

”Demonstration of High-performance Technologies, developed in Germany, for Nitrate Removal from Drinking Water in Iran”

- Final report of the BMBF research project No. 02WT0393 -

”Demonstration in Deutschland entwickelter Hoch- leistungsverfahren zur Entfernung von Nitrat aus Trinkwasser im Iran”

- Abschlussbericht zum BMBF-Forschungsvorhaben 02WT0393 -

Summary

Mashhad is the 2nd largest city in Iran (2.6 Mio people) and it is located in an arid zone in the north-eastern part of the country. Mashhad's water supply mainly depends on groundwater sources and particularly during summer time there is a water scarcity. In recent years, nitrate concentrations of several groundwater wells in Mashhad have increased significantly, up to values of around 150 mg/L. It is assumed that infiltration of untreated domestic wastewater is one of the main sources for the nitrogen input into the aquifer. The guideline value established by WHO (World Health Organization) for nitrate in drinking water is 50 mg/L.

During conventional drinking water treatment (e.g. sand filtration or flocculation) nitrate can not be removed, but there are some advanced treatment technologies which can be applied for nitrate removal. In Germany several of these treatment processes were successfully introduced into drinking water treatment. However, process selection and implementation at different operating conditions (e.g. in arid countries like Iran) is a very challenging task. It requires a lot of adaptation work, technological and scientific skills and large experience with the respective process. Therefore, this research project "Demonstration of High-performance Technologies, developed in Germany, for Nitrate Removal from Drinking Water in Iran" was initiated by the following institutions:

- German Ministry of Education and Research (BMBF)
- Mashhad Water & Wastewater Co. / Iranian Ministry of Energy & Water
- Karlsruhe Institute of Technology (formerly FZK), Germany
- VA Tech Wabag Co. Vienna (formerly Wabag Butzbach, Germany)
- WETECH Institute, Hamburg, Germany
- IWW Water Centre, Mülheim, Germany

The main objectives of this joint research project were as follows:

- Demonstration of high-performance processes developed in Germany for nitrate removal from groundwater in Iran
- Parallel operation and investigations of 4 different technologies in pilot-scale (water quality goal after treatment: 40 mg/L of nitrate)

- Gaining experiences about the nitrate removal processes under the specific conditions of Mashhad (e.g. dry climate, supply of energy and chemicals, education of staff)
- Adaptation and optimization of the processes
- Assessment of the processes with regard to their applicability in arid countries, such as Iran
- Evaluation for planning of a full-scale treatment plant

Pilot plant experiments - setup and results

Since October 2004 three pilot plants - Biological Denitrification, Reverse Osmosis (RO) and Ion Exchange (IE), designed and constructed in Germany, were in parallel operation at the “Golshar” pumping station in eastern Mashhad. In November 2006 a fourth pilot plant for nitrate removal was brought to Mashhad for investigation at the same site. This plant employed Electrodialysis technology (ED). A team of Iranian and German engineers operated these plants until the end of 2007.

All four pilot plants could be operated successfully in Mashhad and the treatment processes were effective for nitrate removal. The WHO guideline value was met as the nitrate concentration could be decreased from ca. 120 mg/L (feed) to 40 mg/L (effluent) or even less.

The Biological Denitrification pilot plant employed two fixed bed reactors operated parallel in downstream with acetic acid as substrate. The two reactors were filled with two different types of expanded clay, which worked as growth surface for the bacteria. In both reactors a reduction to less than 40 mg/L nitrate could be established for a long time. Due to effective post-treatment (aeration, dual media and activated carbon filtration) the water quality of the pilot plant’s effluent was good, as there were no nitrite, sulphide or ammonia detectable. Furthermore TOC, turbidity and bacterial count in the pilot plant’s effluent were low as well. The nitrate degradation rates of the reactors were about 7 kg NO₃ / m³ *d which is a high value, compared to other applications of Biological Denitrification in drinking water. The overall water demand for flushing the reactors and the dual media filter amounted to 7 % of the feed water.

The RO pilot plant (with two RO stages) contained a pre-treatment (pre-filtration, dosage and high pressure pumps), a gas exchanger (for carbon dioxide removal) and a mixing station (for blending RO permeate with a raw water bypass). During the

first 2.5 years of operation the pre-treatment included dosage of antiscalant and hydrochloric acid. The recovery rate of the RO membranes was successively increased to 85 %. Due to its low nitrate content (ca. 7 mg/L) the RO permeate was mixed with ca. 30 % raw water until the allowed nitrate level of 40 mg/L was achieved. By this procedure the overall recovery of the system could be increased to ca. 89 %. After 2.5 years of operation hydrochloric dosage was stopped in order to reduce the chemicals demand and the concerns in terms of occupational safety and environment. It was found that the RO system could be operated successfully without acid dosage. The flux of the RO system was 29 l/m² h in the first stage and 15 l/m² h in the second stage: The permeability was approx. 3.5 l/m²h*bar in the first stage and approx. 2 l/m²h*bar in the second stage. From the technical point of view the RO pilot plant worked very reliable and did not give any reason for complaint. Besides that, the RO process was capable to remove many other ions (and potential contaminants) so that the final water quality was very good.

The performance of the strong-base anion exchangers was affected by the relatively high sulfate concentrations in raw water. During experiments with so-called nitrate-selective anion exchangers the operating capacity resins varied between 0.14 and 0.26 eq/L_{Resin}, depending on the NaCl level during regeneration. Compared to other applications, these values are only moderate. Subsequent experiments with a conventional anion exchanger resulted in a slightly better operating capacity (0.32 eq/L_{Resin}). However, nitrate-selective resins might be a better choice because conventional resins bear the risk of elevated nitrate concentrations in drinking water, due to a so-called “chromatography effect”. A general disadvantage of the Ion Exchange process was the huge amount of NaCl which was needed in excess for regeneration of the ion exchanger. Taking into account the raw water composition of the “Golshar” well, a specific NaCl demand of ca. 0.7 kg/m³ drinking water was found. For a drinking water treatment plant with a capacity of 1000 m³/h this would result in an annual salt consumption of ca. 6000 tons. Furthermore, it was found that the supplied salt quality in Iran was not sufficient with regard to the high content of impurities. Due to the Ion Exchange process (uptake of nitrate and sulfate; release of chloride) the chloride concentration in the final drinking water increased to ca. 270 mg/L which can be disadvantageous with regard to corrosion problems in the distribution net. Additionally such a high chloride concentration may affect the taste of the water, giving cause for customer complaints.

The ED pilot plant was equipped with one ED stack (one stage) employing so-called nitrate-selective membranes. The experiments have shown that one ED stage was

not sufficient to achieve the desired nitrate level of 40 mg/L when the limit current and the design flow rate were observed. However, by operation of the ED plant in a batch mode, a 2-stage process was simulated and the nitrate concentration could be decreased to less than 40 mg/L. It became obvious that nitrate ions were preferred during the desalination process because the nitrate reduction rate was significantly higher than the reduction of conductivity and TDS. Unfortunately, the ED experiments were partly affected by a few technical problems, which were caused by some defect components of the pilot plant, such as measurement instruments and pumps. Apart from these defects, the ED process worked stable and reliable.

Estimation of capital and operating costs

In collaboration with VA Tech Wabag, capital and operating costs of all four treatment processes were estimated for different plant sizes (100, 360 and 1000 m³/h) in consideration of the specific boundary conditions of Iran. During evaluation of the operating costs it became obvious that in Iran the basic costs for labour, wastewater disposal and energy are significantly lower than in central European countries. Particularly the energy price is extremely low, due to the fact that in Iran electrical energy is strongly subsidized by the government. Figure A summarizes the results of the cost estimations.

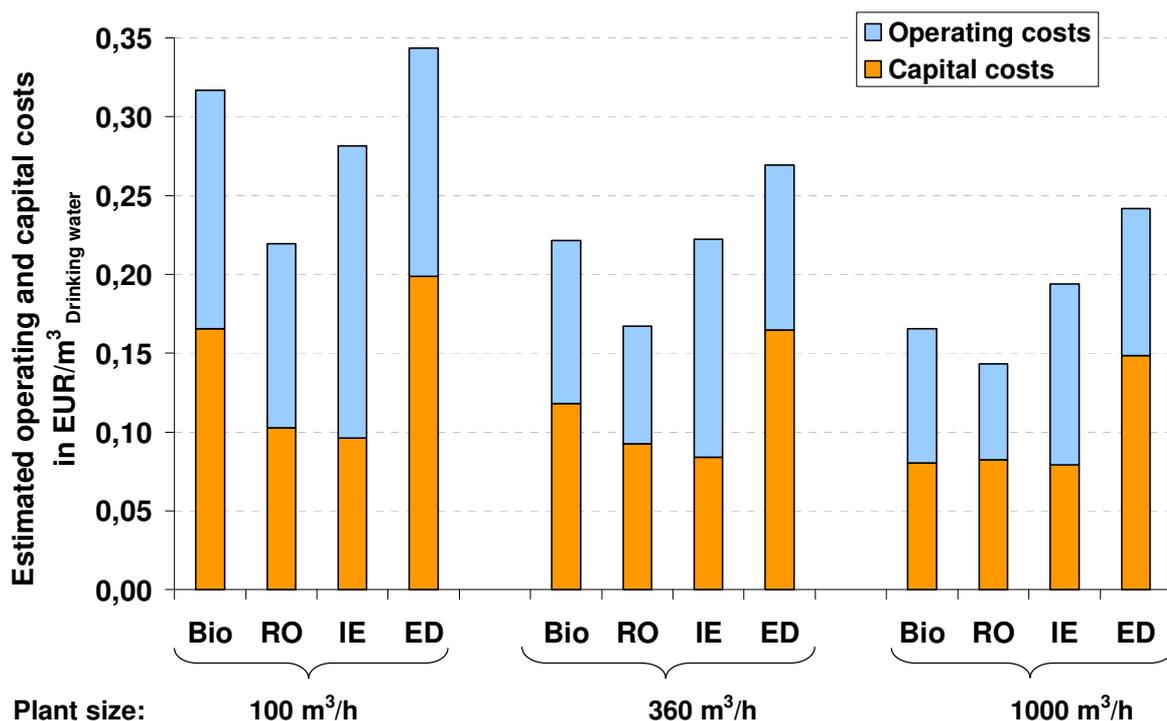


Figure A: Estimated Operating and capital costs of the four treatment processes

This final report also includes one chapter which focuses on the properties and disposal options for the wastewaters which result from the different treatment processes.

Assessment of the treatment processes

Besides the scientific goals, this project should also provide a transparent assessment of the treatment processes and a subsequent recommendation (for the Iranian water authorities) which technology would be most suitable for application in full-scale in Mashhad.

For assessment of the four different treatment processes several aspects had to be considered. The four treatment processes for nitrate removal were assessed on a scale from “+2” (very favourable) to “-2” (very unfavourable) with regard to the following main criteria:

- Effectiveness and stability of the treatment process
- Operating and investment costs
- Drinking water quality after treatment
- Required technical and human resources
- Impacts on the environment during operation

With regard to effectiveness and process stability all treatment processes (Biological Denitrification, RO, Ion Exchange and ED) were assessed as favourable. The assessment of the operating and investment costs refers to the costs which were estimated for a drinking water production of 1000 m³/h (see Figure A). Thus, the specific costs for Ion Exchange and ED were rated as unfavourable whereas Biological Denitrification and RO were found to be neutral or slightly favourable in this regard.

Concerning quality of the final water after treatment, RO was found to be the most favourable process, followed by ED. 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 slightly favourable whereas Biological Denitrification was rated as neutral.

Finally, operation of RO, Ion Exchange and ED 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 three processes, during Biological Denitrification there is no production of any concentrate (with high salinity) and b) almost the entire wastewater could be re-used, if suspended solids (biomass) are removed from this wastewater.

The results of the overall assessment (including the respective weighting factors) are shown in Table A.

Table A: Overall Ratings of the main criteria for assessment of the four treatment processes

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Assessment of the five main criteria	Effectiveness and stability of the process	25 %	0,8	1,0	1,2	1,0
	Operation and investment costs	25 %	0,0	0,3	-0,5	-1,0
	Drinking water quality after treatment	20 %	-0,1	1,0	-0,9	0,6
	Required technical and human resources	10 %	0,2	0,7	0,7	0,4
	Impacts on the environment during operation	20 %	0,9	-0,7	-0,7	-0,9
	Overall assessment	100 %	0,4	0,4	-0,1	0,0

Conclusions and recommendation of treatment processes

Taking into account the boundary conditions of this study (e.g. water quality goals, extreme low costs for energy) and in consideration of the scheme for assessment of the treatment processes (Table A), both Biological Denitrification and RO were found to be the most favourable treatment process 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.

Biological Denitrification is the only process which really eliminates the nitrate ions whereas the other three processes only separate nitrate from the water and displace it into a saline wastewater stream (concentrate or spent brine). This makes Biological Denitrification a favourable process with regard to its effectiveness for nitrate removal and with regard to the properties of its wastewater.

However, the RO process is more advantageous with regard to its process stability and the quality of the final drinking water. Furthermore, in the Middle East region (including Iran) there is much more experience concerning RO technology. Apart from the water experts in Mashhad, there is significantly less experience in the region concerning Biological Denitrification which would therefore require extremely good staff for operation.

Iranian-German co-operation in water technology and research

During this research project, water scientist, engineers and other water experts from Iran and Germany came together during numerous occasions, such as:

- Working visits of German water experts in Mashhad
- Working visits of Iranian water experts in Germany
- Presentations during international conferences and workshops
- Participation in international trade fairs in Germany and in Iran

Several publications, 2 posters and one film were produced about this research project. Besides many Iranian and German water specialists, there were water experts groups from other countries, e.g. one group from Syria who visited the pilot plants in Mashhad. Furthermore, one German Student did his master thesis in Mashhad about Electrodialysis.

The numerous activities between Iranian and German water experts have proven that this research project was a great success – not only in terms of scientific out-

comes. This project largely contributed to the development of a long-lasting and effective co-operation between Iran and Germany in the field of water technology and research.

For the future, there are several interesting ideas and new topics for joint research projects between Iran and Germany, e.g. on

- Integrated Water resources Management (IWRM) and on
- Arsenic and chromate removal from drinking water.

Both topics are very important and challenging, as they address problems (e.g. water scarcity and water contamination) which affect many people in Iran and several other countries in the world. A co-operation of German and Iranian water experts would be very helpful in order to overcome those problems and to continue the fruitful relationship between Germany and Iran in water affairs.

Besides personal contacts and scientific relations, it can be expected that the relationship between German and Iranian water industry will benefit from this research project as well. Mashhad Water and Wastewater Company stated that they intend to construct a full-scale drinking water treatment plant for nitrate removal within the next few years. If a new water works will be realized in Mashhad, this research project would probably become an economic success as well, because most likely German water companies would be involved in such a project.

Zusammenfassung (Deutsch)

Mashhad ist die zweitgrößte Stadt im Iran (2,6 Mio. Einwohner) und liegt in einer ariden Zone im Nordosten des Landes. Derzeit basiert die Wasserversorgung von Mashhad größtenteils auf Grundwasserressourcen und insbesondere in den Sommermonaten herrscht eine ausgeprägte Wasserknappheit. In den vergangenen Jahren sind die Nitratkonzentrationen zahlreicher Brunnen in Mashhad deutlich angestiegen, bis auf Werte um 150 mg/l und teilweise sogar noch darüber. Dieser Nitratanstieg hängt vermutlich vor allem damit zusammen, dass unbehandelte häusliche Abwässer in den Untergrund versickern, was zu einem starken Eintrag an Stickstoff in den Aquifer führt. Der von der Weltgesundheitsorganisation WHO festgelegte Richtwert für Nitrat im Trinkwasser beträgt 50 mg/l.

Mit einer konventionellen Trinkwasseraufbereitung, also z.B. Sandfiltration oder Flockung, wird kein Rückgang der Nitratkonzentration bewirkt. Jedoch gibt es einige weitergehende Aufbereitungsverfahren, die zur Nitratentfernung eingesetzt werden können. Mehrere dieser Verfahren wurden in Deutschland (weiter)entwickelt und sind erfolgreich in deutschen Wasserwerken im Einsatz. Die Auswahl und Implementierung eines bestimmten Verfahrens unter veränderten Randbedingungen, z.B. unter ariden Bedingungen wie im Iran, stellt eine große Herausforderung dar und erfordern in den meisten Fällen umfangreiche Anpassungsarbeiten. Neben technischen und wissenschaftlichen Fähigkeiten ist hierfür viel Erfahrung mit der jeweiligen Technologie erforderlich. Aus diesem Grund wurde das Forschungsprojekt „Demonstration in Deutschland entwickelter Hochleistungsverfahren zur Entfernung von Nitrat aus Trinkwasser im Iran“ unter Beteiligung der folgenden Institutionen initiiert:

- Bundesministerium für Bildung und Forschung (BMBF)
- Mashhad Water & Wastewater Company / Iranian Ministry of Energy & Water
- Karlsruhe Institute of Technology (Forschungszentrum Karlsruhe)
- VA Tech Wabag Co. Wien (ehemals Wabag Butzbach und Kulmbach))
- WETECH Institut, Hamburg
- IWW Zentrum Wasser, Mülheim

Die Hauptziele dieses Forschungsvorhabens waren:

- Demonstration von in Deutschland entwickelten Hochleistungsverfahren zur Nitratentfernung aus Trinkwasser im Iran
- Gleichzeitiger Betrieb und Untersuchungen an vier Versuchsanlagen mit unterschiedlichen Technologien zur Nitratentfernung, mit einem Zielwert von 40 mg/l im Reinwasser
- Aufbau von Erfahrungen und Kompetenzen über den Betrieb dieser Aufbereitungsprozesse unter den spezifischen Bedingungen des Iran (u.a. im Hinblick auf das aride Klima, die Qualifikation des Personals sowie die Versorgung mit Energie und Chemikalien)
- Anpassung und Optimierung der Aufbereitungsprozesse
- Bewertung der Verfahren hinsichtlich ihrer Einsetzbarkeit im Iran und anderen Ländern der Region
- Ermittlung von Basisdaten für die Planung einer zukünftigen Großanlage (Wasserwerk) zur Nitratentfernung in Mashhad

Konfiguration der Versuchsanlagen und Untersuchungsergebnisse

Im Oktober 2004 wurden drei zuvor in Deutschland gebaute Versuchsanlagen an der Pumpstation „Golshar“ in Mashhad in Betrieb genommen. Hierbei handelte es sich um die Verfahren Biologische Denitrifikation, Umkehrosmose (RO) und Ionenaustausch (IE). Im November 2006 traf eine vierte Versuchsanlage in Mashhad ein, die nach dem Verfahren der Elektrodialyse (ED) arbeitete. Ein Team aus iranischen und deutschen Ingenieuren hat diese Versuchsanlagen bis Ende 2007 betrieben.

Die vier Verfahren konnten erfolgreich in Mashhad betrieben werden und sie waren alle wirksam zur Nitratentfernung. Der WHO Richtwert für Nitrat konnte eingehalten werden. Die Nitratkonzentration wurde jeweils von ca. 120 mg/l im Zulauf auf 40 mg/l im Ablauf reduziert, teilweise waren sogar noch geringere Nitratkonzentrationen möglich.

Die Versuchsanlage zur Biologischen Denitrifikation enthielt zwei parallel angeordnete Festbettreaktoren, die im Abstrom mit Essigsäure als Substrat betrieben wurden. Die Reaktoren waren mit unterschiedlichen Arten von Blähton gefüllt, welcher als Aufwuchsfläche für die denitrifizierenden Bakterien diente. In beiden Reaktoren war eine langfristige Nitratreduktion auf Werte unter 40 mg/l möglich. Aufgrund der

sehr gründlichen Nachbehandlung (Belüftung, Mehrschichtfilter, Aktivkohlefilter) konnte eine gute Wasserqualität im Ablauf der Versuchsanlage erreicht werden. In der Regel waren weder Nitrit noch Sulfid oder Ammonium nachweisbar. Die TOC-Konzentration, die Trübung und die Koloniezahlen im Anlagenablauf waren ebenfalls sehr niedrig. Die Nitrat-Abbauraten der Reaktoren lag bei etwa $7 \text{ kg NO}_3 / \text{m}^3 \cdot \text{d}$, was ein sehr hoher Wert ist im Vergleich zu anderen Anwendungen im Trinkwasserbereich. Der Bedarf an Spülwasser für die Reaktoren und den anschließenden Mehrschichtfilter lag bei ca. 7 % des Rohwassers.

Die zweistufige RO Versuchsanlage enthielt eine Stufe zur Vorbehandlung (Vorfiltration, Dosierung, Hochdruckpumpe) einen Riesler zur Entfernung von CO_2 und eine Mischstation, in der RO Permeat mit Rohwasser verschnitten wurde. Während der ersten 2,5 Jahre Versuchsbetrieb wurden zur Vorbehandlung des Rohwassers Antiscalant und Salzsäure dosiert. Dabei wurde die Ausbeute der RO-Stufe sukzessive auf 85 % erhöht. Aufgrund der niedrigen Nitratkonzentration (ca. 7 mg/l) konnte das RO-Permeat mit ca. 30 % Rohwasser verschnitten werden, so dass die Nitratkonzentration im gemischten Reinwasser bei 40 mg/l lag, dem angestrebten Wert. Durch diese Beimischung von Rohwasser lag die Ausbeute der Versuchsanlage bei ca. 89 %. Nach 2,5 Jahren wurde schließlich versucht, auf die Säuredosierung zu verzichten, um a) den Chemikalienverbrauch und b) die damit verbundenen Bedenken hinsichtlich der Arbeitssicherheit und Umwelt zu verringern. Die Untersuchungen haben ergeben, dass - im Gegensatz zu vorherigen Berechnungen und Empfehlungen der Membranhersteller – auf eine Säuredosierung verzichtet werden kann. Die Fluxraten der ersten und zweiten RO Stufe betrugen 29 bzw. 15 $\text{l/m}^2 \text{ h}$. Die entsprechenden Werte für die Permeabilität lagen bei ca. $3.5 \text{ l/m}^2 \text{ h} \cdot \text{bar}$ (Stufe 1) und ca. $2 \text{ l/m}^2 \text{ h} \cdot \text{bar}$ (Stufe 2). Aus technischer Sicht arbeitete die RO-Versuchsanlage sehr gut und zuverlässig. Neben Nitrat war das RO-Verfahren auch in der Lage, zahlreiche andere Ionen - und somit potenzielle Kontaminationen – aus dem Wasser zu entfernen. Die resultierende Wasserqualität war sehr gut.

Die Leistung des Ionenaustauscherverfahrens wurde von der relativ hohen Sulfatkonzentration des Rohwassers beeinträchtigt. Bei Versuchen mit sogenannten „nitrat-selektiven“ Anionenaustauschern wurden nutzbare Kapazitäten zwischen 0,14 und 0,26 $\text{eq/l}_{\text{Harz}}$ ermittelt, was im Vergleich zu anderen Anwendungen nur mäßig ist. Eine etwas höhere nutzbare Kapazität von 0,32 $\text{eq/l}_{\text{Harz}}$ wurde bei anschließenden Versuchen mit einem konventionellen stark basischen Anionenaustauscher festgestellt. Trotzdem sind die nitrat-selektiven Harze möglicherweise zu bevorzugen, weil konventionelle Harze – unter ungünstigen Umständen – das Risiko einer überhöhten

Nitrat-Ablaufkonzentration aufweisen, ausgelöst durch einen sogenannten „Chromatographie-Effekt“. Der generelle Nachteil der diskutierten Ionenaustauschprozesse ist der große Bedarf an Salz, welches für die Regeneration der Austauscher im Überschuss benötigt wird. Für die Brunnenstation „Golshar“ wurde ein spezifischer Salzbedarf von 0,7 kg je Kubikmeter Trinkwasser ermittelt. Für ein Wasserwerk mit 1000 m³/h Aufbereitungsleistung wären demnach jährlich etwa 6000 Tonnen Salz erforderlich. Es wurde außerdem festgestellt, dass die im Iran verfügbare Salzqualität wegen des hohen Anteils an unlöslichen Stoffen für eine direkte Verwendung zur Regeneration unzureichend war. Aufgrund des Ionenaustauschs (Aufnahme von Nitrat und Sulfat, Abgabe von Chlorid) erhöhte sich die Chloridkonzentration im Trinkwasser auf ca. 270 mg/l, was nachteilig im Hinblick auf die Korrosionseigenschaften des Wassers ist. Außerdem könnte eine so hohe Chloridkonzentration zu geschmacklichen Beeinträchtigungen und somit zu Reklamationen seitens der Verbraucher führen.

Die ED Versuchsanlage enthielt ein ED-Stack (einstufig) mit sogenannten nitratselektiven Membranen. Die Untersuchungen ergaben, dass mit einer ED Stufe die gewünschte Nitratkonzentration von 40 mg/l nicht erreicht werden konnten, wenn der maximal zulässige Grenzstrom und der Nenndurchfluss eingehalten wurden. Der Nitrat-Zielwert konnte jedoch eingehalten werden, wenn an der Versuchsanlage mittels Chargenbetrieb ein zweistufiger Prozess simuliert wurde. Die Ergebnisse haben gezeigt, dass durch den ED Prozess Nitrat-Ionen bevorzugt entfernt wurden, denn die Nitrat-Eliminationsrate lag deutlich über dem entsprechenden Wert für den Rückgang der Leitfähigkeit bzw. dem Gesamtsalzgehalt. Leider traten während des Betriebs der ED-Anlage an einigen Komponenten Defekte auf, was die Untersuchungen teilweise beeinträchtigte. Abgesehen von diesen Defekten, arbeitet der ED-Prozess jedoch stabil und zuverlässig.

Abschätzung der Betriebs- und Investitionskosten

Die Abschätzung der Betriebs- und Investitionskosten erfolgte in Zusammenarbeit mit VA Tech Wabag für verschiedene Anlagengrößen und unter Berücksichtigung der Bedingungen im Iran. Dabei wurde deutlich, dass im Iran die Basiskosten für Personal, Abwasserentsorgung und Energie erheblich niedriger sind als in Mitteleuropa. Insbesondere die Energiekosten sind aufgrund von staatlichen Subventionen extrem gering. In Bild A sind die Ergebnisse der Kostenschätzungen dargestellt.

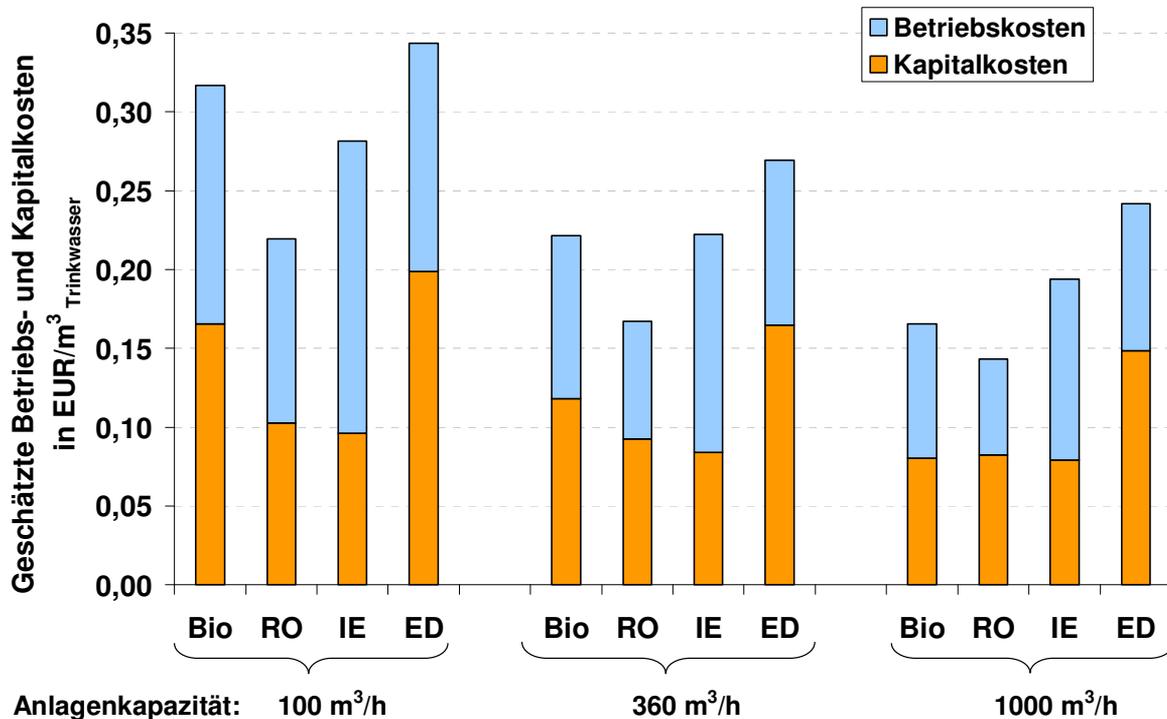


Bild A: Geschätzte Betriebs- und Kapitalkosten für die vier Verfahren

Ein Kapitel dieses Abschlussberichts beschäftigt sich mit der Charakterisierung und den Möglichkeiten zur Entsorgung bzw. Wiederverwendung der Abwässer, die bei den verschiedenen Aufbereitungsverfahren entstehen.

Bewertung der Aufbereitungsverfahren

Neben den wissenschaftlichen Untersuchungen sollten im Rahmen dieses Projekts die Aufbereitungsverfahren verglichen und nach transparenten Kriterien bewertet werden, um schließlich eine Empfehlung abzugeben, welches Verfahren am besten dazu geeignet ist, im großtechnischen Maßstab in Mashhad umgesetzt zu werden.

Für die Bewertung mussten zahlreiche unterschiedliche Aspekte berücksichtigt werden. Die folgenden Kriterien wurden schließlich festgelegt und auf eine Skala von "+2" (sehr vorteilhaft) bis "-2" (sehr nachteilig) bewertet:

- Wirksamkeit und Stabilität des Aufbereitungsverfahrens
- Betriebs- und Investitionskosten
- Wasserqualität am Ende der Aufbereitung
- Benötigtes Personal und technische Ressourcen
- Umweltauswirkungen der Verfahren (während des Betriebs)

Alle vier Aufbereitungsverfahren (Biologische Denitrifikation, RO, IE und ED) wurden positiv bezüglich ihrer Wirksamkeit und Stabilität bewertet. Die Bewertung der Betriebs- und Kapitalkosten bezog sich auf eine Aufbereitungsleistung von 1000 m³/h (Bild A). Die spezifischen Kosten für Ionenaustausch und ED wurden als negativ bewertet, wohingegen Biologische Denitrifikation und RO als neutral bzw. leicht positiv bewertet wurden.

Im Hinblick auf die Wasserqualität am Ende der Aufbereitung wurde das RO-Verfahren am positivsten bewertet, gefolgt vom ED-Verfahren. Die Wasserqualität nach der Biologischen Denitrifikation wurde als neutral beurteilt. Im Gegensatz dazu wurde die Wasserqualität nach dem Ionenaustauscherverfahren als unvorteilhaft angesehen, hauptsächlich aufgrund der erhöhten Chloridkonzentration, welche das Korrosionsrisiko in metallischen Verteilungsnetzen erhöhen kann.

Bezüglich des benötigten Personals und der technischen Ressourcen wurden RO und Ionenaustausch als leicht positiv und die Biologische Denitrifikation als neutral bewertet.

Den Verfahren RO, Ionenaustausch und ED wurden während des Betriebs negative Auswirkungen auf die Umwelt attestiert, hauptsächlich wegen ihres Energie- und Chemikalienverbrauchs sowie des Anfalls von stark salzhaltigen Abwässern, die entsorgt werden müssen. Lediglich das Verfahren der Biologischen Denitrifikation wurden hinsichtlich der Umweltauswirkungen positiv bewertet, vor allem deshalb, weil a) bei der Bio-Deni - im Gegensatz zu den anderen 3 Verfahren - kein salzhaltiges Konzentrat anfällt und b) weil praktisch das gesamte Abwasser (Rückspülwasser) wiederverwendet werden könnte, nachdem die absetzbaren Stoffe (Biomasse) entfernt worden sind.

Tabelle A zeigt die Ergebnisse der Bewertung inklusive der Gewichtungsfaktoren.

Tabelle A: Bewertung der Hauptkriterien zur Beurteilung der vier Aufbereitungsverfahren

	Bewertungskriterien	Gewichtungsfaktor	Bio	RO	IE	ED
Bewertung der fünf Hauptkriterien	Wirksamkeit und Stabilität der Verfahren	25 %	0,8	1,0	1,2	1,0
	Betriebs- und Investitionskosten	25 %	0,0	0,3	-0,5	-1,0
	Trinkwasserqualität nach Aufbereitung	20 %	-0,1	1,0	-0,9	0,6
	Benötigtes Personal und technische Ressourcen	10 %	0,2	0,7	0,7	0,4
	Umweltauswirkungen während des Betriebs	20 %	0,9	-0,7	-0,7	-0,9
	Gesamtbewertung	100 %	0,4	0,4	-0,1	0,0

Schlussfolgerungen und Empfehlungen bzgl. der Aufbereitungsverfahren

Unter Berücksichtigung des vorliegenden Bewertungsschemas (Tabelle A) und der Randbedingungen dieser Studie (u.a. Wasserqualitätsziele, extrem niedrige Energiepreise) wurden die Verfahren Biologische Denitrifikation und RO als die am besten geeigneten Verfahren ermittelt, welche zukünftig in Mashhad/Iran eingesetzt werden können. Es muss aber betont werden, dass veränderte Randbedingungen (z.B. höhere Energiepreise, andere Bewertungskriterien/Gewichtungsfaktoren) zu einem anderen Ergebnis führen können.

Die Biologische Denitrifikation ist das einzige Verfahren, das Nitrat tatsächlich eliminiert, wohingegen die anderen drei Verfahren das Nitrat lediglich abtrennen und in einen salzhaltigen Abwasserstrom überführen. Dieser Umstand macht die Biologische Denitrifikation zu einem vorteilhaften Verfahren hinsichtlich seiner Wirksamkeit zur Nitratentfernung und der Eigenschaften des Abwassers.

Andererseits ist das RO Verfahren vorteilhaft angesichts seiner hohen Prozessstabilität und der sehr guten Wasserqualität. Im Mittleren Osten (inkl. Iran) ist mehr Erfahrung und Kompetenz bezüglich der RO Technologie vorhanden, wohingegen es - abgesehen von den Wasserexperten in Mashhad - in der gesamten Region deutlich weniger Erfahrungen mit der Biologischen Denitrifikation gibt. Aus diesem Grund würde für den Betrieb einer Anlage mit Biologischer Denitrifikation extrem gutes Personal benötigt.

Deutsch-Iranische Kooperation im Bereich Wassertechnologie und Forschung

Während dieses Forschungsvorhabens gab es zahlreiche Anlässe, bei denen Wasserforscher, Ingenieure und andere Wasserfachleute aus Iran und Deutschland zusammen gekommen sind. Anlässe waren beispielsweise:

- Arbeitsbesuche von deutschen Wasserfachleuten in Mashhad
- Arbeitsbesuche von iranischen Wasserfachleuten in Deutschland
- Vorträge auf internationalen Konferenzen und Workshops
- Teilnahme an internationalen Fachmessen in Iran und Deutschland

Über dieses Forschungsvorhaben wurden bereits zahlreiche Veröffentlichungen, zwei Poster sowie ein Film erstellt. Neben vielen iranischen und deutschen Wasserfachleuten gab es auch einige Besuchergruppen aus Drittländern, z.B. eine Expertengruppe aus Syrien, die die Versuchsanlagen in Mashhad besichtigt haben. Zusätzlich hat ein deutscher Student seine Masterarbeit in Mashhad über die Untersuchungen zur Elektrodialyse angefertigt.

Die zahlreichen gemeinsamen Aktivitäten von deutschen und iranischen Wasserexperten belegen, dass dieses Forschungsvorhaben nicht nur in wissenschaftlich-technischer Hinsicht ein Erfolg war. Gleichzeitig hat dieses Projekt entscheidend dazu beigetragen, die Zusammenarbeit zwischen Deutschland und Iran im Bereich Wassertechnologie und Forschung weiter zu entwickeln und zu verbessern.

Es gibt mehrere interessante Ideen und neue Themen für zukünftige, gemeinsame Forschungsprojekte, u.a.

- Integriertes Wasserressourcen Management (IWRM)
- Arsen- und Chromatentfernung aus Trinkwasser

Beide Themen sind sehr wichtig und stellen eine große Herausforderung dar, weil sie Probleme ansprechen (u.a. Wasserknappheit, Verunreinigungen von Wasser durch Spurenstoffe), die zahlreiche Menschen im Iran und vielen anderen Ländern in der Welt betreffen. Eine weitere Zusammenarbeit von deutschen und iranischen Wasserfachleuten wäre einerseits sehr hilfreich, um bei der Lösung dieser Probleme mitzuwirken und andererseits könnte die erfolgreiche Beziehung im Wasserbereich zwischen Deutschland und Iran weiter ausgebaut werden.

Es ist zu erwarten, dass neben persönlichen Kontakten und wissenschaftlichen Beziehungen auch die deutsche und die iranische Wasserindustrie von diesem Forschungsvorhaben profitieren werden. Mashhad Water and Wastewater Company hat mitgeteilt, man wolle in den nächsten Jahren eine großtechnische Aufbereitungsanlage zur Nitratentfernung in Mashhad realisieren. Falls eine solche Anlage umgesetzt wird, würden sehr wahrscheinlich auch deutsche Firmen daran beteiligt sein. Insofern wäre das Forschungsvorhaben dann auch in wirtschaftlicher Hinsicht ein Erfolg.

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List of Abbreviations

BMBF	German Federal Ministry of Education and Research
BV	Bed Volumes
CIP	Cleaning in Place
DIN EN	International Standards (e.g. for materials and methods)
DOC	Dissolved Organic Carbon
DWTP	Drinking Water Treatment Plant
ED	Electrodialysis
EU	European Union
IE	Ion Exchange
IFAT	International trade fair on Water technology (in Munich)
IWA	International Water Association
IWE	International trade fair on Water technology (in Tehran)
HCl	Hydrochloric Acid
HPC	Heterotrophic Plate Count (a microbiological method)
KfW	Kreditanstalt für Wiederaufbau (German Development Bank)
LP RO	Low Pressure Reverse Osmosis
MCL	Maximum Contamination Level
MWWC	Mashhad Water and Wastewater Company
NaCl	Sodium Chloride
PLC	Programmable Logic Controller
RCUWM	Regional Centre on Urban Water Management (in Tehran)
RO	Reverse Osmosis
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
US-EPA	Environmental Protection Agency in the United States
WHO	World Health Organisation
WWTP	Waste Water Treatment Plant

1 Introduction

1.1 Background

1.1.1 Nitrate situation and water supply in Mashhad

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. 2.5 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 a dry area (~ 200 - 250 mm rainfall per year) in north-eastern Iran.



Figure 1: Map of Iran (source: www.yahoo.com)

At present, the water consumption in Mashhad is approx. 190 Mio. m³ per year and Mashhad's water supply mainly depends on groundwater sources. The responsible authority, Mashhad Water and Wastewater Co. (MWWC) 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.

In recent years nitrate concentrations of several groundwater wells in Mashhad have increased. It is assumed that infiltration of untreated domestic wastewater is one of the main sources for the nitrogen input into the aquifer. In the past, traditionally most of the domestic wastewater was drained directly into the ground (without treatment), and there was (almost) no sewer system. However, in recent years considerable efforts have been taken for improving the situation of wastewater collection and treatment in Mashhad. Nowadays there are 4 wastewater treatment plants (WWTP) in and outside of Mashhad. Simultaneously to the improvement and extension of the sewer network, the capacity of the WWTPs is going to be extended.

1.1.2 Properties and sources of nitrate

Nitrate is one of the main compounds of the global nitrogen cycle (**Figure 2**). Nitrate is highly soluble in water and very mobile in the underground (Aquifer). The nitrate ion (NO_3^-) is chemically very stable. However, under certain conditions bacteria are able to reduce nitrate to nitrite (NO_2^-) or nitrogen (N_2). This bacterial process is called "Denitrification". Nitrate can not be removed by conventional drinking water treatment (e.g. filtration or flocculation).

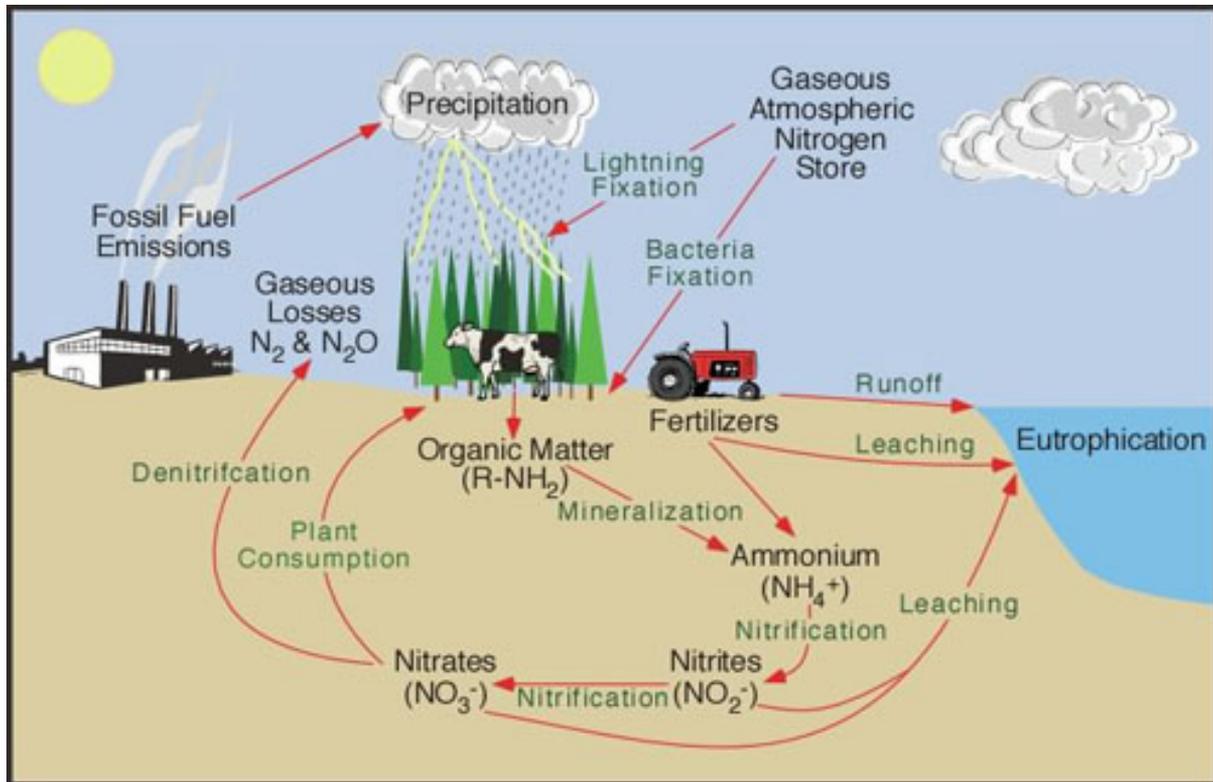


Figure 2: The global nitrogen cycle (Source www.physicalgeography.net)

A high nitrate concentration in water in most cases is an indicator for man-made (“anthropogenic”) pollution. This can be for example:

- discharge of waste water
- excessive use of fertilizers

According to Mutschmann / Stimmelmayer (2003) nitrate concentrations in unpolluted waters normally are below 10 mg/L but in some cases nitrate concentrations can be “naturally” increased, depending on soil type and geological situation. However, nitrate concentrations higher than 20 mg/L in most cases indicate an anthropogenic impact (e.g. agriculture or wastewater) on the groundwater or river water quality.

1.1.3 Toxicological and nutrition aspects of nitrate

According to information of World Health Organization (WHO, 2003) the primary toxicity of nitrate is low. However, in the stomach of infants nitrate can be reduced to nitrite by gastric bacteria. As a consequence of this, the secondary toxicity of nitrate has to be considered: Nitrite is able to react with haemoglobin (Hb) which is respon-

sible for oxygen transport in the human blood. This can lead to “blue-baby syndrome” (Methaemoglobinaemia, Cyanosis), affecting mainly babies of less than 3 month.

There is a tertiary toxicity of nitrate: Under certain conditions nitrite (and secondary amines) can react to N-nitroso-compounds which are also known as nitrosamines. Principally this reaction could also happen in the stomach of humans. However, it is still unclear (and under controversial discussion) if this process affects human health in terms of stomach cancer or not (WHO, 2003).

The amount of nitrate and nitrite in human nutrition is only partly based on the intake of drinking water. According to WHO information, vegetables and cured meat are the main sources of total nitrate intake when nitrate concentration in drinking water is lower than 10 mg/L. In opposite to this, drinking water is supposed to be the main source of total nitrate intake when nitrate concentration in drinking water is higher than 50 mg/L. Furthermore WHO assesses cured meat as the main source of total nitrite intake in most cases.

1.1.4 Drinking water quality standards

There are various drinking water quality standards all over the world, for example:

- WHO Guidelines for Drinking-water Quality (WHO, 2006)
- EU European Drinking Water Directive
- US-EPA National Drinking Water Standards

The WHO Guideline for Drinking-water Quality in the first instance is only a recommendation and not an international law. However, most developed countries usually adopt the WHO recommendations into their national drinking water quality standards. Table 1 gives an overview about limit values (and guideline values) for nitrate and nitrite in different countries.

Table 1: Limit values for nitrate and nitrite in drinking water

in mg/l	WHO	EU	US-EPA
NO₃	50 *	50	44
NO₂	3 *	0,5	3

* WHO Values relevant for **short** term exposure
(0,2 mg/l NO₂ relevant for **long** term exposure)

The Iranian limit values for nitrate and nitrite in drinking water correspond with the WHO guideline values.

1.2 Strategies against high nitrate concentrations

In case of high nitrate concentrations in groundwater there are several options which may contribute to solve the problem.

1. Reducing the amount of fertilizers and liquid manure in agriculture
2. Improvement of the sewer system and advanced wastewater treatment (nitrogen elimination)
3. Use of different drinking water resources, e.g. deeper wells, surface water
4. Advanced drinking water treatment

Although option 1 in most cases is an advisable and sustainable method it has to be considered that it usually becomes effective only in the long-term (e.g. > 10 years), before a significant decrease of nitrate concentration in groundwater can be observed. Option 2 also takes a long time and additionally the technical and financial efforts have to be considered. Different water resources (Option 3) in some cases do not exist. Moreover experiences from many places in Germany have shown that deeper wells (Option 3) sometimes are only a mid-term solution because then the trace of nitrate proceeds to deeper groundwater levels. Thus, in some cases advanced drinking water treatment is the only option which can be chosen to reduce the nitrate concentration in drinking water.

At present there are four state-of-the-art processes which can effectively reduce nitrate concentrations in drinking water treatment:

- Biological Denitrification
- Ion Exchange
- Reverse Osmosis
- Electrodialysis

The basic principles of the four nitrate removal processes will be given in chapter 2.

Generally it can be said that none of the process is THE best process for nitrate removal. Comparison, assessment and selection of the treatment processes are very complicated tasks which mainly depend on the boundary condition of the application.

1.3 Nitrate removal project in Mashhad

Due to the serious nitrate problems in Mashhad, an international research project was initiated, funded by the Iranian Ministry of Energy & Water and the German Ministry of Education and Research (BMBF). Further project partners were:

- Mashhad Water & Wastewater Company (MWWC) Iran,
- Karlsruhe Institute of Technology (formerly FZK), Germany,
- VA Tech Wabag Co., Germany,
- WETECH Institute, Hamburg, Germany and
- IWW Water Centre, Mülheim, Germany.

Since October 2004 three pilot plants, designed and constructed in Germany, were in parallel operation in Mashhad. A team of Iranian and German Engineers operated these plants until the end of 2007. The three processes tested for nitrate removal in pilot scale were:

- Biological Denitrification
- Ion Exchange
- Reverse Osmosis

In November 2006 a 4th pilot plant for nitrate removal was brought to Mashhad for investigation at the same site. This plant employed Electrodialysis technology (ED).

The main objectives of this joint research project were as follows:

- Demonstration of high-performance processes developed in Germany for nitrate removal from groundwater in Iran
- Parallel operation and investigations of 4 different technologies in pilot-scale (water quality goal after treatment: 40 mg/L of nitrate)
- Gaining experiences about the nitrate removal processes under the specific conditions of Mashhad (e.g. dry climate, supply of energy and chemicals, education of staff)
- Adaptation and optimization of the processes
- Assessment of the processes with regard to their applicability in arid countries, such as Iran
- Evaluation for planning of a full-scale treatment plant

Besides the nitrate goal, all requirements of the drinking water guidelines by WHO (World Health Organization) should be met.

2 Basic principles of the nitrate removal processes

2.1 Biological Denitrification

In this anoxic process denitrifying bacteria reduce nitrate to nitrogen by the following equation:



For this reduction process a substrate or “electron donator” [H] is required. In so-called “autotrophic” denitrification processes the bacteria use inorganic compounds (e.g. CO₂ and hydrogen) as an electron donator, whereas in heterotrophic denitrification the bacteria use organic compounds. Due to very low concentrations of these compounds in drinking water treatment the denitrification process usually can only be operated when one of the above mentioned substrates is added to the water (e.g. by dosing acetic acid or ethanol). If acetic acid is used as electron donator, the Biological Denitrification proceeds as follows (Rohmann and Sontheimer, 1985):



In drinking water treatment different processes are applied for Biological Denitrification and several plants are operating in full scale, mainly in Germany (Overath, 2000) and France. In most of these processes after substrate dosage the feed water flows through a fixed bed reactor. In this reactor an inert material acts as surface for bacterial growth. Typical materials for fixed bed reactors are anthracite, activated carbon, sand, expanded clay and organic polymers (e.g. polystyrene). The grain sizes of these materials vary in a wide range and depend on the operating conditions of the reactor. Some processes are operated in upstream, others in downstream (Uhl and Overath, 2004).

During the denitrification process the amount of biomass on the surface material grows and the differential pressure of the reactor increases. Thus, in most processes the reactor has to be backwashed or flushed from time to time. There are some other processes tested in full scale, in which a certain amount of surface material is discharged continuously and then backwashed outside of the reactor, before it is transferred back to the process. Nitrate degradation rates between 0.1 and 5.5 kg NO₃/m³·d are reported in the literature for full scale plants (Sonnenburg and Urban, 2005).

It has to be mentioned that any Biological Denitrification process applied in drinking water treatment needs a very effective post-treatment downstream of the biological stage for the following purposes:

- removal of substrate residual
- gas exchange
- particle removal (filtration) and
- disinfection

2.2 Reverse Osmosis (RO)

Reverse Osmosis (RO) is a wide spread water treatment process which is traditionally used for seawater desalination. It is a pressure driven membrane process in which the majority of the feed water passes through the membrane, the rest is discharged along with the rejected salts as concentrate (**Figure 3**). For most RO applications the pressure varies between 10 and 100 bar.

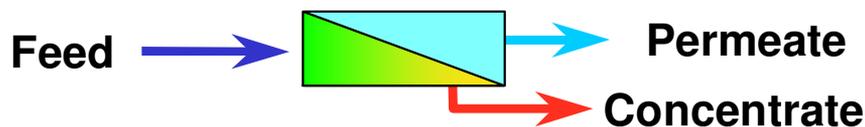


Figure 3: Principle of the RO process

Depending on the raw water quality in most cases the ratio of Permeate and Feed (“Recovery rate”) varies from 50 to 90 % which means that there is a significant amount of concentrate (10 – 50 %) which has to be disposed, mostly into sewers, rivers or into the sea.

RO requires a very effective pre-treatment (e.g. particle removal and sometimes acid or “antiscalant” dosage) for prevention of salt precipitation and to protect the membranes. The RO process effects a (nearly) complete demineralisation of water which means that RO is non-specific for nitrate ions (Panglisch et al., 2005). However, with RO an almost complete removal of nitrate can be achieved and it is used at several places in the world for this purpose. In some cases the RO permeate is blended with a certain amount of raw water, e.g. for adjusting a higher mineralization in the drinking water.

2.3 Ion Exchange

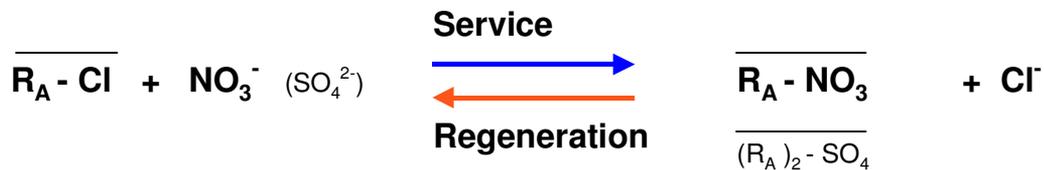
In drinking water treatment Ion Exchange typically is a process in which an exchangeable, presaturant ion (e.g. chloride) on the solid phase of an adsorber (resin) is exchanged for an “unwanted” ion (e.g. nitrate) in the water. In most cases this process is reversible and the adsorber material is employed as a fixed bed, either in up- or in down-flow. In the service cycle the water flows through the resin bed until the exchange capacity is exhausted. Exhaustion usually means that the effluent concentration of the unwanted ion exceeds a tolerable level. If so, the regeneration cycle of the ion exchanger has to be conducted, in which an excess of the presaturant ion (in terms of a brine solution or acid) is used for displacing the unwanted ions from the resin into a wastewater solution.

The two most frequently used anion exchange processes for nitrate removal in drinking water treatment are:

- Strong-base anion exchange (HCO₃-Form):
→ exchange of Nitrate for Bicarbonate (CARIX-Process)
- Strong-base anion exchange (Cl-Form):
→ exchange of Nitrate for Chloride

The CARIX-Process is a mixed-bed process combining a weak acidic cation exchanger and a strong base anion exchanger. Regeneration of both resins is conducted with a CO₂-saturated solution. The CARIX-Process can be used for simultaneous removal of hardness, nitrate and sulphate (Höll and Flemming, 1991). However, in case of high sulphate feed concentration (e.g. > 100 mg/L) this process is not suitable when the primarily goal is the removal of nitrate.

The anion exchange of nitrate for chloride is a relatively wide spread and simple process in which strong base anion exchangers are applied in the chloride form (Clifford, 1993). Thus, regeneration is conducted by using a NaCl-solution (brine). During the service cycle the resin takes up nitrate (and sulphate) from the water and releases chloride, resulting in an increase of the chloride concentration in the treated water. (This can create severe problems concerning corrosion in the distribution net). During regeneration the previously removed nitrate (and sulphate) ions are released and replaced by chloride ions (**Figure 4**). Usually regeneration is carried out by application of a 5 – 10 % solution of sodium chloride (NaCl).



R_A : Anion Exchanger (strong base)

Figure 4: Anion Exchange of nitrate for chloride

“Conventional” strong base anion exchange resins prefer the uptake of sulphate ions before they take up nitrate ions. This means that a high sulphate concentration may decrease the resin capacity for nitrate uptake significantly. Furthermore, under unfavourable conditions the nitrate effluent concentration can be higher than the feed concentration, due to the so called “chromatography effect”. For that reason “nitrate selective” resins were developed and introduced some 15 years ago. These resins prefer the uptake of nitrate before they take up sulphate ions. However, the “nitrate-selective” resins do not take up nitrate exclusively. As the total capacity of “conventional” anion exchangers is higher than the capacity of “nitrate-selective” resins, sometimes the choice of the most suitable resin type can be difficult.

The spent brine solution contains nitrate, sulphate and chloride ions. Due to its high salinity and eutrophication potential the disposal of spent brine solutions can be problematic (and costly), particularly in inland locations.

2.4 Electrodialysis (ED)

Both Electrodialysis (ED) and Reverse Osmosis (RO) are membrane processes which can be applied for desalination of brackish water. In opposite to RO the ED process is not driven by pressure but by an electric current. In a so-called “ED cell” the water does not pass the membrane but the electric current forces ions to pass a membrane. In one ED stack usually there are several alternating cation- and anion-selective membranes which create concentrate and diluate chambers. The raw water enters the diluate chamber and during its way through the chamber the ions are removed progressively. The concentrate is circulating in a loop. It is discharged from this cycle (and replaced with fresh water) when a maximum salt concentration is exceeded.

Unlike RO the ED process principally has a lower risk that the membrane is blocked by precipitation (“scaling”). Thus, the ED process requires less pre-treatment than RO (no dosage of chemicals into the feed water). However, usually some acid is dosed into the concentrate cycle to prevent scaling on that side of the membranes. Another option to prevent scaling is the periodical reversal of the polarity. This procedure is called EDR (Electrodialysis reversal).

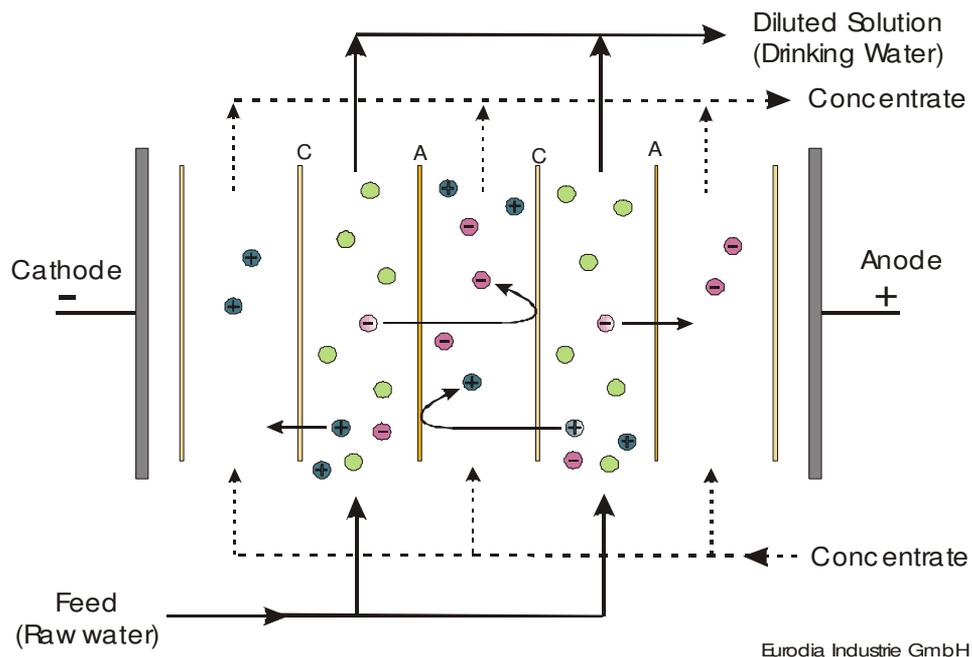


Figure 5: Principle of the ED process

The limit current (I_{Limit}) is an important parameter for the ED process. I_{Limit} is the maximum current which can be applied during ED without interfering the process by effects such as concentration polarization and electrolysis.

In ED applications the limit current (I_{Limit}) is often related to the membrane surface (A). The quotient of the limit current and the membrane surface is the limit current density (i_{Limit}).

$$i_{Limit} = \frac{I_{Limit}}{A}$$

Additionally i_{Limit} is defined by the following equation:

$$i_{Limit} = \beta z F c_D$$

β : Mass transfer number [meq/s]

z : electrochemical valence

F : Faraday's constant: 96,500 [As/mol]

c_D : average initial feed concentration [meq/L]

Thus, i_{Limit} gives information how much membrane surface has to be installed for achieving a certain desalination rate and it is therefore an important parameter for the design of an ED plant.

If the limit current density is exceeded, electrolysis will take place, in order to produce additional ions for the charge transfer through the membranes. As this is an unwanted effect, it has to be ensured that the limit current density will not be exceeded. In Practice, for most technical processes the threshold is 80 % of the limit current density.

Originally ED was a (more or less) non-specific desalination process. In recent years new types of selective membranes have been developed which makes this process become more attractive for special tasks, e.g. nitrate removal in drinking water treatment. By application of so-called "nitrate-selective" membranes predominantly nitrate anions are removed from the water. Thus, the composition of the water (matrix) is only partly affected and the treated water (diluate) is not a de-ionized water – unlike RO permeate. Furthermore, nitrate selective membranes produce a waste water (concentrate) which is less problematic for disposal. Typically in most ED processes the nitrate concentration is reduced by some 60 – 80 % and the recovery ratio (treated water : feed water) is in the range of 80 – 97 %. This means the ED process creates 3 – 20 % of concentrate (waste water) which has to be disposed.

ED processes for nitrate removal are already applied in full-scale in drinking water treatment plants e.g. in USA, England, Italy and Austria.

3 Workflow and Methods

3.1 Project tasks and steps

After approval of this research project by the German Ministry for Education and research (BMBF) in October 2002 several tasks had to be performed.

Task No.	Description	Goals / milestones
1	Detailed planning of the pilot plants and co-ordination of the research program	Preparation of Requirement specification and engineering drawings
2	Construction and testing of the pilot plants (in Germany)	Completion of the functional testing
3	Installation and start-up of the pilot plants (in Iran)	Functioning of all components / Successful start-up
4	Theoretical and Practical Training of Iranian staff members	Ensuring that the staff members are able to operate the plants independently
5	Operation of the plants (in consideration of the scientific work program)	(Almost) uninterrupted plant operation; continuous record of process data
6	Evaluation, analysis and report of project results	Publication in scientific journals and books
7	Scientific exchange (in water technology) between Iran, Germany and other countries	Participation in international conferences, trade fairs, organization of technical excursions, joint (diploma) theses

The first task mainly comprised the technical planning of the pilot plant containers and the detailed clarifying of the research program between the project partners. The second task was the construction and testing of the 3 pilot plants in Germany. After transportation to Iran the pilot plant containers were installed and started up in Mashhad (task # 3).



Figure 6: Installation of the pilot plants

There was an extensive training program (task # 4) for the Iranian staff members so that they were able to operate the plants independently. The process data were recorded continuously and observed frequently for ensuring an uninterrupted plant operation and for achievement of the scientific goals of the project. Finally there were numerous activities during this research project regarding presentation of results and scientific exchange. Table 2 shows the chronological progress of the research project.

Table 2: Chronological progress of the project

Time	Event	Involved IWW staff
Oct 02	Approval of the Research project by BMBF	
Oct 02	1st working visit in Mashhad	Panglisch
Nov 02	Start of planning of the 3 pilot plants	Prof. Overath, Panglisch
Jan - Apr 03	Detailed Plannings, several meetings (IWW, Wabag, Umex)	Dördelmann, Panglisch
May 03	Start of construction of the 3 pilot plants (Wabag Umex)	
Aug 03	RCUWM-BMBF-Workshop in Tehran	Panglisch
Sep - Oct 03	Final Test of the 3 pilot plants in Erfurt (IWW, Wabag, Umex)	Dördelmann, Panglisch
Oct 03	1st visit of Iranian water experts in Germany (training course)	Dördelmann, Panglisch
Nov 03	Transportation of the 3 pilot plant containers to Iran (Wabag)	
Nov 03 - Aug 04	Pilot plant containers in Iranian customs (= delay)	
Oct 04	Start-up of the 3 pilot plants in Mashhad (IWW, Wabag, Umex)	Buchta, Dördelmann
Nov 04	Training of Iranian staff members in Mashhad	Buchta, Dördelmann
Nov - Dec 04	Start of scientific investigations	Buchta, Dördelmann
Feb 05	working visit in Mashhad	Buchta
Apr 05	Participation in IFAT trade fair + BMBF-Workshop in Munich	Dördelmann, Panglisch
May 05	working visit in Mashhad	Dördelmann
Aug 05	working visit in Mashhad	Buchta
Nov 05	working visit in Mashhad	Dördelmann
Nov 05	RCUWM-BMBF-Workshop in Berlin	Prof. Gimbel, Panglisch
Dec 05	Approval of the additional ED research project by BMBF	
Jan 06	working visit in Mashhad	Buchta, Panglisch
Feb 06	Start of planning of the ED pilot plant	Dördelmann, Panglisch
Apr 06	Start of reconstruction of the ED pilot plant (Wabag, Umex)	
May 06	2nd visit of Iranian water experts in Germany	Dördelmann, Panglisch
May 06	IWA Biofiltration Conference in Mülheim	Dördelmann, Panglisch
Sep 06	Symposium "Environmental Challenges" in Tehran (BMBF)	Dördelmann
Oct. 06	Final Test of the ED pilot plant in Erfurt (IWW, Wabag, Umex)	Dördelmann
Nov 06	International Trade Fair IWE 2006 in Tehran (BMBF-RCUWM)	Dördelmann
Nov 06	Transportation of the ED pilot plant container to Iran (Wabag)	
Dec 06 - May 07	ED Container in Iranian customs (= delay)	
Jun 07	Start-up of the ED pilot plant in Mashhad (IWW, Wabag)	Dördelmann, Markmann
Jul 07	Start of scientific investigations (ED); technical problems	Markmann
Aug - Oct 07	Providing spare parts for the ED plant (= delay)	
Nov 07	Continuation of scientific investigations (ED) in Mashhad	Markmann
Nov 07	3rd visit of Iranian water experts in Germany	Dördelmann, Markmann
Jan 08	Technical visit of Syrian + German Engineers to Mashhad	Dördelmann, Dr. Stetter
Jan 08	End of the scientific investigation program	
Jan - Feb 08	Preparation of his diploma thesis about the ED investigations	Markmann
Feb 08 - May 08	Preparation of this Final report	Dördelmann, Panglisch

Besides the above mentioned activities, during the entire time of this project Dr. Panglisch, Mr. Dördelmann and Mr. Buchta were very much involved in accompanying works, such as data assessment, project management, support of the Iranian project partners by e-mail and telephone, preparation of reports etc.

3.2 Description of the pilot plant experiments

3.2.1 The site of the pilot plants

The site of the pilot plants is located at a groundwater pumping station in “Golshar”, which is suburb in the east of Mashhad, some 8 km from the city centre. Figure 7 gives an impression of the location.



Figure 7: View of the Pilot plant's site

Originally the site only contained the pumping station which is inside of the building on the right side of the picture. Before installation of the pilot plant containers, MWWC extended the site significantly and they constructed the laboratory and office building which can be seen on the left hand side of the picture. The blue containers in the middle of the picture included the biological pilot plant. The blue container on the right hand side was the Ion Exchange pilot plant and the white container was the Electrodialysis pilot plant. The RO pilot plant can not be seen from this view as it was behind the containers of the biological plant.

The site was protected by a massive stonewall and guarded 24 hours per day by a watchman.

3.2.2 Raw water quality

The Golshar groundwater well has a depth of 145 m and its water composition is more or less representative for other wells in the eastern part of Mashhad. Table 3 shows the composition of the pilot plants' raw water in 2004 and 2007. It can be seen that the nitrate concentration was 113 mg/L in 2004 and increased to 133 mg/L in 2007. During this period the concentrations of the other major cations and anions (e.g. Ca, Mg, Na, Cl etc.) increased by some 10 %. At other wells a rapid salt increase was observed as well which underlines the severity of the quality problems in Mashhad groundwater.

Table 3: Composition of the raw water in 2004 and 2007

Sampling Point		Well # 261 Feed Pilot Plant	Well # 261 Feed Pilot Plant
Date		01.12.2004	22.11.2007
pH	-	7,2	7,1
Conductivity (25 °C)	µS/cm	1517	1642
Diss. O ₂	mg/l	4,8	-
Turbidity	FNU	0,66	-
Cl	mg/l	182	196
SO ₄	mg/l	157	159
NO ₃	mg/l	114	133
HCO ₃	mmol/l	5,23	5,81
Ca	mg/l	140	150
Mg	mg/l	44	48
Hardness	°dH	29,8	32,1
Hardness	mg/l CaCO ₃	531	573
Na	mg/l	113	120
K	mg/l	1,4	2,2
Fe	mg/l	0,073	< 0,01
Ba	mg/l	0,048	0,064
Sr	mg/l	3,7	2,5
SiO ₂	mg/l	22,8	21,4

3.2.3 Biological pilot plant

Figure 8 shows the process scheme of the pilot plant.

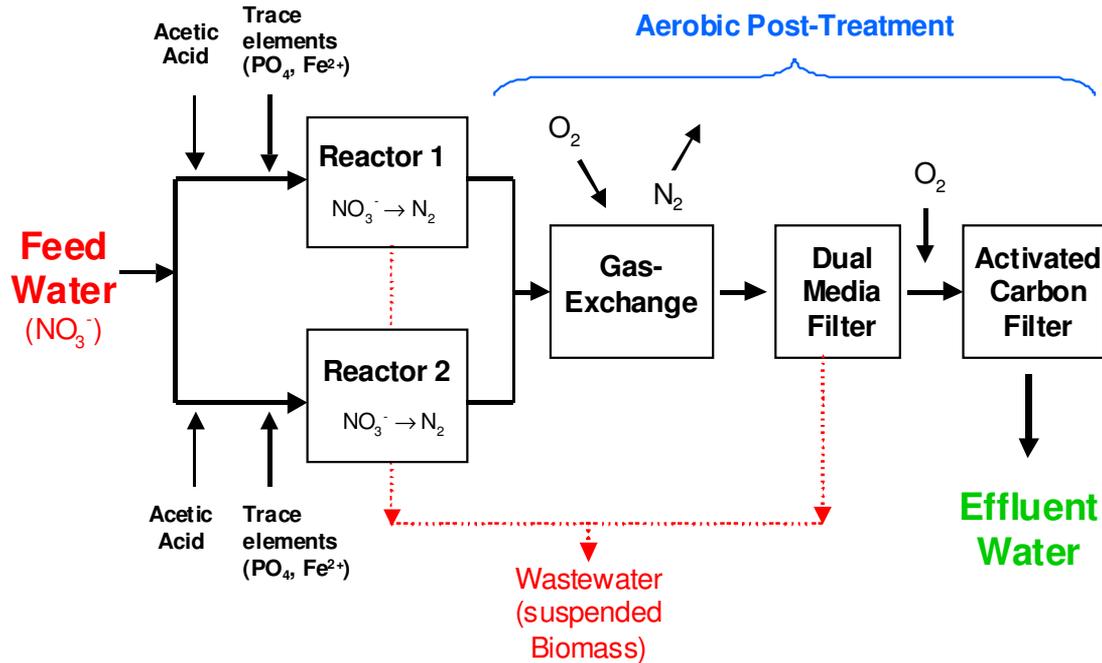


Figure 8: Process Scheme of the Biological Denitrification pilot plant

Acetic acid was dosed as electron donor into the feed of the pilot plant. Additionally ferrous sulphate and sodiumhydrogenphosphate were dosed as nutrients. The two fixed bed bio-reactors were operated downstream and in parallel. Expanded clay (Liapor[®]) was employed as growth material. The bio-reactors were followed by a gas exchange, a dual media filtration (filter stage 1) a second gas exchange and an activated carbon filtration (filter 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. Figure 9 shows the expanded clay filter material with some biomass on its surface.



Figure 9: Expanded clay filter material (with some biomass on its surface)

Table 4 summarizes the basic design parameters of the biological reactors.

Table 4: Design parameters of the biological reactors

Growth Material	-	expanded clay
Reactor diameter	m	0,5
Reactor height	m	5,0
Bed depth	m	3,6
Reactor Volume (Fixed bed)	m ³	0,7
Flow rate	m ³ /h	0,5 - 3,0
Filter velocity	m/h	2,5 - 15,3
Flow direction	-	downstream
c(NO₃)_{Feed}	mg/l	110 - 130
c(NO₃)_{Effluent} (Goal)	mg/l	40

The pilot plant did not have a disinfection stage because the effluent was not used for drinking water purpose. However, for a full-scale Biological Denitrification plant a final disinfection would be obligatory to ensure microbiological safety of the drinking water.

The biological pilot plant worked fully automated with automatic flushing and flow control. Several process data (e.g. nitrate concentration, turbidity, pH, flow rate, differential pressure) were measured and logged continuously. More details on this topic will be given in chapter 3.3.

Within this research project the following operating parameters were varied and optimized:

- Flow rate of the biological reactors (0.5 – 3 m³/h, each)
- Grain size of the expanded clay filter material (2-5 to 4-8 mm)
- Acetic acid dosage
- Pressure in the biological reactors
- Flow rate of the dual media filter
- Flushing programs of the reactors and filters
- Flocculant and flocculant aid dosage

3.2.4 Reverse Osmosis pilot plant

Figure 10 shows the process principle of the RO pilot plant.

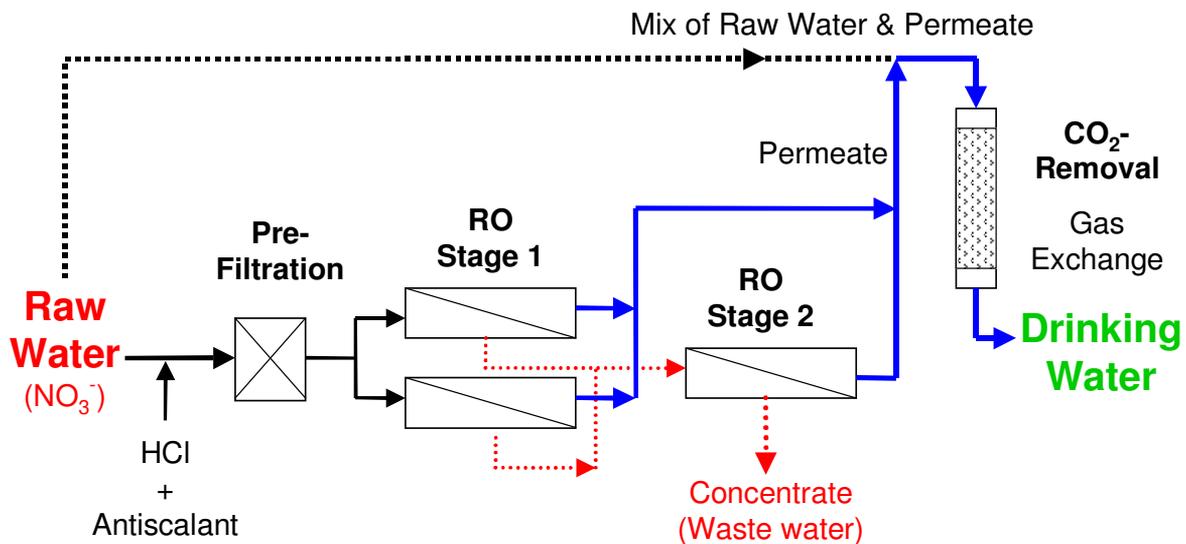


Figure 10: Process principle of the RO pilot plant

After the 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 pressed the water through the two stages of the RO system. The membranes modules (type SUL-G10) were supplied from Toray Industries Inc. The nitrate-low permeates of the two stages were merged and then mixed with a certain amount of ni-

trate-laden raw water so that the nitrate concentration 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 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 (see chapter 3.3).

Figure 11 gives a view into the RO pilot plant container.



Figure 11: View into the RO pilot plant container

Within this research project the following operation parameters were varied and optimized:

- Recovery ratio (70 – 85 %)
- Hydrochloric acid dosage
- Antiscalant dosage
- Blending ratio (RO permeate : raw water)
- Air flow of the blower system (gas exchange for pH adjustment)
- Frequency and mode of chemical cleaning of the membranes

3.2.5 Ion Exchange pilot plant

Figure 12 shows the process principle of the Ion Exchange pilot plant.

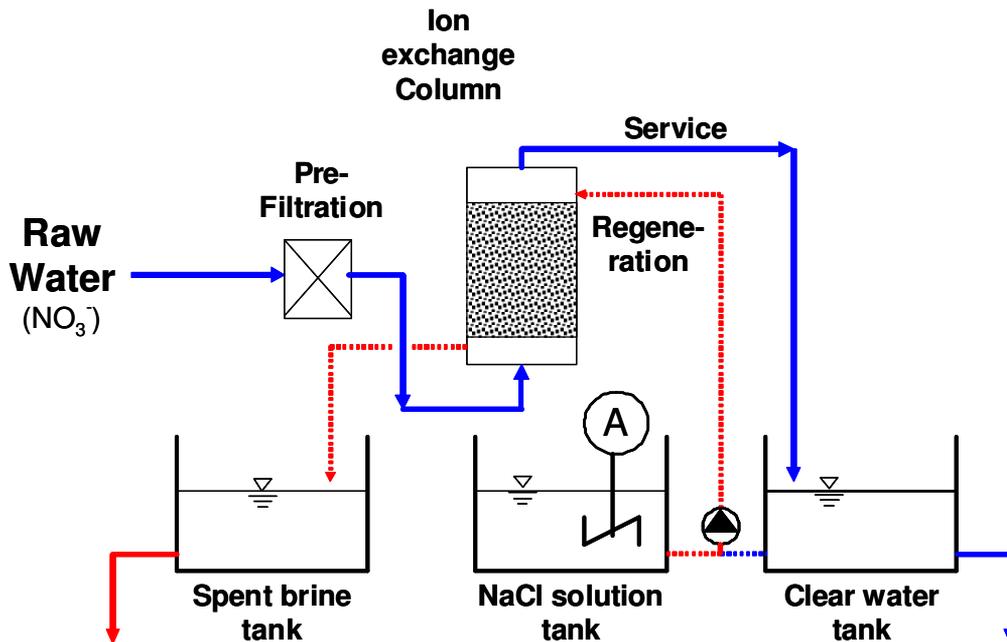


Figure 12: Process principle of the Ion Exchange Pilot Plant

After raw water intake and feed pump the first treatment stage of the Ion Exchange pilot plant was a cartridge filter which removed turbidity and iron from the raw water. Then the water went through one of the two Ion Exchange columns (diameter: 0.4 m) which were operated in parallel (In order to simplify matters, Figure 12 shows only one column). In different periods these columns were filled with different types of resins, conventional and “nitrate-selective” resins. The resins were:

- HP 555 (“nitrate-selective”), manufactured by Rohm and Haas Company
- Ionac SR 7 (“nitrate-selective”), manufactured by Sybron Chemicals Inc.
- Lewatit MP M 600 (conventional), manufactured by Lanxess Company (Bayer)

During most of the time the bed depth was 1.6 m and the resin bed volume was 200 liter in each column. The flow rates were varied between 1.0 and 3.0 m³/h for each column, which is equivalent to a specific flow rate of 5 – 15 BV/h (Bed volumes per hour).

After break-through of nitrate the Ion Exchange system had to be regenerated by a NaCl solution. For this purpose a certain amount of salt was added into the NaCl tank and then dissolved by an agitator.

In most of the experiments the flow direction during operation (service cycle) was upstream while regeneration was conducted in downstream, which means counter-current.



Figure 13: View into the Ion Exchange pilot plant container

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.

3.2.6 Electrodialysis pilot plant

Originally the ED pilot plant container was employed by Wabag Company for pilot tests some years ago in Austria and Spain. Before application in Mashhad, the ED

The ED pilot plant was controlled automatically by a process control system (Siemens S7) and visualized on a PC screen. However, the voltage (DC) of the ED unit had to be regulated manually by turn-switch.

Figure 15 gives a view into the ED pilot plant container. The ED stack can be seen in the middle of the picture.

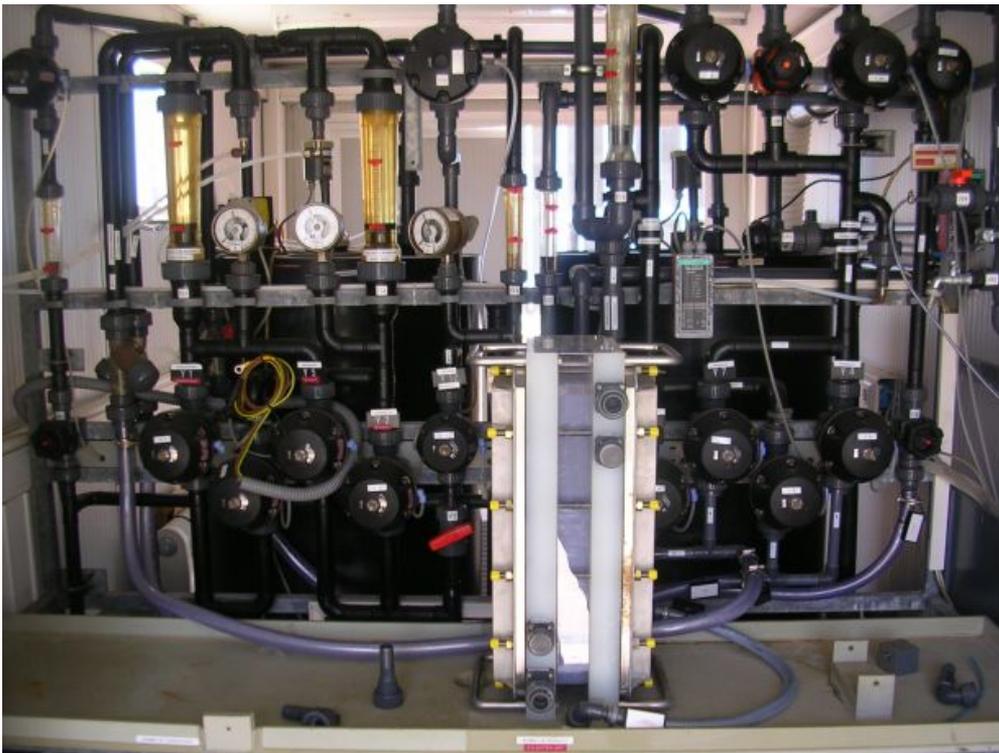


Figure 15: Electrodeionization pilot plant

3.2.6.1 Operation modes

During the experiments in Mashhad the ED pilot plant could be operated by three different modes:

- Direct feed mode
- Batch mode
- Feed and Bleed mode

In the direct feed mode the raw water was directly treated by the ED plant. The diluate was not recycled. Thus, it was a single-stage “one-time-through” process.

In contrast to direct feed, in the batch mode the diluate was desalinated a second time. This procedure simulated a process with two stages (2 ED stacks), although the pilot plant only included one ED stack.

In the feed and bleed mode, a part of the diluate was recycled and mixed with the raw water. In this mode, usually the flow within the ED plant was constant ($1 \text{ m}^3/\text{h}$), but the ratio of raw water and recycled diluate was varied.

3.2.6.2 Evaluation of limit current and limit current density

The limit current density was evaluated according to the “tangent method” by Cowan and Brown (1959). During this procedure, the values of voltage (U) and current (I) were registered for each operation condition. The voltage of the ED plant could be varied in 7 steps from 0 to 70 V. Then the calculated resistance ($R = U/I$) and the reciprocal current were plotted into a diagram, similar as it can be seen in Figure 16. The (reciprocal) limit current can be obtained from the intersection point of the two tangents.

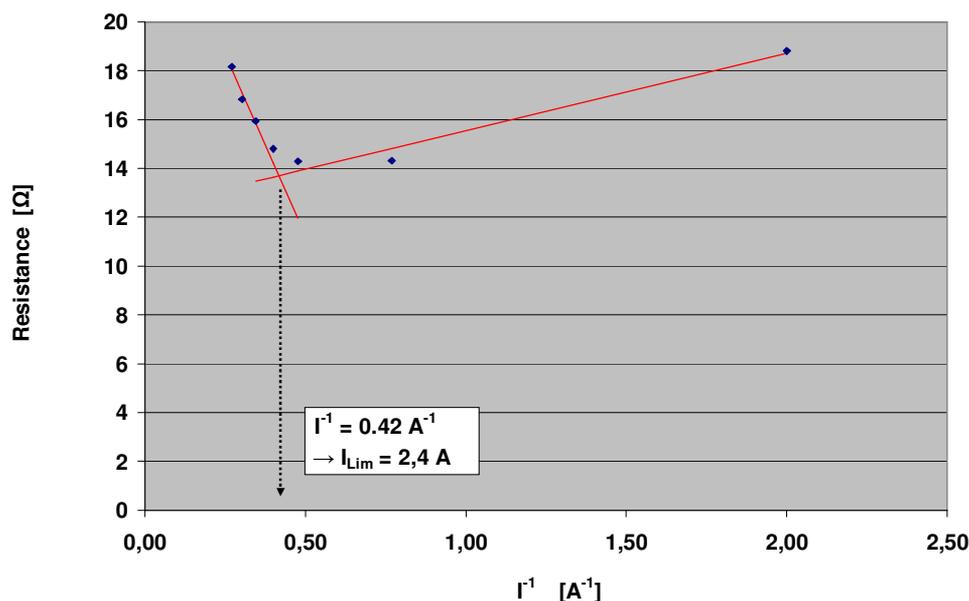


Figure 16: Example for the evaluation of the limit current

3.3 Data record and control

As mentioned before, the pilot plants were equipped with several devices for online-measurement so that all important operating parameters were recorded. All data were transmitted and stored automatically (every minute) by the PC which was installed in the biological plant.

Within the Ion Exchange plant 9 parameters were measured online, the RO plant provided data of 19 measurement instruments whereas in the biological plant 27 parameters were measured online. The following parameters were measured continuously:

- Flow rates (e.g. feed flow, or regeneration flow within the Ion Exchange plant)
 - Flow meter type: “Promag” made by Endress + Hauser Company
- Absolute pressure (e.g. at biological reactors)
 - Pressure sensor type: “SEN3270” made by Kobold Company
- Differential pressure (e.g. within the biological reactors)
 - Differential pressure type “Deltabar PMD235” made by Endress+Hauser
- Nitrate concentration (e.g. effluent of the RO plant)
 - Online nitrate measuring type “Nitrax plus” made by Hach Lange
- pH-value (e.g. in the RO feed and permeate)
 - Online pH measurement made by Endress+Hauser
- Conductivity (e.g. ED concentrate diluate)
 - Conductivity measurement “Liquisys M” made by Endress+Hauser
- Turbidity (e.g. effluent of the filters in the biological plant)
 - Online turbidity measurement made by Endress+Hauser

Some of the online-parameters (e.g. flow rates, pressure) were used for automatic control of the plants whereas other parameters were only recorded for documentation.

The central PC of the biological plant was equipped with a modem which enabled remote control and data transfer to Germany. By this means it was possible to observe and even to change the operating conditions of the plants in Iran while sitting at the desktop in Germany. However, mostly this option was used for data query.

Once the data were transferred to the computer in IWW the responsible project managers could check the data and - if necessary - give advice to the Iranian colleagues for improvement of the pilot plants' operation. Besides these online data, the Iranian colleagues recorded once per day all relevant process data into a plant journal. These journals were sent to IWW by e-mail continuously and then checked by promptly by the responsible engineers in IWW.

3.4 Analytics

Additionally to the online parameters (chapter 3.3), there were several parameters, particularly chemical parameters, which were measured manually on-site or in the central laboratory of Mashhad Water and Wastewater Company (MWWC).

Table 5: Program for manual on-site analysis

	pH	Temp.	O ₂	Cond.	TOC	NO ₃	NO ₂	NH ₄	Turb.	PO ₄
Raw water	w	w	w	w	w	w	w	w	w	w
RO - Feed (after dosage)	d	d		d						
RO - Mixed water (permeate)	d	d	d	d	w	w	w	w	w	
IE - Effluent Column 1				d	w	d			w	
IE - Effluent Column 2				d	w	d			w	
IE - Clear water tank (Mix)	d			d	w	d			w	
Bio - Feed Reactor 1	d		d		d					d
Bio - Effluent Reactor 1	d		d		d	d	d	w	w	d
Bio - Feed Reactor 2	d		d		d					d
Bio - Effluent Reactor 2	d		d		d	d	d	w	w	d
Bio - Effluent of Sand filter	d		d		d	d	d		d	
Bio - Effluent of Carbon filter	d	d	d	d	d	d	d	w	d	

w = weekly Analysis d = daily analysis

The on-site parameters pH, temperature, oxygen and conductivity were analyzed manually by different electrodes from WTW Company. Total organic carbon (TOC) was analyzed by a "TOC 5000" from Shimadzu Company. Turbidity was measured by means of a device from Hach Company. Nitrate, nitrite, ammonia and phosphate were analyzed by means of a Reflectoquant device and different test kits from Merck Company.

Table 6: Program for analysis in the Central laboratory of MWC

	Ca	Mg	Na	K	NO ₃	NO ₂	SO ₄	Cl ⁻	HCO ₃	PO ₄	S ²⁻	Fe	Si	HPC
Feed Reactor 1										w		w		
Feed Reactor 2										w		w		
Effluent Reactor 1										w	w	w		
Effluent Reactor 2										w	w	w		
Effluent Gravel												w		
Effluent Carbon	w	w	w	w	w	w	w	w	w	w	w	w		w
IE Effluent Column 1			w		w		w	w						
IE Effluent Column 2			w		w		w	w						
IE Clear Water Tank	w	w	w	w	w	w	w	w	w					w
RO Mixed Water	w	w	w	w	w	w	w	w	w	w		w	w	w
RO Concentrate	w						w			w		w	w	
Raw Water	w	w	w	w	w	w	w	w	w	w	w	w	w	

w = weekly analysis

3.5 Evaluation of costs

One part of this study covered the estimation of capital costs (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.

The investment costs were estimated by VA Tech Wabag (based on their experiences from several other projects) and included the costs for process technology, electrical engineering and civil engineering. 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 for all 3 types of investment costs. These are typical values and conditions for depreciation of investments goods in Iran at present.

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 labour.

3.6 Assessment of the processes

As mentioned before, besides the scientific goals this project should also provide a transparent assessment of the treatment processes and a subsequent recommendation (for the Iranian water authorities) which technology would be most suitable for application in full-scale in Mashhad.

For assessment of the four different treatment processes several aspects had to be 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 included 5 main criteria:

- Effectiveness and stability of the treatment process
- Operating and investment costs
- Drinking water quality after treatment
- Required technical and human resources
- Impacts on the environment during operation

Every main criterion had some sub-criteria and each of them was rated on a scale from “+2” to “-2” in which the mark “+2” was used for very favourable and beneficial factors and “-2” for very unfavourable factors:

- very beneficial factor +2
- beneficial factor +1
- neutral factor 0
- unfavourable factor -1
- very unfavourable factor -2

By application of this procedure the five main criteria could be assessed in a transparent way. Most criteria were assessed on the basis of the results from the pilot plant investigations. However, 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. Finally, the results of the five main criteria were weighted as described in Table 7.

Table 7: Main Criteria for assessment of the treatment processes

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 %

4 Results and Discussion

4.1 Pilot plant experiments

4.1.1 Biological Denitrification

4.1.1.1 Process performance

Corresponding to the project's water quality goals, a significant nitrate reduction was intended, from ca. 120 mg/L (feed water) to 40 mg/L (effluent). Due to a stoichiometry factor of 0.82 (mole acetic acid / mole nitrate) this amount of nitrate reduction required a dosage of approximately 60 mg/L acetic acid (25 mg/L DOC).

There were two fixed bed reactors working in parallel, both filled with expanded clay and operated in downstream. The main difference between the two reactors was the grain size of the expanded clay which was employed as growth surface for the denitrifying bacteria. The material in reactor 1 had a grain size of 3 – 6 mm, the material in reactor 2 had a grain size of 2 – 5 mm and therefore had a bigger surface. The feasible flow rate was 2.5 m³/h for each of the two reactors.

Figure 17 shows a vertical profile measurement of the two bio-reactors. During this measurement the nitrate feed concentration was 115 mg/L. It can be seen that in reactor 2 the predominant amount of the nitrate was reduced in the upper part of the reactor because in the sample taken from a bed depth of 115 cm the nitrate concentration had already decreased to 55 mg/L nitrate. Simultaneously the TOC concentration was reduced from 29 to 7 mg/L. However, in the middle and lower part of reactor 2 the decline of nitrate and TOC concentrations was less intensive. In contrast to this, in reactor 1 the nitrate and TOC curves declined more uniformly. This means that in reactor 1 the nitrate degradation rates in the upper and lower part of the reactor were almost similar (linear), whereas in the upper part of reactor 2 the nitrate degradation rate was significantly higher than at the bottom, probably because the substrate was limited at the bottom of reactor 2.

During this profile measurement nitrite was detected in two samples taken at bed depths of 60 and 115 cm from reactor 2, obtaining concentrations of 0.7 respectively 0.8 mg/L. In the other profile samples and particularly in the reactor's effluent samples there was no nitrite at this time. However, during the pilot plant investigations sometimes nitrite was detected in the reactor effluents, for example 1 - 2 mg/L. But in those cases nitrite was always removed surely by the aeration and oxidation step during the following two aerobic filter stages. Likewise sulphide was never detected

in the effluent of the pilot plant. More details on the water quality of the treated water will be given in chapter 4.1.1.3.

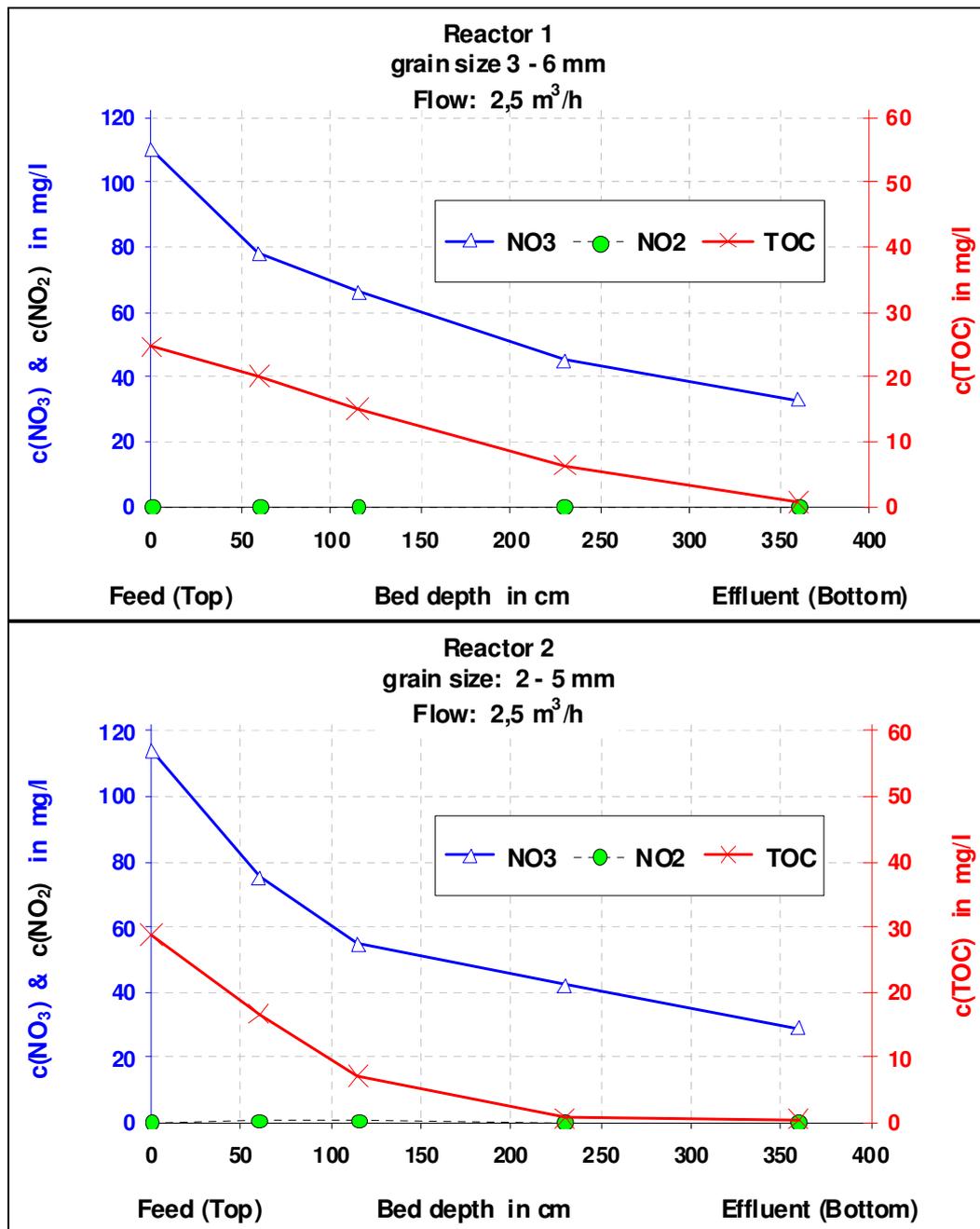


Figure 17: Vertical profile measurement of nitrate-, nitrite- and TOC-concentration in the two reactors

The so-called nitrate degradation rate was calculated from a) the nitrate decrease (feed concentration minus effluent concentration), b) the flow rate and c) the volume of the filter material inside the biological reactors:

$$R_{NO_3 \text{ deg } r} = \frac{(c(NO_3)_{\text{Feed}} - c(NO_3)_{\text{Effluent}}) \times Q_{H_2O}}{V_{\text{Reactor}}}$$

Table 8 gives an overview about the long-term performance of the two reactors in terms of nitrate degradation rate.

Table 8: Nitrate degradation rates (long-term) of the two reactors

		Reactor 1	Reactor 2
grain size	mm	3 - 6	2 - 5
Flow rate (feasible)	m ³ /h	2,5	2,5 *
Filter velocity	m/h	12,7	12,7 *
NO₃-degradation rate as N	Kg N / m ³ d	1,4	1,6 *
NO₃-degradation rate	Kg NO ₃ / m ³ d	6,4	7,0 *

* Flow & NO₃-degr. rate could be increased (result: higher pressure drop)

In reactor 1 (filled with expanded clay; grain size 3 - 6 mm) the long-term nitrate degradation rate was 6.4 kg NO₃/m³d whereas in Reactor 2 (expanded clay, grain size 2 – 5 mm) 7.0 kg NO₃/m³d was found. With the finer material of reactor 2 even higher nitrate degradation rates were feasible for short periods, e.g. by increasing the acetic acid dosage or the flow rate, but this resulted in a much higher pressure drop.

For both reactors the water consumption for flushing was about 3 % of the feed water. In addition to the 4 % water consumption for flushing the dual media filter the total water demand for backwash water was about 7 %.

The spent backwash water contained biomass but no harmful chemicals. After separation of the biomass (e.g. by sedimentation + filtration) the cleared backwash water could be reused for other purposes (irrigation) or recycled to the feed of the plant. However, during the pilot plant experiments the small amount of spent backwash water was discharged to the sewer.

4.1.1.2 Optimization of the process

In the beginning, between November 2004 and May 2005, reactor 1 contained a coarser filter material (expanded clay, 4 – 8 mm). However, this filter material pro-

vided a much lower nitrate degradation rate than reactor 2, due to its lower specific surface (m^2/m^3) and it required higher flow rates during flushing, due to the higher weight of the grains. Therefore, after the initial 6 months of the investigation, the coarse filter material was substituted by a smaller material (expanded clay, 3-6 mm). Thus, most time of the investigation was performed with the two filter materials which had grain sizes 2-5 and 2-6 mm. The respective results were already shown before in chapter 4.1.1.1.

One of the most difficult parts of the research project was the optimization of the flushing procedure (flow rate and duration of air and water flushing) of the two reactors. On the one hand an intensive cleaning of the filter material was desired for reducing the differential pressure. On the other hand a too intensive flushing caused a huge loss of biomass resulting in a low nitrate degradation rate in the initial start-up phase after flushing. Thus, it was necessary to figure out operating conditions which provided both, high nitrate degradation and low pressure drop. At optimum conditions, flushing of the bio-reactors was required after some 20 hours of operation. Figure 18 shows a typical pattern of the differential pressure.

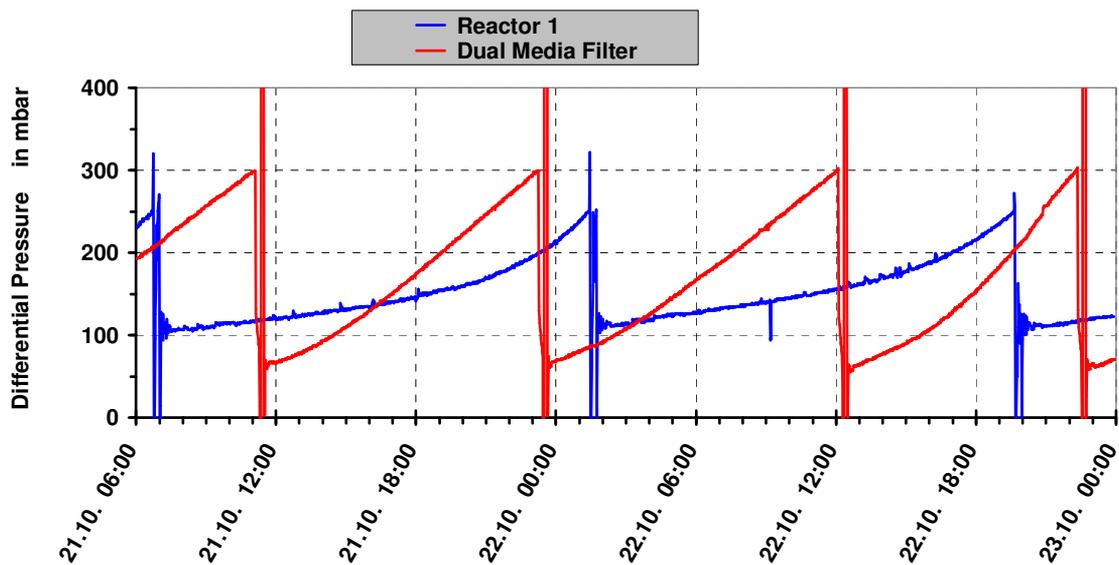


Figure 18: Typical pattern of the differential pressure in reactor 1 and the subsequent dual media filter in response to flushing

Directly after flushing, the increase of differential pressure in reactor 1 (blue line) was very low, but it increased more rapidly after some 15 hours of operation. In contrast to this, the pressure drop increase of the dual media filter was almost linear during the whole filter run time. It was found that the slope of the pressure drop increase mainly depended on the amount of flocculant which was added to the feed of

the dual media filter – and (of course) – from the flow rate. After flushing the differential pressure of the dual media filter decreased to approx. 70 mbar, whereas the differential pressure of reactor 1 decreased to 110 mbar, due to different flushing conditions.

Figure 19 refers to the same period as Figure 18 and it illustrates the development of the nitrate concentration in the feed and in the effluent of reactor 1.

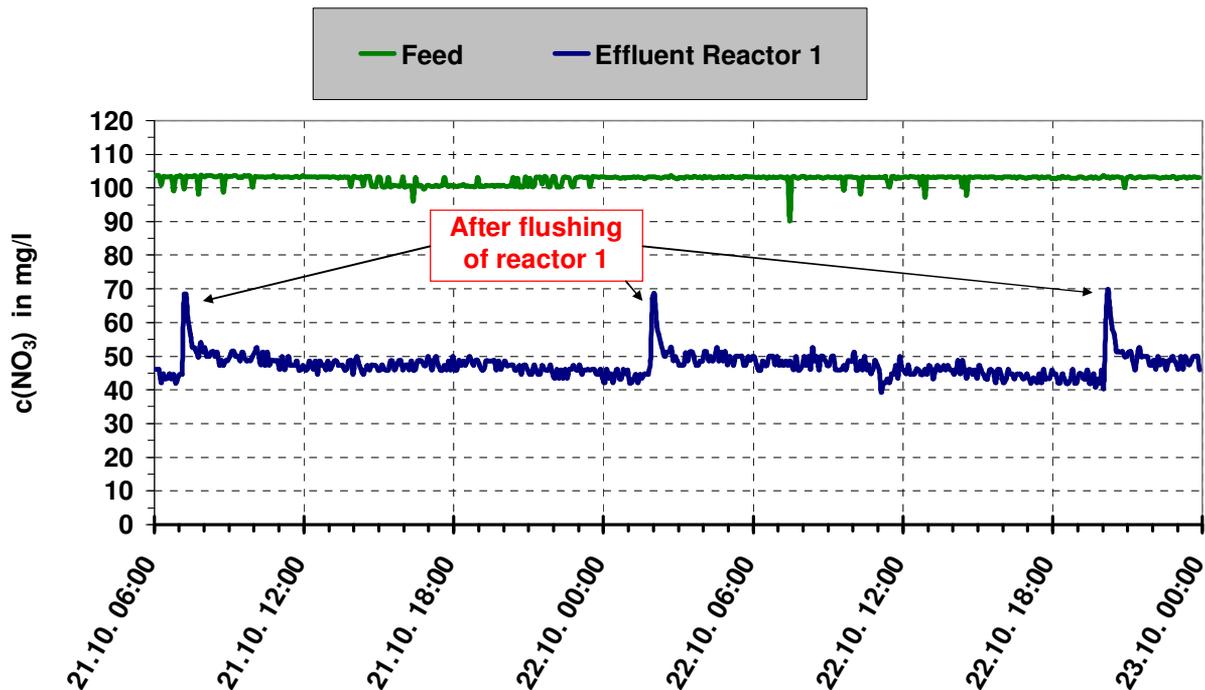


Figure 19: Nitrate concentration in the feed and in the effluent of reactor 1

It can be seen that the nitrate effluent concentration of the reactor had a small peak, each time after the reactor was flushed. As mentioned before, this is due to the fact that after flushing there is less biomass on the reactor material, resulting in a short-term decrease of the biological activity. However, after approx. 1 hour the biological system recovered and the reactor achieved its former nitrate level again.

In this regard it has to be considered, that the Biological Denitrification pilot plant had 2 reactors which were operated in parallel. The reactors were NOT flushed at the same time and the system included several buffer tanks so that in the effluent of the pilot plant no nitrate peaks were detected.

4.1.1.3 Quality of the treated water

Table 9 shows the composition of the feed water (before dosage) and the effluent water (after activated carbon filter).

Table 9: Chemical analysis of feed and effluent of the biological pilot plant

		Feed of Biological Pilot Plant	Effluent of Biological Pilot Plant
Date of Sampling		19.11.05	19.11.05
pH *	-	7,24	7,65
Conductivity (25 °C) *	μS/cm	1516	1472
Temperature *	°C	17	17
Dissolved O ₂ *	mg/l	2,97	4,55
Turbidity *	FNU	0,38	0,33
Turbidity (online)	FNU	-	0,08
TOC	mg/l	0,37	0,38
Ca	mg/l	139	136
Mg	mg/l	43,7	43,1
Na	mg/l	109	106
K	mg/l	1,8	1,7
Cl	mg/l	184	185
NO ₃	mg/l	115	40
SO ₄	mg/l	150	147
HCO ₃	mmol/l	5,36	6,32
NH ₄ **	mg/l	< 0,2	< 0,2
S ²⁻ **	mg/l	-	< 0,02
NO ₂ **	mg/l	-	< 0,02
PO ₄ **	mg/l	< 0,1	< 0,1
Fe	mg/l	< 0,01	< 0,01

* on site analysis

** analysis by rapid test

The table shows a significant decrease in nitrate concentration between the feed and the effluent of the pilot plant. Simultaneously, there was an increase of pH, mainly caused by bicarbonate production during the denitrification process. The concentrations of the other major cations (Ca, Mg, Na, K) and anions (Cl, SO₄) were not affected by the denitrification process. Due to the dosage of acetic acid the TOC was increased significantly during the treatment process. However, at the end of the process the TOC concentrations of the effluent sample (after activated carbon filter)

and the feed sample (before dosage) were 0.4 mg/L both. This means that the acetic acid substrate (~ 25 mg/L TOC) was degraded completely by the denitrifying bacteria. Nitrite, sulphide or ammonia were not detectable in the effluent sample and also the turbidity was very low - 0.08 FNU (online) respectively 0.33 (hand measurement). The water temperature during the whole process was 17 °C.

Between September 2005 and June 2006 twelve samples were taken from the pilot plant effluent and analysed by HPC-Method. The bacterial count of these samples varied between 10 and 300 per ml (average: 144 ml⁻¹), representing a good drinking water quality with regard to this parameter.

4.1.1.4 Process requirements (chemicals, energy)

For optimum operation conditions of the bio reactors the following amounts of chemicals were required:

- Acetic acid (substrate) ca. 65 g/m³
- FeSO₄ x 7 H₂O (nutrient 1)
Fe) ca. 0.5 g/m³ (~ 0.1 g/m³ as Fe)
- Na₂HPO₄ x 2 H₂O (nutrient 2)
as PO₄) ca. 0.02 g/m³ (~ 0.01 g/m³)

For optimum operation conditions of the subsequent dual media filter the following amounts of chemicals were required:

- FeCl₃, x 6 H₂O (Flocculant): ca. 12 g/m³ (~ 2.5 g/m³ as Fe)
- Polyelectrolyte (Flocculation aid): ca. 0.3 g/m³

All chemicals should be purchased from a certified dealer and their compositions and purities should conform to international standards relating to application of chemicals in drinking water treatment (e.g. DIN EN 13194 for acetic acid).

Acetic acid has to be stored at moderate temperatures (5 – 30 °C). For that reason and due to safety reasons, the entire biological pilot plant was equipped with an air condition.

It can be calculated that the energy consumption of a full-scale Biological Denitrification plant (with similar process technology) would be in the range of 0.15 kWh/m³.

4.1.1.5 Operation and Maintenance

Although the biological plant worked fully automated it has to be mentioned that there are several tasks which have to be performed regularly and carefully during its operation, such as:

- Preparation of
substrate solution (acetic acid)
nutrient solutions (iron(II), phosphate)
flocculant solution (ferric chloride)
flocculant aid solution (Polyelectrolyte)
- Flow control of all dosage systems
- Inspection, cleaning and calibration of measuring instruments (pH, conductivity, nitrate, turbidity, pressure, differential pressure, level)
- Cleaning of tanks
- Maintenance of pumps (e.g. feed pumps, dosage pumps)
- Maintenance of blowers
- Maintenance of automatic valves and check valves

For quality and safety reasons an intensive and continuous control of the plant is essential. This includes

- Daily inspection of all major components (including pre- and post-treatment)
- Daily check of process data
- Visual inspection of the flushing process of the biological reactors

- Frequent control of process performance by means of on-site and laboratory analyses
- Keeping a plant journal (operation journal) and a maintenance plan
- Supervision of all process information

4.1.1.6 Operating experiences and potential problems of the process

Generally speaking, Biological Denitrification in drinking water treatment is NOT a simple technology. Denitrification itself is a sensitive biological process and additionally, there are several dosage and post-treatment steps, so that such a plant has to be regarded as a complex technology.

Nevertheless the biological pilot plant in Mashhad could be operated effectively and successfully, mainly due to the great efforts of the local staff members. After completing an intensive training program, prepared by IWW and Wabag, Mr. Moshiri and his team operated the pilot plants independently and absolutely reliable. Operation of the biological plant definitely required most of their time because this pilot plant included a large number of sensors. It took a lot of work to keep all sensors in good condition because there was biomass growing almost everywhere. It became obvious that particularly the nitrate, pH and turbidity sensors had to be inspected and cleaned several times a week.

Accurate dosage of all needed chemicals required a lot of working time as well. It became obvious that staff had to pay attention particularly in the preparation of the solutions and in the flow control of the dosage systems. Even small changes in concentrations and dosage flow may result in big trouble because the biological system is very sensitive to any changes.

Another difficult and time consuming aspect was the adaptation and optimization of the flushing conditions.

Finally, it has to be mentioned that in the beginning there were temporarily problems with regard to water composition of the activated carbon filter's feed. As mentioned before, the pilot plant contained two trickling columns for gas exchange, one before and one after the dual media filter. In the beginning of the experiments, the blower of the second trickling column was working too intensively resulting in a very high pH

value ($> \text{pH } 8$) in the feed of the activated carbon filter. At this pH the Langelier saturation index (LSI) was about $+0.5$ which means the water was super saturated with CaCO_3 . As a consequence of this, there was calcite precipitation in the activated carbon filter. The filter clogged and the pressure drop increased. The clogging could be solved by adding some mineral acid to the feed of the activated carbon filter for a period of 2 weeks. Additionally the activated carbon filter was backwashed once per day. By this measure the pH was decreased, the LSI became negative and the calcite scale disappeared. During the following time of this research project, the air flow rate was decreased significantly so that the water was in the equilibrium ($\text{LSI} = 0$).

4.1.1.7 Staff requirements

The operation and maintenance of a drinking water treatment plant with Biological Denitrification technology requires excellent staff members which have to be absolutely reliable and motivated. At least 1 very well educated engineer plus 3 mechanics or technicians plus 1 lab technician are needed to operate and maintain one medium-size treatment plant (capacity: $400 \text{ m}^3/\text{h}$) in Iran. All persons in charge must be familiar with the plant in detail. An intensive training programme for all personnel is essential.

4.1.2 RO

4.1.2.1 Process performance

In the first 12 month of the investigation the flow rates of the RO pilot plant were adjusted to $3.8 \text{ m}^3/\text{h}$ (feed), $3.0 \text{ m}^3/\text{h}$ (permeate) and $0.8 \text{ m}^3/\text{h}$ (concentrate), which is equivalent to a 80 % recovery rate. The feed water was conditioned by addition of antiscalant (Phosphonate) and the pH was adjusted to 6.7 by dosage of hydrochloric acid.

During this first period the RO pilot plant was operated continuously and no problems such as scaling were noticed. There was no significant increase of transmembrane pressure (TMP) or decrease in permeate water quality (conductivity, nitrate concentration). Thus, after 12 months operation the recovery rate was increased to 85 %, resulting in the following flow rates: $4.0 \text{ m}^3/\text{h}$ (feed), $3.4 \text{ m}^3/\text{h}$ (permeate) and $0.6 \text{ m}^3/\text{h}$ (concentrate).

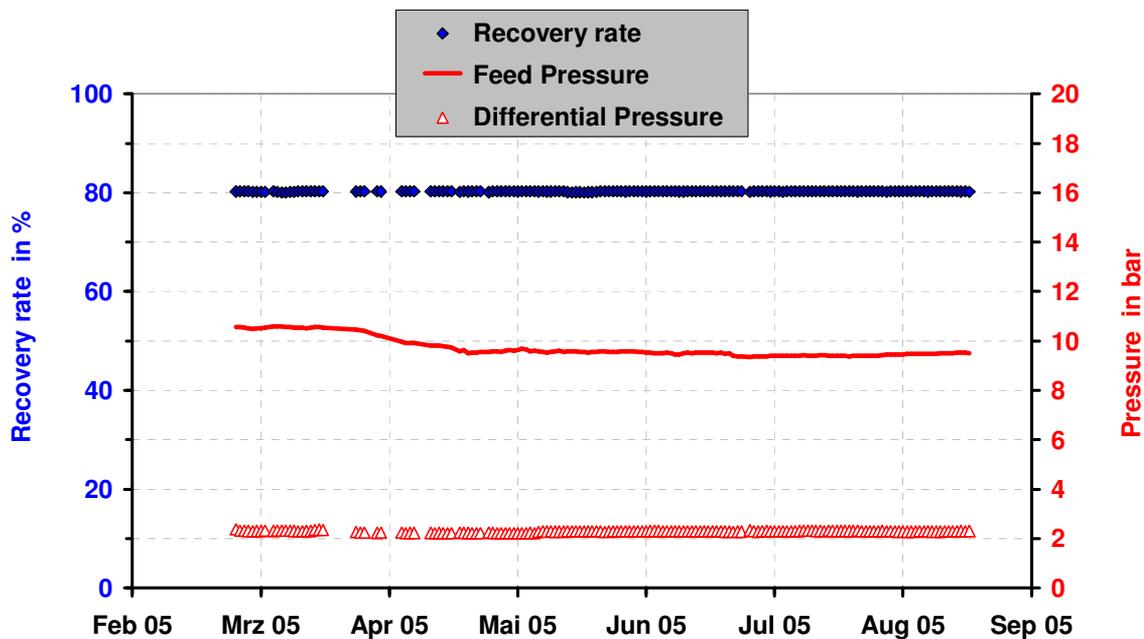


Figure 20: Recovery rate, feed and differential pressure of the RO pilot plant in 2005 (80 % recovery rate)

All salts retained by the RO membrane were collected in the concentrate resulting in a high salinity in this solution (> 5 mS/cm). Therefore the RO concentrate is not convenient for direct irrigation purposes and due to technical and economical reasons in most cases an advanced treatment is not feasible either. Thus the RO concentrate has to be disposed in a suitable way.

In terms of conductivity the salt retention of the RO was about 97 – 98 %. The nitrate concentration decreased by 95 % from 115 to about 6 mg/L. However, the desired nitrate concentration of the effluent water was 40 mg/L. This nitrate concentration was adjusted by blending permeate with a certain amount of raw water. With this procedure the total amount of fresh and product water was increased significantly. Simultaneously the ratio of waste water decreased to 15 % (Phase 1) and 11 % (Phase 2), respectively. Table 2 shows the summarized results of the RO pilot plant experiments in 2005 and 2006.

Table 10: Summarized results from the RO pilot plant experiments in 2005 and 2006

		Phase 1	Phase 2
		Nov. 2004 - Nov. 2005	after Nov. 2005
Recovery Rate	%	80	85
Feed Flow Rate	m ³ /h	3,8	4,0
Permeate Flow Rate	m ³ /h	3,0	3,4
Concentrate Flow Rate	m ³ /h	0,8	0,6
Feed Pressure	bar	10	12
Trans-Membrane Pressure	bar	9	11
Antiscalant Dosage	ppm	3,0	3,5
pH Feed *	-	6,7	6,7
Conductivity Feed	μS/cm	1550	1550
c(NO₃) Feed	mg/l	115	115
Conductivity Permeate	μS/cm	30	40
c(NO₃) Permeate	mg/l	5	7
Salt Retention (Conduct.)	%	98 %	97 %
Raw Water blending Flow rate	m ³ /h	1,4	1,5
Mixed Water Flow rate **	m ³ /h	4,4	4,9
Overall Recovery **	%	85 %	89 %
Wastewater ratio **	%	15 %	11 %
Conductivity Mixed Water **	μS/cm	500	500
c(NO₃) Mixed Water **	mg/l	40	40

* adjusted by Dosage of HCl (Hydrochloric Acid)

** after blending permeate with raw water

The final water quality resulting from the RO treatment process will be discussed in chapter 4.1.2.3.

4.1.2.2 Optimization of the RO process

In July 2007 – after 2.5 years of operation without major problems – operation of the RO process was modified with regard to its pre-treatment: Before that time hydrochloric acid and antiscalant were added to the raw water for prevention of scaling. However, the handling of hydrochloric acid (30 %) was always a matter which caused concerns, particularly in terms of occupational safety. Due to the raw water composition, a high specific acid dosage was necessary for achieving pH 6.7. (In the beginning of the project pH 6.7 was recommended by the membrane manufacturer and it was the result of several calculation programs for RO design.) Besides the

safety concerns, dosage of hydrochloric acid increases the salt content of the concentrate and the operating costs will run up. Therefore it was intended to stop dosage of hydrochloric acid and – if necessary – to substitute it by a higher dosage or a different type of antiscalant. Table 11 summarizes the operating conditions during the optimization of the RO process.

Table 11: Operating conditions during the optimization of the RO process

		Original operating condition	Test # 1	Test # 2	Test # 3	Test # 4	Test # 5	Test # 6	Final operating condition
Recovery rate	%	85%	70%	75%	80%	80%	85%	85%	85%
Feed flow	m ³ /h	4,0	3,6	3,3	3,8	3,8	3,5	3,5	4,0
Permeate flow	m ³ /h	3,4	2,5	2,5	3,0	3,0	3,0	3,0	3,4
Concentrate flow	m ³ /h	0,6	1,1	0,8	0,8	0,8	0,5	0,5	0,6
Hydrochloric acid dosage	mg/l Feed	~ 100	no						no
Antiscalant type	-	OS SH 7 *	Genesys LF **						OS SH 7 *
Antiscalant dosage (undiluted)	mg/l Feed	3,0	3,0	3,0	3,0	2,5	2,5	2,0	2,0
Dilution factor	%	3 %	3 %	3 %	3 %	2 %	2 %	2 %	2 %
Antiscalant dosage (diluted)	ml/m ³ Feed	100	100	100	100	125	125	100	100
Antiscalant dosage (diluted)	ml/h	400	357	333	375	469	441	353	400
Antiscalant dosage (diluted)	l/d	9,6	8,6	8,0	9,0	11,3	10,6	8,5	9,6

* Phosphonate (DTPMP) supplied from OSMO membrane systems company

** Neutralized Phosphonic acid supplied from Genesys RO company

During each test the process data were observed carefully for 3 days. When there were no problems, such as pressure increase, then the next test was performed.

During this optimization tests there was no significant pressure increase and no other indicators for any malfunction. Subsequent to these tests, the RO pilot plant was operated for another 5 months (until the end of the research project) without acid dosage. Also during that time there was no significant pressure increase and no chemical cleaning of the membranes was necessary. Thus, it can be concluded that acid dosage could be stopped without causing any major problems.

In connection with these tests several laboratory analyses were performed additionally. Figure 21 illustrates the development of the ion concentrations in RO concentrate during increase of recovery rate.

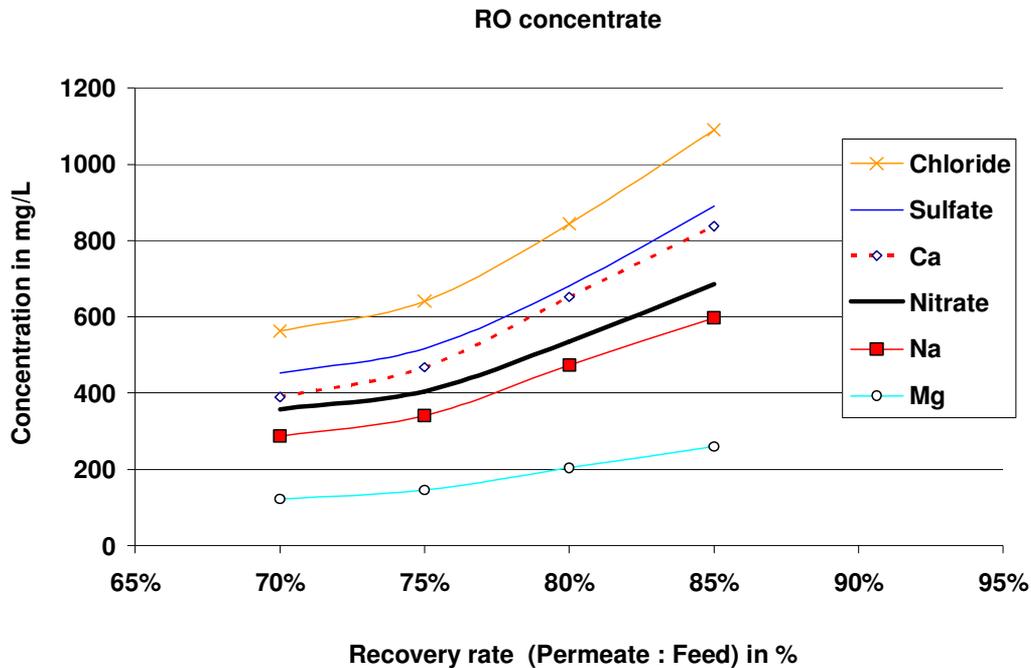


Figure 21: Development of the ion concentrations in RO concentrate during increase of recovery rate

Depending on their concentration in the raw water, the concentrations of the different ions increase in the RO concentrate. A recovery rate of 75 % means that ions will be enriched in the concentrate by approx. factor 4. It becomes obvious that the chloride concentration exceeded 1000 mg/L at 85 % recovery rate. Sulfate, calcium nitrate and sodium were in the range of 600 – 900 mg/L each. The high sulfate concentration of the RO concentrate may give reason for concern: Sulfate concentrations higher than 600 mg/L may affect sewer pipelines in terms of concrete corrosion. This fact has to be considered for the discharge pipeline of a full-scale RO treatment plant.

Figure 22 shows the TDS concentrations (Total Dissolved Solids) in the RO concentrate which were measured during the optimization tests.

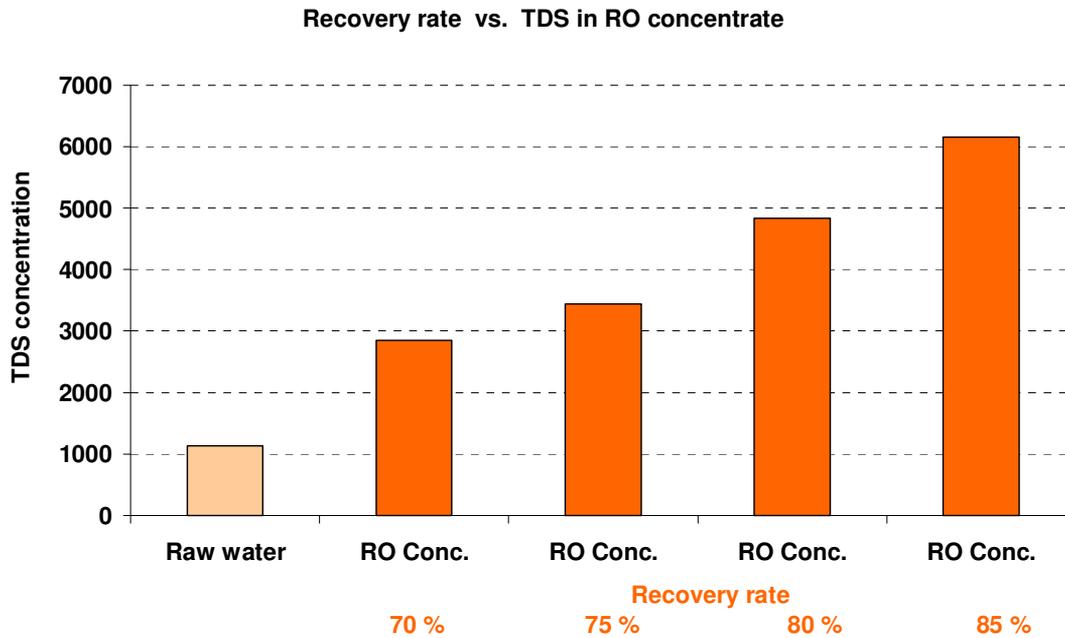


Figure 22: Total dissolved solids (TDS) in the RO concentrate

4.1.2.3 Quality of the treated water

As explained in chapter 2.2, RO technology can achieve an almost entire demineralization. Table 12 shows the composition of the RO permeate and feed water.

Table 12: Composition of the RO permeate and feed water

		Raw water (RO feed before dosage)	RO Permeate (after gas exchange)
pH *	-	7,24	7,20
Conductivity (25 °C) *	μS/cm	1516	35
Dissolved O ₂ *	mg/l	2,97	5,99
Ca	mg/l	139	< 1,0
Mg	mg/l	43,7	< 1,0
Na	mg/l	109	6,1
K	mg/l	1,8	< 0,5
Cl	mg/l	184	2,6
NO ₃	mg/l	115	7,9
SO ₄	mg/l	150	< 1,0
HCO ₃	mmol/l	5,36	0,29

* on site analysis

While the divalent ions (Ca , Mg , SO_4) were completely removed, low concentrations of nitrate, chloride and sodium were still detectable in the RO permeate. The total salt reduction (in terms of conductivity) was approx. 98 % whereas the reduction of nitrate was in the range of 93 %.

Nevertheless, the quality goal for nitrate was 40 mg/L which means that the RO permeate (8 mg/L nitrate) could be mixed with a certain amount of raw water (115 mg/L). Figure 23 shows the nitrate concentration of mixed water and wastewater percentage as a function of the bypass ratio. In this example a recovery rate of 85 % was considered.

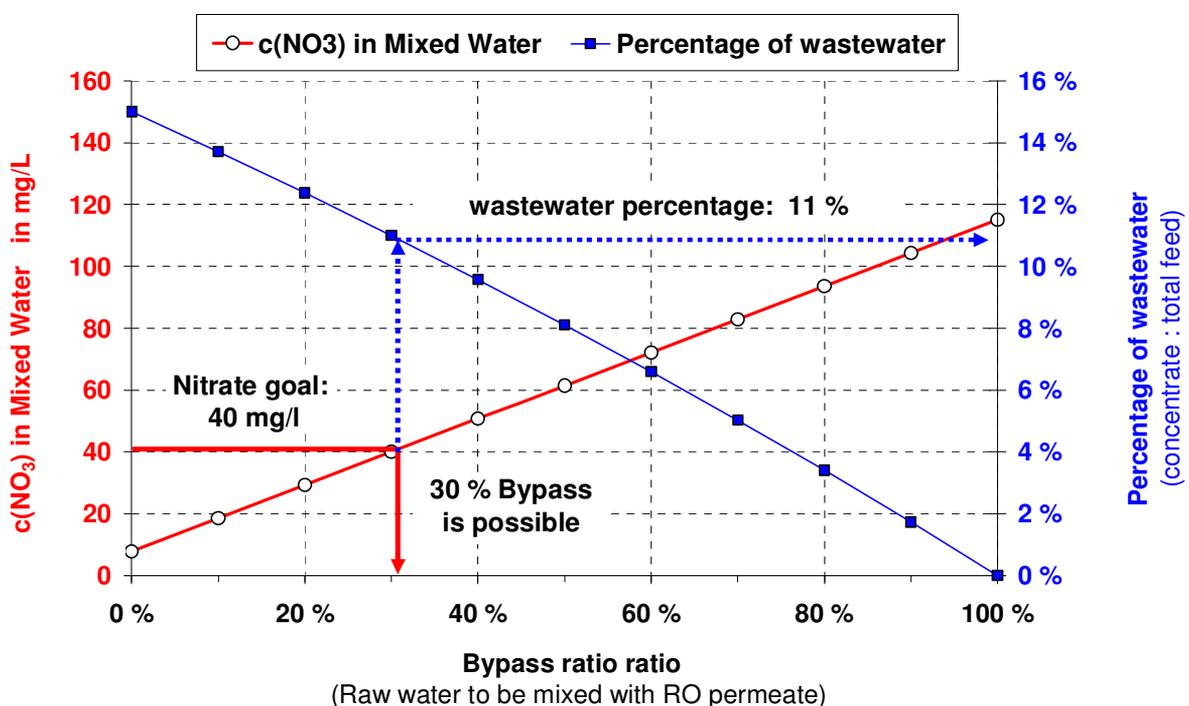


Figure 23: Nitrate concentration of mixed water and wastewater percentage as a function of the bypass ratio

It can be seen that the maximum bypass ratio was 30% if the desired nitrate level of 40 mg/L should not be exceeded. At this operating condition, the percentage of wastewater would be 11 %, compared to the raw water input (total feed).

4.1.2.4 Process requirements (chemicals, energy)

In 2005 and 2006 hydrochloric acid and antiscalant were used simultaneously for pre-treatment of the raw water in order to avoid scaling on the RO membranes. At that time the specific demand of hydrochloric acid (concentration: 30%) was approx. 120 g/m^3 (related to RO feed flow). However, after optimization of the RO process in 2007 (see chapter 4.1.2.2) the dosage of acid was stopped and then antiscalant was the only chemical which had to be added to the raw water. The specific demand of antiscalant was approx. 2.5 g/m^3 (related to RO feed flow).

The Antiscalant (and acid) should be purchased from a certified dealer and its composition and purity should conform to international standards relating to application of chemicals in drinking water treatment (e.g. DIN EN 1210 or DIN EN 15040). Antiscalant has to be stored at moderate temperatures (5 – 30 °C). In Mashhad, for safety reasons the entire RO pilot plant was equipped with an air condition.

The specific energy consumption of the RO pilot plant (incl. pre- and post-treatment, without air condition) was approx. 0.8 kWh/m^3 (related to mixed water flow). It can be calculated that the energy consumption of a full-scale RO plant (with similar process technology) would be in the range of 0.6 kWh/m^3 .

4.1.2.5 Operation and Maintenance

Although the RO plant worked fully automated it has to be mentioned that there are several tasks which have to be performed regularly and carefully during its operation, such as:

- Preparation of antiscalant (and acid) solution
- Flow control of antiscalant (and acid) dosage
- Inspection and calibration of measuring instruments (pH, conductivity, nitrate)
- Control of cartridge filters (and replacement, if necessary)
- Cleaning of tanks
- Maintenance of pumps (high and low pressure pumps, dosage pumps)
- Maintenance of blowers
- Maintenance of the pressurized air system (control air) and pneumatic valves

For quality and safety reasons an intensive and continuous control of the plant is essential. This includes

- Daily inspection of all major components (including pre- and post-treatment)
- Daily check of process data
- Periodical control of process performance by means of on-site and laboratory analyses
- Keeping a plant journal (operation journal) and a maintenance plan
- Supervision of all process information

In 2005 and 2006 chemical cleaning of the RO membranes was performed once per year, although from the technical point of view it was not absolutely necessary because the pressure increase was not significant. However, chemical cleaning was performed once per year due to safety reasons and for getting practical experience with this cleaning procedure.

Replacement of the membranes is a maintenance task which typically has to be done after some 3 to 10 years of operation. The interval largely depends on the operating conditions of the process, such as raw water composition, pre-treatment and recovery rate etc. In 2007 replacement of RO membranes was performed for one pressure vessel, although from the technical point of view it was not necessary, because there was no scaling and no significant pressure increase. However, membrane replacement was performed for getting practical experience with this procedure. The time need for replacement of 6 RO modules (= 1 pressure vessel) was approximately 2 hours.

4.1.2.6 Operating experiences and potential problems of the process

During the entire operation time of the RO pilot plant no serious operating problems were observed.

Although there were no problems in Mashhad, it has to be emphasized that accurate pre-treatment (e.g. pre-filtration and dosage of chemicals) is essential for each RO process. Careless pre-treatment results in worse performance of the RO process and it will decrease the lifetime of the membranes significantly. Therefore, well edu-

cated, absolutely reliable and motivated staff members are essential for successful operation of an RO plant.

4.1.2.7 Staff requirements

Operation and maintenance of a RO drinking water treatment plant requires excellent personnel. At least 1 very well educated engineer plus 2 mechanists or technicians are needed to operate and maintain one medium-size treatment plant (capacity: 400 m³/h) in Iran. All persons in charge must be familiar with the plant in detail and absolutely reliable. An intensive training programme for all personnel is essential.

4.1.3 Ion Exchange

4.1.3.1 Process performance

Figure 24 shows a typical breakthrough curve of the four major anions obtained from effluent samples which were taken during a service cycle. The Ion Exchange column was filled with 200 litre of the nitrate selective resin HP 555. During this service cycle it was operated in upstream and the flow rate was 2 m³/h.

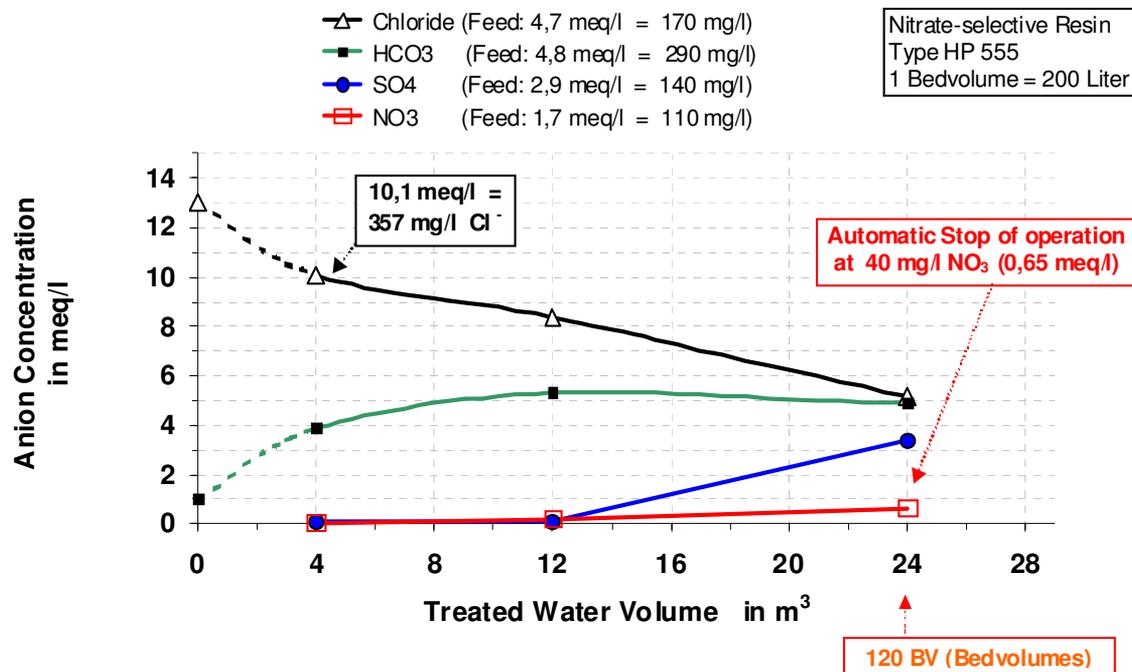


Figure 24: Breakthrough curve of the Ion Exchange Pilot plant

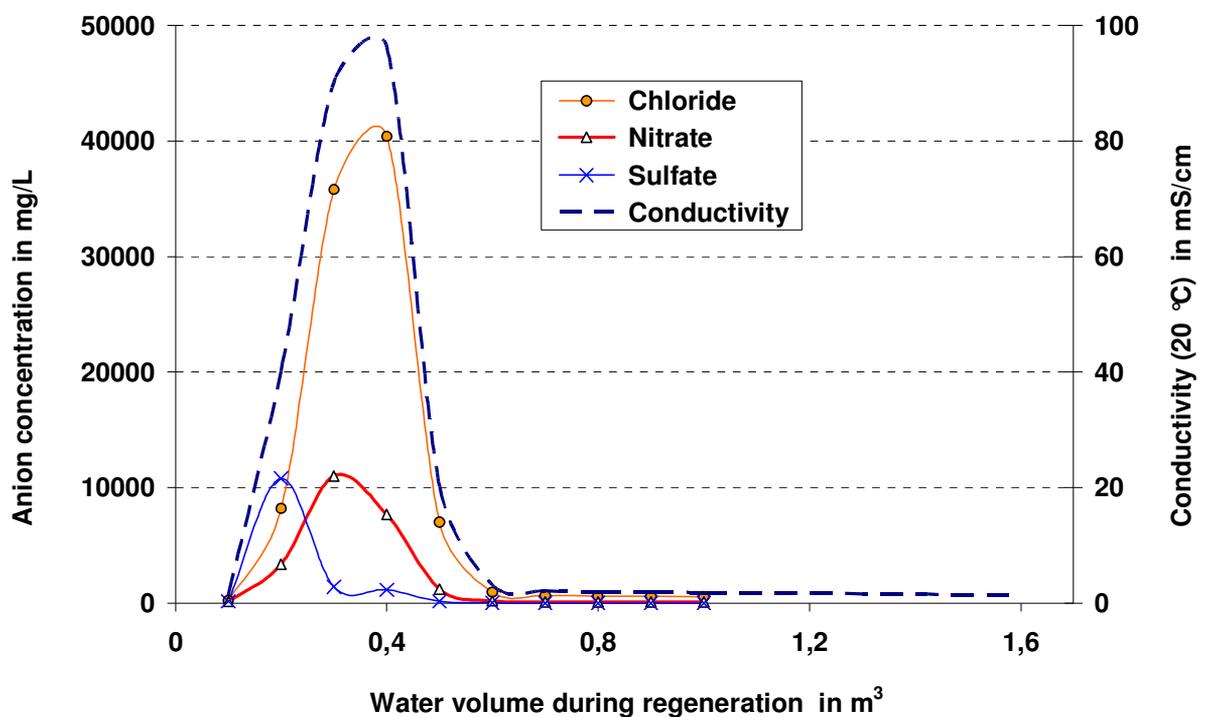
In the beginning of the service cycle nitrate and sulphate were removed almost completely by the anion exchanger. Later the sulphate and nitrate effluent concentrations increased. The service cycle was terminated automatically after 24 m³ (120 bed volumes) when the nitrate effluent concentration exceeded 40 mg/L (in this case). Due to the exchange of nitrate and sulphate the effluent concentration of chloride was increased significantly, particularly in the beginning of the service cycle. After a treated water volume of 4 m³ (20 BV) the chloride concentration was 357 mg/L (10.1 meq/L) which was approx. twice as much as the feed concentration. Assuming an almost complete removal of bicarbonate in the initial phase of the service cycle, it can be estimated that the chloride concentration initially was even higher than 400 mg/L (dashed black line).

Furthermore, Figure 24 illustrates that a “nitrate-selective” resin was employed in this case because the break through of sulphate occurred before nitrate. In contrast to this, during service cycle of a “conventional” strong base anion exchanger nitrate would be released before sulphate.

In this example the average nitrate concentration in effluent was 16 mg/L (see chapter 4.1.3.3) and the average nitrate reduction (feed concentration minus effluent

concentration) was 89 mg/L. In consideration of the treated water volume (24 m^3) and the resin volume (200 litre), an operating capacity of $\sim 0.17 \text{ eq/L}$ (equivalents of nitrate per litre of resin) was calculated for this example. Although HP 555 is a “nitrate-selective” resin, the calculated operating capacity for sulphate was even higher ($\sim 0.29 \text{ eq/L}$).

Regeneration always was conducted with certain amount of a sodium chloride solution (NaCl). Figure 25 shows the development of anion concentrations and conductivity (in effluent) during a typical regeneration cycle. The water quality parameters were measured in laboratory.



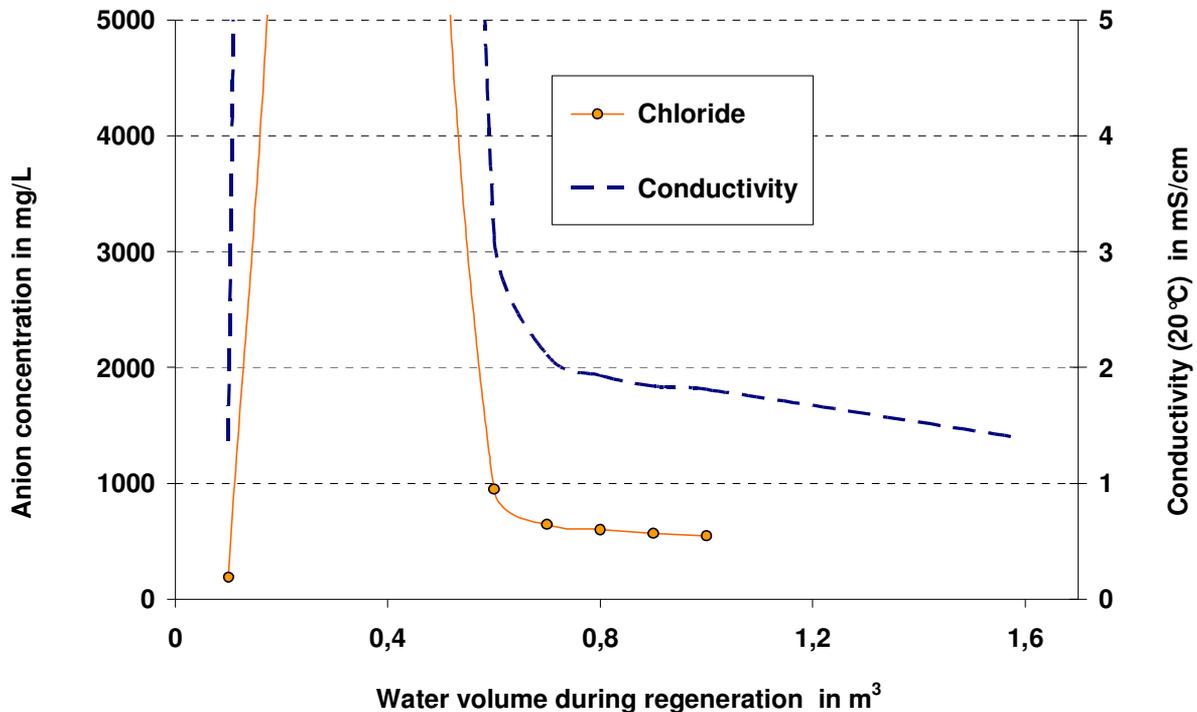


Figure 25: Development of anion effluent concentrations and effluent conductivity during a regeneration cycle

During regeneration with NaCl solution, the first concentration peak resulted from the release of sulphate, whereas nitrate and chloride peaks occurred a little bit later. This indicates that the resin was nitrate selective.

The average conductivity of the initial cubic meter of wastewater (spent brine solution + rinsing water) was about 30 mS/cm, resulting mainly from a “high salinity peak” which represented the spent brine solution and lasted about 3 BV (600 L). Due to the very high salinity of this spent brine fraction it is not suitable for any further utilization and these 3 BV (2.5 % of the treated water) have to be disposed (e.g. to the sewer). The following 4.5 BV of spent rinsing water are significantly lower in conductivity and could be used for other purposes (e.g. irrigation).

In this case, regeneration was conducted with 250 litres (1.25 bed volumes) of a 6 % NaCl solution, representing a specific regenerant level of 80 g NaCl per litre of resin. Then the NaCl solution was displaced by water from the clear water tank which was low in nitrate concentration. About 1.25 m³ of clear water was required for this rinsing step until finally the conductivity of the effluent was similar to the feed water (ca. 1.5 mS/cm). Therefore, in most cases the total waste water volume amounted to ~

1.5 m³ which is 7.5 BV (bed volumes). Thus, total wastewater volume was about 6 % in relation to the treated water volume (ca. 120 BV during service cycle).

The results from the other nitrate-selective resin (SR 7) were almost similar to HP 555.

4.1.3.2 Optimization of the process

In most Ion Exchange applications it is important to find the optimum working point of the regeneration and the service cycle, e.g. with regard to the following aspects:

- Little leakage of the unwanted ions
→ good water quality
- High operating capacity of the resin
→ little resin volume and small plant size (investment costs) or
→ less frequent demand for regeneration (operating costs)
- Little specific demand of regeneration chemicals
→ less operating costs

However, usually a low leakage and a high operating capacity can only be achieved when the specific demand of regeneration chemicals is high. On the other hand, a low level of regenerant in most cases will result in a low operating capacity and a high leakage.

Figure 26 shows the nitrate effluent concentration during a service cycle of HP 555 under optimized conditions. In this case, the flow rate was 3 m³/h, the previous regeneration was conducted in counter-current, and the specific NaCl demand was approximately 120 g/L_{Resin}.

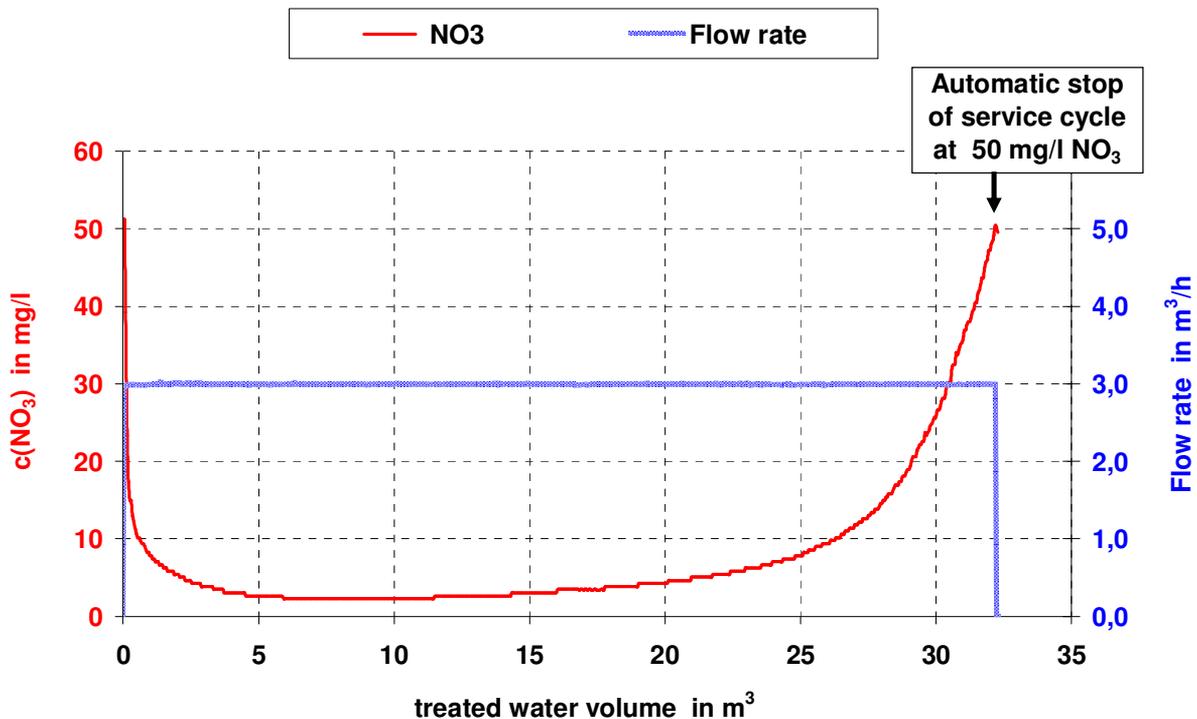


Figure 26: Nitrate effluent concentration during a service cycle (data from online measurement; resin type: HP 555)

The minimum nitrate leakage during this service cycle was 2 mg/L. The service cycle was stopped automatically at 50 mg/L. However, the average nitrate concentration (calculated mixed effluent) was approx. 8 mg/L. The treated water volume was ca. 32.2 m³ which is equivalent to 161 bed volumes. The operating capacity of HP 555 during this service cycle was 0.26 eq/L_{Resin}.

After testing HP 555 additional tests were performed with Lewatit MP M 600, which is a conventional strong base anion exchanger. Under similar operating conditions as before (200 litre resin, counter-current regeneration, 120 g/L NaCl) the operating capacity of Lewatit MP M 600 was 0.32 eq/L_{Resin}, which indicates that this resin might be a better option, at least in terms of operating capacity (see discussion in chapter 4.2).

However, due to the poor quality of NaCl (see chapter 4.1.3.6) and the problems related to the high demand of NaCl for regeneration (see chapter 5), the project partners desired to stop further pilot plant experiments with Ion Exchange technology.

4.1.3.3 Quality of the treated water

As explained before, the water composition of the Ion Exchange effluent changed during the whole time of the service cycle. Thus, it is useful to focus on the average water. The average effluent water quality during the service cycle could be analyzed and it could be calculated by integration of the breakthrough curves (Figure 24). Table 5 presents the concentrations of the four major anions in the feed water and in the (calculated) average effluent water.

Table 13: Anion concentrations in the feed water and the (calculated) average effluent water

		Feed	Mixed Sample *	Difference
			Average Effluent Conc.	Effluent.* - Feed
		measured	calculated	calculated
Cl	mg/l	168	295	127
NO ₃	mg/l	105	16	-89
SO ₄	mg/l	140	25	-115
HCO ₃	mg/l	295	298	3
Cl	meq/l	4,7	8,3	3,6
NO ₃	meq/l	1,7	0,3	-1,4
SO ₄	meq/l	2,9	0,5	-2,4
HCO ₃	meq/l	4,8	4,9	0,0
Anion equivalents	meq/l	14,2	14,0	-0,2

* calculated by integration of the breakthrough curves

In this case the average nitrate concentration in the Ion Exchange effluent was approx. 16 mg/L. This means, on average the nitrate concentration decreased by some 89 mg/l which is 1.4 meq/L. Likewise, the average decrease of sulphate between feed and effluent was 2.4 meq/L. In contrast to this, the average chloride concentration increased by approx. 127 mg/L, resulting in an average chloride concentration of approximately 295 mg/L in the mixed effluent sample.

Although there is no WHO guideline value for chloride in drinking water (and also not in Iran) it has to be considered that in several parts of the world there exists a guideline value or a MCL (maximum contamination level) for chloride. For example, the chloride drinking water MCL in United States and in EU is 250 mg/L. Concentrations above this level may affect the taste of the water but the main reason for pre-

ferring low chloride concentrations in drinking water is that there is an increasing risk of piping corrosion when the chloride concentration is too high.

As shown in table Table 13, the average nitrate concentration in the Ion Exchange effluent was 16 mg/L but the nitrate goal was 40 mg/L. This means that the Ion Exchange effluent could be mixed with a certain percentage of raw water (24 %) until the maximum level was reached. The mixing of Ion Exchange effluent and raw water would result in a (slight) decrease of the chloride concentration which would then be ca. 270 mg/L in the blended water.

4.1.3.4 Process requirements (chemicals, energy)

The specific demand of chemicals (NaCl) mainly depends on the raw water quality, the desired effluent water quality and the desired operating capacity of the resin.

In consideration of the specific conditions of Mashhad (115 mg/L nitrate and 140 mg/L sulfate in raw water) a NaCl level during regeneration of approx. 120 g/L_{Resin} was necessary for achieving a moderate operating capacity (0.25 eq/L) and a moderate effluent quality (approx. 15 mg/L nitrate, on average).

Taking into account these boundary conditions, a raw water bypass of 24 % would be feasible for achieving 40 mg/L in the mixed water (Ion Exchange effluent + raw water bypass). In this case the specific NaCl demand for regeneration would be approx. 0.66 kg/m³ Mixed water.

The specific energy consumption of a full-scale Ion Exchange plant (with similar process technology) would be in the range of 0.1 kWh/m³.

4.1.3.5 Operation and Maintenance

In contrast to RO and Biological Denitrification plant the Ion Exchange pilot plant did not work fully automated. After each service cycle several valve positions had to be changed manually, before regeneration could be started.

Besides that, there were several tasks which had to be performed regularly and carefully, such as:

- Preparation of regenerant solution (NaCl), by dissolving solid salt
- Inspection and calibration of measuring instruments (conductivity, nitrate)
- Control of cartridge filters (and replacement, if necessary)
- Cleaning of tanks

For quality and safety reasons an intensive and continuous control of the plant is essential. This includes

- Daily inspection of all major components (including pre- and post-treatment)
- Daily check of process data
- Periodical control of process performance by means of on-site and laboratory analyses
- Keeping a plant journal (operation journal) and a maintenance plan
- Supervision of all process information

The lifetime of Ion Exchange resins largely depends on the operating conditions and on the resin type. For application of strong base anion exchangers in Mashhad a lifetime of approx. 5 years was expected. The resins were inspected occasionally and furthermore no decrease of their operating capacity was detected. Thus, from the technical point of view a replacement of the resins was not necessary. However, after 1 year of operation HP 555 (nitrate selective resin) was replaced by the conventional resin Lewatit MP M 600.

4.1.3.6 Operating experiences and potential problems of the process

Although the Ion Exchange pilot plant only had a semi-automatic control during service cycle it could be operated successfully and without major problems.

However, there was a significant problem related to the regeneration mode which was caused by the poor quality of NaCl. Due to its high content of impurities (suspended solids) there was a lot of sedimentation in the NaCl tank. The sediment also collected in the regeneration pipelines and affected the cartridge filters which were installed before the ion exchangers. Thus, the NaCl tank had to be cleaned frequently and the cartridge filters had to be replaced frequently as well.

A sample of the solid NaCl was analyzed in IWW laboratory. The content of suspended solids was 1.9 %. According to DIN EN 973 concerning quality of NaCl used for regeneration of ion exchangers the content of impurities (suspended solids) should be less than 0.05 %. This means, the content of impurities in the salt was approx. 40 times higher than the recommended value. Unfortunately large amounts of NaCl with a higher purity were not available in Iran.

Therefore, a full-scale Ion Exchange plant in Iran should have a separate sedimentation and cleaning step for the NaCl solution.

Besides that, it has to be emphasized that accurate preparation of the regeneration solution is essential for each Ion Exchange process. Otherwise the performance of the process might be affected and the lifetime of the ion exchangers could be decreased significantly. Therefore, well educated, reliable and motivated staff members are essential for successful operation of an Ion Exchange plant.

4.1.3.7 Staff requirements

Operation and maintenance of an IE drinking water treatment plant requires excellent personnel. At least 1 very well educated engineer plus 2 mechanists or technicians are needed to operate and maintain one medium-size treatment plant (capacity: 400 m³/h) in Iran. All persons in charge must be familiar with the plant in detail and absolutely reliable. An intensive training programme for all personnel is essential.

4.1.4 Electrodialysis

4.1.4.1 Process performance

Before starting the ED experiments with regard to water treatment and water quality, the limit current of the pilot plant had to be evaluated (see chapter 3.2.6.2). Figure 27 shows the results of the limit current evaluation, obtained for different flow rates during direct feed mode.

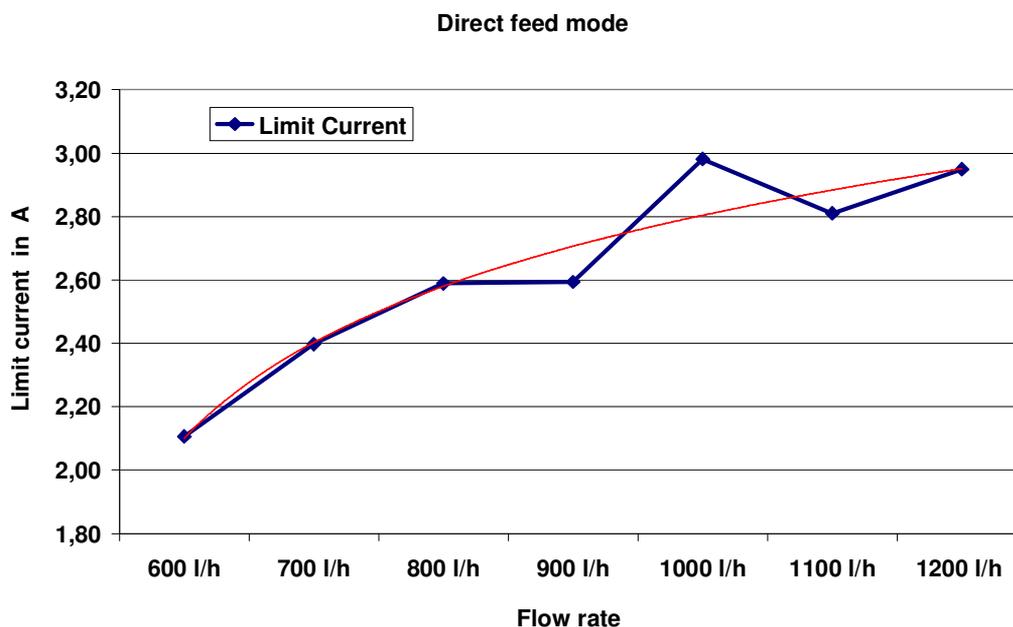


Figure 27: Limit current values for different flow rates in direct feed mode

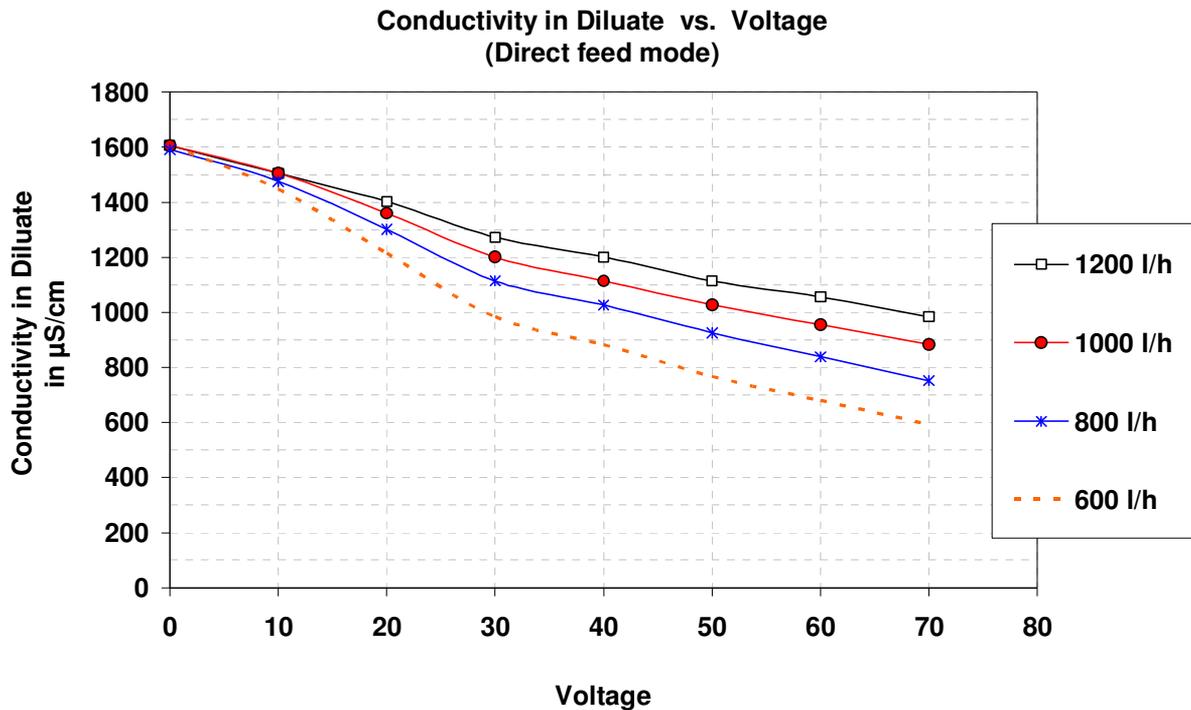
It can be seen that the limit current was higher when the flow rate was increased. As explained in chapter 3.2.6.2, during ED operation the electric current should not exceed 80 % of the limit current. In this case this means, the acceptable maximum current was between 1.7 A (at 600 L/h) and 2.4 A (at 1200 L/h). However, as the voltage was only adjustable in steps of 10 V, the maximum allowable current – in most cases were lower than before mentioned values (Table 14).

Table 14: Relation between flow rate and maximum allowable voltage

Voltage [V]	600 l/h [A]	700 l/h [A]	800 l/h [A]	900 l/h [A]	1000 l/h [A]	1100 l/h [A]	1200 l/h [A]
10	0,4	0,5	0,5	0,5	0,5	0,5	0,6
20	1,2	1,3	1,3	1,3	1,3	1,3	1,4
30	2	2,1	2,1	2,2	2,2	2,3	2,3
40	2,3	2,5	2,5	2,6	2,7	2,7	2,7

It can be seen that for flow rates between 600 and 900 L/h only voltage stage 2 (20 V) was feasible whereas between 1000 and 1200 L/h voltage stage 3 (30 V) was feasible.

Figure 28 shows the relationship between the water quality of ED diluate (conductivity, nitrate concentration) and voltage.



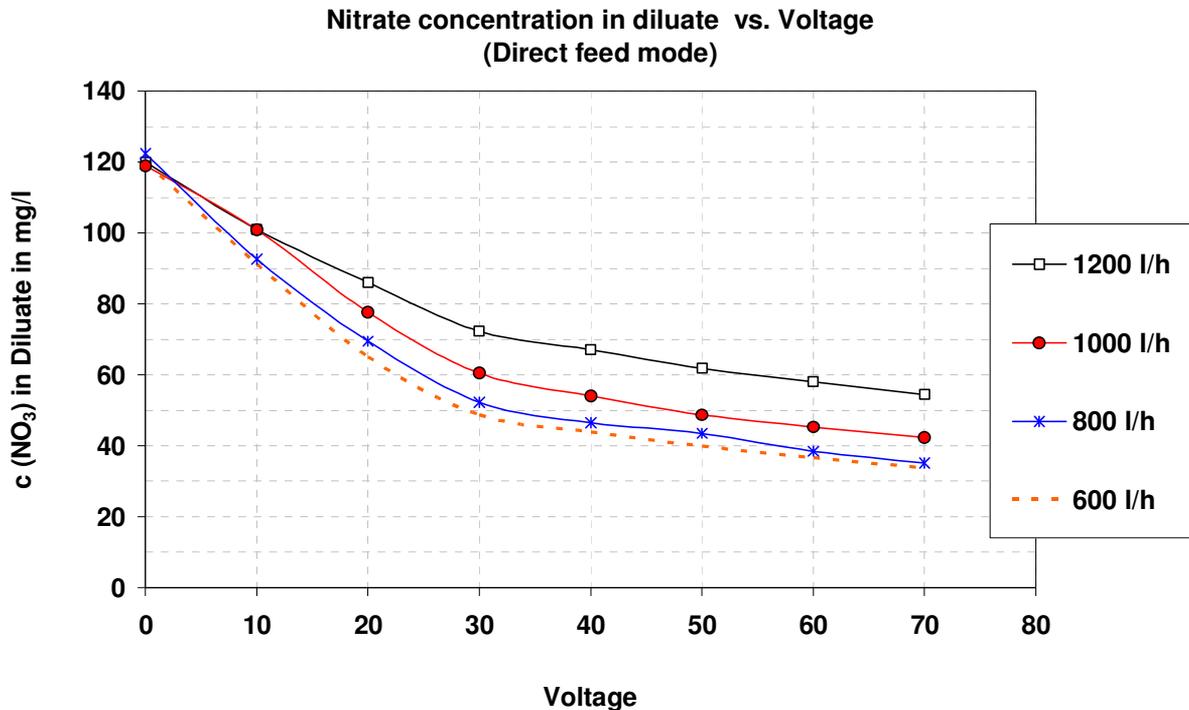


Figure 28: Conductivity and nitrate concentration in ED diluate vs. voltage

It can be seen that both, conductivity and nitrate concentration, were decreased significantly during the direct feed mode. Regarding a certain voltage level, conductivity and nitrate concentration in diluate were high when the flow rate was high. Likewise, conductivity and nitrate concentration in diluate were low when the flow rate was low.

With regard to 1000 L/h flow rate and 70 Volt the conductivity was reduced from 1600 to 900 $\mu\text{S}/\text{cm}$ and the nitrate concentration decreased from 120 to 42 mg/L.

However, at the feasible voltage stages 2 and 3 (20 and 30 V) the nitrate concentrations in the diluate were still between 60 and 70 mg/L. This means, the nitrate goal (40 mg/L) was not achieved during the direct feed mode, provided that the maximum allowable current was observed.

Figure 29 shows the reduction of conductivity and nitrate for a flow rate of 1000 L/h.

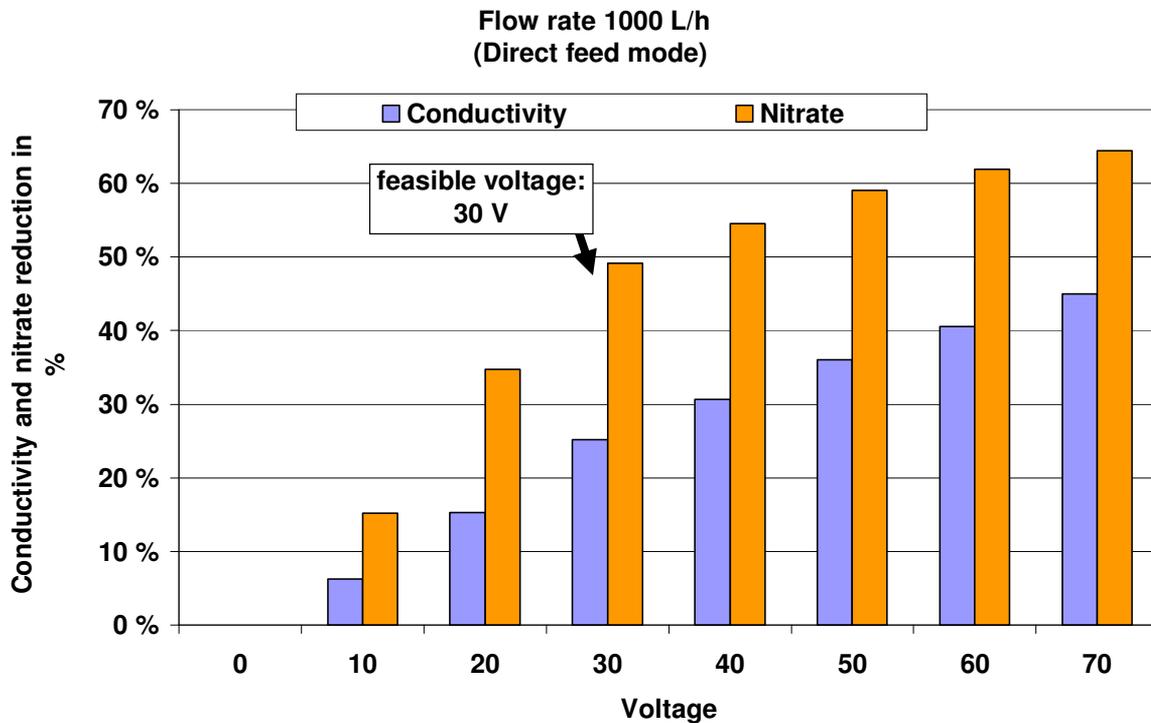


Figure 29: Reduction of conductivity and nitrate vs. voltage

It becomes obvious that nitrate ions were preferred during the desalination process because the nitrate reduction rate was significantly higher than the reduction of conductivity.

In the beginning the recovery rate of the ED system was adjusted to 90 %. Later the recovery rate was increased step by step up to 96 %. However, at this high recovery rate there were some problems in terms of precipitation on the electrodes. More details about this aspect will be given in chapter 4.1.4.6.

4.1.4.2 Optimization of the process

After finishing the experiments in direct feed mode the ED pilot plant was operated in the batch mode, in order to improve the effluent water quality. As explained before, by means of the batch mode a 2-stage process was simulated.

Figure 30 shows the development of the ion concentrations during a batch mode experiment (flow rate: 800 L/h at 20 V).

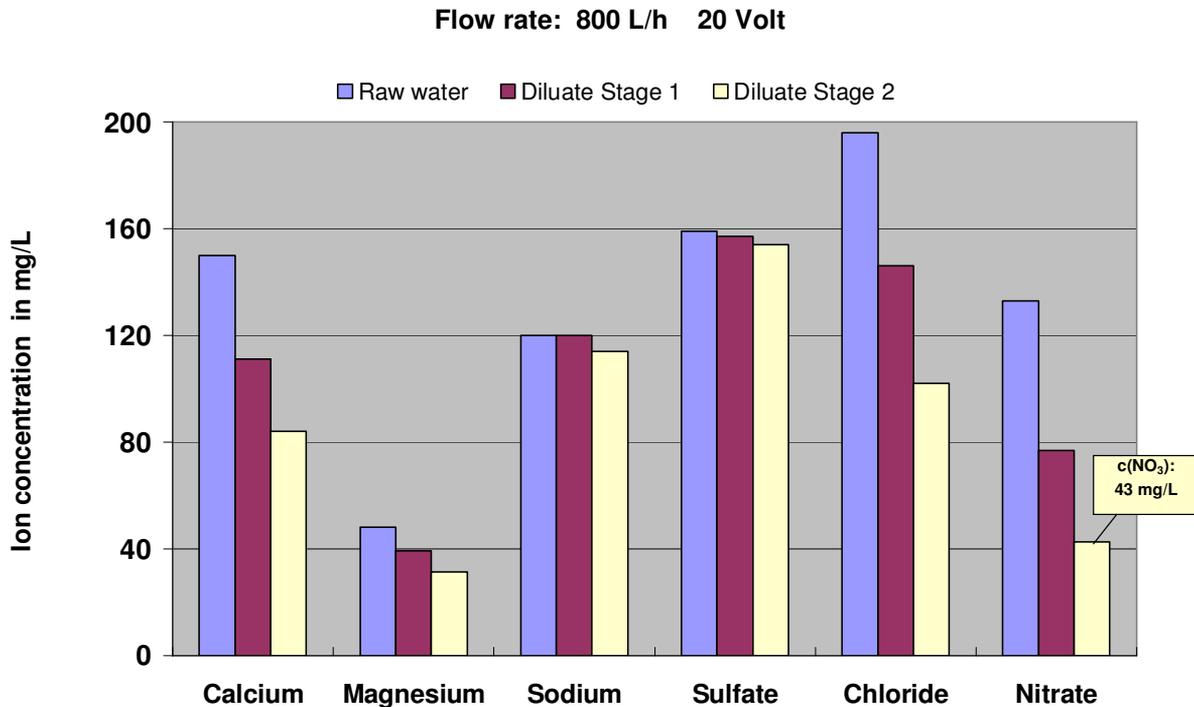


Figure 30: Ion concentrations during a batch mode experiment (flow rate: 800 L/h at 20 V)

It can be seen that both ED stages reduced all major cations and anions but the reduction patterns varied significantly between the different ions. For example on the one hand, calcium and chloride were reduced by some 45 % whereas sodium and sulfate concentrations were decreased only by some 4 %. Nitrate concentration was reduced from 133 mg/L (feed) to 43 mg/L (stage 2 effluent) which is a decrease by some 68 %. In this case, the overall salt reduction (in terms of TDS) was about 27 %.

Nevertheless, it has to be mentioned that the nitrate goal was not met in this case. In order to achieve a better water quality, there were two options:

- a) Reduction of the flow rate
- b) Increase of the voltage

Option a) was not desired because the intended flow rate of the pilot plant should not be lower than 0.8 m³/h. Option b) was only feasible by increasing the flow rate as well because otherwise the limit current would have been exceeded. Thus, the flow rate was increased to 1200 L/h and the voltage to 30 Volt.

Figure 31 shows the development of the ion concentrations during another batch mode experiment (flow rate: 1200 L/h at 30 V).

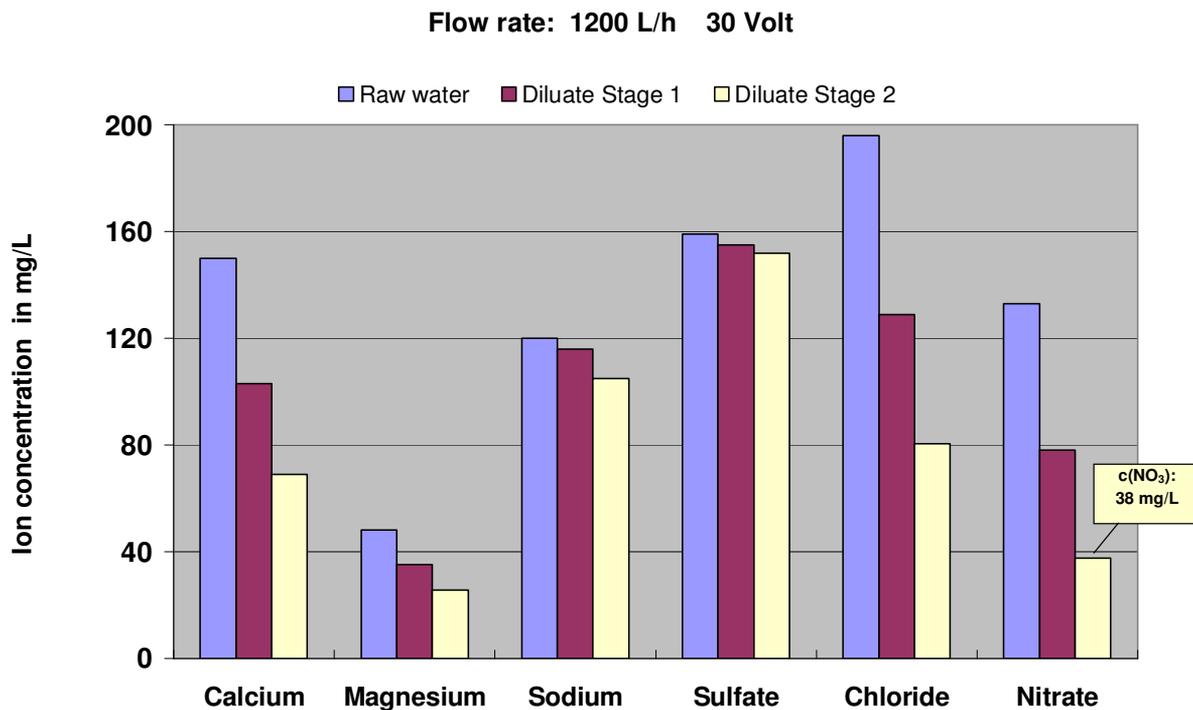


Figure 31: Ion concentrations during a batch mode experiment (flow rate: 1200 L/h at 30 V)

Generally the pattern for reduction of the ions was very similar to the previous experiment. However, in this case the nitrate effluent concentration was 38 mg/L. This means that the nitrate goal (40 mg/L) could be achieved by application of this operating condition.

Another series of experiments was conducted by recycling diluate to the feed of the ED plant. This procedure, also known as “feed and bleed mode”, allowed a flexible adjustment of the effluent quality.

Figure 32 shows the impact of the recycled diluate flow rate on the nitrate and TDS concentration in Diluate. In this case the voltage was 20 Volt and the flow rate through the ED stack was constant at 1000 L/h.

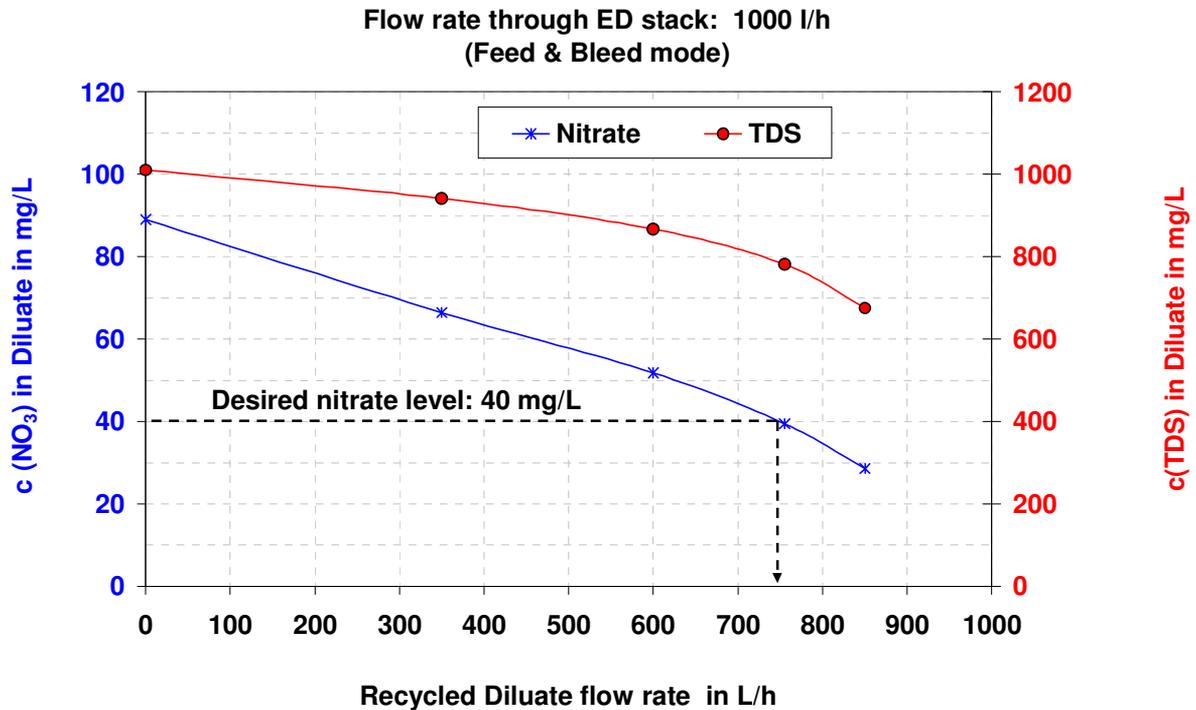


Figure 32: Recycled diluate flow rate vs. Nitrate and TDS concentration in Diluate

The diagram illustrates that nitrate and TDS concentrations were reduced significantly by means of diluate recycling to the feed. However, the desired nitrate level of 40 mg/L could only be met when the recycled diluate flow rate was 750 L/h or higher. This means, at this operating condition the effective diluate flow rate was only 250 L/h which is very low.

4.1.4.3 Quality of the treated water

Figure 33 shows the water composition of diluate 1 and 2 during one of the batch mode experiments, which simulated a 2-stage ED process.

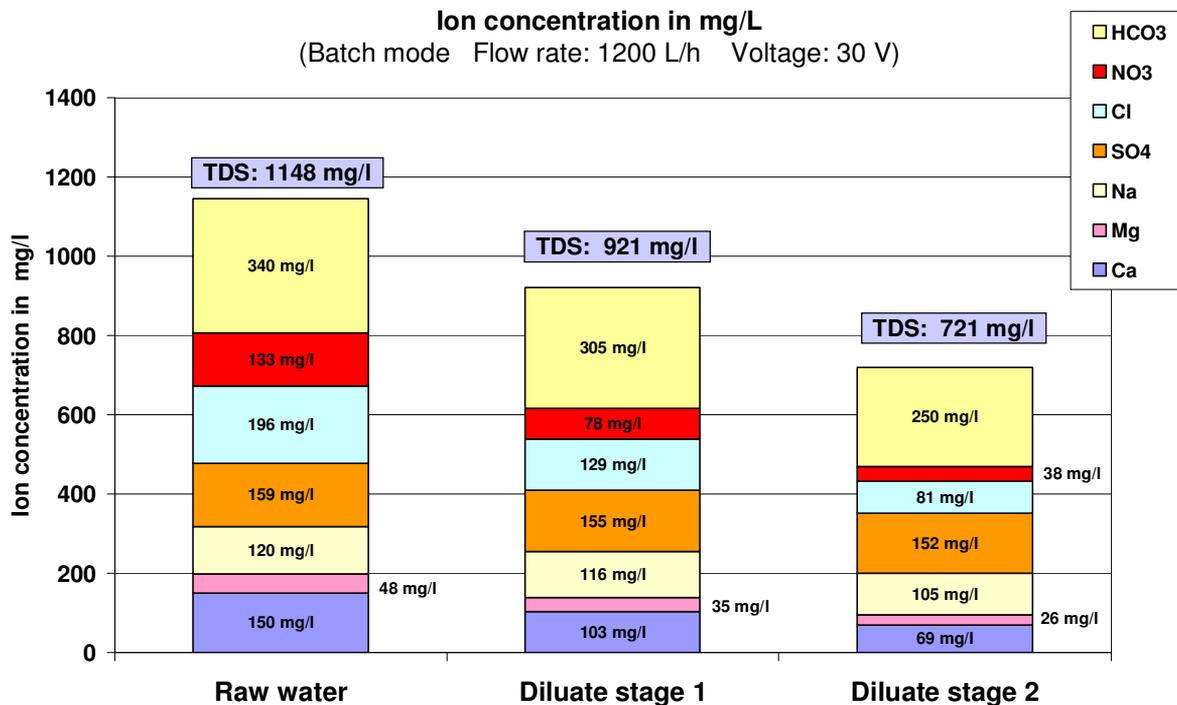


Figure 33: Composition of diluate 1 and 2 during the batch mode experiment at 1200 L/h and 30 Volt

4.1.4.4 Process requirements (chemicals, energy)

Unfortunately during the pilot plant experiments in Mashhad only very few data were obtained concerning the consumption of chemicals. In one case, in feed-and-bleed mode with 600 L/h recycling of diluate, the amount of hydrochloric acid (30 %) was 29 ml/h for 400 L/h of produced diluate. This means, the specific consumption was ca. 70 ml or 80 g per m³ of diluate. This value seems to be a little bit high compared to results obtained during long-term investigations by VA Tech Wabag. According to their experiences, the specific acid consumption can be assumed to be in the range of 50 – 60 g/m³, whereas the specific energy consumption of an ED plant for the specific boundary conditions of Mashhad is approximately in the range of 0.5 kWh/m³.

4.1.4.5 Operation and Maintenance

Although the ED plant worked fully automated it has to be mentioned that there are several tasks which have to be performed regularly and carefully during its operation, such as:

- Preparation of acid (or antiscalant) solution
- Flow control of acid (or antiscalant) dosage
- Inspection and calibration of measuring instruments (pH, conductivity, nitrate)
- Control of cartridge filters (and replacement, if necessary)
- Cleaning of tanks
- Cleaning of the ED stack (CIP)
- Maintenance of pumps (diluate, concentrate, electrode rinse, dosage pumps)
- Maintenance of the pressurized air system (control air) and pneumatic valves

For quality and safety reasons an intensive and continuous control of the plant is essential. This includes

- Daily inspection of all major components (including pre- and post-treatment)
- Daily check of process data
- Periodical control of process performance by means of on-site and laboratory analyses
- Keeping a plant journal (operation journal) and a maintenance plan
- Supervision of all process information

Replacement of the ED membranes is a maintenance task which typically has to be done after some 5 to 10 years of operation. The interval largely depends on the operating conditions of the process, such as raw water composition, pre-treatment and recovery rate etc.

Replacement of the ED electrodes is a maintenance task which typically has to be done after 2-3 years of operation.

4.1.4.6 Operating experiences and potential problems of the process

Generally the ED pilot plant could be operated easily and successfully. However, during the experiments there were some technical problems, caused by defect components of the pilot plant, which complicated the scientific investigations, such as:

- In the beginning of the experiments the conductivity online measurement of the concentrate cycle did not work or the values were inaccurate. Therefore, conductivity had to be measured manually and the concentrate dilution did not work automatically. The problem could be solved after some months, after a new spare part arrived in Mashhad.
- Some weeks after start of the experiments, the electrode rinse pump had a technical problem. At first, it seemed to be impossible that the pump could be repaired in Iran so that a new pump was ordered in Europe. However, it took several weeks until the pump reached in Iran but then the pump was kept by the Iranian customs authorities. For efficient continuation of the ED pilot plant experiments, electrode rinse pump was replaced by the diluate pump. In this mode the ED plant was fed by the pressure of the well pump. Then, a specialized Iranian company was found, which was able to repair the defect pump.

Another aspect, which slightly complicated the ED experiments, was the voltage adjustment, which could only be performed in stages of 10 V.

Finally it has to be mentioned that there was a problem concerning the pH measurement in the concentrate cycle. Originally pH measurement and control of acid dosage were integrated in the PLC of the ED pilot plant. However, this particular PLC control loop did not work so that the acid dosage had to be controlled by the measurement instrument itself and the set-point (target value for pH) of the PLC had to be enabled. Thus, there was no alarm or emergency shutdown of the plant when the pH value was too high. As a consequence of this, sometimes the ED plant was in operation even when the acid dosage container was empty and the pH value in concentrate was too high. During these times precipitation took place on the electrodes. Figure 34 shows scaling on the electrode and on the spacer of the ED stack.

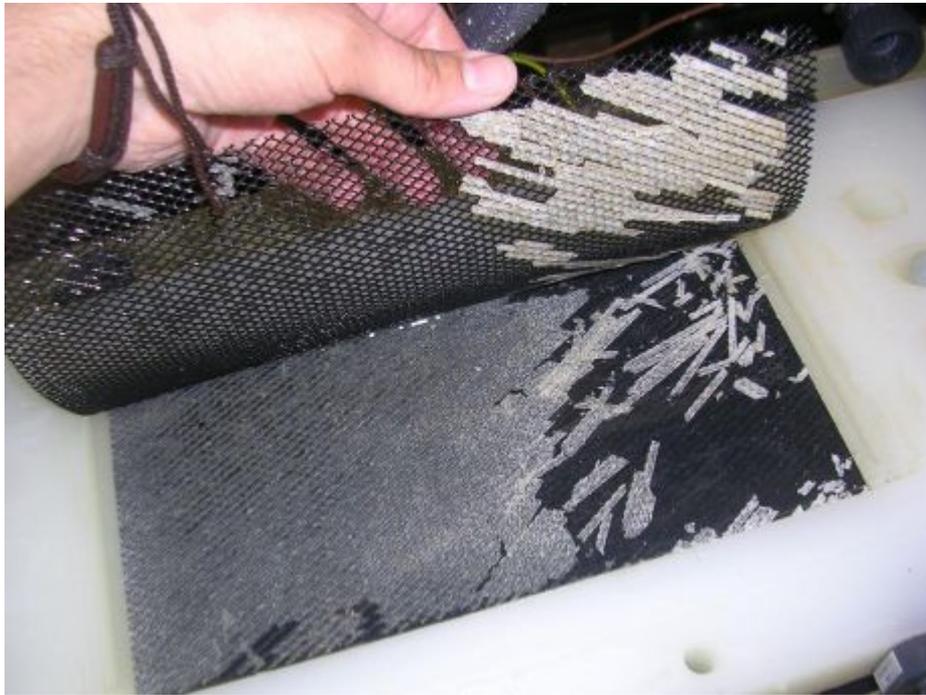


Figure 34: Scaling on the electrode and on the spacer

It was found that these deposits mainly consist of calcium carbonate, which means, they could have been avoided if the pH value in the concentrate had been lower.

It becomes obvious that acid dosage and pH control are crucial aspects for successful operation of an ED plant.

4.1.4.7 Staff requirements

Operation and maintenance of an ED drinking water treatment plant requires excellent personnel. At least 1 very well educated engineer plus 2 mechanists or technicians are needed to operate and maintain one medium-size treatment plant (capacity: 400 m³/h) in Iran. All persons in charge must be familiar with the plant in detail and absolutely reliable. An intensive training programme for all personnel is essential.

4.2 Discussion and conclusions

4.2.1 Performance of the processes

4.2.1.1 Biological Denitrification

The Biological Denitrification pilot plant could be operated very effectively in Mashhad/Iran. The nitrate concentration could be decreased from ca. 120 mg/L (feed) to 40 mg/L in the effluent of reactor 1 and to less than 35 mg/L in the effluent of reactor 2. This means the nitrate degradation rate of this process was 6.4 respectively 7.0 kg NO₃/m³d. In the literature the highest value reported for nitrate degradation in (full scale) drinking water treatment plants is 5.5 kg NO₃/m³d. One reason for the remarkable performance of the biological pilot plant in Mashhad could be the good properties of the expanded clay material, which was used in drinking water denitrification for the first time. The second reason probably was the higher temperature of Mashhad's groundwater (~ 17 °C). In contrast to the typical groundwater temperature in Germany (~ 11 °C) the biological activity in the bio-reactors in Mashhad could be significantly higher.

Due to effective post-treatment (aeration, dual media and activated carbon filtration) the water quality of the pilot plant effluent was very good, as there were no nitrite, sulphide or ammonia detectable. Furthermore TOC, turbidity and bacterial count in the pilot plant's effluent were low as well.

It has to be mentioned that Biological Denitrification in drinking water treatment is a complex process. It needs very reliable and well trained staff members for operating and maintaining of the plant and for conducting the chemical and microbiological analyses. Fortunately the staff members of Mashhad Water and Wastewater Co. were just excellent.

On account of the very good results obtained at the pilot plant in Mashhad (e.g. high performance rate, good effluent water quality and low water demand for flushing), the Biological Denitrification process can be regarded as a very promising technology for application in full scale in water treatment plants in Iran and in other countries affected by high nitrate concentrations in drinking water sources, provided that the high demands on the qualification of the staff are met.

4.2.1.2 RO

The flux of the RO system was 29 l/m² h in the first stage and 15 l/m² h in the second stage: The permeability was approx. 3.5 l/m²h*bar in the first stage and approx. 2 l/m²h*bar in the second stage. From the technical point of view the RO pilot plant worked very reliable and did not give any reason for complaint. Besides that, the final water quality was very good so that RO definitely can be regarded as a suitable technology in order to improve the drinking water quality.

However, taking into account the water shortage in Mashhad (and many other regions in Iran), the main drawback of this process is the relative high amount of concentrate which has to be discharged and the increased raw water demand (see discussion in chapter 4.2.2).

As the RO pilot plant worked fully automated the time and effort for operation and maintenance was limited (~ 5 hours per week). The most time-consuming workings were the calibration of the pH sensors and the preparation of the dosage solutions (antiscalant and hydrochloric acid). These workings have to be performed by well educated staff members. It was a big success that finally dosage of hydrochloric acid could be stopped (without decrease of the performance) because previously handling of this acid always caused concerns in terms of operational safety and environmental aspects.

4.2.1.3 Ion Exchange

Ion Exchange was an effective process in terms of nitrate removal because the nitrate concentration could be decreased from 120 mg/L (feed) to less than 20 mg/L (mixed effluent sample). Besides that, it is a relatively simple process which can easily be automated. During experiments with the so-called nitrate-selective resins (HP 555, SR 7) the operating capacity varied between 0.14 and 0.26 eq/L_{Resin}, depending on the NaCl level during regeneration. Compared to other applications, these values are only moderate. After 1 year of operation HP 555 was replaced by the conventional anion exchanger Lewatit MP M 600 and then a better operating capacity (0.32 eq/L_{Resin}) was observed. Nevertheless, one should keep in mind that conventional anion exchanger prefer the uptake of sulfate ions before they adsorb nitrate ions. At unfavourable conditions (e.g. delayed regeneration due to defect nitrate measurement) application of such a conventional anion exchanger could re-

sult in a nitrate effluent concentration which temporarily even can be higher than the feed concentration (“chromatography effect”). Taking into account this risk, it seems advisable to employ a so called nitrate-selective anion exchanger because such resins avoid this effect.

However, the biggest disadvantage of the Ion Exchange process is the huge amount of NaCl which is needed for regeneration. As mentioned before, NaCl has to be used in excess to achieve an acceptable operating capacity. Taking into account the raw water composition and the effluent goals of this project, a water production of 9 Mio. m³/a drinking water (including raw water bypass) would require some 6000 tons (!) of NaCl. Apart from environmental aspects related to the discharge of brine solution (see chapter 4.2.2.3), supply and transport of such a huge salt amount would probably create problems as well. Additionally, it was found that the quality of the available salt was not sufficient with regard to the high content of impurities.

Another disadvantage is the chloride concentration in the final drinking water which was significantly increased by the Ion Exchange process. 270 mg/L chloride in drinking water may result in severe corrosion problems in the distribution net. Additionally it may affect the taste of the water and give cause for complaints of consumers.

It can be summarized, that Ion Exchange is an effective and simple method for nitrate removal but on the other hand it has considerable disadvantages which are mainly connected with the excessive (but unavoidable) use of NaCl during regeneration.

4.2.1.4 Electrodialysis

Investigations with the ED pilot plant have shown that it can be an effective method for nitrate removal. However, one ED stage was not sufficient to achieve the desired nitrate level of 40 mg/L when the limit current was observed. After 2 stages, simulated by operation in a batch mode, the water quality was good (Nitrate: ca. 40 mg/L and TDS ca. 750 mg/L).

It became obvious that nitrate ions were preferred during the desalination process because the nitrate reduction rate was significantly higher than the reduction of conductivity and TDS. The preferred removal of nitrate ions was due to the special properties of the ED membrane.

Unfortunately the ED experiments were partly affected by technical problems, which were caused by some defect components of the pilot plant, such as measurement instruments and pumps. Besides some delay, the defect pH measurement and control unit caused scaling on the ED membranes, because sometimes dosage of hydrochloric acid was too low.

Apart from the above mentioned defects of a few components, the ED process worked stable and reliable.

4.2.1.5 Conclusions on the performance of the four processes

The performances of the four treatment processes with regard to

- Effectiveness and stability
- Drinking water quality after treatment
- Required technical and human resources

are summarized and assessed in the chapter 5.

4.2.2 Disposal of residuals

It was shown in the previous chapters that during each of the four processes a significant amount of wastewater was created. Due to the climatic situation and the limited water resources in Mashhad it is desired by the water authorities to use as much water as possible and to avoid any water losses, e.g. due to discharge of wastewater. Additionally it has to be considered that Mashhad is located inland. The distance to the Caspian Sea is several hundred kilometres and there isn't any large river which can be used for discharge of wastewaters. This means, these two options for wastewater or concentrate disposal are not feasible.

Therefore, one goal of this research project was to illustrate the amounts and properties of the wastewaters resulting from the different processes. Furthermore it was intended to show possibilities for re-use and options for post-treatment or disposal of the wastewaters.

Table 15 gives an overview on the main properties of the different wastewaters.

Table 15: Characterization of the different wastewaters

	Bio	RO	IE	ED
Type of residual	backwash water ^{b)}	RO concentrate	spent NaCl brine	ED concentrate
Quantity ^{a)}	7 %	11 %	5 %	8 %
pH	neutral	neutral	neutral	neutral
Salinity	like feed water	high	very high	high
TDS	1150 mg/L	ca. 6500 mg/L	ca. 15000 mg/L	ca. 5500 mg/L
Major Components	feed water + biomass	Cl NO ₃ SO ₄ Ca Na	Cl NO ₃ SO ₄ Na	Cl NO ₃ Ca
Possibility for direct re-use	yes ^{c)}	no	potentially partialy ^{d)}	no

a) related to raw water flow (incl. bypass)

b) from biological reactors and dual media filter

c) after separation of biomass, the water could be re-used (e.g. for irrigation)

d) salt rich fraction (2 %) would have to be collected (and disposed of) separately, then the low salt fraction (3 %) could potentially be re-used (e.g. for irrigation)

4.2.2.1 Wastewater from the Biological Denitrification plant

The quantity of wastewater resulting from the Biological Denitrification plant was found to be in the range of 7 %. As it was backwash water from the bio reactors and from the dual media filter, it mainly contained suspended solids (biomass) and its salinity was similar to the raw water. Therefore, this wastewater could be re-used after post-treatment, e.g. by means of a membrane bio reactor (MBR). Due to its moderate salinity the post-treated wastewater then would suitable for irrigation purposes or it could be recycled, e.g. by addition to the feed water. Then the only residual would be some sludge, resulting from the MBR filtration process.

4.2.2.2 RO concentrate

In Table 15, for calculation the amount of RO concentrate, a 85 % recovery rate (RO permeate vs. RO feed) and a 30 % bypass ratio (Bypass vs. Drinking water) were considered. Thus, the quantity of RO concentrate was 11 %, related to the raw water flow (including the bypass flow). In RO concentrate the distribution pattern of the

main ions was almost similar to the raw water but, of course, their concentrations were much higher. The TDS level of the RO concentrate was approx. 6500 mg/L. Thus, this water definitely would not be suitable for any use by humans and it would not be suitable for direct irrigation as well because most crops have a limited salt tolerance. The FAO (Food and Agriculture Organization) recommends for irrigation water a TDS level of less than 2000 mg/L. However, indirect re-use of RO concentrate seems to be feasible when it will be diluted by a larger amount of water which is significantly lower in TDS, e.g. by municipal wastewater. In many countries (including Iran) effluents from WWTP are used for irrigation. However, if disposal of RO concentrate shall be considered, one has to keep in mind that the sulfate concentration is very high which might create corrosion problems in concrete pipelines.

As mentioned before, discharge to the ocean and discharge to a large river are not feasible. Therefore, besides discharge to a WWTP, there are only very few other options which (theoretically) might be possible for disposal of RO concentrate:

- Discharge to a salt lake
- Further treatment (e.g. by Biological Denitrification, Crystallization of calcium sulfate, softening by precipitation, Electrodialysis)
- Volume reduction by evaporation (e.g. solar ponds, thermal evaporators) or crystallization
- Deep well injection

Discharge to a salt lake could be possible if it was allowed by Iranian laws and authorities. It is imaginable that the RO concentrate is discharged into a salt lake in a remote area (e.g. to the desert) where it does not affect the environment, particularly any other water resources. If the RO process would be operated without acid dosage the RO concentrate would not increase the salt load of the water cycle. However, if this option would be considered some 11 % of the raw water would be lost.

The other three options seem to be very costly and/or the water would be lost as well.

4.2.2.3 Spent NaCl brine from Ion Exchange

In Table 15, for calculation of the amount of spent NaCl brine, a 94 % recovery rate (IE effluent vs. IE feed) and a 24 % bypass ratio (Bypass vs. Drinking water) were

considered. Thus, the quantity of spent brine was approx. 5 %, related to the raw water flow (including the bypass flow). The main ions in the spent brine solution were sodium, (excessive) chloride, sulfate and nitrate. With regard to the total amount spent brine, the TDS level was approx. 15000 mg/L which is very high. Thus, this wastewater definitely would not be suitable for any use by humans and it would not be suitable for *direct* irrigation.

However, as shown in Figure 25 there was a significant and sharp salinity peak in the beginning of the regeneration step, whereas afterwards salinity was moderate to low. Calculations have shown that the first 0.6 m³ (3 bed volumes) contained approx. 96 % of the salt load (“salt rich fraction”) and that the subsequent rinsing water (0.9 m³ = 4.5 BV) only contained 4 % of the salt load. The calculated salt concentrations were 36000 mg/L for the salt rich fraction and 1200 mg/L for the low salt fraction. This means, that 4.5 BV rinsing water could be reused, if this volume would be separated from the “salt rich fraction”. However, the salt rich fraction, which was approx. 2 % related to the raw water, would have to be disposed in a suitable way.

In this regard it has to be considered that (due to technical reasons) the spent brine always contains a large amount of excessive NaCl. Thus, the salt load in the water cycle will be increased significantly by the discharge of spent brine.

However, indirect re-use of spent NaCl brine can be feasible when it will be diluted by a larger amount of water which is significantly lower in TDS, e.g. by municipal wastewater. In many countries (including Iran) effluents from WWTP are used for irrigation. If disposal of spent NaCl brine shall be considered, one has to keep in mind that the sulfate concentration in the brine is very high which might create corrosion problems in concrete pipelines.

There are some examples of Ion Exchange treatment plants (e.g. in United States) which operate a post-treatment of brine solution in terms of recycling the brine. However these processes still have a significant brine discharge.

Analogously to what was mentioned already before in the RO chapter, there are only very few other options which (theoretically) might be possible for disposal of spent NaCl brines (see chapter 4.2.2.2).

4.2.2.4 ED concentrate

In contrast to RO, the amount of ED concentrate was a little bit lower (8%, related to the raw water flow). RO and ED concentrates were almost similar in TDS but the patterns of ion distribution were different because the ED process preferred the removal of nitrate, chloride and calcium ions whereas the RO process worked more or less unselective.

Similar as RO concentrate, the ED concentrate can not directly be reused, because of its high salinity. The options for disposal of ED concentrate are similar to RO (see chapter 4.2.2.2).

However, in contrast to RO, the ED concentrate contained a significant amount of additional salt load, due to the dosage of hydrochloric acid into the concentrate cycle. Thus, the salt load in the water cycle would be increased by the discharge of ED concentrate.

4.3 Cost Estimation

For each of the four technologies cost estimations were performed for full-scale plants in 3 different sizes:

- 100 m³/h (ca. 28 L/s)
- 360 m³/h (ca. 100 L/s)
- 1000 m³/h (ca. 280 L/s)

The investment costs were estimated by VA Tech Wabag (based on their experiences from several other projects) and included the costs for process technology, electrical engineering and civil engineering. For calculation of the capital costs 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 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 labour. For cost calculation of all four technologies the following specific costs were considered

- Electrical energy: 0.003 EUR/kWh
- Wastewater disposal: 0.170 EUR/m³
- Wage for an engineer (supervisor) 4 EUR/h
- Wage for a skilled technician 3 EUR/h
- Wage for a worker 2 EUR/h

It becomes obvious that these costs are significantly lower than in central European countries. Particularly the energy price is extremely low. This is due to the fact that in Iran electrical energy is strongly subsidized by the government.

4.3.1 Biological Denitrification

Table 16 shows the results from the cost calculations for Biological Denitrification.

Table 16: Results from the cost calculations for Biological Denitrification

		Biological denitrification		
Capacity	m ³ /h	100	360	1000
Annual production	m ³ /a	876.000	3.153.600	8.760.000
Investment (incl. Civil costs)	€	890.909	2.290.909	4.327.273
amount of annuity	€	144.991	372.835	704.244
Specific capital costs	€/m³	0,166	0,118	0,080
Chemicals	€/m ³	0,082	0,081	0,075
Electrical energy	€/m ³	0,0005	0,0005	0,0005
Discharge of residuals	€/m ³	0,001	0,001	0,001
Labour	€/m ³	0,038	0,010	0,004
Maintenance + other costs	€/m ³	0,031	0,011	0,005
Operating costs	€/m³	0,151	0,103	0,085
Total Costs	€/m³	0,317	0,222	0,166

The cost calculations have shown that costs for Biological Denitrification strongly depend on the size of the treatment plant. The specific costs (EUR per m³) for capital and operation of a 1000 m³/h plant are only about 52 % of the specific costs for a 100 m³/h plant.

Particularly the capital costs decreased more when the size of the plant was bigger. The main factor of the operating costs was the costs for chemicals, whereas costs for energy and disposal of residuals (sludge from the post-treatment) were marginal.

4.3.2 Reverse Osmosis

Table 17 shows the results from the cost calculations for Reverse Osmosis.

The cost calculations have shown that costs for RO depend on the size of the treatment plant, but they do less than the costs for Biological Denitrification. The specific costs (EUR per m³) for capital and operation of a 1000 m³/h RO plant are about 65 % of the specific costs for a 100 m³/h plant.

In contrast to the biological process, particularly the operating costs decreased more when the size of the plant was bigger. The main factors of the operating costs were the costs for chemicals and disposal of residuals. It has to be mentioned that the costs for energy consumption were very low, compared to similar RO applications in other countries. This is due to the fact that the Iranian government strongly subsidizes the energy price.

Table 17: Results from the cost calculations for Reverse Osmosis

		Reverse osmosis		
Capacity	m ³ /h	100	360	1000
Annual production	m ³ /a	876.000	3.153.600	8.760.000
Investment (incl. Civil costs)	€	553.846	1.794.462	4.430.769
amount of annuity	€	90.136	292.040	721.087
Specific capital costs	€/m³	0,103	0,093	0,082
Chemicals	€/m ³	0,031	0,027	0,024
Electrical energy	€/m ³	0,0018	0,0018	0,0018
Discharge of residuals	€/m ³	0,021	0,021	0,021
Labour	€/m ³	0,026	0,007	0,003
Maintenance + other costs	€/m ³	0,037	0,017	0,012
Operating costs	€/m³	0,117	0,074	0,061
Total Costs	€/m³	0,220	0,167	0,143

4.3.3 Ion Exchange

Table 18 shows the results from the cost calculations for Ion Exchange.

The cost calculations have shown that costs for Ion Exchange depend on the size of the treatment plant. The specific costs (EUR per m³) for capital and operation of a 1000 m³/h plant are about 69 % of the specific costs for a 100 m³/h plant.

In contrast to the other 3 technologies, the operating costs during Ion Exchange were always higher than the respective capital costs. The main factors of the operating costs were the costs for chemicals, whereas costs for energy consumption and discharge of residuals were very low.

Table 18: Results from the cost calculations for Ion Exchange

		Ion exchange		
Capacity	m ³ /h	100	360	1000
Annual production	m ³ /a	876.000	3.153.600	8.760.000
Investment (incl. Civil costs)	€	517.241	1.629.310	4.267.241
amount of annuity	€	84.179	265.163	694.474
Specific capital costs	€/m³	0,096	0,084	0,079
Chemicals	€/m ³	0,108	0,097	0,086
Electrical energy	€/m ³	0,0003	0,0003	0,0003
Discharge of residuals	€/m ³	0,009	0,009	0,009
Labour	€/m ³	0,026	0,007	0,003
Maintenance + other costs	€/m ³	0,043	0,025	0,017
Operating costs	€/m³	0,186	0,138	0,115
Total Costs	€/m³	0,282	0,222	0,194

4.3.4 Electrodialysis

Table 19 shows the results from the cost calculations for Electrodialysis.

Table 19: Results from the cost calculations for Electrodialysis

		Electrodialysis		
Capacity	m ³ /h	100	360	1000
Annual production	m ³ /a	876.000	3.153.600	8.760.000
Investment (incl. Civil costs)	€	1.071.429	3.188.571	8.000.000
amount of annuity	€	174.370	518.925	1.301.963
Specific capital costs	€/m³	0,199	0,165	0,149
Chemicals	€/m ³	0,010	0,009	0,008
Electrical energy	€/m ³	0,0015	0,0015	0,0015
Discharge of residuals	€/m ³	0,019	0,019	0,019
Labour	€/m ³	0,026	0,007	0,003
Maintenance + other costs	€/m ³	0,088	0,068	0,062
Operating costs	€/m³	0,145	0,105	0,093
Total Costs	€/m³	0,344	0,270	0,242

The cost calculations have shown that costs for Electrodialysis depend on the size of the treatment plant, but less than for the other 3 processes. The specific costs (EUR per m³) for capital and operation of a 1000 m³/h plant are about 70 % of the specific costs for a 100 m³/h plant.

The capital costs for Electrodialysis were found to be significantly higher than those of the other 3 processes.

The main factors of the operating costs were the costs for maintenance, which is due to the high costs for replacement of ED electrodes and membranes. It has to be mentioned that the costs for energy consumption were very low, compared to similar ED applications in other countries. This is due to the fact that the Iranian government strongly subsidizes the energy price.

4.3.5 Summarized results of the cost estimations

Figure 35 summarizes the results of the cost estimations.

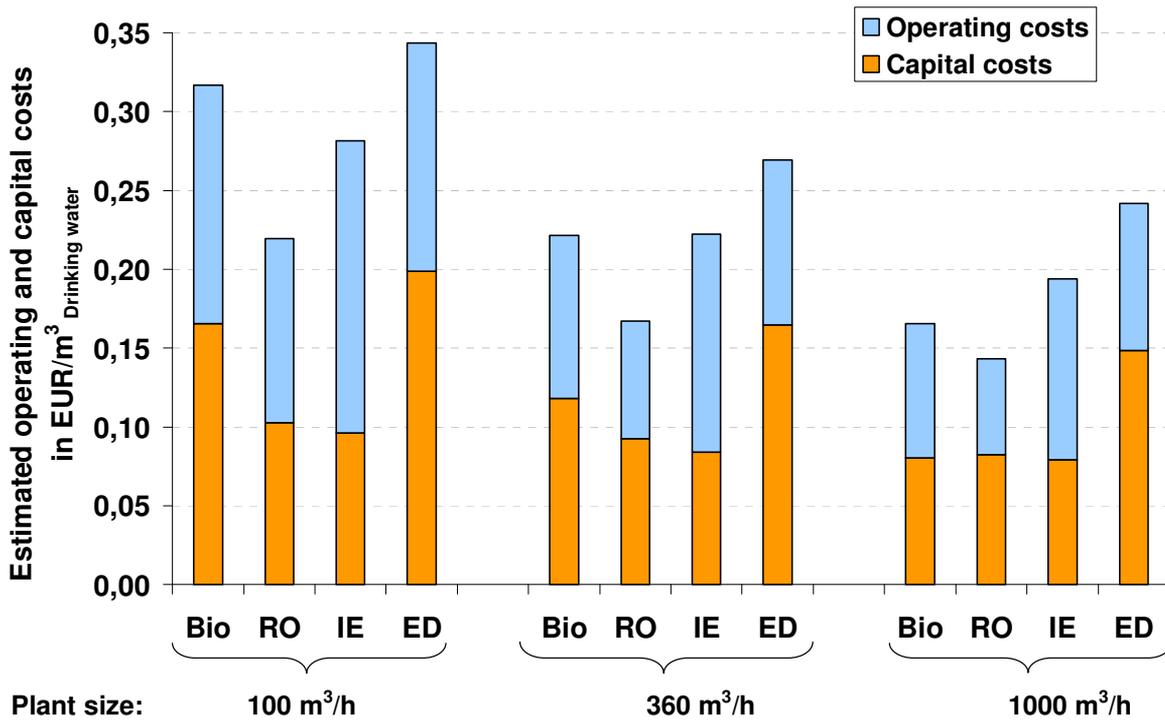


Figure 35: Estimated Operating and capital costs of the four treatment processes

5 Assessment of the processes and recommendations

As explained in chapter 3.6, for assessment of the four treatment processes the following main criteria were rated on a scale from “+2” (very favourable and beneficial factor) to “-2” (very unfavourable factors):

- Effectiveness and stability of the treatment process
- Operating and investment costs
- Drinking water quality after treatment
- Required technical and human resources
- Impacts on the environment during operation

5.1 Effectiveness and stability of the treatment process

All four pilot plants could be operated successfully in Mashhad and the treatment processes were effective for nitrate removal. The WHO guideline value was met surely as the nitrate concentration could be decreased from ca. 120 mg/L (feed) to 40 mg/L (effluent) or even less.

Biological Denitrification is the only process which really eliminates the nitrate ions whereas the other three processes only separate nitrate from the water and displace it into a saline wastewater stream (concentrate or spent brine). This makes Biological Denitrification a favourable process with regard to its effectiveness for nitrate removal. Therefore, the nitrate removal of the biological process was rated as “+2” whereas the other three processes were rated as “+1”.

Concerning the process stability the pilot plant experiments have shown that RO, Ion Exchange and ED 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 ED slightly are more complex processes resulting in a neutral rating for these two processes, whereas Biological Denitrification was rated slightly negative (“-0.5”) in this regard.

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 was 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 ED process is slightly less effective for removal of other contaminants and therefore rated as “+0.5” whereas the other two processes (Biological Denitrification and Ion Exchange) are potentially not effective for removal of other contaminants. Eventually some compounds may be reduced by them (e.g. organic trace compounds during Biological Denitrification), but on the other hand for none of these two processes a removal efficiency can be assured. The ratings on effectiveness and stability of the treatment processes are shown in Table 20.

Table 20: Rating on effectiveness and stability of the treatment processes

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Effectiveness and process stability	Process stability	30 %	1	2	2	2
	Nitrate removal	30 %	2	1	1	1
	Process complexity (Risk of technical difficulties)	30 %	-0,5	0	1	0
	Effectiveness for removal of other contaminants	10 %	0	1	0	0,5
	Total Rating of effectiveness and process stability	100 %	0,8	1,0	1,2	1,0

5.2 Operating and investment costs

Figure 36 shows the estimated capital and operating costs of the four treatment processes for nitrate reduction from ca. 120 mg/L (feed) to 40 mg/L (effluent) at a flow rate of 1000 m³/h (drinking water production) in Iran.

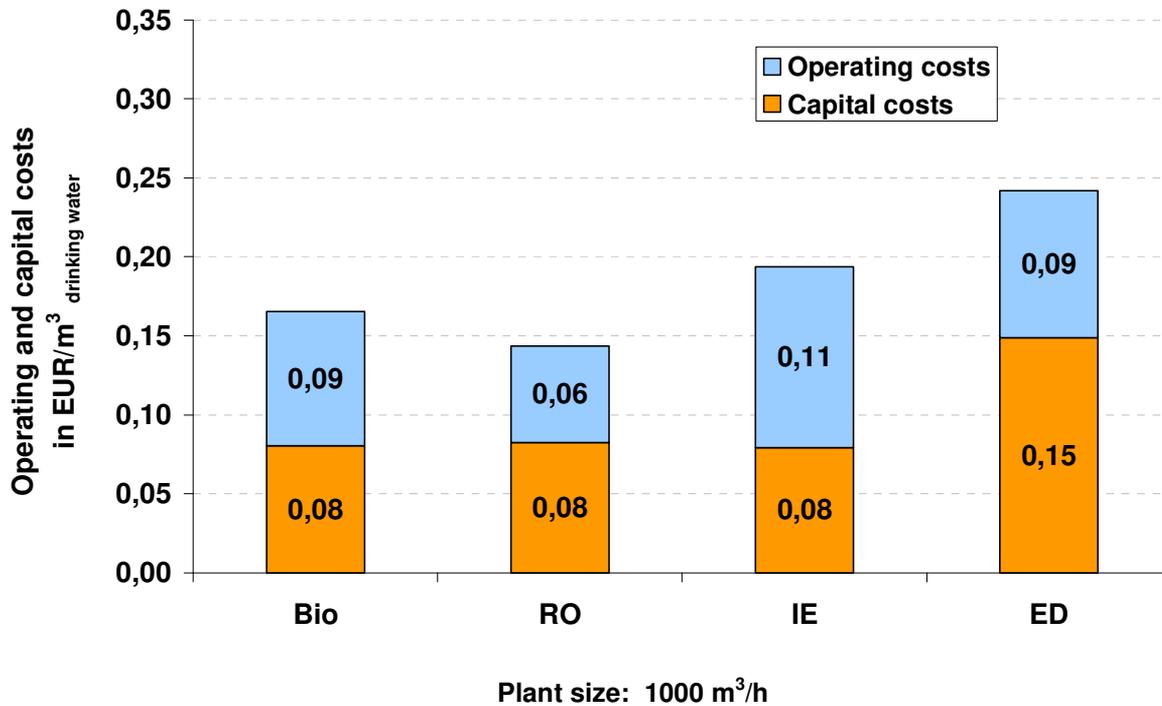


Figure 36: Estimated capital and operating costs of the three treatment processes for nitrate reduction in Iran

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/m³), whereas the capital costs for ED were significantly higher (almost twice as much). The operating costs of all four treatment processes were estimated to be in the range of 6 – 11 ct/m³. The Ion Exchange process had the highest operating costs (11 ct/m³), mainly due to its high costs for chemicals.

In this calculation the RO process was found to have the lowest operating costs (6 ct/m³) although RO has the highest specific energy consumption of all four processes (ca. 0.6 kWh/m³_{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/m³). 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 36. The results of these ratings are shown in Table 21.

Table 21: Rating on investment and operating costs

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Costs	Investment costs for process, electrical and civil engineering	50 %	0,0	0,0	0,0	-1,7
	Operating Costs	50 %	0,0	0,5	-1,0	-0,3
	Total Rating of investment and operating costs	100 %	0,0	0,3	-0,5	-1,0

5.3 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 research study. However, it was not considered for the rating of the processes in terms of water quality because all four 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 low nitrate concentrations such as 8 mg/L in the RO permeate and 16 mg/L in Ion Exchange effluent (mixed sample). Therefore, RO permeate and Ion Exchange effluents could be mixed with a certain amount of raw water (30 % and 24 %, respectively) so that the nitrate concentrations in the final waters of all treatment processes were consistent (ca. 40 mg/L nitrate). Table 22 characterizes the main composition of the final waters (after treatment) and of the raw water. It has to be considered that the samples were not taken at the same time.

Table 22: Composition of raw water and final waters (after treatment and blending)

		Feed	Bio	RO	Ion Exchange	ED
		(raw water)	effluent	effluent ¹	effluent ²	effluent ³
Conductivity	μS/cm	1516	1472	479	1615	ca. 1000
TDS	mg/l	1069	1044	347	937	721
pH	-	7,3	7,6	7,4	7,3	-
TOC	mg/l	0,4	0,4	0,3	0,5	-
Ca	mg/l	139	136	42	128	69
Mg	mg/l	44	43	14	42	26
Na	mg/l	109	106	37	102	105
K	mg/l	2	2	1	1	2
Cl	mg/l	184	185	57	268	81
NO₃	mg/l	115	40	40	40	38
SO₄	mg/l	150	147	46	55	152
HCO₃	mmol/l	5,4	6,3	1,8	4,9	4,1

¹ Calculated for mixing of 70 % RO permeate with 30 % raw water (feed), after gas exchange

² Calculated for mixing of 76 % average effluent sample (see ion exchange chapter) with 24 % raw water (feed)

³ Effluent quality obtained during the batch mode experiment (simulation of 2 stages) with 1200 L/h and 30 V

It can be seen that the effluent waters of all pilot plants had nitrate concentrations in the range of 40 mg/L whereas the nitrate concentration in the feed (raw water) was 115 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 (including subsequent blending) reduced all inorganic parameters by ca. 70 %, compared to the feed water. Electrodialysis reduced the salt content by some 35 % whereas nitrate was reduced by more than 65 %. Regarding the Ion Exchange process it can be seen that sulfate was reduced (besides nitrate) and that the chloride effluent concentration was increased significantly.

The current WHO drinking water guideline does not recommend a health-based guideline value for chloride (WHO, 2004). 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 268 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 processes mentioned before, the chloride concentration after RO and ED treatment were found to be more favourable

because the chloride concentration in the final waters were relatively low at 53 and 81 mg/L, respectively.

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, RO and ED processes reduced TDS significantly, resulting in a more favourable rating ("+1" for RO and "+0,5" for ED).

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 30 % 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"), similar as ED.

The results of the rating on drinking water quality (after treatment) are shown in Table 23.

Table 23: Rating on drinking water quality after treatment

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Final water quality (after blending)	Chloride concentration (Risk of Corrosion in the distribution net)	40 %	0	1,5	-2	1
	TDS concentration	40 %	0	1	0	0,5
	Potential microbiological safety (before final disinfection)	20 %	-0,5	0	-0,5	0
	Total Rating of final water quality	100 %	-0,1	1,0	-0,9	0,6

5.4 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, ED and Ion Exchange were almost similar; they all require very qualified, experienced and reliable personnel. Although these 3 processes can be operated and controlled automatically, for a water works in Iran with 1000 m³/h at least 1 very well educated engineer plus 2 mechanists or technicians would be necessary. Therefore, RO, ED and Ion Exchange were attributed to be favourable (“+1”) in terms of staff requirements.

Biological Denitrification was found to be a process which requires more personnel due to increased efforts for operation and 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 characteristics 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 easily be purchased in Iran. In contrast to the before mentioned processes, supply of ED membranes and electrodes seems to be more complicated and ED electrodes have to be replaced already after 3 years. Therefore the ED process was rated negatively (“-1”) in this regard.

The biological process was attributed more favourable (“+1”) because the intervals for changing the filter materials will probably be much longer.

The results of these ratings are shown in Table 24.

Table 24: Rating on required technical and human resources

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Technical & human resources	Staff requirements (manning level and qualification)	70 %	0	1	1	1
	Spare part demand / frequency for replacement	30 %	1	0	0	-1
	Total Rating of technical and human resources requirements	100 %	0,2	0,7	0,7	0,4

5.5 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 25 gives an overview on the energy and chemicals demand of the four treatment processes.

Table 25: Energy and chemicals demands (related to 1000 m³/h drinking water production)

		Biological process	RO	Ion exchange	ED
Specific energy demand *	KWh / m ³	0,15	0,6	0,1	0,5
Energy demand per year	Mio. KWh / a	1,3	5,3	0,9	4,4
Main chemicals for the treatment process	-	Acetic Acid	Antiscalant	Sodium chloride	Hydrochloric acid (30 %)
Specific chemical demand *	kg / m ³	0,060	0,003	0,680	0,055
Chemicals	To / a	ca. 500	ca. 24	ca. 6000	ca. 500

* related to drinking water

The specific energy consumption of the Ion Exchange and the biological process are relatively low (ca. 0.1 kWh per m³ of drinking water) and therefore rated as favourable (grade “+1”). RO and ED require significantly more energy which results in a less favourable rating (“-1”).

The chemical demands of the four treatment processes are very different and it is difficult to compare them with each other. The RO process requires some 24 tons of antiscalant per year. As Antiscalant usually is not classified as a dangerous good, the low chemical demand is a big advantage of RO 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. 500 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 ED process was found to be unfavourable (“-1”) as it requires some 500 tons per year of hydrochloric acid. Supply, storage and handling of this chemical give cause for concern in terms of occupational and environmental safety.

The chemical demand of the Ion Exchange process was assessed to be very unfavourable (“-2”) as it requires huge amounts of chemicals (about 6000 tons sodium chloride per year). Furthermore, the quality of the supplied salt in Iran was found to be insufficient due to a high fraction of insoluble components.

The quantities and salt loads (TDS) of the wastewaters, resulting from the four treatment processes, vary largely.

Table 26: Wastewater characteristics (related to 1000 m³/h drinking water production)

		Biological process	RO	Ion exchange	ED
Total Raw water demand	m ³ /d	25800	27000	25200	26100
Drinking water production	m ³ /d	24000	24000	24000	24000
Total wastewater amount	m ³ /d	1800	3000	1200	2100
Total wastewater ratio ¹⁾	%	7 %	11 %	5 %	8 %
Type of wastewater	-	backwash water ²⁾	RO concentrate	spent brine + rinsing water	ED concentrate
Re-use possible	-	yes ³⁾	no	partially ⁴⁾	no
Wastewater that can be re-used directly ¹⁾	%	7 %		3 % ⁴⁾	
Concentrate (brine) flow rate	m ³ /d	0	3000	500	2100
Concentrate (brine) salt-concentration (TDS)	g/m ³	-	6000	36000	5500
Salt load (TDS) in the concentrate (brine)	kg/d	-	18000	18000	11550
Wastewater that can not be re-used directly - suitable disposal is required	%	0 %	11 %	2 % ⁴⁾	8 %

¹⁾ related to raw water flow (incl. Bypass)

²⁾ from biological reactors and dual media filter

³⁾ after removal of suspended solids (biomass) the water can be used for irrigation

⁴⁾ salt rich fraction (2 %) would have to be collected (and disposed of) separately, then the low salt fraction (3 %) could potentially be re-used (e.g. 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 18 tons per day (6600 to/y). Although this is a high amount, it has to be emphasized that this TDS load mainly originates 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”.

Similar to RO, the TDS load of the brine solution resulting from the Ion Exchange process would be ca. 18 tons per day. However, during Ion Exchange - in contrast to RO – there is no (significant) reduction of TDS. This means, the main salt load of the brine solution results from the regeneration chemical (NaCl) and the salt input into the environment is increased significantly. This is extremely unfavourable and therefore, the Ion Exchange process was assigned to grade “-2”.

The TDS load resulting from the ED process is less than from Ion Exchange. However, it contains a certain amount of additional chloride ions, due to dosage of hydrochloric acid. Therefore, the TDS load of the ED process was rated as “-1”.

During RO and ED treatment there are significant amounts of concentrates (11 % and 8 %, respectively) which can not be re-used directly. Therefore, RO and ED were assigned to grade “-1.5” and “-1”. With regard to Ion Exchange only ca. 2 % of the brine (“salt rich fraction”) can not be re-used which was rated as “-0,5”. During application of the Biological Denitrification process - apart from the sludge - almost the entire amount of wastewater (ca. 8 %) can be re-used. Therefore, in terms of wastewater re-usability the Biological Denitrification process was rated with mark “+2”.

According to Table 26, the RO treatment process has the highest additional raw water demand (11 %). Therefore it was rated as grade “-1”. Biological Denitrification and ED have an increased raw water demand in the range of 7 - 8 % and are therefore attributed to mark “-0.5”. Ion Exchange process increases the raw water demand by some 5 % resulting in neutral rating (“0”). In Table 27 the ratings on environmental impacts during operation are shown.

Table 27: Rating on environmental impacts during operation

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Environmental impacts during operation	Energy consumption	20 %	1	-1	1	-1
	Chemicals consumption	20 %	0	1	-2	-1
	TDS load of concentrate and spent brine	20 %	2	-1	-2	-1
	Possibility for re-use of wastewater	20 %	2	-1,5	-0,5	-1
	Increased raw water demand	20 %	-0,5	-1	0	-0,5
	Total Rating of environmental impacts	100 %	0,9	-0,7	-0,7	-0,9

5.6 Overall assessment of the four treatment processes

The four 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 the overall assessment are shown in Table 28.

Table 28: Overall Ratings of the main criteria for assessment of the four treatment processes

	Assessment criteria	Weighting factor	Bio	RO	IE	ED
Assessment of the five main criteria	Effectiveness and stability of the process	25 %	0,8	1,0	1,2	1,0
	Operation and investment costs	25 %	0,0	0,3	-0,5	-1,0
	Drinking water quality after treatment	20 %	-0,1	1,0	-0,9	0,6
	Required technical and human resources	10 %	0,2	0,7	0,7	0,4
	Impacts on the environment during operation	20 %	0,9	-0,7	-0,7	-0,9
	Overall assessment	100 %	0,4	0,4	-0,1	0,0

With regard to effectiveness and process stability all treatment processes (Biological Denitrification, RO, Ion Exchange and ED) were assessed as favourable.

The specific costs for investment and operation of a full-scale treatment plant (capacity 1000 m³/h drinking water production) were estimated as follows:

- Biological Denitrification 0.17 EUR per m³ drinking water
- RO: 0.14 EUR per m³ drinking water
- Ion Exchange 0.19 EUR per m³ drinking water
- ED 0.24 EUR per m³ drinking water

Thus, the specific costs for Ion Exchange and ED were rated as unfavourable whereas Biological Denitrification and RO 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, followed by ED. 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 slightly favourable whereas Biological Denitrification was rated as neutral.

Finally, operation of RO, Ion Exchange and ED 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 three processes, during Biological Denitrification there is no production of any concentrate (with high salinity) and b) almost the entire wastewater can be re-used, after suspended solids (biomass) is removed from this wastewater.

5.7 Recommendations

Taking into account the boundary conditions of this study (e.g. water quality goals, extreme low costs for energy) and in consideration of the scheme for assessment of the treatment processes (Table 7), 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.

6 Iranian-German co-operation in water technology and research

During this successful research project, water scientist, engineers and other water experts from Iran and Germany came together during numerous occasions. In the following, the joint activities will be illustrated.

6.1 Working visits of German water experts in Mashhad

Within this research project, in total there were 9 visits in Mashhad by staff members of IWW, Umex and VA Tech Wabag. In October 2004 the pilot plants were installed. Simultaneously IWW staff provided an extensive theoretical and practical training program for the Iranian staff members. The close co-operation and the extensive training during that time were the basis for this fruitful co-operation.

In 2005 IWW staff members came to Mashhad every 3 months for ongoing training, technical support and for supply of spare parts.

Table 29: Working visits of German water experts in Mashhad

Oct 02	Basic plannings and agreement on the research project	Dr. Panglisch
Oct - Dec 04	Start-up of the 3 pilot plants, Theoretical + practical training	Buchta, Dördelmann
Feb 05	training, technical support and supply of spare parts	Buchta
May 05	training, technical support and supply of spare parts	Dördelmann
Aug 05	training, technical support and supply of spare parts	Buchta
Nov 05	training, technical support and supply of spare parts	Dördelmann
Jan 06	technical support, agreement on the new project (ED)	Buchta, Panglisch
Jun - Jul 07	Start-up of the ED pilot plant, Start of scientific investigations	Dördelmann, Markmann
Nov 07	Continuation of scientific investigations (ED) in Mashhad	Markmann

6.2 Working visits of Iranian water experts in Germany

During the first visit an extensive training course about all aspects of nitrate and nitrate removal was given. Additionally, the Iranian group visited the pilot plants which were under construction (and almost finished) at UMEX company in Erfurt.

One main part of the second visit of the Iranian water experts was participation in the **4th International Slow Sand and Alternative Biological Filtration Conference** in Mülheim, organized by IWA (International water association) and IWW.

Additionally during all 3 visits of Iranian water experts in Germany several technical excursions to different water works in Germany (and Austria) were made. It was essential for the success of this project that the Iranian project partners had the chance to see full-scale drinking water treatment plants with latest technology because most of these technologies do not exist in Iran, yet. The Iranians inspected those plants and discussed with the German water utilities staff about their experiences (e.g. operation and maintenance). Now the Iranian decision makers are in a position to make a well-founded decision concerning future technologies for water treatment in Mashhad and other parts of Iran.

Table 30: Working visits Iranian water experts in Germany

Oct 03	Training course and technical excursions (Germany, Austria)	Dördelmann, Panglisch
May 06	Biofiltration Conference and technical excursions	Dördelmann, Panglisch
Nov 07	Technical excursions	Dördelmann, Markmann

6.3 Presentations during international conferences and workshops

Presentations about the contents and (intermediate) results of this research project were given during six international conferences and workshops. Three of these events took place in Germany, the other tree workshops and symposiums were in Tehran. It was important to present about the project in the capital because Tehran is the place in Iran where all information merge and were most decisions are made.

Table 31: Presentations during international conferences and workshops

	Presentations during international conferences and workshops	
Aug 03	RCUWM-BMBF-Workshop in Tehran	Panglisch
Apr 05	BMBF-Workshop in Munich (during IFAT trade fair)	Dördelmann, Panglisch
Nov 05	RCUWM-BMBF-Workshop in Berlin	Prof. Gimbel, Panglisch
May 06	IWA Biofiltration Conference in Mülheim	Dördelmann, Panglisch
Sep 06	Symposium "Environmental Challenges" in Tehran (BMBF)	Dördelmann
Nov 06	RCUWM workshop in Tehran (during IWE Trade Fair)	Dördelmann

In May 2006 IWA's 4th International Slow Sand and Alternative Biological Filtration Conference took place in Mülheim. The conference was attended by about 200 scientists and water experts from all over the world. During the conference Mr. Dördelmann presented the considerable results of the investigation in Mashhad, particularly on the Biological Denitrification. Afterwards there was a discussion in which the water experts from Mashhad, who attended the conference as well, could answer some questions from the audience.

In September 2006 Tehran University of Medical Science organized the symposium on „Environmental Challenges in Caspian Sea Region“. Iranian and German scientists from different disciplines (natural, environmental and medical science) participated in this symposium together with some representatives from German Ministry of Education and Research (BMBF). During the symposium Mr. Dördelmann presented preliminary results from the research project in Mashhad. Besides the symposium there were some meetings in which German and Iranian representatives discussed about joint research projects in the future.

Additionally it has to be mentioned that the results of this research project will be presented in September 2008 (after submission of this final report) during **IWA's World Water Congress and Exhibition** in Vienna, both by oral presentation and by a poster. The title of the presentation will be: "Nitrate Removal from Drinking Water in Iran – Assessment of Three Different Treatment Processes Based on Pilot-Scale Investigations".

6.4 Participation in international trade fairs

The contents and (intermediate) results of this research project were illustrated during two international trade fairs. At IFAT 2005 IWW had a booth at the BMBF pavilion. The project was illustrated by two large posters and several flyers. Furthermore the project was included in the IFAT brochure, presented by BMBF.

During IWE 2006 in Tehran IWW had a booth at the joint RCUWM-BMBF stand. Besides 2 posters and several literatures, an information film (in Farsi) about this research project was presented continuously on a screen. The duration of this film was ca. 15 minutes and it was produced by the project partners in Mashhad. The film attracted attention of many visitors of the trade fair and it was the starting point for several new contacts between Iranian and German water experts.

Table 32: Participation in international trade fairs

Apr 05	IFAT trade fair in Munich	Dördelmann, Panglisch
Nov 06	International Trade Fair IWE 2006 in Tehran	Dördelmann

6.5 Further international activities related to this project

Due to the wide experiences on nitrate removal that were gained during this research project, IWW executed a consulting project in 2007 in Damascus (Syria), ordered by KFW (German developing bank). The consulting project in Damascus mainly focussed on water resources and water technology aspects. After IWW presented some information about the Mashhad research project to the counterparts in Damascus, the Syrian project partners were very much interested in the research project.

In January 2008 a group of six engineers from Syria and four engineers from Germany travelled to Mashhad for inspection of the pilot plants and for discussion with the Iranian water experts about their operating experiences. Once in Mashhad, the participants of this journey were very impressed by the technology and the results that were obtained during the investigations.

This visit underlines the importance and the recognition of this research project for the entire Middle East region.

6.6 Master thesis of a German Student in Mashhad

In June and December 2007 a student of University of Duisburg-Essen came to Mashhad for doing his master thesis. In total he spent almost 3 months in Mashhad and he investigated the start up and the operation of the ED pilot plant. In the beginning he was accompanied by two experienced engineers from IWW and VA Tech Wabag. Later on he performed scientific experiments which were very helpful for the outcomes of this project. Apart from his excellent work and his very good research results (thesis), the student learned the Persian language (Farsi) to a good level so that he could communicate with the Iranian project partners in their own language.

This example shows that student exchange and preparation of thesis in a foreign country was a good opportunity for improving scientific and personal contacts between Iran and Germany.

6.7 Publications, related to this research project

Dördelmann, O., Stetter, D., (2004) Nitrat im Grundwasser – verschiedene Aufbereitungsverfahren im Vergleich. IWW-Journal No. 22, October 2004

Panglisch, S., Dördelmann, O., Buchta, P., Klegraf, F., Höll, W. H. (2005) Nitrate Removal from Groundwater in Mashhad / Iran. Brochure for the BMBF-Workshop "Forschung und nachhaltige Wassertechnologien". IFAT 2005 München,. Projektträger Forschungszentrum Karlsruhe, Bereich Wassertechnologie und Entsorgung (PTKA-WTE) S. 25-26

Dördelmann O., Buchta P., Panglisch S., Klegraf F., Moshiri A. , Emami A. (2006) Heterotrophic Denitrification in Drinking Water Treatment - Results from Pilot Plant Experiments in Mashhad / Iran. In: Recent Progress in Slow Sand and Al-ternative Biofiltration Processes. Rolf Gimbel (Ed.). ISBN: 9781843391203 IWA Publishing, London, UK. 433 - 442

Panglisch, S., Dördelmann, O., Buchta, P., Klegraf, F., Moshiri, A., Emami, A. Fakhraei, M., Höll, W. (2006). Nitrate Elimination from Raw waters – an Iranian-German Joint Co-operation Project. Proceedings BMBF & UNESCO-RCUWM Workshop. „Innovations in Water and Wastewater Technology“. 28.11. – 01.12.2005. in Berlin

Panglisch, Dördelmann (2005). Entfernung von Nitrat aus Grundwasser in Mashhad / Iran. IWW Journal No. 24, November 2005

Panglisch, Dördelmann, Buchta (2006). Forschungsprojekt des IWW zur Nitratentfernung bei der Trinkwasseraufbereitung in ariden und semiariden Ländern. IWW Journal No. 25, May 2006

Panglisch, Dördelmann, Buchta (2006). Nitrat im Grundwasser – verschiedene Aufbereitungsverfahren im Vergleich. IWW Journal No. 25, May 2006

Additionally, a paper was submitted for the **IWA World Water Congress and Exhibition** which will take place in Vienna in September 2008 (after submission of this report). The paper was accepted for oral presentation and it is titled: "Nitrate Removal from Drinking Water in Iran – Assessment of Three Different Treatment Proc-

esses Based on Pilot-Scale Investigations”. It will be published in the congress proceedings and probably later on in the journal “Water Science and Technology”.

6.8 Posters and film about this research project

During IFAT 2005 and IWE 2006 two posters were shown: The title of the posters was: “Water supply research project: Nitrate removal from groundwater in Mashhad”

The film about the nitrate research project in Mashhad was produced by Mashhad Water and Wastewater Company. The language of the film is Farsi and its duration is approx. 15 minutes.

Anyone who is interested in the poster (as pdf-file) and the film (as mpg-file) may contact IWW for getting a copy of it.

6.9 Summary and outlook

The above mentioned activities have proven that this research project was a great success – not only in terms of its scientific outcomes. This project largely contributed to the development of a long-lasting and effective co-operation between Iran and Germany in the field of water technology and research. Several personal contacts between the project partners have been established and they will surely remain after this project is over. Additionally, numerous new contacts resulted from the meetings and conferences.

There are several interesting ideas and new topics for joint research projects between Iran and Germany in the future, e.g. on

- Integrated Water resources Management (IWRM) and on
- Arsenic and chromate removal from drinking water.

Both topics are very important and challenging in terms of scientific aspects, as they address problems (e.g. water scarcity and water contamination) which affect many people in Iran and several other countries in the world. A co-operation of German and Iranian water experts would be very helpful in order to overcome those problems and to continue the fruitful relationship between Germany and Iran in water affairs.

Besides personal contacts and scientific relations, it can be expected that the relationship between German and Iranian water industry will benefit from this research project as well. Mashhad Water and Wastewater Company stated that they intend to construct a full-scale drinking water treatment plant for nitrate removal within the next few years. If a new water works will be realized in Mashhad, this research project would probably become an economic success as well, because most likely German water companies would be involved in such a project.

Furthermore it is possible, that more cities in Iran (and in other Middle East countries) will assign German companies for improvement and construction of water works, stimulated by the positive outcomes of this research project.

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8 References

- Clifford D., Liu X. (1993). Ion exchange for nitrate removal. J. Am. Water Works Assoc. (4), 135-143
- Dördelmann, O.; Buchta, P.; Panglisch, S.; Klegraf, F.; Moshiri, A.; Emami, A. (2006) Heterotrophic denitrification in drinking water treatment - results from pilot plant experiments in Mashhad/Iran. In: Recent Progress in Slow Sand and Alternative Biofiltration Processes. ISBN. 9781843391203. 433-442. IWA Publishing, London
- Höll W. H., Flemming H.-C. (1991). Treatment of Drinking Water with Ion Exchange Resins. In: Ion Exchangers, K. Dorfner (ed.), de Gruyter, Berlin; New York, 835-844
- Overath, H. (2000). Stand der Technologie zur Nitratentfernung im Trinkwasserbereich. Technology of Nitrate Removal from Drinking Water: Actual State and Recent Developments. Vom Wasser, 94, 267-298
- Panglisch, S., Dördelmann, O., Buchta, P., Klegraf, F., Höll, W.H. (2005). Nitrate Removal from Groundwater in Mashhad / Iran. Poster & Presentation. IFAT Munich. BMBF-Workshop: "Forschung für innovative und nachhaltige Wassertechnologien". Projektträger Forschungszentrum Karlsruhe, Bereich Wassertechnologie und Entsorgung (PTKA-WTE) 25-26, 73.
- Rohmann, U., Sontheimer, H. (1985). Nitrat im Grundwasser – Ursachen, Bedeutung, Lösungswege. DVGW-Forschungsstelle. University Karlsruhe
- Sonnenburg A., Urban W. (2005). Untersuchungen zur Denitrifikation in der Wasseraufbereitung mit Hilfe des biologisch abbaubaren Kunststoffes PCL. GWF Wasser Abwasser, 146 (1), 33-39
- Uhl W., Overath H. (2004). Biologische Verfahren der Trinkwasseraufbereitung. In: Wasseraufbereitung - Grundlagen und Verfahren, DVGW Lehr- und Handbuch Wasserversorgung (ed.), vol 6, 339-402. Oldenbourg, München.
- WHO (2003). Nitrate and nitrite in Drinking-water. Background document for development of WHO Guidelines for Drinking-water Quality. Geneva, Switzerland
www.who.int/water_sanitation_health/dwq/chemicals/Nitratenitrite.pdf
- WHO (2006). Guidelines for drinking-water quality, First addendum to 3rd edition. Vol. 1, Recommendations. ISBN 92 4 154696 4. Geneva, Switzerland
http://www.who.int/water_sanitation_health/dwq/gdwq0506.pdf

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