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Cost analysis and selection of advanced water treatment methods for organic matter removal

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ABSTRACT

Istanbul Water and Sewerage Administration have been conducting studies on advanced treatment methods in order to increase the quality of the effluent water in the treatment plants and to provide drinkable water to citizens. In this study, five-year operating costs of nanofiltration (NF) and granular active carbon (GAC) adsorption processes were calculated. The investment cost of the GAC adsorption process requires approximately 1.8 million $ more than the NF membrane process. The operation and maintenance (O&M) cost of the NF membrane process needs 1.1 million $ more than the GAC adsorption process. The O&M cost of GAC adsorption and NF membrane process is almost 5 times expensive than the conventional treatment process. By comparing these costs, conclusions were made on two different advanced treatment methods in terms of their cost-effectiveness and economic performance.

Keywords: Potable water treatment; Advanced water treatment; Granular activated carbon; Nanofiltration; Membrane

1. Introduction

Securing and maintaining an adequate supply of water has been one of the essential factors in the development of human settlements. The earliest developments were primarily concerned with the quantity of water available. The increasing population, however, has exerted more pressure on limited high-quality surface sources, and the contamination of water with municipal, agricultural, and industrial wastes has led to a deterioration of water quality in many other sources [1].

Pollution of water resources is caused by synthetic and natural chemicals that are released from a variety of anthropogenic and natural sources including the geological composition of aquifers. Different technologies for water treatment and purification have been extensively discussed in the literature where the design and operation of affordable methods can be still considered as a challenge [2].

Water treatment process selection is a complex task. Circumstances are likely to be different for each water utility and perhaps may be different for each source used by one utility. Selection of one or more water treatment processes to be used at a given location is influenced by the necessity to meet regulatory quality goals, the desire of the utility and its customers to meet other water quality goals (such as aesthetics), and the need to provide water service at the lowest reasonable cost [3].

Drinking water treatment plants employ a range of treatment techniques to remove organic matter, such as

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chemical coagulation, activated carbon adsorption, sand filtration and ozonation [4]. Previous studies have shown a wide range of efficacy associated with coagulation, with total organic carbon (TOC) and specific ultraviolet absorbance at 254 nm (SUVA) removals ranging from 7%–65% and 3%–80%, respectively [5–8]. Slow sand filtration was less efficient at removing organic matter (dissolved organic carbon removal of approximately 8%) [9]. Li et al. [4] and Baghoth et al. [10] reported that ozonation and biological activated carbon (BAC) filtration reduced the dissolved organic carbon by 5% and 40%, respectively.

The taste and odor in the treated water affect the perception of the drinking water for the customers and causes them to relate it with health risks. Two of the most common taste and odor compounds, MIB (2-methylisoborneol) and geosmin, are detectable by human beings even at concentrations below 10 ng/L [11]. Therefore, taste and odor disturbance is one of the most common customer complaints worldwide. Disinfection and oxidation processes in the treatment plant such as chlorination and ozonation are the main processes that form taste and odor. Through a series of reactions of these oxidation processes, the most common taste and odor compounds; disinfection by-products (DBP's) are created [12].

Numerous laboratory-based and pilot-plant studies have been made for the removal of MIB and geosmin. Previous studies have shown that while conventional treatment processes such as coagulation, flocculation, sedimentation and chlorination are found to be ineffective for the removal of these taste and odor compounds; powdered activated carbon, ozonation and biofiltration processes gave successful results. In the recent past, studies have focused on ozone-based advanced oxidation processes and activated carbon adsorption in order to eliminate the taste and odor problem [13].

Treatment of surface water resources and providing potable water for people is one of the most important objectives of water administrations. Although Turkey is surrounded by seas, it is not rich in freshwater resources. In particular, citizens living in the inner regions are faced with serious difficulties in terms of clean and safe drinking water supply.

If the quality of the water resource is good, water treated in conventional facilities is drinkable. However, the taste perception of people varies among cultures. In some cases, advanced treatment methods need to be applied to treat the parameters affecting the taste of water. The aim of this study is to analyze investment and operation and maintenance (O&M) costs of two different advanced treatment processes which are planned to be added to a conventional treatment plant. The capacity of this conventional plant which named "Elmali" is 23,000 m^3/d. Based on the results of the pilot studies, critical issues will be identified from a technical and economical point of view for nanofiltration or granular active carbon (GAC) treatment plants that are planned by the Istanbul Water and Sewerage Administration (ISKI) for the future.

2. Material and methods

It is essential to determine the treatment method based on the statutory quality parameters determined by countries. Conventional treatment methods can be used in this regard, as well as advanced treatment methods based on eliminating specific pollutants and producing better quality of water.

Advanced treatment technologies for drinking water are not widely used in Turkey, and conventional methods are utilized to treat parameters such as pesticides, organic carbon, softening, taste and odor. Studies conducted around the world provide new findings related to pollutants that threaten human health, and the limit values of these pollutants in drinking water are being reevaluated.

In this study, a feasibility study was conducted for the advanced treatment stage to be established in the Elmali treatment plant in the light of the data obtained from the pilot studies carried out in two different treatment plants. One of the pilot plants contains nanofiltration membranes and was placed in the Omerli treatment plant. The other is GAC filter columns and this pilot facility was established in the İkitelli treatment plant.

2.1. Nanofiltration membrane process in water treatment

Nanofiltration is one of the most effective processes in the removal of inorganic contaminants in surface waters. The removal of multivalent ions involves electrostatic interactions. Nanofiltration (NF) membranes have high permeability for monovalent salts. However, they can hold multivalent salts to a large extent so that the method is effective in removing the hardness caused by ions such as calcium and magnesium [14].

NF process is used for the treatment of organic substances which lead to the formation of DBP's due to the low energy requirement compared to reverse osmosis. When surface water is treated with NF membranes, natural organic compounds are removed by the sieve mechanism since they have larger molecules than the pore size [15].

NF membranes are also used in the treatment of whey, recovery processes from dairy industry waste products, in color and organic matter removal in the textile industry, and in organic matter and salt removal in the pharmaceutical sector. There are applications for the treatment of industrial wastewater where NF membranes are integrated with UF and RO membranes [16].

Within the scope of the pilot study, an NF membrane with a capacity of 100 m^3/d was installed at the Orhaniye Drinking Water Treatment Plant, located within the Omerli Treatment Plant. The TOC and hardness removal performance of this process was examined. DOW Filmtec NF270 membranes were used in the pilot-scale experiments.

NF membrane system was used in the existing facility as pre-treatment. Sodium metabisulphate was dosed to remove the residual chlorine in the process of water. The water was passed through the cartridge filter before the membrane and then the antiscalant chemical was dosed. The permeate from this process is sent back to the facility, and the concentrate and backwash water is discharged into the canal.

In the NF permeate, hardness and TOC was measured during the operation. Water hardness was measured using the EDTA Titrimetric method based on the method from APHA 2340. The TOC was measured on a Shimadzu TOC-VWP analyzer with an ASI-V autosampler.

2.2. Adsorption process in water treatment

The adsorption process has an important role in increasing the quality of treated water. Adsorption is the process where an atom, ion or molecule in a substance accumulate or stick to another substance. Adsorption occurs through accumulation between two different phase surfaces (solid–liquid or solid–gas). Substances that accumulate or stick to the surface of the other substance are called adsorbates, whereas the solid substance that accumulates adsorbates on its surface is called adsorbent [3]. The main adsorbents commonly used in water treatment are active carbon species, ion exchange resins and metal oxides.

Active carbon is widely used for the removal of natural organic substances which cause the formation of organic molecules and DBP's that cause undesired taste and odor in water. Active carbon is also used as an adsorbent for the removal of natural organic substances in groundwater and surface water resources. Active carbon particles used in water treatment are called granular or powdered according to their sizes and there is no significant difference in their adsorptive properties.

The main reason for the widespread use of GAC in water and wastewater treatment is that most of the carbon can be reused by being subjected to a regeneration process. Active carbon becomes saturated with the adsorbate substances accumulated in its pores and fails to adsorb new substances, and adsorption capacity decreases considerably. For this reason, the regeneration process becomes necessary so that GAC particles can be reused. If regeneration is not applied, the use of GAC can be economically costly [17].

The most common regeneration method used for GAC is thermal reactivation. In this process, the active carbon that becomes saturated is heated in the furnace at high temperatures and the adsorbate materials are thrown out and burned. On the other hand, the system is kept under control to prevent active carbon from burning and oxidation. After the reactivation process, GAC is ready for reuse.

In this adsorption performance study, a pilot plant with a total capacity of 20 m^3/d was established. Two separate granular activated carbon columns were installed. Each column has a capacity of 10 m^3/d and the pilot plant has a total capacity of 20 m^3/d. The activated carbon was Norit 1240 which is chosen after lab-scale experiments and used in the pilot tests. The water coming to the pilot facility is the effluent of the rapid sand filter unit of the İkitelli treatment plant.

2.3. ISKI Elmali water treatment plant

New studies are being carried out every passing day in order to use existing water resources efficiently and to treat these resources with modern methods. ISKI treatment plants continuously provide drinkable water to meet the water need of Istanbul. Studies and investments are being made to increase the quality of the treated water and provide high-quality drinkable water to citizens.

The Elmali water treatment plant is located within the borders of the Goztepe neighborhood of Beykoz (Fig. 1). The water treated in this facility supplies the coastal regions of this district. Studies are conducted by ISKI to provide potable water to the region which requires 23,000 m^3 of treated water per day.

With the rapidly increasing population in Istanbul, the present location of the facility is now within city limits. Uncontrolled urbanization has formed shanties and neighborhoods in the reservoir areas and it has been determined that this situation negatively affected some parameters in water quality.

In order to reduce the amount of organic carbon and DBP's found in the effluent water of the treatment plant, it is planned to establish a GAC adsorption process in the facility. The removal of ammonia, geosmin and MIB parameters found in reservoir water by biologically active carbon process is one of the research topics of ISKI.

ISKI has been conducting studies on advanced treatment methods in order to increase the quality of the effluent water in the Elmali potable water treatment plant and to provide drinkable water to citizens. Based on the results of the NF membrane pilot plant established at the Omerli potable water treatment plant, the installation of a nanofiltration process at the effluent of the filter unit of Elmali potable water treatment plant is considered as one of the alternative methods of advanced water treatment.

3. Results and discussion

3.1. Pilot-scale studies

3.1.1. Pilot-scale GAC adsorption process in ISKI Ikitelli WTP

Terkos Lake and Sazlidere Dam are used as raw water sources in İkitelli Water Treatment Plants. In the studies performed, it was determined that the organic carbon parameter measured in the spring water was in a 70% dissolved

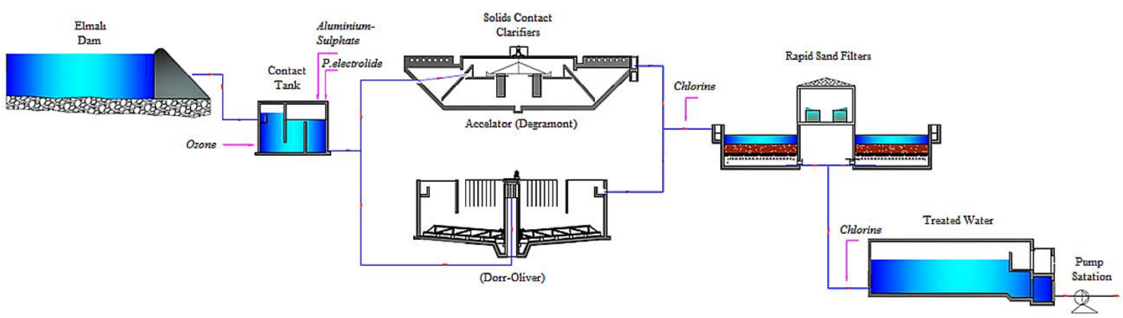

Fig. 1. ISKI Elmali water treatment plant.

form [4]. Conventional methods are currently being used for the removal of this parameter.

The values of organic substances found in the İkitelli treatment plant raw water source are given in Table 1. As can be seen in the table, the removal efficiency of organic substances in the İkitelli treatment plant varies between 25%–30% due to the low SUVA value [4].

Five different activated carbons were tested and one of them was chosen for pilot scale operation. Norit GAC 400, 1240, 1240 W, Filtrasorb 400 and Oxpure PSS 145 was tested in parallel stage laboratory equipment. In the laboratory study, initial inspections were made for the determination of activated carbon to be used for pilot operation. D6586-03 coded "Standard practice for granular activated carbon adsorption with rapid and small-scale column tests" developed by ASTM (American Society Testing and Materials) was used to select the most suitable activated carbon among these different types of active carbons available in the market for the water quality parameters and the structure of the organic compounds contained in the İkitelli treatment plant [18].

After determining the activated carbon to be used, two separate granular activated carbon columns were established for the pilot study. Each column has a capacity of 10 m^3/d and the pilot plant has a total capacity of 20 m^3/d. One of the columns was operated as BAC (without disinfection prior to column), and the other was operated as granular activated carbon (with disinfection prior to column) by dosing 0.3 mg/L ozone before the column inlet. The influent of the pilot plant was the effluent of the rapid sand filters of the treatment plant.

Table 1
Organic substances of two water supplies in Istanbul (Tatar [5])

Parameter	Terkos Lake	Sazlidere Dam
Total organic carbon, mg/L	5.2	4.2
UV_{254}, cm^{-1}	0.07	0.08
$SUVA_{254}$, L/mg m	1.3	1.9

TOC values of the effluent of the sand filtration unit of ISKI İkitelli Water Treatment Plant vary between 2.5 and 4.0 mg/L. Fig. 2 shows the TOC concentration values at the pilot plant. There was a regeneration point between 13.01.2018–06.02.2018 dates. However, effluent TOC of both columns were not drop down to the beginning state of the pilot operation.

3.1.2. Pilot-scale NF membrane process in ISKI Omerli WTP

One of the biggest problems encountered in drinking water treatment is taste and odor. In order to solve this problem caused by the growth of algae and organic substances in surface water resources, ISKI generally uses powdered activated carbon in its treatment plants. A pilot study has been conducted on the use of the NF membrane process in Omerli WTP for the removal of these parameters, which is difficult to eliminate with conventional treatment methods.

Within the scope of the pilot study, an NF membrane plant with a capacity of 100 m^3/d was installed after the rapid filtration stage of the Omerli WTP. Organic material and hardness removal performance of the NF process was examined.

The results of TOC removal of the pilot study are shown in Fig. 3 and the results of hardness are shown in Fig. 4. The TOC removal rate was stabilized after 2 months of operation. The average TOC removal rate of 84%, 54% was obtained during the study. The hardness removal success of the NF was more than the TOC removal rate. 93.39% hardness removal rate was obtained during the pilot operation.

3.2. Cost analysis

In this study, the graph of initial investment and O&M costs calculated for the GAC adsorption process, which is planned to be operated at the Elmali water treatment plant with a capacity of 23,000 m^3/d, is shown in Fig. 5a.

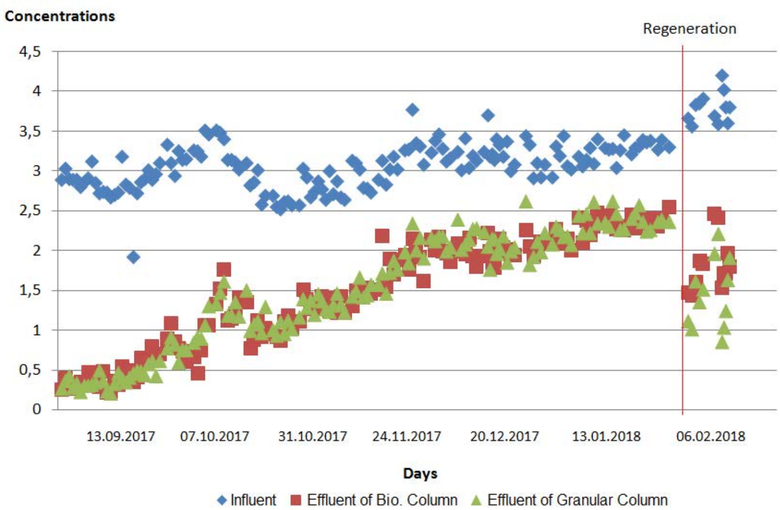

Fig. 2. TOC values of the GAC pilot plant.

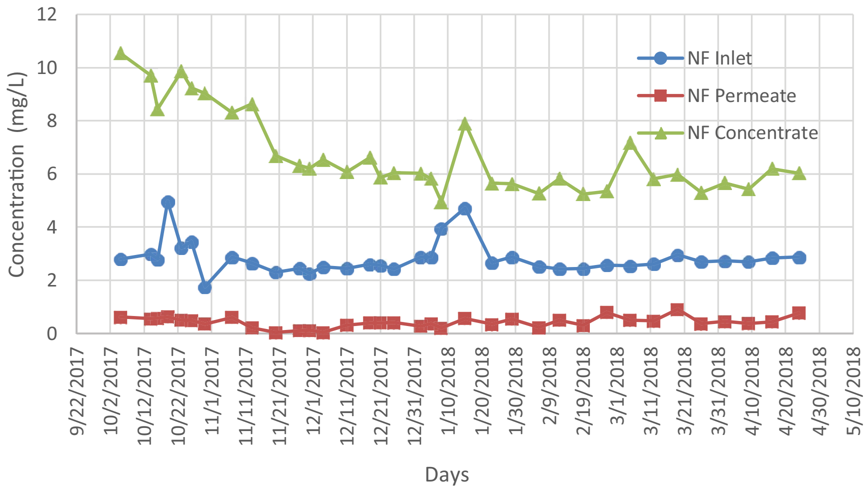

Fig. 3. TOC values of the NF pilot plant.

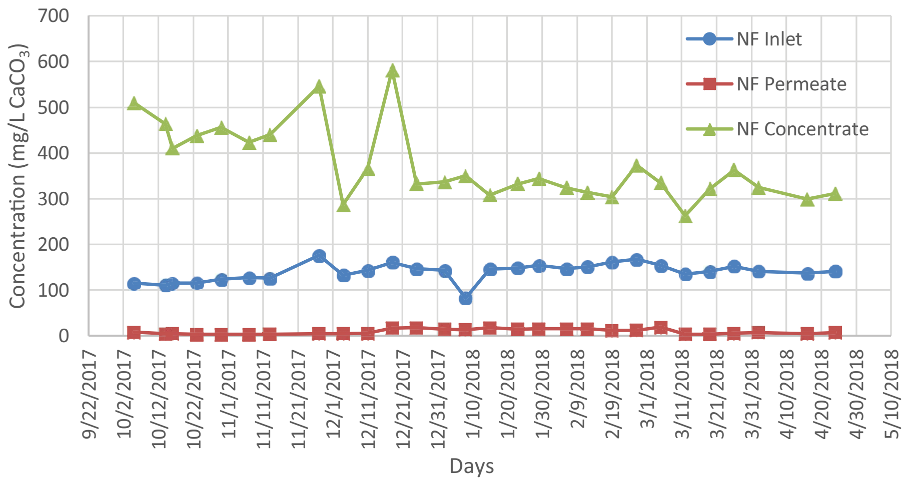

Fig. 4. Hardness concentration change during the pilot study.

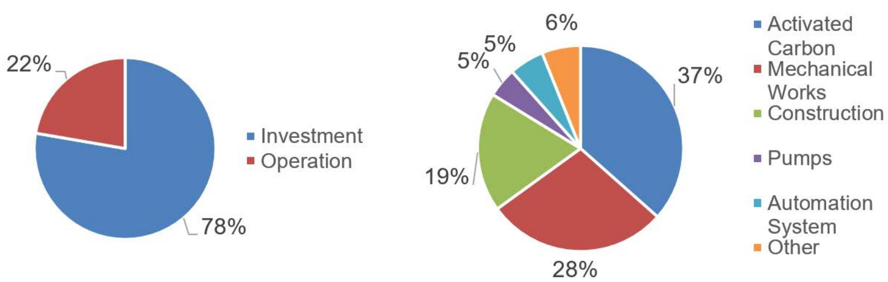

Fig. 5. Total cost (a) and initial investments (b) of the GAC adsorption process.

The effect of initial investment expenditures related to installation and construction on cost is shown proportionally in Fig. 5b.

The operational costs of the GAC adsorption process are calculated for the first 5-year period following the complete installation. Costs to be incurred in this process are shown in Fig. 6, proportionally.

The relationship between the initial investment and operational costs of the NF membrane process planned as an advanced treatment method for the Elmali water

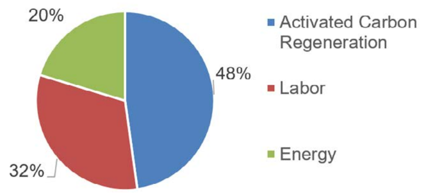

Fig. 6. Operational costs of the GAC adsorption process.

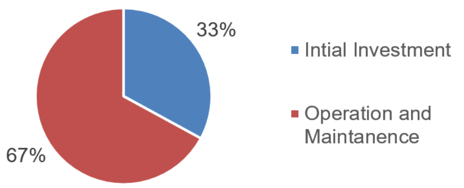

Fig. 7. The total cost of the NF membrane process.

treatment plant with a capacity of 15,000 m^3/d, is shown in Fig. 7.

The cost effects of the expenditure items included in the initial investment works of the NF process are shown proportionally in Fig. 8a. The ratio between the operating costs that will arise in case the process runs for 5 y is given in Fig. 8b.

Drinkable water from the taps is one of the greatest objectives targeted by water administrations. For this purpose, the NF membrane process and GAC adsorption process, two of the advanced treatment methods planned for the Elmali water treatment plant, have been examined comprehensively in this study and the costs have been determined. When the initial investment costs are analyzed, the NF process costs 928,912 $, while the GAC adsorption process costs 2,715,215 $. The main reason for the difference is that the costs of construction and mechanical works of the units in the GAC adsorption process are higher than the NF process. Fig. 9 graphically shows the initial investment costs and operating costs of the processes designed in this study.

The operating costs of the processes are calculated for the 5-year period after completion of installation. Membrane and granular activated carbon, the main equipment used in both processes, are thought to be completely renewed within 5 y. The operational cost of the NF process in this process is calculated as 1,890,823 $, while the operational cost of the GAC adsorption process is calculated as 778,846 $. The energy consumption of the processes and the need for chemical use are the major factors contributing to this difference between the operating costs.

The operation and maintenance costs of two different advanced treatment methods calculated that planned to be installed in the Elmali water treatment plant. The total cost per unit of water production was calculated based on the NF and GAC pilot-scale studies. It is determined that an NF process with a capacity of 15,000 m^3/d to be installed after the rapid sand filter unit of the plant will have a cost of 0.10 $/m^3. It is estimated that the treated water from the NF process will be 65% blended with the water coming out of the rapid sand filter and

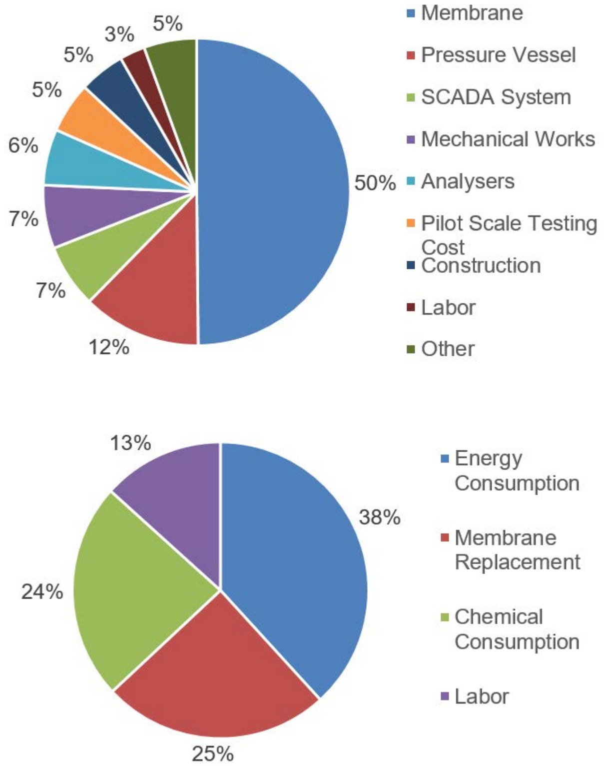

Fig. 8. Initial investments (a) and operational costs (b) of the NF membrane process.

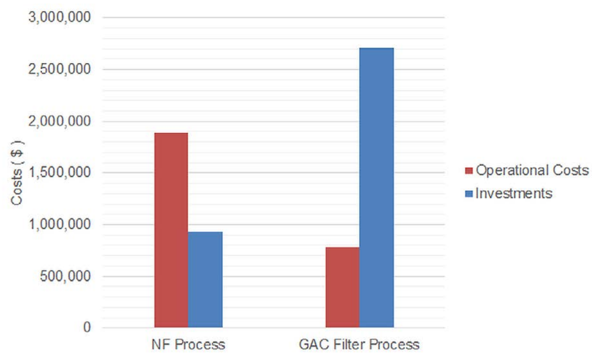

Fig. 9. Comparison of alternative process costs.

delivered to the network at a flow rate of 23,000 m^3/d. On the other hand, it is calculated that the total cost of the GAC adsorption process, which is another advanced treatment method planned to be installed for the treatment plant, will be 0.08 $/m^{3}at a flow capacity of 23,000 m^3/d.

4. Conclusions

The costs obtained in this study cover the process between the treatment plant's rapid sand filter effluent until the water is delivered to the tank for chlorination. The present conventional plant is considered as a pre-treatment process. As a result of the cost study, it was determined that the total cost of the water produced corresponds to 0.02 $/$m^3$. Main results of this study;

The GAC adsorption process achieved approximately 25% TOC removal efficiency during the study. However higher removal rate and higher quality water obtained during the NF process achieved an 85% TOC removal rate.

The investment cost of the GAC adsorption process requires approximately 1.8 million $ more than the NF membrane process. But, the operational cost of the NF membrane process needs 1.1 million $ more than the GAC adsorption process.

When the total costs (investment + O&M) are analyzed, it is found that the granular activated carbon adsorption process is economically feasible than nanofiltration methods.

The O&M cost of GAC adsorption and NF membrane process is almost 5 times expensive than conventional treatment.

A comparison of the O&M costs showed that conventional and advanced water treatment methods still have significant cost differences between them.

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