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Performance of a 270,000 CMD integrated membrane system for water supply in Taiwan

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ABSTRACT

This paper presents an integrated membrane system (IMS) designed, installed by KINTECH Technology Co. Ltd. and its long term performance at Kaotan Water Treatment Plant (KTWTP). The IMS installed at KTWTP is the first membrane system as well as the first IMS for tap water production in Taiwan. The raw waters from Kaoping River, local subsurface flow and groundwater were pumped into KTWTP for the tap water supply of Kaohsiung area. Turbidity of water in the Kaoping River during the typhoon usually increases abruptly up to 5,000–10,000 NTU, greatly surpassing the upper limit of 1,500 NTU for conventional purification to be effective. In addition, field data also showed that the levels of ammonia-nitrogen, total hardness, total dissolved solid and certain inorganic constituents in local groundwater are too high to be effectively removed by conventional system. The KTWTP was established by Taiwan Water Corporation (TWC) in 1972 and initially operated on conventional process. To meet increasingly stringent drinking water standards set by Taiwan EPA, KTWTP was upgraded in 2007 by integrating IMS (ultrafiltration, nanofiltration and reverse osmosis) into the conventional system. A two-year monitoring survey of UF-NF-RO integrated membrane system at KTWTP showed that the treated water quality is far beyond expectation as well as the substantial accomplishment of the IMS process control and data processing resulted in an excellent performance of the integrated membrane system.

Keywords: Integrated membrane system (IMS); Ultrafiltration; Nanofiltration; Reverse osmosis

1. Introduction

The annual average precipitation in Taiwan is about 2,500 mm, i.e. 2.6 times of the world average. However, Taiwan's geography, spectacular mountain ranges across a relatively small area of land to form the steep terrain, contributes to the difficulty of water collection. Taiwan has around 90 billion metric tons of water receives from rain each year and 65.6 billion becomes surface water, the majority of which quickly flows straight down into the sea. Only about 14 billion metric tons of rainwater remains on the island which is not enough to be used. In addition, during typhoon, due to the steep terrain and dense rainfall, floodwaters in southern Taiwan are often accompanied by enormous amounts of sediment. Turbidity frequently exceeds the treatment limit of treatment plants. Public water demands often suffer serious shortage due to the lack of clear raw water.

The water source of Kaohsiung area in Southern Taiwan mainly comes from surface water such as riv-

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ers and reservoirs, other parts are from subsurface flow and ground water. The Kaoping River, the main water source of Kaohsiung area, is the second-longest river in Taiwan with a length of 171 kilometers, has the largest river basin with an area of 3,257 km^2. During typhoon, the turbidity of water in the Kaoping River will usually increase abruptly up to 5,000-10,000 NTU, greatly surpassing the upper limit of 1,500 NTU for conventional purification to be effective. In addition, Kaoping River was contaminated by illegal dumping and sewage discharge from pig farms upstream in the past several decades. Field data showed that the levels of ammonia-nitrogen, total hardness, total dissolved solid and certain inorganic constituents in local groundwater are too high to be effectively removed by conventional system. As a result, human-caused contaminations, climate and geology represented a severe challenge to water purification facilities in Southern Taiwan. To solve the problem of long-term pollution of Kaoping River, Many polices and strategies were adopted by Taiwan government including pollution sources control, system quality and quantity enhancement of wastewater collecting and treating, and pollution source inspection, and so on. In late 1990, the government implemented a plan to subsidize the removal of pig farms from midstream and upstream segments of Kaoping River. From the end of May 2008, a total of 460,000 pigs were eliminated, effectively preventing removed pig farms from recommencing business and reducing pollution of Kaoping River. Besides, advanced equipments have been installed in water purification plants including Kaotan Water Treatment Plant (KTWTP) and Chengcing Lake Water Treatment Plant (CCLWTP) which are the two main water plants for water supply in Kaohsiung area.

The KTWTP was established by Taiwan Water Corporation (TWC) in 1972 and initially operated on conventional process consisted of air stripping, coagulation, flocculation, sedimentation and rapid sand filtration. To meet increasingly stringent drinking water standards set by Taiwan Environmental Protection Administration (EPA), KTWTP was upgraded in 2007 by integrating IMS (ultrafiltration, nanofiltration and reverse osmosis) into the conventional system.

Within membrane technology, UF has been considered as a suitable technology to obtain disinfected water [1]. UF is a technology with more than 20 years of experience that has been successfully implemented in many industrial applications [2]. In UF, separation takes place by size exclusion through a membrane with pore size between 1 and 100 nm, that can retain macromolecules, colloidal and suspended matter as well as protozoa, bacteria and most viruses [3]. In fact, UF membranes are able to achieve values of 7 log in reduction of total coliform bacteria, 4.4–7 log removal for Cryptosporidium, 4.7–7 log removal for *Giardia* lambia and 6 log or higher for some viruses as MS2 bacteriophage [4]. This characteristic makes UF technology feasible to produce drinking water for human consumption, without heating or addition of chemicals [5]. Reverse osmosis is an effective technology to remove organic compounds from water bodies, especially for those that contain low concentration and low molecular weight organic compounds. Traditional reverse osmosis (RO) membrane is limited due to high operational cost and maintenance as RO involves requirement of high pressure to the system and need extensive pretreatment. In addition, more and more current water and wastewater treatment plants are requested to higher their water recovery rate, which should be close to 100%. To overcome the limitations of RO, many researchers investigated an integrated membrane system (IMS) and many evidences indicated that nanofiltration (NF) membranes could be an alternative for the integration system [6-11]. Since NF membranes are generally supplied in the same configurations as RO membranes, utilities could replace RO with NF spiral-wound elements without the need for significant additional capital investment. Main advantages of membrane technology in comparison with conventional clarification and disinfection operations are: (1) no need of chemical agents (coagulants, flocculants, etc.) to produce drinking water; (2) compact process and plant, while the treatment footprint is relatively small and; (3) constant production of drinking water independent of feed water microbiological quality. The developments in the membrane technology field during the last decades resulted in a significant decrease of membrane costs and energy requirements. In addition, membrane systems are built in a modular form which enables easy adaptation of process scale.

This paper presents an integrated membrane system (IMS), UF and NF-RO system, designed and installed by KINTECH Technology Co. Ltd. as well as its long term performance at KTWTP.

2. Kaotan water treatment plant

2.1. Description of site

The KTWTP located at Daliau Township in Kaohsiung County was established by Taiwan Water Supply Corporation (TWSC) in 1972 and currently provides tap water to an estimated 540,000 people in Daliau Township, Linyuan Township, parts of Fongshan City and parts of Siaogang District of Kaohsiung City. The climatic condition in Kaohsiung County is that of subtropical monsoon climate with a mean annual rainfall about 148 mm. The mean monthly air temperature varies between 18.8°C and 28.9°C. During the period of December–February is the coldest period, and the warmest period is between June and September. The raining season in the area runs from April though October although typhoons are most frequent from the late June to October.

2.2. Treatment system

The raw waters from Kaoping River (125,000 CMD), subsurface flow (70,000CMD) and local groundwater are pumped into KWTP which is with a full capacity of 270,000 CMD. The facility utilizes a conventional treatment integrated with an IMS process (UF and NF–RO) as shown in Figs. 1 and 2.

The full system consists of the following sequence of physical and chemical treatments. For raw water Kaoping river (stream 1) (1) grit chamber — river water was pumped into a grit chamber to settle out sand, gravel and silt, the treated water was then transferred into coagulation; (2) coagulation — the addition of coagulant ($Al_2(SO_4)3{\cdot}14H_2O$) to destabilize colloidal particles and facilitate their flocculation with other suspended particles; (3) flocculation — the agitation of coagulated water to promote the aggregation of suspended materials; (4) sedimentation — the stilling of flocculated water to promote the settling of suspended solids and floccules, clear water from the top of sedimentation tank passed over a weir and on to the next process. For raw water from subsurface flow and ground water (stream 2), iron (II) and manganese (II) was oxidized to iron (III) and manganese (III, IV) as water passes through air stripping tower. This was followed by removal of the Fe (III) and Mn (III, IV) precipitates by a rapid sand filter. Both the treated water of streams 1 and 2 were delivered to mixing tank for equalization, after that, stream was divided into three parts to flow into three different rapid sand filters which with the treatment capacity of 150,000, 100,000 and 100,000 CMD, respectively. For one of three sand filters, the feed water was chlorinated prior to a rapid sand filter. The other two sand filters were followed by ultrafiltration system and UF permeate was divided into two parts to flow into disinfection tank directly and NF-RO system, respectively. All three streams came from rapid sand filter, UF and NF-RO were mixed prior to final disinfection tank and then chlorinated for delivering to distribution system.

To guarantee the water production and quality as well as the consideration of RO system maintenance, an operation strategy was involved in the contract between the KTWTP owner (TWC) and operator (KINTECH Technology Co. Ltd.) based on the feed water characteristics. Turbidity was set as a "feed water index" to have the flexible operation modes as followings:

- The water production (CMD) has to meet the requirement of contracted quantity when the feed water turbidity of KTWTP is lower than 1,500 NTU.
- In the case of the feed water turbidity is higher than 1,500 NTU, the water production can be reduced but the permission from TWC is necessary. In this case, UF permeate will be transported directly to disinfection tank and then for distribution system. During the past 2-year operation, this situation always happened to the storm period while the raw water from Kaoping river usually with a turbidity level higher than 10,000 NTU.
- In all cases, the supply water quality has to meet the standards regulated by Drinking Water Management Act (DWMA) of Taiwan.

17 trains with 180 parallelized membrane cartridges of each train were arranged for the UF system. The membrane area of each cartridge was around 40 m^2. The hollow fibre type UF membrane was a Polyvinylchloride (PVC) alloy membrane with a pore size of 0.01 um was applied in this plant. This membrane is excellent in mechanical strength and could easily repel the organic contaminants to reduce the membrane fouling. UF system was carried out at a constant feed pressure of 0.1 kg/cm^2 during the filtration cycle of 25–60 min with a TMP ranged between 0.4–0.6 kg/cm^2. Rinse and backwash were implemented in the end of each cycle using ultra-filtrated water, and

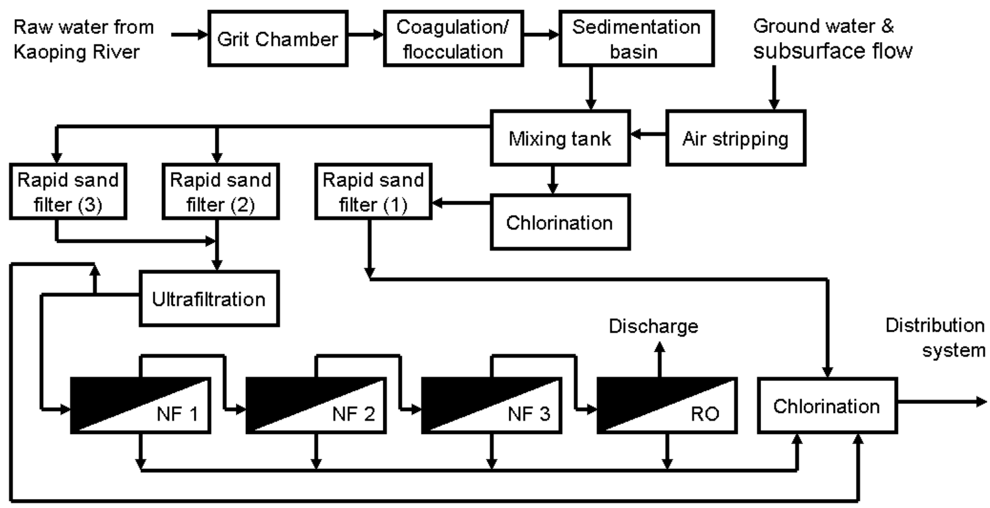

Fig. 1. Schematic flow diagram of KTWTP.

(a)

(b)

Fig. 2. Full-scale integrated membrane system (IMS) of Kaotan water treatment plant for tap water supply located at Kaohsiung County, Taiwan (a) UF system (b) NF-RO system.

clean-in-place (CIP) was carried out for membrane fouling and scaling cleaning using NaOH and NaOCl solutions, respectively.

Pre-treatment is important in NF-RO as the feed water has to pass through very narrow passages during the process. Therefore, it is imperative that suspended solids are removed and the water pretreated to prevent salt precipitation or micro-organism growth on the membranes. Effective pretreatment is thus necessary to increase the efficiency and life span of an NF-RO system. Selection of proper pretreatment minimizes fouling, scaling and membrane degradation, resulting in optimized product flow, salt rejection, product recovery and operating costs. In KTWTP, coagulation-flocculation-settling and UF were adopted as the pre-treatment of NF-RO system. Filtration rate, filter bed depth, sand grain size (fine vs. coarse) and coagulant dose and have been studied in the initial stage of system integration.

For NF-RO system, 16 trains of membrane system were designed and each train was divided into 4 stages. NF membrane was used for the first three stages and the last stage was installed with RO membrane. The numbers of parallelized vessel of each stage are 30, 18, 9 (NF membrane) and 6 (reverse osmosis), respectively. 6 parallelized membrane cartridges were packed inside the vessel. The production from each train was measured and transported directly to the final disinfection tank. Pressure gradient operation was adopted for NF-RO system to save energy and enhance water recovery. A suitable anti-scaling agent was added to the feed water to reduce the precipitation of dissolved salts onto the membrane surface. Clean-in-place (CIP) was carried out for NF-RO membrane by using NaOH and HCl solutions, respectively when 10–15% of permeate reduction was achieved. The total land area of KTWTP's IMS with a full capacity of 270,000 CMD is 1380 m^2.

The treatment plant was completely outfitted with intelligent sensors and measurement instruments to perform the following functions: (1) on line analytical measurements (pH, temperature, turbidity, pressure); (2) flow rate measurements using magnetic field and ultrasound measurement methods; (3) ultrasonic and hydrostatic level measurements; (4) inlet/outlet automatic sampler; (5) pump and blower control. Through the complete plant automation system, the plant can be accessed remotely by the plant operator, service personnel and data acquisition service.

2.3. Raw water characteristics

High turbidity of raw water during typhoons has become one of the major threats to water resources administrators in Taiwan over the last decade. Fig. 3 shows the turbidity variations of Kaoping river water and the mixed water contained local subsurface flow and ground water monitored during the period of October 2007 to November 2009. The data indicated that turbidity of two raw waters were mostly lower than 100 NTU from November to next April in both years. However, most of the turbidity data during June to October were higher than 1000 NTU due to the seasonal storms. Typhoon Kalmaegi of 2008 and Typhoon Morakot of 2009 constituted two particularly representative cases. In both cases, the river turbidity increased abruptly near or higher than 50,000 TU (58,000 TU of Kalmaegi case and 47,000 NTU of Morakot case) while the associated high turbidity in the mixed water of subsurface flow and ground water was also found. In fact, for most of conventional WTP in Taiwan, raw water with a turbidity level higher than 1,500 NTU is far beyond the capacity of treatment system.

Fig. 4 shows that the raw water from local subsurface flow and ground water is typically hard to very hard. The data presented in Fig. 4 also shows that groundwater is typically "harder" than surface water. This occurs because the groundwater has travelled slowly through the soils that are rich in calcium and magnesium which dissolve over time. This is typical of the majority of groundwater supply in all Kaohsiung area.

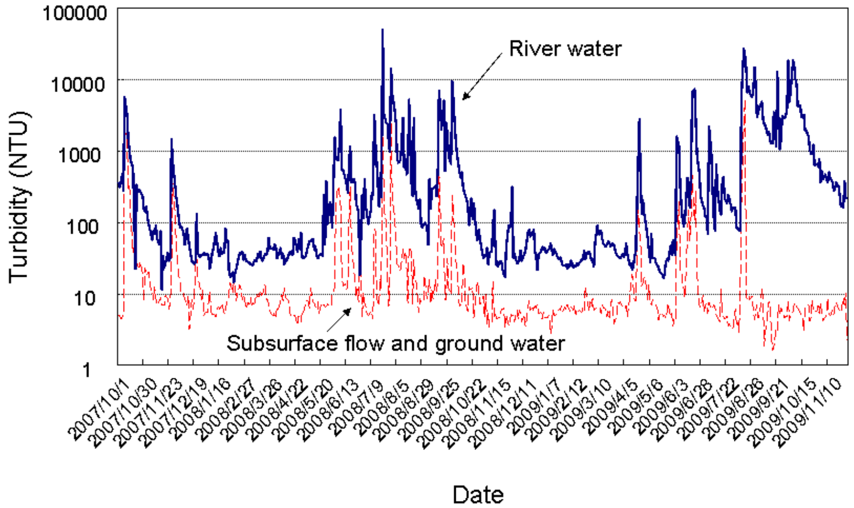

Fig. 3. Turbidity variation of raw waters.

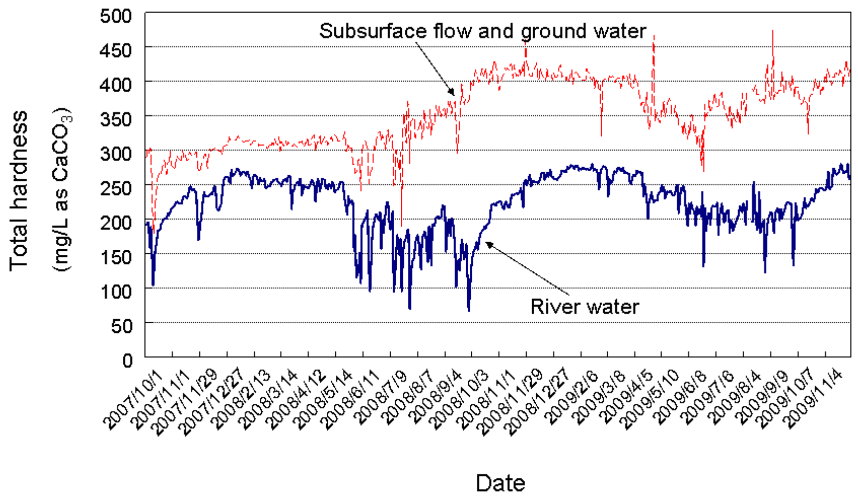

Fig. 4. Total hardness variation of raw waters.

In contrast to water quality criteria related to toxicity for aquatic life for which ammonia is important. For treating drinking water, ammonium is also important since ammonia can react with chlorine and reduce or eliminate the disinfecting ability. Therefore, when a water system is being used for drinking purposes, the ammonia plus ammonium concentration must be considered. Ammonia in natural water can originate from many sources, and are naturally occurring forms of nitrogen. Predominant sources will vary on a watershed or sub-watershed basis. Also, sources and concentrations are greatly influenced by hydrology, including timing and volume of water runoff. It is difficult, if not impossible, to separate the effects of both source and hydrology. Typically, ammonia is naturally present at very low levels (< 0.1 mg/l N) in surface waters. River levels are higher that 0.2 mg/l N are usually indicative of pollution. Ammonia data illustrated in Fig. 5 shows that the levels of ammonia in subsurface and ground water are generally higher than that of river water. Actually, according to DWMA of Taiwan, a regulated ammonia criterion of a water source used for tap water production is 1.0 mg/L.

Iron and manganese may also accelerate biological growths in the distribution system, further exacerbating taste, odor, and color problems. Iron can be a problem, either from the effects of its presence in the water alone, or because iron bearing water has promoted the growth of iron bacteria. Manganese present in water can cause discoloration in laundered goods, “black” water, water main incrustation, debris at water customers’ taps and may negatively impact taste in drinking water and beverages. Data presented in Fig. 6 shows that iron in the mixed water (subsurface flow and ground water) was quite stable except the period of August, 2009. It is probably due

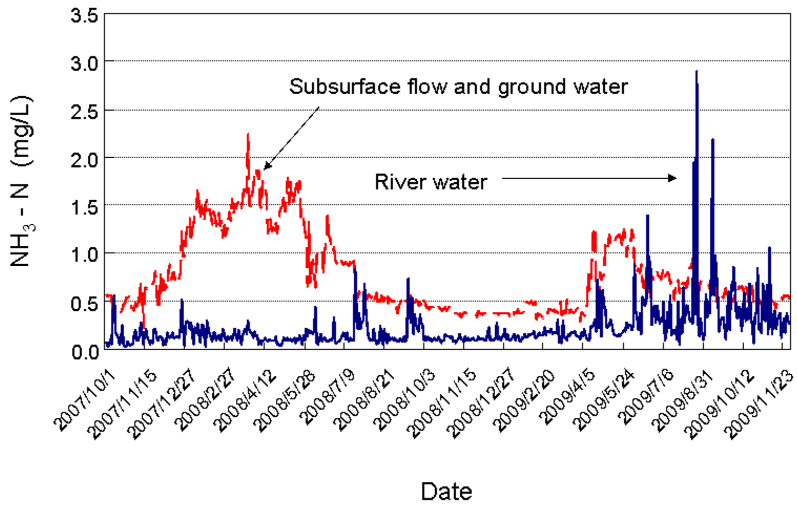

Fig. 5. Ammonia nitrogen variation of raw waters.

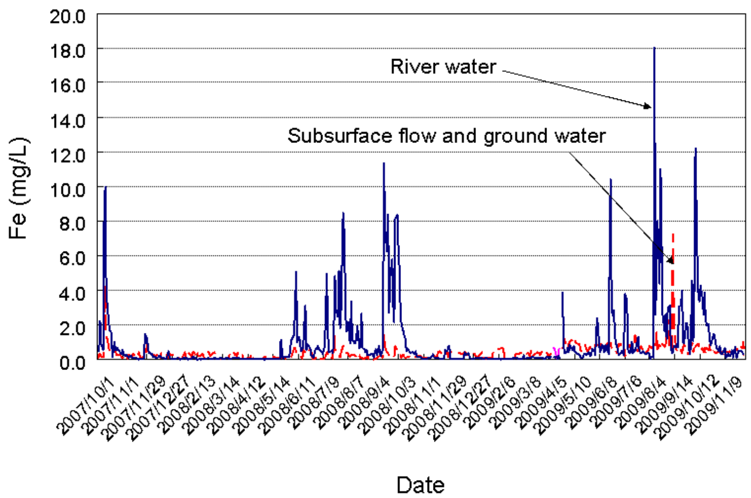

Fig. 6. Fe variation of raw waters.

to the Typhoon Morakot which caused a highest Fe level in river water. Iron rich runoffs from surrounding point pollution sources such as landfill site and industries during typhoon could entry the soil by infiltration resulted in the dramatic increase of iron in ground water. At the same time, river water with high level of iron was also found occasionally during the storm period. Similar phenomena were observed in manganese case (Fig. 7). However, the level of manganese in river water was regularly lower than that of mixed water (subsurface flow and ground water) expect the storm season.

3. Results and discussion

As of the year 2008, Taiwan's water supply system has achieved a supply rate of 90.7% and was serving approximately 20,000,000 people. The quality of drinking water in Taiwan is regulated by the Environmental Protection Administration (EPA). The EPA is responsible for monitoring and confirming that drinking water supplied by Taiwan Water Corporation (TWC) meets the requirements of the Drinking Water Management Act (DWMA) and is safe to drink. TWC is a publicly owned company and is the sole supplier of public drinking water in Taiwan. The EPA supervises all local Environmental Protection Bureaus (EPB) to follow the DWMA to conduct drinking water surveillances. Besides, self-inspection by Water Plant and TWC was also regulated based on different water quality indexes and frequencies. Table 1 shows briefly the water quality inspection program practiced in Taiwan.

UF, NF and RO facilities were integrated into KTWTP in June 2007. Before the installation, the system design approach has been established after a comprehensive analysis of the different parameters that may have a di-

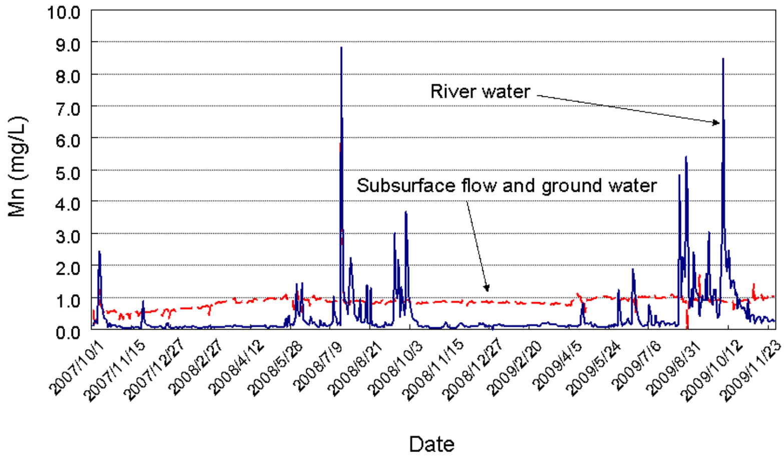

Fig. 7. Mn variation of raw waters.

Table 1
Water quality inspection program practiced in Taiwan

Inspector	Frequency	Items of analysis
Water plant	Immediately	Free residual chlorine, turbidity
	Daily	pH, free residual chlorine, odour, turbidity, colour
	Weekly	Iron, manganese, ammonia-nitrogen
TWC	Monthly	pH, free residual chlorine, odour, turbidity, colour, coliform group, total bacterial count
	Seasonal	pH, free residual chlorine, odour, turbidity, colour, coliform group, total bacterial count, arsenic, lead, selenium, total chromium, cadmium, barium, antimony, nickel, mercury, cyanide, nitrite-nitrogen, total trihalomethanes, trichloroethene, cabon tetrachloride, 1,1,1-trichloroethane, 1,2-dichloroethane, viny chloride, benzene, 1,4-dichlorobenzene, 1,1-dichloroethene, endosulfan, lindane, butachlor, 2,4-d, paraquat, methomyl, carbofuran, isoprocarb, methamidophos, diazinon, parathion, EPN, monocrotophos, fluoride, nitrate-nitrogen, silver, iron, manganese, copper, zinc, sulfate, phenols, MBAS, chloride, ammonia-nitrogen, total hardness as CaCO3, total dissolved solids
EPB	Monthly	All Items in standards of drinking water (totally 59 items)

rect and/or an indirect influence on the plant's feasibility, reliability and availability.

The performances of UF process related turbidity, trans-membrane pressure (TMP) and water production (in terms of CMH per cartridge) are illustrated in Fig. 8. As shown in Fig. 8, the flux of each UF cartridge is quite stably around 3.8 CMH in average. It means a total of 3060 cartridges can produce approximately 280,000 m^3 of water per day, i.e. the full capacity of UF system could singly cover the contracted requirement if the permeate can meet the water quality standard. Fig. 8 also showed that the gradient TPM moved up slowly resulting in a chemical cleaning frequency ranged between 3–5 months with a water recovery of 90–95%. It indicates that the pretreatment of coagulation–settling-sand filter process was effective in KTWTP. Field data showed that SDI value and turbidity of UF permeate were always lower than 2 and 0.2 NTU regardless of the raw water turbidity levels.

In KTWTP, three stages of NF in a series connection followed by one stage of RO were adopted. The advantages of the arrangement are to reduce the energy requirements as well as to raise the water recovery. As shown in Fig. 9, actually, each NF-RO train can be operated continuously at least for 3 months without chemical cleaning above a flux of 300 CMH. In addition, most of the time, the water recovery was higher than 85%. These could be attributed to the effective control of driving force which is increased stage by stage.

The nanofiltration process can pass more water at lower pressure operations than reverse osmosis, can remove particles in the 300–1,000 molecular weight range such as humic acid and organic color bodies present in water, and can reject selected (typically polyvalent) salts. Nanofiltration may be used for selective removal of hardness ions in a process known as membrane softening. Fig. 10 illustrates the total hardness (TH) removal

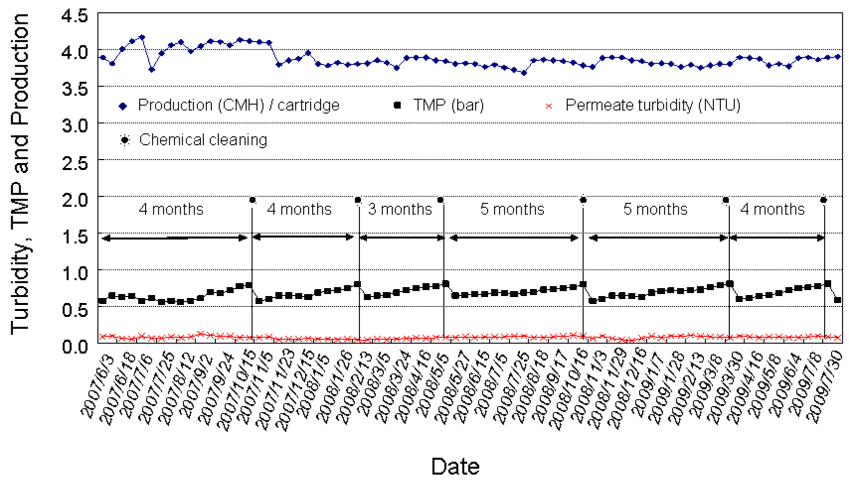

Fig. 8. Performance of UF system in KTWTP.

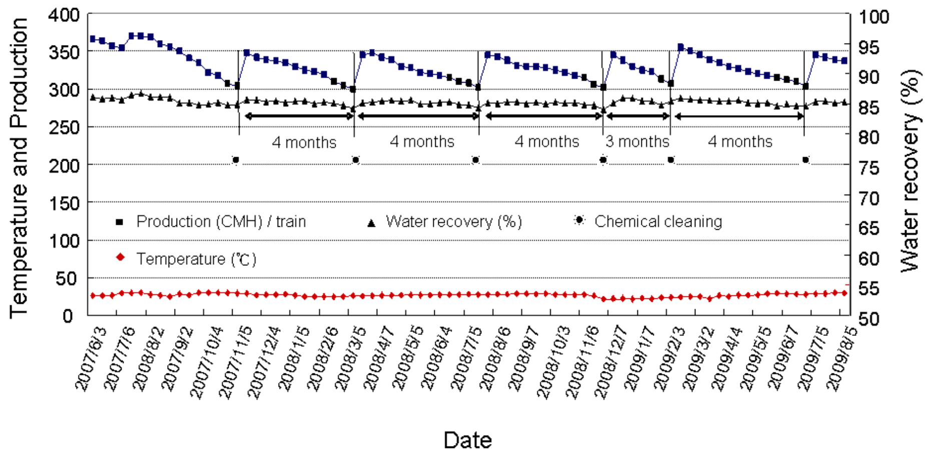

Fig. 9. Performance of NF-RO system in KTWTP.

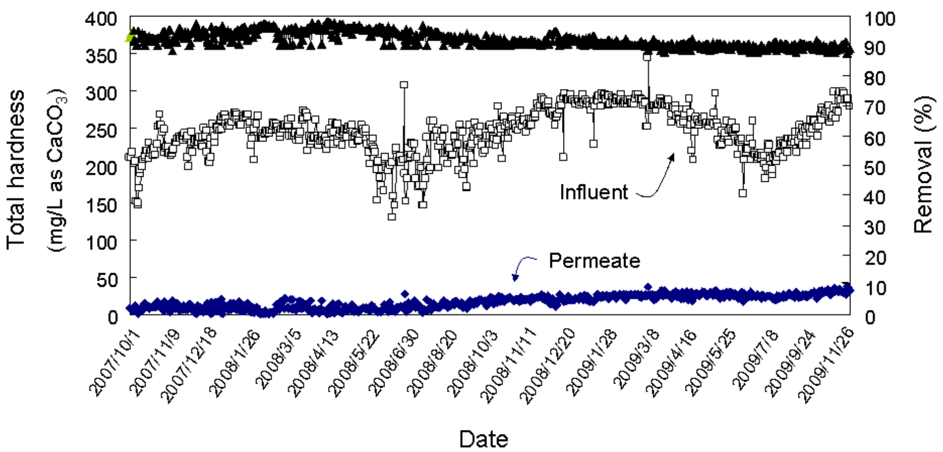

Fig. 10. Total hardness removal of NF-RO system in KTWTP.

by NF-RO system. It is obvious that UF membrane could not remove hardness ions efficiently since the TH of UF permeate, the influent of UF-RO, always has a level higher than 150 mg/L. The result shows that the overall removal efficiency of NF-RO system for total hardness is in the range of 89–99%.

As previously mentioned, treated water of KTWTP for consumers came from 3 different treatment lines. Water quality monitoring was conducted in finished water reservoir to examine the overall system performance and guarantee the finished water quality. Overall system performances related to total hardness (TH), total dissolved solids (TDS), ammonia nitrogen (NH_3-N), total trihalomethanes (TTHMs) and residual chlorine are shown in Figs. 11–15. It is clear that the water quality can meet the standard all the time.

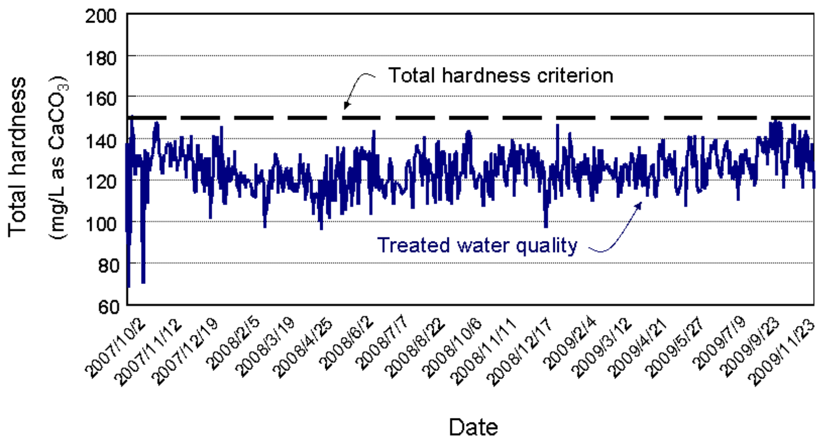

Fig. 11. Total hardness variation of finished water in KTWTP.

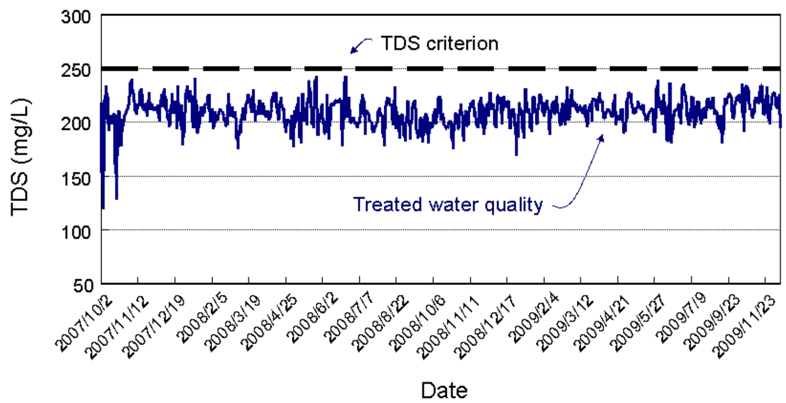

Fig. 12. TDS variation of finished water in KTWTP.

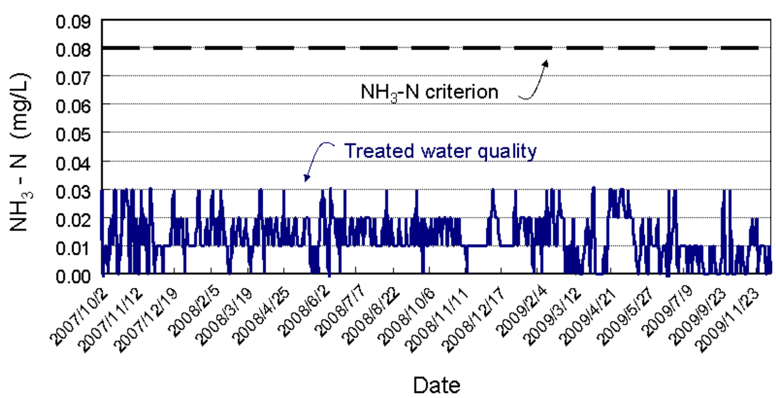

Fig. 13. Ammonia nitrogen variation of finished water in KTWTP.

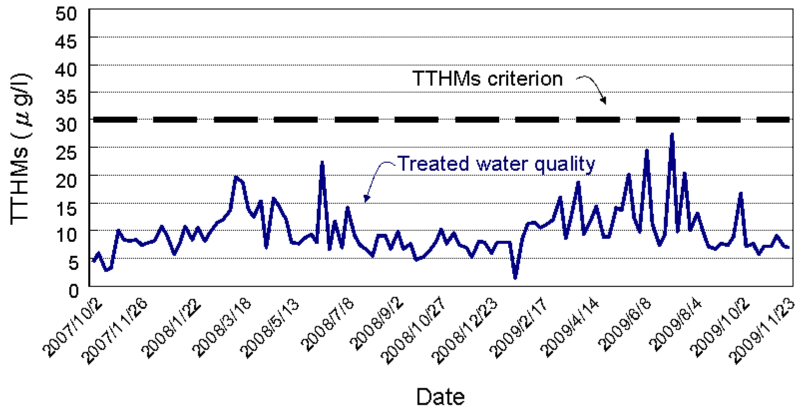

Fig. 14. Total hardness variation of finished water in KTWTP.

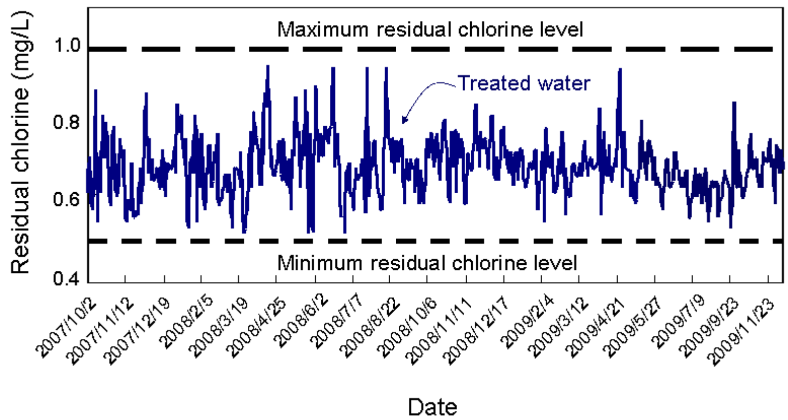

Fig. 15. Residual chlorine variation of finished water in KTWTP.

KINTECH designed and executed the upgrade by IMS to KTWTP and managed to reduce the water supply shortage of Kaohsiung area. Ultimately, the IMS system is there to make sure that the plant is as safe as possible and that it can continually supply safe, high quality drinking water to the population of Kaohsiung area.

4. Conclusions

A two-year monitoring survey of UF-NF-RO integrated membrane system at KTWTP was presented in this paper. Field data showed that SDI value and turbidity of UF permeate were always lower than 2 and 0.2 NTU regardless of the raw water turbidity levels. The data also showed that each NF-RO train can be operated continuously at least for 3 months without chemical cleaning at a high level flux. An operation strategy was involved in the contract between the KTWTP owner (TWC) and operator (KINTECH Technology Co. Ltd.) based on the feed water characteristics to guarantee the water production and quality as well as the consideration of RO system maintenance. Overall system performances related to total hardness (TH), total dissolved solids (TDS), ammonia nitrogen (NH_3-N), total trihalomethanes (TTHMs) and residual chlorine clearly showed that the treated water quality of the integrated membrane system can meet the drinking water standard all the time.

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