MEWAC

Middle East Regional Water Research Cooperation Program

Final Meeting, Module B
4 December 2024
Proceedings

SPONSORED BY THE

Federal Ministry of Education and Research

FONA Research for Sustainability

HighRec - Enhancement of the recovery ratio in brackish water desalination systems for agricultural irrigation

PROJECT OBJECTIVES

In Qatar, over two-thirds of freshwater is supplied by desalination, while Iran faces growing freshwater shortages, impacting industry and agriculture. Conventional desalination technologies struggle with low recovery rates, high energy demands associated with CO_2 emissions, negative impact of brine disposal, and limited adaptability to varying raw water compositions. The HighRec project aims to address these challenges by developing solar-driven desalination systems with advanced pretreatment technologies. These systems achieve high recovery rates and adapt dynamically to changing raw water compositions. Closed Loop Reverse Osmosis (CLRO) was chosen for its flexibility, recirculating brine through the reverse osmosis (RO) module until a calculated salinity threshold is reached for discharge. This process allows continuous pressure adaptation and high water yields across diverse raw water compositions. In Qatar, target groups include infrastructure managers, engineers in the agricultural sector and companies active in renewable energy and water treatment. In Iran, where investors in innovative irrigation and water treatment technologies are scarce, efforts focus on fostering joint municipal investments or agricultural cooperatives alongside the same target groups as in Qatar.

KEY RESULTS

Experiences with the demonstration system

A demonstration system was installed at the industrial farming complex of Agrico in Qatar during October 2023. The conceptual system design was based on a robust seawater RO unit with minimized complexity but hydraulically modified for CLRO operations. The photovoltaic (PV) panels and electronic devices were designed for direct connection on the DC level. This approach allowed the realization of the demonstration system based on industrial standards with high potential for cost effective scale up and transfer to the market. The installation was conducted on time and provided the option for a long-term operation under real site conditions initially planned for two independent sites at Agrico in Qatar and at a saffron farm belonging to the University of Birjand in Iran. During the operation it turned out that the low grade of automatization, intended to keep the system and its operation simple, created several problems since proper manual operation by local staff failed. Because of the political situation it was not possible to send the demonstration system to Iran and commission it locally. Therefore, it was decided to extend the demonstration period at Agrico until November 2024. The operation parameters could be monitored during that period remotely and were evaluated by the project partners.

During the operation of photovoltaic driven pilot system under extreme climate conditions (outside temperature of up to 50°C) in Qatar with local brackish water (see figure 1) important experiences could be made. Recovery rates of more than 75% were achieved. The predictions made by the in-house developed dimensioning and performance evaluation tool fit well together with the measured data (see table 1).

Table 1: comparison of key performance parameters of operation of pilot system and calculation of design tool

	Measured data (avg.)	Design tool
feed flowrate [m^3/h]	2.61	2.39
permeate flowrate [m^3/h]	2.02	1.89
recovery rate [%]	77.4%	78.9%
SEC [kWh/m^3]	1.35	1.49
CL duration [min]	4.56	4.73

The direct coupled PV-system without DC/AC converters works reliably and cost effective in general but it turned out that the controller needs more advanced algorithms in order to optimize the solar energy yield and to increase the overall system efficiency as well as the user friendliness.

The RO system consists of an 8” pressure vessel with 2 membrane elements type LG SW 400 ES. The salt concentration of the brackish water on site is about 8.4 g/L. The normal parameters for operation are a flowrate of 3.8 m³/h, a pressure of 10 bar and a duration of 50 s for the plug flow mode. During closed loop operation the feed flowrate was controlled to 2.14 m³/h, the recirculation flow to 5 m³/h and the feed pressure was limited to 44 bar, which was set as the threshold to switch from closed loop to plug flow mode.

Figure 1: Container with CLRO under a shadowing rooftop of 44 photovoltaic panels at the horticulture farm Agrico, Qatar.

A key advantage of the system is that it can cope well with slowly changing or even short-term fluctuating changes in salt concentration and raw water composition. By shortening the time required to rinse out the concentrate, the situation could be simulated. As expected, the plant and its automation concept were able to cope with these changing salt contents and raw water compositions without any problems.

Whether the measures for scaling prevention (CLRO-Operation, antiscalant dosing, flow reversal in closed loop, CIP before and after the operation) are effective on a long-term view needs further investigations under comparable operation conditions.

Peaks in the permeate conductivity were observed when switching between CL mode to PF Mode. This effect disappeared after changing the membrane elements and switch off the “flow direction change mode” which was initially intended to reduce the risk of fouling. Our analysis came to the conclusion, that these leakages are most likely associated with sealing problems between the membrane elements, which slightly move when pressure is fluctuating. Fixing the membrane elements in place with shimmer rings should avoid this effect in the future.

We observed high wear and tear of the high-pressure pump (plunger pump) and therefore suggest for the future to change to a plug flow mode realized by the feed pump, or to avoid two different flowrates by using an isobaric chamber configuration.

High recovery desalination system as combination of CLRO and EDM

A combination of CLRO and Electrodialysis Metathesis was developed and analysed with a simulation design tool and in the laboratory to realize a chemical free pre-treatment. This approach allows very high recovery rates, reduces the amount of brine significantly and opens opportunities to recover useful salts. The concept is shown in figure 2.

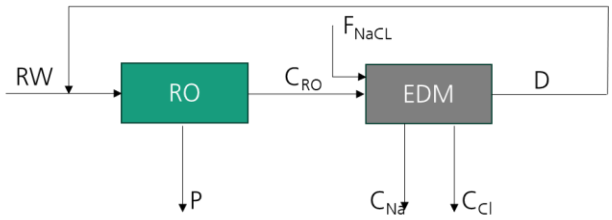


Figure 2: Concept of CLRO and EDM combination process.

With the example of the use case at Agrico (capacity of the pilot plant 2.2 m³/h product water) the potential of this process combination is shown: The recovery, when using RO for the brackish water with 8.4 g/L without any pre-treatment, is limited to 28% (or a concentration factor of 1.38) because of $CaSO_4$ solubility (11.7 g/L). The EDM-CLRO allows recovery rates of up to 87% without using additional antiscalants and without exceeding a solubility limit. The challenges of this configuration turned out when investigating it with the simulation design tool: The results show that a appropriate membrane EDM stack needs an active ion exchange membrane area of 400 m². This leads to an increase of the specific energy demand from 1.5 kWh/m³ to 8.4 kWh/m³. The daily amount of feed salt is 430 kg/d NaCl. The method needs further comprehensive techno-economic evaluations for individual user cases and further research and optimisation work.

Even the concentration of the brine produced with 75% and 87% recovery is still too low to economically treat it in a thermal evaporation. Therefore, TUB developed a concept to further increase the salt concentration of the brine through a precipitation of scaling agents using NaOH and aeration integrated into the CLRO process.

Further important results

A tool for a multi criteria analysis assessing the different technical solutions with respect to the local boundary conditions and demands of different sectors versus their techno-economical soundness was developed. The analysis with weighting factors from surveys among international experts shows a clear advantage for CLRO approach.

A multimedia training platform was developed by inter3 as a contribution to capacity building and has been well received by users. This platform has particularly benefited technicians from Sri Lanka and Nepal, who supervised the majority of the demonstration phase, as it effectively addressed language barriers, but also allowed a very easy introduction to the technology for the 4 students from TUB and Fraunhofer ISE doing student projects at the demonstration site. Several workshops have been conducted in Qatar and Iran with students and experts in form of a hybrid teaching module developed by TUB. Unfortunately, the preparation, training, and collaboration with the German-Iranian training center could not proceed as planned as the demonstration in Iran could not take place. To still achieve the goal of multilateral cooperation, Iranian partners are invited to visit TUB, inter3, and participate in hands-on process operations at similar CLRO facilities at Fraunhofer ISE.

OUTLOOK AND FUTURE APPLICATIONS

The CLRO concept proved as a good solution for high recovery, fluctuating raw water quality and robust against scaling even without comprehensive pre-treatment.

PV coupling without inverter and frequency converter can be considered as a robust, cost effective and reliable solution.

We would recommend for a commercial installation to realize following improvements:

- Avoid operation with two operation points for high-pressure pump. Better realize flushing (plug flow mode) with pre-pressure pump or use CLRO-concept with isobaric chamber (side conduit).
- Automated switching on/off, e. g. via irradiation sensor for a directly coupled PV energy supply
- Maximum power point control strategy for the directly coupled PV energy supply.
- Automized cleaning cycles

Further economic analysis for the combined processes of CLRO and EDM are essential for evaluating each user case individually. This could be conducted with reference to the HighRec pilot system.
The project consortium got positive feedback from the farming company Agrico and the PV provider Salzburg in Qatar to go jointly next steps for a real scale application. At Agrico Farm, there is a desire to make food production more sustainable overall. In addition to smarter greenhouse cooling, environmentally friendly brackish water desalination is seen as one of the key technologies. We were contacted for an initial facility to supply one of their external composting plants. For the company Salzburg, the combination of photovoltaics and water treatment for irrigation has long been an important business model in Qatar. With CLRO, they see an opportunity for greater flexibility and cost-effectiveness. However, it is important for them to work with established technologies. Additional interest has already been shown by another European RO plant manufacturer.

Coordinator
Dr.-Ing. Joachim Koschikowski
Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstr. 2, 79110 Freiburg, Germany
+49 761 4588-5294
Joachim.koschikowski@ise.fraunhofer.de

Project partner
- Technische Universität Berlin, Fachgebiet Umweltverfahrenstechnik, Berlin
- inter3 GmbH Institut für Ressourcenmanagement, Berlin
- Qatar University, Center for Sustainable Development, Doha/Katar
- University of Birjand, College of Agriculture, Birjand/Iran
- Isfahan University of Technology, Department of Soil Science, Isfahan/Iran

Website
www.highrec.de

MiningWater: Mining water recovery using innovative technologies for saving fresh water

PROJECT OBJECTIVES

In arid regions such as Jordan, limited water availability leads to conflicts between drinking water production, agriculture and industry, and is exacerbated by global climate change. Increasing water demands due to growth of population and industry in combination with inadequate cleaning treatment capacities tighten the situation. Industrial water consumers are e.g. phosphate mines with about 3 million m³/a of water and 85.000 tons/a of phosphate being discharged into tailing ponds for a single mine, due to missing of suitable technologies to treat the complex composition of wastewaters with corrosive salts, scaling enhancing compounds and fine particles in low µm size. Considering the current situation, approach of the project is the investigation and use of novel robust process techniques in combination with a valorisation of occurring concentrates to reduce the freshwater demand and decouple partially the production form the freshwater demand, Figure 3. The water and phosphate savings potential for phosphate mines in the Middle East and North Africa is around a factor of 40.

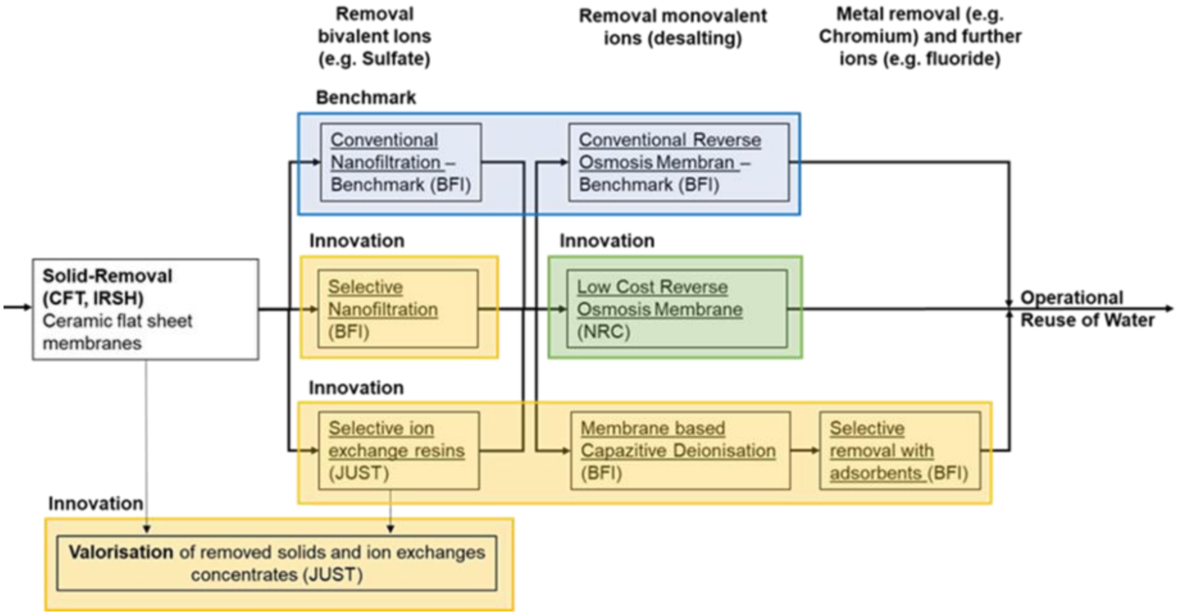


Figure 3 Approaches of the project MiningWater

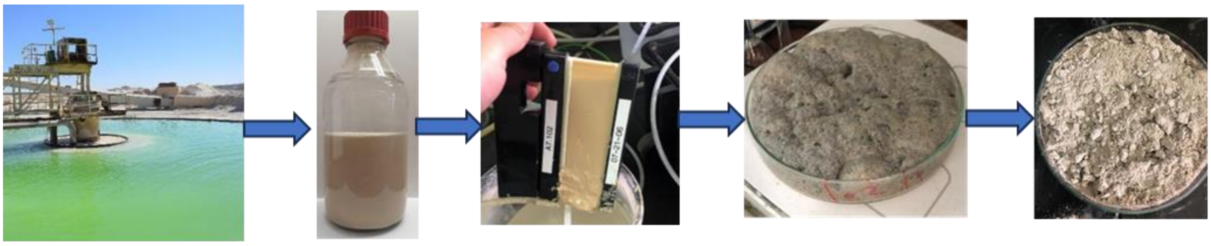
KEY RESULTS

Based on operational samples, taken by Irshaidat, the determined range of the wastewater composition with conductivity, sulphate and calcium varying by more than 50% or up to a factor of 3 due to the decomposition of different ore layers, different possible technology approaches have been investigated (Irshaidat). An exemplary sample contained about 425 mg/L chloride, 1,200 mg/L sulphate with a conductivity of 3,300 µS/cm and a hardness of 11 mmol/l.

Due to high solid contents up to 80 g/L, consisting of abrasive particles, precipitation products and compounds with a high tendency for forming clogging layers on surfaces, a reliable solid removal is a mandatory step before any kind of further desalting or softening technology.

The **under-pressure filtration with ceramic flat sheet membranes** has been **first time applied under the described conditions** by Cerafiltec. It was finally determined as **suitable treatment technology, by** using Al-oxide membranes, allowing a flux up to 200 L/m²*h with a transmembrane pressure (TMP) of < 200 mbar and a turbidity 0.3 NTU in the permeate. The energy demand is about 0.007 kWh/m³, which is about 10 times lower to the operation an overpressure filtration at 4 bar, using ceramic tube modules. Due to the open surface and the

filtration of the wastewater from outside to inside, no clogging was observed, being a high risk with ceramic tube modules with inner diameter of 2 -10 mm and filtration from inside out. The water recovery was about 90%.
The Jordan University developed and tested a concept for the **valorisation** of the up to 21 - 29 wt.-% of **P_2O_5 (orthophosphate)** **in** the **removed solids**, allowing the production of so called "superphosphate", a granulated, fast-acting phosphorus fertiliser, Figure 4.



Operational treatment | Operational wastewater | Ceramic flat sheet filtration | Reaction during valorisation | Final product

Figure 5 From wastewater to superphosphate fertiliser

Different technologies combinations after the solid removal by filtration with ceramic flat sheet membranes have been **investigated**. Treatment aim is the fulfilling of the operational requirements for an internal reuse of the wastewater as freshwater substitute. Requirements are e.g. chloride and sulphate contents below 250 mg/L or 220 mg/L or for instant a conductivity below 1,500 µS/cm.

One of the investigated **technology combinations** is the **selective** removal of bivalent ions by **nanofiltration followed by membrane based capacitive deionisation (MCDI)** for removal of mainly monovalent ion (BFI)**. Background** of this approach **is the production of** two **mono concentrates for** a **potential valorisation** in construction industry or for electrolytical biocides production for e.g. disinfection of cooling water circuits. A suitable nanofiltration membrane have been selected considering lab trial results with synthetic and mining wastewater. The membrane is called "Olremare NANO7", consisting of a composite polyamide membrane with a polypropylene brine spacer. For this membrane, a sulphate retention of > 99% in combination with a chloride retention of < 15% and a flux of up to 132 L/m²*h at 20 bar was achieved.

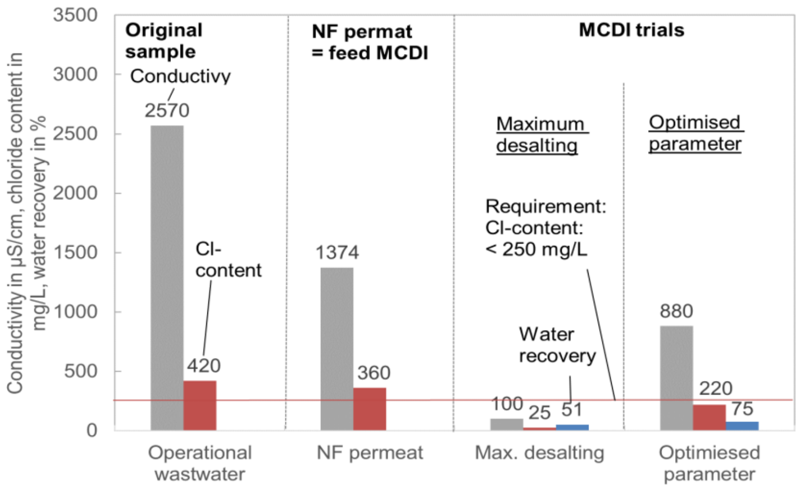
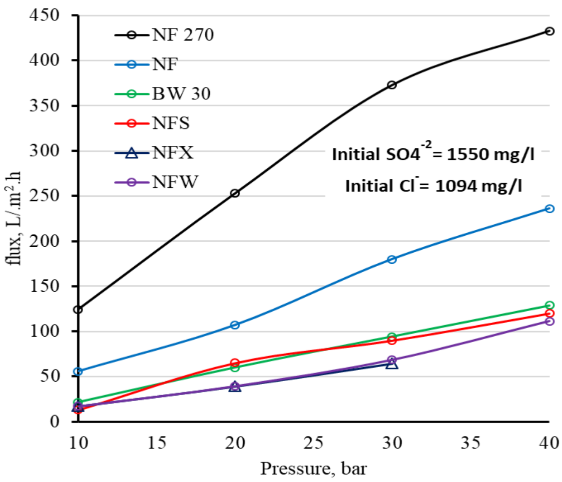


Figure 6 From wastewater to reuseable water by selective nanofiltration and MCDI treatment

The permeate was further treated by MCDI, with the main focus of desalting. Due to parameter optimisation, the operational requirements for internal reuse with a Cl-content: < 240 mg/L was achieved in combination with a water recovery of 75% and an energy demand of < 0,8 kWh/m³. In the case of maximum desalting, the Cl-content was decreased about 93% to 25 mg/L with a conductivity of 100 µS/cm.

A further approach was the **development of a new membrane material for mining water treatment consisting of polymer membranes containing metalorganic particles.** Base for the development of the National Research Center was the determination of suitable material combinations of metal acetylacetonates (Zn, Cu) for improvement of the membrane and antifouling properties, different blends (PVC, CA, PS) and solvents (e.g. acetone, DMF, NMP), considering thermodynamic models for polymeric solution preparation. Further on, suitable steps and parameters for the production of the membrane material were determined, leading to a 6-step process. The membranes were tested with synthetic and relevant waters with the focus of e.g. retention of different ions, flux, and possible impacts to the mechanical strength and the surface structure (scan electron microscope investigation). As a result, a combination of CA, PVC and Cu acetylacetonate particles was selected, allowing the production of a permeate fulfilling the operational requirements, having a permeate flux range from 17 to 30 L/m²*h under pressure 20 bar. The permeate consisted of < 30 mg/L of Chloride and Calcium, while the sulphate content was up to 130 mg/L. Further on, DIN A4 flat sheet membrane for benchmark trials were produced by using an automatic casting lab machine on non-woven polyester support. First benchmark trials with synthetic wastewater showed a higher Chloride rejection of up to 97% compared to 91,7% of the market available DOW NF90 membrane, while the retention of sulphate is about 92% compared to 99% (DOW NF90). Trials with operational wastewater are in ongoing.

A further approach was the use of **resins** for the **removal of e. g. chloride**. In laboratory tests, Jordan University determined suitable operating parameters for efficient separation of suspended solids using ceramic flat sheet membranes. Chloride separation efficiencies of between 70 and a maximum of 88% were achieved depending on the residence time, resin quantity, temperature and pH value. Whitish precipitates from the regeneration of the resin indicate the presence of calcium carbonate in increased concentrations caused by the removal of sulphate by the resin. The later was found to be competitor for chloride in resin treatment. As a result, the investigation of a two-stage treatment was planned (1st stage: sulphate and other bivalent ion removal via nanofiltration using a high flux membrane (130-140 L/m2.h @ 10 bar), 2nd stage: chloride removal via resin treatment) in lab scale. For the 1st stage different types of membranes were tested to choose the best combination of flux and sulphate rejection (Figure 5).



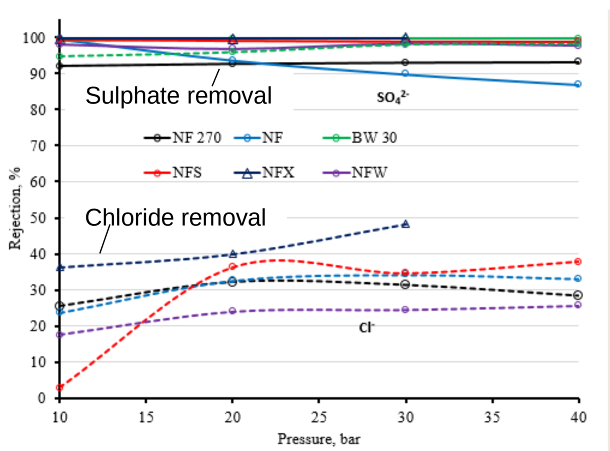


Figure 5. Testing different types of membranes on synthetic water

The results suggest that the best NF membrane was NF270; when tested on real wastewater, up to 92% sulphate removal was achieved coupled with up to 25-30% chloride removal at an operating pressure of 10 bar. For the second stage, a suitable resin and operating parameters were determined as part of the investigation of various ion exchange resins and the final optimization is underway. This will be tested in lab scale with synthetic and operational samples

Summarizing, suitable technology combinations have been determined, allowing a side specific wastewater treatment in phosphate mines for recovery of water and valorisation of occurring solids and concentrates. Key element is the mandatory solid removal with under pressure filtration with ceramic flat sheet membranes and the valorisation of the phosphate containing solids as e. g. fertilizer. Depending on the local site-specific conditions, as e.g. requirements for water reuse, existing wastewater treatment, different technologies can be applied as combination of selective nanofiltration and membrane-based capacities deionisation, polymer membranes with metalorganic particles or resins.
For the field trials at the phosphate mine, the combination of energy saving ceramic flat sheet filtration was used for solid removal, followed by selective nanofiltration (Oltremare NANO7) for removal of bivalent ions (mainly sulphate) and desalting by membrane based capacitive deionisation for removal of monovalent ions (mainly chloride). The basis for the selection was the combination of high flux in combination of low energy demand and no chemical demands. Furthermore, concentrates could be valorised as fertilizer (solid phosphate containing particles), raw materials for construction industry (sulphate concentrate) or the production of biozides for cooling water disinfection (chloride concentrate).
Based on the described work, savings for the considered phosphate mine with a production of 500.000 t of phosphate per year would be around 20.000 t/a of phosphate and around 157.000 m³/a of water. The detailed values have to be verified by the field trials.

The **transfer of the results** is e. g. performed by training the partners on the investigated technologies, as for the ceramic flat sheet filtration done by Cerafiltec to Jordan University, NRC and Irshaidat. Furthermore, the results have been international presented on the 5th International Conference for Membrane Technology & Its Applications 2024, organised by the project partner NRC and will be used for trainings at the different scientific partners.
Considering the lab trials and especially the upcoming field trials, a detailed concept for an industrial implementation of the selected technology combination will be developed by Irshaidat, supported by Cerafiltec and BFI. An industrial realisation would be done by Irshaidat and supported by Cerafiltec.

OUTLOOK AND FUTURE APPLICATIONS

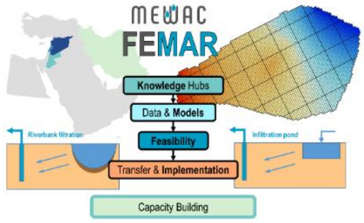
The combination of filtration and desalting technologies will be demonstrated over 2 months in field trials in an exemplary Jordanian phosphate mine.
In addition to phosphate mining, other future applications include the mining of other ores whith washing processes and the occurrence of wastewater being discharged to tailing ponds. Different ores or tramp elements result in different wastewater compositions and compounds, which have to be removed or valorised. Further on, the results could be transferred and adapted to industrial processes for the treatment of waste or processes waters to reduce the dependency of production from freshwater demand.

Coordinator
Dipl.-Ing. Martin Hubrich
VDEh-Betriebsforschungsinstitut GmbH
Sohnstraße 69, 40237 Düsseldorf,
Tel.: +49 211 98492 -343
E-Mail: martin.hubrich@bfi.de

Project partners
- CERAFILTEC Germany GmbH, Germany
- Jordan University of Science and Technology, Jordan
- National Research Center, Egypt
- Irshaidat Company for Trading & Contracting, Jordan

Website
https://www.bfi.de/en/projects/miningwater-mining-water-recovery-using-innovative-technologies-for-saving-fresh-water/

FEMAR—Feasibility of Managed Aquifer Recharge for Safe and Sustainable Water Supply



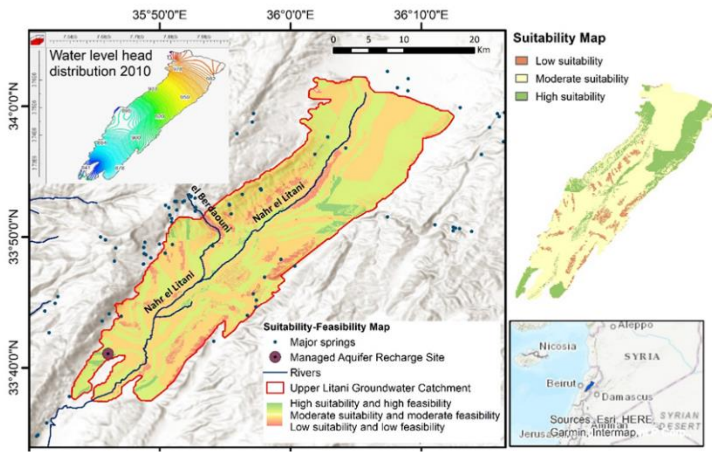
PROJECT OBJECTIVES

The increase in water demand and abstraction in the highly water-stressed eastern Mediterranean region is having a negative impact on its aquifers, causing a decrease in groundwater (GW) resources and a deterioration of the GW quality, as well as saltwater intrusion and land subsidence. Aimed at addressing these issues, the FEMAR consortium investigated the feasibility of managed aquifer recharge (MAR) techniques to enhance water security for drinking and irrigation. To this end, the suitability of sites for the MAR techniques of artificial GW recharge such as aquifer storage and recovery (ASR) and riverbank filtration (RBF) were mapped and evaluated in the Upper Litani, Al-Matekh and Zarqa river basins in Lebanon, Syria and Jordan, respectively. The impact of irrigating fodder crops with polluted water (untreated wastewater) was investigated at a field-test site by the Quaik river in the Al-Hadher area near Aleppo, Syria. Hydrogeological and water quality investigations were aided by multi-criteria decision analyses (MCDA) using “open source” numerical GW modelling tools and geographical information systems such as QGIS. FEMAR included partners from higher education and research institutions and a small-medium enterprise. The project targeted stakeholders from academia and research institutes, decision/policy makers, water supply organisations and farmers.

KEY RESULTS

Site-suitability mapping for artificial recharge in Lebanon and Syria

The Upper Litani Basin (ULB) irrigation plain in Lebanon and the Al-Matekh Plain in Syria were selected as study sites (Fig. 1 & 2). Alongside a calibrated numerical model, a **MCDA assessed MAR feasibility in the ULB, identifying slope (32%), transmissivity (24%), storativity (21%), soil type (14%), and vegetation cover (9%) as key influencing factors for recharge**.



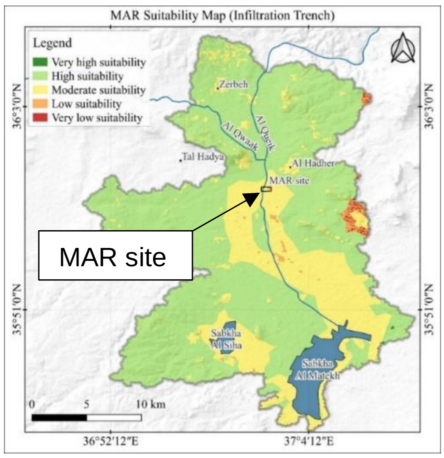


Fig. 1: Suitability and feasibility maps for the ULB showing the selected MAR site and the simulated water head distribution in 2010 in the main aquifer

Fig. 2: Sites feasible for MAR in the Al-Matekh catchment in Syria

A sensitivity analysis identified areas of **high MAR suitability**, mainly on the **eastern and western sides of the syncline and in patches within the plain**. The feasibility study considered factors such as water table changes, hydraulic gradient, GW depth, drainage density and GW flow, using both collected data and the numerical model and identified areas that are both intrinsically suitable and economically feasible for MAR. **In Syria**, the MCDA provided key insights into site suitability for **infiltration trenches**. The results show that **much of the Al-Matekh plain is highly suitable** for this MAR technique, with moderately suitable areas mainly located in Sabkha Al Siha and the central plain, while zones of low to very low suitability are concentrated in the eastern mountainous section of the study area. Furthermore, investigations at the Al-Hadher field-test site showed that irrigation using sewage-polluted water leads to damage to the maize fodder crop by plant pathogens such as *E. coli* bacterial infections and fungal diseases (*Ustilago maidys*).

Workflows for numerical GW modelling in Syria and Lebanon

A **regional numerical** model was applied to the **Al-Matekh plain in Syria**, facilitating the analysis of **GW flow directions and the quantification of water budgets** at both regional and sub-regional scales. Additionally, a **local model using PCSiWaPro** was developed for the Quaik river pilot site to assess GW recharge from infiltration trenches supplied with treated wastewater. This model also evaluated the **impact of trench design on water content in the unsaturated zone, GW levels and soil moisture availability** for nearby farmland.

An automated, generalizable and scalable multi-model framework was developed based on open-source tools, integrating automatic calibration and comprehensive pre- and postprocessing to **model both porous media and karst systems**. In Lebanon, the model successfully simulated observed monthly discharge at the Nabaa El Berdaouni spring; however, it highlighted limitations in assessing MAR feasibility across various injection scenarios, underscoring the importance of critical uncertainty assessment due to data limitations.

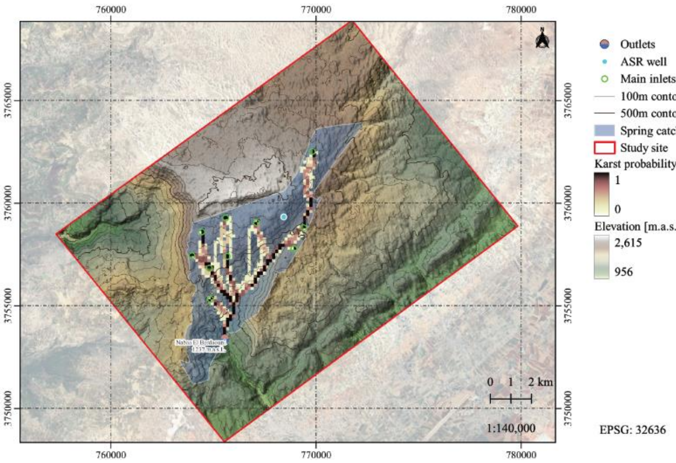


Fig. 3: Selected karst conduit realizations and resulting karst probability map of the Nabaa El Berdaouni spring

Evaluation of the suitability of sites for riverbank filtration in Jordan

The motivation for using RBF along the Zarqa River is driven by its potential for improving the quality of irrigation water for high-value food crops cultivated along the predominantly wastewater-fed river (high organic and microbiological load). **A geospatial MCDA along the Zarqa revealed 18 locations with high to moderately suitable geohydraulic conditions for RBF**. At one such location (Fig. 4), two monitoring wells (MW) were installed to investigate geohydraulic, hydrochemical, and microbiological conditions. The selected Zarqa River site with thin alluvial deposits having limited horizontal extent and high organic and microbiological load poses challenging conditions for RBF, thus requiring an optimization of travel time of bank filtrate, pumping rates and well design. With naturally infiltrating river water (non-pumping conditions), **RBF demonstrated a 3–4 log$_{10}$ removal of coliforms after a travel time of a few weeks** as observed along the river–MW transect (Fig. 4). A significant **attenuation of around 70% was observed for dissolved organic carbon** (sum parameter for organic pollution). Organic trace pollutants, especially **diclofenac was attenuated by 70–90%**.

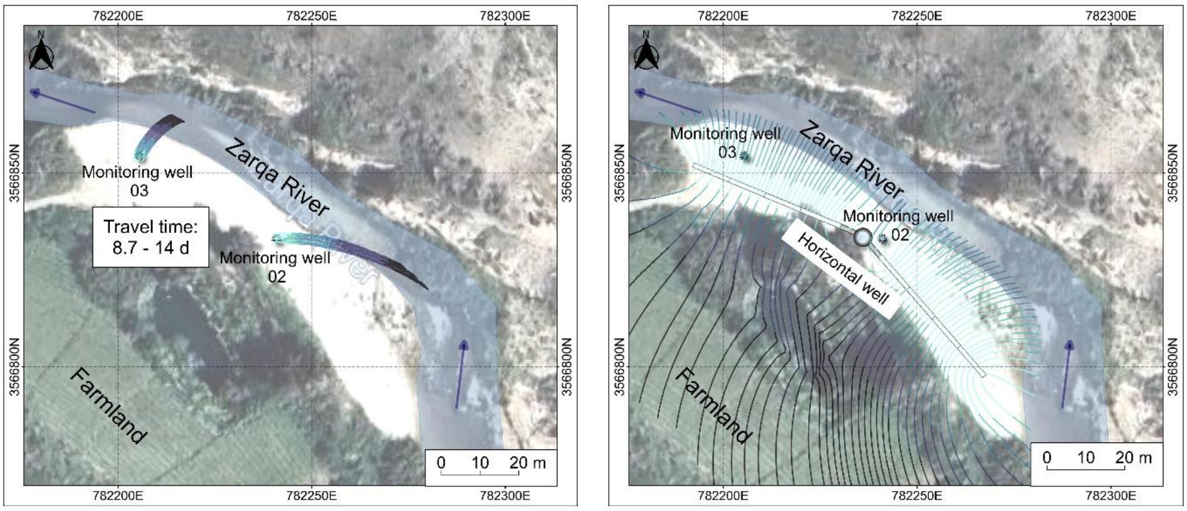


Fig. 4: Flow path of bank filtrate under natural (non-induced) conditions (left) and for a horizontal well design with a 1 m drawdown (right) at the case study site in Jordan

Aquifer storage and recovery application in Lebanon

An **ASR experiment** in a well was further tested and operated during the FEMAR project **in Lebanon**. In 2024, **water from a spring overflow channel**, with a flow rate of 4–11 m³/h, was **successfully infiltrated directly into the well by gravity over a four-month period**. The experimental site is equipped with a climate station, soil moisture sensors, and a data logger for monitoring pumping and water level fluctuations during infiltration.

Development of the riverbank filtration simulation tool – *RBFsim*

RBFsim (https://rbf-sim.streamlit.app/) addresses the initial evaluation of a RBF system and simplifies complex computational effort, particularly for feasibility and risk assessments. Considering that initial system evaluations need to rely on limited data, be cost-effective and need to provide sufficient useful output, it is designed for the early assessment of flow hydraulics in a RBF scheme during site selection, for the optimization of well operation and an evaluation of the impact of riverbed clogging on the operation of the RBF system (Fig. 5). It simulates the travel time and the portion of water contributed by the river in the well discharge. The tool allows simplified computation based on the analytical element method of the flow field for single and multiple wells in a 2D homogeneous and isotropic aquifer with uniform flow. Thus, the tool can be used in handheld (smartphones) or desktop devices with or without internet. *RBFsim's* peer-reviewed (doi.org/10.1007/s40899-024-01137-9) and open-sourced methods and code (licensed under CC-BY 4.0) promote personalized modifications and extensions.

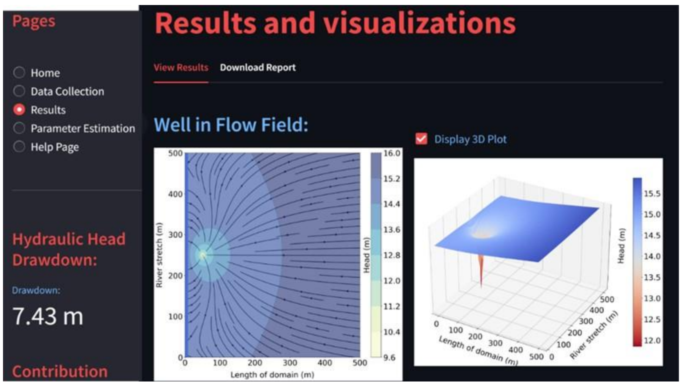


Fig. 5: Visualization of the groundwater flow field, drawdown and catchment of a RBF well using *RBFsim*

Capacity enhancement measures on MAR

Notable measures included the organisation of webinars, workshops and training courses for the regional stakeholders by the Jordanian, Lebanese and till 2022 participating Iranian partners, partly as hybrid events, and their reciprocal participation in the DAAD-funded "Managed Aquifer Recharge International Summer Schools" (MARISS, 2021–2023). A modularized lecture and exercise syllabus was developed for the FEMAR training workshops and successfully tested at the Shiraz University (05/2022). Parallel online tools were developed and adapted. A stakeholder workshop was organized by the Jordanian Royal Scientific Society (Amman, 09/2022). The American University of Beirut organised a webinar on the feasibility of MAR in Lebanon (04/2023). A FEMAR workshop on MAR and RBF was organised by the TU Dresden, HTW Dresden, SME UBV and JUST's Water Diplomacy Center in Irbid (11/2023). The project's results were valorised at the BMBF-funded (CONNECT program) "International Riverbank Filtration Conference" (Dresden, 10/2023), at the DFG-funded "German-Jordanian workshop on integration of RBF into the water-food nexus for arid regions" at the Irbid National University (07/2024) and at the DAAD-funded "MAR Autumn School" in the German Jordanian University (11/2024). FEMAR's events culminated with the "Project MEWAC–FEMAR Symposium on Managed Aquifer Recharge in Middle East" (Amman, 11/2024).

OUTLOOK AND FUTURE APPLICATIONS

While challenges persist with MAR in highly heterogeneous karst aquifers, requiring more experimental sites, the workflow for numerical modelling nevertheless allows an efficient use of GW models as well as future data integration. In Lebanon, MAR faces barriers from limited governance and restricted study area access due to its location in a conflict zone. In Syria, prior treatment of surface water for irrigation is recommended to enhance crop yield, improve fodder quality and to mitigate soil pollution. Studies near Jordan's Zarqa River showed that RBF reduces waterborne pathogen risks, with other meander sites offering promising RBF sites as an alternative to the direct pumping of river water for irrigation. The investigations at the Zarqa River and data from monitoring wells resulted in the development of a concept for siting RBF wells in shallow alluvial sediments with limited horizontal extent (Fig. 4). The capacity of different horizontal collector well designs was assessed, which can be adapted in order to provide adequate irrigation water, thereby conserving GW resources.

The MEWAC program enabled an expansion of the MAR network in the partnering Middle East countries. This will help the work and results of FEMAR to be valorized and built upon beyond 2024. In Jordan, further potential RBF and artificial GW recharge sites will be investigated by the MAR network partners in conjunction with new scientific aspects within other projects. This, and the integration of the Jordanian Ministry of Water and Irrigation will enhance the transfer of the project results. In Lebanon, the operational ASR System will be further modeled to allow up-scaling its technology readiness level and to transfer the results to the Beirut and Mount Lebanon Water Establishment, government ministries, water authorities (Litani Water Authority), NGOs, farmers, local research centers, and WASH officers.

Coordinator
Prof. Dr.-Ing. Thomas Grischek
University of Applied Sciences Dresden,
HTW Dresden
Friedrich-List-Platz 1, 01069 Dresden, Germany
Phone: +49 (0) 351 462 3350
E-mail: thomas.grischek@htw-dresden.de

Project partners
- Technische Universität Dresden
- Umweltbüro GmbH Vogtland, Weischlitz
- Royal Scientific Society, Amman, Jordan
- American University of Beirut, Lebanon
- University of Aleppo, Syria

Website
htw-dresden.de/femar

Forward Osmosis Desalination by Thermo-Responsive Hydrogels with Controlled Morphology, Microstructure, and Molecular Architecture for Small Villages Close to the Persian Gulf

PROJECT OBJECTIVES

The goal of this project is to develop low-capacity forward osmosis (FO) desalination methods tailored for small villages near the Persian Gulf. This approach utilizes thermo-responsive hydrogels as the draw agent and incorporates new thin-film composite (TFC) membranes. A significant benefit of thermo-responsive hydrogels is that they enable water recovery through solar energy, low-grade heat, or waste heat, which helps lower operational costs and reduce the carbon footprint of the process.

Seawater desalination using reverse osmosis is widely adopted in parts of the Persian Gulf region. However, this process typically requires high-capacity systems with substantial capital investments, making it inaccessible for some countries in the area. As a result, desalination plants are not evenly distributed in relation to population needs. The HydroDeSal project seeks to address this issue by developing a new desalination method that is both low-cost and low-capacity, specifically targeting small coastal communities lacking sufficient freshwater for daily needs.

KEY RESULTS

In alignment with the forward osmosis desalination concept, the project was conducted along two main lines. The first approach focused on developing hydrogels to serve as the draw agent, while the second approach concentrated on advancing membrane technology.

Developing the draw agent

Thermo-responsive hydrogels based on poly(N-isopropyl acrylamide) (PNiPAAm) and poly(sodium acrylate) (PSA) were developed as microgels with diameters ranging from 0.1 to 1 µm in Prof. Seiffert's research group. These microgels exhibit a core-shell structure, with PNiPAAm primarily forming the core. The microgels' volume transition temperature is influenced by the PNiPAAm-to-PSA ratio, generally increasing as the PSA content rises. However, due to the core-shell configuration, this temperature increase is notably less pronounced compared to bulk hydrogels. Graphene oxide was integrated into the microgels as a light-absorbing agent, enabling temperature elevation upon exposure to UV or natural sunlight. Results indicate that microgels synthesized with **75 mol% of NiPAAm and 25 mol% of SA** achieve an optimal balance: they contain a substantial amount of ionic groups while maintaining moderate thermo-responsivity at approximately **41°C**.

Developing the FO membrane

In this project, two types of FO membranes were developed. The first, created by Prof. Shakeri's research group, was a thin-film composite (TFC) membrane based on a microfiltration support layer. The second, developed by Prof. Alsalhy's group, was a TFC membrane built on a modified nanofiltration membrane with nanosilica. As the first type showed more promising results, the project continued with these membranes. Specifically, the FO membranes developed here are thin-film composite (TFC) membranes in a flat-sheet configuration. The support layer is a flat-sheet microfiltration membrane made of hydrophilic polyvinylidene fluoride (PVDF) with an average pore size of 100 nm. This membrane was first coated with a zeolitic imidazolate framework (ZIF-67), followed by a thin cross-linked polyamide (PA) film as the active top layer. The ZIF-67 interlayer enables the formation of a homogeneous PA layer on a support with relatively large pores. After TFC formation, the ZIF-67 interlayer dissolves in water, resulting in a membrane that combines the advantages of the support's large pore size with a uniform active layer. The optimal membrane performance was achieved using a 0.5 wt% aqueous solution of Co(II) nitrate hexahydrate and a 0.4 wt% solution of 2-methyl imidazole in hexane. In a standard FO test with 1 M NaCl as the draw solution and DI water as the feed solution, this membrane achieved a water flux of **25.55 L·m^{-2}h^{-1} (LMH)** and a reverse salt flux of **4.25 g·m^{-2}h^{-1}** yielding a selectivity of **0.17 g/L**.

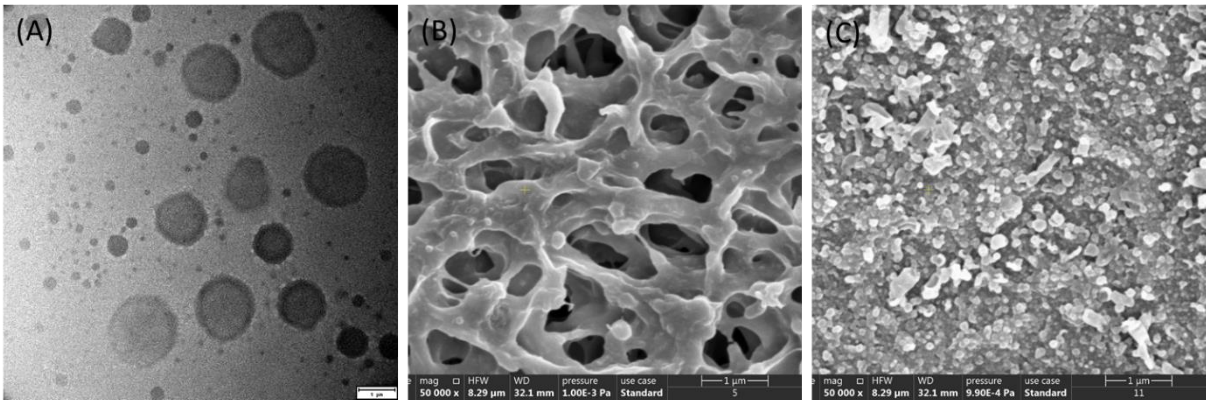


Figure 7. A) Transmission electron microscopy (TEM) image of microgels containing 25 mol% ionic groups. (B) Surface morphology of the PVDF membrane coated with the ZIF-67 layer. (C) Surface morphology of the PA top, active layer.

FO performance

The FO performance of the optimal microgels (75 mol% NiPAAm, 25 mol% SA) was tested against feed solutions of varying salinity .The microgels were evaluated in three forms: dried, as a 40 wt% dispersion in water, and as a 20 wt% dispersion in water. When used to draw a model brackish water solution at 5 g/L containing both monovalent and divalent ions, these samples achieved water fluxes of **2.84, 4.79, and 4.39 LMH**, respectively. Upon increasing the feed solution salinity to 35 g/L, the water fluxes adjusted to **0.81 and 1.36 LMH** for the dried and 40 wt% dispersion samples, respectively, while the 25 wt% dispersion was unable to draw water effectively at this higher salinity. It should be noted that the analysis of Persian Gulf water demonstrated that the salt concentration is around 30 g/L. Our preliminary results by the Persian Gulf water demonstrates that the performance of microgels are almost similar to the data with artificial seawater with salt concentration of 35 g/L. Additional experiments are currently underway in Prof. Hashemifard's group to further validate this performance.

Laboratory demonstrator setups

In this project, three FO demonstrator setups with varying capacities and objectives have been constructed in Germany through collaboration among the research groups of Prof. Maskos, Prof. Seiffert, and Prof. Shakeri. Additionally, one laboratory demonstrator setup is under construction at Persian Gulf University.

The first setup (Figure 2A) is a cross-flow FO system designed to test membrane performance, utilizing **1L** volumes for both feed and draw sides. The second setup (Figure 2B) is similar but includes a specialized FO module, allowing testing of hydrogels in both dried and dispersed states. The third demonstrator setup (Figure 3C) has a medium capacity, with a

100L feed tank and a **200L draw tank**, aimed at evaluating the potential application of our membranes and draw agents in the FO process, as well as exploring key process parameters using conventional draw agents and commercial membranes. This demonstrator setup includes pressure gauges and digital flow meters for both feed and draw sides.

In addition, a microfiltration (MF) setup (Figure 3D) has been paired with the second demonstrator setup to separate swollen microgels from absorbed water. Based on data from these setups, a new FO laboratory demonstrator setup is being constructed in Prof. Hashemifard's group near the Persian Gulf (Figure 3E). This demonstrator setup is designed for continuous water drawing by hydrogels, with separation of absorbed water via heating, leveraging the thermo-responsive nature of the microgels. We anticipate that the selected microgels will be ready for testing in this demonstrator setup within the coming months.

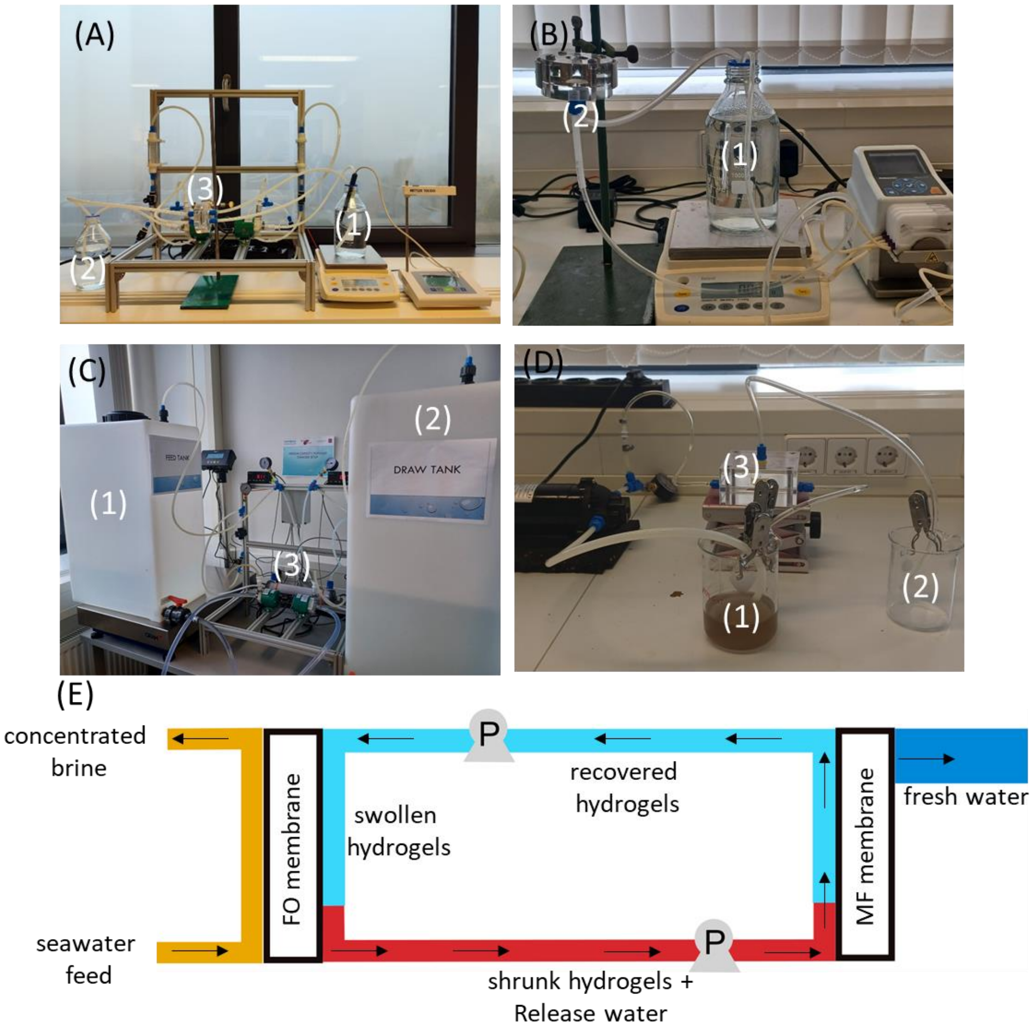


Figure 8. Illustrations of the demonstrator setups constructed in this project and a depiction of the demonstrator setup currently under construction. (A) Cross-flow FO setup: (1) feed solution, (2) draw solution, (3) FO module. (B) FO setup for microgels evaluation: (1) feed solution, (2) FO module. (C) Medium-capacity FO demonstrator setup: (1) feed tank, (2) draw tank, (3) FO module. (D) Microfiltration setup for separating microgels and water: (1) microgels dispersion, (2) separated water, (3) MF module. (E) Schematic of the FO laboratory demonstrator setup under construction at Persian Gulf University, designed for continuous water drawing and release through heating (red) and cooling (blue) cycles.

OUTLOOK AND FUTURE APPLICATIONS

1. Conclusions/lessons learnt from your project. Which challenges remain with respect to the water issue addressed?

Thermo-responsive hydrogels can serve as effective draw agents in forward osmosis (FO) desalination, particularly for brackish water and seawater. Although the performance of these hydrogels is generally lower in terms of water flux compared to conventional draw agents, their potential to achieve zero reverse salt flux and their thermo-responsivity are significant advantages. These hydrogels can release around 70-90% of the absorbed water by heating the microgels above their transition temperature of 41°C, making them promising for the water recovery step. However, a key challenge remains in increasing the water flux to make these hydrogels more competitive with conventional draw agents in FO processes. In terms of membrane development, the main challenges include extending the lifetime of the membranes, preventing fouling over long-term use, and improving their maintenance. Additionally, ensuring consistent repeatability in the membrane formation process, especially in both the ZIF-67 and PA layer steps, is crucial for enhancing the overall performance and reliability of the system.

2. Outlook on future use of your project results. Any other recommendations?

The microgel/membrane system developed in this project has been tested with model brackish water and seawater containing both monovalent and divalent ions. Preliminary experiments using Persian Gulf water have shown comparable performance. Additional experiments are planned in this area. Furthermore, a new FO laboratory demonstrator setup is currently under construction in the Persian Gulf region to facilitate further testing. Additionally, the findings from this study can contribute to an economic assessment of the process, including the capital cost, operational costs, and final product pricing.

Coordinator
Prof. Dr. Sebastian Seiffert
Johannes Gutenberg University Mainz
Duesbergweg 10 – 14, 55128 Mainz
Phone +49 6131 39 23887
E-Mail Sebastian.seiffert@uni-mainz.de

Project partner
- University of Technology, Iraq
- Persian Gulf University; Iran
- Universität Teheran, Iran

Website
https://www.hydrodesal.uni-mainz.de/

Contacts at the sponsoring ministry

Federal Ministry of Education and Research (BMBF), Germany

Dr. Rainer Müssner
E-Mail: rainer.muessner@bmbf.bund.de

Acting on behalf of the BMBF: Project Management Agency Karlsruhe (PTKA), Germany

Dr. Leif Wolf
E-Mail: leif.wolf@kit.edu

Dr. Anna Xanke
E-Mail: anna.xanke@kit.edu

Further information on the MEWAC funding measure is available at
https://www.fona.de/en/measures/funding-measures/mewac-multilateral-water-research.php

Imprint

Edited by
Project Management Agency Karlsruhe (PTKA), Karlsruhe

Layout
Project Management Agency Karlsruhe (PTKA),
Karlsruhe

SPONSORED BY THE
Federal Ministry
of Education
and Research

Photo Credits
p.1 © Michael Xiao/iStock.com