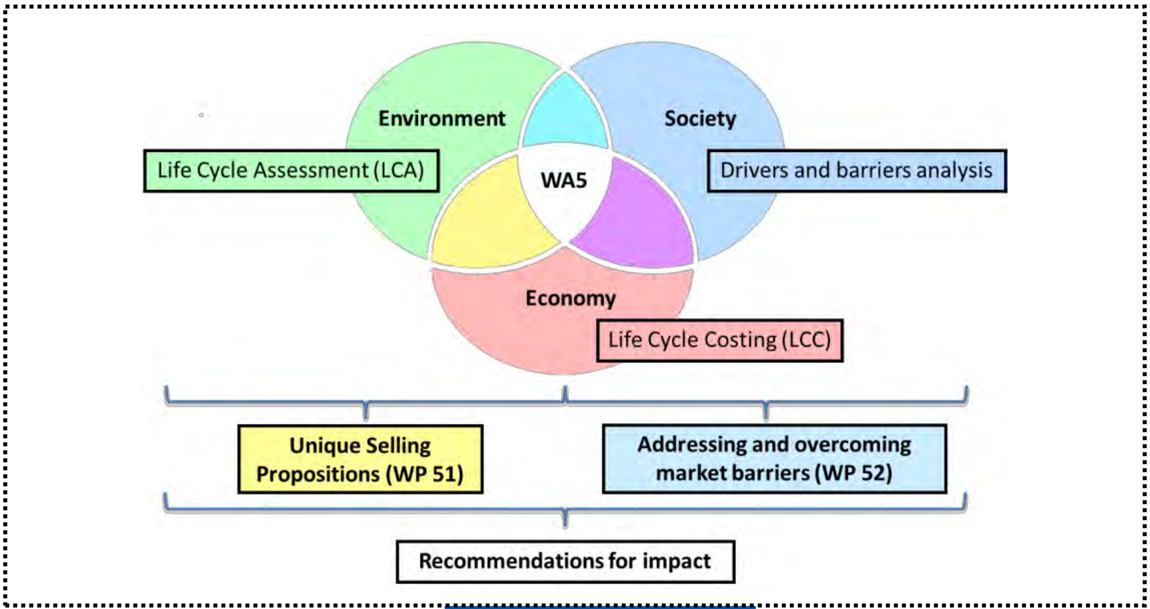
# Recommendations for Impact

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**Title: Recommendations for impact**

**Summary:** This document brings together recommendations for impact in the water market which were elaborated for water technologies to eliminate emerging contaminants from wastewater or drinking water and to detect contaminations based on their effects. The recommendations provided in this document were developed within the DEMEAU project funded under the 7th Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU was to promote the uptake of knowledge, prototypes and best practices from previous EU research in order to enable the water sector to face emerging contaminants and therewith secure water and wastewater services and public health. Recommendations in this document are specific for five different technologies: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF), automatic neural net control (ANCS), advanced oxidation processes (AOPs) and in-vitro bioassays for effects-based screening. These recommendations capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle analyses (LCAs), economic life cycle costings (LCCs) and social drivers and barriers analyses.

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# 1 Introduction

### 1.1 Content of this document

The main contents of this document are recommendations for impact developed for technologies and methods studied and developed during the DEMEAU project. This section provides background information on the DEMEAU project and how the recommendations for impact were developed. The individual sections per technology are self-contained capacity building documents which can be used independently of this report:



The Annexes A to E contain results from work area specific workshops and interviews, which build a part of the recommendations for impact. Further basis of these recommendations are environmental and economic unique selling propositions reported in DEMEAU deliverable 51.1 (‘Unique selling propositions’, Remy et al. 2015A) and results from the drivers and barriers analysis reported in DEMEAU deliverable 52.2 (‘Implementation barriers’, Pieron and van der Zouwen 2014).

### 1.2 Background of DEMEAU: demonstration of promising technologies

The drinking water, wastewater, and public health sectors are facing challenges to assure safe, cost-effective and sustainable water supply and sanitation services. DEMEAU promotes the uptake of knowledge, prototypes and practices from previous EU research, enabling the water sector to face emerging pollutants and thus securing water and wastewater services and public health. The project exploited technologies and methods from former EU research (Figure 1-1): Managed Aquifer Recharge (MAR), Hybrid Ceramic Membrane Filtration (HCMF), Automatic Neural Net Control Systems (ANCS), Advanced Oxidation Processes (AOPs), and in-vitro bioassays.

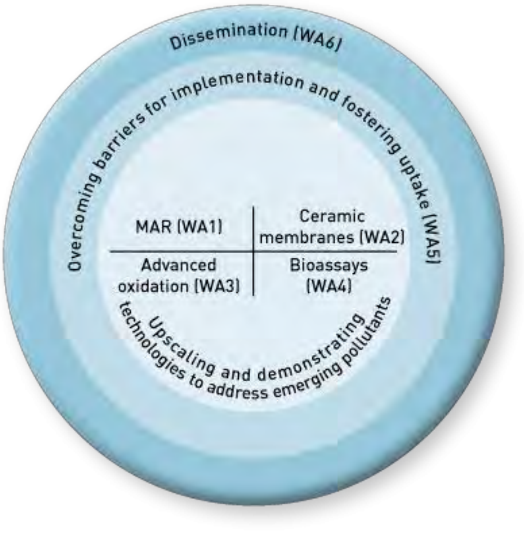



Figure 1-1: Overview of the DEMEAU project organization (source: www.DEMEAU-fp7.eu)

Exploitation took place through action research with universities, research institutions, innovative SMEs, water utilities as launching customers and policy makers. Existing and improved methodologies are used to assess performance of the novel technologies and to demonstrate their suitability and cost-effectiveness. Moreover, drivers and barriers regarding implementation of the innovations are explored within various cases by means of social scientific methods. To foster a broader impact and market penetration of the technologies, DEMEAU seeks cooperation with relevant policy makers, regulators and standardization bodies on Member State and European level in order to address the identified implementation drivers and barriers.

### 1.2.1 Work area 1: Managed Aquifer Recharge (MAR)

Managed aquifer recharge uses natural processes to treat and store water until subsequent (re-)use. Natural processes include biological digestion of organic matter, chemical processes and physical processes (e.g. adsorption) which are due to the complex interplay on one hand less predictable than other treatment methods but on the other hand also have a high buffer potential. DEMEAU explored current MAR systems and developed design, operational and risk management recommendations, involving stakeholders such as utilities and authorities. Apart from establishing recommendations for current MAR systems, several innovative MAR designs were studied at different sites:

- **Additional organic layer:** An additional organic layer to remove organic emerging contaminants was tested in Sant Vicenç dels Hort.
- **AOP as pre-treatment:** The pre-treatment of influent water by an Advanced Oxidation Process ($O_3$/$H_2O_2$/UV) before infiltration was tested at Dunea.

### 1.2.2 Work area 2: Hybrid Ceramic Membrane Systems (HCMSs) and Automatic Neural Net Control System (ANCS)

Current state-of-the-art membranes are usually fabricated from polymers. While ceramic membranes are currently more expensive than polymeric membranes, their higher mechanical strength, longer lifetime and backwash efficiency may provide significant improvement in terms of cost and environmental impact if the entire life cycle of the product is considered. Automatic neural net control, which can help to optimize performance and minimize chemical and energy demand, is a promising tool to decrease operational and investment cost for ceramic membrane filtration, which are still main barriers for its implementation. Innovative ceramic membrane and ANCS aspects in DEMEAU include:

- **Cost and environmental impact over the life cycle.** For products with a long life time, cost and environmental aspects considered over an entire life cycle are especially important.
- **ANCS to control filtration processes.** The application of ANCS full scale was a main goal of DEMEAU WP23.

### 1.2.3 Work area 3: Advanced Oxidation Processes (AOPs)

While oxidative processes have a long history to disinfect the effluent of WWTPs and drinking water, several advanced oxidation processes now exist to provide further treatment which includes the inactivation and/or removal of emerging contaminants. Ozonation with subsequent biological filtration can significantly reduce emerging contaminants in the effluent, but has a high energy consumption and additional safety precautions have to be taken. So far Advanced Oxidation Processes (AOPs) have mainly been used for industrial waste water treatment and only at lab scale for municipal waste water. Innovative aspects of advanced oxidation in DEMEAU included:

- **$O_3$ with $H_2O_2$ and filtration for drinking water production.** At lab scale, a combination of ozone with hydrogen peroxide and subsequent filtration (activated carbon and ultrafiltration) was tested for drinking water production from lake water.
- **Ozonation for emerging contaminant removal in waste water treatment.** The first full-scale ozonation at a WWTP in Switzerland for advanced emerging contaminant removal was assessed.

#### 1.2.4 Work area 4: In-vitro bioassays

Bioassays are effect-based tools that can detect wide ranges of pollutants based on their genotoxicity, mutagenicity and their interference with the endocrine system in mammals. DEMEAU will identify (primarily in-vitro) bioassays which are sensitive for a wide range of emerging contaminants and select appropriate bioassays in terms of cost-efficiency. Innovative aspects of bioassays considered in DEMEAU included:

- **In vitro bioassays as cost-effective integration into chemical-analytical monitoring.** In contrast with chemical-analytical monitoring, bioassays can detect a wide range of even unknown pollutants based on their effects. This makes them interesting as an additional water monitoring step which may prove cost effective in combination with conventional analytics.

### 1.3 Scope and objectives

Within the DEMEAU project, the objectives of Work Area 5 (WA5) were the sustainability assessment and fostering of the market uptake of emerging water technologies in response to rising concerns about contamination by emerging contaminants in waste water and drinking water sources. Here we present technology specific recommendations for impact which are based on case studies conducted in all four technology work areas of the DEMEAU project. For case studies analysed by WA5, environmental and economic unique selling propositions were developed based on environmental life cycle assessment (LCA) and economic life cycle costing (LCC) approaches. Drivers and barriers of market uptake were assessed using online interviews and used as basis for stakeholder workshops where recommendations were developed from a stakeholders' perspective. Drawing from these environmental, economic and sociotechnical analyses conducted at DEMEAU case studies, WA5 developed transferable recommendations for promising water technologies which are documented in self-contained work area specific documents contained in this report.

### 1.4 Methodology

Here we provide a brief overview of the applied methodology in WA5. The methodology is described in detail in DEMEAU deliverable D51.2 'Final guidelines for sustainability assessment of water technologies' (Remy et al. 2015). Analyses are based on case studies conducted in the respective technology work areas.

#### 1.4.1 Environmental and economic properties – Unique selling propositions

DEMEAU WA5 aimed at providing an integrative picture of environmental, economic and sociotechnical aspects of sustainability. Work package 51 assessed the environmental and economic sustainability profiles of promising new water technologies through environmental Life Cycle Assessments (LCAs) and economic Life Cycle Costings (LCCs). Together with the most promising application areas of each technology, results from LCA and LCC helped to formulate Unique Selling Propositions (USPs). The approach is described in more detail in DEMEAU Deliverable 51.1: 'Unique selling propositions'.

### 1.4.2 Socio-technical properties – Drivers and barriers for market implementation

Identifying and stressing the unique selling propositions of each technology is a crucial prerequisite but not sufficient for a successful market penetration. In order to promote a swift market uptake the following issues were addressed in work package 52:

- **Implementation drivers (enabling factors) and barriers (constraining factors):** for the identified innovative technologies various obstacles and difficulties for implementation need to be overcome. On different analytical levels (individual, organisational, institutional and regulatory) barriers have to be carefully taken into account and addressed to achieve successful implementation. For each of the case studies main barriers are identified from the diverse perspectives of the involved stakeholders, which are consequently confronted with each other in order to come to shared solutions.
- **Recommendations for impact:** For each new technology demonstrated in WA1 - WA4 specific recommendations for successful implementation are to be formulated in the context of their most promising application areas.

## 2 Managed Aquifer Recharge (MAR)

This section of the report provides recommendations for impact developed for Managed Aquifer Recharge (MAR). The recommendations are based on detailed Life Cycle Assessments (LCAs), Life Cycle Costings (LCC) and drivers and barriers analyses with a stakeholder workshop and additional information that are provided in the following documents:

**Demeau D51.1: Unique Selling Propositions (Remy et al. 2015A).** Results and discussion of LCA and LCC analyses. Section 3 on MAR.

**Demeau D51.2: Final guidelines for sustainability assessment of water technologies (Remy et al. 2015B).** Description and critical discussion of the methodologies applied.

**Demeau D52.1: Implementation barriers (Pieron and van der Zouwen 2014).** Results and short discussion of the barriers analysis. Section 3.1 on MAR.

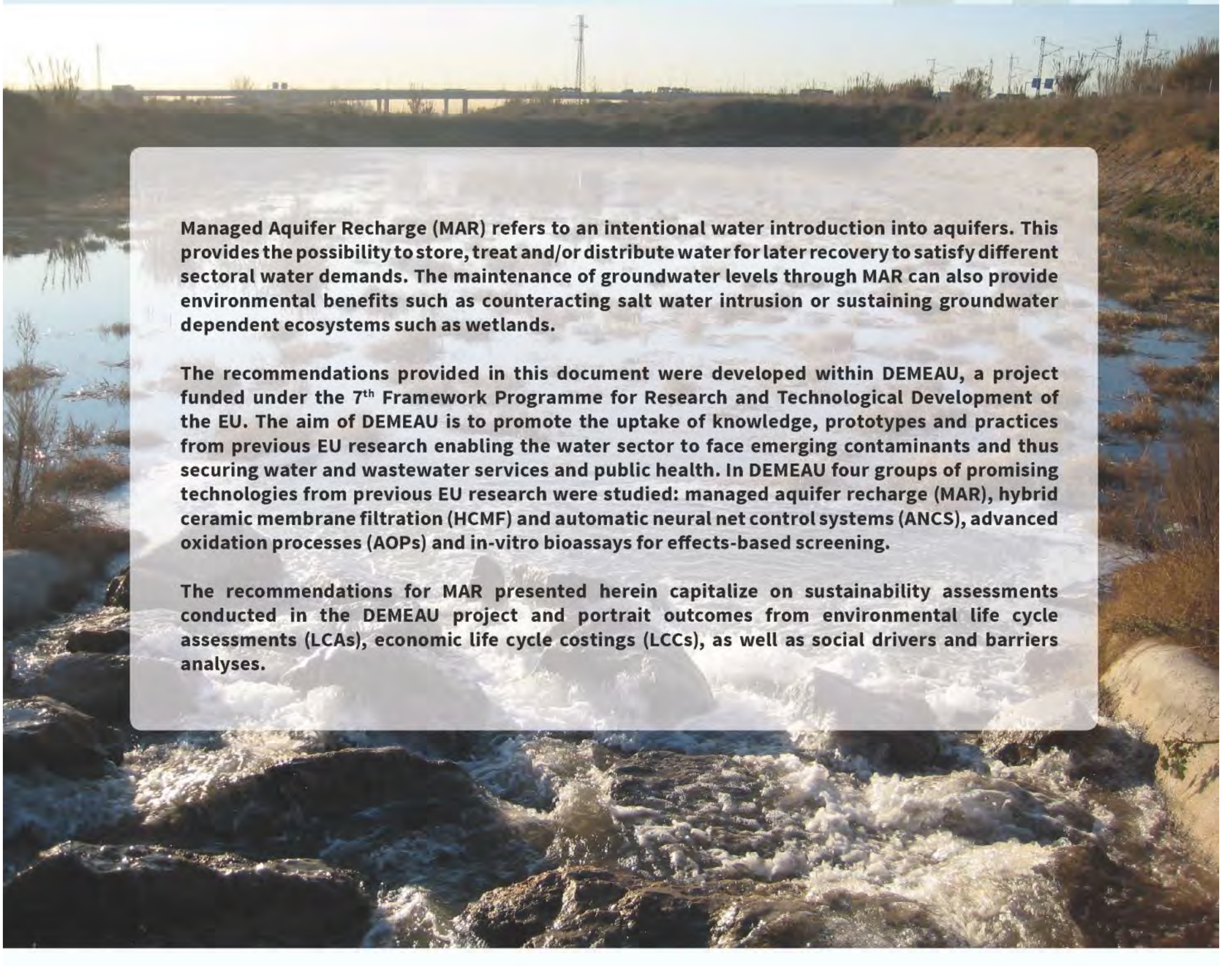
**Annex-A of this report.** Short summary of results from the MAR workshop conducted in Sant Vicenç dels Horts, Spain.

Aforementioned reports and a PDF version of the following recommendations for impact for MAR can be downloaded from the DEMEAU homepage: http://demeau-fp7.eu.

DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER

# MANAGED AQUIFER RECHARGE

## RECOMMENDATIONS FOR IMPACT



Managed Aquifer Recharge (MAR) refers to an intentional water introduction into aquifers. This provides the possibility to store, treat and/or distribute water for later recovery to satisfy different sectoral water demands. The maintenance of groundwater levels through MAR can also provide environmental benefits such as counteracting salt water intrusion or sustaining groundwater dependent ecosystems such as wetlands.

The recommendations provided in this document were developed within DEMEAU, a project funded under the 7$^{th}$ Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU is to promote the uptake of knowledge, prototypes and practices from previous EU research enabling the water sector to face emerging contaminants and thus securing water and wastewater services and public health. In DEMEAU four groups of promising technologies from previous EU research were studied: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF) and automatic neural net control systems (ANCS), advanced oxidation processes (AOPs) and in-vitro bioassays for effects-based screening.

The recommendations for MAR presented herein capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle assessments (LCAs), economic life cycle costings (LCCs), as well as social drivers and barriers analyses.

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## MANAGED AQUIFER RECHARGE AND EMERGING CONTAMINANTS

Managed aquifer recharge (MAR) is an umbrella term for different methods to intentionally introduce water into an aquifer (Dillon et al. 2009). Main objectives are replenishment and maintenance of groundwater resources, storage of surplus surface water or reclaimed municipal wastewater for times of less water availability, introduction of an additional purification step for water from different sources, and establishment of a hydraulic barrier e.g. against sea-water intrusion (Asano and Cotruvo 2004). Common MAR techniques in Europe can be classified as follows (Sprenger et al. 2015):

- **Enhanced infiltration** which relies on gravitational infiltration and percolation and includes surface spreading methods such as infiltration ponds and basins, point or line recharge for instance through borehole infiltration and in-channel modifications
- In **induced bank filtration** surface water infiltration is induced by pumping from a nearby well where the river or lake bank fulfils water treatment functions
- **Well injection** is applied where the aquifer is covered by strata with a low permeability
- **Enhanced groundwater storage** includes sub-surface dams.

Within a multi-barrier approach combining different contaminant removal methods, MAR can be an important barrier for the degradation and/or adsorption of organic emerging contaminants (Maeng et al. 2011). Reduction and transformation efficiency during the soil passage varies with aquifer properties and an overview for DEMEAU target compounds can be found in the deliverable **Decision trees for MAR impact evaluation** (Miret et al. 2013). Additional information is also available at http://demeau-fp7.eu/toolbox.

## CASE STUDIES

The analyses and recommendations presented in this document are based on the following two MAR case studies conducted in the DEMEAU project: Pond infiltration at Sant Vicenç dels Horts in Spain and dune infiltration near Den Haag in the Netherlands.

### Sant Vicenç dels Horts – Barcelona (Spain)

The MAR system lies in the vicinity of Barcelona in the Llobregat area and was built in 2007 as a **pond infiltration system** (Figure 1, left panel). To enhance the removal and degradation of emerging contaminants from source water, a **reactive organic layer** had been added to the bottom of the infiltration pond during the ENSAT (2012) project, which is the first large-scale application worldwide (Figure 1, right panel). Several measures for pond management such as regular washing of the top-layer sand and alternatives for groundwater replenishment such as scarification of the river bed or infiltration in constructed channels were analysed and compared to the existing pond system.


***Figure 1:*** Left panel: An infiltration pond at Sant Vicenç dels Horts; right panel: schematic cross-section of the reactive organic layer

### Dunea - Den Haag (the Netherlands)

Dunea uses water from the Meuse River to produce **drinking water in a multi-barrier approach** including pre-treatment by coagulation, dune infiltration and recovery (MAR) and subsequent post-treatment by activated carbon adsorption and slow sand filtration. Dune infiltration serves as a **barrier for chemical and microbial contaminants and helps maintaining the freshwater lens under the dunes**. In addition, dune infiltration can also help buffering variations in quantity and quality of the feed water, so that a continuous supply with good drinking water can be provided. Dune infiltration is realized through open pond infiltration and a deep well injection facility can be operated as backup. After an average residence time of 120 days, the water is recovered in abstraction wells and pumped to post-treatment at three different locations. The water is distributed to the customers without further need for disinfection.

The water utility has performed **research to extend the current drinking water treatment by advanced oxidation processes (AOPs)** as pre-treatment before dune infiltration. Options studied at pilot-scale include combinations of ozone with hydrogen peroxide ($O_3/H_2O_2$) and additionally ultraviolet light ($O_3/H_2O_2/UV$). These AOPs should increase the elimination of emerging contaminants and make use of aquifer properties to further degrade possible oxidation by-products via biological processes during the aquifer passage.

## ENVIRONMENTAL AND ECONOMIC UNIQUE SELLING PROPOSITIONS OF MAR AGAINST EMERGING CONTAMINANTS

### Method: lifecycle - based environmental and economic assessments

Building on **key application areas** of different MAR techniques against emerging contaminants and their **environmental and economic profiles** we propose unique selling propositions for each technique (Box 1). In DEMEAU both the pond infiltration system in Sant Vicenç dels Horts and the Dune infiltration for drinking water production in Dunea were analysed using **environmental Life Cycle Assessments (LCAs)** and **economic Life Cycle Costings (LCCs)**. These tools are based on a set of indicators to estimate environmental and economic benefits and impacts/costs to compare between different options. Environmental indicators encompass not only local emissions to the environment but along the entire life cycle of the system.

Details about the methodology can be found in DEMEAU deliverable **Guidelines for sustainability assessment of water technologies** (Remy et al. 2015B). Results and discussion of LCA and LCC analyses are reported in DEMEAU deliverable **Unique selling propositions** (Remy et al. 2015A).

### Key application areas of MAR

MAR can **substitute or complement other solutions of water storage, treatment, transfer and supply** (Dillon et al. 2009). Both DEMEAU case studies in Sant Vicenç dels Horts and Dunea fulfil to various extents these application areas. Examples of such application areas studied during the DEMEAU project are summarized in table 1.

The natural treatment function of the aquifer and its properties play important roles in the **degradation and/or adsorption of emerging contaminants**. At Sant Vicenç dels Horts these natural properties are extended by an **organic layer** to enhance the microbial degradation of organic emerging contaminants. At Dunea the pre-treatment of the infiltration water by **advanced oxidative processes** oxidises a wide range of emerging contaminants while the subsequent MAR helps reducing possible oxidative by-products by natural processes.

***Table 1:*** Application areas of MAR systems studied in DEMEAU in terms of water source (river water, storm water and reclaimed water) and removal of emerging contaminants

| Treatment | Removal of emerging contaminants[1] | Source water in DEMEAU | Application area in DEMEAU |
|---|---|---|---|
| Pond infiltration | + (site specific) | River water | *Full-scale:* Improving quantity and quality of groundwater for various uses |
| Pond infiltration with organic layer | ++ | River water; tertiary WWTP effluent (lab scale) | • *Full-scale:* Finding alternatives to technological removal of emerging contaminants through an organic reactive layer<br>• *Lab-scale:* Water reuse from a nearby wastewater treatment plant as an option but not yet implemented, tested in column experiments |
| Dune infiltration | + (site specific) | River water | *Full-scale:* Multi-barrier approach for drinking water treatment and restoration and maintenance of fresh water lens under the dune area |
| Dune infiltration with AOP pre-treatment | +++ | River water | Dune infiltration with *pilot-scale* additional treatment against emerging contaminants using AOP pre-treatment and subsequent MAR to degrade possible oxidation by-products |

[1] Removal of emerging contaminants: + = only partially effective, highly dependent on emerging contaminants present and MAR conditions; ++ = moderately effective, most emerging contaminants removed to >50%; very effective, most emerging contaminants removed to >80%; blank = ineffective

### Pond infiltration with reactive layer in Sant Vicenç dels Horts: LCA and LCC

In the pond infiltration system at Sant Vicenç dels Horts (scenario *'Ponds',* Figure 2) the implementation of a reactive organic layer (scenario *'Ponds + organic layer'*) improves the removal of emerging contaminants from source water. The measurable **direct benefit - a decrease in (eco)-toxicity of the infiltrated water -** is small at this specific site because the concentrations of target contaminants considered is low. Direct benefits have trade-offs from the production of materials, fuels, electricity and chemicals, leading to impacts in (eco)toxicity, climate change and eutrophication potential. Compared to surface water treatment with coagulation, filtration and subsequent well injection (scenario: *'Treatment and injection'*), a **reactive organic layer has lower indirect impacts but at the same time benefits in terms of reduced freshwater eutrophication** from phosphate elimination during soil passage (Figure 2). Due to the low concentration of emerging contaminants, the positive direct effect is not 'visible' in Figure 2. Calculated over a life cycle of 30 years and including investment and operation cost, life cycle costs are similar for the three MAR techniques (0.1-0.2 EUR/m³, depending on the infiltration rate). At the infiltration rates applied, pond infiltration is ca. 15% less expensive than surface water treatment with subsequent well injection. These results are described in detail in **Unique selling propositions** (Remy et al. 2015A).

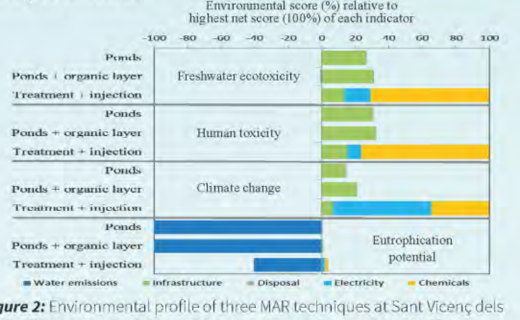


***Figure 2:*** Environmental profile of three MAR techniques at Sant Vicenç dels Horts, % net impact relative to highest net impact scenario = 100 %

### AOP as pre-treatment for dune infiltration: LCA and LCC

The BAU (business-as-usual) drinking water treatment at Dunea (see 'case studies') already removes some emerging contaminants considered here below the limit of quantification: Bezafibrate, Carbamazepine, Diclofenac and Metoprolol. **Pilot-scale pre-treatment with AOP in addition reduced Sulfamethoxazole by -80% and Iopromide by -27% compared to BAU for both $O_3/H_2O_2$ and $O_3/H_2O_2$/UV**. A trade-off is the increased carbon footprint due to additional electricity demand by +23% for $O_3/H_2O_2$ (+0.1 kWh/m³; 0.5 kg $CO_2$-eq/m³) and +64% for $O_3/H_2O_2$/UV (+0.4 kWh/m³; 0.7 kg $CO_2$-eq/m³) compared to BAU. Because 64% of the BAU electricity demand in this case are for water transport, the relative increase by AOP would be higher considering water treatment alone.

Background processes related to increased energy and chemical demand lead to some global (eco)toxicity and freshwater eutrophication impacts (Figure 3). Aforementioned benefits on the drinking water quality are however not fully represented by LCA because the impacts were only calculated for seven emerging contaminants, which are only a small fraction of contaminants possible in source water. When calculated over a lifecycle of 30 years, full-scale implementation of **$O_3/H_2O_2$ or $O_3/H_2O_2$/UV would increase water treatment cost by +15% and +35%** compared to BAU (ca. 0.2 EUR/m³).

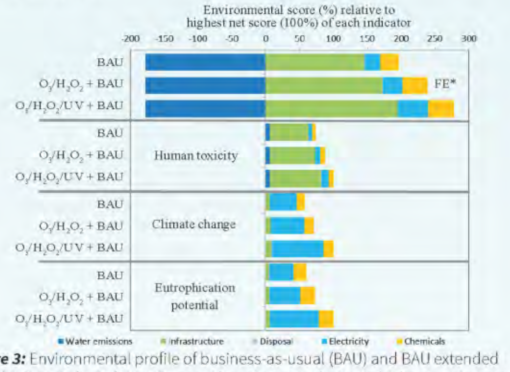


***Figure 3:*** Environmental profile of business-as-usual (BAU) and BAU extended by $O_3/H_2O_2$ or $O_3/H_2O_2$/UV at Dunea, % net impact relative to highest net impact scenario = 100 % (FE* = freshwater ecotoxicity)

***Box 1*** Environmental and economic unique selling propositions of MAR for groundwater recharge and replenishment

- **Managed aquifer recharge in general fulfils multiple objectives which can not be replaced by a single technological system** including replenishment of groundwater resources, water storage, water quality improvements and water distribution.
- **Pond infiltration** is a low-energy and low-cost groundwater recharge option with water quality improvements through soil passage. An **additional reactive organic layer** can provide water quality improvements during the soil passage and increased elimination of organic emerging contaminants with low additional efforts in energy.
- **Dune infiltration** – a form of managed aquifer recharge - is a multi-functional barrier to contaminants with low energy and chemical needs. **AOP pre-treatment** for dune infiltration based on ozone and hydrogen peroxide can mitigate potential risks from emerging contaminants taking also advantage of the biologically active zone in the dune aquifer to further degrade possible transformation products of the oxidation.

## RECOMMENDATIONS FOR MARKET UPTAKE

The following recommendations for market uptake have been developed from a drivers and barriers analysis involving stakeholders from the DEMEAU MAR case studies and researchers of the DEMEAU consortium.

### Transferable recommendations to administration and policy makers

► **Collaborate on realistic guidelines and regulations**

Local administration and regulators should ensure that MAR schemes do not negatively affect the environmental protection goals set by European, national and local legislation. European directives do not yet cover specific MAR guidance, however different relevant regulations apply. The European Water Framework Directive requires a good water status for surface and groundwater bodies through a coordinated approach at riverbasin scale. Further important regulations include the Groundwater Directive and the Urban Wastewater Treatment Directive. On a national level, it is important that directives allow for local adaptation, in such a way that specific circumstances with specific solutions can be taken into account. Stakeholders in Sant Vicenç dels Horts felt that already enough regulations exist and request to rather improve existing regulations then adding new ones:

> *"Improve current norms and regulations (instead of adding new ones)."*

Regulations are still perceived inflexible and do not (yet) include quantitative water quality requirements, especially with regard to water reuse. With regard to emerging contaminants explicit evaluation criteria such as measurable parameters in local regulations would provide important guidance and increase planning dependability.

► **Coordination and dialogue between administrative levels and the public**

MAR projects generally require a coordinated approach between different administrative levels, the general public and potentially affected interest groups such as for instance environmental and landscape protection. Thus in addition to clearly coordinated responsibilities and actions between different administrative players, cooperation between governmental and non-governmental organizations is essential. For instance in the case of Dunea the close involvement of local, regional and national governments from the initial stage of the project was mentioned as an important project success factor. Also in Sant Vicenç dels Horts the active involvement of relevant authorities is perceived as a driver of the implementation process.

► **Water planning at hydrological levels**

Within MAR projects water quantity and quality issues usually need to be considered not only between the water providers, consumers and regulators but also within a wider context because such projects affect natural water cycles. In-line with requirements by the Water Framework Directive stakeholders of the Sant Vicenç dels Horts MAR reinstated the importance to:

> *"Consider water quality on basin level."*

Such a system approach includes financial aspects such as the consideration of benefits derived from reclaiming water in order to sustain for instance groundwater levels. MAR stakeholders in Sant Vicenç dels Horts request to:

> *"Consider savings derived from reclaiming water" and "integrate costs of water reclamation in the water bill."*

The development of life-cycle views on investments, operations and savings would allow comparing initial investments with long-term benefits and allow the integration of additional costs or savings in water fees. Life cycle costing may help to transparently analyse possible costs of different development scenarios and guidelines for water technologies were developed in the DEMEAU project: **Guidelines for sustainability assessment of water technologies** (Remy et al. 2015B).

### Transferable recommendations to scientific community and technology developers

► **Take an active role in knowledge transfer between MAR sites**

One focus of MAR research should be on the transfer of experiences from other countries and sites to new projects. While different MAR schemes have been shown to eliminate a broad spectrum of emerging contaminants, local site characteristics have important implications on the applicability of MAR for given source water and intended uses. The DEMEAU deliverable **Decision trees for MAR impact evaluation** (Miret et al. 2013) can help with this task. The following site criteria have been identified as most relevant influencing the removal of emerging contaminants: MAR type, aquifer type, redox conditions, organic carbon content in water, residence time, concentration of the emerging substances, and temperature.

- **Target also non-scientists for dissemination of results**

Research findings should be disseminated not only through scientific channels, but further target groups should involve also regulators, utilities and the general public. Stakeholders in Sant Vicenç dels Horts expect that scientists to:

> *"Share insights and findings with policy makers and regulators (engage in a dialogue)" and "communicate findings outside the scientific community."*

Sharing insights and findings from MAR research and specific case studies supports the development of facilitating regulatory and social frameworks. By engaging in multi-stakeholder dialogues, scientific knowledge can be translated to the language of policy makers and the public opinion, and views and knowledge from policy, practice or public perspectives can be taken into account in further research.

- **Studies on the combination of MAR with other advanced treatment processes**

Depending on the source water, the concentration and type of emerging contaminants and aquifer properties, MAR alone is not always sufficient to remove all contaminants to required thresholds (Maeng et al. 2011). Additional pre- or post-treatment may be required in order to remove additional contaminants before drinking water usage. This is particularly important where groundwater recharge with reclaimed water is considered. Apart from emerging contaminants, also the microbial water quality, total dissolved solids and presence of heavy metals are important (Asano and Cotruvo 2004). Further research on cost-effective and efficient multi-barrier approaches will be beneficial fostering scientific advancement, trust and application. Different combinations were studied in DEMEAU such as a reactive layer in pond infiltration and different combinations with AOP (Advanced Oxidation Process) processes described above and in **Unique selling propositions** (Remy et al. 2015A).

- **Address open questions regarding emerging contaminants in MAR**

One of the difficulties of implementing MAR projects is the risk perception by regulators who in Sant Vicenç dels Horts – according to workshop participants – are perceived to have a conservative attitude. Environmental and public health risks are dependent on the quality of the source water and properties of the MAR system, aquifer and the soil. The scientific community can help communicate best practices from other sites and is in the best position to assess the local applicability. Scientists should help to:

> *"Translate experiences [from other sites to the local situation]."*

To predict the fate during soil passage, further studies on physicochemical properties of emerging contaminants such as log $K_{ow}$ and log D are required (Maeng et al. 2011). Furthermore, the human toxicity and ecotoxicity of many substances is not yet well understood and also further research is needed with regard to the fate of emerging contaminants during soil passage (Maeng et al. 2011). Based on initial research results, scientists should together with public authorities work on a:

> *"List of priority substances (including threshold values) to monitor."*

Such a list is currently under development within the frame of the Water Framework Directive. Further research in that direction will also improve the definition of characterization factors needed to estimate toxicity in Life Cycle Assessments (LCAs).

### Transferable recommendations to utilities

- **Engage and interact with research**

The involvement of water utilities in applied research is crucial in terms of provision of facilities for pilot and full-scale studies and also with regard to learning from past or on-going experiences. The scientific assessment both of success stories and challenges are important to foster the implementation of MAR and its pre- and post-treatment technologies at other sites.

- **Share experiences**

Although it might be intuitively preferable to keep insights confidential, these insights can help speeding up the learning curve for MAR. Especially learning from failed experiments can help not reproducing them at other sites. Stakeholders in Sant Vicenç dels Horts ask utilities to:

> *"Be transparent, show results, provide test data on costs and also failures."*

- **Collaborate on realistic guidelines and regulations**

Water utilities have much knowledge and expertise that is valuable and required to improve existing norms and regulations. Such expertise is often not available to policy makers. Instead of perceiving regulations as barriers, utilities should engage in the process of regulatory innovation together with public authorities and scientist:

> *"Participation in local discussions and decision-making processes."*

It is thus important that utilities participate in water related local decision-making processes.

### Transferable cross-cutting recommendations

► **Cost-benefit analyses at appropriate system boundaries**

MAR can have several benefits, some of which are difficult to quantify in economic terms. The water storage capacities, for instance, could also be achieved above ground by dams rather than in the aquifer. The water cleaning capacities which can be achieved by the soil passage and enhanced by certain measures such as an additional organic layer in the Sant Vicenç dels Horts case study could also be provided by technological solutions such as AOP in Dunea. A combined Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approach studying different options can help transparently quantify environmental benefits and impacts and related costs of different possible options. Within DEMEAU environmental LCAs and economic LCCs were applied to quantify the environmental benefits and possible impacts on one hand, and the economic perspective on the other hand. Guidelines to conduct LCA and LCC were developed: **Guidelines for sustainability assessment of water technologies** (Remy et al. 2015B).

► **Consideration of bioassays for effects-based water quality monitoring**

In-vitro bioassays (Figure 4) can be a viable way for the screening of water quality based on (eco)toxicological effects. In-vitro bioassays have been developed to analyse complex mixtures based on their effects such as genotoxicity, mutagenicity and endocrine disruption. The main advantage of in-vitro bioassays is the **integrated response to biological effects of compounds in a complex mixture** such as for instance surface water (Simon et al. 2015). **Recommendations for impact in the water sector: In-vitro bioassays** (Gross et al. 2015) are available from the DEMEAU homepage.

In Sant Vicenç dels Horts in Spain bioassays were used for the monitoring of groundwater, source water and pre-treated wastewater as potential future water source.

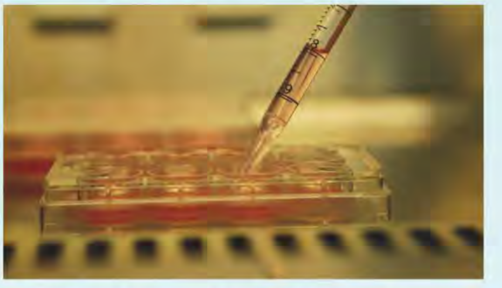

***Figure 4:*** Microplate as used for in-vitro bioassays, which can be an effective and efficient monitoring solution

► **Close involvement of local, regional and national governments and non-governmental bodies from the beginning of the project**

Planning and implementation of MAR schemes entails a complex interdisciplinary communication among various stakeholders including different administrative units national to local level and, depending on the scope of the MAR scheme, different sectors such as environmental agencies, agriculture departments, regulators concerned with wastewater and drinking water etc. An open and transparent communication including the public was mentioned as an important enabling factor both at Sant Vicenç dels Horts and Dunea. At Dunea the good communication between the water utility and the regulating municipality at initial project stages was mentioned as an important factor to address environmental concerns raised with regard to perceived degradation of nature reserves.

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Quantis Sustainability counts

CETaqua WATER TECHNOLOGY center

VEOLIA ENVIRONNEMENT

KOMPETENZZENTRUM Wasser Berlin

More information on MAR, other technologies and approaches studied in DEMEAU and detailed reports of Life Cycle Analyses, Life Cycle Costings and drivers and barriers analyses can be found here:

**http://demeau-fp7.eu**

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# 3 Hybrid Ceramic Membrane Filtration (HCMF)

This section of the report provides recommendations for impact developed for Hybrid Ceramic Membrane Filtration (HCMF). The recommendations are based on detailed Life Cycle Assessments (LCAs), Life Cycle Costings (LCC) and drivers and barriers analyses with a stakeholder workshop and additional information that are provided in the following documents:

**Demeau D51.1: Unique Selling Propositions (Remy et al. 2015A).** Results and discussion of LCA and LCC analyses. Section 4.3 on HCMF.

**Demeau D51.2: Final guidelines for sustainability assessment of water technologies (Remy et al. 2015B).** Description and critical discussion of the methodologies applied.

**Demeau D52.1: Implementation barriers (Pieron and van der Zouwen 2014).** Results and short discussion of the barriers analysis. Section 3.2.1 on HCMF.

**Annex-B of this report.** Short summary of results from the comined HCMF and Automatic Neural Net Control Systems (ANCS) workshop conducted in Roetgen, Germany.

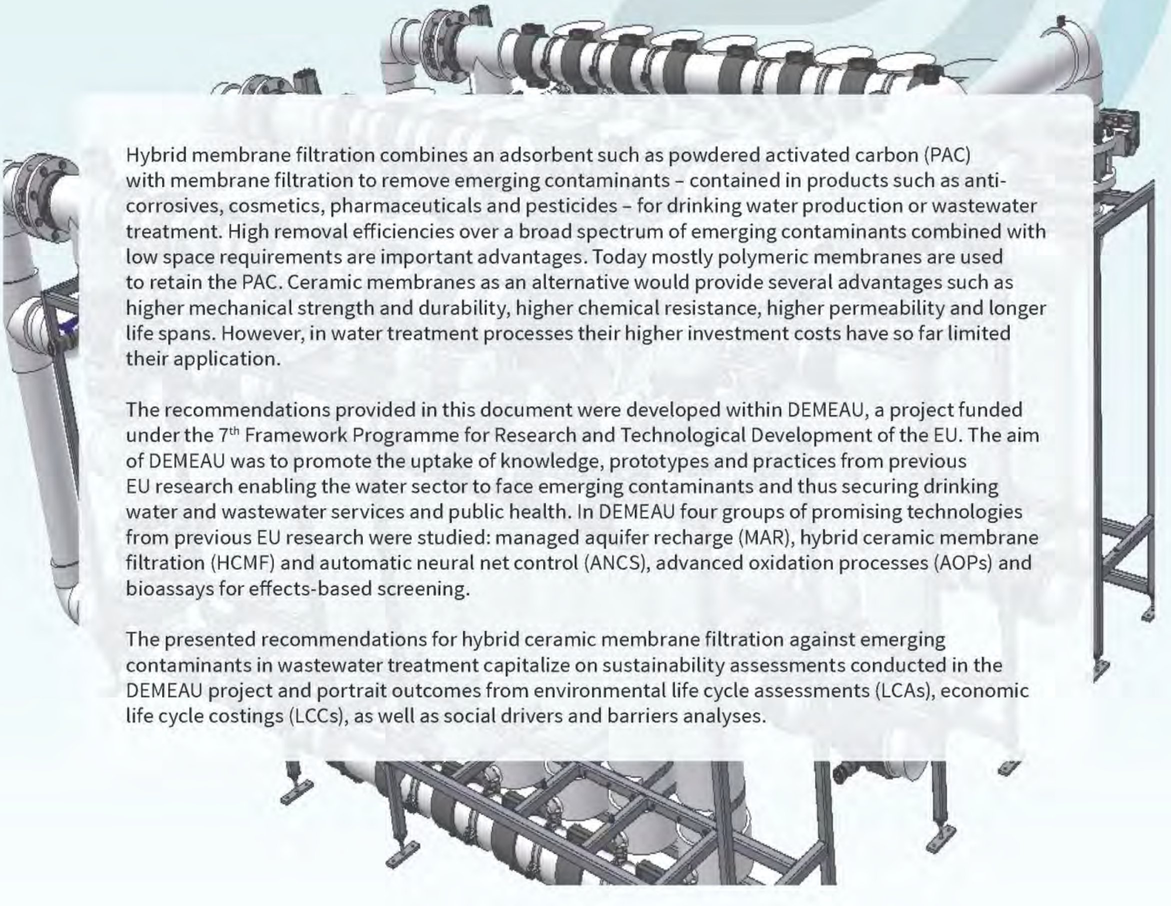
Aforementioned reports and a PDF version of the following recommendations for impact for HCMF can be downloaded from the DEMEAU homepage: http://demeau-fp7.eu.

# DEMEAU

**DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER**

# HYBRID CERAMIC MEMBRANE FILTRATION

## RECOMMENDATIONS FOR IMPACT



Hybrid membrane filtration combines an adsorbent such as powdered activated carbon (PAC) with membrane filtration to remove emerging contaminants – contained in products such as anti-corrosives, cosmetics, pharmaceuticals and pesticides – for drinking water production or wastewater treatment. High removal efficiencies over a broad spectrum of emerging contaminants combined with low space requirements are important advantages. Today mostly polymeric membranes are used to retain the PAC. Ceramic membranes as an alternative would provide several advantages such as higher mechanical strength and durability, higher chemical resistance, higher permeability and longer life spans. However, in water treatment processes their higher investment costs have so far limited their application.

The recommendations provided in this document were developed within DEMEAU, a project funded under the 7th Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU was to promote the uptake of knowledge, prototypes and practices from previous EU research enabling the water sector to face emerging contaminants and thus securing drinking water and wastewater services and public health. In DEMEAU four groups of promising technologies from previous EU research were studied: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF) and automatic neural net control (ANCS), advanced oxidation processes (AOPs) and bioassays for effects-based screening.

The presented recommendations for hybrid ceramic membrane filtration against emerging contaminants in wastewater treatment capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle assessments (LCAs), economic life cycle costings (LCCs), as well as social drivers and barriers analyses.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308339.

## HYBRID MEMBRANE FILTRATION AND EMERGING CONTAMINANTS

In response to rising concerns about threats from emerging contaminants contained in anti-corrosives, cosmetics, pharmaceuticals, pesticides and other products, several advanced technologies exist today to remove such contaminants from wastewater or drinking water.

Powdered activated carbon (PAC) adsorption is an effective and easily adjustable way to remove emerging contaminants in wastewater treatment and drinking water production. In so-called **hybrid ceramic or polymeric membrane filtration systems (HCMF and HPMF, respectively)**, PAC is dosed to pre-treated water and subsequently separated from the effluent by either polymeric or ceramic membranes. Sedimentation and sand filtration are more common separation steps, however **membrane filtration has the advantages of complete PAC and bacteria retention, high virus removal and low footprint** (Löwenberg et al. 2014).

**Ceramic membranes** have several advantages compared to current state-of-the-art polymeric membranes such as higher mechanical strength and durability, higher chemical resistance, higher permeability and longer life spans. However, in water treatment processes their higher investment costs have so far limited their application (Park et al. 2015). Ceramic membrane filtration can achieve a stable operation and performance under high permeate flux rates, high feed water recovery rates and less chemical cleaning needs when compared to polymeric membranes. The strength of the ceramic membranes allows high backwash pressure to provide a very good backwash efficiency and makes them furthermore resistant to chemical pre-treatment of the water with oxidants (Lehman and Liu 2009). This would also enhance opportunities to combine oxidative treatment and membrane filtration as a hybrid ceramic membrane system.

## CASE STUDIES

The recommendations presented in this document are based on sustainability analyses conducted during the DEMEAU project. These include environmental Life Cycle Analysis (LCA) and economic Life Cycle Costing (LCC) at a Swiss wastewater treatment plant (WWTP) and a drivers and barriers analysis with stakeholders involved in different membrane related research and/or implementation projects.

### HCMF pilot system at a Swiss wastewater treatment plant

The WWTP treats wastewater from municipalities and industries before the effluent is discharged to the receiving water body. With a capacity of ca. 150'000 population equivalents, it is among the ten largest municipal WWTPs in Switzerland. Its current design is based on multi-stage mechanical treatment, biological treatment in sequencing batch reactors and phosphorus removal by precipitation.

In a **pilot-scale hybrid membrane filtration** (Figure 1) WWTP effluent was mixed with PAC at dose of 15 mg/L and after a retention time of three to five hours separated by either polymeric or ceramic submerged ultrafiltration membrane modules (HCMF and HPMF, respectively). If the systems were built at full-scale, ceramic or polymeric membranes would be aerated by compressed air at a rate of ca. 0.3 $m^3/(m^2 * h)$. PAC, other particles, bacteria and viruses would be separated from the permeate by forcing water through the membranes with a suction pressure of 0.1 to 0.6 bar. The retained PAC would be recycled to the biological stage, finally removed with excess sludge and go to incineration after digestion and dewatering. Backwash and chemically enhanced backwash with sodium hypochloride of the membranes would be done regularly. The pilot-scale system, on which these full-scale estimates are based, are shown in Figure 1. More detailed information are provided in the DEMEAU report **Unique selling propositions** (Remy et al. 2015A).

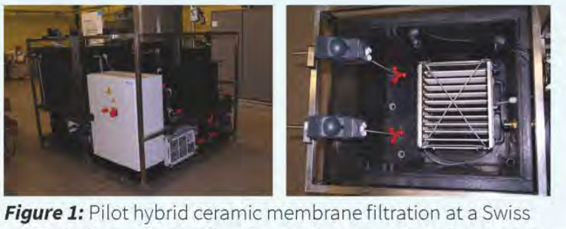


***Figure 1:*** Pilot hybrid ceramic membrane filtration at a Swiss WWTP (left panel) with view from above on suspended ceramic membranes and agitators (right panel)

### Other case studies in DEMEAU

Further case studies of HCMF were conducted in the DEMEAU project, including:

**Ceramac® concept for drinking water treatment:** The new Ceramac® concept was implemented at full-scale at the drinking water treatment plant at Andijk of PWN in the Netherlands. The concept is based on an increased number of ceramic membranes per pressure vessel and therewith realising reduced footprint, piping and instrumentation.

## ENVIRONMENTAL AND ECONOMIC UNIQUE SELLING PROPOSITIONS OF HYBRID CERAMIC MEMBRANE FILTRATION AGAINST EMERGING CONTAMINANTS

**Method: lifecycle - based environmental and economic assessments**

Building on **key application areas of ceramic membranes in general and HCMF against emerging contaminants in wastewater treatment** and their environmental and economic profiles, unique selling propositions were derived and presented in Box 1.

In DEMEAU the pilot implementation of a HCMF system at the wastewater treatment plant Birsfelden was analysed using environmental **Life Cycle Assessment (LCA)** and economic **Life Cycle Costing (LCC)**. These tools are based on a set of indicators to estimate environmental and economic benefits and impacts/costs to compare different options. Environmental indicators encompass not only local emissions to the environment but along the entire life cycle of the system. This document focuses on wastewater treatment but other application areas are briefly summarized in the next section. Detailed results of LCA and LCC can be found in the DEMEAU report **Unique selling propositions** (Remy et al. 2015A).

**Key application areas of ceramic membrane filtration and HCMF systems**

The strength and chemical resistance of ceramic membranes has led to their application in **various industrial applications** to separate solids from liquids in chemical, pharmaceutical, food, semiconductor and textile industries (Park et al. 2015). Ceramic membranes are also increasingly used in different water treatment applications e.g. to treat wastewater from oil tank dewatering, treating backwash water in water treatment plants.

In the DEMEAU project, ceramic membranes were studied in **advanced drinking water and wastewater treatment to remove emerging contaminants**. Apart from the removal of emerging contaminants the HCMF treatment provides bacteria retention and a low footprint. Especially in Japan ceramic membrane processes have been increasingly applied in drinking water treatment (Park et al. 2015). At the Dutch drinking water plant Andijk III of PWN, ceramic filters along with ion exchange are used to achieve high water clarity and subsequently improve the efficiency of following UV and $H_2O_2$ treatment against emerging contaminants (Table 1).

This document focus is on **advanced municipal wastewater treatment** to remove emerging contaminants from pre-treated wastewater. Hybrid membrane filtration provides an effective broadband elimination of emerging contaminants of ≥ 80% at a PAC dose of ca. 15 mg $L^{-1}$ according to studies in Swiss wastewater treatment plants (Margot et al. 2013).

***Table 1*** Application areas of ceramic membrane filtration studied in DEMEAU in terms of water source (WWTP effluent, pre-treated river water) and removal of emerging contaminants

| Treatment | Removal of emerging contaminants[1] | Source water in DEMEAU | Application area in DEMEAU |
|---|---|---|---|
| PAC adsorption with ceramic ultrafiltration | +++ | Tertiary WWTP effluent | *Pilot-scale:* Advanced **wastewater** treatment before discharge into receiving water body with **suspended** membranes |
| PAC adsorption with ceramic ultrafiltration | +++ | Secondary WWTP effluent | *Pilot-scale:* Advanced **wastewater** treatment before discharge into receiving water body with **pressurized** membranes |
| Iron exchange, ceramic ultrafiltration, UV, $H_2O_2$ and active carbon | +++ | Pre-treated river water | *Full-scale:* **Drinking water** treatment by ion exchange followed by ceramic membranes and post-treatment with UV, $H_2O_2$ and active carbon filtration |

[1] Removal of emerging contaminants: + = only partially effective, ++ = moderately effective, +++ = very effective, blank = ineffective

## HCMF pilot at a Swiss WWTP: LCA and LCC

An additional hybrid membrane filtration with powdered activated carbon adsorption (PAC) by either ceramic membranes (scenario: HCMF) or polymeric membranes (scenario: HPMF) was compared to the current WWTP (scenario: base) in terms of environmental and economic performance over a lifecycle. LCA and LCC were modelled for **theoretical full-scale designs of HCMF and HPMF** for the WWTP (Figure 2). The designs are not related with any concrete future plans of the WWTP or the intention of the operator and were developed during a master thesis (Oberschelp 2014). Membrane lifetimes of 12 years for ceramic and 7 years for polymeric membranes were assumed based on producer estimates and a PAC dosage of 15 mg/L had been shown to provide good elimination of emerging contaminants in a previous study (Löwenberg et al. 2014).

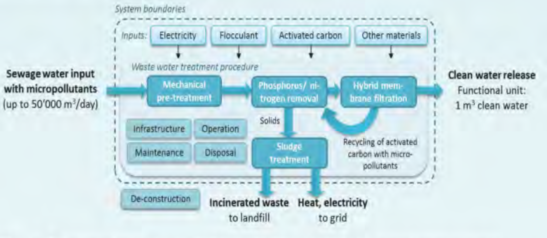



***Figure 2*** System boundary of LCA and LCC with hybrid membrane system ('adsportion/filtration')

Both HCMF and HPMF **significantly reduce ecotoxicity and human toxicity of the WWTP effluents** (Figure 3) due to the removal of emerging contaminants with average removal rates of 99% for benzotriazole, 93% for carbamazepine, 76% for diclofenac, 77% for mecoprop, and 54% for sulfamethoxazole at a PAC dose of 15 mg/L (Löwenberg et al. 2014). **Taking into account off-site emissions due to PAC and electricity production**, overall freshwater ecotoxicity is reduced by ca. -30% and human non-cancer toxicity by ca. -45%.

To realise these substantial benefits, **off-site greenhouse gas emissions increase significantly mainly due to emissions from PAC production** and increased electricity demand for membrane aeration. These lead to an increase in climate change potential of around +0.3 kg $CO_2$eq./m³ effluent treated. The **lack of specific PAC production data and transparency on raw materials used** puts some uncertainty on these numbers and the impact may be lower if regenerative raw materials or organic by-products from other processes are used (also see section recommendations for market uptake). Some increases in human cancer toxicity occur due to additional electricity generation, transmission infrastructure and - in the case of polymeric membranes - specific solvents needed in production. However, these are currently difficult to quantify due to uncertainties in current state-of-the-art LCAs.

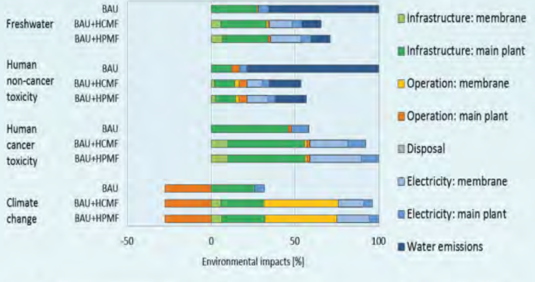



***Figure 3*** Environmental profile of hybrid ceramic membrane filtration (HCMF) in comparison to hybrid polymeric membrane filtration (HPMF) and a WWTP (Base): % net impact relative to highest impact scenario = 100 %

Due to the longer life time of ceramic compared to polymeric membranes, the specific cost increase for treatment of 1 m³ of wastewater is about the same for both systems (0.14 EUR/m³) calculated over an assumed lifecycle of 30 years. Since membranes are the main cost drivers, specific costs are sensitive to membrane lifetimes when deviating from manufacturer assumptions and ceramic membrane prices are expected to drop if they become more widely applied.

***Box 1*** Environmental and economic unique selling propositions of hybrid ceramic membrane filtration

- **Over the lifecycle of a wastewater treatment plant hybrid membrane filtration with ceramic membranes (HCMF) is about as expensive as with polymeric membranes (HPMF).** This is due to an expected longer lifetime of ceramic membranes leading to reduced needs for replacement and related investment and disposal costs compensating for the higher initial investment costs.
- **The ecological performance of HCMF is slightly better than HPMF, due to a smaller membrane area required and therewith related lower aeration requirements.**
- The application of Powdered Activated Carbon (PAC) in combination with ceramic or polymeric membrane filtration provides a **highly effective broadband elimination of emerging contaminants with complete particle retention, disinfection properties and no by-products**. **On the other hand PAC production also causes noteworthy environmental impacts especially with regard to the climate change potential.** The environmental profile should be improved through sensible sourcing and minimized PAC dosing by utilizing its maximum adsorption capacity and by exploring possible dosing optimization strategies with e.g. ANCS and/or bioassay applications. The sourcing and the use of regenerative PAC raw materials such as agricultural by-products (e.g. fruit stones and nut shells), which are already today used to some extent (e.g. coconut shells), may provide improvement opportunities.

## RECOMMENDATIONS FOR MARKET UPTAKE

The following recommendations were developed from drivers and barriers analyses involving stakeholders and researchers from HCMF case studies during the DEMEAU project. Also experiences from other relevant water technologies studied in DEMEAU are reflected. The recommendations are aimed at public authorities and policy making, scientific community and technology developers, as well as water utilities.

### Transferable recommendations to administration and policy makers

#### ► Supporting environmentally friendlier powdered activated carbon (PAC)

LCA shows that PAC production has significant environmental impacts from the energy intensive activation of the coal and carbon emissions. Common feedstock for the production of activated carbon are anthracite, bituminous or lignite coal, peat, wood and/or coconut shells (Bayer et al. 2005). Today, specific data on the production process and raw materials of individual PAC products are not available. Policy makers and public authorities on a national or European level could help minimizing the environmental impacts and improving the transparency through specific guidelines requiring e.g. labelling of raw materials and their environmental impacts and supporting research on renewable raw materials such as by-products from agriculture and food industry, e.g. nut shells or fruit stones (Aygün et al. 2003, Angin 2014) .

#### ► Legal framework for water reuse

Water reuse for industries, agriculture or urban uses offers a promising field for hybrid membrane systems. In addition to the highly effective emerging contaminants removal, microfiltration removes most particles and bacteria, while ultrafiltration in addition removes macromolecules, colloids and most viruses (Bixio et al. 2006). ***"Legal conditions for water reuse"*** such as water reuse targets and therewith related water quality requirements requiring effective and reliable technological solutions were identified as a crucial driver for hybrid membrane systems during a DEMEAU workshop.

#### ► Put emerging contaminants and their removal on the political agenda

In Switzerland – where several DEMEAU case studies were conducted - the high priority that the national and sub-national government has attributed to the removal of emerging contaminants has been a strong driver for research and adaptations of the national water protection act in 2014 to reduce emissions of emerging contaminants from wastewater. This act requires the implementation of technological upgrades at selected WWTPs in Switzerland to remove 80% of the load of emerging contaminants from the wastewater. This political decision is likely the most important driver for the implementation of advanced technologies such as ozonation or activated carbon in Switzerland.

Direct effects of specific emerging contaminants and the mix of hundreds of different contaminants in the environment are often not yet completely understood. Thus stakeholders of a DEMEAU membrane conference felt that the …

> *"... precautionary principle ..."*

… is especially important to foster the uptake of specific measures against emerging contaminants.

#### ► Funding the transition to advanced treatment against emerging contaminants

The additional removal of emerging contaminants from wastewater comes not without costs. Based on a pilot-scale application additional total costs of a supplementary hybrid ceramic or polymeric membrane filtration system at a PAC dosage of 15 mg/L were estimated at 0.14 EUR/$m^3$. Depending on local conditions such as effluent quality and suitability of the current wastewater treatment plant total additional costs of PAC with filtration for the Swiss context vary between 0.35 - 0.45 EUR/$m^3$ for smaller WWTPs around 14'000 person equivalents and 0.15 to 0.20 EUR/$m^3$ for larger WWTPs around 590'000 person equivalents (Abegglen et al. 2012). Due to the high quality of the water achieved, the HCMF treatment of WWTP effluents could be especially interesting for water reuse schemes. How additional costs are covered depends on local conditions and can include the integration into the water tariffs, fees imposed on significant polluters and/or national and local subsidies. Such changes are only feasible if the general public is sufficiently informed on the benefits and willing to accept the additional costs.

#### ► Integrative decision making

An integrative decision-making approach can promote regulations which foster the removal of emerging contaminants taking into account technological, environmental, economic and social aspects. On a national level, e.g. Swiss authorities based their decision on: (i) studies using ozonation or activated carbon showing a significant reduction of emerging contaminant discharges, (ii) social and political acceptance to extend water treatment to enhance water protection, and (iii) technical feasibility and cost-effectiveness (Eggen et al. 2014). In the DEMEAU project different technologies were tested from pilot- to full-scale and results can be found on demeau-fp7.eu. 'Hands-on' experiences on environmental, economic and social aspects of water technologies against emerging contaminants are available in the document **Guidelines for sustainability assessment of water technologies** (Remy et al. 2015B).

### Transferable recommendations to scientific community and technology developers

**Minimizing environmental impacts of PAC and aeration**

The significant benefits of PAC in hybrid membrane filtration by reducing emerging contaminants have environmental trade-offs due to impacts of PAC production and - depending on the system - additional aeration needs. ***"Studies on alternative PAC raw materials"*** was one of the suggestions from stakeholders of hybrid membrane processes. Studies on renewable raw products and their application would help to reduce climate change impacts of carbon being released to the atmosphere during the carbon activation process. Furthermore, research on minimizing PAC dosing for instance based on regular toxicological monitoring data to determine a time dependent optimum dose.

**Studies on the combination of hybrid membrane systems with other technologies**

Depending on the wastewater composition and the therein contained contaminants, technologies based on PAC or oxidative processes such as ozonation have their strengths and limitations. One stakeholder involved in both PAC and ozonation in Switzerland mentioned:

> *"The combination of ozonation with PAC would also provide the capacity to react to changes in regulations with regard to new priority contaminants."*

Due to the higher resistance of ceramic membranes to ozone compared to polymeric ones (Lehman and Liu 2009), ceramic membranes seem particularly suitable for such combined processes. Hybrid membrane filtration is also an interesting option for the pre- and post-treatment of managed aquifer recharge (MAR) systems and can provide an effective multi-barrier approach against many contaminants. Depending on the source water, the concentration and type of contaminants and aquifer properties, MAR alone is not always sufficient to remove emerging contaminants sufficiently (Maeng et al. 2011). This is particularly important where reclaimed water is considered as source. Research on cost-effective and efficient multi-barrier approaches would be beneficial.

**Exploring effects of emerging contaminants on aquatic ecosystems**

The effects of emerging contaminants on aquatic ecosystems are still not fully understood. The presence of many different contaminants at the same time, their low concentrations and changing mixtures make it difficult to attribute specific ecological effects to individual contaminants (Eggen et al. 2014). Understanding cause-effects relationships could help optimizing wastewater treatment to eliminate the most relevant contaminants. Integrating evolving knowledge into LCA will strengthen the capability of this tool to assist in the selection of environmentally sound solutions. The knowledge of specific locally prevalent contaminants and their environmental effects and/or high presence helps in the selection of priority compounds to be included in regulations with specific thresholds. Such a list is currently under development in the frame of the Water Framework Directive.

**Improving detection and monitoring of emerging compounds**

Due to the high number of emerging contaminants in wastewater, the compound-specific detection is only feasible for a narrow range of known target compounds. For the selection of a site-specific treatment technology and the monitoring of its effectivity and efficiency, the measurability of target compounds for regular monitoring should be further improved. For the broad-band quantification of the toxicological potential of effluents, in-vitro bioassays provide a valuable tool. These bioassays do not detect individual contaminants, but indicate negative effects of complex mixtures of different compounds in terms of endocrine disrupting effects, mutagenicity and acute toxicity.

**Communicating findings beyond the scientific world**

The general public should be informed about emerging contaminants, their possible effects and options to remove them from water and/or replace them by other product. Thus, stakeholders at the hybrid membrane workshop in Germany stressed the importance of ***"popular science communication."*** Such communication from scientists directly and other means such as media coverage and information by public authorities have been an important driver in Switzerland to adapt the water act in 2014 (Eggen et al. 2014).

### Transferable recommendations to water utilities

**Sharing experiences**

Hybrid membrane systems have several advantages for water utilities including stable operation and efficient use of area in comparison to sand filtration. Ceramic membranes also have a high strength and long lifetime. Stakeholders of the DEMEAU hybrid membrane filtration workshop hoped that utilities will ***"communicate experiences"*** to improve the applied knowledge. Such communication can be for instance through knowledge exchange meetings or water associations.

**Optimising operation in terms of aeration, PAC dosing and backwash**

Some hybrid membrane systems in wastewater treatment require aeration and increase the energy requirements of WWTPs. Utilities can help reducing these impacts by …

> *"… optimizing operations."*

One tool to optimize operations are automatic neural net control systems (ANCS) which are presented in another 'recommendations for impacts' document and LCA/ LCC results from a case study in a German drinking water treatment plant can be found in the DEMEAU report **Unique Selling Propositions** (Remy et al. 2015A).

**► Testing new technologies and approaches in collaboration with researchers**

The involvement of water utilities in applied research is crucial in terms of provision of facilities for pilot and full-scale studies. In the case of the ozonation at the WWTP Neugut several stakeholders acknowledged the research at different WWTPs in the region as an important driver for the implementation of this first full-scale implementation:

> *"The openness and willingness to test the new technologies [such as ozonation against emerging contaminants]"*

The utilities are also in a good position to support re-searchers with the knowledge of site-specific information and can

> *"Supply information about the composition of the wastewater with regard to specific contaminants, special industries within the catchment etc."*

### Transferable cross-cutting recommendations

**► Promoting awareness about emerging contaminants, their threats and related technologies**

The awareness about of (eco)toxicological threats from emerging contaminants has often been mentioned as a key driver for the implementation of measures in the various case studies in the DEMEAU project:

> *"... the concern about possible effects from emerging contaminants is a driver for technologies against these contaminants."*

For instance in Switzerland, public consultation showed that the reduction of emerging contaminants was widely accepted (Eggen et al. 2014), thus enabling the adaptation of the Swiss water act to address discharges of emerging contaminants from WWTP.

**► Demonstrate HCMF at various scales**

Several stakeholders of the ozonation at the WWTP Neugut considered the 'courage' to invest in a new technology as a significant contributor. Despite much research there were still

> *„...uncertainties in the dimensioning (ozone reactor, generator) from a revisionary installation into a fixed full-scale implementation."*

Such demonstration requires a coordinated approach between different stakeholders depending on the willingness and motivation to engage in the new technology and also to accept certain risks. Administration and politics need to provide favourable framework conditions including regulations and funding structures, while scientist provide the basic knowledge and can verify the effectiveness of the technology. Utilities need to be willing and capable to implement and operate the technology.

**► Supporting the transition from pilot- to full-scale**

Experience from the WWTP Neugut shows the importance of supporting initial full-scale applications to promote the transition of pilot-scale applications into practice. One stakeholder stressed the importance that ...

> *„... administration should be ready to provide funding [in order to promote this transition]."*

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More information on HCMF, all deliverables and reports can be found on the DEMEAU homepage:

**http://demeau-fp7.eu**

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# 4 Automatic Neural Net Control Systems (ANCS)

This section of the report provides recommendations for impact developed for Automatic Neural Net Control Systems (ANCS). The recommendations are based on detailed Life Cycle Assessments (LCAs), Life Cycle Costings (LCC) and drivers and barriers analyses with a stakeholder workshop and additional information that are provided in the following documents:

**Demeau D51.1: Unique Selling Propositions (Remy et al. 2015A).** Results and discussion of LCA and LCC analyses. Section 4.4 on ANCS.

**Demeau D51.2: Final guidelines for sustainability assessment of water technologies (Remy et al. 2015B).** Description and critical discussion of the methodologies applied.

**Demeau D52.1: Implementation barriers (Pieron and van der Zouwen 2014).** Results and short discussion of the barriers analysis. Section 3.2.2 on ANCS.

**Annex-C of this report.** Short summary of results from the combined HCMF and ANCS workshop conducted in Roetgen, Germany.

Aforementioned reports and a PDF version of the following recommendations for impact for ANCS can be downloaded from the DEMEAU homepage: http://demeau-fp7.eu.

DEMEAU

DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER

# AUTOMATIC NEURAL NET CONTROL SYSTEMS

## RECOMMENDATIONS FOR IMPACT IN THE WATER SECTOR

**Artificial neural networks (ANNs) are mathematical models used to predict and forecast complex parameters. ANNs have originally been designed to mimic activities in the human brain and have been increasingly used in water resources engineering (Hamedet al. 2004). In recently developed automatic neural net control systems (ANCS), ANNs are used in conjunction with genetic algorithms to modify process settings in wastewater and drinking water treatment to achieve optimization targets - such as minimal energy and chemical demand - while at the same time assuring regulatory thresholds such as water quality criteria.**

**The recommendations provided in this document were developed within DEMEAU, a project funded under the 7th Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU is to promote the uptake of knowledge, prototypes and best practices from previous EU research enabling the water sector to face emerging pollutants and thus securing water and wastewater services and public health. In DEMEAU four groups of promising technologies from previous EU research were studied: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF) and automatic neural net control systems (ANCS), advanced oxidation processes (AOPs) and in-vitro bioassays for effects-based screening.**

**The presented recommendations for ANCS capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle analyses (LCAs), economic life cycle costings (LCCs), and social drivers and barriers analyses.**

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308339.

## AUTOMATIC NEURAL NET CONTROL SYSTEMS (ANCS) AND EMERGING CONTAMINANTS

In response to rising concerns about threats from emerging contaminants contained in anti-corrosives, cosmetics, pharmaceuticals, pesticides and other products, several advanced technologies exist today to remove these contaminants from wastewater or drinking water.

The performance of these and other water treatment technologies depend on a multitude of different parameters influencing the treatment processes and their optimal settings at the same time. **Automatic neural net control systems (ANCS) are process control systems designed to find optimal settings depending on the simultaneous analysis of input parameters, optimization targets** – such as minimum energy use – defined by the user, and specified boundary conditions such as water quality thresholds. ANCS can thus help to find favourable settings in terms of economic, operational and also environmental targets. In order to solve such tasks, ANCS realizes a combination of artificial neural networks (ANN) to predict process variables and genetic algorithms to find 'optimal' process settings. A schema of the process is given in Figure 1 and more details are provided in the DEMEAU technology brochure **ANCS - Automatic neural net control systems** (Gebhardt and Lukat 2015).

In the DEMEAU project ANCS was tested for the operation of membrane systems, which can be a highly effective treatment against emerging contaminants both in wastewater and drinking water treatment. The aim of ANCS application is to modify flow rate, filtration time and/or chemical cleaning frequency flexible based on process parameters to achieve an optimal performance with minimal chemical or energy demand. Eventually, ANCS may thus also help reducing investment cost for new membrane plants, which is of special interest also for ceramic membrane systems where investment cost are still higher to more conventional polymeric membranes. Hybrid ceramic membrane filtration (HCMF) is discussed in more detail in **Recommendations for impact: Hybrid Ceramic Membrane Filtration (HCMF)** (Gross et al. 2015).

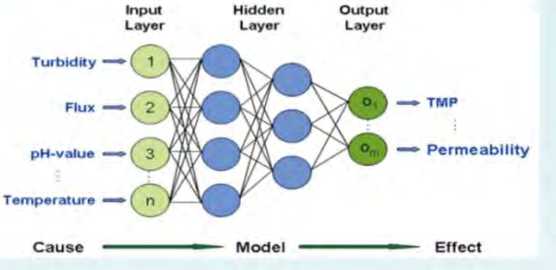


***Figure 1:*** Schematic representation of an ANCS model with process parameters (input layer)and the effects on operating settings (output layer) influencing for instance transmembrane pressure (TMP) and/or permeability

## CASE STUDIES

The analyses and recommendations presented in this document are based on the following ANCS case study conducted in the DEMEAU project. Further case studies are briefly described in the section 'Key application areas of ANCS in the water sector.'

### ANCS at the drinking water treatment plant Roetgen of WAG (Germany)

The drinking water company WAG (Wassergewinnungs- und -aufbereitungsgesellschaft Nordeifel) treats and supplies drinking water to about 500'000 inhabitants in the Aachen area. The drinking water treatment plant (DWTP) Roetgen was constructed in 1953 and in 2004 extended by an ultrafiltration (UF) membrane plant of 6'000 $m^3 h^{-1}$ capacity and a second UF stage of 600 $m^3 h^{-1}$ capacity to treat backwash water of the first stage. The recovery rate was lower than expected, resulting in more backwash water to be treated, and the performance of the existing backwash water line is aimed to be increased by process optimizations using ANCS (Figure 2). Therefore, a UF pilot with ANCS control was run in parallel to the full-scale treatment plant. Based on pilot results, the new process control system using automatic neural networks may be integrated in an existing membrane treatment system in order to optimize the process performance at full-scale.

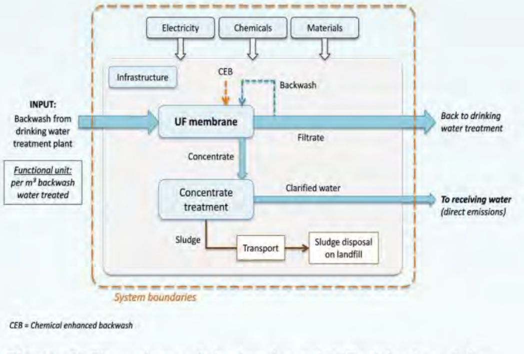


***Figure 2:*** Flow chart of the backwash UF with electricity, chemicals and other materials required

## ENVIRONMENTAL AND ECONOMIC UNIQUE SELLING PROPOSITIONS OF ANCS IN WATER TREATMENT AGAINST EMERGING CONTAMINANTS

**Method: lifecycle - based environmental and economic assessments**

Building on key application areas of ANCS in the water sector and its environmental and economic profile, unique selling propositions were derived and presented in Box 1 on the next page.

In DEMEAU the pilot implementation of ANCS for an ultrafiltration process at the DWTP Roetgen of WAG was analysed using **environmental Life Cycle Assessment (LCAs) and economic Life Cycle Costings (LCC)**. These tools are based on a set of indicators to estimate environmental and economic benefits and impacts/costs to compare between different options. Environmental indicators encompass not only local emissions to the environment but along the entire life cycle of the system.

Detailed results of the sustainability analyses can be found in the following DEMEAU report: **Unique Selling Propositions** (Remy et al. 2015A).

The sustainability methodology used in DEMEAU is described in **Final guidelines for sustainability assessment of water technologies** (Remy et al. 2015B).

**Key application areas of ANCS in water treatment**

ANCS can support various water treatment processes. Different application areas in water treatment - with a specific focus on emerging contaminants - that were demonstrated and tested in the DEMEAU project, include (Table 1, Gebhardt and Lukat 2015):

- **Membrane filtration in drinking water treatment:** ANCS was able to adjust flux, filtration time and/or chemical cleaning frequency of a membrane filtration backwash process depending on feed water quality in order to achieve a target performance and minimized chemical or energy demand (also see next page).
- **Biological stage in wastewater treatment:** In one of the largest wastewater treatment plants (WWTPs) in Germany, aeration, recirculation of volume flow and precipitant dosage were optimized for biological treatment and final sedimentation steps. During dry weather conditions, 15% of energy of the WWTP could be saved.
- **Leakage detection in a drinking water network:** The drinking water network can be simulated based on selected sampling points and indicate leakages and potential failures.

***Table 1:*** Application areas of ANCS studied in DEMEAU in terms of application area, processes optimizations and operational settings (with information from Gebhardt and Lukat 2015)

| Application area in DEMEAU | Process optimization | Operational settings optimized |
|---|---|---|
| Drinking water treatment in a DWTP in Germany | *Pilot-scale ANCS:* Ultrafiltration of backwash at DWTP | Flux, filtration time and/or chemical cleaning frequency of a membrane filtration |
| Wastewater treatment in a WWTP in Germany | *Full-scale ANCS:* Minimal use of energy and chemicals in biological treatment | Aeration, volume flow of recirculation to second stage, precipitant dosage |
| Leakage detection in a water supply network in Germany | *Full-scale ANCS:* Optimization recommendations for the water supply network | Detection and localization of leakages |

**ANCS at the drinking water treatment plant Roetgen of WAG (Germany): LCA and LCC**

The goal of LCA and LCC analysis was to quantify potential savings from ANCS based optimization for a full-scale backwash UF stage at the DWTP WAG Roetgen. ANCS based operation was compared to the *status quo* based on results from a pilot-scale ANCS application (see 'case studies'). In reference to first results of the pilot trials at the DWTP, two scenarios for ANCS operation were defined:

- **Conservative:** Compared to the current operation of the UF membranes, electricity demand required for feed pump and the backwash pump operation would drop by -17% (concentrate treatment not included).
- **Potential:** Best estimates indicate a reduction of -27% in electricity demand and -30% in chemical demand for chemically enhanced backwash (sodium hydroxide and sulphuric acid). Requirements for regular backwash and concentrate treatment were considered constant.

***Figure 3:*** Left picture: Pilot installation of backwash precess; right picture: current full-scale backwash water treatment by UF at WAG

Electricity and chemical demand of the backwash water treatment by UF were based on reference data of the year 2014. Processes included are regular backwash, chemically enhanced backwash (CEB), thickening and dewatering of concentrate as well as transport and final disposal of sludge. Life Cycle Analysis (LCA) showed that ANCS has the potential to substantially cut down environmental impact of the backwash by reducing electricity demand for feed and backwash pumps as well as chemicals demand for chemically enhanced backwash. These savings translate to reductions in the carbon footprint of -10% (-13 g $CO_2$-eq/$m^3$ backwash water) for the conservative scenario and -21% (-26 g $CO_2$-eq/$m^3$) for the potential scenarios, compared to backwash without ANCS (124 g $CO_2$-eq/$m^3$). Both reduced demand for chemical and energy provide benefits in terms of freshwater ecotoxicity, human toxicity and freshwater eutrophication (Figure 4), which are all related to emission during their production processes. Direct water emissions are responsible for some freshwater ecotoxicity potential. However, ANCS implementation does not affect direct emissions to surface waters in this study.

In comparison to the investment cost of a full-scale backwash system of about 1.37 EUR/($m^3$/year), the additional ANCS system would cost between 0.01 and 0.04 EUR/($m^3$/year) depending on the funding system. As the operational costs could be decreased at the same time by up to ca. -5% from 0.19 to 0.18 EUR/$m^3$ due to reduced electrical and chemical demand, this investment can amortize very quickly depending on savings reached by ANCS and the financing mode chosen for investment. If the expected maximum savings are almost met ANCS implementation may already turn profitable in the second year after implementation.

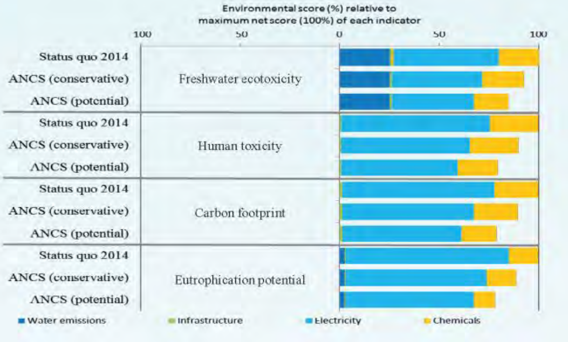


***Figure 4:*** Environmental profile of status quo, ANCS with conservative estimates and ANCS with potential estimates; % net impact relative to highest net impact scenario = 100 %

**Box 1** Environmental and economic unique selling propositions of ANCS in the water sector

- **Optimisation of electricity and chemicals demand for operation with reasonable pay-back time.** ANCS has been shown in DEMEAU to be a reasonable approach to reduce electricity and chemicals demand for operation. Although the costs of ANCS implementation are strongly case specific, variable financing modes offered by the ANCS provider would ensure that a reasonable pay-back-time can be realized in most cases.
- **Capacity optimisation possible.** The cycles of chemically enhanced backwashes for membrane cleaning could be reduced in a drinking water treatment plant studied in DEMEAU. An optimal use of the capacity resulting in reduced capacity requirements for future installations may be feasible.

## RECOMMENDATIONS FOR MARKET UPTAKE

The following recommendations for market uptake have been developed from a drivers and barriers analysis involving stakeholders from the DEMEAU ANCS case studies and researchers of the DEMEAU consortium.

### Transferable recommendations to administration and policy makers

► **Find incentives to promote resource efficiency measures at wastewater and drinking water treatment plants**

The implementation of ANCS requires initial funding which can result in significant savings on the long run. Thus ***"cost-conscious"*** and more generally ***"resource-conscious"*** behaviour would support a broader implementation of ANCS. LCA and LCC of the DEMEAU case study shows that the return on investment depends on various factors, of which the plant size (capacity) is probably the most important one. Considering that savings from ANCS have a direct benefit in terms of reduced resource requirements such as reduced electricity and chemicals demand and therewith related also benefits on the environmental profile, financial support to overcome the initial investment barrier could be a justifiable option. ***"Simplified access to financial support"*** was thus mentioned during a DEMEAU ANCS workshop as a way to overcoming this barrier.

***"Lacking legislative demand for resource efficiency in water treatment"*** was one of the barriers mentioned by ANCS stakeholders. Thus, apart from financial incentives promoting a resource efficient water treatment, specific regulations would most likely be a most significant driver for ANCS.

► **Development of guidelines: When to apply ANCS?**

Apart from providing incentives for resource efficiency measures, guidelines for resource efficient drinking water and wastewater treatment - including the option of ANCS - could contribute toward the continued achievement of water quality thresholds while at the same time minimizing resources required and associated environmental impacts and economic cost.

***"Openness to innovation"*** was requested by ANCS stakeholders from administration and policy makers and supporting case studies focusing on resource efficiency possibly with the help of ANCS would be a practical way to learn from practice and develop relevant guidelines.

### Transferable recommendations to scientific community and technology developers

► **Increasing the transparency of the optimisation process**

ANCS provides an optimization process with an underlying algorithm, of which the calculation process is not easily understandable by non-experts. This optimization was perceived as not transparent enough by some stakeholders. Ways of helping to overcome this barrier could be further increasing the visualisation of the optimization process. Also, the technical communication with water treatment plants and involved operators was perceived very important in order to convey the message that ANCS can actually support rather than replace operators, according to Aquatune.

► **Advance performance in distribution (sales) phase**

Decision making on implementing an ANCS system or not at utility level requires profound knowledge on the expected savings that can be reached by ANCS as well as the costs of its implementation. As this information is strongly case specific, it can only be gained in close collaboration with the technology provider. Providing sound advice on realizable earnings and possible financing modes for ANCS investment (e.g. project financing, contracting) is therefore a task that should be provided by technology providers in order to advance in the distribution of ANCS.

► **Cost/benefit analysis at appropriate system boundaries**

A combined Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approach can help to transparently quantify environmental benefits and impacts and related costs of different ANCS implementation scenarios. By taking account of cost/benefits not only in financial turns but also with regard to environmental indicators such as climate change impacts from electricity and/or chemicals production, a fair assessment can be provided. Such assessments should be communicated beyond the scientific world and can contribute to convincing administration and policy makers to support resource efficiency measures in the water sector. Within DEMEAU LCAs and LCCs were applied to quantify the environmental benefits and possible impacts on one hand, and the economic perspective on the other hand. The methodology used in DEMEAU is described in **Final guidelines for sustainability assessment of water technologies** (Remy et al. 2015B). Results for the DEMEAU case study on ANCS at WAG and other case studies can be found in **Unique Selling Propositions** (Remy et al. 2015A).

► **Building trust by independent scientific research**
Engagement in research projects to independently verify the effects of ANCS along with communication of results through various means would increase the trust in the approach. While pilot studies on real water treatment plants such as during the DEMEAU project help to acknowledge and promote benefits, later evaluation of the full-scale implementation and transparent and standardized assessment will be beneficial. ***"Independent scientific examination"*** was thus an important key word emphasised during an ANCS workshop within the DEMEAU project.

► **Communicating benefits and concept of ANCS**
It is the responsibility of the ones who have access to this information, i.e. scientific community and technology developers, to translate their knowledge to meet other stakeholders' information needs. These other stakeholders are for example utilities as end-users of ANCS, regulators as developers of guidelines for water treatment and possibly efficiency targets. For the communication of such benefits, ***"reference projects"*** are good means, as mentioned during an ANCS workshop.

### Transferable recommendations to utilities

► **Communicating experiences**
Stakeholders of the DEMEAU ANCS workshop felt that water utilities that have applied ANCS could help by ***"communicating experiences."*** The presence of expertise from previous experiences shared between different utilities would be an important driver. Utilities could thus act as multipliers and help building trust for new ANCS projects.

► **Trust building among employees**
Some employees and other stakeholders fear that the application of ANCS might lead to job losses due to automation. According to ANCS developers, the tool is rather designed to improved decision making processes still requiring active involvement of employees. An active corporate communication addressing these issues seems important in that context and stakeholders suggest putting emphasis on...

> *"...advanced training [of employees with regard to ANCS]..."* and *"...communication of [job] security..."*

in order to build trust within the utility. The integration of employees from an early stage during the implementation process of ANCS appears quite important.

► **Cooperate in pilot and demonstration projects**
Showcasing successes in practice can be a major driver for further implementation of new technologies and approaches such as ANCS and other technologies studied in DEMEAU. Pilots and demonstration projects serve different goals, such as pointing out practical challenges that still need to be solved, but also proving the benefits of new technologies and showing opportunities for improvement that arise from implementation. These insights are required to get support from authorities and policy makers.

► **Testing ANCS and evaluating its performance in collaboration with researchers**
While scientists and technology developers have the responsibility to take note of the practical questions in the field that need to be answered to implement ANCS in practice, it is up to the utilities to make optimization needs explicit and provide guidance for further research. This involves an interactive dialogue and cooperation between practitioners at water utilities and researchers and developers, opening up opportunities for pilot studies in real-life test environments, exchange of sometimes implicit knowledge, and continuous improvement of new solutions.

### Transferable cross-cutting recommendations

► **Best practices of ANCS planning and implementation**
The knowledge on best practices has been perceived as a crucial driver for the development and further implementation of ANCS. Such best practices could be developed jointly between ANCS developers and scientists, utilities that have gained experience with the approach and policy makers and administration relevant for new regulations or providing incentives.

Planning and implementation of ANCS at wastewater or drinking water treatment plants requires the interaction between the technology developers and utilities. The ***"clarity of roles between the different stakeholders"*** and ***"clearly defined goals of the ANCS application"*** were mentioned as an important success factors. Best practices could exemplify good interaction and possible definition of goals through description of case studies.

**References:**

Gebhardt J, Lukat E (2015). ANCS. Automatic neural net control systems. Technical brochure from the DEMEAU project (FP 7 framework), http://demeau-fp7.eu

Gross T, Gallice A, Kounina A, Pieron M, Remy C, Wencki K, Hugi C (2015). Recommendations for impact. Deliverable 52.2 from the DEMEAU project (FP 7 framework), http://demeau-fp7.eu

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Remy C, Gallice A, Kounina A, Pieron M, Wencki K, Hugi C, Gross T (2015B). Final guidelines for sustainability assessment of water technologies. Deliverable 51.2 from the DEMEAU project (FP 7 framework), http://demeau-fp7.eu

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More information on ANCS, other technologies and approaches studied in DEMEAU and detailed reports of Life Cycle Analyses, Life Cycle Costings and drivers and barriers analyses can be found here:

**http://demeau-fp7.eu**

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# 5 Advanced Oxidation Processes (AOPs)

This section of the report provides recommendations for impact developed for ozonation against emerging contaminants in wastewater treatment. The recommendations are based on detailed Life Cycle Assessments (LCAs), Life Cycle Costings (LCC) and drivers and barriers analyses with stakeholder interviews and additional information that are provided in the following documents:

**Demeau D51.1: Unique Selling Propositions (Remy et al. 2015A).** Results and discussion of LCA and LCC analyses. Section 5 on advanced oxidation processes.

**Demeau D51.2: Final guidelines for sustainability assessment of water technologies (Remy et al. 2015B).** Description and critical discussion of the methodologies applied.

**Demeau D52.1: Implementation barriers (Pieron and van der Zouwen 2014).** Results and short discussion of the barriers analysis. Section 3.3 on ANCS.

**Annex-D of this report.** Short summary of results from interviews conducted with stakeholders of the ozonation at the WWTP Neugut.

Aforementioned reports and a PDF version of the following recommendations for impact for ozonation against emerging contaminants in wastewater treatment can be downloaded from the DEMEAU homepage: http://demeau-fp7.eu.

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DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER

# OXIDATIVE PROCESSES AGAINST EMERGING CONTAMINANTS

## RECOMMENDATIONS FOR IMPACT IN WASTEWATER TREATMENT

Oxidative processes have a long history to disinfect the effluent of wastewater and drinking water treatment plants. Several (advanced) oxidation processes nowadays exist for the inactivation and/or removal of a broad spectrum of emerging contaminants. Here we present recommendations for market impact for ozonation with subsequent biological filtration in wastewater treatment to protect receiving water bodies from ecotoxicological and human toxicological effects.

The recommendations provided in this document were developed within DEMEAU, a project funded under the 7th Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU was to promote the uptake of knowledge, prototypes and practices from previous EU research enabling the water sector to face emerging contaminants and thus securing drinking water and wastewater services and public health. In DEMEAU four groups of promising technologies from previous EU research were studied: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF) and automatic neural net control systems (ANCS), advanced oxidation processes (AOPs) and in-vitro bioassays for effects-based screening.

The presented recommendations for ozonation against emerging contaminants in wastewater treatment capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle analyses (LCAs), economic life cycle costings (LCCs), and social drivers and barriers analyses.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308339.

## OXIDATIVE PROCESSES AND EMERGING CONTAMINANTS

Oxidative agents such as chloride, ozone and UV are established in water treatment to reduce pathogen loads, organic substances and odour components. Increased knowledge of threats from emerging contaminants and their derivates has led to the **development of dedicated drinking and wastewater technologies - including oxidative processes.**

Emerging contaminants are contained in products such as anti-corrosives, cosmetics and pharmaceuticals and end up in the environment via diverse routes. **Current wastewater treatment plants (WWTPs) are not effective barriers for most of these contaminants** and upgrading with additional technologies such as ozonation and/or powdered activated carbon could help mitigating environmental hazards. Oxidation in many cases eliminates deleterious effects of emerging contaminants, but the formation of **unwanted oxidation by-products** is an important consideration and has been studied in the DEMEAU project.

Ozone ($O_3$) is a strong oxidizing agent that in contact with water forms hydroxyl radicals (OH), which are among the most powerful oxidising substances known. Both ozone and hydroxyl radicals react with many inorganic and organic substances in water and are referred to as 'direct oxidation' and 'indirect oxidation', respectively.

**Both direct and indirect oxidation increase the susceptibility of these substances to subsequent biological degradation** (Abegglen and Siegrist 2012), e.g. by biological reactions in a sand filter. Because ozone is not stable and explosive at high concentrations and high pressure, it has to be generated on-site through electrical discharges in an ozone generator from purified air or oxygen.

The reaction between the water to be purified and ozone takes place in the ozone reactor (Figure 1) and off-gas is degraded by a residual ozone destruction unit. Since ozone is a highly irritating gas causing irritated airways, nausea and respiratory distress, maximum air concentrations have to be assured (e.g. in Switzerland max. 200 μg $m^{-3}$ air: SUVA 2006).

## CASE STUDIES

### Ozonation at the wastewater treatment plant Neugut – Duebendorf (Switzerland)

The recommendations presented in this document are based on sustainability analyses conducted during the DEMEAU project at the WWTP Neugut in Switzerland.

The first full-scale ozonation in Switzerland was constructed in the existing WWTP Neugut with a capacity of ca. 150'000 person equivalents and started operation in 2014. The WWTP with biological treatment and phosphorus removal was extended by an **ozonation stage to eliminate emerging contaminants**. The ozone reactor (Figure 1) was placed between the existing final clarifier and **sand filter**, thereby making use of the biological activities in the sand filter to further degrade transformation products from ozonation.

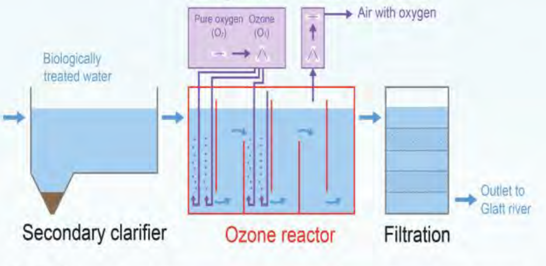


***Figure 1:*** Flow chart of the new ozone reactor at the wastewater treatment plant Neugut (source: WWTP Neugut)

### Other case studies in DEMEAU

Further case studies of (advanced) oxidation processes in water treatment were conducted in the DEMEAU project:

**Oxidative pre-treatment for dune infiltration:** At Dunea in Den Haag, the Netherlands, drinking water has been produced through a multi-barrier process including dune infiltration and post-treatment after recovery. Dune infiltration is a method of Managed Aquifer Recharge (MAR), where water is intentionally introduced into the groundwater for different purposes. A prototype of an advanced oxidative process (AOP) by hydrogen peroxide, ozone and ultraviolet light ($H_2O_2/O_3/UV$) prior to infiltration was tested to degrade different emerging contaminants found in the source water from Meuse River. More details are described in **Recommendations for impact: Managed Aquifer Recharge** (Gross et al. 2015) and **Unique selling propositions** (Remy et al. 2015A).

**Ozonation in drinking water treatment:** The drinking water treatment plant Lengg in Zurich, Switzerland, produces drinking water from lake water with several treatment steps including ozonation. In a pilot-scale setup, treatment with ozone and $O_3/H_2O_2$ followed by activated carbon filtration was tested under different conditions to provide optimized emerging contaminant control. Further details are described in **Demonstration of design, application, controlling and long-term stability of drinking water oxidation technology** (Hofman-Caris et al. 2015).

## ENVIRONMENTAL AND ECONOMIC UNIQUE SELLING PROPOSITIONS OF OXIDATIVE PROCESSES AGAINST EMERGING CONTAMINANTS

**Method: lifecycle - based environmental and economic assessments**

Building on key application areas of oxidation processes against emerging contaminants in wastewater and water treatment and their environmental and economic profiles we propose a set of unique selling propositions (Box 1).

In DEMEAU both the ozonation at the WWTP Neugut and the AOP pre-treatment for dune infiltration and drinking water production at Dunea were analysed using **environmental Life Cycle Assessments (LCAs)** and **economic Life Cycle Costings (LCCs)**. These tools are based on a set of indicators to estimate environmental and economic benefits and impacts/costs to compare between different options. Environmental indicators encompass not only local emissions to the environment but along the entire life cycle of the system. This document focuses on applications in wastewater treatment and results of AOP pre-treatment for dune infiltration are described in **Recommendations for impact: Managed Aquifer Recharge** (Gross et al. 2015). Detailed results of LCA and LCC can be found in the DEMEAU report **Unique selling propositions** (Remy et al. 2015A).

**Key application areas oxidative processes**

Oxidative processes in water treatment have been used for disinfection, elimination of taste and odour compounds and advanced treatment of refractory wastewater from industrial processes. The treatment against emerging contaminants is a more recent area of application for drinking water treatment, pre-treatment for managed aquifer recharge (MAR) and wastewater treatment. Some of these were demonstrated in DEMEAU of which table 1 provides an overview.

**Ozonation in wastewater treatment:** Ozonation in wastewater treatment - the focus of this document - can eliminate >80% of a broad spectrum of emerging contaminants, depending on substance, properties of the pre-treated wastewater and ozone dose (Hollender et al. 2009). Investigations within Demeau at the WWTP Neugut showed that ozonation performed very smoothly, stable and beneficial, guaranteeing the aim to eliminate emerging pollutants by >80% compared to the raw water at the recommended ozone dose of 2.0 - 3.3 mg/L (0.55 g ozone /g DOC) (McArdell et al. 2015). Relatively persistent to ozonation are, however, x-ray contrast media (iopromide), some herbicides (mecoprop, atrazine) or the anti-corrosive agent benzotriazole.

**Oxidative pre-treatment for Managed Aquifer Recharge (MAR):** MAR encompasses different processes to intentionally introduce water into an aquifer and can substitute or complement other solutions of water storage, treatment, transfer and supply (Dillon et al. 2009). Depending on the source water, the concentration and type of emerging contaminants and aquifer properties, MAR alone is not always sufficient to remove all contaminants to required thresholds (Maeng et al. 2011). Pre-treatment by (advanced) oxidative processes can be applied in a multi-barrier approach to produce water of a very high quality (also see 'case studies').

**Advanced Oxidative Processes (AOPs) in drinking water treatment:** Ozone in drinking water treatment has been successfully used to eliminate bacteria, cysts and viruses, and reduce colour, taste and smell causing contaminations. In a pilot-scale study, treatment with ozone and with the AOP $O_3/H_2O_2$ under different raw water conditions has been tested at a drinking water treatment plant in Switzerland for the elimination of emerging contaminants and by-product formation (Table 1).

***Table 1:*** Application areas of oxidative processes studied in DEMEAU in terms of water source (lake water, river water, WWTP effluent) and removal of emerging contaminants

| Treatment | Removal of emerging contaminants[1] | Source water in DEMEAU | Application area in DEMEAU |
|---|---|---|---|
| $O_3$ with sand filtration | +++ | Secondary WWTP effluent | *Full-scale:* Advanced wastewater treatment before discharge into receiving water body |
| $H_2O_2/O_3$/UV pre-treatment for managed aquifer recharge | +++ | River water | *Pilot-scale:* Advanced treatment to produce drinking water in a multi-barrier approach including AOP, dune infiltration, recovery from groundwater, and post-treatment (PAC) |
| $O_3$ and $O_3/H_2O_2$ in drinking water treatment | +++ | Lake water | *Pilot-scale*: Study to compare treatment with $O_3$ and $O_3/H_2O_2$ at different raw water conditions |

[1] Removal of emerging contaminants: + = only partially effective, ++ = moderately effective, +++ = very effective, blank = ineffective

### Oxidation against emerging contaminants in the wastewater treatment plant Neugut in Switzerland: LCA and LCC

At many locations , the concentrations of some emerging contaminants such as Diclofenac are above chronic environmental quality standards in the receiving water after the discharge of conventional WWTPs. Long-term exposure to specific compounds may lead to endocrine disruption, genotoxicity and/or mutagenicity in aquatic organisms. The ozonation installed at WWTP Neugut abates many emerging contaminants present in wastewater and the potential for ecotoxicological effects of WWTP effluents is significantly reduced (McArdell et al. 2015).

The quantification of the toxicity potential in LCA is expressed in so called comparative toxic units: CUTh for human toxicity impacts and CTUe for freshwater ecotoxicity impacts. In the effluent, the ozonation at the WWTP Neugut reduced **cancerogenic effects by -66%** ($8.1 \times 10^{-13}$ to $2.7 \times 10^{-13}$ CTUh), **non-cancerogenic human toxicity by -99%** ($2.2 \times 10^{-10}$ to $6.7 \times 10^{-13}$ CTUh), and **freshwater ecotoxicity by -95%** ($4.2 \times 10^{-3}$ to $0.2 \times 10^{-3}$ CTUe) (Figure 2, 'water emissions'). Because only a narrow range of emerging contaminants are currently described as LCA characterization factors, the reduced water emissions shown in Figure 2 are therefore an underestimation.

The ozonation requires oxygen which is converted to ozone on site using 0.03 kWh $m^3$ electricity. Including all background processes such as the production of oxygen the cumulative energy demand with ozonation increases by +12% (+0.06 kWh/$m^3$) of fossil sources and +11% (+0.8 kWh/$m^3$) of nuclear sources compared to the business-as-usual (BAU) WWTP without ozonation (0.9 and 2.8 kWh/$m^3$ from fossil and nuclear sources, respectively). With the Swiss electric energy mix of which less than 10% is generated from fossil sources, **ozonation adds about +8%, ca. 0.018 kg $CO_2$eq/m³ water treated, to climate change impacts of the BAU WWTP** (0.218 kg $CO_2$eq/$m^3$) (Figure 2). The local electric energy mix is critical in terms of climate change trade-offs and the ozonation unit would for instance with the German electricity mix lead to an increase of more than 0.034 kg $CO_2$eq/$m^3$ water treated, >80% more compared to the implementation in Switzerland.

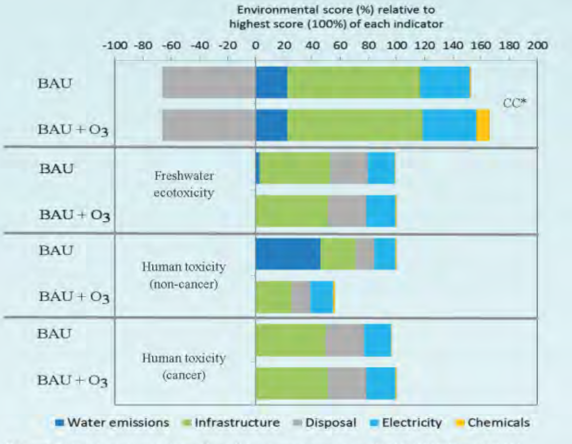


***Figure 2:*** Environmental profile of business-as-usual (BAU) WWTP and BAU extended by ozonation (BAU + $O_3$), % net impact relative to highest net impact scenario = 100 % (CC* = climate change)

The WWTP Neugut provided very favourable conditions for the implementation of an ozonation due to the existence of sand filters and the possibility to place the ozone generator into a position where no additional pumping is required. These resulted in comparably low capital expenditures of approximately 20 EUR per person equivalent (PE), which were estimated at 4% of the total WWTP investment costs. Additional operational costs of the ozonation stage are about +0.01 EUR/$m^3$ of water treated, increasing the operation cost compared to the WWTP without ozonation (0.19 EUR/$m^3$) by +6%. When integrating these different cost over an estimated life cycle of 30 years, the net present value of the additional treatment with ozonation is only +3% (+0.02 EUR/$m^3$ treated) more expensive than the treatment without ozonation (0.60 EUR/$m^3$ treated) in this specific case. More details can be found in the DEMEAU report **Unique selling propositions** (Remy et al. 2015A).

Based on these analyses we propose the following environmental and economic unique selling propositions (Box 1):

***Box 1*** Environmental and economic unique selling propositions of ozonation against emerging contaminants in wastewater treatment

- Ozonation with subsequent biological sand filtration as last stage in wastewater treatment provides an effective **broadband elimination of emerging contaminants.** The magnitude of environmental trade-offs depends mainly on the **source of electric energy** used.
- The additional ozonation can be **installed and operated economically in existing WWTPs**, especially if the conditions at the WWTP are favourable. Such cost saving conditions include a design allowing an operation without additional pumping requirements and the existence of a last biological filtration stage.

## RECOMMENDATIONS FOR MARKET UPTAKE

The following recommendations for impact have been developed from a drivers and barriers analysis involving stakeholders from the DEMEAU oxidation case studies and researchers of the DEMEAU consortium. The recommendations are aimed at administration and policy makers; the scientific community and technology developers; and utilities.

### Transferable recommendations to administration and policy makers

#### ► Integrative decision making

The Swiss Government has decided to reduce emissions of emerging contaminants from wastewater. The adaptation of the water protection act in 2014 requires the implementation of technological upgrades at selected WWTPs in Switzerland in order to remove 80% of emerging contaminants from the wastewater. This political decision is likely the most important driver for the implementation of advanced technologies such as ozonation or activated carbon in Switzerland. One stakeholder of the WWTP Neugut noted that:

> *"The regulative goal to remove 80% of emerging contaminants from wastewater is not a purely 'scientific' or 'political' decision, but requires furthermore the consideration of technological and operational possibilities."*

An integrative decision-making approach can promote regulations which foster the removal of emerging contaminants taking account of technological, environmental, economic and social aspects. On a national level, Swiss authorities based their decision on: (i) full- and pilot-scale studies using ozonation or activated carbon showing a significant reduction of emerging contaminant discharges, (ii) social and political acceptance, and (iii) technical feasibility and cost-effectiveness (Eggen et al. 2014). 'Hands-on' experiences on the assessment of environmental, economic and social aspects of water technologies against emerging contaminants are available in **Guidelines for sustainability assessment of water technologies** (Remy et al. 2015B).

#### ► Funding the transition to advanced treatment against emerging contaminants

The additional removal of emerging contaminants from wastewater comes not without costs which depend on local conditions such as effluent quality and suitability of the current WWTP. How these additional costs are covered depends on local conditions and can include the integration into the water tariffs, fees imposed on significant polluters and/or national and local subsidies. One stakeholder stressed the importance that:

> *„Administration should be ready to provide funding [in order to promote this transition]."*

Such changes are only feasible if the general public is sufficiently informed and willing to accept the additional costs for the perceived benefits. Experiences from the WWTP Neugut show the importance of supporting initial full-scale applications to promote the transition of pilot-scale applications into practice.

#### ► Pro-active interaction and transparent communication from an early stage

A strong driver for the implementation of the ozonation at the WWTP Neugut was the high priority that the Swiss national and local government have attributed to the removal of emerging contaminants from wastewater. There seemed to be a consent among the interviewed stakeholders that:

> *"Authorities have signalled very early in the case of [the WWTP] Neugut, that an upgrade against emerging contaminants was the right way."*

The awareness about (eco)toxicological threats from emerging contaminants has also eventually led to changes in the Swiss water act. Likewise, the positive experiences with ozonation through pilot and test applications in close-by WWTPs seem to have been an essential basis to generate enough trust in the technology. While several factors have contributed to this, the positive attitude of the local authorities together with the political will at national level were described as essential for this implementation.

#### ► Dependable selection of target emerging contaminants and thresholds

The elaboration of a dependable selection of priority substances of concern with threshold values in effluents and receiving water bodies will help to design and implement efficient wastewater and drinking water treatment against these substances. Such a list of priority substances is under development within the frame of Water Framework Directive (WFD). In Switzerland, assessment concepts for the evaluation of organic emerging contaminants from municipal wastewater (Götz et al. 2011) and diffuse sources (Wittmer et al. 2014) have been recently published.

### Transferable recommendations to the scientific community and technology developers

► **Exploring effects of emerging contaminants and oxidation by-products on aquatic ecosystems**

The effects of emerging contaminants on aquatic ecosystems are still not completely understood. The presence of many different contaminants at the same time, their low concentrations and changing mixtures make it difficult to attribute individual contaminants to specific ecological effects (Eggen et al. 2014). Some stakeholders of the ozonation at the WWTP Neugut also specifically mentioned the uncertainties related to the oxidation by-products:

> *"The effect of specific by-products of ozonation in the receiving water bodies is unclear, also at which concentrations these substances become critical."*

and

> *"[Science should] find out how by-products are formed and try minimizing their formation."*

Understanding environmental cause-effects relationships could help optimizing wastewater treatment processes to degrade the most relevant contaminants while minimizing the formation of by-products. Integrating evolving knowledge of effects on aquatic ecosystems into Life Cycle Assessments (LCAs) will strengthen the capability of this tool to assist in the selection of environmentally sound solutions. The knowledge of specific locally prevalent emerging contaminants and their environmental effects and/or significant presence helps in the selection of priority compounds to be included in regulations with specific thresholds.

► **Improving detection and monitoring of emerging compounds**

Due to the high number of emerging contaminants in wastewater and possible unknown oxidation by-products, the compound-specific detection is only feasible for a narrow range of known target compounds. For the selection of a site-specific treatment technology and the monitoring of its effectivity and efficiency, the measurability of target compounds for regular monitoring should be further improved, as one stakeholder of the WWTP Neugut requested. For the broad-band quantification of the (eco)toxicological quality of effluent, in-vitro bioassays provide a valuable tool and further information can be found in **Recommendations for impact: In-vitro Bioassays** (Gross et al. 2015). These bioassays do not detect individual contaminants, but can indicate effects of complex mixtures of different compounds in terms of endocrine disruption, mutagenicity and acute toxicity. Schindler Wildhaber et al. (2015) have recently proposed a test procedure to assess the suitability of ozonation to treat different wastewater by (i) a step-wise test of the ozone stability in the wastewater to be tested, (ii) the efficiency of emerging pollutant removal, (iii) the formation of by-products, and (iv) the application of in-vitro and in-vivo bioassays.

► **Studies on the combination of oxidative processes with other technologies**

Depending on the wastewater composition and the therein contained emerging contaminants, both oxidative processes and technologies based on adsorption (usually activated carbon) have their strengths and weaknesses:

> *"A combination of ozonation with PAC would also provide the capacity to react to changes in regulations with regard to new priority contaminants."*

Also a combination of ozonation as pre-treatment for managed aquifer recharge can be an interesting option. Since the soil above the aquifer can act as a biological filter, depending on local aquifer conditions and composition of source water this may be a favourable option within the frame of a multi-barrier approach. At Dunea, for instance, AOP processes were tested as a pre-treatment before dune infiltration. Because MAR alone is not always sufficient to remove all contaminants (Maeng et al. 2011), additional pre- or post-treatment may be required. This is particularly important where groundwater recharge with reclaimed water is considered. Further research on cost-effective and efficient multi-barrier approaches will be beneficial fostering scientific advancement, trust and applications. Different combinations were studied in DEMEAU such as a reactive layers in pond infiltration and different AOP (Advanced Oxidation Process) processes described above and in **Unique selling propositions** (Remy et al. 2015A).

### Transferable recommendations to utilities

► **Openness towards testing and piloting of new technologies and approaches**

The involvement of water utilities in applied research is crucial in terms of provision of facilities for pilot and full-scale studies. In the case of the ozonation at the WWTP Neugut several stakeholders acknowledged the research at different WWTPs in the region as an important driver towards the first full-scale implementation:

> *"The openness and willingness to test new technologies [such as ozonation against emerging contaminants]."*

The utilities are also in a good position to support researchers with the knowledge of site-specific information:

*"Supply information about the composition of the wastewater with regard to specific contaminants, special industries within the catchment etc."*

While scientists and technology developers have the responsibility to tackle practical questions in the field that need to be answered, utilities should make needs explicit and provide guidance for further research. This involves an interactive dialogue and cooperation between practitioners at water utilities and researchers and developers, opening up opportunities for pilot studies in real-life test environments, exchange of (implicit) knowledge, and continuous improvement of new solutions.

► **Showcasing benefits**
The ozonation at the WWTP Neugut has been described as 'flagship' project and is expected to showcase the applicability of ozonation in WWTPs in Switzerland. Access to funding for such early adopters is crucial:

*„The ozonation at the WWTP Neugut was the first full-scale application [of ozonation against emerging contaminants] in Switzerland. Thus there was willingness to support the implementation financially also through research funds."*

Showcasing successes in practice is a major driver for further implementation of new technologies. Pilots and demonstration projects serve different goals, such as pointing out practical challenges that still need to be solved, but also proving the benefits of new technologies and showing opportunities for improvement that arise from implementation. These insights are required to get support from authorities and policy makers.

**Transferable cross-cutting recommendations**

► **Awareness raising among the general public regarding emerging contaminants and related technologies**
The awareness about (eco)toxicological threats from emerging contaminants has often been mentioned as a key driver for the implementation of measures in the various case studies conducted in the DEMEAU project. This is also true in Switzerland, where media reports on the occurrence of emerging contaminants raised public concern. When the Swiss Government proposed an adaptation in the Swiss water ordinance in 2009 to address discharges of emerging contaminants into receiving water bodies, public consultation of institutions, parties and interest groups showed that the reduction of emerging contaminants was widely accepted (Eggen et al. 2014).

► **Demonstrate ozonation at various scales**
Several stakeholders of the ozonation at the WWTP Neugut considered the 'courage' to invest in a new technology as a significant facilitator. Despite much research there were still

*„... uncertainties in the dimensioning (ozone reactor, generator) from a revisionary installation into a fixed full-scale implementation."*

To overcome these hurdles requires a coordinated approach between different stakeholders depending on the willingness and motivation to engage in a new technology and also to accept certain risks. Administration and politics need to provide favourable conditions including regulations and funding structures, while scientist provide the basic knowledge and can verify the effectiveness of the technology.

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More information on MAR, all deliverables and reports can be found in the DEMEAU tool box:

**http://demeau-fp7.eu/toolbox/**

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# 6 In-vitro bioassays

This section of the report provides recommendations for impact developed for in vitro bioassays. The recommendations are based on qualitative Life Cycle Assessments (LCAs), Life Cycle Costing's (LCC) and drivers and barriers analyses with stakeholder interviews and additional information that are provided in the following documents:

**Demeau D51.1: Unique Selling Propositions (Remy et al. 2015A).** Results and discussion of LCA and LCC analyses. Section 6 on in-vitro bioassays.

**Demeau D51.2: Final guidelines for sustainability assessment of water technologies (Remy et al. 2015B).** Description and critical discussion of the methodologies applied.

**Demeau D52.1: Implementation barriers (Pieron and van der Zouwen 2014).** Results and short discussion of the barriers analysis. Section 3.4 on in-vitro bioassays.

**Annex-E of this report.** Short summary of results from stakeholder interviews conducted with stakeholders of the DWTP WAG.

Aforementioned reports and a PDF version of the following recommendations for impact for in-vitro bioassays can be downloaded from the DEMEAU homepage: http://demeau-fp7.eu.

DEMEAU

DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER

# IN-VITRO BIOASSAYS

## RECOMMENDATIONS FOR IMPACT IN THE WATER SECTOR

**Bioassays have emerged as a new, promising technology that is particularly useful for assessing harmful effects of complex mixtures of pollutants in water, even if they are unknown. Bioassays hold the potential to serve as a complementary monitoring technology, for use in conjunction with chemical analysis, and provide therefore an opportunity for introduction and integration into current water monitoring strategies (Simon et al. 2015).**

**The recommendations provided in this document were developed within DEMEAU, a project funded under the 7th Framework Programme for Research and Technological Development of the EU. The aim of DEMEAU is to promote the uptake of knowledge, prototypes and best practices from previous EU research enabling the water sector to face emerging pollutants and thus securing water and wastewater services and public health. In DEMEAU four groups of promising technologies from previous EU research were studied: managed aquifer recharge (MAR), hybrid ceramic membrane filtration (HCMF) and automatic neural net control (ANCS), advanced oxidation processes (AOPs) and bioassays for effects-based screening.**

**The presented recommendations for in-vitro bioassays capitalize on sustainability assessments conducted in the DEMEAU project and portrait outcomes from environmental life cycle analyses (LCAs), economic life cycle costings (LCCs) and social drivers and barriers analyses.**

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308339.

## IN-VITRO BIOASSAYS AND EMERGING CONTAMINANTS

In-vitro bioassays (Figure 1) have been developed to suit **complex mixture characterization** covering complex endpoints such as genotoxicity, mutagenicity and particularly endocrine disruption. Bioassays can perform screenings at very low contaminant concentrations through dedicated methods. The main advantage of in-vitro bioassays is the integrated response to biological effects of compounds in a complex mixture such as for instance surface water (Simon et al. 2015).

Previously bioassays have been applied mainly in the food and feed sector (Sjerps et al. 2014). Currently, their applications for the water sector - specifically for **drinking water** - are studied more in-depth, because of expected broader coverage and efficiency related benefits for monitoring programmes, and various water utilities are involved in tests and pilots.

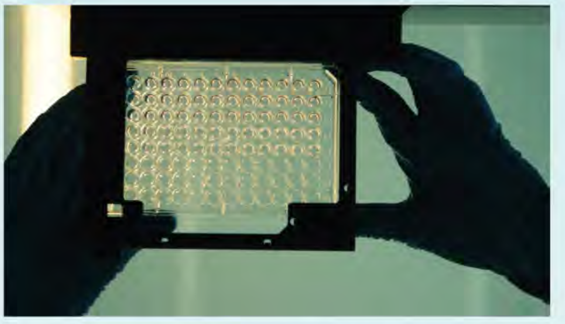

***Figure 1:*** Microtitre plate as commonly used for in-vitro bioassays

## CASE STUDIES

### Waternet – Amsterdam area (Netherlands)

The recommendations presented in this document are based on a case study conducted in the DEMEAU project at the drinking water utility Waternet in the Amsterdam area, the Netherlands.

Recently, the AREc32 bioassay was presented as a **novel tool to determine effects mediated via the oxidative stress response pathway**. This pathway is an important part of cellular defence against different reactive chemicals, such as disinfection byproducts. The AREc32 bioassay has been validated at the KWR laboratory and applied at a pilot installation of Waternet, a Dutch drinking water utility. The pilot installation resembles the full scale plant and includes treatment of raw water by ozonation and activated carbon adsorption. In addition to the AREc32 bioassay, CALUX bioassay panels were used to **test for endocrine disruption in the treated drinking water** including estrogen (ER), androgen (AR), glococorticoid (GR) and progesterone (PR), **genotoxicity** and **cytotoxicity** (Table 1).

Results illustrate that the AREc32 assay is highly reproducible and sensitive to a number of reference compounds (Simon et al. 2015). After validation, a number of raw water samples from the various treatment barriers at the pilot installation of Waternet were tested. The concentrations of most target chemicals were reduced after ozonation, however the oxidative stress of the treated water was increased. This toxic effect, probably due to reactive ozonation byproducts, disappeared after the activated carbon treatment.

Waternet is interested in the application of bioassays because of two main reasons. First of all, bioassays provide the opportunity to **screen for toxic effects in source water** that is used for drinking water production (after which chemical analyses can be applied in a more dedicated and efficient way to identify the responsible toxic compounds). Secondly bioassays provide insights in the **effects and efficiency of the various drinking water treatment steps on toxicity levels**. These insights could assist Waternet to adapt their treatment strategy to the quality of source water.

### Further case studies within DEMEAU

Further in-vitro bioassay case studies were conducted in the DEMEAU project but not analysed in detail through sustainability analyses. These included:

**Bioscreening for Managed Aquifer Recharge (MAR):** In a MAR project at Sant Vicenç dels Horts in Spain, in-vitro bioassays were applied for bioscreening of groundwater, surface water as current source water for infiltration and pre-treated wastewater as potential source water.

**Monitoring and evaluation of water quality in wastewater treatment with ozonation:** In the wastewater treatment plant Neugut in Switzerland effluent following a new full-scale ozonation with subsequent biofiltration was monitored and evaluated by bioassays.

## ENVIRONMENTAL AND ECONOMIC UNIQUE SELLING PROPOSITIONS OF IN-VITRO BIOASSAYS IN WATER TREATMENT AGAINST EMERGING CONTAMINANTS

### Method: lifecycle - based environmental and economic assessments

Building on key application areas of different in-vitro bioassays in water treatment against emerging contaminants and environmental and economic considerations we propose unique selling propositions (USPs) for each technique studied in DEMEAU. Proposed USPs for Bioassays are shown in Box 1 on the next page.

More detailed results from environmental and economic assessments can be found in the DEMEAU report **Unique selling propositions** (Remy et al. 2015).

### Key application areas

Relevant application areas of in-vitro bioassays in the water sector include (examples in Table 1):

- **Monitoring of possible (eco)toxicological risks** in treated drinking water, wastewater treatment plant effluents, water reuse applications and managed aquifer recharge (MAR);
- **Measurement of toxicity reduction performance** of individual treatment steps and treatment trains in drinking and wastewater treatment plants.

***Table 1:*** Application areas of in-vitro bioassays studied in DEMEAU in terms of specific effects tested (abbreviations are described in the section 'case studies'), water analysed (groundwater, surface water, drinking water, wastewater and treated wastewater) and application areas

| Objective | Specific effects tested | Water analysed | Application area in DEMEAU |
|---|---|---|---|
| Measurement of toxicity reduction performance and monitoring | Oxidative stress (AREc32), endocrine disruption (ERa, AR, GR, PPARg, anti-ERa, anti-AR), genotoxicity (Nrf2), cytotoxicity | Drinking water | Drinking water treatment: *Pilot* at Waternet (Netherlands) |
| Monitoring of water quality in managed aquifer recharge | Endocrine disruption (ERa, GR, PPARg, anti-AR, anti-PR), genotoxicity (Nrf2), cytotoxicity | Groundwater, surface water, wastewater, WWTP effluent | Managed Aquifer Recharge (MAR): *Pilot* at Sant Vicenç dels Horts (Spain) |
| Monitoring of water quality in wastewater treatment with ozonation and sandfiltration | Endocrine disruption (ERa, PPARg, anti-AR, anti-PR), genotoxicity (Nrf2), cytotoxicity | WWTP effluent, surface water | Wastewater treatement: *Pilot* at WWTP Neugut (Switzerland) |

### Environmental and economic benefits and costs

Qualitative analysis of potential environmental impacts of in-vitro bioassays indicates that **additional energy and resource demand for water sampling and monitoring is most probably not significant**. In comparison to total energy and resource demand for water treatment and distribution, analytical tools (both chemical analysis and bioassays) are not expected to contribute a major share to energy and resource demand of water treatment and related environmental impacts. Emission control and waste handling routes in the controlled lab environment should keep direct environmental impacts of in-vitro bioassays to a minimum. From this perspective, bioassays are not expected to have a significant environmental impact in terms of resource demand or emissions.

If bioassays are used as a screening tool to complement traditional strategies of chemical screening in drinking water production, they **can broaden the scope and save significantly costs of monitoring** for specific groups of chemicals with dedicated effects (e.g. endocrine disrupting compounds). Based on reproducible in-vitro bioassay signals and defined threshold levels for positive response, bioassays can be used for regular chemical screening prior to frequent and expensive chemical analysis (e.g. LC-MS/MS) of multiple target substances. Due to the lower cost of a single in-vitro bioassay compared to costs for chemical analytics, the use of bioassays is expected to reduce total costs of monitoring a set of endocrine disrupting substances by 45-65% in a specific case study by significantly reducing the number of samples that would have to be analysed routinely with LC-MS/MS. In addition, bioassays can also detect emerging or new contaminants which have not yet been identified or cannot be measured. Hence, safety of water quality with regard to unknown or emerging contaminants of concern could be enhanced with the use of bioassays in regular screening of water quality.

***Box 1*** Environmental and economic unique selling propositions of in-vitro bioassays in the water sector

- In-vitro bioassays for specific groups of compounds provide a cost-effective way of regular screening of water quality by substituting a significant number of expensive chemical analysis. Besides the reduction in monitoring costs for known substances, effect-based in-vitro bioassays give additional safety in water quality monitoring towards unknown or emerging compounds with potentially negative effects.
- The use of bioassays is not expected to cause any substantial negative environmental impacts associated with required chemicals or materials compared to chemical analysis. In general, resource demand and related emissions caused by material and infrastructure for analytical techniques are expected to have only marginal contribution to the overall environmental impact of water treatment.

## RECOMMENDATIONS FOR MARKET UPTAKE

The following recommendations for market uptake have been developed from a drivers and barriers analysis involving stakeholders from DEMEAU case studies and researchers of the DEMEAU consortium. Most significantly, these recommendations follow from a series of interviews with experts that have been involved in the Waternet case study from different perspectives.

### Transferable recommendations to administration and policy makers

**Develop standards and guidelines for application**

Standards and guidelines could promote implementation of bioassays in different ways, for example by setting the basic standards of 'good practice' with which utilities need to comply, but also by motivating water utilities to improve and extend their water quality monitoring practices and providing them with concrete options for action to do so. Such guidelines should include areas of application, standard bioassay compositions, relevant trigger values, and follow-up actions in case these values are exceeded.

**Find the right incentives to support implementation**

The opinions on whether enforcement by law is the best way to promote implementation of bioassays differ among stakeholders. Laws and regulations might hinder further development of in-vitro bioassays and screening practices, because every time 'new best practices' or new insights are found, also new regulations would be required. The field of bioassays is still very much in development, so that other incentives would foster implementation of bioassays (or improvement of monitoring strategies in general) more effectively. Examples are setting a minimum amount of financial resources that water utilities need to invest (individually or in joint programmes) to improve their monitoring strategies, or rewarding best practices in the field. Policy makers could play a major role in the implementation of technologies by finding the right incentives that motivate end users to adopt them.

### Transferable recommendations to the scientific community and technology developers

**Make the concept of 'toxicity' understandable**

The concept of 'toxicity' has a negative connotation among the general public and other non-expert stakeholder groups. Especially in relation to water quality the general public tends to be risk averse, implying that – although not realistic from the perspective of scientists – the toxicity of water should preferably be 'zero'. This makes communication about the results of in-vitro bioassay screenings a challenging activity. One of the needs to be able to start the dialogue on the benefits of in-vitro bioassays is to make the scientific concept of 'toxicity' understandable and interpretable as a 'neutral' indicator, removing the immediate negative associations.

**Focus research and development activities on end-users' demand**

Whereas scientists tend to be driven by a match between a deep personal interest and the appealing field of unmet scientific challenge, the last steps in the implementation of in-vitro bioassays needs a focus on questions and demands from end-users. Answering questions that matter for water utilities, selecting useful assays for specific practices, optimizing screening processes, translating measurement outcomes to implications for human health, and developing thresholds and trigger values are important steps. These will make it easier to involve utilities as end-users of the in-vitro bioassays and policy makers setting the boundary conditions and regulations for application of in-vitro bioassays.

Successful outcomes of such projects - as could be seen within the DEMEAU project - lead to increased interest in in-vitro bioassay application and more opportunities for continued research and development.

- **Start sharing the knowledge and insights with society**

A lack of knowledge on application areas and the potential benefits of bioassays at water utilities and other end-users is one of the main barriers for implementation. It is the responsibility of the ones who have access to this information, i.e. scientific community and technology developers, to translate their knowledge to meet other stakeholders' information needs. These other stakeholders are for example utilities as end-users of in-vitro bioassays, regulators as developers of guidelines for water quality monitoring or the general public as a group that is able to put pressure on both utilities and regulators to improve water quality monitoring strategies, for reasons of human and environmental health.

### Transferable recommendations to utilities and other end-users

- **Provide guidance for further research and development**

While scientists and technology developers have the responsibility to take note of the practical questions in the field that need to be answered to implement in-vitro bioassays, it is up to the utilities to make needs explicit and provide guidance for further research. This involves an interactive dialogue and cooperation between practitioners at water utilities and researchers and developers, opening up opportunities for pilot studies in real-life test environments, exchange of (implicit) knowledge, and continuous improvement of new solutions.

- **Cooperate in pilot and demonstration projects (in kind or financial contribution)**

Showcasing successes in practice turns out to be a major driver for further implementation of new technologies, such as done within the DEMEAU project. Pilots and demonstration projects serve different goals, such as pointing out practical challenges that still need to be solved, but also proving the benefits of new technologies and showing opportunities for improvement that arise from implementation. These insights are required to get support from authorities and policy makers. To further implement in-vitro bioassays in the water sector it is thus recommended that utilities with positive experiences actively share their enthusiasm with others and demonstrate the benefits.

- **Be open to innovations**

Risk management is a central topic in water management practices. However, a strong focus on risk management seems in practice not very compatible with processes of innovation, characterized by change and uncertainty. However, innovative technologies – such as in-vitro bioassays – might prove to be a valuable improvement compared to current practices. Therefore, it is important that water management practitioners give innovations a chance, of course with a critical eye on the feasibility of new technologies to support, and join forces with researchers and developers.

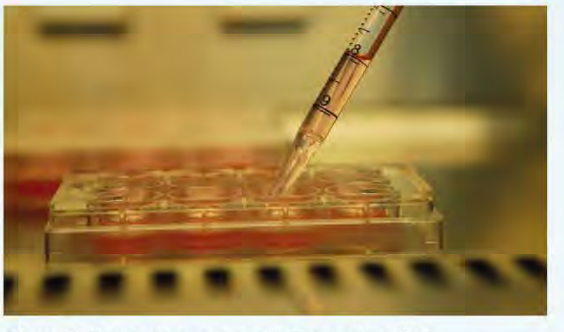

***Figure 2:*** Test substances applied to a microplate

### Transferable cross-cutting recommendations

- **Take shared responsibility and establish ownership**

A recommendation that was often mentioned, concerns the importance of shared action and responsibility. Implementation is not likely to take place if different stakeholders do not join their strengths and add to each others' expertise from different perspectives. Good cooperation between science, practice and policy was identified as one of the most important drivers for successful implementations. One of the conditions for good cooperation that was identified is that in order to achieve implementation stakeholders should not wait for each other to take action, but take on active roles, ownership of the process, and shared responsibility.

- **Develop a shared vision on 'water quality monitoring of the future'**

In-vitro bioassays are complementary to current monitoring strategies. To change well-established monitoring strategies new techniques, norms, standards, infrastructures and behaviours are required. In other words, the whole 'monitoring system' - including both technological and social aspects - needs to change. A clear future vision, jointly developed and/or supported by all stakeholders that play a role in the transition to this new system, is identified as a key driver for implementation. This future vision should answer questions as 'why do we need to change the current monitoring system?', 'how will this be done?', 'how to address the identified risks which were unknown before?', 'which changes are needed?' and 'at which point in time?' Such a vision does not emerge by itself, but requires commitment, time and energy of all involved stakeholders.

KWR Watercycle Research Institute

University of Applied Sciences and Arts Northwestern Switzerland

IWW

Quantis Sustainability counts

VEOLIA ENVIRONNEMENT

KOMPETENZZENTRUM Wasser Berlin

More information on in-vitro bioassays, other technologies studied in DEMEAU and detailed reports of Life Cycle Analyses, Life Cycle Costings and drivers and barriers analyses can be found here:

**http://demeau-fp7.eu**

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# Annex-A Workshop results: Managed Aquifer Recharge (MAR)

An online survey conducted during 2013 aimed to identify the main drivers and possible barriers during the implementation of MAR at the Sant Vicenç dels Horts case study (further details in Pieron and van der Zouwen 2014). During a workshop conducted in Barcelona on October 2, 2014, an interactive session was organized with 39 participants from different backgrounds including scientists, policy makers, water associations and water utilites. The aim of the interactive session was to elaborate on the survey findings and confront the various perspectives (with regard to the major barriers that were identified) with each other. For that purpose, the major barriers that had been identified from the online survey were translated into statements, which were presented at the workshop. The participants were asked to agree or disagree with the statements and comment on their choice and results are shown in Table A-1.

Table A-1 Overview of drivers and barriers from online questionnaires (summarized from D52.1) and responses to questions during a stakeholder event (number of respondents between 10 and 13 persons per stakeholder group)

| | Drivers and barriers for market implementation | |
|---|---|---|
| Contextual | **Online questionnaires**<br>**(-)** Public and governmental resistance because of required changes in physical environment (pools, fences, shutting down nature reserves for public)<br>**(-)** Use of reclaimed water is not yet fully accepted by the general public (perceived environmental and health risks)<br>**(-)** Strict/inflexible regulations leading to very high requirements that are very expensive to meet. This is caused by lack of knowledge (on MAR and case context) at public institutions<br>**(-)** Application of MAR is very context specific and is therefore not perceived as a valuable investment option for authorities | |
| | **Questions during workshop**<br>*"Use of reclaimed water is not yet fully socially accepted by the general public; people are easily scared by potential negative impacts for environment and health"* | **Participants' agreement**<br>Science: 13/13<br>Administration: 12/13<br>Operators: 11/12 |
| | *"Strict and inflexible regulations – especially with regard to reclaimed water – pose very high (unnecessary) requirements that are very difficult and expensive to meet"* | Science: 12/13<br>Administration: 9/13<br>Operators: 11/13 |
| Inter-organizational | **Online questionnaires**<br>**(+)** Good relationships, with clear division of tasks, transparent communication and shared views are important. Especially: Existence of a network with required expertise and well-known relations; good experiences with previous collaborations; absence of 'knowledge wars, presence of trust.<br>**(+)** Active involvement of relevant authorities is perceived as a driver of the implementation process, because of the importance to include the regulatory perspective in the project planning and development.<br>**(-)** Communication about financials was perceived as challenging. When it comes to the question: 'who will pay?', resources seem difficult to allocate.<br>**(-)** Learning from other cases (especially on an international level) is found to be a challenge/barrier, since boundary conditions are very case specific. | |

| | | |
|---|---|---|
| | **Questions during workshop**<br>*"Communication about financials is relatively challenging: when it comes to the question 'who will pay?' resources seem difficult to allocate"* | **Participants' agreement**<br>Science: 12/13<br>Administration: 12/12<br>Operators: 12/12 |
| Intra-organizational | **Online questionnaires**<br>**(+)** Willingness of the involved stakeholders to make this project a shared success and the positive attitude towards innovative approaches are perceived by the majority of the stakeholders as a driver for successful implementation.<br>**(-)** Lack of experience and knowledge on best practices<br>**(-)** This knowledge gap causes an investment risk and difficulties to get the required financial resources together | |
| | **Questions during workshop**<br>*"Lack of experience and knowledge on best practices on emerging contaminant removal/degradation in MAR systems (due to their context specificity) results in much uncertainty and high risks"* | **Participants' agreement**<br>Science: 3/13<br>Administration: 4/10<br>Operators: 9/12 |
| Individual | **(+)** Specific knowledge about the technique was present at the research organization, and knowledge on the specific context was available at the regional water board. From this perspective individual characteristics enabled development and implementation of the technique<br>**(-)** In general it was perceived that regulators and policy makers (as organizations) lack the knowledge and/or capacity to adapt the current regulations to a more MAR-friendly frame (especially regarding the use of reused water for artificial recharge) | |
| | **Questions during workshop**<br>*"Regulators and policy makers (as organizations) lack the knowledge and/or capacity to adapt the current regulations to a more MAR-friendly framework (especially regarding the use of reused water)"* | **Participants' agreement**<br>Science: 10/10<br>Administration: 8/9<br>Operators: 9/9 |

This interactive session built the starting point for break-out sessions into the following stakeholder groups: science, operators and regulators. In these sessions, stakeholders were asked to discuss and summarize the most important implementation barriers and write down what – from their perspective – should be done by each of the stakeholder groups (including themselves) to overcome the barriers. During the workshop, the following implementation barriers were considered the most important as mentioned during the different break-out sessions (Table A-2).

Table A-2 Overview of implementation barriers and requirements from scientific community, administration and operators to overcome such barriers according to break-out sessions

| | BARRIERS | REQUIRED FROM SCIENTIFIC COMMUNITY | REQUIRED FROM ADMINISTRATION | REQUIRED FROM OPERATORS |
|---|---|---|---|---|
| | | • Establishment of MAR communities, with special attention to the science-policy interface: exchange of knowledge, local options and consequences<br>• Cooperate on realistic guidelines and regulations that consider the health and environmental effects in a measurable way<br>• Willingness to communicate with each other, openness, transparancy | | |
| TECHNOLOGICAL | • Well clogging<br>• Lack of maintenance protocols<br>• Quality of infiltration water<br>• Effects on ecotoxicology of groundwater are unknown | • Model clogging effects and find solutions<br>• Translate experiences from other countries to local projects<br>• Stop solving problems that already have been solved somewhere else<br>• Determine the boundary condtions under which MAR is an effective solution. | • Make existing technological questions explicit | • Make plants/playgrounds available for pilots and tests |
| REGULATORY | • Regulators still see too many risks<br>• Regulation are inflexible<br>• Conservative attitude of regulators<br>• Regulation does not (yet) include the variety of water qualities (incl recycled water)<br>• Lack of health and environmental parameters<br>• Complex communication among various administrative levels | • Define health and environmental parameters to be able to make MAR practices measurable<br>• Listing priority substances to monitor.<br>• Dissemmination to and coordination with regulators | • Aim for regulations that are locally adaptable<br>• Inlcude measurable parameters (also of emerging pollutants) in regulations that allow measurement of the effects on water quality (instead of being strict on the inflow water)<br>• Consider water quality on basin level<br>• Don't come up with new regulations, but improve existing ones<br>• Improve communication among adm. levels<br>• Adapt EU regulations to local circumstances | • Be transparent: show results, provide test data, real costs, reasons for failure, etc. to look jointly for solutions<br>• Participate in discussions (especially local discussions regarding specific solutions)<br>• Don't just 'assume' that regulations are and will always be a barrier. |
| FINANCIAL | • MAR competes with other water related solutions<br>• High costs for pre-treatment of (recycled) water for well injection<br>• Open question of who pays the bill<br>• Viability of solution is questioned | • Conduct and communicate Lifecycle Costing and Lifecyle assessments to clarify the 'choices' and longer term effects | • Aim for public funding on a longer term (avoid limited subdidies)<br>• Integrate costs of water reclamation in water bill (to allow for higher investments)<br>• Consider also the (partly qualitative) savings done by reclaiming water<br>• Extending exploitation period (for operators), redistribution of costs<br>• Not "coffee for all" (refers to autonomous regions) | • Contribute financially to development and maintenance of technology and regulations (is already done by some)<br>• Invest in tertiary treatment (which enables infiltration of cleaner water) |
| SOIAL | • Conservative attitude of consumers<br>• Lack of dissemination on local level | • Communicate findings (in understandable language) outside scientific community | • Start public dialogue about MAR, including various stakeholders | |

The wrap-up of the different breakout sessions was summarized by exponents of each stakeholder group:

**Scientists**

- MAR is sometimes in competition with other DW production methods and often doesn't receive funds.
- Regulators should be realistic and decide based on the context. Case-to-case decisions are important.
- If flaws exist, it is also important to communicate. Not only best practices should be communicated.
- Operators should be aware of technology needed and provide funding for research.
- MAR is only a management measure appropriate in some cases, but not in all cases (pers. Comment Prof. Custodio)

**Operators**

- Barriers seem to be similar to scientific community.
- There is not one single regulator that can give an answer to everything.
- It is always nice to put up something visible, but aquifers of course are not so visible.
- We can offer experience and sites, so researchers can do field tests.
- We could develop indicators with thresholds to manage the systems.
- Admin should provide tools, so operators can protect/manage the resource.
- Scientific community should provide information on impact of emerging pollutants on public health and admin should provide such information to operators.
- Studies should take into account environmental and economic aspects (LCA/LCC).
- All the different costs need to be included in the water bill. We currently don't know how to do it.
- More communication is needed. This is the first such gathering between different levels (admin, regulator, scientific).

**Regulators**

- Complex administrative structure with lacking communication/coordination between different bodies.
- We also have to work on other compounds (e.g. priority lists of WFD), not only on the emerging contaminants.
- Direct/indirect beneficiaries should pay at least part of the costs which are currently paid by administration (structures, canals etc.).
- Results from LCA/LCC are not implemented in Spain.
- Politicians and lawmakers need to realize that European laws need to be adapted to local conditions (hydrological etc.).

## Annex-B Workshop results: Hybrid Ceramic Membrane Filtraton (HCMF)

An online survey conducted during 2013 aimed to identify the main drivers and possible barriers during the implementation of Hybrid Ceramic Membrane Filtration (HCMF) at the WWTP Birs case study in Switzerland (further details in Pieron and van der Zouwen 2014). During a workshop conducted in Roetgen on June 11, 2015, an interactive session was organized with participants from different backgrounds involved with membrane filtration and/or Automatic Neural Net Control Systems (ANCS, also see Annex-C). The aim of the interactive session was to confront the various perspectives on driving forces and barriers for HCMF market implementation between different stakeholders involving scientist, water utilities and consultants. The following tables provide a summary of barriers (Table B-1) and drivers (Table B-2) identified by stakeholders at the workshop and how the scientific community, administration and operators could help to overcome barriers and make best use of drivers.

Table B-1 Barriers for market implementation of HCMF and how these could be overcome based on output of interactive session

| Barriers | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|
| Life cycle costs of additional installations | further development of mebranes [and] adsorption | | optimising operations |
| Energy requirements | enhancements mebranes [and] adsorption | | optimising operations |
| Anonymousness | Communication [between stakeholder groups] | | |
| Technical feasability, technical stability | Exchange with other application sectors | | "ERFA" meetings [i.e. meetings for knowledge exchange] |
| • PAC raw materials | Alternative materials | Guidelines | Certificates, auditing |

Table B-2 Drivers for market implementation of HCMF and how these could be tapped in future projects based on output of interactive session

| Drivers | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|
| Next generation [higher water] quality requirements | | Administrative processes, administrative actions | |
| Water reuse goals | | Legal framework conditions for water reuse | |
| Robustness | Communicate experiences | | Communicate experiences |
| Stable operation and efficient use of area | Further optimisation of flow rate per $m^2$ membrane surface area | Landscape planning | |
| Fear [concern] about emerging contaminants and inquiry at costumer/end-user | Popular science publications; publicity | Precautionary principle | |

## Annex-C Workshop results: Automatic Neural Net Control Systems (ANCS)

An online survey conducted during 2013 aimed to identify the main drivers and possible barriers during the implementation of Automatic Neural Net Control Systems (ANCS) at the DWTP WAG case study in Germany (further details in Pieron and van der Zouwen 2014). During a workshop conducted in Roetgen on June 11, 2015, an interactive session was organized with participants from different backgrounds involved with ANCS and/or membrane filtration (also see Annex-B). The aim of the interactive session was to confront the various perspectives on driving forces and barriers for ANCS market implementation between different stakeholders involving scientist, water utilities and consultants. The following tables provide a summary of barriers (...) and drivers (...) identified by stakeholders at the workshop and how the scientific community, administration and operators could help to overcome barriers and make best use of drivers.

Table C-1 Barriers for market implementation of ANCS and how these could be overcome based on output of interactive session

| Barriers | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|
| Intransparence of the optimisation processes | Technical communication and visualisation | | Transparency; Integration of employees during introduction [of ANCS to facility]; exchange of experience |
| Assignement practice | | Pre-qualification or quote request assignement by private contract | |
| Not all operational states mapped [visualized in software] | Technical communication and visualisation | | Transparency; Integration of employees during introduction [of ANCS to facility]; exchange of experience |
| Possible opposition from public authorities | Improved communcation with public authorities; idependent scientific examination | Improved implementation of national guidelines; openness for innovation | |
| fear of job loss | Communication/education | | Corporate communication; advanced training; communicate security |

Table C-2 Drivers for market implementation of ANCS and how these could be tapped in future projects based on output of interactive session

| Drivers | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|
| Cost pressure | Advance performance in distribution [sales] phase; value-added chain analysis [cost/benefit analysis] | Cost-conscious behaviour | |
| Rising requirements and threshold values | Reference projects | Regular life cycle analyses | |
| Support of plant operation | | Increasing security during plant operation | |
| Support [financial] | | Simplified access [to financial support] | |
| Psychological security | | | Communication |

# Annex-D Interview results: Ozonation in wastewater treatment

An online survey conducted in 2013 aimed to identify the main drivers and possible barriers during the implementation of ozonation followed by biological sand filtration at the WWTP Neugut in Switzerland (further details in Pieron and van der Zouwen 2014). This survey was in 2015 followed by a series of in-depth interviews with experts involved in the case study in different roles and have different perspectives on drivers and barriers. Representatives from various stakeholder groups that are involved in the Neugut case study provided insights in perceived drivers and barriers and expectations between the various groups.

Table D-1 Barriers for market implementation of ozonation against emerging contaminants in wastewater treatment and how these could be overcome based on stakeholder interviews

| Barriers | | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|---|
| **Technological** | • Oxidation by-products are a central criterion and co-determine if ozonation should be applied in a specific case<br>• Uncertainties in the dimensioning (ozone reactor, generator) from pilot to full-scale<br>• Experience with just one technology [at a specific site, region] may lead to the usage of just this particular technology<br>• The effect of specific by-products in aquatic ecosystems is still unclear | • Determine which oxidation by-products are generated and try minimizing their generation, more basic research required<br>• Assure high removal efficiencies for target contaminants<br>• Improve measurability of problematic substances<br>• Science should signalise that the technology works<br>• The development status of a technology is an important factor in the technology selection<br>• Text combination of different technologies in order to be able to react to changing regulations [e.g. with regard to target contaminants] | • Request/support more pilot implementations | • Supply information with regard to the composition of the wastewater at specific WWTPs (contaminants present, special industries in their catchment areas etc.)<br>• Openness toward new technologies<br>• Readiness to conduct pilot studies together with research |

| | Barriers | Required from scientific community | Required from administration | Required from operators |
|---|---|---|---|---|
| **Regulatory** | • Utilities are confronted with new challenges and their respective regulations (safety concerning oxygen and ozone etc.)<br>• General regulations such as operation with dangerous substances are clear, there are some uncertainties with regard to insurances<br>• Flexibility with regard to indicators [target contaminants] is positive on one hand, but makes planning more difficult | • Administration needs a decision basis from science to distingish problematic from non-problematic substances and to define thresholds | • Should signalise that the decisions taken are long-term decisions so that investments are save<br>• Early communication of who should be involved with which responsibilities in new projects | |
| **Financial** | • In cases where regulatory pressure is absent, in is prinicpally a matter of financial resources and sources of this funding<br>• Governments usually not willing to fund, unless there is a legal obligation | | • Subventions are a strong driver<br>• Fines [for non-compliance] usually lead to a fast technological upgrade | |
| **Social/cooperation** | • Possible uncertainties and inclarities in the process | • Scientits should be willing and motivated to support with scientific background information, measurement of effects etc. | • Partners such as communes, cantonal and national players should be motivated to engage in the project (financial contributions, adaptations of regulations etc.)<br>• Signalization of interest from administration can have a motivating effect among other stakeholders | • Operators should be willing to test/implement the technology |

## Annex-E Interview results: In-vitro bioassays

An online survey conducted in 2013 aimed to identify the main drivers and possible barriers during the implementation of bioassays at Waternet (further details in Pieron and van der Zouwen 2014). This survey was in 2015 followed by a series of in-depth interviews with experts involved in the case study in different roles and have different perspectives on drivers and barriers. Representatives from various stakeholder groups that are involved in the Waternet case study provided insights in perceived drivers and barriers and expectations between the various groups. We distinguish three groups: the utility (Waternet and Vitens), research and development (Het Waterlaboratorium, KWR), and national policy (RIVM) and results are presented in the following tables.

Table E-1 Expectations of policy makers and authorities to achieve successful implementation of in-vitro bioassays

| Participants' expectations | Comments |
|---|---|
| *Technological* | |
| Formulate basic level of information/knowledge that is required to develop guidelines and standards. | For researchers/developers, in order to know what kind of knowledge/information they should deliver |
| *Financial* | |
| Explore different incentives for water utilities to innovate and invest in innovative monitoring methods and strategies | Explore different options and consider what would be more efficient to facilitate innovation, for example: making the regulations more restrictive OR demand a minimum amount of money to be invested in research and development of water quality monitoring? |
| *Regulatory* | |
| Develop a vision on the future of drinking water quality monitoring standards/strategies | Together with experts and practitioners; existing guidelines (WFD) are old-fashioned and do not represent the state-of-the-art possibilities and newest insights. |
| Train water quality inspection to compare/obtain info on/keep an eye open for innovative monitoring techniques | Although inspection generally only checks whether minimum regulatory demands are being met it would be helpful if extra interventions (such as bioassays) and their performance would also be assessed and compared to each other, to gain an overarching view on potential improvements to the monitoring system. |
| Lobby on the European level | Water quality standards are determined on European level. In order to standardize bioassays for drinking water quality monitoring, it is required that national authorities lobby on the European level. |
| Translate scientific outcomes to guidelines and standards (not regulations) | Research experiments and set-ups need to be translated to standard procedures and monitoring strategies. Policy makers need to cooperate closely with scientists and developers (for a good understanding of the matter) to be able to do this. |
| *Social* | |
| Be open to the potential of innovations | High risks are unwanted in relation drinking water quality, resulting in a conservative attitude in the sector. However, policy makers need to be open to new solutions, such as bioassays, give it a chance, and most importantly: ask questions! |

Table E-2 Expectations of scientific community and technology developers (to achieve successful implementation of in-vitro bioassays)

| Participants' expectations | Comments |
|---|---|
| *Technological* | |
| Translate bioassay measurements to effects for the ecosystem and human health | The toxic effect of a concentrated mixture on cell lines needs to be translated to the effect of the original water sample on humans and the environment. Therefore it is not enough to know the toxic effect, but you need to know which compounds in the mixture cause the effect; therefore a clear link is needed between bioassay measurements and (follow-up) chemical analyses. |
| Develop trigger values that represent toxicity thresholds for water samples | High margins of uncertainty ('soft science'), when does a green light become a red light? |
| Ask utilities which questions still need to be answered | Independent researchers/scientists tend to dive deep into details and forget the big lines that are important to get to implementation in practice; they should thus use utilities as a 'guide' in establishing the research agenda. |
| *Financial* | |
| Initiate research projects on bioassays (in cooperation with universities and other researchers/developers) | Apply for funds (such as NWO in The Netherlands) with consortia that include perspectives from science and practice. This is the only way to develop bioassays in such a way that they are ready for the drinking water market |
| Be clear and realistic about expected results of bioassay research projects and be clear about benefits for utilities and society as a whole. | To prevent disappointment, keep up the enthusiasm at stakeholder groups. Experimentation takes a long time and many resources; funders and co-operators need to understand why this is needed in order to keep financing bioassay research. |
| *Regulatory* | |
| Validate bioassays that are applicable in the drinking water sector | Guidelines can only be developed if the methods and tools are validated. As long as there is no 'standard' it will be challenging to include bioassays in monitoring strategies |
| Explain methods of interpretation | Bioassays as 'soft science', interpretation of measurements is more complex than interpretation of chemical analyses. Policy makers (in utilities and in governments) need to understand this in order to translate them to guidelines and regulations |
| Initiate multi-stakeholder workshops and showcase and share successes, benefits and potential | Showcase and discuss the success and possible applications to policy makers and end users (utilities), to convince them to join activities and share their future visions of monitoring strategies. In this phase of development researchers have most knowledge and might thus be considered the ones to start multi-stakeholder dialogues in order to design joint roadmaps towards implementation |
| *Social* | |
| Explain meaning and implications of 'toxicity' (educate people) | Word has a negative connotation right now among the public. Establish a simple understandable storyline of bioassays. |
| Share information, insights, agendas and meetings with other stakeholders in order to create more 'ambassadors' | It is important that people meet and share. |

Table E-3 Expectations of utilities (to achieve successful implementation of in-vitro bioassays)

| Participants' expectations | Comments |
| --- | --- |
| *Technological* | |
| Share conditions of application with researchers and developers | Price, duration, resources, etc. Utilities should give direction to science to make things applicable. |
| Start demonstration projects (together with researchers) | Start with experimenting with low-threshold (inexpensive and easy to adapt) set-ups. This way it stays easy to understand for lay audiences, such as policy makers. Moreover, if expensive set-ups don't function as expected utilities tend to lose interest. |
| *Financial* | |
| Funding or in kind cooperation in demonstration project | Financial contribution for research projects would be great (if it's important for your operation you should invest as a utility), but in kind cooperation is already very helpful, to make infrastructure and tools/strategies available and jointly develop a showcase/ demonstration project |
| Reach out to other contributors | Labs, assays, etc. Many things are required for research on bioassays. Water utilities should use their network and convince other parties to cooperate in consortia (in-kind for example) |
| *Regulatory* | |
| Express societal benefits of application of bioassays to policy makers | … to emphasize importance of continuing development of technique/method. Raise awareness and increase societal pressure on policy makers/funders to take action and provide support. |
| Active lobby (government) | Actively put pressure on institutions and emphasize the importance of new developments and their regulatory requirements, to get the attention of policy makers. |
| *Social* | |
| Have a more innovative mindset | Be open to changes; don't fear that new methods and new insights in the water quality lead to negative public opinion or fear. Better to know toxic effects now than never. And it is possible to explain it (not if monitoring is possible now but you stick your head in the sand and don't do anything while it would have been possible looking backward) |
| Be an ambassador | If utilities are enthusiastic about bioassays, they should be an ambassador and spread the message to other utilities and stakeholder groups (policy makers, society, etc.) |
| Share insights | Share insights as a 'public good', don't keep them to yourselves |
| Develop a communication strategy | … that helps you to explain your monitoring outcomes/toxicity effects and implications to the general public. Prevent public fear, negative public opinions, etc. |

Table E-4 Expectations from workshop participants with regard to joint actions

| Participants' expectations | Comments |
| --- | --- |
| Don't blame each other, but take responsibility and action! | Stakeholder groups can and should not blame each other for not taking action with regard to bioassay development and implementation, because it's everyone's responsibility to take steps. The only way is to join forces, stick together, cooperate. |
| Develop a shared vision document | Develop a shared vision on the future of drinking water quality monitoring standards/strategies |