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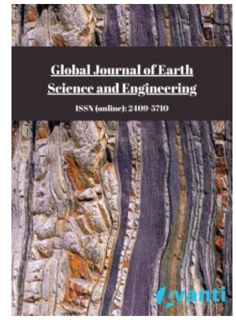

Application Research of an Automatic Control Seawater Reverse Osmosis (SWRO) System Based on the Siemens PLC

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ABSTRACT

To solve the global environmental problem of a shortage of freshwater resources, seawater desalination is considered one of the most promising solutions. In this research, the main novelty of the seawater desalination system lies in its utilization of a reverse osmosis unit as the core process for producing drinking water. By optimizing the pretreatment section in the process flow, a seawater reverse osmosis (SWRO) control system based on Siemens PLC with a high degree of automation was developed, which has the advantages of convenient maintenance and monitoring. In addition, through research on reverse osmosis systems, the results showed that within two years of operation, the total desalination rates of the primary and secondary reverse osmosis systems were not less than 99% and 97.5%, respectively. Furthermore, the water quality after desalination was tested. When the doses of $CaCl_2$, $MgCl_2$ and $NaHCO_3$ were 20 mg/L, 15 mg/L, and 50 mg/L, respectively, high-quality drinking water was obtained. Finally, a reasonable process plan and corresponding estimates were given for the complex water source conditions. Compared with traditional seawater desalination systems, our system has the advantages of easy operation, efficient water production and lower price. Accordingly, this study will help to solve drinking-water problems in some freshwater-scarce regions.

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1. Introduction

Water resources are one of the resources closely related to human life. In recent years, the total amount of global water resources has been decreasing, which has seriously affected social and economic development [1-6]. In 2011, California's drought, the worst in its history, could cost up to $1.8 billion in agricultural losses [7]. In 2018, Cape Town, South Africa, implemented water rationing [8]. In addition, 80 percent of U.S. state water management agencies expect freshwater shortages within the next 10 years [9]. In China, increasing water demand and limited water resources have always existed, especially in the northern coastal areas [10-14]. As the population continues to gather along the coast and the economy continues to develop toward coastal cities, the excessive use of surface water and groundwater has resulted in land subsidence, the drying up of rivers and lakes, and serious water pollution [15, 16]. Specifically, since the end of 2020, the rainfall in Jiangnan, most of South China, and the southwest has been 40% to 70% lower than that in the same period of the previous year [17-19]. Some cities, counties, and towns experienced water supply shortages, and the direct economic loss was as high as 175 million yuan [20]. Thus, the efficient desalination of marine resources has become an urgent problem to be solved.

In recent decades, many well-known scholars in the field of seawater desalination at home and abroad have carried out much research. In 1960, American researcher S. Loeb improved the asymmetric cellulose acetate membrane for desalination, which has a good stiffness-free performance [21]. In 1972, the B-10 reverse osmosis membrane successfully developed by the American DuPont Company was first used in seawater desalination [22]. Subsequently, research and development companies in the United States and Japan successfully developed three kinds of cellulose acetate hollow fiber reverse osmosis membranes, which can be used for desalination and freshwater treatment [23]. In 1985, the research and application of reverse osmosis membranes were developed rapidly. Two technologies, reverse osmosis seawater desalination composite membrane technology and high-recovery process technology, have become the fastest growing technologies in the field of seawater desalination [24, 25]. Meanwhile, as the technology matures, the desalination cost also decreases. Research on reverse osmosis technology in China started in the 1960s, and strategic technological research on reverse osmosis technology was conducted [26]. Currently, great progress has been made in the construction of reverse osmosis desalination projects. Song *et al*. prepared a high-performance PA-poly (ionic liquid) (PIL, poly (1-vinyl-3-butylimidazolium tetrafluoroborate)) RO membrane by two-step polymerization, which exhibited excellent antifouling antimicrobial properties and long-term separation stability [27]. Li *et al*. provided a facile method to modulate the PA microstructure via micelles to prepare high-performance TFC RO membranes for seawater desalination [28]. Yin *et al*. constructed a seawater reverse osmosis (SWRO) desalination system to evaluate the effect of seawater axial piston pump (SWAPP) discharge pressure on RO brine pressure [29]. Xu *et al*. proposed the future direction of electrospun nanofibrous membranes (ENMs) in developing more advanced desalination membranes and expounded the research of ENMs in advancing high-performance desalination [30]. To reduce the system operating cost, system optimization and energy management have received increasing attention [31, 32]. Zhu *et al*. discussed the optimal design and operation of RO networks under various operating parameters (such as time-dependent membrane fouling) and obtained time-dependent system performance [33]. Wu *et al*. and Lu conducted in-depth analysis and research on the optimal design of reverse osmosis and hot-film hybrid desalination technology [34, 35]. By designing the mixing structure for different feeding conditions, He *et al*. established hourly average operating cost equations for RO and multistage flash (MSF) processes [36].

The abovementioned studies show that the traditional seawater pretreatment method cannot meet its high requirements for influent water quality. Affected by the fluctuation of raw-seawater turbidity, the operational stability of the reverse osmosis system is poor. Furthermore, the effluent flow of the system is significantly attenuated. Because of this, chemical cleaning is often needed, which indirectly results in a short service life of the reverse osmosis membrane. Moreover, the use of traditional pretreatment requires regular replacement of filter materials and security filter elements, resulting in higher investment costs for system operation and maintenance. Therefore, it will be gradually replaced by the new type of SWRO technology.

To overcome these challenges, an improved seawater desalination system mainly adopts a reverse osmosis unit as the core process of high-quality, drinking-water production. For the pretreatment section in the technological process, through local optimization, a set of control systems of seawater desalination plants with a high degree of automation based on Siemens PLC is designed. In addition, the water quality of the desalinated seawater is tested. When the doses of $CaCl_2$, $MgCl_2$ and $NaHCO_3$ are 20 mg/L, 15 mg/L and 50 mg/L, respectively, the water quality to achieve the target is obtained. By optimizing seawater desalination technology, the drinking-water problem in some freshwater-scarce areas can be solved.

2. SWRO System Analysis

Fig. (**1**) represents the basic process flow of a SWRO system. The SWRO process is generally divided into four parts: the water intake system, pretreatment system, reverse osmosis system and posttreatment system [37]. Among them, the water intake system contains raw water, which mainly includes turbid water, water containing saltwater, harmful chemical substances, biological agent-contaminated water, war- contaminated water, brackish water with high salt content, and seawater. As shown in Fig. (**2**), the system has a strong ability to intercept suspended substances, dust, bacteria, asbestos, salt (seawater), nitrate, heavy metals, and surfactants. Nevertheless, no retention of chlorine is possible. Seawater enters the reverse osmosis membrane through water extraction, flocculation, dosing, and filtration. Subsequently, low-salinity freshwater and concentrated brine are formed by reverse osmosis (RO). Finally, the freshwater is further conditioned into drinking water through the product pool. On the other hand, high-pressure concentrated brine is discharged into the sea after recovering its pressure through an energy recovery device. For the existing seawater desalination system, considering the membrane performance and system stability, the fixed operation mode is generally preferred [38]. When the equipment constraints and water requirements cannot be met, the use of simple start–stop control will result in high overall operating costs. In addition, in the actual process, the seawater temperature fluctuates greatly on a summer day and has a quasi-periodic characteristic (Fig. **3a**). Meanwhile, parameters such as seawater salinity also change (Fig. **3b**). Similarly, the water-production process using fixed operating conditions will cause the quality constraints of drinking water to be difficult to achieve edge-to-edge control or will even be substandard. The flow of the SWRO system shows that the reservoir has a certain buffering effect as the intermediate unit of the RO water-production process and water-supply process. Adjusting the water level can increase the flexibility of operation, providing space for reducing system operating costs.

Based on the above situation, the quality of drinking water and effluent performance can be significantly improved by local optimization of the pretreatment section in the process flow. In addition, by using the buffer capacity of the reservoir to consider the water production and water inflow processes in a unified manner and fully analyzing the time-varying influence of seawater-feeding parameters, it is expected to achieve better optimization results.

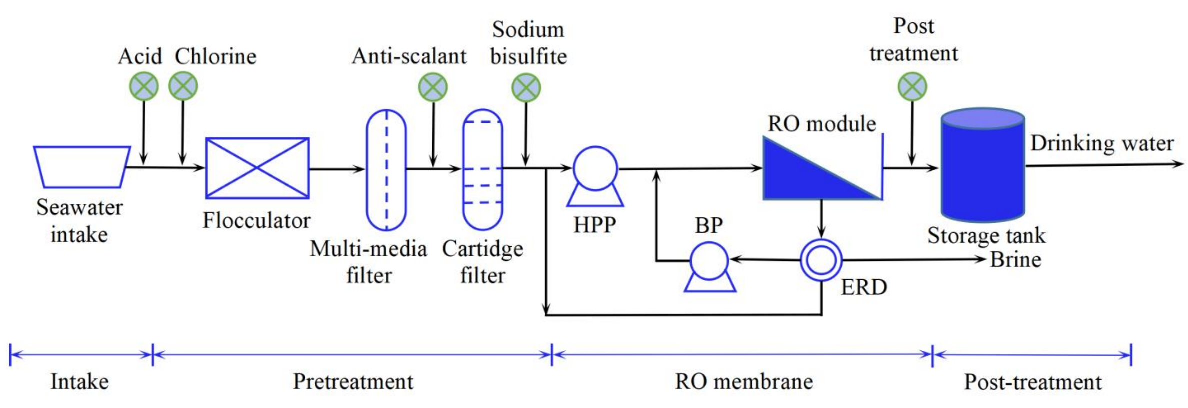

Figure 1: Schematic diagram of SWRO process.

3. Methods

3.1. AF Series Bernoulli Self-Cleaning Filter

3.1.1. Bernoulli Effect Cleaning Principle

The first pretreatment of the SWRO system adopts an AF series Bernoulli self-cleaning filter [39, 40], which can filter suspended solids and particulate impurities from water with various water qualities, such as seawater, lake water and river water. Here, coarse-precision filtration with a filtration precision between 150 μm and 2000 μm can be efficiently filtered. The filter is designed based on the Bernoulli effect, using high-speed cross-flow and backwashing water on the surface of the filter screen for cleaning, and requires an extremely low inlet pressure (minimum 30 kPa).

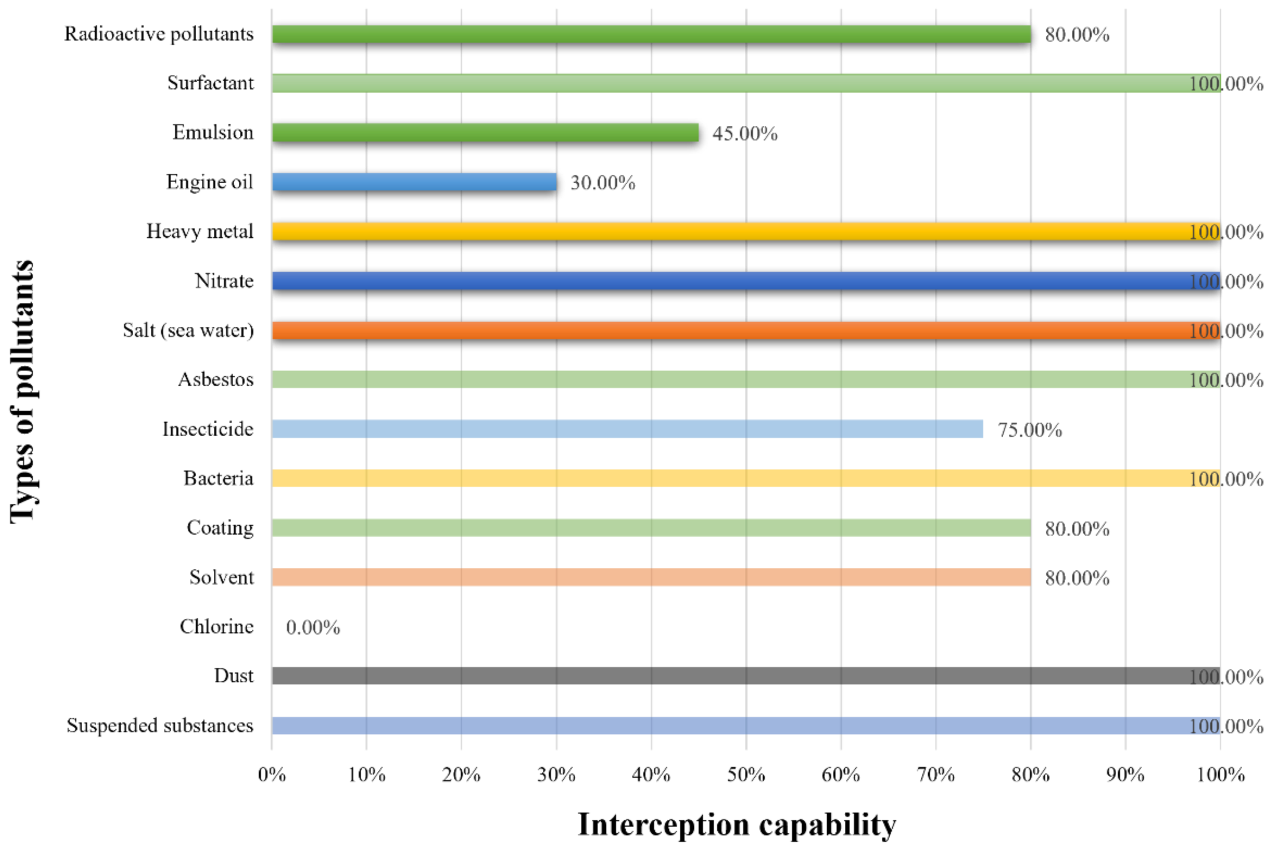

Figure 2: Contaminant retention capacity of a SWRO system.

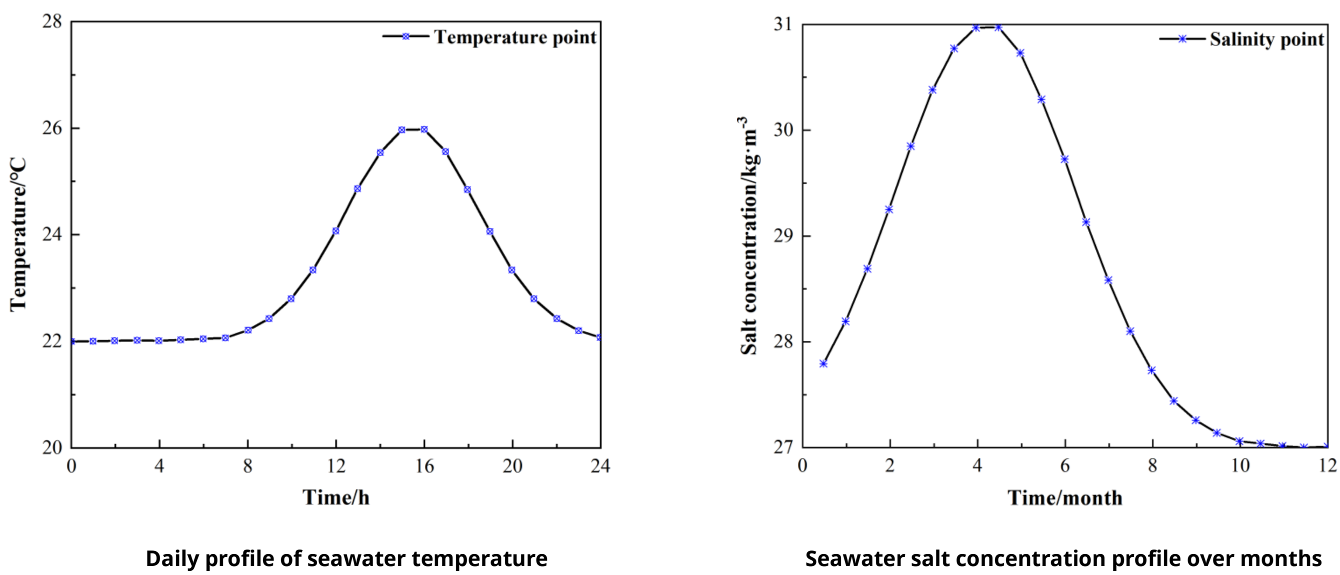

Figure 3: Seawater temperature-hour and salinity-month curves.

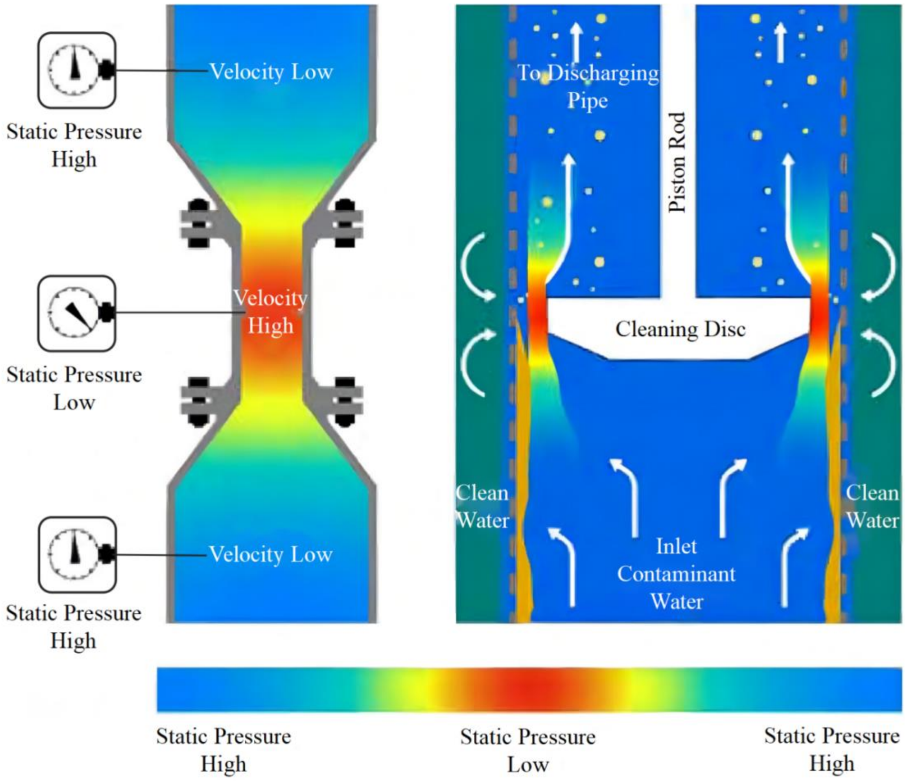

Figure 4: Bernoulli effect principle.

Fig. (**4**) represents the Bernoulli effect generated within the filter. The principle is that the water inside the filter screen flows through the gap between the cleaning disk and the filter screen, resulting in an increase in the water flow rate around the cleaning disk. Due to the Bernoulli effect, the pressure is suddenly reduced, and the suction produced by the low pressure causes the external water to backwash the inner surface of the screen.

3.1.2. Filter's Work Phase

The working stages of the AF series Bernoulli self-cleaning filter are as follows (Fig. **5**):

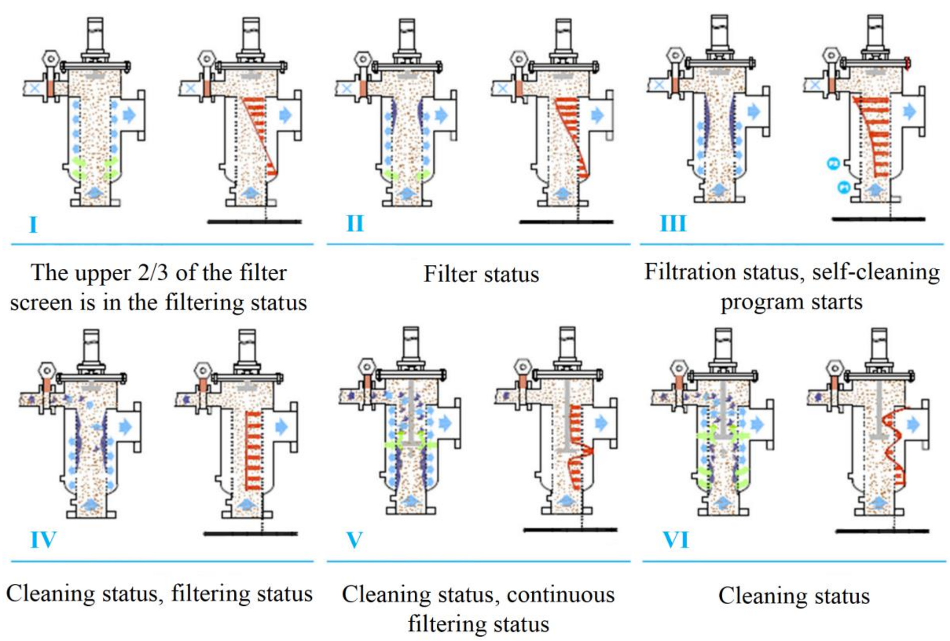

Figure 5: Work phase.

(I) Due to the high-speed flow of the liquid at the inlet of the filter screen, the clear liquid filtered out of the lower 1/3 section backflush the filter screen. Therefore, no impurities are deposited on the surface of this part of the filter screen.

(II) The impurities on the inner surface of the filter screen gradually deposit from top to bottom, and the pressure difference gradually increases. Here, the lower 1/3 of the screen is still in the filtering status.

(III) The upper 2/3 section of the filter screen is almost completely blocked, the pressure difference is further increased, and the entire filter screen surface is in the filtering status. When the differential pressure reaches the preset value, the self-cleaning program starts.

(IV) The drain valve is opened, and the large particles of impurities on the surface of the filter screen fall off and are discharged with the liquid. The lower 1/3 of the filter screen is still in the filtering phase.

(V) The cleaning pan moves down until the lower 2/3 of the filter screen. Due to the Bernoulli effect, impurities are discharged into the sewage pipe with the liquid.

(VI) The upper 2/3 section of the filter screen and the lower 1/3 section of the filter screen is cleaned to filter out the clear liquid and backwash the filter screen surface again. All impurities are discharged with the liquid, and the entire cleaning process is completed.

3.2. Multimedia Filter

The second pretreatment of the SWRO system uses a fully automatic multimedia filter. It is composed of a standard high-speed sand tank unit, with a unique two-way automatic flushing valve, which can realize the individual backwashing of the standard high-speed sand tank one by one in the normal system operation, as well as fully automatic program control. Considering the practical application of the system, we use carbon steel rubber-lined material as the shell material of the pretreatment system. The greatest advantage of this filter is that it saves electricity and water. Under the normal operation of the system, backwash is performed one by one. Compared with other sand-filter equipment, the required filter pump head is 6~7 m lower. On the other hand, the backwash water is filtered with clean water; therefore, less backwash water is consumed. The backwash water volume and time of a single tank are 1 m^3/min and 2~3 minutes, respectively.

3.2.1. Working Principle

1) Washing Filter Status: When the system is in the filter state, the water flows to the packing layer in a laminar flow state. As water flows through the packing layer, impurities are trapped in the packing layer. There are multiple evenly distributed water collectors at the bottom of the filter, which evenly collect and direct the filtered water. Among them, advection filtration can achieve better results.

2) Backwashing Status: As impurities build up in the packing layer, the internal head loss will continue to increase. When the head loss of the inlet and outlet water reaches the set value, the system will automatically activate the constant pressure device to switch to the backwashing state. When the backwashing of this station is completed, the hydraulic valve changes the direction of the water supply to realize backwashing one by one, which is convenient for cleaning the accumulated impurities. In the process of the high-speed sand tank fully automatic filtration system, the special water collector design can make the fillers rub each other, maximize the backwashing efficiency and reduce the required backwashing water (clean water). At the same time, there is no material running phenomenon during backwashing. In this study, a standard unit sand tank is backwashed for two minutes at the end of the backwash.

3.3. Precision and Security Filters

For precision and security filters, we choose large flow and high dirt capacity filter elements. Here, the filtration precision of the precision filter and the security filter is 10 μm and 1 μm, respectively. In our design, the outer diameter and length of the high-flow, high-contamination filter element are 6 inches and 40 inches, respectively (Fig. **6**). Filtration flows from the inside out, and the foreign particles are collected in the filter element. More than 5 layers of ultrafine fiber membrane filter material are used, including the diversion layer, the multistage prefiltration layer, the final filter layer and the diversion layer. There are two design structures, vertical and horizontal. In the filtration process, 304 stainless steel and corrosion- resistant coating are used as materials to prevent the corrosion of equipment by seawater or chemicals. As shown in Fig. (**6**), the fiber diameter gradually becomes finer from upstream to downstream, forming a gradient pore structure, which can intercept pollutants in the filter material step by step. This greatly increases the dirt-holding capacity of the filter element and prolongs its service life. Polypropylene, polyester or fiberglass are available as options [41-43]. In addition, the filter element is joined by heat fusion, which will not cause contamination. Fig. (**7**) represents the flow rate of the filter element under the comparison of different filtration precisions. The results show that with the continuous increase in the MaxSEP flow rate, the pressure drop variation range decreases with the continuous increase in the filtration precision value. In other words, the smaller the filtration precision of the high-flow and high- contamination-capacity filter element is, the stronger the contamination-holding capacity. Furthermore, in our study, the filtration precision ranged from 0.5 μm to 100 μm, and the filtration efficiency was not less than 99%.

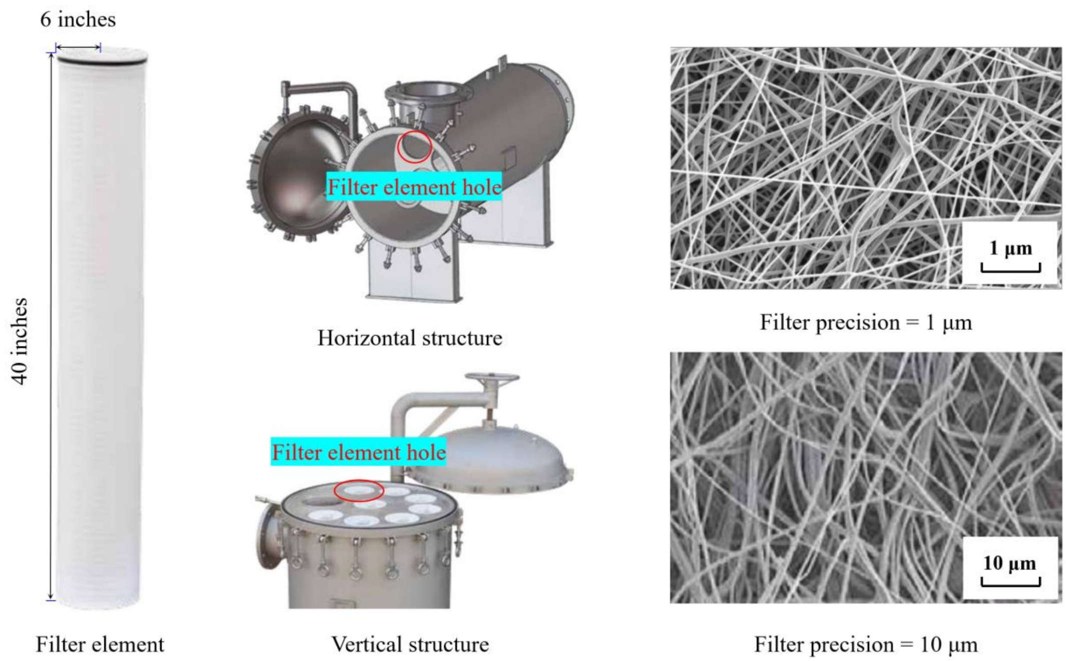

Figure 6: Large flow and high dirt capacity filter element.

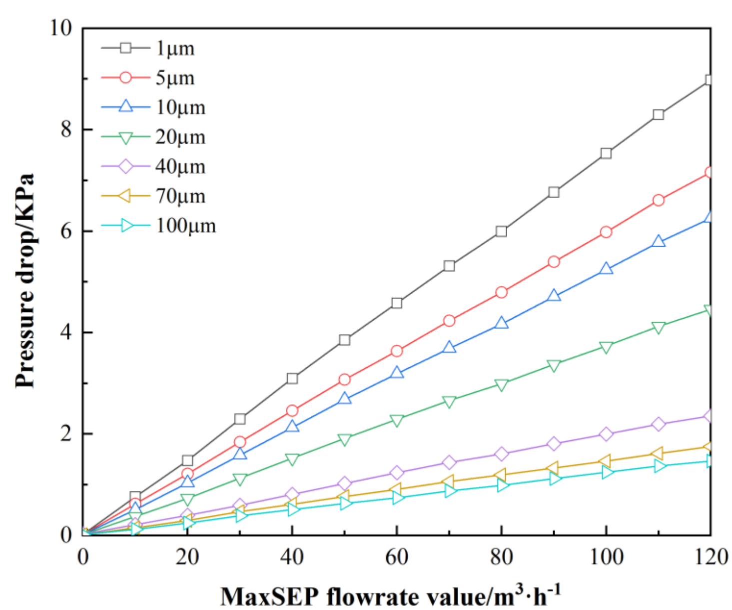

Figure 7: MaxSEP flowrate chart.

3.4. Reverse Osmosis System

The primary reverse osmosis membrane can remove inorganic ions, bacteria, viruses, organic matter, colloids, nuclides and other impurities in seawater to obtain high-quality freshwater. As shown in Fig. (**8**), the reverse osmosis membrane has the property of selectively passing water and retaining ionic species. When the pressure on the saline side of the membrane is greater than the osmotic pressure, the water in the saline will flow to the freshwater side, thereby realizing the separation of saline in the solution [44]. For reverse osmosis membranes, membrane fouling refers to the degradation of membrane performance caused by the blockage of the membrane surface by pollutants. To prevent reverse osmosis membrane fouling, a new type of membrane pretreatment technology was proposed using a reverse osmosis unit as the core process of desalination water production. Among them, the primary reverse osmosis system mainly includes the primary RO lifting pump, the primary RO high-pressure pump, the primary reverse osmosis component, the energy recovery system, and the dosing pump. In detail, the membrane module adopts the polyamide composite membrane provided by DOW Company in the United States. The surface layer is composed of aromatic polyamide with a thickness of approximately 2000 angstroms, which can withstand high pressure and has good resistance to mechanical tension and chemical attack. In addition, the module has a large membrane area and relatively large flux of water production. When radionuclide treatment is required for seawater purification, a secondary reverse osmosis system is used [45].

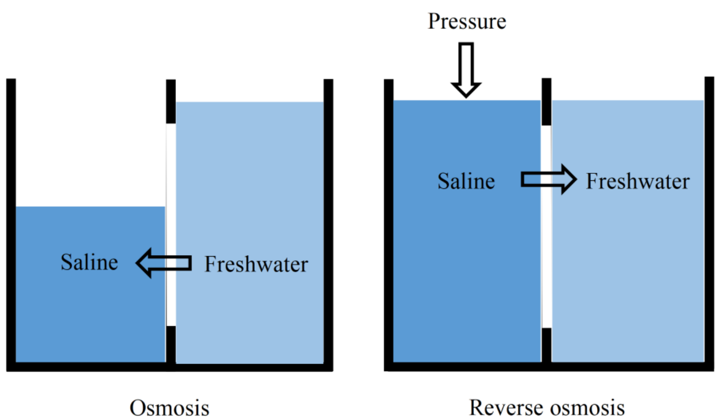

Figure 8: The principle of reverse osmosis.

4. Results and Discussion

4.1. Reverse Osmosis Plant Design Results

Whether it is a primary reverse osmosis device or a secondary reverse osmosis device, the design guidelines for 8-inch membrane elements in water treatment applications are as shown in Table **1** [46, 47]. Herein, the membrane element selected for the primary reverse osmosis unit is SW30HRLE-400, and its membrane area is 37 m^2. Based on the membrane design guidelines, the pretreated water (SDI<2) has an average membrane design flux of 13 L/m^2h. The permeation design water yield is 4.4 m^3/h/set. In addition, according to Eq. (1), it can be concluded that the number of design membranes and pressure membrane shells are both 8. Table **2** shows the water production of different components of the primary reverse osmosis system. On the other hand, the membrane element selected for the secondary reverse osmosis system is BW30HRLE-440, and its membrane area is 41 m^2. For the primary reverse osmosis effluent (SDI<1), the average membrane design flux is 38.5 L/m^2h according to the membrane design guidelines. The designed water yield of the secondary reverse osmosis is 4 m^3/h/set. Through calculation, the number of membranes and shells in the designed secondary reverse osmosis system are both 3.

In general, the primary reverse osmosis system is designed with a reverse osmosis unit of 4.4 m^3/h. Each reverse osmosis unit is equipped with 8 pressure membrane tubes (8 inches) and 8 SW30HRLE -400-type membrane elements. Here, the water inflow is 12 m^3/h, the operating pressure is not more than 6.0 MPa, the recovery rate is 35%, and the water production is 4.4 m^3/h. The secondary reverse osmosis system is designed as a 4 m^3/h reverse osmosis device. Each reverse osmosis unit is equipped with 3 pressure membrane tubes (8 inches) and 3 BW30HRLE-440 type membrane elements. Here, the water inflow rate is 4 m^3/h, the operating pressure is not more than 1.0 MPa, the recovery rate is not less than 85%, and the water production rate is 4 m^3/h. In the test, concentrated water partial return technology is used to improve the recovery rate, optimize the influent water quality, and prevent the generation of concentration polarization. Finally, the test results show that within two years of operation, the total desalination rate of the primary reverse osmosis system is not less than 99%, and the total desalination rate of the secondary reverse osmosis system is not less than 97.5%.

Table 1: Design guidelines for 8-inch membrane elements in water-treatment applications [46, 47].

Water Source	Average Membrane Flux	
	gfd	L/m²h
Treated seawater (SDI<5)	7-10	11-17
Treated seawater (SDI<3)	8-12	13-20
Treated seawater (SDI<1)	21-25	36-43
Reverse osmosis water (SDI<1)	21-25	36-43

Table 2: Water production meter of different components of the primary reverse osmosis system.

Element Number	Recovery Rate (%)	Feed Water Flow (m³/h)	Feed Water Pressure (bar)	Feed Water TDS (mg/L)	Concentrated Water Flow (m³/h)	Product Water Flow (m³/h)	Permeate Flux (LMH)	Product Water TDS (mg/L)
1	7.3	11.4	55.6	39757	10.6	0.84	22.5	100.7
2	6.9	10.6	55.2	42882	9.87	0.72	19.5	123.4
3	6.3	9.84	54.8	46018	9.25	0.62	16.6	152.5
4	5.6	9.23	54.4	49081	8.73	0.52	14.0	190.0
5	5.0	8.71	54.1	51989	8.30	0.43	11.6	238.4
6	4.3	8.28	53.9	54676	7.94	0.35	9.5	300.7
7	3.6	7.93	53.6	57093	7.65	0.29	7.7	380.6
8	3.0	7.64	53.3	59215	7.42	0.23	6.2	482.5

Note: TDS denotes total dissolved solids.

$$N = a/(S \times L) \quad (1)$$

In the equation, *N* represents the number of designed membranes, *a* represents the water output, *S* represents the area of a single membrane, and *L* represents the membrane flux.

4.2. Mineralization and Conditioning of Desalinated Seawater

At present, SWRO desalination is difficult to directly use as drinking water due to its "soft water" characteristics [48]. Thus, desalination water conditioning is utilized, which can increase the salinity and stability of desalination seawater [49, 50]. Generally, the water-quality adjustment methods of seawater desalination are divided into three types: dosing, dissolving ore, and mixing with raw water. In this subsection, we adopt the dosing method for water-quality adjustment of desalinated seawater. Next, we discuss three different dosing methods.

1) $Ca(OH)_2$ and CO_2

The reaction equation of this method is as follows:

$$Ca(OH)_2 + 2CO_2 = Ca(HCO_3)_2$$

$Ca(OH)_2$ can increase alkalinity and hardness at the same time but cannot increase carbonate alkalinity, and supplementation with CO_2 can increase the buffer capacity of desalinated water. The disadvantage is that if the utilization rate of suspended $Ca(OH)_2$ is less than 96%, the turbidity of the effluent will exceed the WHO limit of 5 NTU. In addition, pH fluctuates with $Ca(OH)_2$ availability.

2) $Ca(OH)_2$ and Na_2CO_3

The reaction equation of this method is as follows:

$$Ca(OH)_2 + Na_2CO_3 = CaCO_3 + 2NaOH$$

Since $CaCO_3$ is slightly soluble in water, it has little adjustment effect on the hardness of desalinated water. Furthermore, the pH of the effluent exceeds 10, resulting in a higher water alkalinity. Hence, the use of this method has limitations.

3) $CaCl_2$ and $NaHCO_3$

The reaction equation of this method is as follows:

$$CaCl_2 + 2NaHCO_3 = Ca(HCO_3) + 2NaCl$$

Compared with the first two methods, this method increases the hardness but also increases the carbonate alkalinity. In addition, this method does not have the problem in which the turbidity of the effluent exceeds the standard.

Comparing the RO water quality of the secondary desalination with the research water quality, the water quality has the characteristics of low pH, low alkalinity, low calcium and magnesium content, low hardness, and extreme corrosion. To achieve high-quality drinking-water standards, the water-quality components, water-quality characteristics, partial ions and water-quality stability are analyzed. Then, we set up three conditioners for feasibility tests and dose optimization tests. During conditioning, the concentration gradient of $CaCO_3$ is set to 20, 50, and 80 mg/L; the concentration gradient of $MgCl_2$ is set to 5, 15, 25, and 35 mg/L; and the concentration gradient of $NaHCO_3$ is set to 50, 70, 90, and 110 mg/L. In our study, $CaCl_2$, $MgCl_2$, and $NaHCO_3$ conditioners are added to adjust the pH of the water to reach the standard. According to the suitable concentration range suggested by GJB1335-92 (Table **3**), the dosage of $MgCl_2$, 5 mg/L, does not meet the requirements. As shown in Table **3**, when $CaCl_2$ is 80 mg/L and $MgCl_2$ is 35 mg/L, the hardness exceeds the appropriate value, indicating that

Table 3: Drinking-water mineralization standard (GJB1335-92).

Indicators	Unit	Suitable Concentration Range	Maximum Limit Value
Potassium (K^+)	mg/L	5~10	20
Sodium (Na^+)	mg/L	20~100	200
Calcium (Ca^{2+})	mg/L	20~50	75
Magnesium (Mg^{2+})	mg/L	10~20	50
Chloride (Cl^-)	mg/L	50~100	250
Sulfate (SO_4^{2-})	mg/L	30~100	250
Bicarbonate ($HCO3^-$)	mg/L	50~150	250
Total hardness ($CaCO_3$)	mg/L	100~200	450
TDS	mg/L	200~500	1000
pH value	–	7.0~8.5	6.5~9.0

this dosage combination should be abandoned in actual conditioning. After conditioning, the pH value is mostly between 7.0 and 7.5, and the water stability is improved. Any combination of $CaCl_2$ at 50 and 80 mg/L and $MgCl_2$ at 25 and 35 mg/L has a serious scaling tendency of calcium carbonate precipitation potential (CCPP), and this dosage combination is unreasonable.

Hence, with a comprehensive consideration of preventing scaling, ensuring compliance with drinking water quality standards, and prolonging the life of RO membranes, high-quality drinking water can be produced when the dosages of $CaCl_2$, $MgCl_2$, and $NaHCO_3$ are set at 20 mg/L, 15 mg/L, and 50 mg/L, respectively. Additionally, to accommodate the varying salinity of seawater, our system integrates a water quality monitoring module that continuously measures key parameters, including salinity and pH levels. When necessary, the system can automatically adjust the dosing rates of $CaCl_2$ and $MgCl_2$ or trigger alarms for manual intervention to maintain optimal operating conditions (See section 4.3 for details).

4.3. SWRO Instrument Control System

To better meet the needs of industrial production, based on the high automation level of Siemens PLC, we designed a control system for a small seawater desalination plant. It can reduce labor intensity and save industrial costs. In addition, the control system can support automatic operation and cleaning and can also trigger an alarm or stop in the event of failure. Fig. (**9**) shows the hardware design of the SWRO control system. A Siemens PLC is used for control and communication with the LCD touch screen through a serial port. By collecting the signals of induction switches, pressure sensors, liquid level gauges, water production valve induction switches, and start/stop buttons, the operations of seawater desalination pumps, flushing water pumps, low-pressure pneumatic valves, high-pressure pneumatic valves, and sound and light alarms are realized.

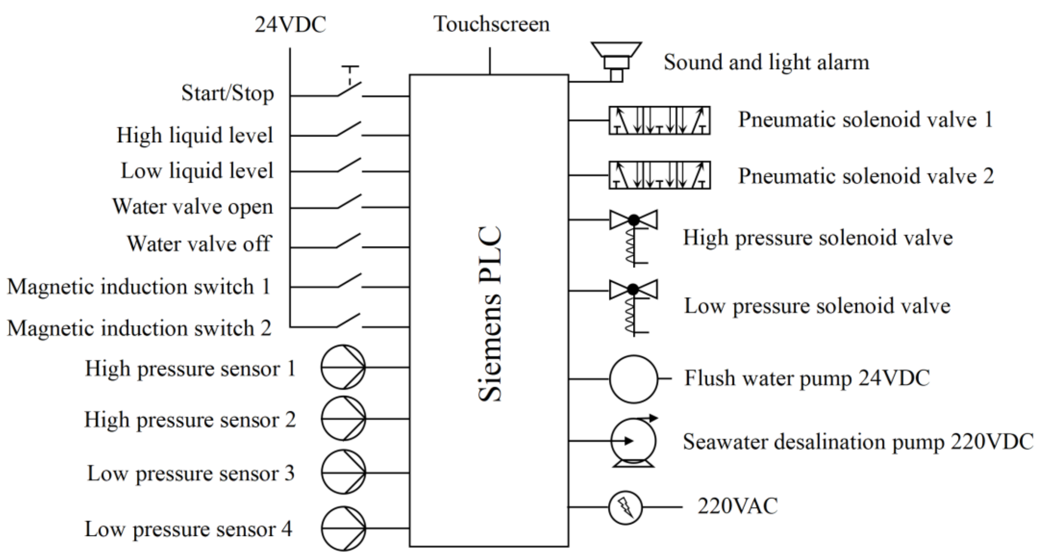

Figure 9: Siemens PLC control system.

Fig. (**10**) represents the layout of the touch screen and the working state of the system software. After turning on the power of the device, the PLC automatically records the changes in various times and parameters, the touch screen displays real-time data, and the system status is displayed in the information bar. As shown in Fig. (**10**), the system software workflow mainly includes the initialization process, normal running process, cleaning process, setting process, debugging process, query process, and alarm process. In our design, we focus on the development of the cleaning process and alarm process.

1) Cleaning Process

- Seawater-flushing process. When the pressure difference between the two ends of the reverse osmosis membrane exceeds the limit value (the initial value is 1.4 bar) or the running time exceeds the limit

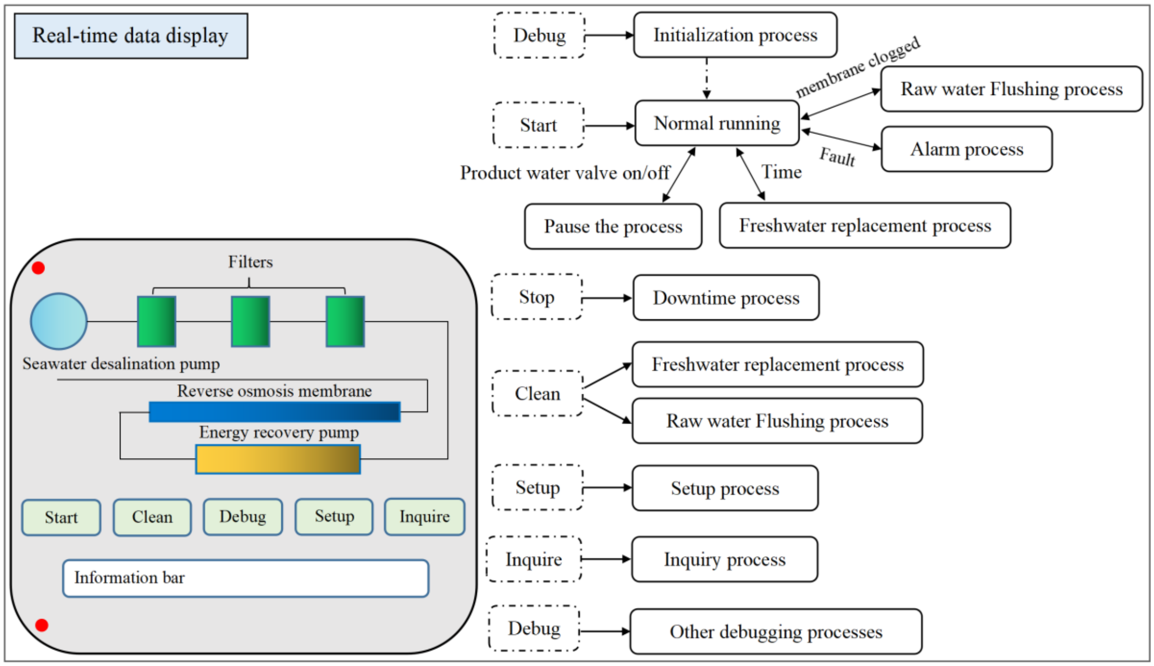

Figure 10: Touch screen layout and system software working state diagram.

value and the water is at a trough (the initial value is 48 h, 2:00 am), seawater flushing is performed automatically. Raw-water flushing can also be performed manually when deemed necessary. Specifically, two pneumatic three-way valves are placed in the position where the function port is connected to high-pressure water and the high-pressure pneumatic valve is opened. After one hour, it is restored to its original position, the high-pressure pneumatic valve is closed, and the raw-water-flushing process ends.

- Freshwater replacement process. After the running time exceeds the limit value (the initial value is 96 h, 2:00 am), the system automatically replaces the freshwater of the reverse osmosis membrane module. Likewise, freshwater replacement can also be performed manually.

2) Alarm Process

The following are the specific conditions to meet the system entry alarm and exit alarm.

- When the system low-pressure circuit value is greater than 6.5 bar and less than 7 bar, the overpressure alarm is triggered. Above 7 bar, severe overpressure is shutdown. In contrast, when the system low-pressure circuit value is less than 6.4 bar, the sound and light alarms are turned off and the system operates normally.
- When the system high-pressure circuit value is greater than 5.8 MPa and less than 6 MPa, the overpressure alarm is triggered. Above 6 MPa, severe overpressure is shutdown. In contrast, when the system high-pressure circuit value is less than 5.5 MPa, the sound and light alarms are turned off and the system operates normally.
- When the differential pressure value of the low-pressure circuit reaches the limit value (the initial value is 0.5 bar), the membrane filter device is polluted and triggers the alarm.
- After the primary RO lift pump water is flushed three times, the reverse osmosis membrane is still blocked, and the machine is shut down.
- In the normal operation process, when the premembrane pressure is less than 1 bar, the primary RO high-pressure pump is blocked and triggers the alarm.
- When the flow rate is less than the set value, the desalination pump triggers the alarm due to insufficient power supply.

- When the change in the premembrane pressure and postmembrane pressure is less than 0.2 bar, the primary RO high-pressure pump triggers the circuit (short circuit) alarm.

In addition, to address the potential problem of scale deposition and roughness increase due to exceeding the permissible limits of $CaCl_2$ and $MgCl_2$, our system incorporates real-time water quality monitoring. When the concentration of $CaCl_2$ and $MgCl_2$ approaches or exceeds the preset maximum limits, the monitoring system will automatically adjust the dosing rates or trigger an alarm, alerting operators to take immediate action. Additionally, we have implemented a regular maintenance schedule for the reverse osmosis membranes to prevent fouling and ensure optimal performance. And the control system designed for the SWRO plant not only supports automatic operation and cleaning but also incorporates advanced water quality monitoring. By integrating sensors that continuously measure parameters such as $CaCl_2$ and $MgCl_2$ concentrations, the system can automatically adjust dosing rates or issue alerts when preset limits are exceeded. This feature ensures that the quality of the desalinated water remains within acceptable standards, even under varying source water conditions.

4.4. Process Treatment Plan for River, Lake, Saltwater, Seawater, and Radioactively Polluted Water

In this section, we discuss the developed SWRO system's process solutions and corresponding estimates for river, lake, brine, seawater and radioactively polluted water. Fig. (**11**) represents a process flow diagram for treating the water source. In this test, raw-water contaminants generally include turbid water (impurities, colloids, and suspended solids), biological contamination (bacteria, viruses, and toxins), chemical contaminants (inorganic salts, organic compounds, pesticides, and herbicides), saltwater, seawater and war-contaminated water (radionuclide contamination) [51, 52]. Subsequently, the aspects of pretreatment and refined treatment system technology will be elaborated.

During preprocessing, the raw water is first disinfected with an oxidant-dosing device. Then, the water is further processed through the raw-water booster pump, Bernoulli self-cleaning filter, automatic multimedia filter, and precision filter. Among them, the raw-water booster pump provides sufficient water pressure and flow for the backwash system. The Bernoulli self-cleaning filter mainly removes algae, mud and suspended solids from the turbid water. The automatic multimedia filter mainly removes colloids and large suspended solids from the water. The precision filter mainly removes visible particulate matter and fine suspended matter from the water. Ultimately, a reducing agent-dosing device is used to reduce the residual oxidant to prevent it from oxidatively decomposing the membrane system.

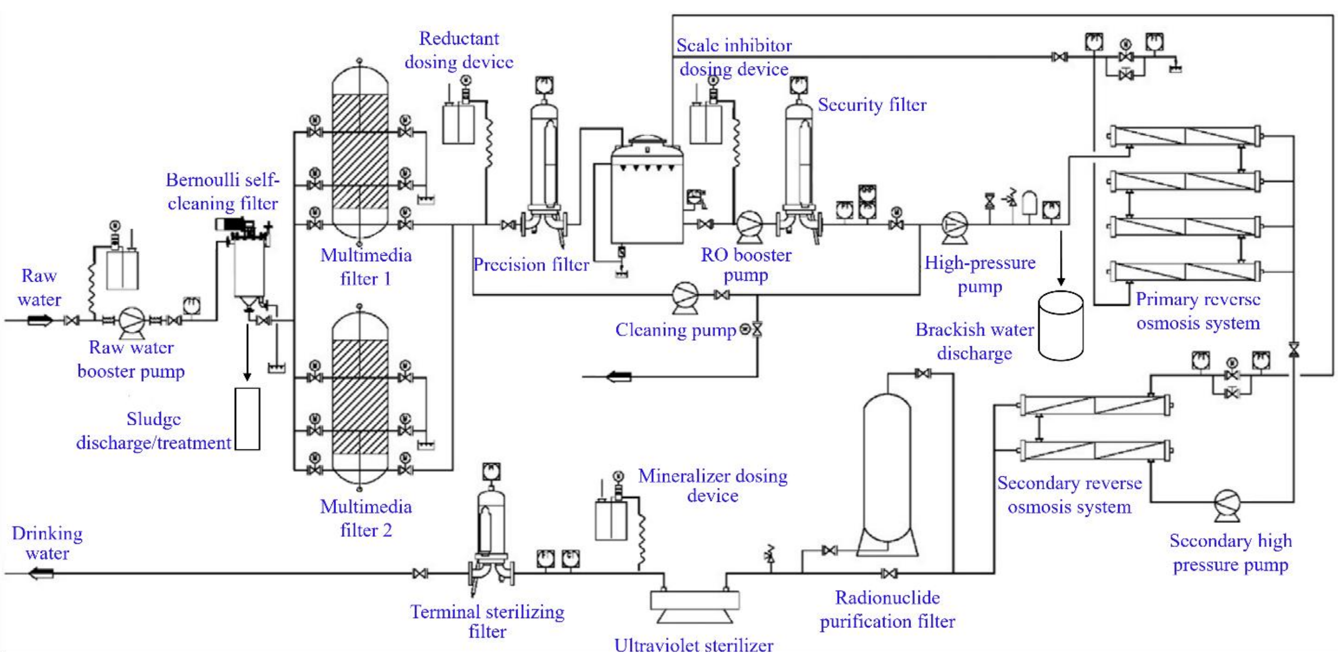

Figure 11: Process flowchart for the treatment of river, lake, saltwater, seawater, and radioactively polluted water.

After the pretreatment stage of the raw water, we use the scale inhibitor-dosing device to effectively prevent the scaling phenomenon on the RO concentrated water side. Later, the pretreated water is further treated by an RO booster pump, security filter, high-pressure pump, primary reverse osmosis system, secondary reverse osmosis system, radionuclide purification filter, and ultraviolet sterilizer. Here, the RO booster pump provides sufficient water pressure and flow for the security filter so that it can further filter the water in the RO, ensuring that the SDI is not greater than 3. In addition, primary and secondary reverse osmosis systems are used to remove water bacteria, viruses, toxins, organic matter, inorganic salts, small-molecule inorganic salts, and organic compounds. The radionuclide purification filter can efficiently remove thiophilic ions such as Mn-54, Co-60, Co-58, Fe-59, and Ag-110m in radioactive wastewater. The ultraviolet sterilizer uses ultraviolet light to sterilize the bacteria remaining in the water purification pipeline. To achieve the quality standard of drinking water, a certain amount of minerals are added to the purified water. Using the terminal sterilization filter, the bacteria remaining in the pipeline and the bacteria brought by the mineralization-dosing device are filtered out, and finally, high-quality drinking water is produced [53-55]. As shown in Table **4**, the price of the SWRO system we developed is 797,000 RMB (approximately 114,550 USD). Previous studies have indicated that primary and secondary reverse osmosis systems are the most costly to develop. With the same output, the cost of our entire system is approximately 75% of that of conventional desalination plants on the market. Compared with traditional desalination systems, this system is more efficient, convenient and affordable [56].

Table 4: Process treatment plan quotation table [56].

Name	Quantity	Unit	Cost Price	Total Cost
Preprocessing system	1	Set	¥129,000.00	¥129,000.00
Primary and secondary reverse osmosis system	1	Set	¥406,000.00	¥406,000.00
Chemical cleaning unit	1	Set	¥21,000.00	¥21,000.00
Complete processing and auxiliary materials	1	Batch	¥50,000.00	¥50,000.00
Radionuclide purification filter	1	Batch	¥78,000.00	¥78,000.00
PLC electric control	1	Batch	¥65,000.00	¥65,000.00
Guide installation and debugging	1	Batch	¥48,000.00	¥48,000.00
Total	—	–	–	¥797,000.00

In order to comprehensively assess the energy consumption of different desalination technologies, we conducted a detailed analysis and visualized the energy consumption differences through Table 5. Reverse osmosis (RO) has a significant advantage in terms of energy consumption over other mainstream desalination technologies (e.g., multi-stage flash MSF, multi-effect distillation MED). This is mainly due to the fact that RO utilizes pressure difference as the driving force instead of heat, thus reducing energy consumption. In particular, we designed a SWRO system based on Siemens PLC control, which further reduces energy consumption and improves energy efficiency by optimizing the pretreatment and operation processes.

Table 5: Energy consumption of different technologies.

Technology Type	Energy Consumption (kWh/m^3)
Multi-stage flash distillation MSF	10-15
Multi-effect distillation MED	6-10
Reverse osmosis RO (general purpose)	3-5
Our SWRO systems	2.5-3.5

4.5. System Risk Management and Control Means

To ensure the efficient and reliable operation of our SWRO system, we have designed a control system based on Siemens PLC, which offers a high degree of automation. This automation not only reduces labor intensity and saves industrial costs but also enhances system performance through precise control of various parameters. However, the high level of automation requires the presence of skilled operators and maintenance personnel to ensure smooth operation and timely troubleshooting in case of any failures.

To mitigate the risk of control system failures, we have implemented several measures:

(1) Redundancy and Backup Systems: Key components of the control system, such as PLCs and sensors, are provided with redundancy to ensure continuous operation even in the event of a single component failure. Backup power supplies and communication channels are also included to further enhance reliability.

(2) Comprehensive Training and Support: To ensure that operators are equipped with the necessary skills to handle the high level of automation, we provide comprehensive training programs that cover both theoretical knowledge and practical hands-on experience. In addition, we offer ongoing technical support to address any operational challenges that may arise.

(3) Regular Maintenance and Inspection: Regular maintenance and inspection of the control system and associated equipment are crucial for ensuring its long-term reliability and performance. We have established a comprehensive maintenance schedule that includes regular checks, calibrations, and replacements of worn-out components.

While the high level of automation in our SWRO system does require skilled workers, we believe that the benefits in terms of reduced labor intensity, improved performance, and enhanced reliability far outweigh the challenges. By implementing the measures outlined above, we can ensure the successful operation of our technology in practical applications and minimize the risk of control system failures.

4.6. Highlights and Future Prospects

The highlight of our research is the development of a SWRO system based on Siemens PLC control. By partially optimizing the pretreatment section in the process flow, the quality of drinking water is significantly improved. In addition, according to the practical application function of the SWRO system, the process treatment plan and corresponding estimates for complex water source conditions are given. Compared with traditional seawater desalination systems, it has the advantages of easy operation, efficient water production and lower price.

Currently, we are applying this technology to the complete desalination of seawater and making it into drinking water (Shanghai, China). Specifically, we installed this SWRO system (water purification truck) on a truck. Considering that some areas in China and even the world lack freshwater resources, the advantages of flexible truck traffic can be used to conveniently provide high-quality drinking water. Furthermore, we believe that this study may be more applicable to military and rescue teams. In future plans, system functionality will continue to be optimized to reduce operating costs and increase output yields. On the other hand, we intend to roll out this technology to all parts of the country and other countries.

Conclusions and Prospects

Through the local optimization of the pretreatment section in the process flow, a SWRO system based on Siemens PLC automatic control was developed. The main conclusions that may be drawn from the results obtained are as follows:

1) Experimental results show that when the MaxSEP flow rate increases continuously, the variation range of the pressure drop decreases with the continuous increase in the filtration precision value. In other words, the smaller the filtration precision of the high-flow and high-contamination filter element is, the stronger the contamination-holding capacity.

2) The reverse osmosis unit is used as the core process for the production of high-quality drinking water. By optimizing the pretreatment section in the technological process, a set of seawater desalination control systems based on Siemens PLC with a high degree of automation is designed, which has the advantages of convenient operation, maintenance and monitoring.

3) The test results of the reverse osmosis system show that within two years of operation, the total desalination rates of the primary and secondary reverse osmosis systems are not less than 99% and 97.5%, respectively. In addition, comparing the reverse osmosis water quality of the secondary desalination with the research water quality, when the doses of $CaCl_2$, $MgCl_2$ and $NaHCO_3$ are 20 mg/L, 15 mg/L and 50 mg/L, respectively, high-quality drinking water can be produced. Ultimately, according to the practical application function of the SWRO system, the process treatment plan and corresponding estimates for complex water source conditions are given. Compared with traditional seawater desalination systems, our system has the advantages of easy operation, efficient water production and lower price. Therefore, this study could address the drinking-water problem in some freshwater-scarce regions.

In future plans, regarding reverse osmosis model devices, the composition of reverse osmosis membranes will be further optimized, manufacturing costs will be reduced, and operating functions will be improved. Focus on the removal rates of Engine oil and Emulsion. Additionally, there will be vigorous promotion in areas lacking fresh water such as central and western parts of China, as well as certain foreign countries.

Author's Contribution

Qihang Li: Resources, Software, Conceptualization, Project administration, Methodology, Funding acquisition, Writing - original draft, Review & editing.

Kai Li: Conceptualization, Methodology, Software, Data curation.

Canming Yuan: Conceptualization, Methodology, Software, Review & editing.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of Data and Materials

Data will be available from the corresponding author upon request.

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