AQUA
Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 72 No 2, 173 doi: 10.2166/aqua.2023.198

Efficiency of a gravity-driven membrane in a water treatment plant

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ABSTRACT

Membrane filtration technology is widely applied in conventional surface water treatment plants because of its low power load and high filtration accuracy. This study follows the transition from a power-driven to a gravity-driven siphon-submerged ultrafiltration membrane system in a drinking water treatment plant in Shandong Province, China. The proportion of space membrane areas in the tank was further developed, by increasing the membrane areas of a single tank to 1.6 times that before the transformation, and the design production capacity of a single tank is increased from 10,000 m^3/d before the transformation to 16,700 m^3/d. The recovery rate of a single tank was also increased from 96.28 to 97.77%. The energy consumption per ton of water decreased from 0.06 to 0.017 MJ. The annual carbon emissions reduction reached 197.13 tons per tank. In terms of the water quality, the algae removal rate from surface water by the ultrafiltration membrane reached 100%. Further, the removal rates of 2 μm particles, turbidity, and chlorophyll were above 99%. Our results suggest that gravity-driven siphon-submerged ultrafiltration promotes environmental protection, energy conservation, and emissions reduction. This technology introduces a new development direction for membrane filtering in drinking water treatment plants.

Key words: emission reduction, energy-saving, gravity siphon, submerged ultrafiltration

HIGHLIGHTS

- A power-driven water treatment system was upgraded to be gravity-driven.
- The gravity siphon membrane modules required excellent hydrophilicity properties.
- The flow and transmembrane pressure were linearly related to the water level.
- Energy consumption and CO_2 emissions decreased with the gravity-driven system.

INTRODUCTION

The current situation regarding drinking water safety is concerning. Problems such as water shortages, pollution risks, and quality changes are becoming increasingly serious. People are growing more concerned than before about the safety and quality of drinking water, which pushes drinking water quality indicators to become increasingly stricter. Because of its efficient filtration accuracy and stable effluent quality, membrane technology has attracted extensive attention in the field of drinking water purification (Cevallos-Mendoza *et al.* 2022).

The microfiltration or ultrafiltration membrane used in municipal drinking water in China is a mature technology that has been applied on a large scale (Li & Chen 2018; Yuan *et al.* 2020; Shen *et al.* 2021). For most of these applications, power-driven external pressure column and submerged ultrafiltration processes were adopted. Both membrane treatment processes are designed to separate and purify contaminants in the water using pump pressurization or suction. Figure S1 shows the 300,000 m^3/d pressure ultrafiltration process in the Ling Zhuang zi water plant in Tianjin, China. Figure S2 shows the 30,000 m^3/d submerged ultrafiltration process in the Dingwu water plant in Laoling, Shandong Province, China.

In recent years, some researchers have studied the application of gravity-driven siphons to the membrane filtration process (Patterson & Pease 2005; Janson *et al.* 2006; Crossley *et al.* 2007; Song *et al.* 2020). Gravity-driven siphon water production is achieved through a height difference between the water levels of the membrane tank and the clean water tank, following the

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Bernoulli equation. Compared with the traditional power-driven water production process, the gravity-driven siphon has a lower energy consumption and simpler operation and maintenance (Capitaine 1984; Shorney-Darby *et al.* 2007; Tang *et al.* 2018). Once the technology is developed further, it will be well worth promoting. In Singapore, Water Treatment and Process Group of General Electric Company carried out the transformation of a gravity-driven siphon-submerged membrane system for a 182,000 m^3/d-Phase I V-shaped filter in the Choa Chu Kang Water Plant in 2008. The membrane system occupied only four of its nine filters, and the three filters are transformed into supporting equipment rooms, reagent rooms, backwashing, cleaning water tanks, etc. The other two filters are reserved spaces. The system carried out the maximum trans-membrane pressure (TMP) difference of the membrane through a 4.65 m water level difference between the membrane and clean water tanks. The energy consumption of the entire membrane system after the transformation was only 0.0178 MJ/m^3 (Luo 2008). Gravity-driven siphons have also appeared in China in recent years. In 2020, Tianjin Motimo Membrane Technology Co., Ltd adopted this technology for the reconstruction of a 125,000 m^3/d water plant in Tangshan, Hebei Province. In this project, the Phase I sand filters of the water plant were transformed, and the energy consumption per ton of water was reduced from 0.045 to 0.0185 MJ/m^3 (Hu *et al.* 2021). Also in 2020, the Ningbo Taoyuan Water Plant, the largest submerged waterworks in China with a capacity of 500,000 m^3/d, adopted the gravity-driven submerged membrane process located in a mountainous area. However, the above-mentioned application cases and published articles rarely mention the design details of the gravity siphon process. Taking the gravity siphon membrane process transformation project of a water supply plant in Shandong Province as an example, the study analyzes the progressiveness of the gravity siphon-driven immersion membrane technology from three aspects: (1) component selection to process design; (2) changes in water volume, energy, consumption and recovery rate before and after system transformation; (3) stability of membrane system operation and water quality of membrane inlet and outlet. It provides a new reference for the development of the membrane water treatment process in surface water plants.

METHODS

Project overview

The existing process route of the drinking water treatment plant in Tai'an is to draw water from the bottom of the Huangqian reservoir. After flocculation and precipitation, it is filtered using a submerged ultrafiltration process and then chlorinated. The water source was changed to the surface water intake of the reservoir from June to mid-August every year, but the concentrations of algae and Mn in the water increased. In 2012, the drinking water treatment plant began operating with a submerged ultrafiltration process, with a water production scale of 100,000 m^3/d. We can get the process route of the drinking water treatment plant from Figure 1. In 2019, urban planning water consumption increased significantly, and the existing membrane components reached the end of their service life, which seriously affected the water supply. Under the condition of maintaining the original structure, the water treatment plant plans to

- implement energy-saving transformations on 6 of the 12 existing membrane tanks;
- install Polyvinylidene fluoride (PVDF) ultrafiltration membranes with high filling density, high flux, and low transmembrane pressure difference;
- transform and replace part of the process equipment, pipes, and electrical and automatic control; and
- achieve the water production and energy conservation goals for the gravity-driven siphon water system.

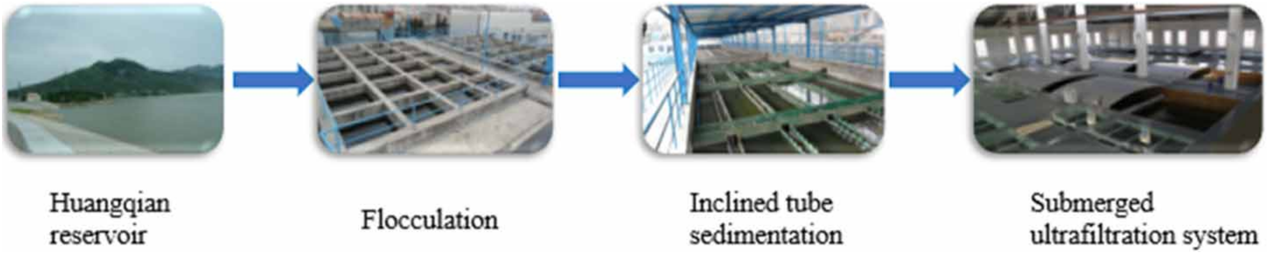


Figure 1 | The process route of the drinking water treatment plant in Tai'an.

Efficiency optimization of the process design

The power-driven submerged ultrafiltration system was transformed into a gravity-driven siphon ultrafiltration system. In addition to the approved upgrade of existing equipment parameters and the dismantling of the pipeline, the four key elements were as follows:

(1) selecting ultrafiltration components with better membrane performance;
(2) selecting an appropriate membrane flux;
(3) ensuring a water level difference to act as a driving force;
(4) designing a stable, reliable, and flexible process operation sequence.

Membrane performance requirements

The pressure difference produced by siphon water is not too high, generally approximately 20–30 kPa. Therefore, the selected ultrafiltration membrane components should exhibit excellent hydrophilicity and pollution resistance. The ideal component performance for the gravity-driven process is shown in Figure 2.

The material, filtration accuracy, pure water flux, and hydrophilic contact angle must be improved when selecting membrane modules. Further details are provided in Table 1.

Selection of the membrane flux

To guarantee membrane performance, the selection of the membrane flux is key. If the membrane flux selected is too high, the membrane operation load will be too heavy, contamination will increase rapidly, the cleaning cycle will be frequent, and operation costs will rise. Selecting a small membrane flux will lead to increased investment costs and space occupation. We investigated the membrane flux of several submerged membrane process water plants that treat similar water sources.

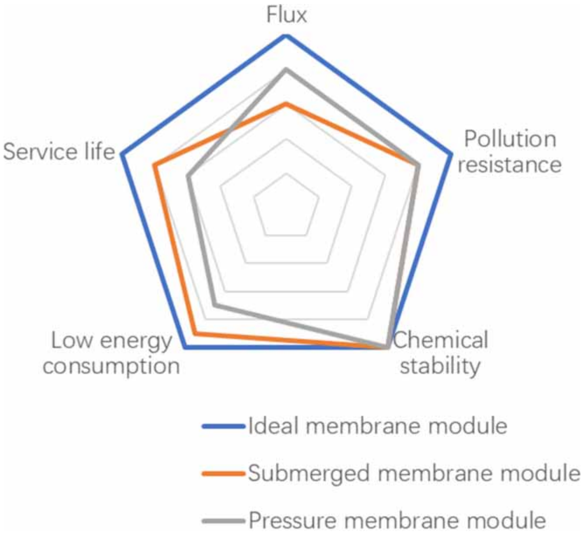


Figure 2 | Performance comparison of ideal, conventional submerged, and pressure membrane modules applied to a gravity-driven siphon.

Table 1 | Comparison of performance before and after the membrane replacement

Project	Before replacement	After replacement	Note
Membrane component material	PVDF	PVDF	High chemical stability and pollution-resistant materials
Average pore size (μm)	0.03	≤0.03	High filtration precision ensures the safety of water quality
Pure water flux (L/m^2·h/bar)	≥800	≥1,200	High pure water flux ensures a stable production capacity
Hydrophilic contact angle (°)	≤65	≤35	The hydrophilicity is related to the membrane flux properties

See Table S1 for details, which is used as the basis for the selection of membrane flux for this transformation project. Considering that the membrane area space can be expanded according to the existing membrane tank, the final instantaneous flux was selected to be 24.33 LMH ($L/m^2 \cdot h$) (specific data are shown in Table S1).

Design of the membrane tank and water level

Because there was no extra space in this project, the renovation was based on an existing membrane tank. Table 2 compares the main parameters before and after the renovation.

The modified plan and section of the membrane tank are shown in Figures S3 and S4, while the submerged ultrafiltration module for the gravity-driven siphon is shown in Figures S5 and S6. The capacity of the membrane tank was increased by 10,680 m^2 with the same floor area owing to the vertical space in the tank being fully utilized. Simultaneously, a membrane assembly with better performance was used in the membrane tank, which improved the average membrane flux. The water production capacity of a single tank was expected to increase 1.67 times.

Water level difference design

We calculated the inlet channel water level, existing membrane tank operating level, highest clean water tank level, and possible head loss in the water treatment process. The difference between the available membrane and clean water tank levels was 2.9 m. After subtracting the various pipe and head losses, the water level difference obtained by the submerged membrane system was 2.617 m. The driving force of this difference could reach up to 26.17 kPa. To increase the driving force of the water level difference, the height of the adjustable weir plate of the inlet channel was raised.

Process operation step sequence

The gravity-driven siphon membrane system is mainly composed of water inlet channel, membrane tank, drainage system, water production system, backwashing system, and other supporting systems (air compressors, chemical washing, and programable logic controllers). Figure 3 shows the membrane system process after transformation and Table 3 shows the main equipment and valves of the membrane tank. The only requirement for daily operation involved opening the siphon production valve to control water flow.

To avoid membrane fouling – the main problem in the application of ultrafiltration membranes – an effective cleaning method to reduce membrane contamination was key (Qiu & Zhang 2002; Liu *et al.* 2014; Huang *et al.* 2021). This project refers to the operating experience of the submerged membrane system before the transformation and realizes the settable and revisable functions on some key parameters. In this way, when the water quality changes or the physical/chemical cleaning effect is poor, the parameters can be adjusted to delay membrane pollution.

The gravity-driven siphon-submerged ultrafiltration process included the following stages:

- Water replenishment

Raw water went through the inlet channel into the membrane tank after opening the inlet valve. To improve the water production efficiency, the time it took for water to reach the set operating level was constrained at 60 s.

Table 2 | Main parameters before and after renovations

Project	Original membrane tank design	Film tank transformation design
Membrane tank size $L * W$ (m)	10.6 × 5.5	10.6 × 5.5
Number of membrane frames (table)	16	22
Number of membrane components (branch)	512	572
Single-branch assembly membrane area (m^2)	35	50
Total membrane area (m^2)	17,920	28,600
Design flux ($L/m^2 \cdot h$)	23.25	24.33
Total capacity (m^3/d)	10,000	16,700
Water production supervisor pipe diameter (mm)	DN400	DN500
Aeration pipe diameter (mm)	DN200	DN250

Notes: L, length; *W*, Width.

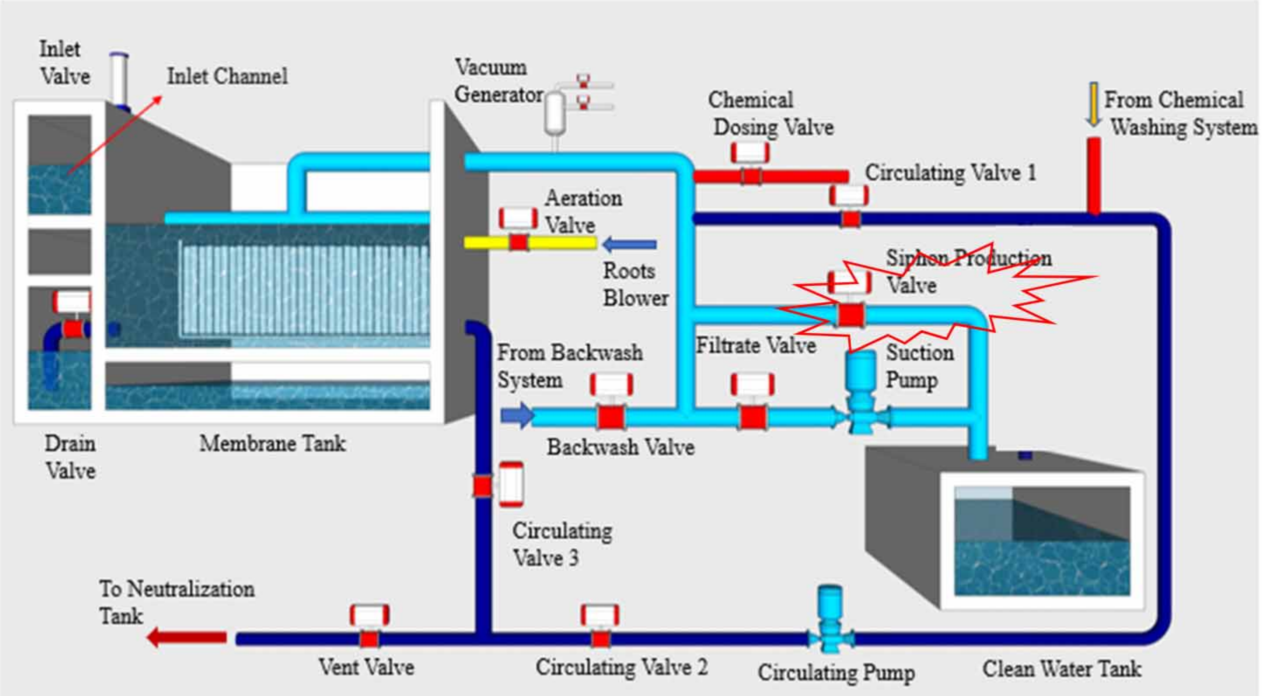


Figure 3 | Process flow chart of gravity-driven siphon-submerged ultrafiltration.

Table 3 | The equipment/valve list of gravity-driven membrane tank

Serial No	Equipment/valve	Function
1	Inlet channel	Water storage to quickly replenish water for membrane tank
2	Inlet valve	Control the level of membrane tank
3	Membrane tank	Place for membrane production, backwashing, and chemical cleaning
4	Membrane modules	Used to filter impurities and pollutants in water
5	Vacuum generator	It is used to extract the air in the pipeline to avoid breaking the vacuum environment
6	Siphon production valve	Control the flow of gravity-driven siphon membrane production
7	Filtrate valve/suction pump	When siphon cannot meet the membrane water production, the water production can be pumped
8	Aeration valve/roots blower	Control the membrane air washing
9	Backwash valve/backwash system	Control the membrane backwashing
10	Chemical dosing valve	Dosing chemicals during EFM
11	Drain valve	Control the discharge of membrane tank
12	Circulating valve1/2/3 and circulating pump	Drive the chemicals to circulate inside and outside the membrane to enhance the cleaning effect
13	Vent valve	Control the discharge of cleaning waste liquid

- Water production

The siphon production valve was opened after the set level was reached, there was feedback between the valve and the set water-flow rate. The system will automatically adjust the siphon production valve opening through the proportional integral differential according to the set flow and start to produce water. During this stage, the vacuum generator would also start and stop automatically according to the flow switch supervisor of the generator. This prevented the water production pipeline from affecting the gravity-driven siphon with air bubbles.

- Physical backwash

The flux of the ultrafiltration membrane gradually decays as the membrane pores get plugged with organic matter, inorganic chemicals, and microbial pollutants (Zheng *et al.* 2011). Physical backwashing slowed down the formation of fouling and filter cake layers and eliminated pollutants accumulated on the membrane surface in the short-term through aeration, air washing, and drainage.

(1) Aeration. After the water level of the membrane tank was lowered to the backwash level, the water production control valve was closed, triggering the air washing procedure. A blower started working and the aeration valve of the membrane tank was opened. Air rose gradually from the bottom of the membrane frame along the membrane assembly. The large air bubbles removed the suspended particles accumulated on the surface of the filaments.
(2) Air washing. The backwash pump and backwash valve were opened at the same time. Backwashing water is generally produced by a membrane, and the backwashing flow is 1.5 times that of the produced water flow. In this step, the pollutants on the membrane surface can be further peeled off through the synergetic effect of air and water.
(3) Drainage. The drain valve of the membrane tank was opened, and the backwash sewage was discharged by gravity. The purpose was to remove the contaminants that had fallen into the water from the membrane tank. Simultaneously, the rapid drop in the water level during the discharge process could also scour the membrane surface.

The conventional water production and backwashing process steps are shown in Figure S7.

- Chemical cleaning

Conventional physical backwashing cannot remove all the contaminants from the membrane surface (e.g., microbial pollution, organic pollution, and inorganic salt scales). Therefore, to guarantee production capacity, the membrane operating pressure difference exhibits a slow growth trend. Because of the accumulation of membrane contamination, this trend rises sharply in later stages, which has a substantial impact on the continuous production capacity. To ensure the recovery of the membrane performance and achieve long-term stable operation, chemical agents aimed at eliminating pollution must be added. Two units of chemical cleaning were used in this project: enhanced flux maintenance (EFM) and cleaning-in-place (CIP).

(1) EFM

This type of maintenance cleaning involved the use of chemical cleaning equipment to add low concentrations of chemicals. It could effectively reduce the contamination by organic and inorganic colloids on the membrane surface after a short cycle and submergence. After the flux was restored, the stable operation of the system was maintained for 3–7 days.

(2) CIP

This restorative cleaning is the use of a chemical cleaning system to add high concentrations of chemical agents. Through multiple cycles and prolonged submerging, chemical reactions to separate and dissolve the compound contaminants accumulated on the membrane surface.

The EFM and CIP process steps of maintenance cleaning and chemical online cleaning are shown in Fig S8 and Fig S9. Cleaning agents are commonly used for different pollutants. The selection of cleaning agents for different pollutants is shown in Table S2.

Theoretical basis of the gravity-driven siphon operation

Figure 4 shows a typical siphon environment formed by a submerged membrane tank and a clean water tank. Section 1–1 marks the level of the membrane tank, section 2–2 marks the siphon-crossing point, section 3–3 marks the outlet point of water production pipe. Sections 1 and 2 can be calculated with a formula using the Bernoulli equation:

$$\frac{P_1}{\rho g}+Z_1+\frac{u_1^2}{2g}=\frac{P_2}{\rho g}+Z_2+\frac{u_2^2}{2g}+h_f \tag{1}$$

where P_1 and P_2 are the apparent pressure of sections 1–1 and 2–2, respectively; Z_1 and Z_2 are the datum plane and H_1,

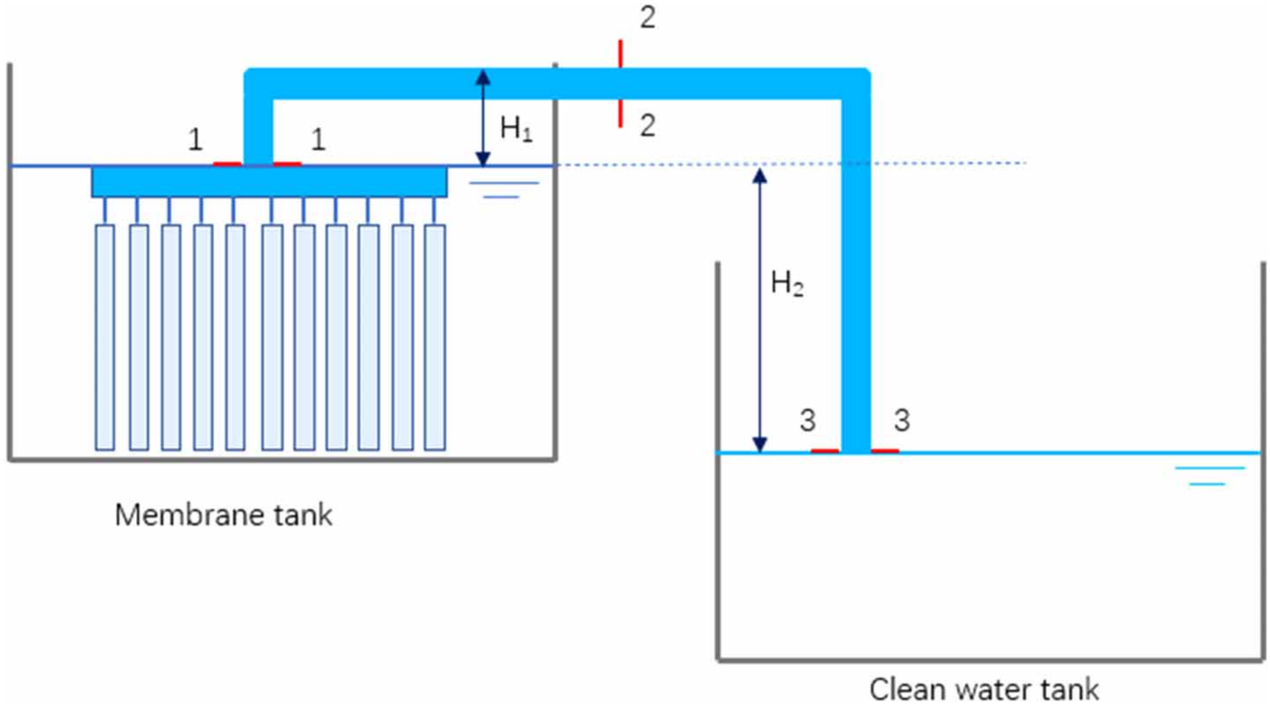


Figure 4 | Schematic diagram of a gravity-driven siphon.

respectively; u_1 and u_2 are the flow rate of sections 1–1 and 2–2, respectively; ρ is water density; g is gravitational acceleration; and h_f is the pipeline loss.

As section 1–1 is taken at the datum plane of the water level, P_1, Z_1, and u_1 are zero. The datum plane is very large and is obtained using Equation (1)

$$0 + 0 + 0 = \frac{P_2}{\rho g} + Z_2 + \frac{u_2^2}{2g} + h_f \tag{2}$$

Considering that $Z_2 > 0$, $u_2 > 0$, and $h_f > 0$, we can obtain $P_2 < 0$ for section 2–2 to generate negative pressure and a siphon effect.

RESULTS AND DISCUSSION

Flow and pressure changes with different water levels

The gravity-driven siphon ultrafiltration membrane system has been stable since it was put into operation at the beginning of 2020, and the average flow of a single tank has been maintained at approximately 700 m^3/h. The membrane pressure difference during transmembrane operation was always 9–20 kPa. The daily production capacity reached the design target. Figure 5 describes the changes in flow and differential pressure of different membrane tank water levels at the beginning of the operation. It was found that the water production flow and TMP difference increased with the water level of the membrane tank; there was a certain linear relationship when membrane pollution had not affected the water production resistance in a substantial way. Evidently, the upper capacity limit of the gravity-driven ultrafiltration system was mainly affected by two factors: (1) the water level difference between the inlet and outlet water of the membrane tank and (2) the hydrophilicity of the membrane.

Stability of membrane system operation

The operating parameters of the membrane system are very important for the stability of the membrane system operation, such as the TMP, production flow and other parameters of the membrane. In production, in order to facilitate the analysis

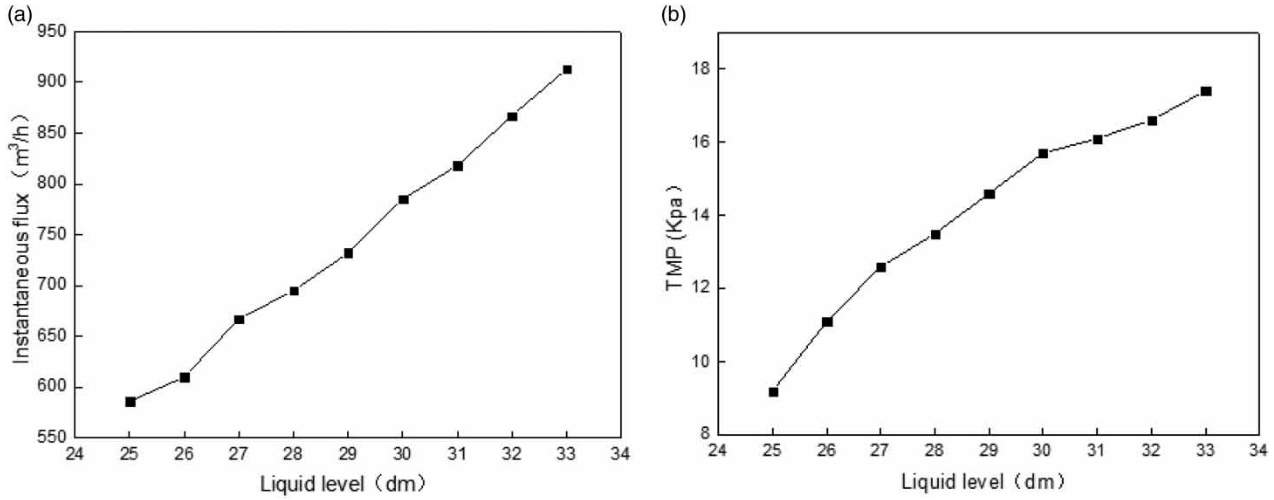


Figure 5 | (a) Instantaneous flux and (b) TMP change curves with different water levels.

of membrane system operating parameters, a constant flow control mode is usually adopted, and the production flow of the membrane system is kept constant through frequency conversion control. The TMP will increase with the continuous accumulation of pollution, and its trend indicates whether the membrane operation is stable. After the project is changed to gravity siphon water production, the production flow is controlled by controlling the siphon production valve opening. Therefore, in order to eliminate the impact of data fluctuation on the analysis effect, it is more objective to use membrane-specific flux to analyze the stability of membrane operation and the speed of pollution (Liu *et al.* 2020). Specific Flux (SF) is defined in the following formula:

$$\mathrm{SF}_0 = J/\Delta P \tag{3}$$

SF_0 is the membrane specific flux before temperature correction, $\mathrm{L/(m^2 \cdot h \cdot kPa)}$; J is the membrane flux, $\mathrm{L/(m^2 \cdot h)}$; $J = Q/A$, Q: membrane system flow $\mathrm{m^3/h}$; A: Membrane area, $\mathrm{m^2}$; $\triangle P$ is the measured transmembrane differential pressure, kPa.

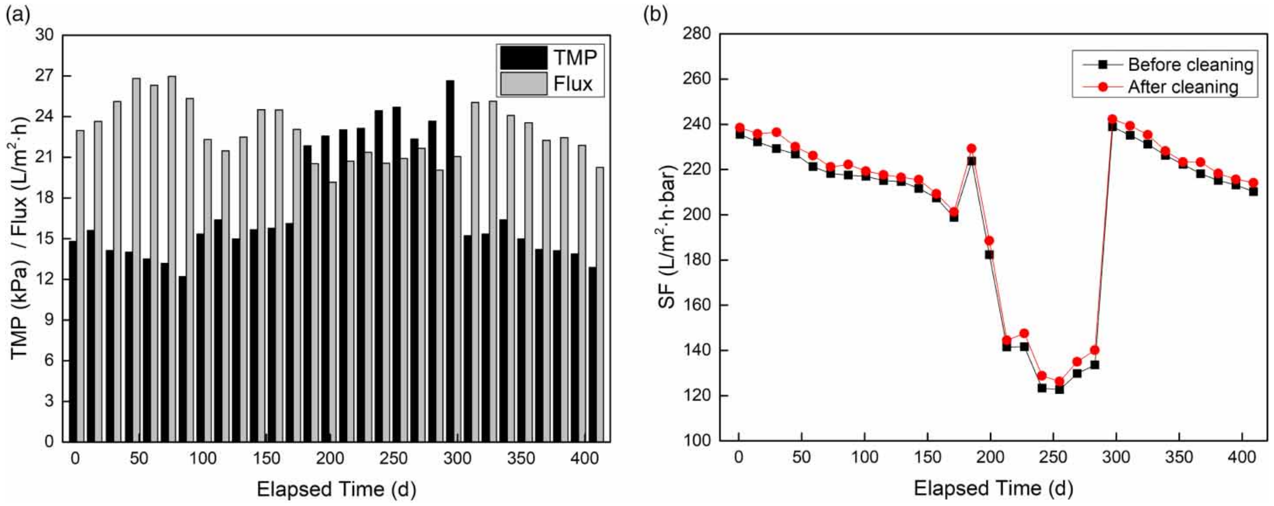
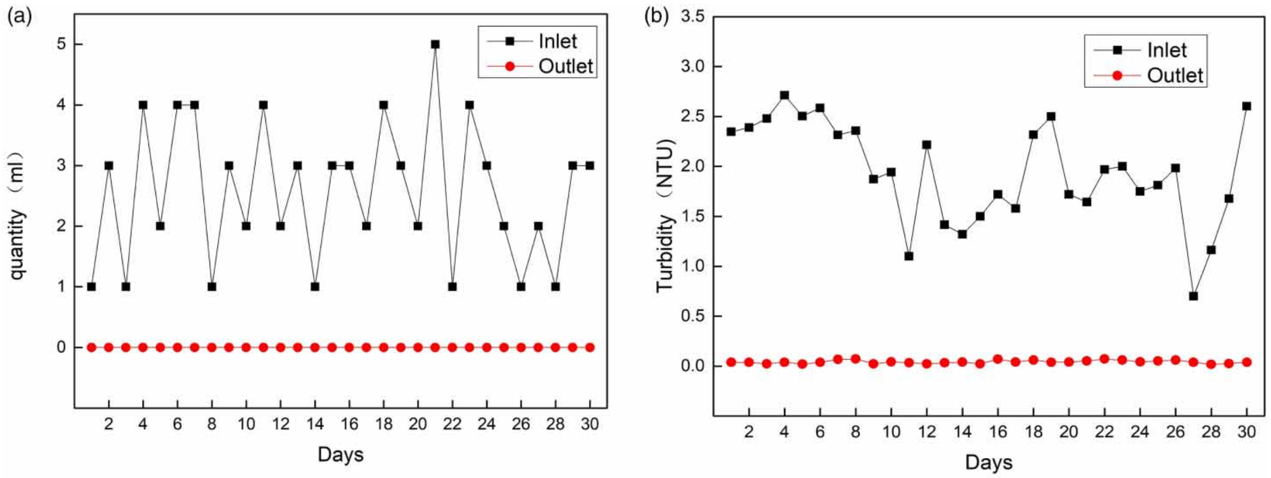
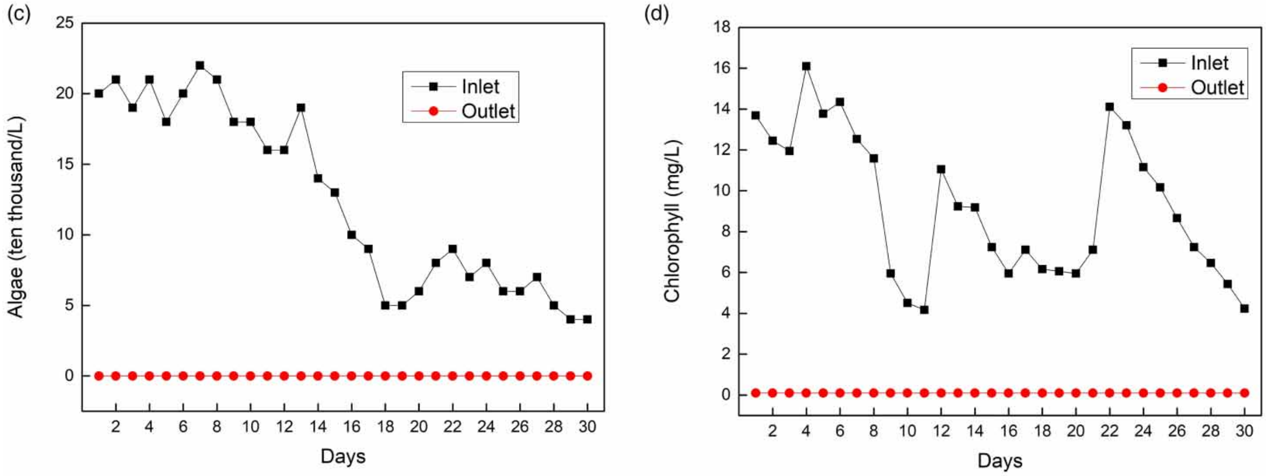


Figure 6 | (a): TMP/Flux and (b): SF trend of the membrane system.



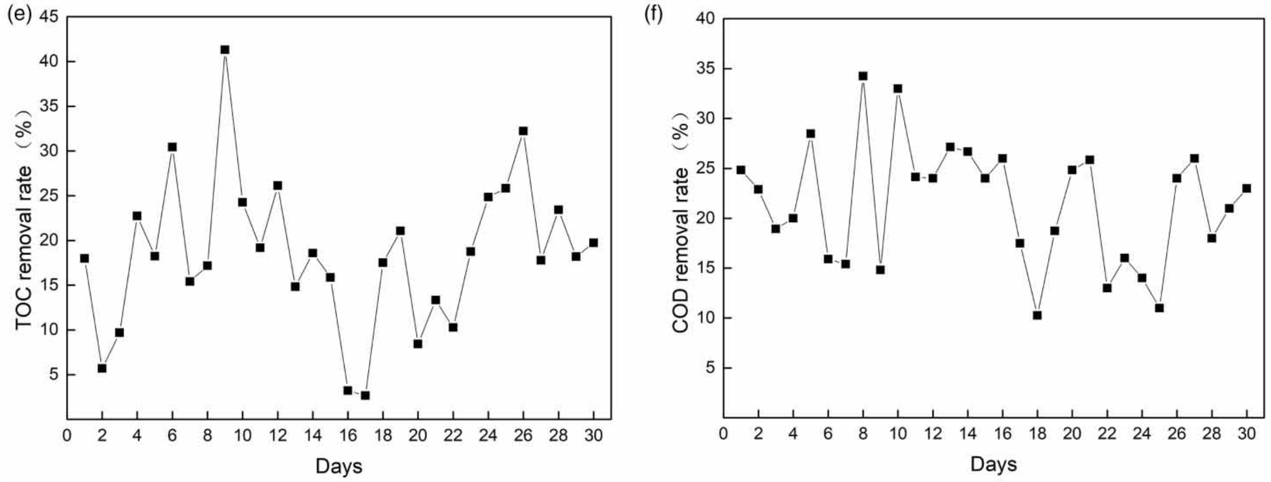
2 μm particles removal effect

Inlet and Outlet turbidity



algae removal effect

chlorophyll removal effect



Removal rates of TOC

Removal rates of COD

Figure 7 | Concentration of the main pollutants: (a) 2 μm particles, (b) turbidity, (c) algae, (d) chlorophyll. Removal rates of (e) TOC and (f) COD.

Table 4 | Comparison of energy consumption, chemical consumption, and recovery rate per ton of water between the membrane systems

Project	Before the transformation	After the transformation	Remarks
Daily output (t/d)	10,000	16,700	–
Energy consumption (MJ[a]/d)	2,160	1,022	–
CO_2 emission due to power consumption[b] (tons/tank·year)	$2160 \times 0.28 \times 0.544 \times 365 \div 1000 = 120.09$	$1022 \times 0.28 \times 0.544 \times 365 \div 1000 = 56.82$	CO_2 emission reduction can reach 120.09–56.82 = 63.27
Energy consumption per ton of water (MJ/t)	0.216	0.061	Energy consumption can reach 0.216–0.061 = 0.155
Chemical consumption[c] (Yuan/t)	NaClO: 0.005 Citric acid: 0.033 Total: 0.038	NaClO: 0.003 Citric acid: 0.02 Total: 0.023	NaClO price: 800 RMB/T[d] Citric acid price: 15,000 RMB/T
Recovery rate (%)	96.28	97.77	Recovery rate = $F1 - F2 \div F0 \times 100\%$[e]

[a] MJ, Million joules, 1 MJ = 0.28 kWh.

[b] According to the Statistical Bulletin of the People's Republic of China on National Economic and Social Development in 2020 issued by the National Bureau of Statistics, thermal power generation in China will account for 68.51% in 2020; According to the Statistical Data of National Electric Power Industry in 2020 issued by the National Energy Administration, the standard coal consumption per kilowatt hour of electricity under the premise of dynamic power generation is 305.5 g; According to the Construction Scheme of National Carbon Emission Trading Market (Power Generation Enterprises), the carbon dioxide emission per ton of standard coal shall be 2.6 tons; The comprehensive carbon dioxide emission per kilowatt hour is $0.6851 \times 0.3055 \times 2.6 = 0.544$ kg.

[c] The difference in the consumption of chemicals per ton of water in membrane tanks before and after transformation is mainly caused by the difference in the production flow.

[d] RMB/T means Renminbi (RMB) per ton.

[e] *F*0, Inlet flow; *F*1, Production flow; *F*2, Backwash flow.

In order to facilitate the comparison of membrane SF at different temperatures, it is necessary to compare the flux for temperature correction;

$$\mathrm{SF} = \mathrm{SF}_0 \times e^{-0.0239\times(T-25)} \tag{4}$$

SF is the membrane specific flux corrected to 15 °C, $\mathrm{L/(m^2 \cdot h \cdot kPa)}$; T is the water temperature, °C.

We can obtain Figure 6 according to the above methods.

It can be seen from Figure 6 that the membrane SF is relatively stable at the initial stage of operation, showing a slow decline, and each physical backwash can play a certain recovery effect. When operating for more than 200 days, the SF drops rapidly. It can be seen from the reference flux and TMP curve that the membrane flux maintains a low operating state during this period, which may be due to the relatively small water demand during this period. At the same time, the TMP has obviously increased in 200–290 days, indicating that the membrane has been deeply polluted, and it is difficult to recover with conventional physical cleaning. So the water plant carried out the first chemical cleaning after the system was put into operation, using 3,000 ppm sodium hypochlorite and 5,000 ppm citric acid for chemical cleaning. After cleaning, the recovery effect of TMP and SF is ideal, and the subsequent operation parameters are relatively stable.

Removal effect of the main membrane filtration pollutants

In addition, the inlet and outlet water quality of the membrane system is also an important indicator for stable operation of the membrane system. The quality of influent water directly affects the speed of membrane pollution, while the membrane itself has a high filtering accuracy, and the quality of produced water is generally relatively stable. If the quality of produced water from the membrane fluctuates greatly or the quality index of produced water is generally poor, the high probability indicates that the integrity of the membrane module is damaged and the operation of the membrane system is defective.

We know from Table 1 that the filtration precision of membrane modules used before and after the project transformation is 0.03 μ m. According to the data fed back by the water plant, the quality of produced water has not changed obviously at all. The removal effect of main membrane filtration pollutants is shown in Figure 7. Surface water entered the siphon-submerged ultrafiltration system after flocculation and sedimentation. The turbidity of the influent fluctuated from 1 to 5 nephelometric turbidity unit (NTU), while the turbidity of the effluent after membrane filtration was less than 0.05 NTU. Most 2 μm particles were intercepted by the membrane. The fluctuation of chlorophyll ranged from 4.89–16.43 mg/L. The pollutant removal rates described were maintained at approximately 98%. The average total organic carbon (TOC) and chemical oxygen demand (COD) removal rates were 18.12 and 21.46%, respectively. The quality data of the produced water met the requirements of the Sanitary Standards for Drinking Water (GB 5749-2006).

Economic analysis

The original pressure-driven submerged membrane system was transformed into a gravity-driven siphon one. There were clear, observable effects of energy conservation and emissions reduction (Young & Perri 2015). The energy consumption per ton of water, chemical consumption, and recovery rate were improved to varying degrees. Table 4 shows the advantages of the gravity-driven submerged ultrafiltration system.

CONCLUSIONS

(1) The membrane modules used in the gravity-driven siphon-submerged ultrafiltration system required excellent hydrophilicity and antipollution properties.
(2) The upper filtration pressure limit of this system depended on the absolute height difference between the membrane and clean water tanks. The maximum membrane filtration pressure difference of this project was 26.17 kPa.
(3) The flow velocity and TMP of the gravity-driven siphon system had a linear relationship with the water level.
(4) The algae removal rate of the siphon membrane system was 100%. The removal rates of 2 μm particles, turbidity, and chlorophyll were all $>$99%. The average TOC removal rate was 18.12%. The average permanganate index removal rate was 20.43%.
(5) Compared with the traditional power-driven submerged membrane system, the energy consumption per ton of water of the gravity-driven system was reduced by 0.155 MJ. The annual CO_2 emissions reduction was of 63.27 tons per tank. The chemical cost was reduced by 0.015 yuan per ton of water and the recovery rate increased from 96.28 to 97.77%.

ACKNOWLEDGEMENTS

This study was supported by the National Key R&D Program of China (grant number: 2021YFC3201304).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 11 November 2022; accepted in revised form 16 January 2023. Available online 9 February 2023