Advanced processed wastewater for different uses: constellations favouring future implementation of a multimodal water reuse concept

Engelbert Schramm, Dennis Becker and Michaela Fischer

ABSTRACT

Advanced wastewater treatment is often used to produce one single water quality. In recent years, technologies have been developed that allow the production of different qualities that are fit for their purpose. These technology bundles are still not being marketed, and market requirements are unclear. Two constellations in West Basin, California and in Oman were analysed to shed light on the different constellations of actors, resource situations and institutions. The first led to the industrial reuse of several water qualities, while the second produced an application in holiday resorts, leisure and food production. A hypothetical solution was contrasted with an historical case. The analysis of the constellations showed that multi-sectoral investments and dependencies require strong cooperation arrangements and long-term agreements. Governmental institutions were revealed to be suitable for coordinating the process, especially during the initial phase, but also in view of security of supply. A (comparative) examination allows an initial, still provisional systematic overview of other constellations that favour systems with recycled water of different qualities. Further research is required to understand the welfare and distribution effects of multimodal water pricing policies and the feasibility of co-financing of agricultural irrigation and opportunities for more sustainable water reuse.

Key words | advanced treatment, agriculture, industry, tourism, water reuse

Engelbert Schramm (corresponding author)
Michaela Fischer
ISOE – Institute for Social-Ecological Research, Hamburger Allee 45, 60486 Frankfurt am Main, Germany
E-mail: *schramm@isoe.de*

Dennis Becker
DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V,
Theodor-Heuss-Allee 25, 60486 Frankfurt am Main, Germany

HIGHLIGHTS

- Application of a constellation analysis to find out the conditions for advanced treatment and supply with two or more water qualities.
- Introduction of the concept of multimodality.

INTRODUCTION

Water reuse can support 9 of the 17 Sustainable Development Goals: zero hunger, good health and well-being, clean water and sanitation, decent work and economic growth, industrial innovation and infrastructure, sustainable cities and communities, responsible consumption and production, life below water and partnerships for the goals.

Advanced treatment was initially developed for a small number of high-value water reuse applications, in particular groundwater recharge and drinking water production (Rizzo *et al.* 2019). For most applications, simpler treatment processes were initially considered sufficient. In the past, treatment was very simple, especially for agricultural applications; in many cases, secondary wastewater treatment with additional hygienisation is still considered sufficient (see European Union 2020). However, examples from many countries now show that such simple wastewater

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treatment can lead to environmental damage such as groundwater pollution, for example through the emission of environmental chemicals and anthropogenic micropollutants, especially contaminants of emerging concern (CEC, e.g. endocrine disruptors; Seis *et al.* 2016). Such long-term consequences are considered unacceptable in sustainability assessments (Kennedy & Tsuchihashi 2005). Accordingly, efforts are being made, such as advanced water treatment that includes further process stages (Kennedy & Tsuchihashi 2005; Drewes *et al.* 2019). These innovations potentially increase the range of sustainable applications for water reuse. In addition to agricultural irrigation, it can also be used for livestock breeding, for irrigating tourist facilities and public green areas, and for a variety of industrial, commercial and domestic purposes (Drewes *et al.* 2019).

In many cases, advanced treatment has so far only been applied to produce a single water quality. In view of the numerous possible applications, however, it is also conceivable that the wastewater treatment plant (WWTP) effluent is treated to produce different qualities for various uses. The provision and supply of different water qualities, which are used for different purposes, are abbreviated here as multimodal. Multimodal supply is the (usually simultaneous) supply of water of varying quality, which is differentiated and usually carried out using different transport carriers (usually pipelines). Accordingly, multimodal water use refers to the use of several separately transported water qualities (usually) for different purposes.

To date, systematic investigations of constellations that favour treatment and distribution systems with recycled water (in different qualities for various purposes) have not been carried out. The aim of the research was to identify promising examples of multimodal reuse of water in order to draw conclusions about the possibility of targeted dissemination of technologies to support sustainable water reuse.

The application of constellation analysis (CA) allows the identification of methods for introducing the advanced and multimodal treatment technologies tested in the MULTI-ReUse project, which can reduce the risks both to human health and the environment. The research questions were:

- What are the (existing) constellations for water reuse of different water qualities where advanced treatment is appropriate?
- Which aspects promote their realisation and sustainable operation?

The identified cases were examined using CA to assess whether they lead to a sustainable solution.

METHODS AND MATERIALS

The CA concept

The method used in this paper is based on CA, as explained by Schön *et al.* (2004). CA was developed to analyse and solve complex problems involving social, technical and natural aspects that are closely interlinked. Furthermore, CA claims to bridge prevailing problems in interdisciplinary settings and to integrate practical and scientific knowledge of various disciplines and societal groups (Ohlhorst & Schön 2015). Elements of the constellation are heterogeneous – individual or collective actors as well as technical norms and laws, technical objects and natural resources. Each of these element types is treated as equally important in the CA; the elements can either be the components of a specific problem situation or parts of a solution. It is possible to identify promoting and hindering factors of innovations, and a special feature of CA is the visualisation of the constellation, which helps to identify networks, dynamics and the relationships between the elements. Conventional water reuse is analysed in Nölting & Mann (2018). The process can be summarised in the following steps:

- identification of the elements of the constellation and description of their relations,
- analysis of the functional principles and characteristics of the constellation under consideration, including the identification of destabilising and stabilising elements,
- examination of the dynamics in the constellation and its development and
- evaluation of the constellation and strategy making (optional).

The CA was applied in an interdisciplinary research process in which competencies from ecology, engineering (from water management, agriculture and chemical engineering, landscape planning) and social sciences were used. Thus, the knowledge considering the elements and their relationships could be drawn from various scientific fields and combined with practical knowledge.

Broad expertise and the graphically based design procedure of CA allow a quasi-experimental optimisation and stabilisation of constellations in its development process. Thus, it is possible to simplify or improve the constellation, e.g. by omitting or replacing actors or by changing relationships and incorporating technical innovations. Inhibiting factors (e.g. acceptance problems of traditional farmers) can also be changed by focusing on new products and sales markets.

Concept application

In this paper, constellations of two different cases are considered and evaluated. The cases describe examples of water reuse in different sectors, which are applied in practice in the fields of industry, agriculture, tourism and landscape irrigation. The first case has its starting point in the constellation that led to the reuse of different water qualities by industry in California's West Basin district in 1994. The second case deals with the water reuse in the Arab peninsula and analyses so far hypothetical applications in aquaculture, tourism and landscape.

Based on an initial market analysis for the MULTI-ReUse methods (Becker *et al.* 2017), typical problem situations were identified and described. In an interdisciplinary group process, several cases were discussed with the aim of identifying the benefits of providing different water qualities and highlighting bottlenecks for sustainable development. For different cases (an industrial application and an agricultural and domestic application), a situation was selected that is as conducive as possible in order to present possibilities that favour advanced water reuse and where the financial feasibility of the supply of different water qualities can be assumed.

THE MULTI-REUSE CONCEPT

The MULTI-ReUse process produces three different, precisely defined water qualities from a base product of municipal wastewater already being conventionally treated. The water is processed further either at the same treatment plant or at its site of use (cf. Nahrstedt *et al.* 2020). Thus, no raw wastewater is used, but rather the effluent from the WWTP. Due to its orientation towards user requirements, it can be seen as a fit-for-purpose approach. In the production process, which is quality-assured using specific monitoring procedures, certain modules of an advanced water treatment system are used according to the defined quality. The MULTI-ReUse process also includes observation of the microbiological quality of the treated water, which is close to real-time control. The process has been tested since 2018 in a trial and demonstration plant (pilot plant) at the Nordenham WWTP by the MULTI-ReUse consortium. There, the following qualities were produced, including side by side if required (cf. Nahrstedt *et al.* 2020).

- Process water 1 is practically free of undissolved substances and pathogenic bacteria, but still contains nutrient salts and CEC. The water can be used industrially for washing processes (e.g. for street cleaning) or for cooling processes with low requirements (e.g. for the concentration of dissolved salts). It can also be used for domestic applications (e.g. toilet flushing and washing machine) and for irrigation of urban greenery and energy and industrial plants. However, the nutrient content may affect water storage and distribution (which needs to be considered during the operation of the plants).
- Process water 2 is practically free of undissolved ingredients and pathogenic bacteria and viruses. The concentration of nutrients is considerably reduced compared with process water 1 (this increases the microbiological stability of the water, i.e. less microbial regrowth during storage and distribution). It also contains significantly fewer CEC of anthropogenic origin. The water can be used for industrial washing or cooling processes with higher quality requirements, as well as for high-quality agricultural applications (e.g. underground irrigation of fruit and vegetables for human consumption and supply of livestock) or for groundwater recharge.
- Reverse osmosis (RO) water (process water 3) is free of particles and pathogenic germs, and ions and macromolecules (e.g. CEC) dissolved in the water are removed as far as possible by RO in further process steps. This highly treated water can, therefore, be used in a wide

range of applications as process water, e.g. as boiler feed water, for the production of ultrapure water or as mixed water for dilution purposes. However, the low ion concentration and free carbonic acid cause the water to have a corrosive effect on certain metallic materials, which should be compensated for by suitable materials during water storage and distribution (alternatively, the water can be adjusted by buffering and pH correction). In comparison with the other two water qualities, a maximum of microbiological stability is also achieved (cf. Nocker *et al.* 2020). RO water is used in industrial processes and agriculture, for example, especially in greenhouse horticulture.

MATERIALS USED FOR THE CA

Oman and California were selected because of the advanced water treatment and water reuse in both countries. Furthermore, there is good availability of information in English in both cases. Different sources of information were used to understand developments and the current situation with regard to water reuse in California and Oman.

In the case of California, droughts and early institutional developments (West Basin Municipal Water District established in 1947) created an early case in advanced water reuse, which is well documented. The CA was based on scientific and online information. The most detailed and comprehensive information is presented in the website of the West Basin Municipal Water District (https://www.westbasin.org). One of the main scientific sources was Lazarova *et al.* (2012).

With regards to water reuse in Oman, there is an abundance of scientific publications, especially on technologies for different water reuse applications. Furthermore, information was supplied by institutions in the water sector in Oman. Haya Water in particular provides detailed information on their website about the technology currently used and the challenges of water reuse. Moreover, policy documents and interviews in professional magazines and newspapers were used to understand historical developments and current challenges. An analysis of the water sector in general, and of trends and investments can also be found on websites such as German Trade and Investment. Furthermore, scientific and online information on agriculture and tourism was used for the analysis.

RESULTS

CA: supplying industries with different water qualities

The United States was chosen because it is one of the world's pioneers in water reuse and there is good data availability. It is an example of an industrialised country where industrial water reuse plays a remarkable role. Experiences from Northern America can be transferred to similar environments on a global scale, such as Europe, Mexico, China, India and the Middle East (particularly, the member states of the Gulf Cooperation Council) (Becker *et al.* 2017).

Preconditions and framework analysis

The United States, with an area of approximately 9.06 million km², is the third largest country in the world. Due to the enormous size of the country, the population density is relatively low at 33 inhabitants per km² (BMWi 2018), despite a population of more than 321 million (as of 2016). In some states, the increased salinity in aquifers and surface waters poses a serious water quality problem. The steady increase in salinity is a result of excessive irrigation and increasing urban water use. In California, the biggest salinity problems are in the aquifers in the southern Central Valley and the Salton Sea. There is currently no sign of a slowdown in the trend (BMWi 2018). Further saline inputs to groundwater are via saltwater intrusions in coastal areas.

Economy and legal framework

The US water sector generates annual revenues of more than US$ 157 billion (as of 2015) and, with average growth of about 4%, is one of the promising future markets for global investors and new water-related technologies. The market is influenced by various external factors such as regulations or the financing instruments offered, resulting in a state of constant change in the water sector (Water Technology 2016). Water abstraction law in the USA is regulated very heterogeneously due to the size of the country. In the east and mid-west of the country, most states apply the Riparian Law, which links water abstraction to land ownership. The person who owns the land with the water source may use the water within reasonable limits. What is meant by reasonable use, however, remains a matter of interpretation and, in case of doubt, will be decided by the competent courts. In some countries, water abstraction also requires a permit from the competent environmental authority. In the western states, on the other hand, the Prior Appropriation Doctrine is predominantly represented. According to this legal text, the use of water for the benefit of the general public (Beneficial Use) enjoys priority. Water abstraction is, therefore, independent of land ownership. In California and the other remaining states, aspects of both systems are combined into a hybrid system (BMWi 2018). At the federal level, there are also numerous laws and executive orders that specify the practical implementation of environmental laws. The 'Clean Water Act' and the 'Safe Drinking Water Act' are the two most important laws in the area of water quality and wastewater treatment. The Office of Water (BMWi 2018) is responsible for implementing these two laws. The Clean Water Act regulates all wastewater discharged into US waters and sets pollutant limits and quality standards for surface waters. The Safe Drinking Water Act exists to protect drinking water and applies equally to groundwater and surface water used for drinking water production. Plant operators have to comply with it. However, the introduction and enforcement of these laws is the responsibility of the individual states and heavily dependent on environmental and industrial influences (BMWi 2018). In addition, there are separate guidelines and standards at the state level for the use of recycled wastewater. The pioneer in this case was once again the state of California. California's legal regulations on this are more detailed than all previously enacted laws and regulations, and serve as the basis for a large number of water reuse projects (Becker *et al.* 2017). California's Regulations related to Recycled Water, Title 22 of the Code of regulations, Title 22, Division 4, Chapter 3, include four water types for water reuse (Becker *et al.* 2017).

Water reuse as a challenge

The West Basin Municipal Water District is a water agency that provides imported drinking water to 17 cities (and unincorporated areas) in Los Angeles County. The agency was created by a vote of the people in 1947 to reduce local groundwater over-exploitation and to make local water supplies more reliable (e.g. by groundwater recharge). In 1948, West Basin became a member agency of the Metropolitan Water District of Southern California and began wholesaling imported water from the Colorado River, and later also from Northern California (Lazarova *et al.* 2012).

West Basin is the sixth largest water district in the State of California and serves a population of more than 900,000 people. The West Basin service area consumes 271 million km^3 of water annually. The managed aquifers are near the Pacific Ocean. Due to the abstractions, saltwater intrusion was occurring here as early as the 1940s.

By 1947, it had become apparent that concentrating water extraction on (desalinated) seawater (and supporting the groundwater by infiltration) was too expensive compared with importing water from other basins. It was only the differentiation by type of use that made it possible to identify industry as a priority customer for reclaimed water. During the 1976/1977 drought, a water conservation programme was implemented; regional industry was very active in reducing water use, and the West Basin's Board of Directors discussed the possibility of using secondary treated wastewater from the Hyperion Treatment Plant in Playa del Rey for industrial use. The nearest industrial user to this plant was the Chevron refinery in El Segundo. Initial consideration was given to water reuse for Chevron's cooling towers in 1978, and a pilot programme was launched (Joham 1978).

Description of the constellation

In the major drought of the late 1980s and early 1990s, West Basin's Board of Directors led the agency in developing alternative local water supplies that included water recycling for industrial use and landscape management. Industrial applications were seen as the main applications; in terms of volume, applications with seawater intrusion barriers and landscape irrigation (which were actually the agency's objective) were secondary (Lazarova *et al.* 2012). An overview of the constellations of actors, resources, legal constraints and technical solutions in the California West Basin is given in Figure 1.

The West Basin Municipal Water District is the key actor in this constellation, along with the facility manager and operator (SUEZ) of the Edward C. Little Water Recycling Facility (ECLWRF), and the following three satellite treatment facilities:

- Carson Regional Water Recycling Facility (CRWRF),
- Chevron Nitrification Facility (CNF) and
- ExxonMobil Water Recycling Facility (EMWRF).

The City of Los Angeles' Hyperion Wastewater Treatment Plant (HWWTP) is currently the sole source of supply for West Basin's treatment facilities and recycled water systems. ECLWRF is the only treatment facility that receives secondary treated wastewater effluent as supply from the HWWTP. The satellite facilities rely on water from ECLWRF as a supply source, which produces tertiary water (Title 22) for them as well as stabilised RO water for the West Coast Barrier Blending Station for the barrier for seawater intrusion (Lazarova *et al.* 2012). CNF further treats Title 22 recycled water received from the ECLWRF through a biological nitrification process to remove ammonia for cooling water tower application. EMWRF (XOM) further treats Title 22 recycled water through biological nitrification and microfiltration (MF)/RO processes for use at the ExxonMobil Refinery in Torrance. The water produced is used for cooling tower and boiler feed applications. CRWRF further treats Title 22 recycled water through MF/RO and biological nitrification, before it is blended and sent to the BP Refinery in Carson for industrial use.

ECLWRF and the three satellite facilities produce five different qualities of recycled water (Lazarova *et al.* 2012):

- tertiary water (Title 22) for a wide variety of industrial and irrigation uses,

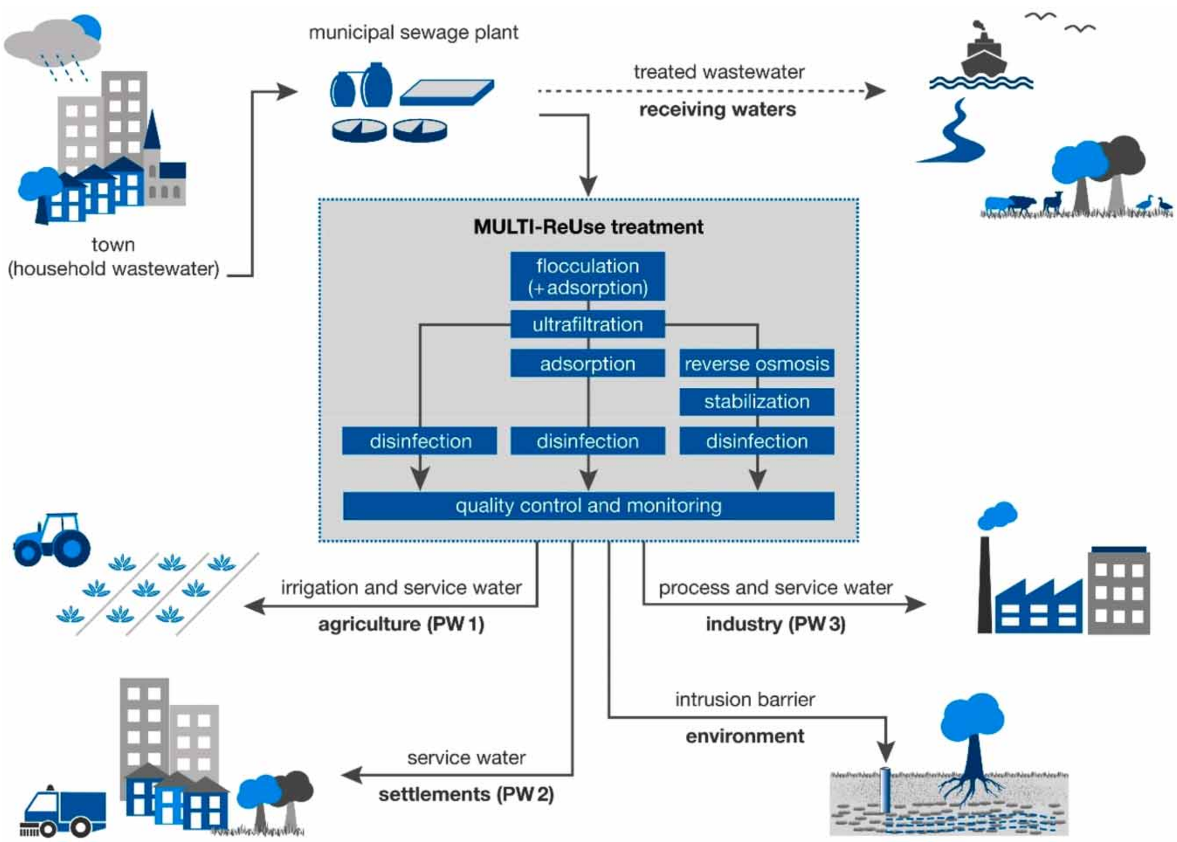

Figure 1 | Process diagram of the MULTI-ReUse-treatment technologies and applications (adapted from Becker *et al.* (2017)).

- nitrified water for industrial cooling towers,
- pure RO water for refinery low-pressure boiler feed water,
- ultrapure RO water for refinery high-pressure boiler feed water and
- barrier water or stabilised RO water.

Regarding the use of the recycled water from ECLWRF, the majority (53%) goes to industrial supply, while the seawater intrusion barrier uses 36%, landscape irrigation 10% and mixed use 1%.

Key milestones of the constellation are as follows (Lazarova *et al.* 2012):

- West Basin launched its water recycling programme in the mid-1990s.
- Contractual obligations with the industry to be supplied and the operation of the recycling facilities (by SUEZ) led to a public/private partnership.
- West Basin has invested more than $500 million dollars in this programme.
- Daily production capacity is 150,000 m^3/d (SUEZ group 2020) and in 25 years has produced 750 million m^3 of recycled water – every cubic metre recycled is a water volume not imported from Northern California or the Colorado River.
- The water is used for various purposes such as refinery cooling towers and boilers, street cleaning and irrigation.

The California Department of Public Health (DPH) issued the California Wastewater Reclamation Criteria (Title 22 regulations) in 1978. The department controls compliance and has not been a fundamental veto player against water reuse.

An example is given below of a typical communication and decision process among industrial customers in their switch from imported water to the use of recycled water at ECLWRF:

- contact made between West Basin and customer,
- basic information is exchanged – potential use and amount of recycled water/role of West Basin in the process,
- determination of the feasibility of West Basin serving the site,
- determination of interest by customer,
- development of drawings of retrofit based on customer plans,
- determination of feasibility for customer conversion,
- submission of plans to the California DPH for review,
- site inspection prior to construction by DPH,
- retrofit construction with ongoing inspection by DPH and West Basin, completion of retrofit construction and final inspection by DPH including cross connection testing and
- after approval by DPH, completion of conversion by connecting recycled water.

Although customers have unique needs, it has been possible to meet them with only a few classes of water produced, and tertiary water (Title 22) representing the majority. The satellite facilities treat the tertiary water (Title 22) further for the specific purposes of industrial partners. The so-called barrier water or stabilised RO water produced by ECLWRF, a secondary treated wastewater purified by MF and followed by RO and disinfection, is used as a seawater intrusion barrier. For most applications, MF is coupled with RO. The key advantages of this double membrane system are considered to be highly efficient in CEC removal and desalination (Lazarova *et al.* 2012).

ECLWRF in El Segundo, California, is nowadays one of the largest and a well-known example of water recycling facilities with advanced treatment in the United States. Its five different types of water, which are conditioned together with the three satellite facilities, meet the needs of the industrial, commercial and municipal customers of the West Basin Municipal Water District. One of the main keys to success in this example was the willingness of local leaders to diversify water resources in partnerships with federal and local authorities and operate the plant with public–private partnership integration (Lazarova *et al.* 2012).

When departing from the historical course, the question can be addressed in the CA as to which stage of development the Californian constellation favoured multimodal water reuse. The technical possibilities of the MULTI-ReUse procedure were used for this investigation. An overview of a hypothetical favouring constellation of actors, resources, legal constraints and technical solutions in the California West Basin is given in Figure 2.

With the West Basin Municipal Water District, a very strong actor was already created in the 1950s that was

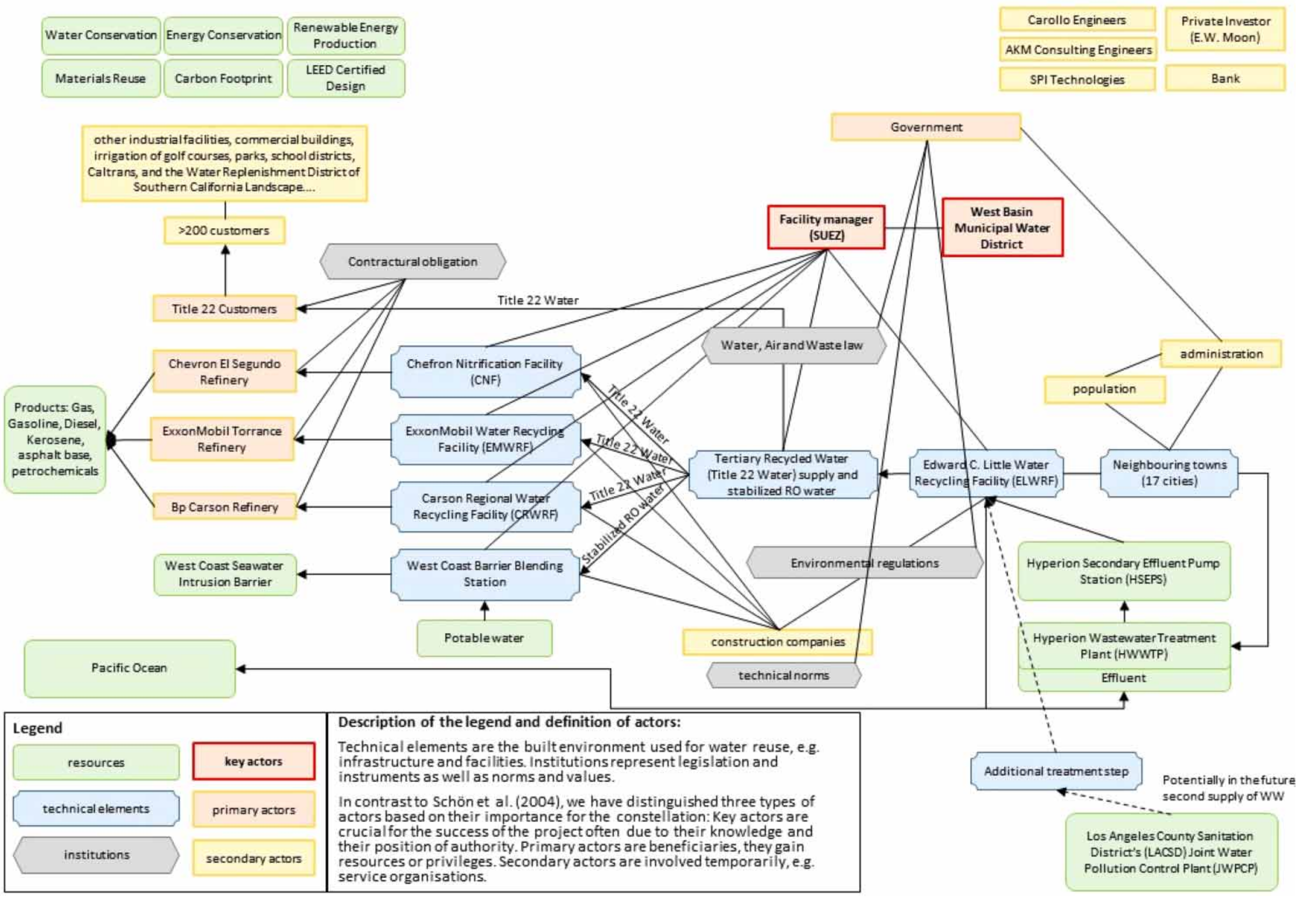

Figure 2 | Constellation of actors in the Californian West Basin 1994, illustration is based on information from https://www.westbasin.org and Lazarova *et al.* (2012).

able to promote water reuse. At the end of the 1970s, it became clear that there were potentially different groups of customers and uses, including industry, agriculture and groundwater protection. Different water qualities were needed side by side to supply them. Recycling capacities could only be established after the demand was contractually guaranteed. Due to the distances to the treatment plant, one option could be to initially treat the water only to PW 1 quality and to process it to higher qualities only in the vicinity of the customers. If several qualities are transported in parallel in different pipelines, these satellite facilities could only be used for quality control and disinfection. By mixing water from the PW 2 and PW 3 treatment lines, other wishes of industrial customers can also be satisfied. By mixing water qualities PW 2 and PW 3, the intrusion barrier is no longer dependent on the addition of tap water, which means less water has to be brought into the area from outside.

Assuming sufficient quantities of wastewater, it is technically possible to supply all interested parties with water of a higher quality than tertiary treatment effluent. For applications where this water enters the soil (and possibly also contributes to groundwater recharge), this water is preferable to Title 22 water. Its use can also be recommended for healthcare reasons. Due to methodological limitations, it is not possible to investigate in the CA whether all customers would agree to a corresponding payment for better quality. Should a large number of these users decide to use conventionally treated wastewater, it is nevertheless possible to opt for multimodal water use due to the industrial customers (Factories 1–3) and the importance of intrusion prevention.

CA: MULTIMODEL SUPPLY OF TOURIST AREAS, AGRICULTURE/AQUACULTURE AND LANDSCAPE

Oman was selected as a potential country for multimodal purpose water reuse for several reasons, explained below. Beneficial for the analysis was good data availability and the possible transferability of the results to other countries in the Arabian Peninsula.

Preconditions and framework analysis

The Sultanate of Oman covers the south-eastern corner of the Arabian Peninsula. With the exception of the humid Dhofar region and some mountains, the climate is arid or semi-arid. Potential evaporation varies between 2,200 mm/year in the interior and 1,660 mm/year on the southern Salalah plain (FAO 2008). Rainfall in Oman can exceed 350 mm/a in the mountains and is less than 50 mm/a in the desert, in the foreland the average is 100 mm/a (Lehane 2015).

Oman is a high-income country and its economy is heavily depending on oil production; other important sectors in terms of GDP are tourism, shipping, mining, manufacturing and gas-based industries (The Heritage Foundation 2019). Agriculture, forestry and especially fishery are traditional activities, but account for only 1.3% of the GDP (FAO 2017). Economic growth in Oman is estimated to be slowing down, and diversification investments to reduce dependencies will lead to growth in the medium term (World Bank 2019). Oman has a population of 4.4 million people, with half of the population living in densely populated areas in the north of the country, mainly in al-Batinah and Muscat (FAO 2008). Due to a rural-urban shift, only 21.5% of the population lives in rural areas (FAO 2017), with 16% of the population employed in the agricultural sector (Kotagama & Al-Farsi 2019).

Most of the farmers run small farms with low technology, while 0.2% of the farmers account for 21% of the land and have modern technologies and access to markets (FAO 2017). Only 7% of the total area (22,000 km^2) is suitable for farming; an additional 14,000 km^2 are suitable, but less productive (McDonnell 2016). Currently, 680 km^2 are used for agriculture (McDonnell 2016), which is located mainly in the northern part of the country. Agriculture is based on irrigation: as well as dates, bananas and limes, vegetables (eggplants, carrots and tomatoes) and cereals are also produced. With the number of greenhouses in Oman increasing steadily in recent years, supported by the Ministry of Agriculture and subsidies as a climate change adaptation strategy (Choudri *et al.* 2013), further research has been done on cooling technologies, water supply and energy consumption to increase the sustainability of greenhouse production (Mendoza 2019). Oman's fishery is the largest producer in the region, with fish farming, currently rather small, supported by the government, e.g. by Fish Farming Centres and Fisheries Training Centres. Furthermore, there is potential for increasing the value of the products from agriculture and fisheries (FAO 2017).

Water supply and sanitation

Water supply in Oman is mainly provided by groundwater (83%), with most of it used for agricultural production (Haya Water n.d.). Over-extraction leads to declining groundwater levels and saline intrusion in coastal aquifers and on many farms. The area of extreme degraded land almost doubled between 2005 and 2010 (from 34,385 to 65,595 ha) (Al-Balooshi & Charabi 2012). Water reuse has been supported by national policy since 2000 (McDonnell 2016), and according to the Oman Salinity Strategy (MAF & ICBA 2012), the use of treated wastewater for irrigation is suitable to protect the land from degradation. Al-Batinah, the 250-km-long narrow coastline on the Gulf of Oman between Muscat and Suhar, is a fertile, frequently irrigated plain whose groundwater is fed by the gorge-like wadis from the Oman Mountains, which only occasionally carry water. The region, which traditionally exported dates and dried lemons, has developed a great deal of water-intensive horticulture along the coast, which has reached its limits. Meanwhile, the demand for groundwater is so great that plans are being made to ensure irrigation by seawater desalination.

Haya Water is the public wastewater service company, which started in 2005 in Muscat and by 2014 had taken over WWTPs and infrastructure of the entire country from the Ministry of Regional Municipalities & Water Resources. Currently, Haya Water is 'rebranding as a water reuse company' (Freyberg 2018) and has prepared a master plan for the reuse of treated water in Muscat in order to increase water reuse in the different sectors (Haya Water n.d.).

Investments in sewage infrastructure, such as WWTPs, have been focusing on urbanised areas and around 50% of Muscat's inhabitants are not currently connected to the sewer system. For Muscat, the aim is to connect 80% of the households (National Water Sector Master Plan), and this is expected to be accomplished by 2026 (Freyberg 2018).

Haya Water has started to build a network for the distribution of treated wastewater in the north of the country in the Muscat and al-Batinah region. As of 2018, 230 km of the distribution network for treated wastewater was completed (Espey 2018). As well as palm trees, parks and district cooling in Muscat (Freyberg 2018), four golf courses, sport stadiums and five farms are also supplied with the irrigation water. The Ministry of Agriculture supports these farmers by providing modern irrigation systems, financial support for water fees and advice on crop cultivation.

Currently, two different qualities of irrigation water are produced in Oman (Table 1):

1. irrigation water for fodder, cereal and seed crops, vegetable consumed after cooking, etc. as well as pastures (Standard B)
2. irrigation water for vegetables and fruits likely to be eaten raw, as well as public parks, lawns and recreational areas (Standard A).

Table 1 | Quality standards for vegetables and fruits likely to be eaten raw, etc.

Parameter Max. allowable limits	Standards A (mg/l)	B (mg/l)
Biochemical oxygen demand (BOD)	15	20
Chemical oxygen demand (COD)	150	200
Suspended solids (SS)	15	30
Total dissolved solids (TDS)	1,500	2,000
Electrical conductivity (EC) (μs/cm)	2,000	2,700
pH (within range)	6–9	6–9
Chloride ion	650	650
Ammoniacal nitrogen	5	10
Nitrate	50	50
Organic nitrogen (Kjeldahl)	5	10
Phosphorus	30	30
Sodium	200	300
Sulphate	400	400
Faecal coliform bacteria (per 100 ml)	200	1,000

Note: (A) and other crops, etc., (B) according to the Regulation for wastewater reuse and discharge, MD 145/1993 (MRMWR 1993).

Current problems in Oman for water reuse

Market for water reuse: One of the main challenges facing Haya Water is finding customers to utilise the irrigation water. Farmers do not want to pay for it since traditionally the groundwater was free of charge (Freyberg 2018) and electricity is subsidised (McDonnell 2016). Currently, an excess amount of treated wastewater is discharged into the marine environment, as there is no optimal water reuse but only 52% demand.

Health risks: Technology and skilled labour are required to increase the safety of water reuse (Haya Water n.d.). Little research has been done so far on the health and environmental risks connected to water reuse (Al-Riyami *et al.* 2018). Sampling of treated wastewater in Muscat shows compliance with Omani standards (COD, BOD, pH, EC, turbidity and total suspended solids (TSS)), however 'such a reuse application of wastewater treatment needs to comply with public health and environmental requirements, both locally and internationally' (Baawain *et al.* 2019). Studies by Al-Farsi *et al.* (2018) indicate that in Oman, frequently consumed pharmaceuticals remain in tertiary treated wastewater, which can accumulate in the soil and plants if the water is reused for irrigation.

Public acceptance: The public has general understanding of water treatment technologies and supports the idea of water reuse; however, there are concerns with regards to health and environmental risks. A survey of 115 people showed that Omanis have a general idea of wastewater treatment technologies and are very positive about irrigation of non-food crops and different green spaces or urban uses such as cooling, fire hydrants and toilet flushing (Baawain *et al.* 2019). Irrigation of edible crops was not preferred by 49%, somewhat preferred by 23% and well preferred by 28%. In addition, the discharge of the treated effluent into the marine environment was not preferred by 50% and only well preferred by 9%. According to Baawain *et al.* (2019), this reflects environment and health concerns and the wish to protect the environment.

Financing: The need to increase the cost efficiency of operations and find investments for technology includes the search for international partners for investments, but also for possible partnerships (Freyberg 2018).

Description of the constellation

For Oman, water reuse has been under discussion for some time; there is a high level of acceptance, however, for the irrigation of edible crops, but there are concerns among the public. Where there are sewer systems in Oman, 98% of the wastewater is already reusable in terms of treatment technology. So far, corresponding efforts have been made for the capital Muscat in particular.

Just a few years ago, Oman was a country for adventurous individual travellers, but in the meantime, state-sponsored tourism has developed that meets international standards. In the last ten years, some government plans have been postponed to develop large areas for high-quality tourism, in particular to build extensive hotel complexes in the northern coastal region (e.g. Al Madina A'Zarqa).

Nevertheless, demand in the area of superior individual tourism (diving, snorkelling and fishing) is growing strongly. It can, therefore, be assumed that there will be an increasing number of private initiatives. These initiatives offer windows of opportunity to construct sewerage and wastewater treatment plants at the same time, and to protect the sensitive coral reefs and fishing grounds. An overview of a hypothetical favouring constellation of actors, resources, legal constraints and technical solutions is given in Figure 3.

If the water is treated according to the MULTI-ReUse process (cf. Figure 4), it can be reused for various purposes. In hotels, this water can be applied for garden irrigation and toilet flushing (PW 1), but also to produce fruit, vegetables and fish for tourism and local needs (PW 2). PW 3 is the highest quality, as after ultrafiltration, RO is also applied. This water is suitable for hydroponic greenhouses, where

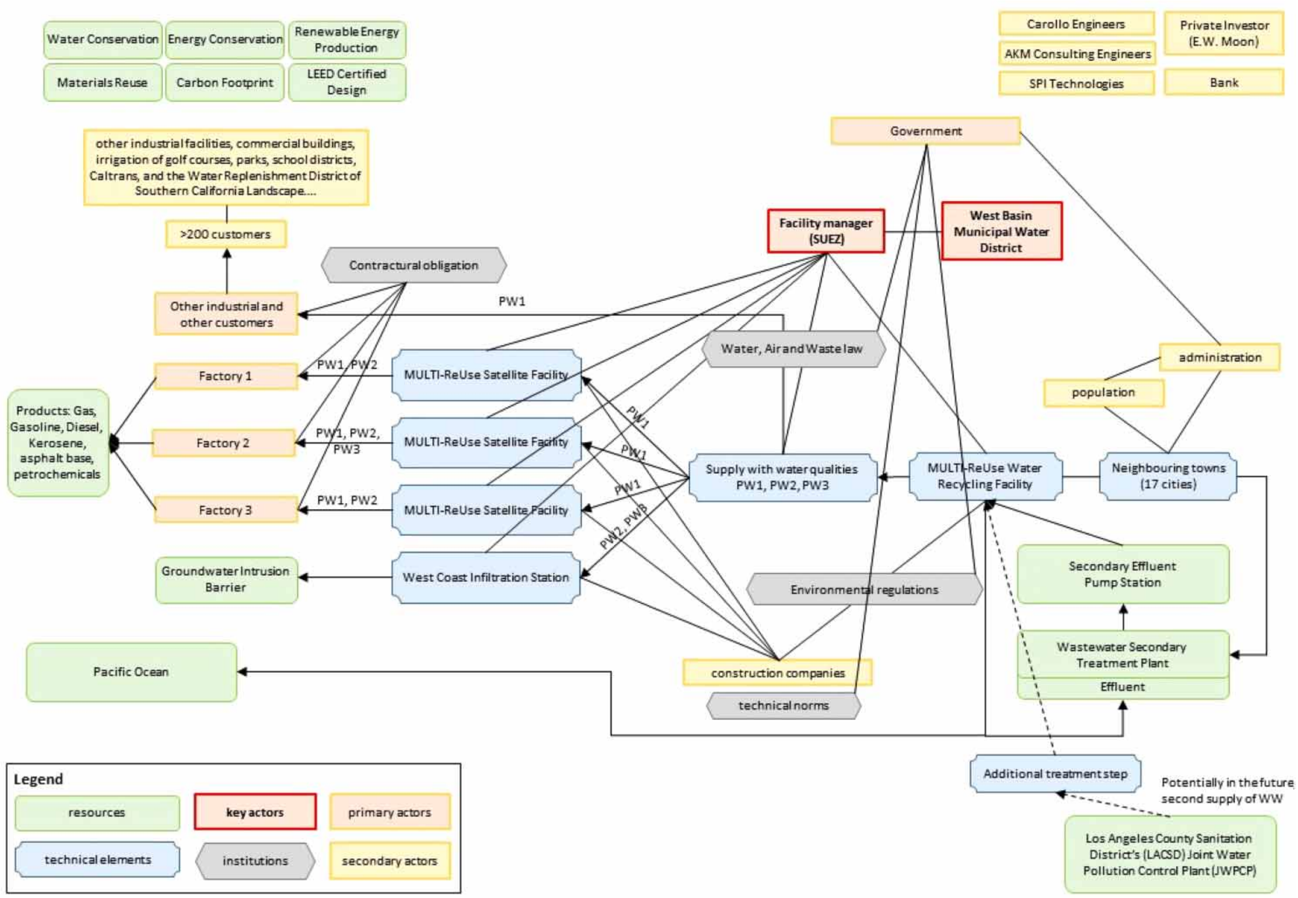

Figure 3 | CA of hypothetical industrial and other water reuse in California (for definitions of legend and actors cf. Figure 1).

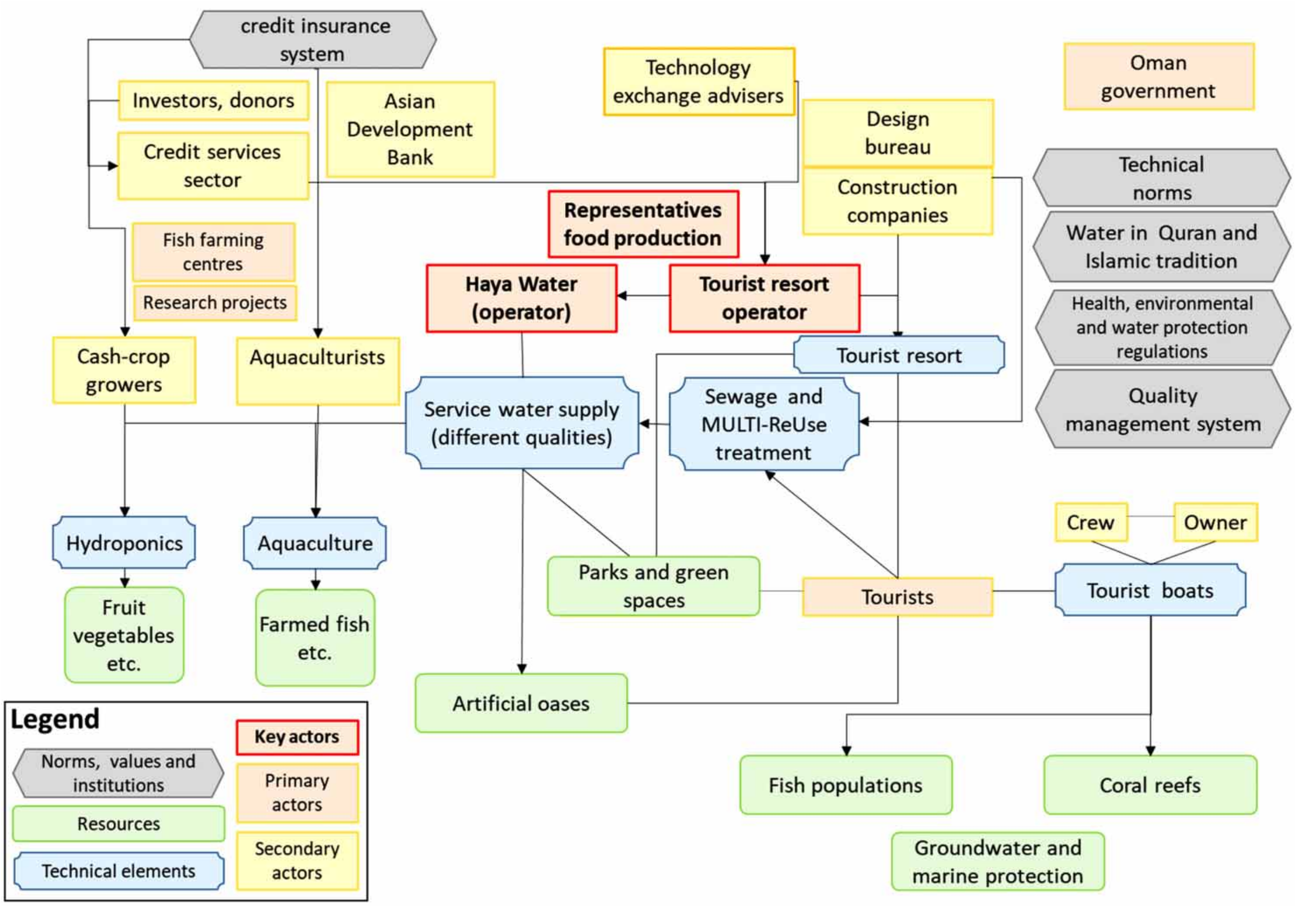

Figure 4 | CA of hypothetical rural water reuse with tourist resorts and food production in Oman (for definitions of legend and actors, cf. Figure 1).

salinity in the irrigation water can be reduced by mixing it with PW 3. The occasional use of RO water for the dilution of secondary treated wastewater for agricultural irrigation is also suggested by Bunani *et al.* (2015). Moreover, water for the pool can be produced with the help of PW 3. Multimodal water reuse can, therefore, be developed here.

When planning new tourist spots and green areas in water-scarce regions, the water infrastructure should be the starting point. Since different water qualities are supplied to different water users, the location of buildings and facilities should be based on treatment and supply of water, otherwise construction, maintenance and pumping might increase costs tremendously.

Wastewater must be treated and discharged in such a way that the sea is not polluted. After all, this is the main attraction for scuba divers and snorkelers in the coral reefs and for fishing tourists. At the same time, the hotel sector also requires high-quality fruit, vegetables and meat, preferably from locally controlled production. Given the scarcity of water, it is also necessary to irrigate oases.

For this, a certain constellation of actors must be available and willing to cooperate under a shared vision. As Haya Water is currently '… rebranding as a water reuse company …' (Freyberg 2018), they would be key actor and most suitable for guiding the coordination process between the different actors (see CA (Figure 3) for an overview). Next to Haya Water, the operator of the tourist resort and representatives of aquaculture and horticulture are also key actors. An institution that has been formed in Oman to support aquaculture is fish farming centres. Moreover, research and support for agricultural production such as horticulture comes from universities and government institutions. Aquaculturists and horticulturists with interest in cash crops might be suitable partners representing primary actors, alongside technology exchange advisers, design bureaus and construction companies who are secondary actors in the constellation.

One possible option to start and succeed in this process of knowledge exchange and negotiation during the initial phase of the project is to set up a board, e.g. chaired by a member of Haya Water, since the different competences for water reuse should be merged here. Joint decision-making on the board can include planning processes for the location of the different buildings, the quality assurance system and arrangements necessary for the supply chain. Tourist and leisure facilities include hotels and numerous (artificially created) palm oases, for example, which can also be used as lying or picnic areas, as well as a golf course and a leisure park with water-based facilities, e.g. rowing areas, coral and fishing grounds. It is conceivable to develop these different business plans on the basis of long-term cooperation. This can be based on long-term contracts, e.g. for the supply of fish, fruit and vegetables for the tourist gastronomy.

The constellation must remain stable in the long run in order to encourage cross-sectoral investments. Long-term contracts can bring about the desired stability if the resort is well accepted by tourism. A good prerequisite for this is a clean coastal environment, which depends on the success of water reuse in the Muscat region. Whether the drinking water is also produced by another, spatially isolated line of the plant using seawater desalination and mineralisation, or is obtained from the outside via a district water pipeline, depends on the local conditions.

The WWTP can either be financed and built by the state or with private funds. A private finance initiative is conceivable here. Veto players in the decision process can prevent or block water reuse. No veto players have been identified in the CA, showing a supportive situation.

The commission board is an instrument important for the cross-sectoral coordination in the initial and concept phase. In addition, the coordination later on during the operation can be arranged in different ways. The management of the tourism, agriculture and landscape park can be executed by a public–private partnership, but also by a public authority or a private company on its own. Other forms of operation are based on self-administration, such as a cooperative or an association.

For the constellation as analysed for Oman, and given the fact that also during the operations complex processes have to be coordinated, including quantitative adjustments and qualitative monitoring, a public authority such as Haya Water, which is also the operator of the WWTP, might be suitable to take over the operational coordination of the different facilities. Oman has good preconditions for water reuse in different sectors: Haya Water is an institution that already has the competences and knowledge for water reuse in agriculture. If Haya Water becomes a key actor in water reuse in tourism and food production (e.g. aquaculture and horticulture), it might be possible to cover the costs since these sectors have higher profit margins than traditional agriculture.

DISCUSSION

Multimodality means that several (e.g. 'dual') supply networks must be set up and operated on a permanent basis. Crucial to the cost of water is the length of the pipes. To save costs and reduce problems due to reinfection of the water, it is important that the advanced treatment takes place close to the water user. The WWTP, however, could be at some distance since one pipe is sufficient to supply treated wastewater for advanced treatment. The Californian example highlights this: the central facility is located near the WWTP, but has satellites in direct proximity to the customers. If only small quantities of one quality are required (e.g. RO water for a hotel's dishwasher), transport, e.g. by trucks, can be considered instead of a cost-intensive network of pipes.

The results of this CA confirm and specify a preliminary market analysis for multimodal water reuse (Becker *et al.* 2017). Fairly similar constellations to that in California can be assumed in comparable situations, especially in more industrialised countries such as in Europe or Mexico, China, India, South Africa and countries in the Middle East. As a result, multimodal water reuse could be implemented there. Comparable constellations to that in Oman can be expected in tourism destinations in Europe, the USA, the Middle East and North Africa, but also in countries in the Far East, Mexico, the Caribbean, New Zealand, Australia, South Africa and Kenya, so that opportunities for multimodal water use might also be realised there.

In order to prevent water shortages, it is necessary to involve intermediaries for the water management of a region with water stress. Intermediaries can facilitate processes and carry out a comprehensive problem analysis. They need to be independent of the 'free play of forces' otherwise a short-term analysis of the initial constellation alone may lead to the adoption of the wrong strategy. The Californian example shows that a high level of regional suffering (several supply crises caused by drought) leads to a rethink and an initially rejected task is pursued after all. In both cases, the CA clarifies that a large number of cooperation arrangements must be mastered in order to implement the discussed innovation successfully in the long term. Cooperation management can support this (Kerber *et al.* 2017).

Both constellations are characterised by joint use of new water resources. The coordination for planning and operation can either be carried out by a utility or water agency as shown in the CA, but also by private entities such as the users themselves (e.g. in a cooperative). A private initiative of this kind can start by means of integrated business planning for supply chain design and collaborative planning. For the conversion of land into tourism, leisure facilities and food production systems area development are required. This involves the construction of a new WWTP, including advanced treatment and distribution of various (guaranteed) qualities of process water. In the initial phase, as well as the coordination of planners, water technology advisers, aquaculture and horticulture advisers, the financing of initial investments and financial architecture for the different businesses is required. In this real estate development scenario, a key actor might be a private enterprise experienced in area development and infrastructure projects.

For constellations with industry partners as well as for those with tourism partners, there was an initial investigation (not documented here) about whether such private partners could also play a key role as a 'central node' and act as a catalyst. Public actors would seem to be more capable of taking all the different interests involved in water reuse into account.

In the two constellations examined, state (or inter-municipal) intermediaries play a decisive role. A utility or an intermediary has a professional perspective on the users' water quality requirements. Therefore, it is possible to find a suitable typology of process water, pooling the different user requirements in order to increase cost efficiency. These classes are also related to the WWTP effluent and the available technology.

In one of the two cases, a constellation in which the national wastewater company is the key actor coordinating the important customers has proven to be stable. As a counterweight in this constellation, it will be necessary for the tourist resort and other users to participate responsibly on a board. However, state (or inter-municipal) independence is not required for the implementation and actual operating phase of the multimodal water reuse. Once the planning phase is finalised, the intermediary can also assign an operator from the private sector (e.g. SUEZ).

CONCLUSIONS

Reclaimed wastewater can be used for many different purposes. In practice, when developing a market for advanced water reuse, it is problematic to limit this to a single use and a single user group since an increase in water stress will affect all user groups. In this respect, a fit-for-purpose approach can be pursued. Based on further constellation analyses and supplementary investigations, it will be possible to introduce multimodal water reuse systematically.

Multimodal water reuse is a technically complex and cost-intensive process. There are constellations in which advanced water reuse is favoured. The CA makes it plausible that advanced treatment for reuse will be implemented more frequently in future due to a reduction in the associated risk to human health and the environment. Furthermore, if constellations can be established by forward-looking governmental agencies, private actors and civil society, such cases will increasingly replace simpler forms of water reuse. The target visions linked to water reuse in the United Nations' Sustainable Development Goals can then be realised sustainably.

The CA revealed a greater complexity regarding cooperation between actors compared with traditional water reuse. Hence, the venture needs to be supported by reliable (perhaps even strong) institutions as essential network nodes, supported by steering committees and participative planning processes for example.

Another drawback of multimodal water reuse is the cost of advanced treatment. In countries where the price of (irrigation) water is not subsidised, the supply of sufficiently treated water will only be available to target groups with sufficient capital. If water treatment can be covered by cross-financing, it might be possible to provide farmers with irrigation water at prices that are adapted to their income and the market prices of their products (e.g. by cross-subsidising the water tariff of irrigation water with the tariff of RO water). In this way, local food production, small-scale agriculture and landscape quality will be preserved.

Based on specific local preconditions, other opportunities for sustainable water supply always need to be considered. Moreover, further research is required to understand the welfare and distribution effects of multimodal water pricing policies and the feasibility of co-financing agricultural irrigation.

The following favourable constellations can be noted:

1. Multimodal water reuse can be established either when sewage transport and (semi-) centralised wastewater treatment is already in place, or in the case of new development.
2. A multimodal approach is possible in areas in which water users carry out activities that require a wide range of different water qualities.
3. Multimodal water reuse is appropriate in constellations in which cooperation between heterogeneous actors (from operators of WWTPs to monitoring institutions and customers) can be initiated and maintained in the long term.
4. In principle, multimodal water reuse is suitable for countries that:

   - offer a high degree of legal security and contractual reliability (customers have to take the water for an agreed period of time),
   - are comparatively wealthy and have the possibility to engage qualified personnel (advanced wastewater treatment depends on energy and material input as well as on knowledge and skills) and
   - have different water users capable and willing to pay the cost (in a way that ultimately covers costs).

The stated conditions allow countries to be identified in which constellations can be formed beneficially for multimodal water reuse. Industrialised countries and countries in transition are eligible. These include BRIICS, as well as Thailand, South Korea, OPEC countries and possibly some other MENA countries as well.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Al-Balooshi, A. & Charabi, Y. 2012 *Assessment of Land Degradation in Al-Bathina Region*. Oman. Available from: https://www.squ.edu.om/Portals/97/Activities/Workshop/WWD2017/HayaWater.pdf (accessed 27 March 2020).

Al-Farsi, R., Ahmed, M., Al-Busaidi, A. & Choudri, B. S. 2018 Assessing the presence of pharmaceuticals in soil and plants irrigated with treated wastewater in Oman. *International Journal of Recycling of Organic Waste in Agriculture* **7** (2), 165–172. http://dx.doi.org/10.1007/s40093-018-0202-1.

Al-Riyami, I. M., Ahmed, M., Al-Busaidi, A. & Choudri, B. S. 2018 Antibiotics in wastewaters: a review with focus on Oman. *Applied Water Science* **8** (7), 2046. http://dx.doi.org/10.1007/s13201-018-0846-z.

Baawain, M., Sana, A., Al-Yahyai, R. & Amoatey, P. 2019 Sustainable reuse options of treated effluents: a case study from Muscat, Oman. *Journal of Environmental Engineering and Science* 1–9. http://dx.doi.org/10.1680/jenes.19.00019.

Becker, D., Frey, A., Jungfer, C., Krömer, K., Kulse, P., Maaßen, S., Schramm, E., Wencki, K., Zimmermann, B. & Zimmermann, M. 2017 *Marktpotentiale der Wasserwiederverwendung: Anforderungen und Kriterien in unterschiedlichen Sektoren und mögliche Zielmärkte für das MULTI-ReUse-Verfahren (Market Potential of Water Reuse: Requirements and Criteria in Different Sectors and Possible Target Markets for the MULTI-ReUse-Process)*. ISOE Materialien Soziale Ökologie 49.

BMWi – Federal Ministery for Economic Affairs and Energy (ed.) 2018 *Wasserwirtschaft Kalifornien (Water Management in California): Zielmarktanalyse 2018 mit Profilen der*

Marktakteure (Analysis of Target Market 2018 Including Profiles of Market Players). Berlin.

Bunani, S., Yörükoğlu, E., Yüksel, Ü., Kabay, N., Yüksel, M. & Sert, G. 2015 Application of reverse osmosis for reuse of secondary treated urban wastewater in agricultural irrigation. *Desalination* **364**, 68–74. http://dx.doi.org/10.1016/j.desal.2014.07.030.

Choudri, B. S., Al-Busaidi, A. & Ahmed, M. 2013 Climate change, vulnerability and adaptation experiences of farmers in Al-Suwayq Wilayat, Sultanate of Oman. *International Journal of Climate Change Strategies and Management* **5** (4), 445–454. http://dx.doi.org/10.1108/IJCCSM-11-2012-0061.

Drewes, J. E., Schramm, E., Ebert, B., Mohr, M., Beckett, M., Krömer, K. & Jungfer, C. 2019 Potentiale und Strategien zur Überwindung von Hemmnissen für die Implementierung von Wasserwiederverwendungsansätzen in Deutschland (Potentials and strategies to overcome barriers of the implementation of ideas for water reuse in Germany). *KA Korrespondenz Abwasser, Abfall* **66** (12), 995–1003.

Espey, R. 2018 *Oman Investiert in Umwelttechnik: Ausbau des Abwassernetzes/Moderne Müllentsorgung im Aufbau*. Dubai/Maskat. Available from: https://www.gtai.de/GTAI/Navigation/DE/Trade/Maerkte/suche,t=oman-investiert-in-umwelttechnik,did=1902744.html (accessed 10 October 2019).

European Union 2020 *Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on Minimum Requirements for Water Reuse*. Official Journal of the European Union L 177/32.

FAO – Food and Agriculture Organization of the United Nations (ed.) 2008 *Country Profile – Oman: Version 2008*. Rome.

FAO – Food and Agriculture Organization of the United Nations (ed.) 2017 *Country Programming Framework for the Sultanate of Oman*.

Freyberg, T. 2018 *Taking Water Reuse Haya Across Oman*. Available from: https://www.waterworld.com/municipal/technologies/article/16201270/taking-water-reuse-haya-across-oman (accessed 10 October 2019).

Haya Water (ed.) n.d *Haya Water: Presentation by Buthaina Mahfoud Al Whaibi*. Available from: https://www.squ.edu.om/Portals/97/Activities/Workshop/WWD2017/HayaWater.pdf.

Joham, J. 1978 West Basin's plans for water reuse. In: *Industrial Water Reuse: Conference Proceedings*, Culver City, pp. 45–48.

Kennedy, L. & Tsuchihashi, R. 2005 Is water reuse sustainable? Factors affecting its sustainability. *Arabian Journal for Science and Engineering* **30**. Available from: https://www.researchgate.net/publication/228379299_Is_Water_Reuse_Sustainable_Factors_Affecting_Its_Sustainability (accessed 25 March 2020).

Kerber, H., Kunkis, M. & Schramm, E. 2017 Kooperationsmanagement: Ein Instrument zur Differenzierung der Wasserinfrastruktur (Cooperation management: an instrument for differentiation of water infrastructure). In: *Wasserinfrastruktur: Den Wandel gestalten: Technische Varianten, räumliche Potentiale, institutionelle Spielräume. Edition Difu – Stadt Forschung Praxis, 16 (Water Infrastructure: Shape the Change: Technical Variants, Potentials of Area, Institutional Scopes)* (M. Winker & J. H. Trapp, eds). Difu, Berlin, pp. 219–235.

Kotagama, H. B. & Al-Farsi, H. 2019 Impact of the domestic labor market on sustainability of agriculture in Oman. *Journal of Agricultural and Marine Sciences [JAMS]* **23** (1), 24–24. http://dx.doi.org/10.24200/jams.vol23iss1pp24-28.

Lazarova, V., Oelker, G. & Oelker, W. 2012 Production of custom-made recycled water for various reuse purposes: lessons learned from one of the world's largest recycling facilities. *Water Practice and Technology* **7** (3). http://dx.doi.org/10.2166/wpt.2012.052.

Lehane, S. 2015 *The Sultanate of Oman: Food and Water Security to 2025*. (accessed 9 October 2019).

MAF – Ministery of Agriculture and Fisheries & ICBA – Sultanate of Oman International Center for Biosaline Agriculture Dubai (ed) 2012 *Oman Salinity Strategy: Annex 4. Governance, Legal/Regulatory Frameworks and Policies in Agriculture and Water*.

McDonnell, R. 2016 *Groundwater use and Policies in Oman*. IWMI report 14

Mendoza, J. 2019 First Sustainable Greenhouse Research Facility Launched in Oman. *Oman Daily Observer*, (16.03.2019). Available from: https://www.omanobserver.om/first-sustainable-greenhouse-research-facility-launched-in-oman/ (accessed 21 January 2020).

MRMWR – Ministry of Regional Municipalities and Water Resources – Oman (ed.) 1993 *Ministerial Decision 145/93 Dated 13 June 1993: Regulations for Wastewater Re-use and Discharge*.

Nahrstedt, A., Gaba, A., Zimmermann, B., Jentzsch, T., Krömer, K., Tiemann, Y., Harsanyi, L., Buchta, P., Dölchow, U., Lipnizki, J., Mende, K., Koch, T. & Rohn, A. 2020 Reuse of municipal wastewater for different purposes based on a modular treatment concept. *Journal of Water Reuse & Desalination* (this issue). https://doi.org/10.2166/wrd.2020.040.

Nocker, A., Schulte-Illingheim, L., Müller, H., Rohn, A., Zimmermann, B., Gaba, A., Nahrstedt, A., Mohammadi, H., Tiemann, Y. & Krömer, K. 2020 Microbiological changes along a modular wastewater reuse treatment process with a special focus on bacterial regrowth. *Journal of Water Reuse and Desalination* (this issue). https://doi.org/10.2166/wrd.2020.012.

Nölting, B. & Mann, C. 2018 Governance strategy for sustainable land management and water reuse: challenges for transdisciplinary research. *Sustainable Development* **26** (6), 691–700.

Ohlhorst, D. & Schön, S. 2015 Constellation analysis as a means of interdisciplinary innovation research – theory formation from the bottom up. *Historical Social Research/Historische Sozialforschung* **40** (3), 258–278.

Rizzo, L., Malato, S., Antakyali, D., Beretsou, V. G., Đolić, M. B., Gernjak, W., Heath, E., Ivancev-Tumbas, I., Karaolia, P., Lado Ribeiro, A. R., Mascolo, G., McArdell, C. S., Schaar, H., Silva, A. M. T. & Fatta-Kassinos, D. 2019 Consolidated vs new advanced treatment methods for the removal of contaminants of emerging concern from urban wastewater. *The Science of the Total Environment* **655**, 986–1008. http://dx.doi.org/10.1016/j.scitotenv.2018.11.265.

Schön, S., Nölting, B. & Meister, M. 2004 Konstellationsanalyse: Ein interdisziplinäres Brückenkonzept für die Technik, Nachhaltigkeits- und Innovationsforschung (Constellation analysis: an interdisciplinary concept for technic, sustainability and innovation research). Discussion paper Nr. 12/04.

Seis, W., Lesjean, B., Maaßen, S., Balla, D., Hochstrat, R. & Düppenbecker, B. 2016 *Rahmenbedingungen für die umweltgerechte Nutzung von behandeltem Abwasser zur landwirtschaftlichen Bewässerung (Frame Conditions for an Environmental Friendly Usage of Treated Sewage Water for Agricultural Irrigation)*. UBA-Texte 34/2016. Dessau-Roßlau.

SUEZ group (ed.) 2020 *SUEZ Renews the Contract to Operate One of the Largest Wastewater Recycling Plants in the United States*. Available from: https://www.suez.com/en/news/press-releases/suez-renews-contract-operate-one-of-the-largest-wastewater-recycling-plants-united-states (accessed 25 March 2020).

The Heritage Foundation (ed.) 2019 *Index of Economic Freedom: OMAN*.

Water Technology (ed.) 2016 *U.S. Water Industry Revenues Rise to $160 Billion: Water Instruments and Information Segment Leads Growth*. Available from: https://www.watertechonline.com/wastewater/article/16205061/us-water-industry-revenues-rise-to-160-billion (accessed 23 March 2020).

World Bank (ed.) 2019 *OMAN*. Available from: http://documents.worldbank.org/curated/en/984551556570728787/pdf/Macro-Poverty-Outlook-for-Oman.pdf (accessed 21 January 2020).

First received 1 May 2020; accepted in revised form 1 September 2020. Available online 25 November 2020