figure 1). The hydraulic load is 20,000 t/d. The effluent quality is equivalent to that of pure drinking water, which is better than China’s national industrial water quality standards (GB/T19923-2005) (Table 1). The effluent is reused as boiler supplementary water and circulating cooling water to supply
the industrial park. The data have been obtained from the environmental impact report of plant A and a site investigation. The lifetime of the RWRS is designed to be 25 years.

![Diagram of plant A](image)

**Figure 1.** The main flow process diagram of plant A.

**Table 1.** The influent and effluent quality of plant A.

| Item                              | pH     | Turbidity (NTU) | COD (mg/L) | NH$_3$-N (mg/L) | SS (mg/L) | Conductivity (mg/L) | Fecal Coliforms (MPN/L) |
|-----------------------------------|--------|-----------------|------------|-----------------|-----------|--------------------|------------------------|
| Influent                          | 6.0–9.0| -               | 45         | 3               | 10        | 5600               | 1000                   |
| Effluent                          | 7.0–7.5| <3              | <2         | No detection    | 0         | <100               | -                      |
| Remove (t/y)                      | -      | -               | 313.9      | 15              | -         | -                  | -                      |
| The reuse of urban recycling water–Water quality standard for industrial uses (GB/T19923-2005)| 6.5–8.5| ≤5              | ≤60        | ≤10             | -         | -                  | ≤2000                  |
| Standards for drinking water quality (GB5749-2006)| 6.5–8.5| -               | <3         | <0.5            | -         | -                  | -                      |

3. Methods

3.1. Emergy Analysis

In emergy analysis, the various inputs (e.g., material, energy, information, labor, and money) and outputs of a system are all converted into a unified unit—solar emergy equivalent through UEV. Through multiplying the inputs and outputs by certain UEVs, the emergy of each resource, service and corresponding product can be calculated. Thereby, the environmental performance and sustainability of a system are evaluated through a series of emergy indicators [42]. However, emission impacts are not taken into account in traditional emergy analysis. Many of the emissions are harmless, but they still require the services provided by the ecosystem to be diluted or degraded to acceptable concentrations or states. They mainly include the environmental impact of the emissions discharged during the construction and the production processes of the system [43]. In this study, the influent quality has met the Chinese national standards of pollutant discharge (GB 18918-2002), and
we therefore ignore the environmental impact of emissions during the water treatment process. We only considered the air emissions’ impact during the construction of plant A and the sludge treatment process. The calculation process of traditional emergy analysis and improved emergy analysis is shown in Table 2.

Table 2. Emergy indices calculated for plant A.

| Emergy Index                          | Traditional Emergy Analysis | Improved Emergy Analysis |
|---------------------------------------|-----------------------------|--------------------------|
| Local renewable resources (R)         | Re + Rs                     | Re + Rs                  |
| Local nonrenewable resources (N)      | N                           | N                        |
| Purchased resources from main economy (F) | F_N + F_R                   | F_N + F_R                |
| Total emergy (U)                      | R + N + F                   | R + N + F + E_s          |
| Emergy yield ratio (EYR)              | U/F                         | U/F                      |
| Environmental loading ratio (ELR)     | (F_N + N)/(F_R + R)         | (F_N + N + E_s)/(F_R + R) |
| Emergy sustainability index (ESI)     | EYR/ELR                     | EYR/ELR                  |

The emergy flow diagram of plant A is depicted below (Figure 2). For the studied system, the input emergy can be aggregated into local renewable resources (R, including free renewable resources from the environment (Re) and influent (sewage works effluent, Rs)), local nonrenewable resources (N), purchased resources from the main economy (F, including the renewable fraction of resources (F_R) and the nonrenewable fraction (F_N)), and ecological services needed to dilute emissions to an acceptable level (Es, the emergy inputs of diluting air emissions to an acceptable level). The detailed emergy calculations for Es are provided in the Appendix A.

Figure 2. System diagram of the emergy flows in the studied system.

3.2. Improving the Assessment of Environmental Economic Value

Referring to the relevant research results of Shen et al. and Yang et al. on the environmental economic value accounting system of sewage treatment systems, the environmental economic value accounting system of the reclaimed water treatment system is divided into
environmental economic value \( (\text{Ve}) \) and cost value \( (\text{Vc}) \) (Figure 3) [38,44]. \( \text{Ve} \) is divided into environmental capacity value \( V_1 \) (the maximum value of the system to accommodate for pollutants), resource value \( V_2 \) (the value of the system output), and social value \( V_3 \) (the value of landscape aesthetics and the science popularization value of the system). \( \text{Vc} \) mainly includes the artificial transformation value \( C_1 \) (the input of original environment transformation into the production system and the input of various structures) and the late operation and maintenance value \( C_2 \) (the cost required for normal system operation). However, this system did not take into account ecological cost \( C_3 \) (the ecological services required to dilute emissions to an acceptable level), and it was improved in this study.

![Figure 3. The improvement assessment of environmental economic value.](image)

At the same time, the above environmental economic value accounting system is refined based on the energy theory, whereby currency, materials, and services can be converted into a unified unit through UEV. In the economic accounting system of the reclaimed water environment, \( V_1 \) is refined into the capacity of the system to accommodate the COD and NH\(_3\)-N in this study [44]. \( V_2 \) means the value of the effluent water. Due to its complexity, \( V_3 \) is not calculated in this study. \( C_1 \) refers to the emergy input of steel, cement, and other materials during the construction period of the treatment system. \( C_2 \) refers to the emergy input of electricity, chemical substances, labor, and so on. \( C_3 \) is the kinetic energy of air required to dilute emissions.

The \( V_e \), \( V_c \), the environmental economic benefit \( (V_b) \), and the cost/benefit \( (\eta) \) can be calculated as follows:

\[
V_e = V_1 + V_2 + V_3 \\
V_c = C_1 + C_2 + C_3 \\
V_b = V_1 + V_2 + V_3 - C_1 - C_2 - C_3 \\
\eta = \frac{C_1 + C_2 + C_3}{V_b}
\]

4. Results and Discussion

4.1. Air Emission Impacts

Air can be used to dilute different types of emissions; therefore, only the largest emergy of the ecological services required to dilute the emissions is included in the accounting system [45]. As shown in Table 3, the largest of the ecological services is \( 1.78 \times 10^{18} \) sej/y, related to diluting NO\(_X\). The emergy of Es is small, only accounting for 0.51\% of the U (\( 3.48 \times 10^{20} \) sej/y). This shows that air emission has little effect on the RWRS [40,41].
### Table 3. Energy evaluation table for reclaimed water reuse.

| Note | Item                                              | Raw Data  | Renewable Factor | UEV(sej/unit) | References | Solar Emergy (sej/y) |
|------|---------------------------------------------------|-----------|------------------|---------------|------------|---------------------|
|      | Local renewable resources                         |           |                  |               |            |                     |
|      | Environment (Re)                                  |           |                  |               |            |                     |
| 1    | Rain (J)                                          | $8.75 \times 10^{10}$ | 1.00            | $2.31 \times 10^{4}$ | [46]       | $2.02 \times 10^{15}$ |
| 2    | Sunlight (J)                                      | $1.15 \times 10^{12}$ | 1.00            | $1.00$        | [46]       | $1.15 \times 10^{12}$ |
| 3    | Wind (J)                                          | $5.22 \times 10^{10}$ | 1.00            | $1.86 \times 10^{3}$ | [46]       | $9.69 \times 10^{13}$ |
| 4    | Earth cycle (J)                                   | $3.87 \times 10^{10}$ | 1.00            | $4.40 \times 10^{4}$ | [46]       | $1.70 \times 10^{15}$ |
|      | Sewage works effluent (Rs)                        |           |                  |               |            |                     |
| 5    | Outer drainage (J)                                | $6.63 \times 10^{13}$ | 1.00            | $4.36 \times 10^{6}$ | [47]       | $2.89 \times 10^{20}$ |
|      | Total R (Re + Rs)                                 |           |                  |               |            | $2.89 \times 10^{20}$ |
|      | Total N                                           |           |                  |               |            | 0                   |
|      | Purchased resources from main economy (F)         |           |                  |               |            |                     |
| 6    | Fiberglass/fiber reinforced plastic (g)          | $1.55 \times 10^{5}$ | 0.00            | $7.40 \times 10^{9}$ | [48]       | $1.15 \times 10^{15}$ |
| 7    | Brick and cement (g)                              | $1.25 \times 10^{8}$ | 0.00            | $2.30 \times 10^{9}$ | [49]       | $2.89 \times 10^{17}$ |
| 8    | Steel (g)                                         | $2.77 \times 10^{6}$ | 0.00            | $3.21 \times 10^{9}$ | [50]       | $8.91 \times 10^{15}$ |
| 9    | Sand (g)                                          | $1.02 \times 10^{8}$ | 0.00            | $1.27 \times 10^{9}$ | [47]       | $1.29 \times 10^{17}$ |
| 10   | Machinery (g)                                     | $2.58 \times 10^{6}$ | 0.00            | $8.53 \times 10^{9}$ | [49]       | $2.20 \times 10^{16}$ |
| 11   | Materials expenses (USD)                           | $4.66 \times 10^{3}$ | 0.05            | $7.46 \times 10^{12}$ | [51]       | $3.48 \times 10^{16}$ |
| 12   | Labor (USD)                                       | $7.14 \times 10^{4}$ | 0.90            | $7.46 \times 10^{12}$ | [51]       | $5.33 \times 10^{17}$ |
| 13   | Tax (USD)                                         | $8.12 \times 10^{4}$ | 0.05            | $7.46 \times 10^{12}$ | [51]       | $6.06 \times 10^{17}$ |
| 14   | Poly aluminum chloride (g)                        | $3.16 \times 10^{9}$ | 0.00            | $3.37 \times 10^{9}$ | [52]       | $1.07 \times 10^{19}$ |
| 15   | Polyacrylamide (g)                                | $1.60 \times 10^{7}$ | 0.00            | $3.37 \times 10^{9}$ | [52]       | $5.39 \times 10^{16}$ |
| 16   | Hydrated lime (t)                                 | $2.49 \times 10^{3}$ | 0.00            | $1.27 \times 10^{15}$ | [53]       | $3.16 \times 10^{18}$ |
| 17   | Ethylenediaminetetraacetic acid (USD)             | $1.17 \times 10^{4}$ | 0.00            | $7.46 \times 10^{12}$ | [51]       | $8.69 \times 10^{16}$ |
| 18   | Hydrochloric acid (kg)                            | $2.27 \times 10^{5}$ | 0.00            | $2.01 \times 10^{12}$ | [54]       | $4.56 \times 10^{17}$ |
| 19   | Sodium hypochlorite (g)                           | $3.69 \times 10^{8}$ | 0.00            | $3.29 \times 10^{9}$ | [55]       | $1.21 \times 10^{18}$ |
| 20   | Scale inhibitor (USD)                             | $6.56 \times 10^{4}$ | 0.00            | $7.46 \times 10^{12}$ | [51]       | $4.89 \times 10^{17}$ |
| 21   | Sodium hydrogensulfite (USD)                      | $1.30 \times 10^{4}$ | 0.00            | $7.46 \times 10^{12}$ | [51]       | $9.71 \times 10^{16}$ |
| 22   | Non-oxidizing fungicides (USD)                    | $4.25 \times 10^{1}$ | 0.00            | $7.46 \times 10^{12}$ | [51]       | $3.17 \times 10^{14}$ |
| 23   | Sodium hydroxide (g)                              | $1.21 \times 10^{8}$ | 0.00            | $1.86 \times 10^{9}$ | [55]       | $2.25 \times 10^{17}$ |
| 24   | Activated carbon (t)                              | $2.55 \times 10^{2}$ | 0.00            | $1.98 \times 10^{16}$ | [55]       | $5.05 \times 10^{18}$ |
| 25   | Filter membranes (USD)                            | $4.31 \times 10^{6}$ | 0.00            | $6.70 \times 10^{9}$ | [51]       | $2.89 \times 10^{16}$ |
| 26   | Electricity (kw-h)                                | $2.63 \times 10^{7}$ | 0.05            | $7.95 \times 10^{11}$ | [56]       | $2.09 \times 10^{19}$ |
| 27   | Maintenance (USD)                                 | $1.78 \times 10^{6}$ | 0.05            | $7.46 \times 10^{12}$ | [51]       | $1.33 \times 10^{19}$ |
|      | Renewable fraction of purchased resources (FR)    |           |                  |               |            | $5.14 \times 10^{18}$ |
|      | Nonrenewable fraction of purchased resources (FN) |           |                  |               |            | $5.22 \times 10^{19}$ |
|      | Total F (FR + FN)                                 |           |                  |               |            | $5.73 \times 10^{19}$ |
|      | Ecological services needed to dilute emissions to an acceptable level (Es) | | | | | |
| 28   | CO$_2$ (J)                                        | $6.49 \times 10^{13}$ | 0.00            | $1.86 \times 10^{3}$ | [45]       | $1.26 \times 10^{17}$ |
| 29   | SO$_2$ (J)                                        | $8.38 \times 10^{13}$ | 0.00            | $1.86 \times 10^{3}$ | [45]       | $1.56 \times 10^{17}$ |
| 30   | NO$_x$ (J)                                       | $9.60 \times 10^{14}$ | 0.00            | $1.86 \times 10^{3}$ | [45]       | $1.78 \times 10^{18}$ |
| 31   | Dust (J)                                          | $3.47 \times 10^{12}$ | 0.00            | $1.86 \times 10^{3}$ | [45]       | $6.43 \times 10^{15}$ |
|      | Total Es                                          |           |                  |               |            | $1.78 \times 10^{18}$ |
|      | Total F                                          |           |                  |               |            | $3.48 \times 10^{20}$ |
|      | Output                                           |           |                  |               |            |                     |
| 32   | Reclaimed water ($m^3$)                           | $7.30 \times 10^{6}$ |               | $4.76 \times 10^{13}$ | [47]       | $3.48 \times 10^{20}$ |

Note: The global emergy baseline is $12.0 \times 10^{34}$ sej/y.

#### 4.2. The Emergy Flow of Plant A

The total emergy input of plant A was $3.48 \times 10^{20}$ sej/y (Table 3). Here, the emergy input of free renewable resources (R) was $2.89 \times 10^{20}$ sej/y, which is much higher than the
emergy inputs of other resources. It shows that the RWRS relies heavily on inflow water (outer drainage of the sewage treatment plant) and free local environmental resources. Notably, the emergy inputs of Rs accounts for 83% of the U. Therefore, sewage works effluent is a valuable renewable resource that contains a variety of nutrients as well as water, which is consistent with the results of Vassallo et al. (2009) and Zhang et al. (2010) [40,57].

The total emergy input of F was $5.73 \times 10^{19}$ sej/y, accounting for 16% of the U. Among the resources purchased from the main economy, electricity ($2.09 \times 10^{19}$) was the largest, accounting for 37.5% of the total F. The emergy of maintenances was $1.33 \times 10^{19}$ sej/y, accounting for 23.82% of the total F. These indicate that the maintenance of this studied system requires a large emergy input; in particular, the reverse osmosis system consumes a large amount of electricity. Therefore, the energy control of the reverse osmosis process is the key to the power control of this system.

4.3. The Environmental Performance of the Plant A

In this study, we selected two other RWRSs and one seawater desalination system (similar treatment processes to plant A) to compare with and analyze the environmental performance of plant A (Table 4). Scenario A (reclaimed water reuse subsystem in Wudongkou sewage treatment plant in Zhengzhou City): The advanced treatment approach is coagulation + precipitation + filtration + disinfection, and the effluent is reused in Jinshui River as landscape water, park water, and municipal water. Scenario B (reclaimed water reuse system in Bishan county of Chongqing City): The method is D filter filtration + ClO$_2$ disinfection, and the effluent is reused in Binan River as landscape water and municipal water. Scenario C (seawater desalination system in Baifa plant in Qingdao City): The main method of seawater desalination is pretreatment + ultrafiltration + reverse osmosis + post-treatment process; the desalinated water reaches the standard of drinking water, and can be used for daily living water. Scenario D (reclaimed water reuse system in Qingdao City): This study.

| Scenario | EYR   | ELR   | ESI   | Method                    | Reference |
|----------|-------|-------|-------|---------------------------|-----------|
| A        | 55.41 | 2.99  | 18.55 | Traditional emergy analysis | [58]      |
| B        | 142.8 | 0.005 | 28560 | Traditional emergy analysis | [59]      |
| C        | 1.01  | 5.46  | 0.19  | Traditional emergy analysis | [60]      |
| D        | 6.04  | 0.196 | 30.79 | Traditional emergy analysis | This study |
|          | 6.07  | 0.202 | 30.01 | Improved emergy analysis   |           |

As presented in Table 4, the EYR, ELR, and ESI of these systems were calculated. In scenario D, the EYR and the ELR calculated by the improved emergy index system were higher than those calculated by the traditional emergy index system. However, the ESI calculated by the improved emergy index system was lower than that calculated by the traditional emergy index system. This shows that the environmental performance and the sustainability of scenario D are reduced by integration into the environmental impact of emissions. It can also be seen that the improved emergy index system is more stringent than the traditional emergy index system. The varying quantities of EYR, ELR, and ESI in the traditional emergy analysis and the improved emergy analysis are 0.5%, 3% and 2.5%, respectively, which indicates that Es has a great influence on ELR and ESI, but has little influence on EYR. This is mainly because the emission of pollutants as non-renewable resources is more closely related to ELR (the degree of dependence on non-renewable resources in the process of system operation) and ESI (the output efficiency of the system under unit environmental pressure) than EYR.

The EYR of the four systems ranks in the order of Scenario B (142.8) > Scenario A (55.41) > Scenario D (6.04) > Scenario C (1.01). This illustrates that the three RWRSs are more efficient than the desalination systems in utilizing the local free resources. The EYRs of Scenario A and B are much larger than that of Scenarios C and D, which is related to the
different methods of the system. The treatment approaches of Scenario A and B are simple, while those of Scenario C and D all use “ultrafiltration + reverse osmosis”, which requires more external resources to develop local free resources.

The ELR of the four systems ranks in the order of Scenario C (5.46) > Scenario A (2.99) > Scenario D (0.196) > Scenario B (0.005). The ELR of the seawater desalination system is higher than that of the reclaimed water reuse system, which further indicates that the RWRS is more conducive to the environment. Under the same water quality requirements, reclaimed water can be a better choice than desalination water in order to increase freshwater resources.

The ESI of the four systems ranks in the order of Scenario B (28560) > Scenario D (30.79) > Scenario A (18.55) > Scenario C (0.19). This indicates that the RWRSs have better sustainability than the desalination system. The ESI of Scenario B is much higher than that of the other three systems, which is related to the simple water treatment approach of the system. However, Scenarios C and D have similar treatment methods, but their ESIs are significantly different, which is related to the source and quality of the influent water.

4.4. The $V_e$ of Plant A

As presented in Table 5, we calculated the $V_e$ and the cost value ($V_c$) of the studied system. The results show that the $V_e$ was $3.52 \times 10^{20}$ sej/y. The emergy of reclaimed water was $3.48 \times 10^{20}$ sej/y, accounting for 98% of the $V_e$. This result reinforces Al-Jayyousi’s (2003) assertion that reclaimed water is an economic commodity, and is a very valuable renewable natural resource [61]. The environmental capacity value ($V_1$) of the studied system was $4.08 \times 10^{19}$ sej/y, accounting for only 2% of the $V_e$. Few pollutants are removed in the RWRS, as the influent water quality has met the relevant standards. The social value in this study is not calculated due to the limitation of data sources.

Table 5. The calculated $V_e$ of plant A.

| Note | $V_e$       | $V_c$       | $V_b$       | $\eta$ |
|------|-------------|-------------|-------------|--------|
| Value (sej/y) | $V_1$ | $V_2$ | $V_3$ | $C_1$ | $C_2$ | $C_3$ | Total |
| Total | $4.08 \times 10^{18}$ | $3.48 \times 10^{20}$ | 0 | $1.62 \times 10^{18}$ | $5.57 \times 10^{19}$ | $2.10 \times 10^{16}$ | $2.93 \times 10^{20}$ | 1:4.96 |

The $V_c$ of plant A was $5.91 \times 10^{19}$ sej/y. The maintenance cost ($C_2$) was $5.57 \times 10^{19}$ sej/y, which occupied 94% of the total cost value. The emergy of electricity was $2.09 \times 10^{19}$ sej/y, accounting for 38% of the total maintenance cost. The construction cost ($C_1$) was $1.62 \times 10^{18}$ sej/y, only 3% of the total cost value. Therefore, the operation and maintenance of RWRS needs a large emergy input, while the emergy input in the construction period is not high.

Environmental cost ($C_3$) mainly refers to the cost of environmental quality decline caused by economic activity [38]. According to the concept of environmental cost, we included Es as the ecological cost in the cost value accounting system. The ecological cost of the studied system was $1.78 \times 10^{18}$ sej/y, which occupied 3% of the total cost value.

The economic benefit of the studied system was $2.93 \times 10^{20}$ sej/y, and the cost/benefit was 1:4.96. This reveals that the environmental and economic benefits of RWRSs are high.

5. The Application Prospect of Reclaimed Water Reuse System in China

This analysis reveals that the RWRS has large environmental and economic benefits, and achieves good sustainability, fully meeting the requirements of sustainable development. However, the utilization rate of reclaimed water is not high (about 10%) in China due to public skepticism about reclaimed water, the defects of engineering construction, and the imperfect present system [9,62]. At present, urban sewage treatment is developing at an
unprecedented speed in China. According to statistics, there were 2471 sewage treatment plants in China, with sewage treatment capacity reaching 178,631,700 m³/d, by the end of 2019 [63]. Despite the presence of some pollutants, organisms and their metabolites in the effluent of the sewage treatment plant, which will pose certain ecological risks to the receiving water [64], these effluents provide stable and reliable water sources for reclaimed water reuse. Whether based on eliminating pollution or increasing water supply, the reclaimed water reuse rate will be greatly improved [65]. With the increasingly serious shortage of water resources, reclaimed water reuse will develop a more extensive application prospect in China.

From this analysis, it can be found that the RWRS with “ultrafiltration + reverse osmosis” is faced with the problems of expensive membrane components and the high power consumption. RWRSs with simple methods have good sustainability. Therefore, it is also of importance to choose the appropriate treatment method according to the raw water quality and the reuse purpose of the reclaimed water in practical applications. In addition, strengthening the new technology of reclaimed water treatment, increasing financial support, and actively carrying out publicity for reclaimed water reuse are of great significance to the promotion of reclaimed water reuse.

6. Conclusions

Air emissions’ impacts were incorporated into the emergy indicator system in this study. Based on the improved emergy indices system, we assessed the sustainability, as well as the environmental and economic benefits, of the RWRS in Huangdao District, Qingdao City. The results show that the U of this system was $3.48 \times 10^{20}$ sej/y, and the emergy of Es was small, only accounting for 0.51% of the U. This shows that the air emissions have little impact on the RWRS. However, the environmental performance and the sustainability of this system are reduced by integrating the environmental impact of emissions. It can also be seen that the improved emergy index system is more stringent than the traditional emergy index system.

By comparing with two other RWRSs and one seawater desalination system, it can be found that the sustainability of RWRSs is better than that of the seawater desalination system. Therefore, with the same water quality requirements, RWRSs should be preferred as a way to obtain alternative water resources. This result also indicates that the reclaimed water treatment approach has a great impact on the sustainability of the RWRS. It is necessary to choose the appropriate method according to the raw water quality and the intended practical application of the reclaimed water.

RWRSs have high environmental and economic benefits. Reclaimed water reuse has great development potential in China. It is very important to strengthen the relevant technologies, increase the financial support, actively carry out publicity for reclaimed water reuse, and develop the related laws and regulations in order to further improve the RWRSs.

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Appendix A

Ecological services required to dilute emissions to an acceptable concentration \( (E_s) \):

\[
M = \frac{d \times w}{c} - M_{\text{air}} \tag{A1}
\]

\(M\) is the mass of dilution air, \(g\); \(d\) is the air density, 1.29 kg/m\(^3\); \(w\) is the mass of a given air emission, \(g\); \(c\) is the acceptable concentration under agreed regulations (Table A1), g/m\(^3\); \(M_{\text{air}}\) is the mass of discharged air during the construction of the system, g [40].

\[
E_s = 0.5 \times M \times v^2 \times UEV_{\text{air}} \tag{A2}
\]

\(E_s\) is the emery of the required ecological services, sej/y; \(v\) is the average value of local wind speed in a year, m/s; \(UEV_{\text{air}}\) is the unit emery value of the kinetic energy of dilution air, sej/j.

Table A1. Some accepted air emission concentrations used in this study.

| Name     | Accepted Concentrations | References                                      |
|----------|-------------------------|------------------------------------------------|
| CO\(_2\) | 2000 mg/m\(^3\)        | Indoor air quality standard (GB/T 18883-2002)   |
| SO\(_2\) | 0.02 mg/m\(^3\)        | Ambient air quality standards (GB 3095-2012)    |
| NO\(_X\) | 0.04 mg/m\(^3\)        | Ambient air quality standards (GB 3095-2012)    |
| dust     | 0.08 mg/m\(^3\)        | Ambient air quality standards (GB 3095-2012)    |

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