

Direct potable reuse – a feasible water management option

J. Lahnsteiner, P. van Rensburg and J. Esterhuizen

ABSTRACT

Direct potable reuse (DPR) can be more economic than indirect potable reuse as no environmental buffer is needed and conveyance and blending of the purified water with other potable sources is basically less expensive. Long-term experience in Windhoek (48 years) shows that treated domestic sewage can be safely and cost-efficiently utilized for potable reclamation (0.72 €/m³). A multiple barrier strategy is employed in order to attain the highest possible safety levels. There are three types of barriers: non-treatment, treatment and operational barriers. In recent years, new DPR schemes have been implemented in South Africa and in the USA, and the major difference between all the new reclamation processes and the Windhoek New Goreangab water reclamation plant lies in the employment of desalination process units. This topic and other issues, such as the use of ozone and biological activated carbon filtration, are addressed. Reclamation process optimization (increase in sustainability) and the attainment of greater public acceptance are the major challenges facing the promotion of DPR, which should become a common and widely used water management option within the next 5–10 years.

Key words | direct potable reuse, multiple barrier approach, ozone, reverse osmosis

J. Lahnsteiner (corresponding author)
VA TECH WABAG GmbH,
Dresdnerstrasse 87-91,
1200 Vienna,
Austria
E-mail: josef.lahnsteiner@wabag.com

P. van Rensburg
City of Windhoek,
80 Independence Avenue,
Windhoek,
Namibia

J. Esterhuizen
WINGOC,
Matshitshi Street, Goreangab,
Windhoek,
Namibia

ABBREVIATIONS

aDOC	anthropogenic dissolved organic carbon	DOC	dissolved organic carbon
ARBs	antibiotic resistant bacteria	DPR	direct potable reuse
ARG	antibiotic resistance genes	EfOM	effluent organic matter
AOP	advanced oxidation process	GAC	granular activated carbon
BAC	biological activated carbon	IPR	indirect potable reuse
CAPEX	capital expenditure	LRV	log removal values
COD	chemical oxygen demand	MBR	membrane bioreactor
DAF	dissolved air flotation	NF	nano-filtration
DMF	dual media filtration	NGWRP	New Goreangab water reclamation plant
		non-RO	non-reverse osmosis
		O&M	operations and maintenance
		OPEX	operational expenditure
		RO	reverse osmosis
		RWPF	raw water production facility
		TCEQ	Texas Commission on Environmental Quality

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TDS	total dissolved solids
THMs	trihalomethanes
UF	ultra-filtration
WRP	water reclamation plant
WTP	water treatment plant

INTRODUCTION

Due to severe water stress, in many regions (southern Africa, southwest USA, Australia, etc.) the practice of indirect and direct potable reuse (IPR and DPR, respectively) has to be employed in order to secure the drinking water supply. The Orange County Groundwater Replenishment System and the Singapore NEWater scheme (blending in reservoirs) are prominent examples of IPR.

In India, e.g. in the Bengaluru (Bangalore) metropolis with its ten million inhabitants, both IPR and DPR are being considered in order to cope with the water crisis derived mainly from population growth and climate change. Potable reuse is even a topic of interest in the water-rich country of Brazil, and in the megacity of Sao Paulo, IPR and DPR are under discussion as alternative drinking water sources in response to population growth, polluted drinking water and droughts. A potential cause of the latter is deforestation in the Amazon, as diminishment of the rainforest has reduced its evaporation capacity. This has resulted in lower rainfall in the region (Argentina and Brazil) that includes Sao Paulo (30 million inhabitants in the so-called 'Macro Sao Paulo'), which is located in the south-east of Brazil.

DPR does not require environmental buffers (groundwater replenishment or discharge to surface water reservoirs). The conveyance and blending of the purified water with other potable sources is basically less expensive than with IPR. Therefore, in many cases DPR is, or could be, more cost-efficient than IPR (Gerrity *et al.* 2013; Raucher & Tchobanoglous 2015; Tchobanoglous 2015). Moreover, in situations where environmental buffers are unavailable, it would be the only potable reuse option. Due to the aforementioned benefits and the general need for alternative potable sources, interest in DPR has risen sharply during recent years and DPR guidelines addressing issues such as

source control, hazard identification and risk assessment, the identification and validation of control measures, verification and quality assurance, case studies, public perception and acceptance, regulatory and legal considerations have been issued in Australia (Natural Resource Management Ministerial Council *et al.* 2008), in the USA (Texas Water Development Board 2015; WateReuse *et al.* 2015) and South Africa (Water Research Commission 2015). The World Health Organization (WHO) has also drafted a guideline, which will be issued in 2016 or 2017.

The city of Windhoek is well known for its lengthy DPR experience (48 years). The city is water stressed and several severe droughts mean that DPR is vital for its sustained development. At present, there is an ongoing drought that has been classified by the authorities as a water crisis, which in line with local classification represents the most serious drought category. According to the drought response plan announced by the Windhoek authorities in November 2015 (City of Windhoek 2015), in such a water crisis, water availability may extend for less than 12 months and forced water consumption restrictions have to be imposed. The current water crisis restrictions were upgraded in May 2016 with the aim of achieving 40% water savings, i.e. an increase from an already achieved 23% to 40% (City of Windhoek 2016). The president of the Republic of Namibia declared a national emergency in June 2016. The major reservoirs are nearly empty and according to models, at a minimum the water supply is only secured until September 2016 and at a maximum until December 2016. After the depletion of the surface water, the water supply for Windhoek is reliant upon two sources only, namely strategic groundwater reserves (which have been augmented by managed groundwater recharging/water banking) and high-quality reclaimed water (from domestic secondary effluent). A minor additional supply from northern aquifers (7–8% of Windhoek's water demand) might be available through the national supply network. Should the drought continue, it is estimated that the strategic groundwater reserves will suffice for 2 to 3 years.

In recent years, further DPR schemes have been implemented in South Africa: Beaufort West (source water: secondary municipal effluent; 2011) and eMalahleni (source water: acid mine drainage; 2007, first extension in 2010, second extension in 2016), and in the USA: Big

Spring, Texas/USA (source water: tertiary municipal effluent; 2013) and Wichita Falls, Texas/USA (source water: secondary municipal effluent; 2014–2015). Furthermore, additional projects are in the planning, piloting/demonstration (e.g. El Paso, Texas/USA and San Diego, California/USA), approval or completion stage (e.g. Cloudcroft, New Mexico/USA). In Windhoek, the planning of an additional DPR facility is ongoing in order to meet the mid-term water demand of this rapidly growing city.

METHODS

The long-term DPR experience in Windhoek is described and the non-reverse osmosis (non-RO), multiple barrier system employed is compared with the newer DPR schemes using reverse osmosis (RO). The interest in non-RO systems would appear to be increasing as sustainability and efficiency is improved (no generation of brines and lower power consumption). Within this context, the advantages and disadvantages of both schemes are addressed and subsequently topics such as operational and economic feasibility, key quality factors, ozonation impact, antimicrobial resistance and brine management are discussed.

DPR FACILITIES

Table 1 provides an overview of the major DPR projects and includes information with regard to the type of water reclamation plant (WRP) inlet (source water), reclamation plant capacity, reclamation process, blending with other water sources and the additional treatment of the blended water.

Windhoek, Namibia

In Windhoek, domestic secondary effluent is used for potable reclamation. In order to attain the highest possible safety levels for this sensitive practice, a multiple barrier approach is employed (Lahnsteiner et al. 2013). There are three types of barriers comprised of non-treatment (management), treatment and operational barriers.

An essential *non-treatment barrier* (management barrier) is the strict separation of domestic and industrial

used water, i.e. only domestic sewage is utilized for potable reclamation. Industrial used water (1.2–1.3 million m³/y), which is discharged mainly by a brewery, a tannery and an abattoir is dealt with separately in a central treatment plant with a membrane bioreactor (MBR) as its core technology (operational since October 2014). Another crucial non-treatment barrier is the comprehensive monitoring of the sewage treatment plant (Gammams water care works) inlet and outlet, as well as the extensive monitoring of purified/reclaimed water (drinking water) quality. The blending of the reclaimed water with other potable sources (treated Von Bach Dam water and borehole water, maximum 35% reclaimed water) is also worthy of mention as a further important non-treatment barrier (management barrier). Only blended water is distributed to consumers. Apart from diluting the dissolved solids in the reclaimed water, blending provides the dilution of effluent organic matter (EfOM which can be expressed as anthropogenic dissolved organic carbon (aDOC)). The aim is the supply of drinking water (i.e. a blend of reclaimed, treated dam and borehole water) with an anthropogenic DOC concentration of <1 mg aDOC/L. This target value is an internal standard of the City of Windhoek and is not required in the terms of compliance of any existing regulatory framework.

Treatment barriers are formed by purification systems that are in constant operation, i.e. the Gammams sewage treatment plant (nutrient removal plant), maturation ponds and the New Goreangab WRP (NGWRP). The NGWRP transforms secondary domestic effluent (maturation pond effluent) into high-quality drinking water by means of an advanced multi-barrier system. It produces a maximum of 21,000 m³/d of drinking water that is constantly controlled in order to ensure its suitability and safety for human consumption. The plant was started up in mid-2002 and officially inaugurated in December 2002. The treatment train includes the following single treatment barriers (Figure 1): powdered activated carbon dosing (optional), pre-ozonation, enhanced coagulation and flocculation, dissolved air flotation (DAF), dual media filtration (DMF), main ozonation, biological activated carbon (BAC) filtration, granular activated carbon (GAC) adsorption, ultra-filtration (UF) and disinfection with chlorine and stabilization with caustic soda (NaOH).

Table 1 | Major DPR projects

DPR project	WRP inlet	WRP Q (m ³ /d)	Water reclamation process	Blending – reclaimed water/ 'natural water' (%)	Additional treatment
Windhoek, Namibia, NGWRP (2002)	Secondary domestic effluent ^a	21,000	Pre-O ₃ , coagulation, DAF, DMF, main-O ₃ , BAC, GAC, UF, Cl ₂ , NaOH	25/75 ^b (treated dam water [70] + groundwater [5]); Pipe-to-pipe blending in the distribution network	None
Beaufort West, South Africa (2011)	Secondary municipal effluent	2,000	Cl ₂ , sedimentation, Cl ₂ , SF, UF, RO, AOP (H ₂ O ₂ + UV), Cl ₂	20/80 (treated dam water + ground water); max. 30% of reclaimed water; blending in a storage tank	None
Big Spring, TX, USA (2013)	Disinfected tertiary municipal effluent	7,600	De-chlorination, MF, RO, AOP (H ₂ O ₂ + UV)	15/85 (untreated lake and dam water); blending in raw water pipeline	Conventional WTP
Wichita Falls ^c , TX, USA (2014–2015)	Secondary municipal effluent	19,000	Cl ₂ , NH ₃ , coagulation, sedimentation, MF, RO, UV; lagoon	50/50 (untreated lake water); blending in a splitter box	Conventional WTP
Cloudcroft, NM, USA	Secondary effluent from MBR	379	RO, AOP (H ₂ O ₂ + UV), Cl ₂	49/51 (spring/well water); blending in an engineered storage buffer	Advanced WTP (UF, UV, GAC, NaOCl)
Brownwood ^d TX, USA	Tertiary municipal effluent	5,700	Cl ₂ , UF, UV, NH ₃ , de-chlorination, RO, GAC, UV, NH ₃ , Cl ₂	Blending in the distribution system with treated lake water	None
El Paso ^e , TX, USA (2020)	Tertiary municipal effluent	27,300	MF, NF or RO, AOP	Primary goal: blending in the distribution system	None

AOP, advanced oxidation process; BAC, biological activated carbon filter; DAF, dissolved air flotation; DMF, dual media filtration; DPR, direct potable reuse; GAC, granular activated carbon filter; IPR, indirect potable reuse; MF, micro-filtration; NF, nano-filtration; RO, reverse osmosis; SF, sand filtration; UF, ultra-filtration; WRP, water reclamation plant; WTP, water treatment plant.

^aPolished in maturation ponds.

^bAverage ratio, maximum permitted portion of reclaimed water is 35%; however, in the current emergency situation the reclaimed water portion could rise to 40%.

^cDPR decommissioned in July 2015, conversion to IPR.

^dProject put on indefinite hold.

^ePilot testing.

Figure 2 shows local technicians servicing the UF process unit (total of six racks), which employs a pressure driven, inside/outside, poly-ether-sulfone membrane (cut-off = 0.04 µm; total membrane area = 9,800 m², design net flux = 87 L/m²*h).

Operational barriers represent additional treatment options or operational measures that can be used on demand. An additional treatment option is powdered activated carbon, which can be dosed if the adsorption capacity of the GAC is too low or the organic load of the reclamation plant inlet is too high. One example of an operational measure involves switching to the recycle mode when the water quality fails to meet the online monitoring 'absolute' values set for the different process units.

Beaufort West, South Africa

Beaufort West is located in the water-stressed Great Karoo approximately 500 km north-east of Cape Town. The Beaufort West WRP (Q_{max} = 2,000 m³/d) was commissioned in January 2011 and employs the following process units: pre-chlorination, sedimentation, intermediate chlorination, rapid sand filtration, UF, RO, advanced oxidation process (AOP; H₂O₂/UV) and final chlorination (Ivarsson & Olander 2011; Burgess 2015; Matthews 2015; Water Research Commission 2015; GWI 2016b). The reclaimed water quality exceeds the national standard for potable water (Burgess 2015) and is blended with borehole and treated dam water (typically 1,000 m³ of reclaimed water with 4,000 m³/d of

the aforementioned conventional/'natural' sources) in a storage tank before being pumped to the distribution system.

Wichita Falls, Texas, USA

Due to a severe drought (stage 5: catastrophe) in 2014, the city of Wichita Falls (population: 104,000) employed emergency DPR for approximately a year (July 2014 to July 2015). The existing, advanced brackish lake water treatment plant (WTP) was used for potable reclamation (capacity: 28,400 m³/d secondary municipal effluent, 18,900 m³/d RO permeate). The water reclamation process incorporated coagulation/flocculation, chloramination, sedimentation, micro-filtration and RO (McDonald 2014; WateReuse et al. 2015). The RO permeate was stored in a lagoon and blended 1 + 1 with raw lake water. The blend was treated in a conventional WTP using chloramination, coagulation/flocculation, sedimentation, re-stabilization with CO₂, granular filtration and disinfection (Cl₂). The DPR scheme was operated successfully and the Texas Commission on Environmental Quality (TCEQ) only requested the additional installation of an UV process unit for the disinfection of the RO permeate (McDonald 2014). The project was decommissioned in July 2015 due to sufficient spring rainfall in 2015 (McDonald 2015; WateReuse et al. 2015). A conversion to IPR is in progress involving the upgrading of the existing 60,560 m³/d River Road wastewater treatment plant in order to purify water for IPR (GWI 2016a, 2016b). The reclaimed water will be pumped to Lake Arrowhead for blending with raw dam water. The upgrades include a 27 km-pipeline, the installation of disc filters, aeration systems and disinfection technology, as well as chemical phosphorus removal process steps in order to meet TCEQ water quality permitting guidelines (GWI 2016a).

Big Spring, Texas, USA

The Colorado River Municipal Water District operates an advanced WRP (raw water production facility – RWPF) for the augmentation of its ground and surface water sources. The source water of the RWPF is dechlorinated tertiary effluent from the Big Spring wastewater treatment plant. The RWPF advanced process consists of micro-filtration, RO and AOP. The reclaimed high-quality water is

blended with raw reservoir water (in the raw water pipeline from the E. V. Spence Reservoir; no environmental buffer) and treated in the Big Spring WTP (conventional treatment: coagulation/flocculation, sedimentation, filtration, disinfection). This DPR scheme has been operational since May 2013 (McDonald 2014; WateReuse et al. 2015; GWI 2016b).

Brownwood, Texas, USA

The town's (population 19,000) primary supply is Lake Brownwood (the town's only reservoir). The WRP (Q = 5,700 m³/d) utilizes chlorination, UF, UV-disinfection (stage 1), chloramination, de-chlorination, RO, activated carbon filtration, UV disinfection (stage 2) and chloramination. The reclaimed water will be stored in a ground storage tank (9,500 m³) and pumped directly to the distribution network (McDonald 2014). The TCEQ already approved construction in December 2012, but the project was put on indefinite hold (GWI 2015a) owing to sufficient spring rainfall in 2015.

Cloudcroft, New Mexico, USA

The village of Cloudcroft is a mountain community with limited groundwater resources and no surface water resources. During the peak tourist season the population doubles or triples and it is difficult to meet potable water demands. As a result, a DPR scheme has been developed. The reclamation plant (379 m³/day) consists of an MBR followed by RO and AOP. The reclaimed water is then blended with ground and spring water (>51%) and stored in an engineered storage buffer (two-week retention period). The blend is further treated by an advanced water purification system (UF, UV disinfection, GAC and chlorination). The project has been delayed due to budget overrun and sub-optimum project execution, but is now back on track (GWI 2016b).

El Paso, Texas, USA

El Paso Water Utilities is developing a DPR scheme for the reclamation and direct reuse of unchlorinated secondary effluent (from the Roberto R. Bustamante Waste Water Treatment Plant) for the augmentation of its potable water supply. It is planned that the reclamation plant (advanced

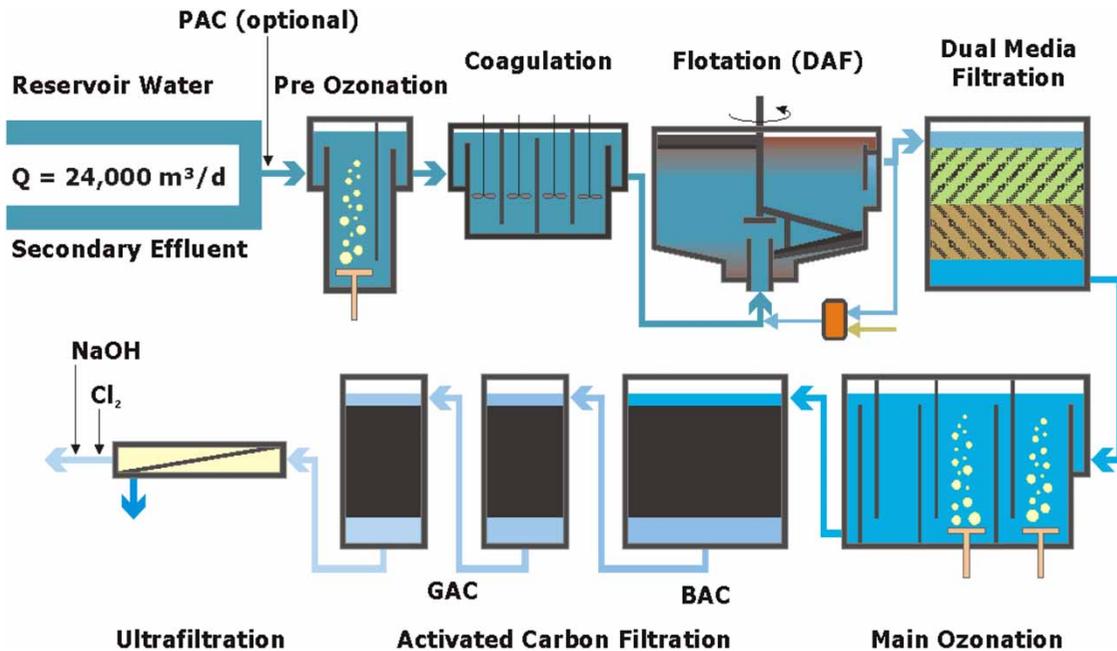


Figure 1 | Simplified process flow diagram. PAC: powdered activated carbon.



Figure 2 | NGWRP – Ultra-filtration undergoing servicing by local staff.

water purification facility) will transfer the reclaimed water directly to the distribution system (pipe-to-pipe blending). At present, an advanced process is being piloted. The process units employed consist of membrane filtration (microfiltration and UF), desalination (RO and nano-filtration (NF)), AOP, GAC and disinfection (Cl₂). Based on the pilot test results and TCEQ approval, the aim is to complete the final design for the 37,850 m³/d advanced water purification facility by 2018. Commissioning of the plant is planned for 2020 (GWI 2015b).

RESULTS AND DISCUSSION

NGWRP produces continuously good water quality that consistently meets the required final water specifications (van der Merwe *et al.* 2008; du Pisani & Menge 2013). Table 2 shows the final water specifications and typical operational results (50% and 95% tile). The final water specifications were derived from the following standards: the 1993 WHO Guidelines, the 1996 Rand Water Guidelines Potable Water Quality Criteria and the 1998 Namibian Guidelines for Group A Water. New Namibian drinking water quality standards were drafted in 2012, but have yet to be implemented. As part of their latest DPR project, the City of Windhoek has conducted a review on the standards, monitoring requirements and final water quality requirements with a view to implementing any changes required at the NGWRP.

Operational and economic considerations

The total log removal values (LRVs) achieved for microorganisms by the Windhoek treatment barriers (Gammams Water Care Works and NGWRP water reclamation process) are as follows: 12.4–13.9 log for viruses, 15.2–15.7 log for

bacteria and 7.9–9.4 log for protozoa (Law *et al.* 2015; Water Research Commission 2015). This performance is in accordance with the Australian Guidelines for Water Recycling/AGWR (Natural Resource Management Ministerial Council *et al.* 2008): virus LRV = 9.5 log, bacteria LRV = 8.1 log and protozoa LRV = 8.0 log. These cautious LRVs were established by Law *et al.* (2015) from Disability Adjusted Life Years (DALYs) used in the AGWR 2008. It is assumed that the aforementioned log removal rates (accomplished by the Windhoek treatment barriers) should provide sufficient health safety for the population of Windhoek. In fact, since the beginning of potable reuse in 1968 there have been no outbreaks, which could have been attributed to the consumption of reclaimed water. Within this context,

it should also be mentioned that a conventional WRP (without ozone and membrane filtration and subsequently lower LRVs) was operated from 1968 to 2002 (Old Goreangab WRP).

The total operating costs amount to 0.72 €/m³ (capital costs 0.12 €/m³, operational costs 0.60 €/m³; 1 € = 16.5 N\$), which is far cheaper than the other options for importing water to Windhoek (e.g. transport from the Okavango River or desalination at the coast). The UF membrane replacement cost is 0.012 €/m³ and was calculated on the basis of an average membrane life of 9 years, an interest rate of 10% and annual production of 5.8 million m³ of reclaimed water (76% utilization ratio). A typical value for the conveyance power demand (pumping with high lift pumps to the

Table 2 | Reclaimed water specification and quality

Parameter	Units	Final water specification	Actual operational results	
			50% tile	95% tile
Physical and organic				
Chemical and oxygen demand	mg/L	10–15	6.6	11
Colour	mg/L	8–0	0.5	0.5
Dissolved organic carbon (aDOC) ^a	mg/L	3	1.7	2.8
Total dissolved solids	mg/L	1,000 max or 200 above incoming	838	938
Turbidity	NTU	0.1–0.2	0.05	0.10
UV ₂₅₄	abs/cm	0.00–0.06	0.015	0.027
Inorganic				
Aluminium	Al mg/L	0.15	0.005	0.05
Ammonia	N mg/L	0.1	0.05	0.18
Iron	Fe mg/L	0.05–0.10	0.01	0.03
Manganese	Mn mg/L	0.01–0.025	0.005	0.0015
Microbiological				
Heterotrophic plate count	per 1 mL	80 100	0	4
Total coliforms	per 100 mL	0	0	0
Faecal coliforms	per 100 mL	0	0	0
Chlorophyll	µg/L	1	0.27	2.58
<i>Giardia</i>	per 100 L	0 count/100 L or 5 log removal	0	0
<i>Cryptosporidium</i>	per 100 L	0 count/100 L or 5 log removal	0	0
Disinfection by-products				
Trihalomethanes	µg/L	20–40	35	57

^aDefinition and related information above in the 'DPR facilities' subsection and below in the 'Results and discussion' subsections 'Key quality parameters' and 'DOC removal considerations'.

pipe-to-pipe drinking water network blending station) is 0.46 kWh/m³ (0.046 €/m³).

As indicated in [WateReuse et al. \(2015\)](#), CAPEX + OPEX (capital expenditure + operating expenditure) for *advanced water treatment facilities without RO* at a comparable capacity (5 Mgal/d = 18,921 m³/d; NGWRP average purified water production = 16,000 m³/d) is 0.51 €/m³ (1 € = 1.11 US\$). This means that the NGWRP cost is approximately 0.2 €/m³ higher. This difference is plausible, as the NGWRP employs an advanced multiple barrier process with 10 process units (designed, engineered and sourced at the end of the 1990s and beginning of the 2000s, respectively), which consists of more treatment steps than the aforementioned advanced water treatment facilities without RO.

The power demand of the reclamation process (without power for pumping to the network) is 0.88 kWh/m³. The conveyance/blending CAPEX (storage tank at NGWRP, pipeline and blending station) + OPEX (power for pumping, operations and maintenance (O&M) for tank, pipeline and blending station) is 0.092 €/m³ + 0.051 €/m³ = 0.143 €/m³. Thus, the costs for water purification (water reclamation) and conveyance to the drinking water network (including blending) are 0.72 €/m³ + 0.143 €/m³ = 0.86 €/m³. This represents an economic solution, which for a comparable capacity, could hardly be achieved by IPR, as the O&M costs for environmental buffers are relatively high. In [WateReuse et al. \(2015\)](#) a range of 0.08–0.81 €/m³ is provided for the (site specific and therefore widely varying) conveyance and blending costs. As compared to this range, the Windhoek costs of 0.143 €/m³ are relatively low.

Key quality parameters and salinity reduction study

If the major parameters of turbidity, DOC (aDOC and 'natural' DOC (nDOC)), trihalomethanes (THMs) and UV₂₅₄ in the water from the NGWRP (reclaimed water) and the Von Bach Dam (treated dam water) are compared, the reclaimed water shows superior quality to that from the dam ([Table 3](#)). Only the total dissolved solids (TDS) concentration is poorer in the reclaimed water and is vastly improved by blending with dam water.

The TDS concentrations of both the dam and reclaimed water fluctuate in accordance with the hydrological

Table 3 | Comparison of reclaimed water and treated dam water quality

Parameter	Unit	Treatment plants	
		NGWRP 50% tile	Bach Dam WTP 50% tile
Turbidity	NTU	0.05	0.6
aDOC, nDOC	mg/L	1.7	3.6
THM	µg/L	35	73
UV ₂₅₄	abs/cm	0.015	0.05
TDS	mg/L	871	161

situation (annual rainfall), and the reclaimed water TDS standard (TDS = 1,000 mg/L) was exceeded temporarily on several occasions. In order to test the desalination options, within the framework of a training programme for Namibian water professionals, laboratory-scale RO and NF testing was conducted using synthetic water at a German institute ([Cronje et al. 2006](#)). [Figure 3](#) shows some of the results obtained with two different RO membranes (Dow Filmtec BW 30 and Dow Filmtec XLE) and a NF membrane (Dow Filmtec NF 270). As can be seen in this figure, as expected the conductivity and mono-valent ion (nitrate and bromate) removal rates are substantially higher in the RO than in the NF. Apart from TDS/conductivity removal (owing to the aforementioned reason), the second aim was to assess the bromate removal rate, which amounted to 97.50% and 98.75%, respectively, in hyper-filtration (RO) and 60.63% in NF. Bromate is a disinfection by-product that is formed during ozonation and is discussed subsequently in the 'Impact of ozonation' subsection.

On the basis of the laboratory-scale tests, RO pilot testing was conducted (membrane: Torray TM 710). The feed water consisted of UF permeate from the NGWRP. The pilot tests largely confirmed the RO results of the laboratory-scale tests (>97% conductivity and bromate removal).

Based on the results of the pilot tests, a full-scale brackish water RO process unit was designed for the desalination of a partial stream of the NGWRP UF permeate. The design was based on the following parameters: feed-water = UF permeate, capacity = 11,200 m³/d, feedwater TDS = 1,300 mg/L, permeate TDS = 65 mg/L, recovery = 90%, brine TDS = 12,500 mg/L, blending of RO and UF permeate (approximately 50% each). The resulting RO unit consists of a one-pass system with three internal

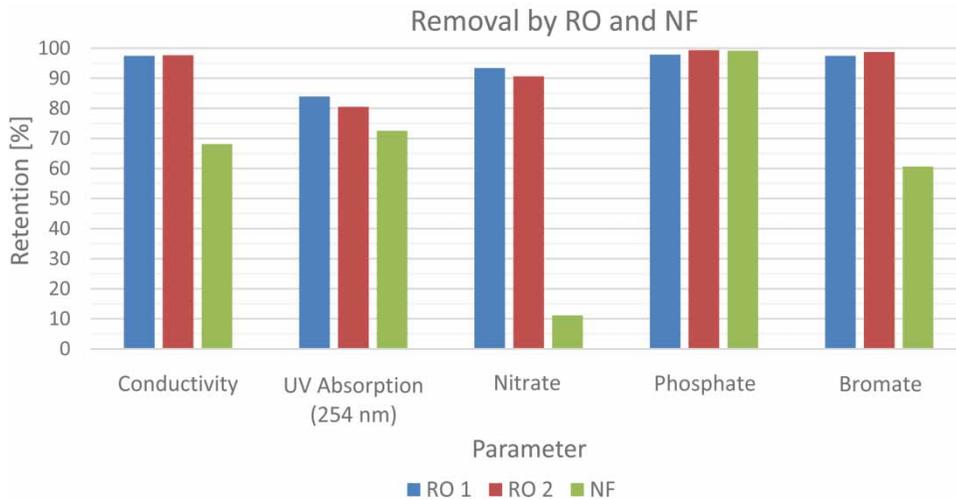


Figure 3 | Laboratory-scale desalination using RO and NF.

stages (total membrane area: approx. 25,000 m²). CAPEX (15 years, 10% interest) amounts approximately to 0.1 €/m³ RO permeate and 0.05 €/m³ blended water respectively. OPEX is approximately 0.23 €/m³ for RO permeate and 0.12 €/m³ for blended water. These figures include a power demand of approx. 0.8 kWh/m³ RO permeate and 0.4 kWh/m³ blended water. Consequently, CAPEX + OPEX amounts to 0.17 €/m³ blended water. This means that the aforementioned NGWRP total operating cost of 0.72 €/m³ would be increased by the operation of an additional process unit (RO) for TDS and bromate removal to approximately 0.89 €/m³ (brine management not included). A higher recovery rate could be accomplished by the operation of a brine concentrator (employing seawater membranes), which concentrates the brine of RO unit 1 (brackish water RO). On the one hand, this would cut brine disposal costs and on the other, increase potable water recovery. However, the CAPEX and OPEX of the reclamation plant would also rise. CAPEX due to the installation of both a second RO unit (brine concentrator) and a precipitation step for bivalent cation removal and OPEX owing to higher chemicals costs (precipitating agent, precipitation sludge disposal) and increased power demand (additional RO unit). The optimum recovery rate has to be established in a detailed study that assesses all the economic and environmental aspects of brine concentration and disposal (availability and cost of land, etc.).

Brine disposal considerations

As can be seen in Table 1, all the reclamation plants listed, except for that in Windhoek, employ RO. The major disadvantages of RO derive from relatively high energy consumption and the production of a concentrate, which as discussed above requires disposal. Within this context, it has to be emphasized that brine management can be a difficult task, especially in inland applications (no sea/ocean disposal possible) such as in Windhoek (more than 300 km from the ocean), which in addition has no perennial rivers for discharge. Against this background, solar ponds would appear to be the most logical disposal option in Windhoek. However, due to the relatively large amounts of brine (550–1,100 m³/d at recovery rates of 95% and 90%, respectively) relatively large areas for the solar ponds would be required. In this context, it must be mentioned that unlike any other urban situation there is fierce competition for land (residential areas, farms, touristic and commercial facilities). However, in a water-stressed region it should be politically possible to find a suitable plot of land (approximately 110,000 m² for 1,100 m³ brine per day or 55,000 m² for 550 m³ brine per day) for brine disposal.

In Beaufort West the relatively small amount of brine (approximately 200 m³/d) can be concentrated by solar evaporation in disused ponds at the wastewater treatment plant (Matthews 2015). In Big Spring the brine is discharged into a creek (Beals Creek; McDonald 2014), but this does not

represent the most environment-friendly and sustainable solution. In El Paso, brine disposal (6,800 m³/d) into an irrigation canal following dilution with treated effluent from the Roberto R. Bustamante Waste Water Treatment Plant is under consideration (McDonald 2014), but is not to be recommended due to the salt content, micro-pollutants and pathogens contained in the brine. However, a great deal depends upon the degree of brine dilution. In Cloudcroft, the RO brine together with the UF backwash water is intended for reuse in road dust control, construction, snow making for the ski area, gravel mining operations, forest fire fighting and other applications (Koch Membrane Systems 2015). However, this could be seen as the disposal of contaminants into the environment and is also not to be recommended.

Antimicrobial resistance

An emerging topic in used water treatment, reclamation and reuse is antimicrobial resistance, i.e. antibiotic resistant bacteria (ARBs) and antibiotic resistance genes (ARGs). ARBs are removed largely by microfiltration and UF, but due to their molecular size ARGs are mainly separated by RO. Therefore, an assessment has to be made as to whether brines require treatment (e.g. by AOP) before being released to the environment. It is assumed, that in the Windhoek multiple barrier NGWRP, the ARBs and ARGs are largely removed. This assumption is based on the fact that ARGs, which are located inside the ARBs and therefore more or less protected from chemical action, should be mainly inactivated/eliminated by both of the two ozonation stages (ARB cell wall destruction by both pre and main ozonation, DNA cracking/splitting by main ozonation) and the subsequent BAC (biological removal of DNA fragments). This hypothesis is to be verified/disproved in an upcoming research project.

Impact of ozonation

Another major difference between the NGWRP and other applications lies in the employment of ozone and BAC (in the Windhoek system). The major advantage of this process combination is formed by effective DOC removal, which generally reduces THM formation potential in

drinking water purification and in particular the organic matter of human origin (aDOC) in potable reclamation and reuse.

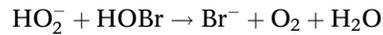
Furthermore, ozone provides both micro-pollutant oxidation and disinfection (viruses, bacteria and protozoa). As mentioned above, the disadvantage of ozonation is the formation of bromate. There is no defined mechanism for bromate formation. Instead it is a complex network of chemical reactions that are influenced by ozone stability and hydroxyl radical ($\cdot\text{OH}$) formation, as well as the chemical speciation of hypo-bromic acid, which is an intermediate product in the reaction chain from bromide to bromate. In addition, carbonate radicals, which are formed by the reaction of $\cdot\text{OH}$ radicals with bicarbonate and carbonate, can intensify bromate formation. The kinetics are determined by different parameters such as organic matter, bicarbonate, carbonate and pH. These parameters can act synergistically, as well as antagonistically. Therefore, bromate formation can hardly be predicted (von Gunten 2003). This means that as a rule, formation potential and avoidance strategies have to be established by experimental work.

The European Union (EU), US-Environmental Protection Agency (US-EPA) and WHO standards have been fixed at 10 $\mu\text{g/L}$, and in Namibia there is a draft drinking water directive, which includes a bromate standard that is also set at 10 $\mu\text{g/L}$. However, largely for political reasons, this directive is yet to be implemented. Within this context, it must be said that the aforementioned standard is under discussion, as new research indicates that the carcinogenic potential of bromate has probably been overstated. On the one hand there are chemical mechanisms (e.g. in the acidic stomach fluid), which reduce bromate concentrations significantly and on the other, it has been shown that bromate-induced cancers in rats do not arise from a genotoxic mode of action (Kolisetty et al. 2013; Water Research Foundation 2012) as was originally assumed. Therefore, Kolisetty et al. (2013) propose to increase the US-EPA maximum contaminant level goal to 20 $\mu\text{g/L}$. The US-EPA is aware of this study, but the revision of the bromate standard (started in 2012) is still ongoing (Cummings 2016). The work was used by Canada Health to develop a physiologically based pharmacokinetic model, but again to date nothing has been realized (Cummings 2016). In the Windhoek drinking

water network (and at the consumer's tap), the bromate concentration is in the range of 10–20 µg/L (after blending with bromate-free surface and groundwater). The current (EU, US-EPA, WHO) 10 µg/L standard could be met if the NGWRP ozone dose, which is relatively high, were to be reduced. According to experts, this could be achieved without compromising disinfection (protozoa destruction, etc.). However, as the NGWRP operation contract requests a Ct-value of 20 mg·min/L, this measure (ozone dose reduction) has to be agreed between the plant operator (Windhoek Goreangab Water Reclamation Company) and the Windhoek civic authorities. In this context, it has to be mentioned that protozoa are relatively resistant to ozone. However, at the aforementioned high Ct-value (corresponding to specific ozone concentrations of 3.0–3.5 mg O₃/mg aDOC) no viable protozoa have been detected after main ozonation. A phased reduction of the ozone dose and the observation of the resulting protozoa concentration has been planned in order to achieve guidance regarding a decision on this issue.

Another option for lowering the bromate formation is AOP with ozone and hydrogen peroxide. The latter reacts with hypo-bromic acid (an intermediate product of bromate

formation) to form bromide and thus achieve a bromate minimizing effect:



The required O₃/H₂O₂ ratio depends upon the nature of the water (nDOC and aDOC, bicarbonate, etc.) and as previously mentioned has to be established experimentally. As H₂O₂ is already used in the NGWRP for the destruction of ozone (in order to protect the beneficial bacteria in the BAC), in future it could also be employed for AOP.

Another ozonation by-product is N-nitroso-dimethylamine; a preliminary grab sample regime has shown that this is not present in the final water. A more detailed examination is to be conducted in the near future.

DOC removal considerations

Figure 4 shows the DOC removal using the major NGWRP process phases (pre-treatment, DAF, DMF, main ozonation, BAC, GAC and UF) in the period from June to December 2012.

As DOC (in this case aDOC) removal is an important design parameter, a quantitative assessment has been

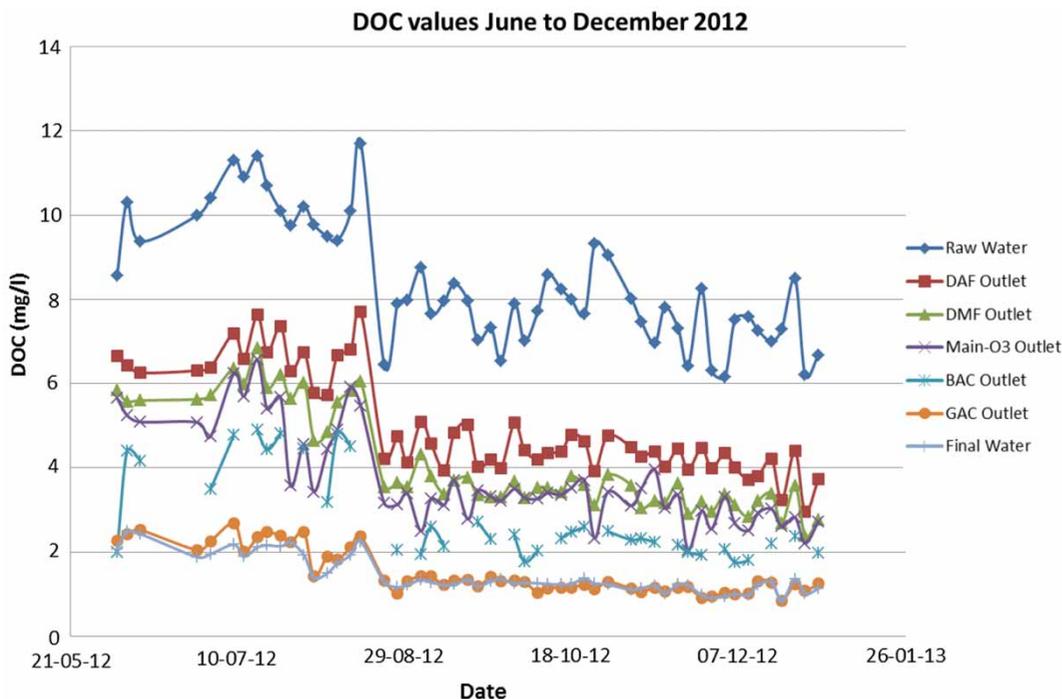


Figure 4 | DOC removal in the NGWRP.

conducted (Table 4). Within this context, the major aim was to quantify statistically the DOC removal rates ($a\text{DOC}_{\text{removed}} = a\text{DOC}_{\text{in}} - a\text{DOC}_{\text{out}}$) in all the aforementioned process units by calculating the average values and standard deviations. In addition, outlier tests were conducted and the values identified as outliers were eliminated.

As can be seen in this table, the highest (*absolute*) DOC removal is accomplished in pre-treatment (pre-ozonation, coagulation/flocculation and DAF): 3.38 ± 0.68 mg/L ($n = 54$), or 40.24% of the raw water DOC (8.40 mg/L).

In DMF, 0.88 ± 0.21 mg/L ($n = 53$) or 17.53% of the DAF outlet DOC (5.02 mg/L) is removed. Removal during ozonation is, as would be expected, relatively low: 0.32 mg/L ± 0.27 ($n = 48$), or 7.73% of the DMF outlet DOC (4.14 mg/L). The reason for this low degradation rate is that the (anthropogenic) DOC (EfOM, i.e. polysaccharides, proteins, humic acids, building blocks, etc.) is mainly cracked and not degraded (oxidized to CO_2), but nonetheless made bio-degradable. By contrast, UV absorption (UV_{254}) reduction is much higher owing to the splitting of the aromatic rings contained in the aforementioned compound groups: 0.087 abs/cm (in the DMF outlet) – 0.032 abs/cm (after ozonation) = 0.055 abs/cm representing a 63.32% removal rate during ozonation.

The bio-degradable DOC (produced during ozonation) is removed in the subsequent BAC: 0.97 mg/L ± 0.39 ($n = 36$),

or 25.39% of the ozonated water DOC (3.82 mg/L). In GAC filtration, 1.28 mg/L ± 0.53 ($n = 35$), or 44.91% of the BAC filtrate (2.85 mg/L) is adsorbed. This represents the highest removal *rate* in the entire process. DOC removal in the GAC depends largely on the carbon adsorption capacity status. With virgin carbon (e.g. during commissioning in 2002) reclaimed water DOC values of 1.0 mg/L (median at performance test) can be accomplished (Lahnsteiner & Lempert 2007) with a corresponding THM value of 11 $\mu\text{g/L}$.

In UF practically no DOC is removed, as no high molecular compounds are present following main ozonation and activated carbon filtration (BAC and GAC). The removal of 0.05 mg/L is insignificant, as it is both too close to DOC measurement error and smaller than the standard DOC removal deviation. By contrast, significant organic matter removal by UF was observed in water reclamation processes employing the same membranes, but neither ozonation nor activated carbon filtration (BAC and GAC). Chemical oxygen demand (COD) removal of 26% was noted in the case of secondary municipal effluent and 10% COD removal with regard to secondary refinery effluent (Lahnsteiner & Mittal 2010).

The aforementioned NGWRP results show that the (*absolute*) highest amount of DOC (3.38 mg/L) is removed by pre-treatment (mainly by coagulation/flocculation and DAF). This demonstrates the importance of (conventional)

Table 4 | aDOC removal – average values in the period from June to December 2012

	aDOC (mg/L)	Removal (mg/L)	Removal (%)	Removal cumulated (mg/L)	Removal cumulated (%)
Raw water	8.40				
DAF outlet	5.02				
Removal pre-treatment		$3.38 \pm 0.68, n = 54$	40.24	3.38	40.24
DMF outlet	4.14				
Removal DMF		$0.88 \pm 0.21, n = 53$	17.53	4.26	50.71
Ozonation outlet	3.82				
Removal ozonation		$0.32 \pm 0.27, n = 48$	7.73	4.58	54.52
BAC outlet	2.85				
Removal BAC		$0.97 \pm 0.39, n = 36$	25.39	5.55	66.07
GAC outlet	1.57				
Removal GAC		$1.28 \pm 0.53, n = 35$	44.91	6.83	81.31
UF outlet	1.52				
Removal UF		$0.05 \pm 0.13, n = 52$	3.18	6.88	81.90

pre-treatment. The more DOC is removed in this treatment phase, the lower is the consumption of ozone and activated carbon, and the fouling potential in UF and subsequently OPEX. Overall (anthropogenic) DOC removal amounted to 6.88 mg/L or 81.90%, resulting in a final purified/reclaimed water concentration of 1.5 mg/L. As already stated, a maximum of 35% of reclaimed water is permitted in the drinking water network. This means that at this maximum value (of 35%) the aDOC (i.e. EfOM) is diluted 1 + 2 (or by a factor of approx. 3) by 'natural' sources (treated dam water and groundwater) containing only 'natural' DOC (nDOC, i.e. NOM). The resulting aDOC concentration in the drinking water network is 0.5 mg/L which is significantly lower than the non-treatment barrier internal distribution limit of 1 mg aDOC/L.

Non-treatment barriers/management barriers

Blending

Non-treatment barrier blending is not only important for the dilution of both TDS and aDOC, but also for psychological reasons (public acceptance). In Windhoek and Beaufort West the reclaimed water is blended in the network (Table 1). The only difference is that in Windhoek pipe-to-pipe blending is used and in Beaufort West blending (typically 1,000 m³/d + 4,000 m³/d borehole and treated dam water respectively) in a storage and buffer tank is employed. Pipe-to-pipe blending is not as efficient and safe as blending in a storage tank, but more cost-efficient. In the El Paso project (which is in the piloting stage) blending in the network (pipe-to-pipe) is foreseen as the primary goal (McDonald 2014).

Separation of domestic and industrial used water

Windhoek and Beaufort West (a small community with only a few commercial and industrial enterprises) are the only DPR cases in which domestic and industrial used water are strictly separated. In Windhoek, the major effluents are discharged by an abattoir, brewery and tannery, and treated at Ujams in a WRP using fine sieving (micro-sieving), MBR and UV disinfection as the main treatment steps. The plant is being operated on a BOOT (build, own, operate, transfer) basis for 21 years. The design of the Ujams industrial WRP was verified by pilot tests and has been based on the following average concentrations:

COD = 3,314 mg/L, biochemical oxygen demand₅ = 1,657 mg/L, total suspended solids = 1,132 mg/L, total Kjeldahl nitrogen = 96 mg/L and PO₄-P = 25 mg/L. The major challenge facing the pilot plant operation was to cope with high and fluctuating COD (peaks > 10,000 mg/L) and nitrogen (peaks > 300 mg/L) concentrations that change within hours (Proesl *et al.* 2013). The full-scale plant has been operated successfully since its start-up in October 2014. Typical MBR permeate quality is as follows: COD = 68 mg/L, turbidity 0.1 NTU, total nitrogen = 10 mg/L, NH₄-N < 0.1 mg/L, NO₃-N = 6.2 mg/L and total phosphate = 0.1 mg/L. Currently, the reclaimed water is mainly reused for the augmentation of the ephemeral Klein Windhoek river. Reuse in industry is another option. Due to the ongoing water crisis, industry is very interested in reusing the reclaimed water.

PUBLIC PERCEPTION AND ACCEPTANCE

It is clear that in spite of the fact that several water reuse applications have already been developed and established in various countries, there are still a number of hurdles preventing the widespread implementation of water reuse on a truly global scale. On the positive side the looming, global water crisis has seen a definite increase in the level of interest, especially in the less conventional practice of DPR. However, reviewing the number of published findings on the obstacles hindering global water reuse, the following were seen as the primary problems (van Rensburg 2016), especially as far as DPR is concerned:

1. Public perception/acceptance.
2. Appropriate/standardized technical solutions.
3. Monitoring/management of health considerations and risks.
4. Reuse not being a part of integrated water supply strategies.
5. Water pricing and business models.
6. Regulatory and policy issues (lack of local/regional/global standards/best practice).

The implementation of water reclamation and reuse therefore not only suffers from technical barriers (2 and 3 above), but also faces other, often far more intimidating challenges such as a limited institutional capacity, a lack

of financial incentives and public perceptions with regard to water reclamation and reuse.

Nevertheless, it can be predicted that by far the greatest emphasis will be placed on managing health risks on a level at which public acceptance can be obtained. These two interlinked obstacles are expected to remain at the forefront of emerging DPR schemes, together with technological advances that are seen as presenting publicly acceptable, technologically robust and economically sound solutions.

For the city of Windhoek the future is unmistakably tied to intensified water reuse to a point at which the motto of 'every drop counts' becomes a reality to each and every citizen. Building on the success attained by past generations, the planning of an additional direct potable reclamation facility is currently ongoing in an effort to secure medium-term water supply as an economically feasible alternative.

CONCLUSIONS

Both the Windhoek experience and the other DPR installations demonstrate that treated domestic and municipal used water can be utilized successfully (safely and economically) for potable reuse. However, non-RO schemes would appear to be more sustainable than RO schemes. The major reasons are the generation of brines and the higher energy demand in schemes employing RO. On the contrary, a distinct disadvantage of non-RO schemes using ozone is the formation of bromate, although this can be managed by means of a proper ozonation design and operational control.

The multiple barrier approaches employed in both types of schemes guarantee reclaimed water of a quality that constantly meets all the required drinking water standards and is superior to that of conventional sources. The major challenges facing the promotion of DPR are reclamation process optimization (increased sustainability) and the attainment of greater public acceptance. In Windhoek, the inhabitants have accepted DPR, as there are no other affordable choices and since the beginning of potable reuse 48 years ago, no DPR-related outbreaks have been experienced.

DPR can be more economic than IPR as no environmental buffer is needed and conveyance and blending of the purified water with other potable sources is basically less expensive. In general, it can be stated that there appears

to be no reason why DPR should not become a common and widely used water management option within the next 5 to 10 years.

REFERENCES

- Burgess, J. 2015 Water reuse in South Africa. *Water* **42** (5), 42–44. City of Windhoek, Department of Infrastructure, Water and Technical Services 2015 Drought Response Plan. http://www.windhoekcc.org.na/documents/0fb_drought_response_plan_-_final_draft.pdf.
- City of Windhoek, Department of Infrastructure, Water and Technical Services 2016 Water Crisis Restrictions. http://www.windhoekcc.org.na/documents/fd3_cow_-_001962_-_diwts_-_increased_water_savings.pdf.
- Cronje, G., Esterhuizen, J., Buchta, P., Loi-Bruegger, A., Panglich, S. & Lahnsteiner, J. 2006 Report on TDS and Bromate Removal Lab Scale Tests conducted at IWW Muelheim a. d. Ruhr, Germany, October 2006.
- Cummings, B. S. 2016 Department of Pharmaceutical and Biomedical Sciences, College of Pharmacy, University of Georgia, Athens, USA, Personal Communication.
- du Pisani, P. & Menge, J. 2013 Direct potable reclamation in Windhoek: a critical review of the design philosophy of new Goreangab drinking water reclamation plant. *Water Sci. Technol. Water Supply* **13**, 214–226.
- Gerrity, D., Pecson, B., Trussell, R. S. & Trussell, R. R. 2013 Potable reuse treatment trains throughout the world. *J. Water Supply Res. Technol.* **62** (6), 321–338.
- GWl 2015a Reuse Tracker, *Global Water Intelligence Magazine*, August 2015, p. 59.
- GWl 2015b Reuse Tracker, *Global Water Intelligence Magazine*, October 2015, p. 49.
- GWl 2016a Reuse Tracker, *Global Water Intelligence Magazine*, January 2016, p. 50.
- GWl 2016b Direct potable reuse projects. *Global Water Intelligence Magazine*, July 2016, p. 6.
- Ivarsson, O. & Olander, A. 2011 *Risk Assessment for South Africa's First Direct Wastewater Reclamation System for Drinking Water Production, Beaufort West, South Africa*. Master Thesis 2011:113, Chalmers University of Technology, Gothenburg, Sweden.
- Koch Membrane Systems 2015 *Pioneering Water Reuse in the Old West*. Water World/Water and Wastewater International. Available from: <http://www.waterworld.com/articles/wwi/print/volume-24/issue-2/editorial-focus/pioneering-water-reuse-in-the-old-west.html>.
- Kolisetty, N., Bull, R. J., Muralidhara, S., Costyn, L. J., Delker, D. A., Guo, Z., Cotruvo, J. A., Fisher, J. W. & Cummings, B. S. 2013 Association of brominated proteins and changes in protein expression in the rat kidney with subcarcinogenic to carcinogenic doses of bromate. *Toxicol. Appl. Pharmacol.* **272**, 391–398.

- Lahnsteiner, J. & Lempert, G. 2007 *Water management in Windhoek, Namibia*. *Water Sci. Technol.* **55**, 441–448.
- Lahnsteiner, J. & Mittal, R. 2010 *Reuse and recycling of secondary effluents in refineries employing advanced multiple barrier systems*. *Water Sci. Technol.* **62**, 1813–1820.
- Lahnsteiner, J., du Pisani, P. L., Menge, J. & Esterhuizen, J. 2013 More than 40 years of direct potable reuse experience in Windhoek, Namibia. In: *Milestones in Water Reuse. The Best Success Stories* (V. Lazarova, T. Asano, A. Bahri & J. Anderson, eds). IWA Publishing, London, UK, pp. 351–364.
- Law, I. B., Menge, J. & Cunliffe, D. 2015 *Validation of the Goreangab reclamation plant in Windhoek, Namibia against the 2008 Australian guidelines for water recycling*. *J. Water Reuse. Desalin.* **5**, 64–71.
- Matthews, S. 2015 Water reclamation: water – precious resource to be used again, and again and again... *The Water Wheel* **14** (3), 26–29; published by the South African Water Research Commission: http://www.wrc.org.za/Pages/Preview.aspx?ItemID=11184&FromURL=%2fPages%2fDisplayItem.aspx%3fItemID%3d11184%26FromURL%3d%252fPages%252fKH_WaterWheel.aspx%253fdt%253d4%2526ms%253d%2526d%253dThe%2bWater%2bWheel%2bMay-June%2b2015%2526start%253d1.
- McDonald, E. 2014 Status of Potable Reuse Initiatives in Texas. In *Oral Presentation at I Forum Tecnico Internacional – Reuso Direto e Indireto de Efluentes para Potabilizacao*, 15–16 October 2014, São Paulo, Brazil.
- McDonald, E. 2015 Alan Plummer Associates, Inc., Personal Communication.
- Natural Resource Management Ministerial Council, Environment Protection and Heritage Council and National Health and Medical Research Council 2008 *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2), Augmentation of Drinking Water Supplies*. May 2008.
- Proesl, A., Dammert, R., Klegraf, F., Menge, J., Esterhuizen, J., Lahnsteiner, J., Leopold, G. & du Pisani, P. 2013 Reclamation of blended industrial effluents – pilot tests at Ujams, Windhoek. In *Oral Presentation at the 9th IWA International Conference on Water Reuse*, 27–31 October 2013, Windhoek, Namibia.
- Raucher, R. & Tchobanoglous, G. 2015 *Direct Potable Reuse – Opportunities and Economic Benefits*. World Water: Water Reuse and Desalination, Spring 2015, pp. 26–29. WEF Publishing, London, in association WaterReuse Association & WaterReuse Research Foundation. Available from: <http://edition.pagesuite-professional.co.uk/html5/reader/production/default.aspx?&edid=d494614b-73c0-47de-afeb-7d822194d267>.
- Tchobanoglous, G. 2015 *Understanding DPR Economics for Informed Decision Making*. World Water: Water Reuse and Desalination, Summer 2015, p. 12. WEF Publishing, London, in association WaterReuse Association & WaterReuse Research Foundation. Available from: <http://edition.pagesuite-professional.co.uk/html5/reader/production/default.aspx?&edid=9d034939-c1b7-433f-a0da-7b0bca12e1c0>.
- Texas Water Development Board 2015 *Final Report*. Direct Potable Reuse Resource Document, TWDB Contract No. 1248321508, April 2015.
- van der Merwe, B., du Pisani, P., Menge, J. & Koenig, E. 2008 Water reuse in Windhoek, Namibia: 40 years and still the only case of direct water reuse for human consumption. In: *Water Reuse – An International Survey of Current Practices, Issues and Needs* (B. Jimenez & T. Asano, eds). IWA Publishing, London, UK, pp. 434–454.
- van Rensburg, P. 2016 *Overcoming global water reuse barriers: the Windhoek experience*. *Int. J. Water Res. Develop.* **32**, 622–636.
- von Gunten, U. 2003 *Ozonation of drinking water: part II. Disinfection and by-product formation in presence of bromide, iodide or chlorine*. *Water Res.* **37**, 1469–1487.
- WaterReuse, AWWA, WEF and NWRI 2015 *Framework for Direct Potable Reuse*. WaterReuse Project Number 14-20.
- Water Research Commission 2015 Report to the Water Research Commission by Swartz, C. D., Genthe, B., Menge, J. B., Coomans, C. J. and Offringa, G. Direct Reclamation of Municipal Wastewater for Drinking Purposes. Volume 1: Guidance on Monitoring, Management and Communication on Water Quality. WRC Report No. TT 641/15.
- Water Research Foundation and International Ozone Association 2012 *Bromate Disposition and Mechanisms of Toxicity at High and Low Doses*. Web Report # 4042.

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