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Closed circuit desalination series no-5: high recovery, reduced fouling and low energy nitrate decontamination by a cost-effective BWRO-CCD method

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ABSTRACT

The newly conceived and recently reported closed circuit desalination (CCD) Technology has been successfully demonstrated for nitrate decontamination. The application of the brackish water reverse osmosis- CCD (BWRO-CCD) Technology to feed sources of 98, 144 and 197 ppm NO_3 gave the respective amounts of 19, 27 and 45 ppm NO_3 in permeates from said sources obtained with 90% recovery at 20˚C. The illustrated NO_3 rejection finding of the BWRO-CCD Technology, considered in the context of high flux, high recovery, low energy demand and reduced fouling factors may suggest the plausibility of this cost-effective approach for nitrate decontamination of drinking water worldwide.

Keywords: Reverse osmosis; Closed circuit desalination; Nitrate removal from drinking water by CCD

1. Introduction

Nitrate contamination of ground drinking water is an issue of great concern worldwide, especially in advanced countries (e.g. Great Britain, France, Germany, the Netherlands, Switzerland, the USA, Israel and many more), primarily due to health risk factors such as methemoglobinemia ("blue baby" syndrome in infant) and the suspected *in vitro* source of the strongly suspected carcinogenic entities such as nitrosamine, nitrosamide and others. In view of public health considerations, the allowed level of nitrate in drinking water has been restricted to 44.3 ppm (or 10 mg/L based on nitrogen content) in the US [1] and Canada, 50 ppm by the WHO [2] with a European recommended guide level of 25 and 70 ppm in Israel. Average human consumption of 3.0 L/day of water with 50 ppm nitrates implies a daily dose of 150 mg of a disputed chemical of no useful physiological function which could be transformed into cancer-stimulating molecules. Except for extreme levels of nitrate in drinking water which can cause central nervous disorders, most adults are not immediately susceptible to moderately high levels of nitrates in drinking water and the restricted level allowed are intended for safeguard protection.

Nitrate contamination of groundwater originates primarily from fertilizers, animal waste, openly disposed domestic sewage and/or leaking septic tanks and/or local sewage treatment centers. Most nitrate-contaminated water is commonly found next to the source of contamination, leaving no doubt concerning the origin of contamination. The nitrate concentration of unused contaminated groundwater sources normally increases in time and causes a severe deterioration of water quality around it.

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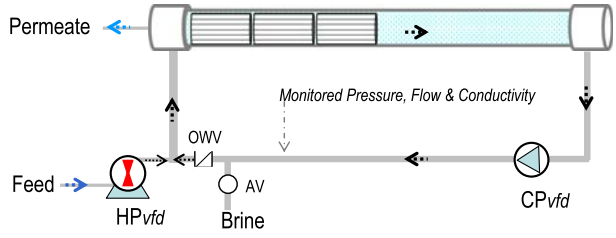
The principle methods for nitrate decontamination of drinking water include electro-dialysis reversal (EDR), reverse osmosis (RO), ion exchange and biological treatment techniques membrane bioreactor, of which the first two are the most common for large-scale operation. Prevailing views suggest the preference of EDR for high recovery of sources with elevated silt density index (SDI) and expected bio-fouling characteristics; whereas, RO preferred for low recovery, low SDI and low capacity production [3]. Low recovery RO for nitrate decontamination probably manifests the relatively poor rejection of the nitrate ion through semi-permeable membrane elements at an ordinary average flux of conventional techniques.

The current paper describes the application of closed circuit desalination (CCD), a proprietary [4,5] technology just disclosed [6–9], for nitrate decontamination with high performance efficiency and cost effectiveness.

2. Procedure and results of BWRO-CCD nitrate decontamination

Trials performed with a brackish water reverse osmosis- CCD (BWRO-CCD) ME3 (E = RE8040-BE440) Unit comprising a single module with three membrane elements according to the schematic design in Fig. 1; wherein, the entire concentrate is recycled and mixed with fresh pressurized feed at module inlet. The unit performs a CCD of 100% recovery until the salinity of the recycled concentrate inside the closed circuit manifests the desired recovery, at which point brine is replaced by fresh feed with a brief Plug Flow Desalination step of ~25% recovery. The schematic BWRO-CCD ME3 Unit design displayed in Fig. 1 was used during the Nitrates Contamination trials and further information about such a consecutive sequential



HP *vfd* - Feed pressurizing Pump with a variable frequency drive
CP *vfd* - Circulation Pump with a variable frequency drive
AV – Two-way actuated Valve
OWV – One way check valve

Fig. 1. Schematic design of the BWRO-CCD ME3 unit with 8´´ elements used during the nitrate decontaination trials.

desalination type processes under fixed flow and variable pressure conditions is provided elsewhere [6–9]. The feed solution to the BWRO-CCD unit during the trials reported herein comprises rich $NaNO_3$ solutions with nitrate content in the range 100–200 ppm.

Nitrate decontamination trial with $NaNO_3$ feed solution of 196.9 ppm NO_3 using the BWRO-CCD ME3 (E = RE8040-BE440) Unit was performed at 30.0°C under CCD fixed flow and variable pressure (7.5 → 8.9 bar) conditions with 4.5 m^3/h pressurized (high pressure pump, HP) feed flow (389 μS/cm) and 5.8 m^3/h concentrate recycling flow (circulation pump, CP) which manifest fixed flux of 37 lmh, module recovery of 43.7% and head element recovery of 17.5%. A consecutive sequence during this process comprises a CCD step (42 min) of 100% recovery and a plug flow desalination (PFD) step (4 min) of 30% recovery which together manifest an overall sequence recovery just above 90%. The parameters monitored during the trial included flow and electric conductivity (EC) of feed, recycled concentrate and permeate as well as pH of feed (6.42) and permeates (9.0-start → 6.5-end of CCD sequence). Permeate samples retrieved periodically at predetermined EC levels of recycled concentrate during the system recovery progress were analysed for NO_3 by a certified analytical laboratory (BactoChem—Israel) and the final brine

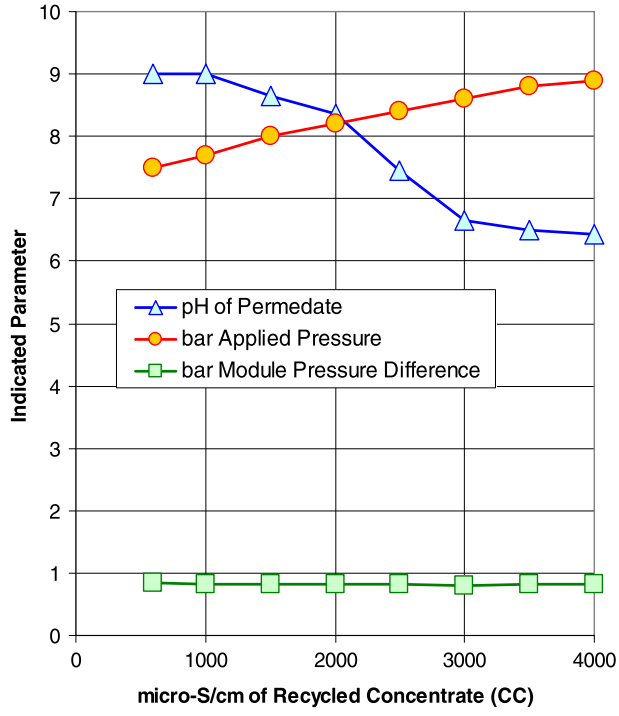


Fig. 2A. CCD sequence pressure variation, module pressure difference and pH of permeate vs. EC of recycled concentrate.

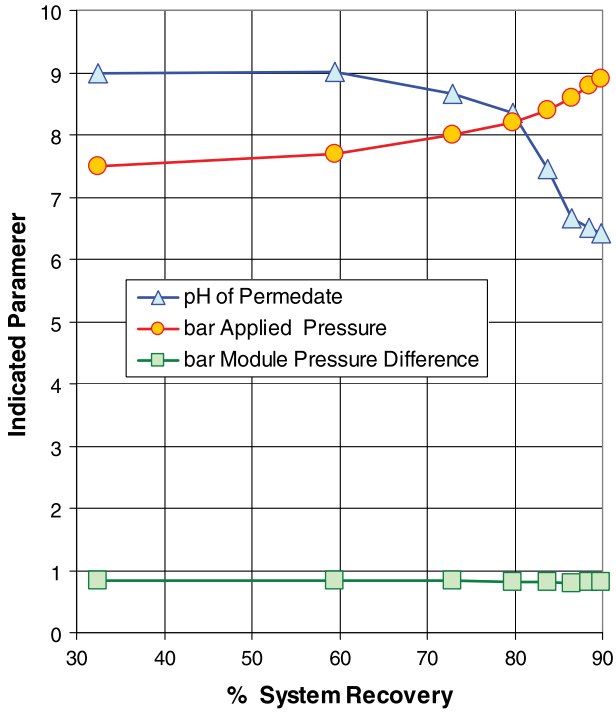


Fig. 2B. CCD sequence pressure variation, module pressure difference and pH of permeate vs. % recovery.

rejected from the sequential process was also analysed and found to contain 2,105 ppm NO_3. The analytical data pertaining to feed and final brine manifest 90.6% system recovery as already pointed previously on the basis of a different calculation. The CCD pressure difference over the membrane was found fixed at 0.82 + 0.03 bar and pumps' efficiencies based on power consumption, flow and pressure were found to be 67% for HP and 36.7% for CP.

The results obtained during the trial with nitrate feed solution of 196.9 ppm NO_3 are displayed as follows: Fig. 2 describes CCD sequential pressure variations, module pressure difference and pH of permeates produced vs. EC of recycled concentrate (Fig. 2(A)) and vs. % system recovery (Fig. 3(A)); Fig. 3 describes Permeates NO_3 ppm content vs. EC of recycled concentrate during the CCD sequence at 30˚C (Fig. 3(A)) and vs. % system recovery (Fig. 3 (B)); and Fig. 4 describes both NO_3 ppm per step (Fig. 4(A)) and average NO_3 ppm per entire sequence (Fig. 4(B)) vs. % system recovery at 20, 25 and 30˚C. The average permeates NO_3 content (ppm) of the different feed solutions with 197, 144 and 98 ppm nitrates are displayed in Fig. 5 as function of temperature.

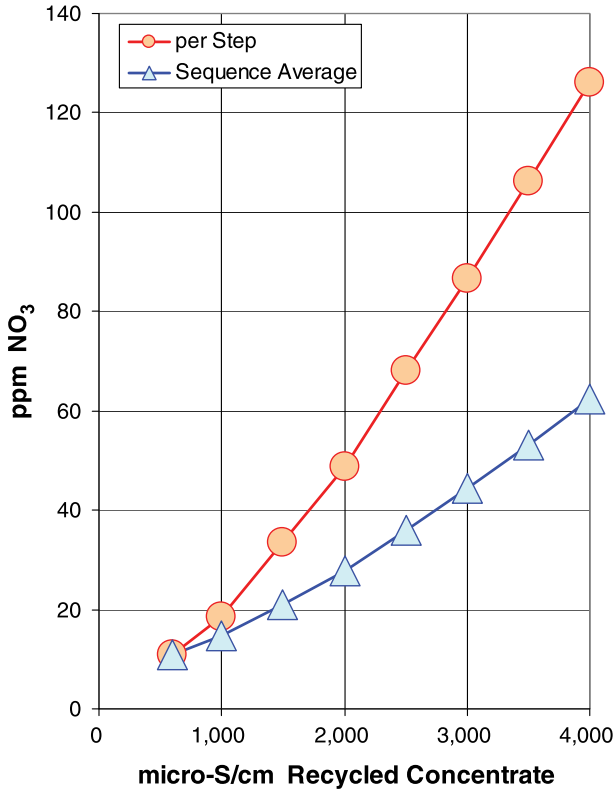


Fig. 3A. Permeate ppm NO_3 vs. recycled concntrate EC during a CCD sequence at 30˚C.

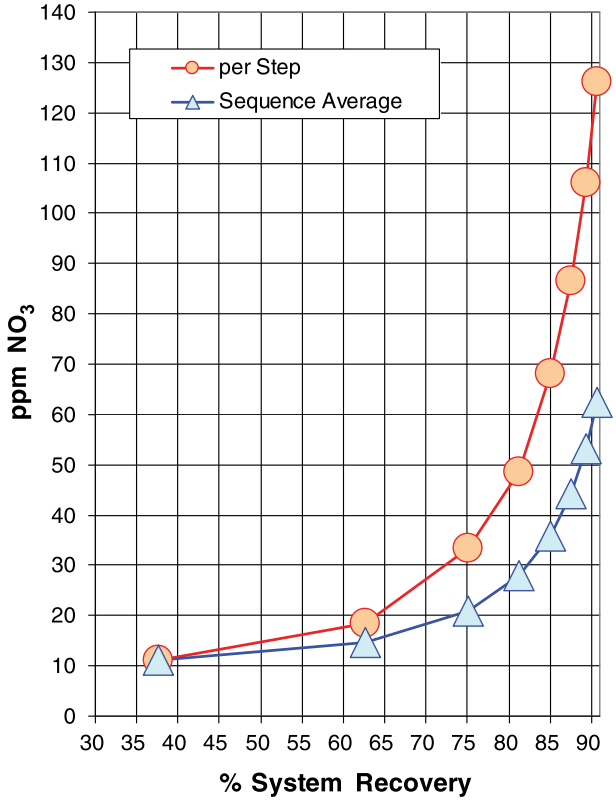


Fig. 3B. Permeate ppm NO_3 vs. % recovery EC during a CCD sequence at 30˚C.

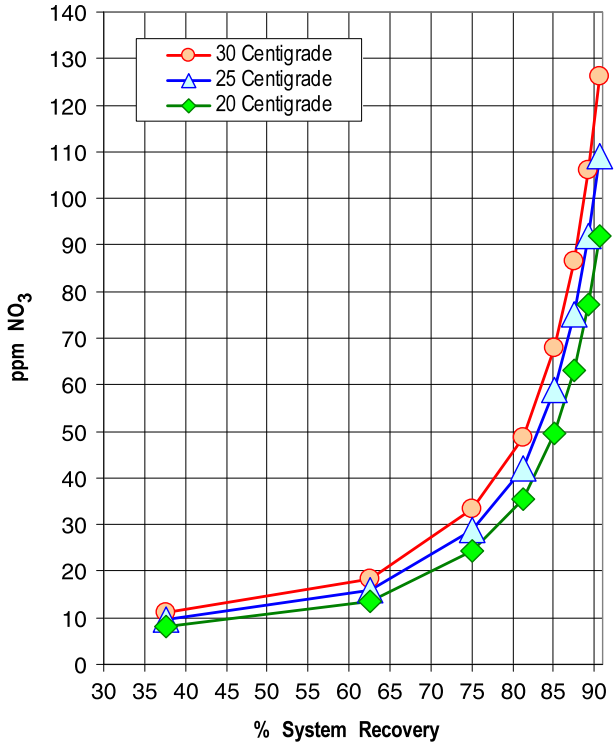


Fig. 4A. Step ppm NO_3 vs. % recovery at temperature of 20, 25 and 30°C.

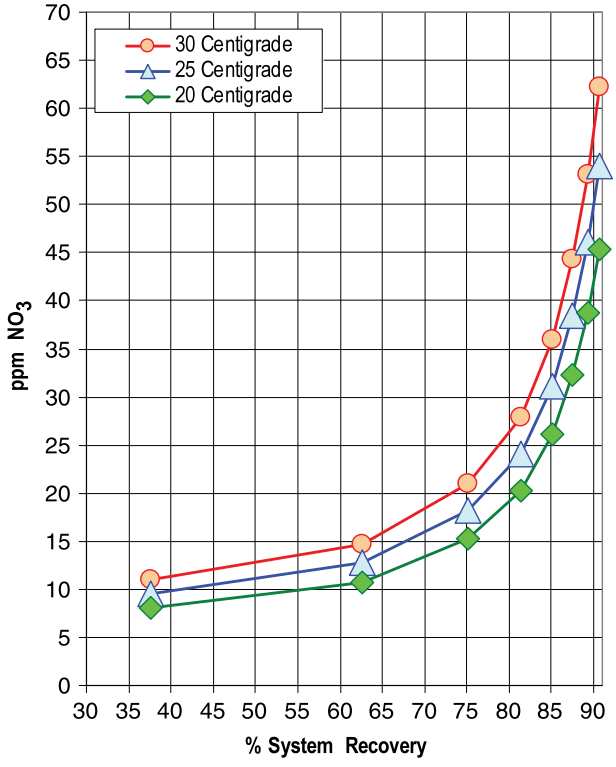


Fig. 4B. Average ppm NO_3 vs. % recovery at temperature of 20, 25 and 30°C.

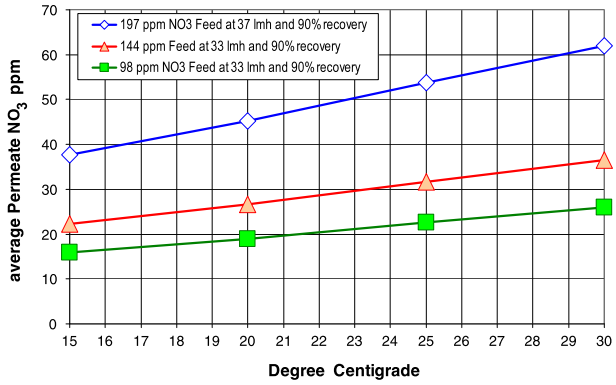


Fig. 5. Average permeates NO_3 ppm of various nitrate feed vs. temperature.

3. Discussion

The worldwide growing problem of nitrate contamination of drinking water requires cost effective techniques for large-scale operations. Most reasonable size ($\geq$20 m^3/h) nitrate decontamination systems installed during the past decade are based on the EDR technique. The inferior number of RO compared with EDR installations for nitrate decontamination is also evident in the state of Israel; wherein only one of the 12 installed systems for nitrate decontamination is based on RO (3-stage RO Unit for 27 m^3/h at Zur-Moshe Israel for feed of 92 ppm NO_3 and permeate of ~24 ppm NO_3 received with ~82% recovery before blend) [10]. The inferior application of conventional RO for high recovery nitrate decontamination arises primarily form the low rejection ratio of the small size Nitrate ion and the confinement of operating to a normal flux under which nitrate rejection is relatively poor. Moreover, high flux operation of a conventional three-stage RO system at high recovery increases the risk of fouling and scaling which require frequent CIP procedures. Design Programs of membrane manufacturers, an essential design tool, could not be used effectively for RO systems intended for nitrate decontamination due to lack of sufficient knowledge to enable the generation of reliable nitrate rejection parameters.

In order for RO to become competitive for nitrate decontamination, certain criteria need to be met such as high recovery, high flux, low energy consumption and high cost effectiveness with respect to the specific membrane elements chosen for such an application. The recently reported and demonstrated BWRO-CCD technology [6–9] appears ideal for nitrate decontamination, since it utilizes short modules (3/4 elements per module) which enable attainment high of recovery with high flux without exceeding Test Conditions

specifications of elements, under conditions of low fouling characteristics with low energy consumption. This fully automated unique technique enables complete online control of modules and membranes performance; thereby, achieve maximum process optimization, a feature unattainable by any conventional method. The trial results reported and discussed herein do indeed fully confirm the aforementioned theoretical assessment concerning the suitability of BWRO-CCD for nitrate decontamination of drinking water.

The leading trial experiment reported herein was conducted on a feed solution of 196.9 ppm NO_3 with system recovery up to 90% at a temperature of 30˚C. Pressure variations, module pressure difference (Δp) and pH of produced permeates during a typical CCD sequence of 90% recovery are displayed in Fig. 2(A) as function EC of recycled concentrate and in Fig. 2(B) as function of system recovery. The specific energy during said CCD sequence of 90% recovery is 0.418 kWh/m^3 of which 0.34 kWh/m^3 (81.3%) contributed by HP and 0.078 kWh/m^3 (18.7%) by CP, and the relatively high contribution of CP was due to its low efficiency (36.7%). The attainment of 90% recovery during said trial was confirmed by the NO_3 analysis of the final brine (2,105 ppm) as well as from the flow rates of feed and permeate during the CCD and PFD steps of the consecutive sequential process and the duration of each.

The build up of NO_3 (ppm) in the produced permeate during a typical CCD sequence of 90% recovery is essentially a function of nitrate content in the recycled concentrate because flux remains unchanged (37 lmh) throughout the entire process. Analytical data furnished in Fig. 3(A) reveals the NO_3 content in permeates as function of monitored EC of recycled concentrate, and likewise in Fig. 3(B) as function of system recovery up to 90%. The term "per step" in Fig. 3 and hereinafter stands for nitrate content in permeate generated at a specific salinity level (or EC instead) of recycled concentrate; whereas, the term "Sequence Average" applies to the calculated average data at a specific system recovery level by accounting to all the previous data points. In simple terms, permeates produced with 75, 80, 85, 87.5 and 90% recovery during the illustrated CCD trial at 30˚C starting with feed of 196.9 ppm NO_3 are 20, 28, 37, 45 and 62 ppm, respectively. The temperature corrected trial results at 20 and 25˚C furnished in Fig. 4(A) vs. EC of recycled concentrate and in Fig. 4(B) vs. system recovery, reveal even lower NO_3 values in permeates produced during the high recovery (90%) trial under consideration starting with a 196.9 ppm NO_3 feed source.

Nitrate decontamination procedures of drinking water are common for sources with $NO_3 \leq 100$ ppm, less common for sources of NO_3 in the range 100–150 ppm; and such a procedure for a source of 200 ppm NO_3 is exemplified herein for the first time. In order to allow meaningful comparison with existing nitrate decontamination procedures, the new BWRO-CCD technology was also tried with nitrate feed sources of 144 and 98 ppm NO_3 under the specified conditions described in the experimental section, and the NO_3 content in the produced permeates was determined analytically up to the recovery level of 90%. The experimental results of average NO_3 content in permeates received from feed sources of 98, 144 and 197 ppm NO_3 in the temperature corrected range 15–30˚C are furnished in Fig. 5. The data in Fig. 5 reveal that the BWRO-CCD Technology allows nitrate decontamination of drinking water with high recovery in full compliance with required/recommended level by the WHO [2] and the US EPA [1] even at a very high source contamination, well above the conventional level which is treated today.

The monitored NO_3 content in permeates vs. the NO_3 content in the recycled concentrate by the BWRO-CCD Technology enables us to determine the nitrate rejection ratio during the course of a CCD sequence in progress, and such data are presented in Fig. 6 for the extreme case of nitrate rejection from feed of 196.9 ppm NO_3. The rejection range displayed in Fig. 6 reveals ~96.5% rejection up to 63% recovery, a drop of $96.5 \rightarrow 95.2\%$ in the respective recovery range $63 \rightarrow 82\%$ and a further drop of $95.2 \rightarrow 94.0\%$ in the respective recovery range $82 \rightarrow 91\%$. The mean nitrate rejection of said feed solution above 63% recovery is therefore $95.2 \pm 1.3\%$. In contrast with the experimental findings, the predicted nitrate rejection under the same trial conditions with RE8040-BE440 elements is 99.7%

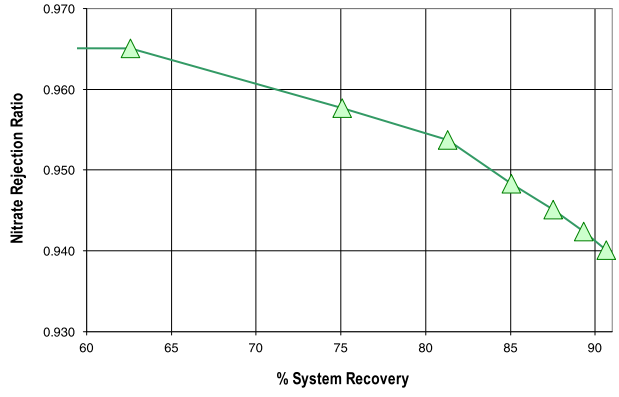


Fig. 6. NO_3 rejection ration vs. % recovery starting with 196.9 ppm NO_3 at 30˚C.

according to the CSM Design Program and similar high nitrate rejection values (>99%) are also predicated by the Design Programs of other membranes manufacturers. The low rejection of Boric acid and Nitrate through semi-permeable RO membrane is well established experimentally and membrane Design Programs should be updated in order to account for his feature, since nitrate is obviously not just another ion from the stand point of RO rejection.

The extensive experience already gained with the CCD technology [6–9] reveals that a single module (ME3) performance is easily expanded to any desired capacity by the modular design NxME3; wherein, N stands for the number of modules with their inlets and outlets connected in parallel. Module performance under CCD conditions is independent of N; therefore, a single module apparatus and plants comprising many such parallel modules should display the same performance charactereistics. Typical BWRO-CCD Units of 1,500 m^3/h (62.5 m^3/h) suitable for nitrate decontamination with 90% recovery using elements of 40 m^2 membrane area each should exhibit the design 14xME3 (37 lmh) or 10xME4 (39 lmh) with concentrate recycling means of 100 ± 10 m^3/h. The blending of permeate with source for an overall increased recovery represents an available option when the nitrate level in produced permeates is well below that of the desired blend. The expected low installation costs of high flux BWRO-CCD units, evident from their disclosed principle components, combined with the low fouling and bio-fouling characteristics of CCD, makes this approach for removing nitrates from drinking water noteworthy in particular from the economic point of view.

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