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# AUXILIARY DEMINERALIZED AND POTABLE WATER SUPPLIES FROM SEAWATER AT EL-DABAA NPP (EGYPT)

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*Design solutions are offered for obtaining demineralized seawater for filling and replenishing loops and full-value potable water to meet the needs of service personnel as well as design solutions for disposal of the wastewater resulting from desalination without causing the environmental damage at the El-Dabaa NPP (under construction in Egypt). The proposed engineering solutions are based on microfiltration, ultrafiltration, reverse osmosis, ion exchange, and filtration and reagent conditioning of desalinated water. Wastewater disposal, taking dilution into account, into the Mediterranean Sea is setup 550 m from the shoreline.*

The Mediterranean Sea is the only source of water for the nuclear power plant being built in the coastal town of El Dabaa in Egypt. The composition of the seawater is as follows (mg/dm$^3$):

| | |
|---|---|
| Salinity, $10^3$ | 43 |
| Chlorides, $10^3$ | 24 |
| Sulfates, $10^3$ | 4.22 |
| Bicarbonates | 160 |
| Fluorides | 1.2 |
| Sodium, $10^3$ | 13.5 |
| Magnesium, $10^3$ | 1.6 |
| Calcium | 500 |
| Potassium | 460 |
| Ammonium | 0.05 |
| Silicon | 0.5 |
| Boron | 4 |
| Oxidizability, mg $O_2$/dm$^3$ | 38 |
| Total alkalinity, mg·eqv/dm$^3$ | 2.8 |
| Total hardness, mg·eqv/dm$^3$ | 150 |
| Turbidity (formazin) | 0.4 |
| pH | 7.9–8.2 |

The seawater is the source of the desalinated water to be used for filling and replenishing the primary and secondary loops of each of the four NPP power units being designed, for the needs of industrial water supply and the creation of an emergency water supply as well as for drinking water to meet the needs of maintenance personnel. The design-basis demand for demineralized water for each power unit is equal to 91 m$^3$/h. Its electrical conductivity must not exceed 0.1 μS/cm and the content of total organic carbon must not exceed 0.1 mg/dm$^3$. The total design-basis demand for potable water for all four power units, taking into the general plant facilities into consideration, reaches 2500 m$^3$/day. Under the terms of the contract, the potable water quality indicators must comply with Russian standards [1]. Egyptian regulations for potable water must also be taken into account [2]. In addition to the main chemical indicators, sanitary-microbiological and parasitological indicators, radiation safety indicators and the concentration of more than 1300 other chemicals not listed in Table 1 are also standardized. All indicators are taken into consideration for the preparation of potable water.

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TABLE 1. Maximum Permissible Indicators of Drinking Water Quality According to Egyptian and Russian Standards, mg/dm$^3$

| Index | Norm | |
|---|---|---|
| | Egypt [2] | Russia [1] |
| pH | 6.5–8.5 | 6–9 |
| Total mineralization (dry residue) | 1000 | 1000 |
| Hardness: | | |
| total, mg·eqv/dm$^3$ | – | 7 |
| in terms of $CaCO_3$ | 500 | – |
| calcium (in terms of $CaCO_3$) | 350 | – |
| magnesium (in terms of $CaCO_3$) | 150 | – |
| Sulfates | 250 | 500 |
| Chlorides | 250 | 350 |
| Nitrates | 45 | 45 |
| Nitrites | 0.2 | 3 |
| Fluorides | 0.8 | 1.5 |
| Iron | 0.3 | 0.3 |
| Boron | 1 | 0.5 |

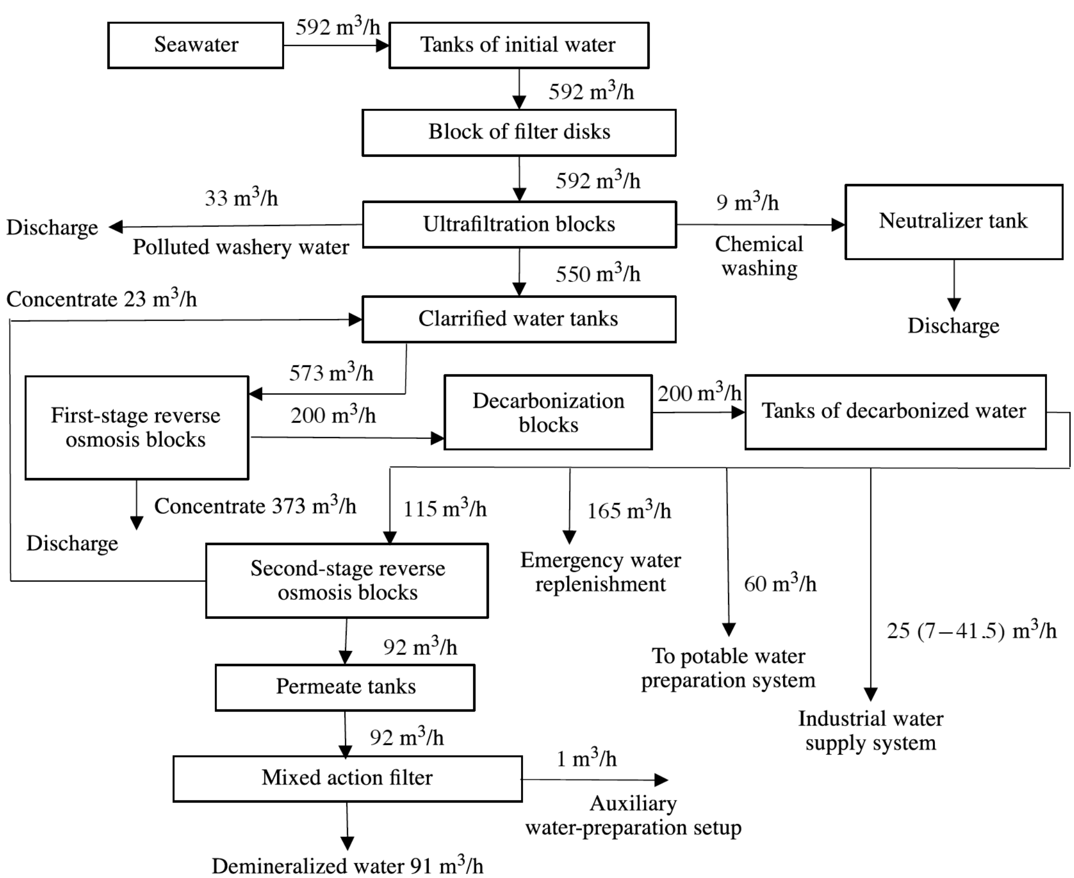


Fig. 1. Balance diagram of the water treatment plant.

TABLE 2. Reckoned Composition of Demineralized Sea Water after the First and Second Stages of Reverse Osmosis in a Water Treatment Plant, mg/dm$^3$

| Index | After reverse osmosis stage | | |
|---|---|---|---|
| | first | | second |
| | 13°C | 33°C | 25°C |
| pH | 4.9 | 4.78 | 6.5–7.5 |
| Salinity | 48.9 | 145.8 | 4 |
| Calcium | 0.14 | 0.41 | – |
| Magnesium | 0.48 | 1.44 | 0.02 |
| Sodium | 16.9 | 50.8 | 1.1 |
| Potassium | 0.69 | 2.07 | 0.05 |
| Fluorides | 0 | 0.01 | – |
| Carbon dioxide | 24.7 | 34.1 | 0.01 |
| Bicarbonates | 0.99 | 1.53 | 0.06 |
| Sulfates | 0.4 | 1.2 | 0.01 |
| Chlorides | 27.93 | 84 | 1.72 |
| Boron | 0.23 | 0.76 | 0.19 |

Design-basis solutions, taking the specified requirements for the El-Dabaa NPP into account, have been developed for obtaining demineralized and potable water as well as for disposal of the concentrate obtained on desalination of the seawater. To obtain desalinated and demineralized water, each of the four NPP power units is provided with a water treatment plant, whose block diagram indicating the water balance is displayed in Fig. 1.

Reverse osmosis, which has the lowest gross energy consumption and operating cost compared with other known methods, was chosen for the desalination of sea water [3, 4]. The proposed composition of the setup provides high-quality pre-treatment prior to reverse osmosis as a result of ultrafiltration, adequate water desalination for its subsequent mineralization after the first stage of reverse osmosis, obtaining demineralized water after the second stage of reverse osmosis, and a mixed-action ion-exchange filter. Important factors are compact arrangement of the setup and ease of maintenance.

First, the initial seawater is purified from suspended impurities on disc filters with filtration fineness 200 μm. Then it goes to ultrafiltration units with pre introduction of a coagulant, where substances in a dispersed and colloidal state are almost completely removed (filtration fineness 0.01–0.1 μm on ultrafiltration membranes), and the content of organic compounds is reduced by 50% on average. Ultrafiltration provides a treated water colloidal index (SDI) of less than 3, which is favorable for the life of reverse osmosis membranes. After ultrafiltration, the seawater is supplied for desalination and final removal of organic impurities by reverse osmosis. Demineralization occurs at two stages of reverse osmosis, between which a decarbonizer is installed to remove carbon dioxide.

The reverse osmosis units of the first stage are equipped with membrane elements for seawater brand SW30XHR-440i (USA) and pumps with head up to 800 m. The degree of extraction of permeate (demineralized water) is equal to 35%. To save energy, the reverse osmosis concentrate of the first stage is sent to an energy recovery device (hydro turbine). The reverse osmosis units of the second stage are equipped with BW30HR-440i brackish water membrane elements and pumps with up to 100 m head. The permeate recovery rate is 75%. The reckoned salt composition of the demineralized water after the first and second stages of reverse osmosis is given in Table. 2.

The selectivity of membrane elements significantly decreases with increasing water temperature, the residual salt content of demineralized water increases. For the conditions at the location of the El-Dabaa NPP, according to long-term observations, the minimum and maximum water temperatures are 13 and 33°C, respectively, so that, the calculated data for this temperature are given in Table 2.

TABLE 3. Russian Standards for the Physiological Value of Potable Water [3]

| Index | Standard |
|---|---|
| Total mineralization, mg/dm$^3$ | 100–1000 |
| Hardness, mg·eqv/dm$^3$ | 1.5–7 |
| Alkalinity, mg·eqv/dm$^3$ | 0.5–6.5 |
| Calcium, mg/dm$^3$ | 25–130* |
| Magnesium, mg/dm$^3$ | 5–65* |
| Bicarbonates, mg/dm$^3$ | 30–400 |
| Fluoride ion, mg/dm$^3$ | 0.5–1.5 |

* Calculated, based on the maximum allowable hardness 7 mg·eqv/dm$^3$ and taking into account the minimum required level of magnesium content on determining the maximum allowable calcium content and vice versa.

The final desalination, to obtain water with electrical conductivity not exceeding 0.1 μS/cm, for filling and replenishing the loops is performed on a mixed-action filter with a mixture of cation exchanger and anion exchanger.

The water balance of the water treatment plant was determined taking into account the possibility of withdrawing partially demineralized water after the first stage of reverse osmosis and decarbonization unit for the needs of industrial water supply, the creation of an emergency water supply, and the preparation of potable water.

The selected water purification technology, which includes micro- and ultra-filtration as well as reverse osmosis performed in succession, provides almost complete removal of dispersed and colloidal substances, organic impurities, metal ions, viruses, and bacteria as well as reduction of the content of dissolved salts to 48.9–145.8 mg/dm$^3$ after the first stage of reverse osmosis, depending on the temperature of the seawater.

The quality of desalinated water after the first stage of reverse osmosis will meet the potable water standards of both Russia and Egypt. The exceptions are the boron content and the pH value. The boron content at temperature in the range 13–26°C will be within the norm (no more than 0.5 mg/dm$^3$) according to Russian standards, but at a higher temperature it will be exceeded.

If necessary, to maintain the concentration of boron in water at a level of not more than 0.5 mg/dm$^3$ at seawater temperature 26°C and above, the project provides for the mixing of permeate after the first and second stages of reverse osmosis. When mixed, for example, in a ratio of 1:1, desalinated water with salt content about 98 mg/dm$^3$ and boron content of not exceeding 0.5 mg/dm$^3$ will be obtained.

The desalinated water obtained at the water treatment plant meets the standards for potable water, but it is not physiologically complete, since it contains mainly chlorides and sodium. For the physiological efficacy of potable water, hardness salts (calcium, magnesium) and fluoride ion should be added to it. At the same time, the pH of the water should be in the range of 6.5–8.5. The composition of physiologically high-grade potable water according to the main indicators in the Russian standards for bottled potable water is given in Table 3 [5]. It complies with the recommendations of the World Health Organization [6].

For the preparation of physiologically high-grade potable water, the El-Dabaa NPP project provides for a plant designed to meet the needs of personnel at the four power units being designed (Fig. 2). During the operation of one or two NPP power units, desalinated water with flow rate up to 60 m$^3$/h is supplied to the reserve tanks from one water treatment unit, while three or four power units are operating – from two units with a flow rate of up to 120 m$^3$/h. Th design-basis conditioning of desalinated water is based on the filtration method for introducing calcium and magnesium and the reagent mineralization method for introducing fluorides and active chlorine. The first method is implemented by filtering desalinated water through special loads that enrich the water with salts [7, 8]. To initiate the process, carbon dioxide is introduced into the water before the filters with mineral loading.

When desalinated water with carbon dioxide is filtered through a granular layer of a mineral, a reaction occurs with calcium bicarbonate being formed according to the equation

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2. \quad (1)$$

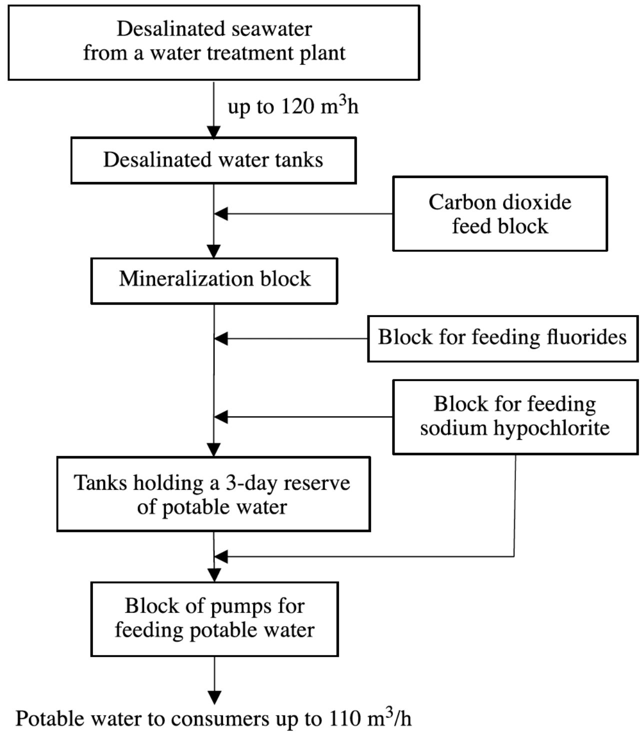


Fig. 2. Block diagram of a setup for preparing potable water.

Calcium bicarbonate dissociates according to the equation

$$Ca(HCO_3)_2 \leftrightarrow Ca^{2+} + 2HCO_3^-. \quad (2)$$

Similarly, when appropriate minerals are used, desalinated water is enriched with magnesium. Two-component mineral loadings are used for simultaneous enrichment with calcium and magnesium.

To develop the technology for obtaining high-grade potable water, the ability of various natural mineral sorbents and compositions based on them to saturate water with hardness salts was investigated. The investigations were performed on a laboratory mineralization unit using model solutions simulating the composition of desalinated sea water (permeate after the first stage of reverse osmosis).

The laboratory setup included two filter columns with upper and lower drainage devices to eliminate leaching of material particles, into which sorbents were loaded (loading height in each column 0.8 m), a carbon dioxide cylinder with a reducer, a saturator for mixing carbon dioxide with water, a container with the original model solution, a pump for supplying source water to filter columns, control devices (flow meters, pressure gauges and conductivity bridge), pipelines, and fittings. To intensify the use of the entire volume of the sorbent along the bed height, prevent caking of the load, and stabilize the hydrodynamic characteristics, water was fed into the columns from the bottom up. The volume of the investigated materials was weighed before and after each test cycle. In the course of the tests one or two columns were connected in series. For effective dissolution of the investigated materials, carbon dioxide was introduced into the source water before the columns from a cylinder through a reducer. The experiments were performed at water flow rate through the columns of 1.2, 2.5, and 4 m/h, which corresponded to the contact time of the loads with water of 12, 20, and 40 min, respectively. During the filter cycle, the water flow rate, pressure, and salinity were controlled in automatic mode.

The efficiency of water mineralization was evaluated by comparing the physicochemical parameters of the original and treated water after the first and second columns. The frequency of sampling was 15–30 min. The samples were analyzed according to the following parameters: the content of the ions $Ca^{2+}$, $Mg^{2+}$, $MH_4^+$, $Na^+$, $K^+$, $Cl^-$, and $SO_4^{2-}$, total alkalinity, free carbon dioxide, pH value, and salinity. The analysis was performed according to the methods standardized for potable water [9–13].

TABLE 4. Cationic Composition of the Investigated Samples of Materials, %

| Load | Ca | Mg | Na |
|---|---|---|---|
| Calcite | 36.1 | 0.83 | 1.61 |
| Limestone | 29.23 | 0.72 | 1.23 |
| Dolomite | 16.07 | 9.16 | 0.95 |
| Magnesium oxide | 1.8 | 72 | 4.3 |

TABLE 5. Quality of the Resulting Water in Terms of Calcium and Magnesium for Different Loads

| Load | Concentration, mg/dm$^3$ | | Contact time, min |
|---|---|---|---|
| | $Ca^{2+}$ | $Mg^{2+}$ | |
| Calcite | 40 | 0.6 | 24 |
| Dolomite/calcite | 31.8 | 10.1 | 24 |
| Calcite/magnesium oxide | 21.9 | 20 | 24 |
| Dolomite/limestone | 40 | 8.1 | 50 |

TABLE 6. Effect of Filtration Rate Through an Experimental Filter with Calcite on the Resulting Water Quality

| Index | Filtration rate, m/h | | |
|---|---|---|---|
| | 1.2–1.3 | 2.5 | 4 |
| Contact time, min | 40 | 20 | 12 |
| $Ca^{2+}$ concentration, mg/dm$^3$ | 47 | 40 | 37 |
| $Ca^{2+}$ yield, mg/h | 564 | 1000 | 1480 |

In the experiments, natural mineral sorbents recommended for the preparation of potable water were investigated (Tables 4, 5). Mixed loads of dolomite-calcite, dolomite-limestone showed optimal results. Moreover, the variants for filling the experimental filters with materials (each material in its own filter when the filters are connected in series or layer by layer in one) had almost no effect on the results. The effect of the filtration rate on the enrichment of water with calcium and magnesium ions is shown by the example of calcite tests (Table 6). An increase in the filtration rate from 1.2 to 4 m/h increases the calcium yield, but at the same time effects a reduction of its concentration in water, which indicates that the dissolution process is limited by the external diffusion stage. In connection with such features of the process, it is most convenient to optimize it by the contact time.

The influence of the concentration of carbon dioxide at the ingress into a filter on the saturation of water with calcium and magnesium ions is shown by the example of the operation of sequentially connected filters with dolomite and calcite (Fig. 3). The concentration of free carbon dioxide at the ingress into a filter in the range of 60–70 mg/dm$^3$ can be considered optimal and sufficient, at which the required water quality in terms of calcium ions 35 mg/dm$^3$ and magnesium ions 12 mg/dm$^3$ is provided. The hardness of the prepared water at the indicated concentration of calcium and magnesium will be equal to 2.75 mg·eqv/dm$^3$. Since calcium and magnesium are released into the water in the form of bicarbonates (see Eqs. (1), (2)), the alkalinity of water will increase by the same amount, and the total salt content of water will be equal to 315 mg/dm$^3$ at an initial concentration of 100 mg/dm$^3$. In practice, taking into account changes in the temperature of the initial sea water and, accordingly, the salinity of desalinated water and the kinetics of dissolution of mineral sorbents, the concentration of calcium, magnesium, bicarbonates and the total salt content of the prepared water will change within certain limits.

Desalinated water as part of the installation mineralizes in bulk filters (internal diameter 2.6 m) with a 2 m high mixed load of calcite-dolomite or similar mineral materials. From one to three filters can be in operation, depending on the number of simultaneously operating NPP units. The contact time of the mineral load with desalinated water in any case is at least 20 min.

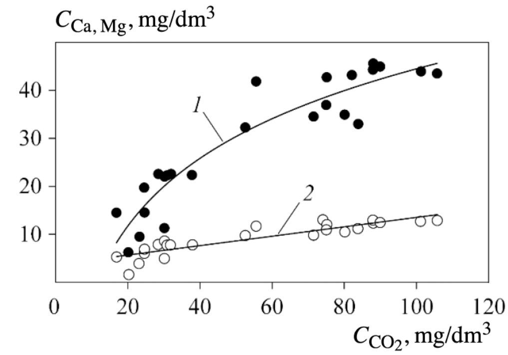


Fig. 3. Content of calcium (*1*) and magnesium (*2*) on the concentration of $CO_2$ at the ingress into a filter.

To bring the quality of potable water to the normalized values for fluoride, a solution of sodium fluoride is used, which, using a dosing unit, is fed proportionally to the consumption of mineralized water into a vortex mixer installed in the pipeline after the mineralizing filters. The recommended range of fluoride concentration according to the Russian norm is 0.5–1.5 mg/dm$^3$. If necessary, it can be limited, taking into account the Egyptian norm – no more than 0.8 mg/dm$^3$. The final stage of water preparation is the introduction of active chlorine into it with a concentration in the range 0.1–0.3 mg/dm$^3$ in the form of a sodium hypochlorite solution. Sodium hypochlorite is dosed into a vortex mixer in proportion to the consumption of mineralized water and the concentration of residual free chlorine after the mixer. Sodium hypochlorite with a chlorine equivalent concentration of 5–8 g/dm$^3$ is produced in a separate plant by electrolysis of a sodium chloride solution. Prepared potable water is sent to two three-day supply tanks. The need to create such a reserve is due to the lack of an alternative source of potable water.

For the microbiological safety of potable water supplied from supply tanks to consumers, sodium hypochlorite is additionally dosed into the pressure pipelines of the supply pumps in proportion to the flow rate of the supplied water to maintain the concentration of residual free chlorine in the water at the level 0.1–0.3 mg/dm$^3$.

By and large, the described technology makes it possible to produce physiologically high-grade potable water with the following parameters, mg/dm$^3$:

| | |
|---|---|
| Salt content | 180–350 |
| Calcium | 25–40 |
| Magnesium | 5–15 |
| Sodium | 20–50 |
| Chlorides | 40–60 |
| Sulfates | 0.5–1.5 |
| Potassium | 0.8–1.5 |
| Fluorides | 0.5–1.5 |
| Total hardness, mg·eqv/dm$^3$ | 1.5–3 |
| Alkalinity (bicarbonates), mg·eqv/dm$^3$ | 1.5–3 |
| pH | 6.5–8.5 |

In seawater desalination, the removal of the resulting concentrate from reverse osmosis plants without harming the environment is problematic. In total, the concentrate contains the same amount of salts as the original seawater, but they are concentrated in a smaller volume of water. The consumption of concentrate from each water treatment plant is equal to 357 m$^3$/h (see Fig. 1). To prevent salting of the coastal zone, the project provides for a general plant for mixing and discharging wastewater, which, in addition to the concentrate from the reverse osmosis units of the first stage, receives sludge water from the preliminary treatment systems for the source water (mechanical filters and ultrafiltration units), regeneration solutions and washing water from neutralizer tanks, treated wastewater after domestic wastewater treatment facilities, treated wastewater after a complex of treatment facilities for industrial and storm water and wastewater containing oil products. The reckoned average hourly wastewater discharge from four NPP units will be up to 1865 m$^3$/h.

The plant for mixing and discharging wastewater includes two tanks, each of volume 3000 m$^3$, for collecting and smoothing wastewater, pumps for circulating water in tanks during smoothing and supplying smoothed effluents for discharge

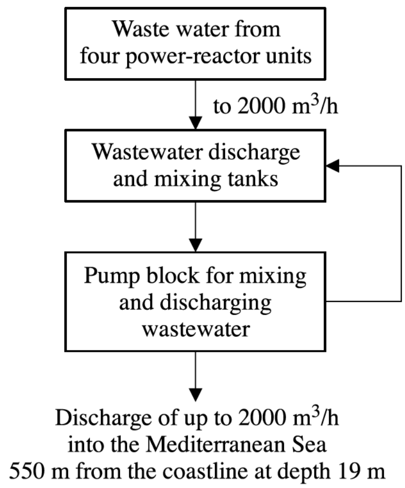


Fig. 4. Block diagram of a plant for mixing and discharging wastewater.

into the pipeline draining wastewater into the Mediterranean Sea 550 m from the coastline (Fig. 4). The depth of the sea at the point of wastewater discharge is equal to about 19 m. To disperse the flow, a diffuser is installed at the end of the wastewater discharge pipe. The reckoned average concentration of the main components in waste water will not exceed the standards established by the environmental legislation of Egypt for waste water discharged into a body of water [14]. The exception is two parameters of the composition of wastewater – total mineralization and boron content, which exceed the background indicators of sea water in the area of the projected facility by almost two-fold. At the same time, the discharge contains an amount of salts and boron that does not exceed the amount taken from sea water during the purification process at the reverse osmosis unit. Taking into consideration the dilution of discharged waters in the Mediterranean Sea 550 m from the coastline, no negative impact on the environment is expected.

So, for the NPP at El-Dabaa, where the Mediterranean Sea is the only possible source of water, engineering solutions are provided for obtaining demineralized and potable water from seawater, as well as for removing the resulting wastewater without harming the environment.

Of note is that the described technology for obtaining potable water, if necessary, can be applied not only for auxiliary needs of the El-Dabaa NPP, but also for the creation of an installation with capacity, for example, 100 thousand $m^3$/day or more, for supplying potable water to external consumers. The use of reverse osmosis technology at the desalination stage makes it possible to place the unit outside the NPP site without changing the master plan. From the nuclear power plant, only the supply of electricity is required. The water intake of the initial seawater, the supply of prepared water to consumers, and the discharge of the concentrate are organized within the context of this installation.

The technology can also be applied to other sites with a shortage of fresh water but having reserves of saline and brackish waters.

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