Nitrate Removal from Drinking Water in Iran – Assessment of Three Different Treatment Processes Based On Pilot-Scale Investigations

O. Dördelmann*, S. Panglisch*, F. Klegraf, F. Hell**, A. Moshiri***, A. Emami*** and W.H. Höll******

* IWW Institute for water research, Moritz Str. 26, 45476 Mülheim, Germany
** VA Tech WABAG, Siemens Str. 89, A- 1211 Vienna, Austria
*** Mashhad Water and Wastewater Co., Felestine 26 Str., Mashhad, Iran
**** Forschungszentrum Karlsruhe, 76344 Eggenstein-Leopoldshafen, Germany

Abstract Between 2004 and 2007 three pilot plants with different technologies for nitrate removal have been operated in Mashhad (Iran). The nitrate concentration in the groundwater was 115 mg/l and the water quality goal after treatment was 40 mg/l. The objectives of this study were: gaining experiences about the operation of the nitrate removal processes with regard to the specific conditions in Iran and evaluating the processes for decision-making concerning the most suitable treatment option for a full-scale nitrate removal plant in Mashhad. It was found that all three processes (Biological Denitrification, Reverse Osmosis (RO) and Ion Exchange) are capable to achieve the water quality goal. However, there are significant differences between these processes. Therefore, the treatment processes were assessed with regard to several aspects, e.g. effectiveness, stability, costs, drinking water quality, human resources and environmental impacts. An assessment scheme with five main criteria and individual weighting factors for these criteria was developed. Taking into account the local boundary conditions, Biological Denitrification and RO were assessed to be the most favourable treatment processes for being operated in Mashhad/Iran in the future. However, changing boundary conditions, e.g. higher energy prices or different weighting of assessment criteria may lead to different results.

Keywords Biological Denitrification, Drinking Water treatment, Ion Exchange, Nitrate Removal, Process Assessment, Reverse Osmosis

INTRODUCTION

In several middle-east countries including some places in Iran (e.g. Mashhad, Shiraz and southern parts of Tehran) high nitrate concentrations in groundwater have been detected. In most cases it is supposed that the high nitrate concentrations result from discharge of untreated wastewater and from agriculture. Mashhad is the 2nd largest city in Iran. It has a population of approx. 2.4 million people and a high population growth. Additionally, over 12 Million pilgrims per year come to Mashhad for visiting the holy shrine of Imam Reza, which is one of the holiest places for Shiite people. The city is located in north-eastern Iran in a dry area (~ 200 - 250 mm rainfall per year).

At present, the water consumption in Mashhad is approx. 190 Mio. m^3 per year and Mashhad's water supply mainly depends on groundwater sources. Mashhad water and wastewater Co. operates some 350 groundwater wells for drinking water supply. In some of these wells the nitrate concentrations are higher than 100 mg/l - sometimes even higher than 250 mg/l. Besides chlorination, currently there exists no groundwater treatment in Mashhad. Therefore, an international research project was initiated, funded by the Iranian Ministry of Energy & Water and the German Ministry of Education and Research (BMBF). Project partners were:

- Mashhad Water & Wastewater Company, Iran,
- Forschungszentrum Karlsruhe (Karlsruhe Research Centre), Germany,
- VA Tech Wabag, Germany,
- WETECH Institute, Hamburg, Germany
- IWW Institute for Water Research, Mülheim, Germany.

Between October 2004 and November 2007 three pilot plants, designed and constructed in Germany, were in parallel operation in Mashhad. The flow rates of the pilot plants were in the range of 1 – 3 m^3/h each. A team of Iranian, German and Austrian Engineers operated these plants. The three processes tested for nitrate removal in pilot-scale were:

- Biological Denitrification,
- Reverse Osmosis and
- Ion Exchange.

Additionally, starting from June 2007, a 4th pilot plant has been operated in Mashhad. This plant was equipped with Electrodialysis technology. However, at the time of writing this paper, there were still very few results from the Electrodialysis pilot plant and therefore this paper only focuses on the 3 technologies which were mentioned before.

The objectives of this research project were to gain experiences about the operation of the nitrate removal processes under the specific conditions of Iran (e.g. dry climate, supply of energy, chemicals and spare parts, education of staff). Furthermore it was intended to adapt, to optimize and to evaluate the processes. The findings of this research study should be used for decision-making concerning the most suitable treatment option for nitrate removal in Mashhad and for the subsequent planning of a full-scale drinking water treatment plant. The water quality goal for all processes was a nitrate concentration of 40 mg/l after treatment. Additionally all requirements of the drinking water guidelines by WHO (World Health Organization) should be met.

METHODS

In this chapter, at first the design and the operation of the three pilot plants will be described. Then the challenge water (ground water) will be characterized. Finally, the concept for assessment and rating of the processes will be illustrated.

Biological Denitrification pilot plant

The basics and general principles of Biological Denitrification in drinking water treatment were already described in the literature, e.g. by Kapoor et al. (1997), Overath (2000), Uhl et al. (2004) and WHO (2004). The biological pilot plant in Mashhad had 2 biological reactors which were operated downstream and in parallel at 1.5 bar. The flow rates could be varied from 0.5 to 3.0 m^3/h for each reactor. Expanded clay (Liapor®) with two different grain sizes (2-5 mm and 3-6 mm, respectively) was employed as growth material in the two reactors. An aqueous solution of acetic acid was dosed as electron donator into the feed of the pilot plant. Additionally ferrous sulfate and (di-sodiumhydrogen-) phosphate were dosed as nutrients. Within the bio-reactors the bacteria reduce nitrate to nitrogen, which means that the nitrate is really eliminated and not only separated. The bio-reactors were followed by a gas exchange (for nitrogen removal and addition of oxygen), a dual media filtration (filter stage 1) a second gas exchange and an activated carbon filtration (stage 2). From time to time the bio-reactors and the dual media filter had to be backwashed for removing biomass and reducing the differential pressure. The pilot plant did not have a disinfection stage because the effluent water was not used for drinking water purposes. However, a full-scale Biological Denitrification plant definitely requires a final disinfection stage. The biological pilot plant worked fully automated with automatic flushing and flow control. Several process data (e.g. nitrate concentrations, turbidity, differential pressures and flow rates) were measured and logged continuously. Besides online-measurement some 10 chemical parameters (e.g. DOC, pH, nitrite, oxygen) were analyzed daily on-site. Additionally the main cations and anions and microbiological parameters were analyzed weekly by the central laboratory of Mashhad Water and Wastewater Company. **Figure 1** shows the process scheme of the Biological Denitrification pilot plant.

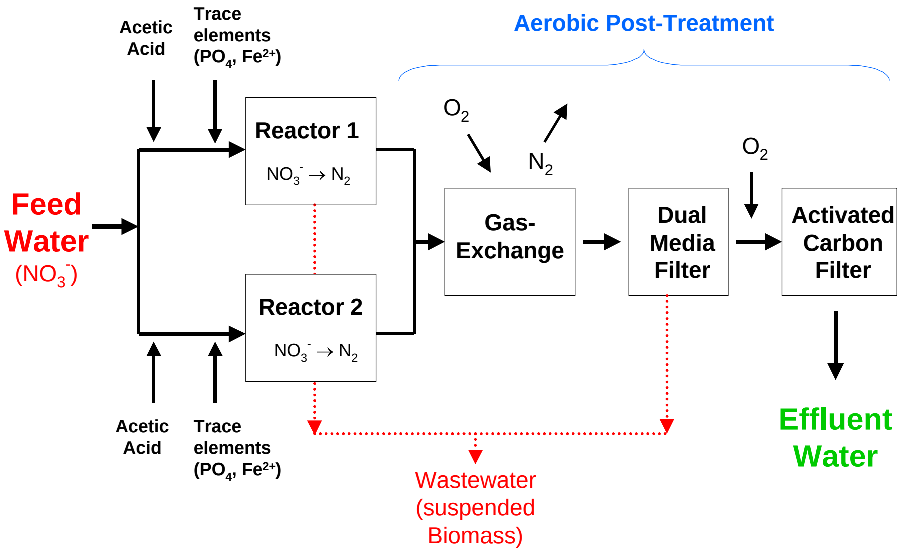

Figure 1 Process scheme of the Biological Denitrification pilot plant

Reverse Osmosis pilot plant

Reverse Osmosis (RO) is a drinking water treatment process which is wide-spread e.g. for seawater desalination. However, it can be employed for nitrate removal from groundwater as well. The basics and general principles of RO in drinking water treatment are comprehensively described in the literature, e.g. by: AWWA (2007). **Figure 2** shows the process scheme of the RO pilot plant. Its capacity was 3 m^3/h (RO permeate).

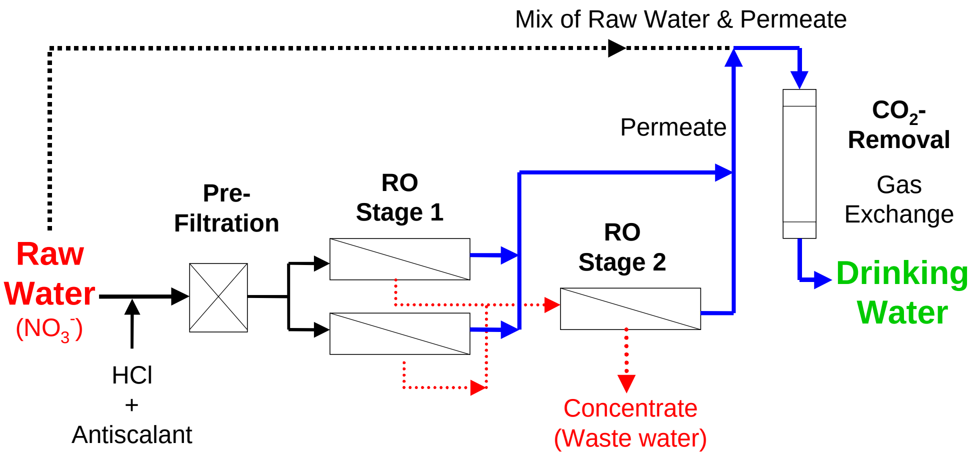

Figure 2 Process scheme of the RO pilot plant

After raw water intake and low pressure feed pump, hydrochloric acid and antiscalant were added to the feed water. Pre-filtration was conducted in 2 steps by a self cleaning automatic filter (50 µm) followed by a cartridge filter (1 µm). Then, a high pressure pump delivered the water for the two-stage RO system. The membranes modules (type SUL-G10) were supplied from Toray Industries Inc. After RO, the nitrate-free permeates of the two RO stages were merged and then mixed with a certain amount of nitrate-rich raw water so that the nitrate concentrate in the mixed water was approx. 40 mg/l. Finally the mixed water was trickled in a gas exchange column for reducing the carbon dioxide concentration (respectively raising the pH value) of the water. Besides raw water blending and gas exchange no further post-treatment stages were found to be necessary, because - apart from nitrate - the raw water did not contain considerable concentrations of toxic (trace) compounds. The RO pilot plant worked fully automatic and some 15 process parameters (including nitrate concentration and differential pressure) were measured and logged continuously. The chemical parameters to be analyzed at the RO pilot plant were almost similar to the biological pilot plant.

Ion Exchange pilot plant

Ion Exchange processes for nitrate removal are comprehensively described in the literature, e.g. by: Rohmann et al. (1985), Van der Hoek (1987), Clifford (1993 and 1999) and Höll (2006). In the Ion Exchange pilot plant the first treatment stage was a cartridge filter which removed turbidity and iron from the raw water. Then the water was pumped trough one of the two Ion Exchange columns (diameter: 0.4 m). These columns were filled with two different types of "nitrate-selective" resins and operated in parallel. The resins were:

- HP 555, manufactured by Rohm and Haas Company
- Ionac SR 7, manufactured by Sybron Chemicals Inc.

The resin bed depth was 1.6 m and the resin bed volume (BV) was approx. 200 liter in each column. The flow rates were varied between 1.0 and 3.0 m^3/h for each column, which is equivalent to a specific flow rate of 5 - 15 BV/h (Bed volumes per hour). In most of the experiments the flow direction during operation (service cycle) was upstream while regeneration was conducted in downstream, which means regeneration was counter-current.

The Ion Exchange pilot plant was equipped with a continuous measurement and registration of the nitrate effluent concentration of each column. Furthermore, flow rate, effluent pH and effluent conductivity of the spent brine solution were measured and recorded continuously. The pilot plant worked semi-automatic which means that the service cycle was stopped automatically when a certain nitrate effluent concentration was exceeded but the valve positions (e.g. for change between service and regeneration cycle) had to be changed manually.

Groundwater well and raw water composition

This pilot plant study was conducted at the "Golshar" pumping station in an eastern suburb of Mashhad. This groundwater well has a depth of 145 m and its water composition is more or less representative for other wells in this part of the city. During the time of this study the average nitrate concentration of the "Golshar" well water was about 115 mg/l. The electrical conductivity was about 1550 µS/cm and the pH value was about 7.2. Further parameters which characterize the raw water composition can be found later on in **table 2**.

Concept for Assessment of the treatment processes

For assessment of the three treatment processes several aspects were considered. Besides technical and financial considerations there were some other important aspects as well, e.g. the quality of drinking water after treatment. Therefore, during this study an assessment matrix was created which includes 5 main criteria. Every main criterion has some sub-criteria and each of them was rated on a scale from "+2" to "-2" in which the mark "+2" is used for very favourable and beneficial factors, "0" for neutral factors and "-2" for very unfavourable factors. By application of this procedure the five main criteria could be assessed in a transparent way. Finally, the results of the five main criteria were weighted as described in **Table 1**.

The most criteria were assessed on the basis of the results from the pilot plant investigations in Mashhad. For estimation of investment costs of full-scale treatment plants it was assumed that the basic design would be (almost) similar to the pilot plants, besides the fact that each full-scale treatment option included a final stage for disinfection.

Table 1 Main Criteria for assessment of the treatment processes for nitrate removal

Assessment criteria	Weighting factor
Effectiveness and stability of the process	25 %
Operation and investment costs	25 %
Drinking water quality after treatment	20 %
Required technical and human resources	10 %
Impacts on the environment during operation	20 %
Total	**100 %**

RESULTS AND DISCUSSION

This paper mainly focuses on the assessment of the three treatment processes (RO, Ion Exchange and Biological Denitrification) and on the assessment procedure itself. Further detailed results from the pilot plant experiments on nitrate removal in Mashhad were already published by Panglisch (2005) and Dördelmann (2006).

Effectiveness and stability of the treatment processes

All three treatment processes were found to be very effective for nitrate removal. However, Biological Denitrification is the only process which really eliminates the nitrate ions whereas the other two processes only separate the nitrate from the water and displace it into a wastewater stream (concentrate) which then has a very high nitrate concentration. Therefore, the nitrate removal of the biological process was rated as “+2” whereas the other two processes were rated as “+1”. Concerning the process stability the pilot plant experiments have shown that RO and Ion Exchange can be equally regarded as very stable processes (“+2”). The stability of the biological process was rated favourable as well (“+1”), although there is a (little) risk of instability due to the sensitivity of the biological system.

The process complexity of the Ion Exchange process is relatively low. Therefore it was rated positively (“+1”). RO and Biological Denitrification are more complex processes resulting in a neutral rating (“0”) for RO and a slightly negative assessment (“-0.5”) for the biological process.

While RO membranes surely are very effective for removal of other contaminants (e.g. trace compounds or bacteria) it has to be considered that the RO plant had a raw water bypass which is not treated by the RO membranes. Therefore, regarding the removal of other contaminants the RO treatment process is rated as “+1”. In contrast to RO the other two processes are potentially not effective for removal of other contaminants. Eventually some compounds may be reduced by a process (e.g. organic trace compounds during Biological Denitrification), but on the other hand for none of the two other processes a removal efficiency can be assured. The ratings on effectiveness and stability of the treatment processes are shown in **Table 5**.

Costs for investment and operation

One part of this study covered the estimation of capital (investment) and operating costs with regard to full-scale treatment plants. Therefore several options with different technologies and capacities (flow rates) were investigated. Apart from the plant size, the basic designs of the full-scale treatment plants were similar to the respective pilot plants. Additionally each full-scale treatment option included a final stage for disinfection. For calculation of the capital costs of the full-scale treatment plants a depreciation time of 10 years and an interest rate of 10 %/a were assumed. These are typical values for depreciation of investments goods in Iran at present. The estimated investment costs include the costs for process technology, electrical engineering and civil engineering. The specific operating costs are based on the results from the pilot plant investigations and include the local costs (in Iran) for chemicals, energy, maintenance, spare parts, wastewater (concentrate) discharge and labor. **Figure 3** shows the estimated capital and operating costs of the three treatment processes for nitrate reduction from 115 mg/l (feed) to 40 mg/l (effluent) at a flow rate of 1000 m^3/h.

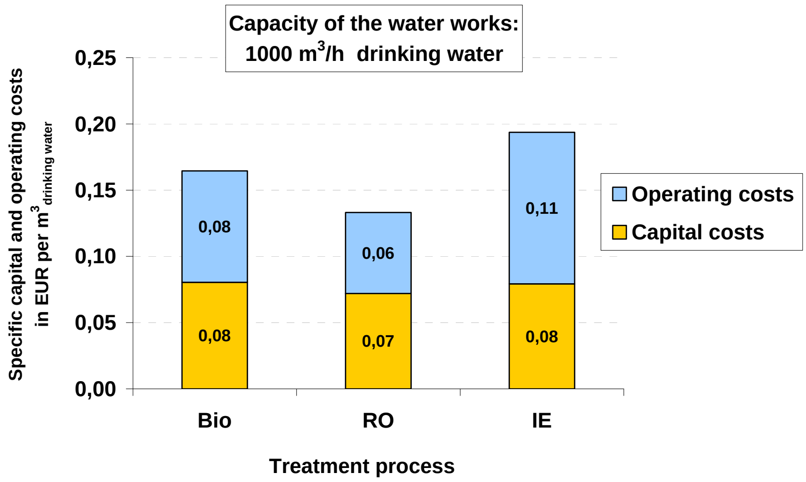

Figure 3 Estimated capital and operating costs of the three treatment processes for nitrate reduction in Iran

It can be seen that the capital costs of RO, Ion Exchange and Biological Denitrification process were estimated to be almost similar (ca. 8 ct/m^3). The operating costs of the three treatment processes were estimated to be in the range of 6 – 11 ct/m^3. Mainly due to its high costs for chemicals, the Ion Exchange process had the highest operating costs (11 ct/m^3). In this calculation the RO process was found to have the lowest operating costs (6 ct/m^3) although RO has the highest specific energy consumption of all three processes (ca. 0.6 kWh/$m^3_{\text{drinking water}}$). The relatively low operating costs of RO result from low costs for concentrate discharge and from an extremely low price for electrical energy in Iran (ca. 0.3 ct / kWh). Therefore, in countries which have higher (unsubsidized) energy prices the operating costs of the RO process would be significantly higher (ca. 10 ct/m^3). However, this study considered the current boundary conditions of Iran and the ratings of capital and operating costs are based on the values which were given in **Figure 3**. The results of these ratings are shown in **Table 5**.

Required technical and human resources

According to its title, this criterion focuses on human resources and technical resources: Other basic resources such as chemicals and energy were considered in the chapters on operation costs and environmental impacts.

The pilot plant experiments have shown that staff requirements of RO and Ion Exchange were almost similar and both processes require very qualified, experienced and reliable personnel. Although these 2 processes can be operated and controlled automatically, for a water works with 1000 m^3/h at least 1 very well educated engineer plus 3 mechanists or technicians plus 1 lab technician are necessary. Therefore, RO and Ion Exchange were attributed to be favorable ("+1") in terms of staff requirements. Biological Denitrification was found to be a process which requires more personnel due to increased efforts for maintenance. Therefore the staff requirement of the biological process was assigned to grade "0".

The demand for spare parts, its availability (in Iran) and the frequency of replacement is another important factor which influences the operation of a water treatment plant. The RO process needs membrane replacement approximately after 5 years, similar to the Ion Exchange process which has an expected resin lifetime of approximately 5 years as well. Both processes were assessed to be neutral (grade "0") in terms of this criterion because RO membranes and Ion Exchange resins can be purchased in Iran. The biological process was attributed more favourable (“+1”) because the intervals for changing the filter materials will probably be much longer.

Drinking water quality after treatment

For the assessment of this criterion the following sub-criteria were taken into account:

- Chloride concentration (Risk of Corrosion)
- TDS concentration
- Potential microbiological safety

The nitrate concentration was the most important parameter of this study. However, it was not considered for the rating of the processes in terms of water quality because all three treatment processes were able to meet the water quality goal of 40 mg/l. RO and Ion Exchange were capable to remove even more nitrate resulting in very low nitrate concentrations such as 10 mg/l in the RO permeate. Therefore, RO permeate and Ion Exchange effluents were mixed with a certain amount of raw water (ca. 25 %) so that the nitrate concentrations in the final waters of all three treatment processes were consistent (ca. 40 mg/l nitrate). Table 2 characterizes the main composition of the final waters after treatment and the raw water.

Table 2 Composition of raw water and final waters (after treatment and blending)

		Feed	**Biological plant**	**Ion Exchange**	**RO**
		(raw water)	effluent	effluent [1]	effluent [2]
Conductivity (20 °C)	µS/cm	1400	1378	1451	480
TDS	mg/l	975	960	927	307
pH	-	7,3	7,3	7,3	7,4
TOC	mg/l	0,9	0,5	0,7	0,7
Ca	mg/l	126	125	125	38
Mg	mg/l	41	40	41	12
Na	mg/l	99	99	99	34
K	mg/l	1,2	1,1	1	0
Cl	mg/l	168	176	261	53
NO_3	mg/l	**105**	**46**	**39**	**35**
SO_4	mg/l	140	140	67	41
HCO_3	mmol/l	4,8	5,5	4,8	1,6

[1] Average effluent sample (calculated from several single effluent analyses) - after blending with raw water (feed)

[2] After blending of RO permeate with raw water (feed)

It can be seen that the effluent waters of the three pilot plants had nitrate concentrations in the range of 40 mg/l whereas the nitrate concentration in the feed (raw water) was 105 mg/l. During the Biological Denitrification process - besides nitrate - no other inorganic parameters were reduced significantly but bicarbonate was increased. In opposite to that, the RO process reduced all inorganic parameters by ca. 70 %, compared to the feed water. Regarding the Ion Exchange process it can be seen that sulfate was reduced (besides nitrate) and that the chloride concentration was increased significantly.

The current WHO drinking water guideline does not recommend a health-based guideline value for chloride (WHO, 2006). However, concentrations of 250 mg/l and more may affect the taste of water adversely. Furthermore, the chloride concentration may strongly influence the corrosion properties of drinking water during its distribution. A high chloride concentration (such as 261 mg/l in the effluent of the Ion Exchange pilot plant) usually increases the corrosion risk of certain metallic materials in the distribution net and in housing installations. Therefore, the chloride

concentration of the Ion Exchange process was attributed to grade “-2”. The biological process was assessed to be neutral (“0”) as the chloride concentration in the effluent was similar to the raw water. In contrast to the two before mentioned processes, the chloride concentration after RO treatment was found to be more favourable (“+1”) because the chloride concentration in the final water (after blending with raw water) was still relatively low 53 mg/l.
The concentration of TDS (total dissolved solids) strongly influences the taste of water, which is one of the most important aspects with regard to the acceptance of water by the consumers. Water with a high TDS concentration (e.g. > 1000 mg/l) is likely to have a salty and unappetizing taste. Therefore, Ion Exchange and Biological Denitrification were rated as neutral (“0”) because these two processes do not affect the TDS significantly. In opposite, the RO process reduces TDS significantly, resulting in a favourable rating (“+1”).
Finally, the potential microbiological safety - before disinfection - was assessed. During this study dozens of microbiological investigations were performed, particularly focusing on the effluent quality of the biological pilot plant. Although the Biological Denitrification pilot plant did not have a disinfection stage, it was found that the bacterial counts in the plant’s effluent usually were not higher than in the feed water - mainly due to very effective post-treatment after the biological stage (Dördelmann, 2006). However, the Biological Denitrification stage (of a full-scale plant) potentially may be a risk with regard to undesirable microorganisms in the plant’s effluent (before disinfection) and therefore the microbiological safety of the biological treatment process was supposed to be slightly unfavourable (“-0,5”). Likewise, the potential microbiological safety of the Ion Exchange process was regarded as slightly unfavourable as well (“-0.5”), because under certain conditions Ion Exchangers may contribute to a microbiological contamination of water by promoting growth of undesirable microorganisms. For assessment of the potential microbiological safety of the RO process two important aspects have to be considered: a) the (advantageous) very good removal of microorganisms by the RO membranes and b) there is a 25 % raw water bypass which is not treated by the RO membranes. Therefore the potential microbiological safety the RO process was rated to be neutral (“0”).

Impacts on the environment during operation

This main criterion has the following sub-criteria

- Energy consumption
- Chemicals consumption
- TDS load of concentrate and spent brine
- Possibility for re-use of wastewater
- Increased raw water demand

Consumption of chemicals in water treatment plants generally is connected to complicated issues such as supply, handling, storage and operational safety. Furthermore, of course, it is a very important economic factor in terms of operational costs. **Table 3** gives an overview on the energy and chemicals demand of the three treatment processes.
The chemical demands of the three treatment processes are very different and it is difficult to compare them with each other. The RO process only requires about 24 tons of antiscalant per year, which is very favourable compared to the other processes. However, for ensuring a sufficient quality the antiscalant has to be imported to Iran. The chemicals demand of the RO process was evaluated as favourable (“+1”). For operation of the Biological Denitrification process ca. 530 tons acetic acid are required per year. This chemical is available in Iran at reasonable costs and in sufficient quality. Therefore, the chemical demand of the Biological Denitrification process was rated as neutral (“0”). In contrast to this, the chemical demand of the Ion Exchange process was assessed to be very unfavourable (“-2”) as it requires huge amounts of chemicals (about 5.500 tons

sodium chloride per year). Furthermore, the quality of the supplied salt was found to be insufficient due to a high fraction of insoluble components.

Table 3 Energy and chemicals demands (related to 1000 m3/h drinking water production)

		RO	Ion Exchange	Biological process
Specific energy demand *	kWh / m^3	0.6	0.1	0.15
Energy demand per year	Mio. kWh / a	5.3	0.9	1.3
Main chemicals for the treatment process	-	Antiscalant	Sodium chloride	Acetic Acid
Specific chemical demand *	kg / m^3	0.003	0.645	0.060
Demand of Chemicals per year	To / a	24	5650	526

* related to drinking water

The energy consumption of the Ion Exchange and the biological process are relatively low (ca. 0.1 kWh per m^3 of drinking water) and therefore rated as favourable (grade "+1"). The RO process requires significantly more energy which results in a less favourable rating ("-1").

The salt load (TDS load) of concentrate and brine resulting from the three treatment processes varies largely (**Table 4**).

Table 4 Wastewater characteristics (related to 1000 m3/h drinking water production)

		RO	Ion exchange	Biological process
Total Raw water demand	m^3/d	28800	25500	26000
Drinking water production	m^3/d	24000	24000	24000
Total waste water amount	m^3/d	4800	1500	2000
Wastewater ratio (related to drinking water)	%	20 %	6 %	8 %
Wastewater from pre- or post-treatment	m^3/d	300	300	2000
Re-use possible	-	yes *	yes *	yes *
Wastewater that can be re-used (related to drinking water)	%	1 %	1 %	8 %
Concentrate (brine) flow rate	m^3/d	4500	1200	0
Concentrate (brine) salt-concentration (TDS)	g/m^3	4700	21500	-
Salt load (TDS) due to discharge of concentrate (brine)	kg/d	21150	25800	-
Wastewater that can not be re-used - suitable disposal is required	%	19 %	5 %	**0 %**

* after removal of suspended solids (e.g. sedimentation) the water can be used for irrigation

With regard to TDS load of the concentrate, the most favourable process is Biological Denitrification because it creates no concentrate at all. Therefore it is assigned to grade "+2". The TDS load of the RO concentrate is about 21000 tons per year. Although this is a high amount, it has to be emphasized that this TDS load originates mainly from the raw water, due to desalination

of the drinking water. This means the salt load of the entire system (drinking water + concentrate) is not increased significantly by the RO process. However, the TDS load of RO concentrate is rated as unfavourable "-1". In contrast to RO the brine solution of the Ion Exchange process has a TDS load which is even higher. Furthermore, the TDS balance of the Ion Exchange process is extremely unfavourable because - in contrast to RO - during Ion Exchange there is no reduction of TDS in the drinking water (compared to the raw water). This means, the entire salt load of the brine solution results from the treatment process itself and the salt input into the environment is increased significantly. Therefore, the Ion Exchange process was assigned to grade "-2".
During RO and Ion Exchange the amount of wastewater that can be re-used (e.g. for irrigation) is almost similar: only about 1 % (related to the drinking water production). Therefore, these two processes are assigned to grade "-1". During application of the Biological Denitrification process almost the entire amount of wastewater (ca. 8 %) can be re-used. Therefore, in terms of wastewater re-usability the Biological Denitrification process is rated with mark "+2".
According to Table 4 the RO treatment process has the highest raw water demand, due to its high wastewater ratio (20 %). Therefore it is rated as grade "-2". The other two processes have an increased raw water demand in the range of 7 % and are therefore attributed to mark "0".

CONCLUSIONS

The three treatment processes for nitrate removal were assessed with regard to different criteria on a scale from "+2" (very favourable) to "-2" (very unfavourable). The results of this assessment are shown in **Table 5**.
With regard to effectiveness and process stability the three treatment processes (RO, Ion Exchange and Biological Denitrification) were assessed as favourable.
The specific costs for investment and operation of a full-scale treatment plant (1000 m^3/h) were estimated to 0.13 EUR per m^3 (for RO), 0.16 EUR / m^3 (for Biological Denitrification) and 0.19 EUR / m^3 (for Ion Exchange). Thus, the specific costs of an Ion Exchange treatment plant - particularly the specific operation costs- were rated as unfavourable whereas the other 2 processes were found to be neutral or slightly favourable in terms of investment and operation costs.
Concerning quality of the final water after treatment, RO was found to be the most favourable processes. The drinking water quality after application of Biological Denitrification was regarded as neutral. The water quality after Ion Exchange treatment was found to be unfavourable, mainly due to its increased chloride concentration which might raise the corrosion risk within the distribution net.
With regard to the required technical and human resources RO and Ion Exchange were assessed as favourable whereas Biological Denitrification was rated as neutral.
Finally, operation of RO and Ion Exchange treatment processes were assessed to have unfavourable impacts on the environment, mainly due to energy consumption, chemicals consumption and discharge of concentrated salt solutions. Only the Biological Denitrification process was regarded as favourable in terms of environmental impacts. Two important factors for the better result of the biological process were: a) in contrast to the other two processes, during Biological Denitrification there is no production of any concentrate (with high salinity) and b) almost the entire wastewater possibly can be re-used.

Table 5 **Summarized results from the assessment of the three treatment processes**

	Assessment criteria	Weighting factor	RO	IE	Biological process
Effectiveness and process stability	Process stability	30 %	2	2	1
	Nitrate removal	30 %	1	1	2
	Process complexity (Risk of technical difficulties)	30 %	0	1	-0,5
	Effectiveness for removal of other contaminants	10 %	1	0	0
	Total Rating of effectivness and process stability	**100 %**	**1,0**	**1,2**	**0,8**
Costs	Investment costs for process, electrical and civil engineering	50 %	0	0	0
	Operating Costs	50 %	0,5	-1,0	0
	Total Rating of investment and operating costs	**100 %**	**0,3**	**-0,5**	**0,0**
Final water quality (after blending)	Chloride concentration (Risk of Corrosion in the distribution net)	40 %	1	-2	0
	TDS concentration	40 %	1	0	0
	Potential microbiological safety (before final disinfection)	20 %	0	-0,5	-0,5
	Total Rating of final water quality	**100 %**	**0,8**	**-0,9**	**-0,1**
Technical & human resources	Staff requirements (manning level and qualification)	70 %	1	1	0
	Spare part demand / frequency for replacement	30 %	0	0	1
	Total Rating of technical and human resources requirements	**100 %**	**0,7**	**0,7**	**0,2**
Environmental impacts	Energy consumption	20 %	-1	1	1
	Chemicals consumption	20 %	1	-2	0
	TDS load of concentrate and spent brine	20 %	-1	-2	2
	Possibility for re-use of wastewater	20 %	-1	-1	2
	Increased raw water demand	20 %	-2	0	0
	Total Rating of environmental impacts	**100 %**	**-0,8**	**-0,8**	**1,0**
Assessment of the five main criteria	**Effectiveness and stability of the process**	25 %	1,0	1,2	0,8
	Operation and investment costs	25 %	0,3	-0,5	0,0
	Drinking water quality after treatment	20 %	0,8	-0,9	-0,1
	Required technical and human resources	10 %	0,7	0,7	0,2
	Impacts on the environment during operation	20 %	-0,8	-0,8	1,0
	Overall assessment	**100 %**	**0,4**	**-0,1**	**0,4**

Taking into account the boundary conditions of this study (e.g. water quality goals, extreme low costs for energy and low costs for concentrate discharge in Iran) and in consideration of the scheme for assessment of the treatment processes (**Table 1**), Biological Denitrification and RO were found to be the most favourable treatment processes for being operated in Mashhad/Iran in the future. However, it has to be emphasized that changing boundary conditions, e.g. higher energy prices or different assessment criteria and weighting factors may lead to different results.

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