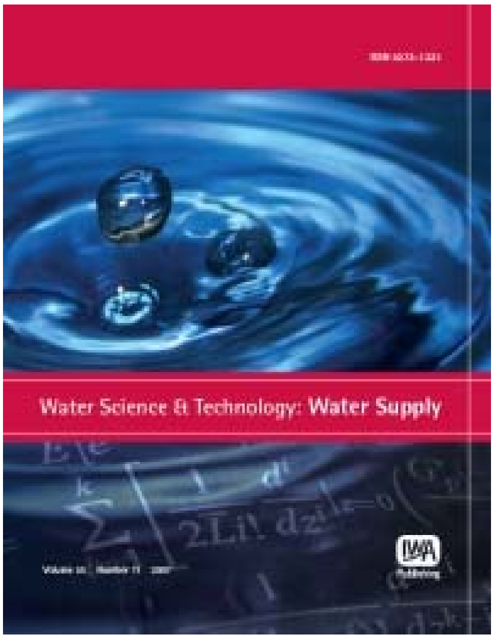
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Direct potable reclamation in Windhoek: a critical review of the design philosophy of new Goreangab drinking water reclamation plant

P. du Pisani and J. G. Menge

ABSTRACT

Direct drinking water reclamation from the Goreangab reclamation plant, has been a reality in Windhoek, Namibia since 1968. Potable reclamation is a fixed part of the water supply and waste water has become an indispensible resource for the survival and continued growth of the city. The multi barrier concepts that were applied 40 years ago have been refined over many years. Improvements in water treatment technology have made it possible to improve the reliability and the drinking water quality of the reclamation treatment process. With the latest upgrade, which was designed 14 years ago and commissioned in 2002, a specific design philosophy was followed. This paper will assess whether the objectives of the design philosophy have been met in terms of removal efficiencies and safety of drinking water, which contains at present 25% reclaimed water. The basis and aims of the multi barrier design that was applied is discussed and with the aid of natural organic matter (NOM) and microorganism removal, the reliability of the philosophy is tested and compared with the goals set. Comparisons are drawn between the new plant and the previous plant and how the new plant is able to accommodate changes in raw water quality. It can be concluded that the water quality has been improved and the barrier principle does reduce the risk and improve the water quality.

Key words | direct drinking water reclamation, effluent organic matter, multi barrier concept, potable reclamation

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BACKGROUND

Windhoek is the capital city of Namibia. It lies in the central highlands of the country which is classified as the most arid country in sub Saharan Africa. Around 1847 the first settlement took place around the hot springs in what is today Windhoek. As early as 1911, the water table had dropped to the extent that the springs had stopped flowing and the first borehole was drilled to supply water to the settlement.

The country, then called South West Africa, has no perennial rivers, except on the very southern and very northern borders, the closest of which is 750 km from Windhoek. Population growth and agricultural activities put groundwater reserves under severe stress. A small dam was built in 1933, but due to the small catchment, erratic rainfall, on average 360 mm per year and the high evaporation rate of around 3,400 mm per year, this dam added little to the water needs of Windhoek.

Reuse of treated sewage effluent for the power station, was first considered in 1954, but not implemented. A water crisis in 1957 led to the construction of the Goreangab dam and treatment works on an ephemeral river just west of the town, which was completed in 1959.

Growing demand in the early 1960s again forced the consideration of treated sewage effluent as a resource and after extensive piloting, in 1968, the Goreangab water treatment plant was converted to a two train operation, respectively treating secondary sewage effluent and dam water. Both product waters were combined and introduced directly into the drinking water supply. On 24 November

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1968, the Sunday Tribune declared: 'Windhoek drinks sewage water! It's a purified world first'. The total capacity of this plant was 4.3 Ml per day which represented between 10 and 12% of maximum daily demand.

The process train employed had been the object of almost eight years of pilot studies and although the phrase had not been coined, was based on what is today referred to as the multiple barrier principle. The process train was upgraded four times between 1968 and 1992. This plant, the old Goreangab reclamation plant (Old Plant) also served as full scale test site for the new Goreangab reclamation plant (New Plant), which is the subject of this paper.

NEW GOREANGAB RECLAMATION PLANT

A study conducted in 1991 (Haarhoff 1991) into the treatment capacity of the Old Plant concluded that it could be extended to 14.4 Ml per day with minor changes. In 1992 a decision was taken to increase the capacity to 21 Ml per day (Burmeister *et al*. 1992; Haarhoff & van der Merwe 1996).

Process train

The New Plant would equally use secondary treated sewage effluent and Goreangab dam water as feed. After comparing 27 raw water parameters, consultants FMG Goreangab Joint Venture in the process train report concluded that, the two sources were sufficiently similar to treat both in the same process train.

Water quality standards

As no specific guidelines or standards for potable reclamation were available, the following standards and guidelines were considered to develop guidelines for the New Plant:

- Guidelines for the Evaluation of Drinking water for Human Consumption (1991) Dept of Water Affairs, Namibia (Namibian Guidelines 1991).
- Potable Water Quality Criteria (Rand Water 1994).
- WHO Drinking Water Guidelines (WHO 1993).
- The National Drinking Water Standards and Health Advisories USEPA (USEPA 1996).
- The European Community Guidelines for the use of water for human consumption (80/778/EWG) (1980 and 1994 draft) (EC 1980).
- A guide for the planning, design and implementation of a water reclamation scheme (Meiring & Partners 1982).

The process train report recognized that, in potable reclamation from waste water, microbiological safety would be the overriding concern. It was however also realized that trying to set guidelines to guarantee the protection of people's health over a lifetime of exposure, would often be idealistic.

The USEPA approach adopted, which considered either a maximum contaminant level (MCL) (USEPA 1989), or a treatment technique specification according to the surface water treatment rule (USEPA 1989). For microbiological contaminants which are not easily measured, such as protozoan cysts, the product of disinfectant residual concentration and effective contact time in mg.min/l (Ct) technique was adopted to ensure that the contaminant is exposed to a certain disinfection concentration for a defined time to ensure a minimum of 3 log removal for protozoan cysts and 4 log removal for viruses. The report further suggested that, by achieving a higher Ct product, higher log removals could be achieved. The approach was further based on a guideline for total organic carbon (TOC) from Water Factory 21, in California, where the TOC of the injected water is less than 1 mg/l (Williams 1996) and their standard was set at less than 2 mg/l based on health risk model and risk criteria of 1 in 1 million. Breakthrough of *Giardia* cysts and *Cryptosporidium* oocysts during the operation of the Old Plant between 1994 and 1996 prompted the immediate upgrade of the Old Plant to include a filter-to-waste and automatic filter backwash system. For the New Plant, an additional partial and complete safety barrier was added to include ozonation and ultra-filtration (UF) (Menge *et al*. 2001). A partial safety barrier removes between 40 and 60% of a constituent and a complete barrier would remove more than 99.9%.

Another specific quality concern identified, were the high number of natural organic matter (NOM) (Jacquemet *et al.* 2007; Haarhoff *et al.* 2009) and anthropogenic organic compounds found in waste water. Because the treatment of these would rely on high ozone dosages for oxidation of organic compounds, coupled with breakpoint disinfection with chlorine would cause the formation of trihalomethane (THM), bromate and other byproducts. Bromate and THMs are accepted as being potentially carcinogenic and of special interest in the plant design. The removal of organic compounds to minimize the formation of byproducts and to prolong the lifetime of the activated carbon therefore featured strongly in the process design (NIWR 1981; Haarhoff & Menge 1994). Other contaminants in waste water that required special attention were defined as aromatic hydrocarbons such as benzene and toluene, as well as phenols and pesticides. The plant was designed to reduce the organic load, measured as dissolved organic carbon (DOC) with enhanced coagulation (EC), dissolved air flotation (DAF) and rapid sand filtration (RSF) and subsequent ozone, biological activated carbon (BAC) and activated carbon adsorption (GAC) (Haarhoff *et al.* 1998).

Ultimately, the proposed final water quality guidelines were defined as shown in Table 1. This table only contains the main operational test parameters. Other parameters of concern such as heavy metals, aromatics or pesticides are specified according to the Rand Water (Rand Water 1994) or USEPA (USEPA 1996) guidelines.

The multiple barrier concept

At the time of the process train report (WHO 1975; Haarhoff *et al.* 1998), the concept of multiple barriers was more or less synonymous with margins of safety built into the process train. If a certain contaminant would manage to pass through a process specifically installed for such contaminant, there should be further downstream processes that could eliminate or reduce such contaminant to within the acceptable MCL.

In the philosophy adopted for the New Plant, three types of barriers were considered:

- Non treatment barriers, such as diversion of all industrial effluent.
- Treatment barriers, which comprise the actual process steps built into the plant.
- Operational barriers such as powdered activated carbon (PAC) dosing only used as and when needed.

In the elaboration of the process design, the following water quality concerns would be addressed: (a) physical and organoleptic, (b) microbiological and biological, (c) organics and disinfection byproducts, (d) macro elements, (e) stability.

Physical and organoleptic

As potable reclamation from sewage has to contend with the so-called 'yuk' factor and customer acceptance has to be maintained 100% of the time, the aesthetic parameters are extremely important. For these parameters, it was proposed to provide at least two barriers namely EC, DAF and RSF as the first barrier and UF as the second barrier for suspended particles. For the removal of colour, taste and odour, one barrier which is ozone, BAC and GAC. See Table 2 and Figure 1.

Microbiological and biological

The main concerns that had been catered for in the process design, were viruses and bacteria. Certain bacteria groups were defined that would serve as indicators. These were total coliform, faecal coliforms (including *Escherichia coli*), faecal streptococci, sulphite-reducing *Clostridium* and somatic coliphage. *Giardia* and *Cryptosporidium* were also considered as of major concern in waste water reclamation. Even though not yet well defined in water guidelines at the time, four barriers were included for *Giardia* cysts. For *Cryptosporidium* oocysts, two complete barriers and one partial barrier were defined. See Table 2 and Figure 1.

Organics and disinfection byproducts (DBPs)

At the design stage of the plant, DBPs were not yet well defined in international standards and guidelines. It was however suspected that these products contributed to cancer formation in laboratory tests. The anthropogenic character of the raw water needs special attention. In the Old Plant only two partial barriers existed, namely coagulation, DAF and RSF followed by carbon adsorption. In the New Plant four partial barriers would be used,

Table 1 | Final water quality

	Units	Target	Maximum
Physical and organoleptic			
Calcium carbonate precipitation potential	mg/l $CaCO_3$	4	0–8
Chemical oxygen demand	mg/l	10	15
Colour	mg/l Pt	8	10
Dissolved organic carbon	mg/l	3	5
Total dissolved solids	mg/l	≤1,000	≤1,200
Turbidity	NTU	0.1	0.2
UV_{254}	abs/m	5.0	6.0
Macro elements			
Aluminium	Al mg/l	N/A	0.15
Ammonia	N mg/l	N/A	0.10
Chloride	Cl mg/l	Not removed	250
Iron	Fe mg/l	0.05	0.1
Manganese	Mn mg/l	0.0025	0.005
Nitrate and nitrite	N mg/l	Not removed	10
Nitrite	N mg/l	Not removed	0.2
Sulphate	SO_4 mg/l	Not removed	200
Microbiological indicators			
Heterotrophic plate count	per 1 ml	80	100
Total coliforms	per 100 ml	N/A	0
Faecal coliforms	per 100 ml	N/A	0
E. coli	per 100 ml	N/A	0
Coliphage	per 100 ml	N/A	0
Enteric viruses	CPE per 10 l	N/A	≤ 0 or 4 log Rem
Faecal streptococci	per 100 ml	N/A	0
Clostridium spores	per 100 ml	N/A	0
Clostridium viable cells	per 100 ml	N/A	0
Disinfection byproducts			
Total trihalomethanes	μg/l	20	40
Biological			
Chlorophyll *a*	μg/l	N/A	1
Giardia	per 100 l	≤0 or 6 log Rem	≤0 or 5 log Rem
Cryptosporidium	per 100 l	≤0 or 6 log Rem	≤0 or 5 log Rem

Note: Other parameters will be adhered to as by Rand Water Guidelines (Rand Water 1994).

pre-ozonation, EC, DAF and RSF and subsequent ozone, BAC and GAC. See Table 2 and Figure 1.

It was realized that organics subjected to oxidation by ozone and chlorine, were the cause of DBP formation. During the pilot phase it was not possible to test for bromate residuals. Proper instrumentation for the determination of bromate was not available in Southern Africa at that time and an ion chromatograph was only obtained in 2005. The process would therefore focus on maximal reduction of organics and control of the ozone dosage to prevent the formation of DBPs. A set

Table 2 | Barriers provided in design for different critical parameters. A comparison between the Old Plant and the New Plant is made. The different treatment steps are abbreviated. (C: Complete barrier; P: Partial barrier)

	Barrier 1	Barrier 2	Barrier 3	Barrier 4
Old Plant				
Physical and organoleptic	CD/DAF/RSF : C	GAC : P		
Microbiological: bacteria and viruses	BPCL2 : C	BPCL2 : C	BPCL2 : C	
Biological: *Giardia, Cryptosporidium*	CD/DAF/RSF : C	BPCL2 : P	BPCL2 : P	BPCL2 : P
Organics and DBPs	CD/DAF/RSF : P	GAC : P		
Macro elements: Fe, Mn	GAC : P			
Stability	CD (Lime, NaOH) : C			
New Plant				
Physical and organoleptic	CD/DAF/RSF: C	UF: C	GAC: P	
Microbiological: bacteria and viruses	POZ: P	OZ: C	UF: C	BPCl2: C
Biological: *Giardia, Cryptosporidium*	CD/DAF/RSF: C	OZ: P	UF: C	BPCl2: P
Organics and DBPs	POZ: P	CD/DAF/RSF: P	OZ: P	BAC-GAC: P
Macro elements: Fe, Mn	POZ: P	CD/DAF/RSF: P	OZ: P	BAC-GAC: P
Stability	CD (NaOH): C			

Where MIX is mixture of dam and treated waste effluent, CD is chemical dosing, POZ is pre-ozonation, DAF is dissolved air flotation, RSF is dual media rapid sand filtration, OZ is ozone contact, BAC is biological activated carbon, GAC is granular activated carbon, UF is membrane ultra-filtration, CT is contact chamber, PS is high lift pumps Treatment chemicals added: PAC is powder activated carbon, O_3 is ozone, Fe is Ferric ion, HCl is hydrochloric acid, Poly is polymer, MnO_4 is permanganate, H_2O_2 is peroxide, $BPCL_2$ is break point chlorination, NaOH is caustic soda.

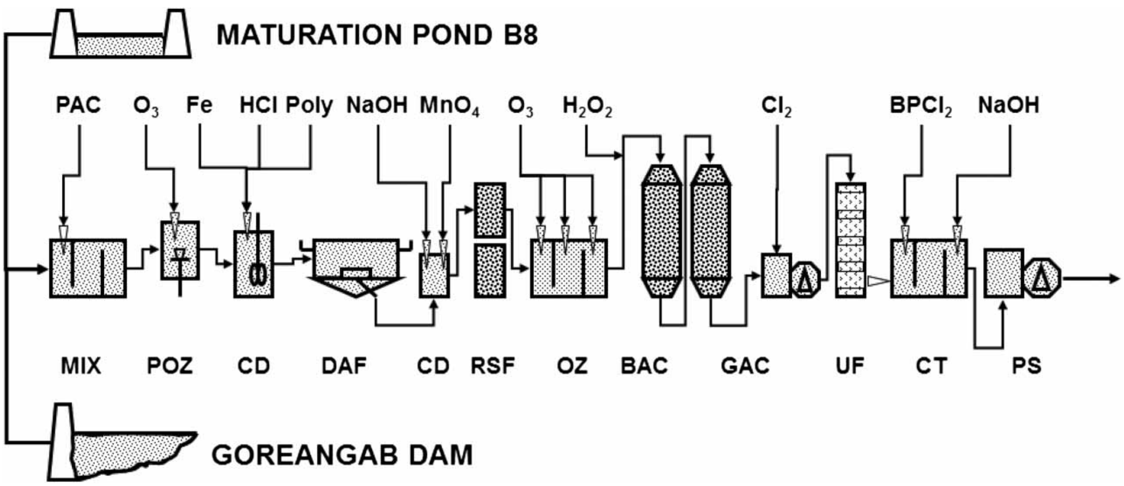

Figure 1 | Diagram of New Plant. For a description of symbols see Table 2.

of operational guidelines was therefore prescribed to minimize organics and thereby minimizing DBPs. These were:

- The use of EC, not only to remove turbidity, but to maximally precipitate organic carbon.
- Moving the chlorination step right to the end of the process after maximal organics removal.
- Use of alternative oxidants where possible (permanganate, ozone).
- Provide activated carbon steps for DBP adsorption.

Macro elements

The process train report recognized nitrogen (nitrate) as a main inorganic concern. It was however recommended that this parameter be best dealt with during secondary sewage treatment through biological nitrification and de-nitrification. This risk could be controlled through an operational barrier however, the blending of reclaimed water with water from natural sources.

Iron and manganese were two other inorganic parameters of special concern. Special measures were incorporated in the New Plant to reduce their concentration. Four partial barriers would be used to reduce these, pre-ozonation, EC, DAF and RSF and subsequent ozone, BAC, GAC. See Table 2 and Figure 1.

The plant design did not provide for total dissolved solids (TDS) removal, because reverse osmosis (RO) was not considered as a treatment option at the time. The technology was regarded as too expensive and there was no proven track record with the type of water to be treated. TDS would be reduced by blending the treated water with natural water which is low in TDS.

Stability

Only one barrier, dosing of caustic soda for stability was added before the final disinfection. See Table 2 and Figure 1.

Final process design

The ultimate design of the new Goreangab water reclamation plant, relying on the above proposals and which culminated from a Design and Construct Turnkey tender procedure, were accepted as shown in Figure 1. For a comparison between the two plants the diagram of the Old Plant is provided in Figure 2.

RESULTS

The New Plant was completed in August 2002 and the operation and maintenance of the plant was contracted out to WINGOC, a consortium consisting of Veolia Water, Berlin Water International and VA Tech Wabag. The agreement is based on water quality achieved, with strict penalties for exceeding any target values and a prohibition on supply of water exceeding any absolute values.

Quality standards were furthermore defined as intermediate values to be achieved after every process step, and final water standards to be achieved in the final product water (du Pisani 2006). For this purpose, a rigorous sampling regime was prescribed as well as online instrumentation connected to a SCADA system and refrigerated composite samplers that monitor water quality throughout the process at critical control points (CCP). As a result of the above, extensive quality data are available, which is analysed and reported hereunder, to critically review the efficiency of the multiple barrier system adopted for New Plant. From about one million test results of numerous parameters analysed for the whole Windhoek water cycle, over a period of 16 years, the following operational parameters are selected to demonstrate the improvement in water quality between the Old Plant and New Plant. Table 3 shows

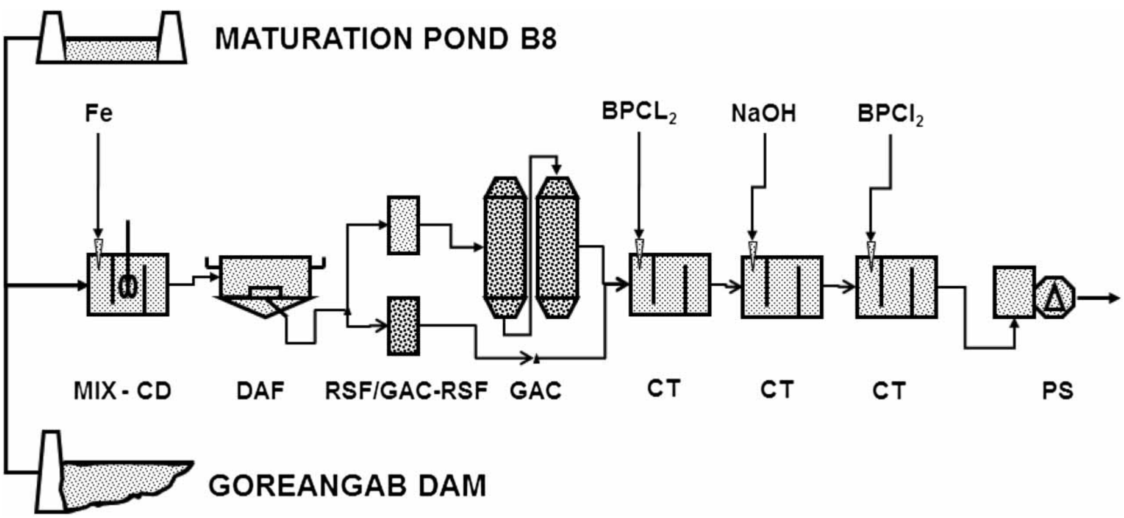

Figure 2 | Diagram of Old Plant. For a description of symbols see Table 2.

the raw water mixture of wastewater treated effluent and dam water that was treated in the Old and New Plants. Table 4 and Figures 3–7 show the final reclaimed water that was to be blended with a conventional water source. The 50^{th}, 85^{th}, 95^{th} and 99^{th} probability data for the period 1995 to 2001 for the Old Plant and 2002 to 2010 for the New Plant respectively are shown. Table 5 presents the macro elements for the raw untreated and treated final water of the New Plant. Table 6, presented at the end of the paper, shows the water quality of different water sources in Windhoek's distribution system. The reclaimed water is compared with the surface water and three different borehole groups, individually and grouped together, with the primary objective to determine if the advanced wastewater treatment system can reliably reduce contaminants of public health concern to levels such as that the health risk posed by any proposed potable use of the treated water are no greater than those associated with the present water supply, as recommended by the Western Consortium for Public Health (1997).

DISCUSSION

Numerous desktop, pilot and full scale studies have been conducted on the Old Plant between 1991 and 1998 as well as on the New Plant between 2002 and 2010. Many reports have been published about the performance of the plant, the removal of *Giardia* and *Cryptosporidium*, viruses and other substances (Menge *et al.* 2001, 2007). It will not be possible to deal with all data and information in this publication. For the purpose of this paper, only five operational parameters (turbidity, chemical oxygen demand (COD), DOC, ultraviolet absorbance (UV_{254}) and heterotrophic plate count (HPC)) are used to discuss the improvement of water quality by adding additional barriers to reach the water quality standards stet in the design report. The 95% probability data show that the new plant has achieved the target values for all the parameters, except COD. The aesthetic final water quality improved by a factor of 10, microbial risk was

Table 3 | Raw water quality data of the Old Plant and New Plant. The amount of data (n) are shown at the bottom of the table

	Old Plant Turbidity (NTU)	New Plant Turbidity (NTU)	Old Plant COD (mg/l)	New Plant COD (mg/l)	Old Plant DOC (mg/l)	New Plant DOC (mg/l)	Old Plant UV_{254} (abs/m)	New Plant UV_{254} (abs/m)	Old Plant Total coliform (cfu/100 ml)	New Plant Total coliform (cfu/100 ml)
50%P	12.28	2.17	34.31	26.00	11.26	9.18	25	18	3,133	4,800
85%P	28.50	6.20	39.96	33.00	13.63	10.75	28	20	14,335	19,095
95%P	41.00	15.48	43.80	37.00	14.44	12.00	31	23	42,235	39,150
99%P	93.27	49.15	49.28	41.00	16.14	13.17	34	26	71,170	78,765
(n)	318	368	307	368	215	368	317	370	223	348

Table 4 | Performance data of the Old Plant and New Plant are compared with highlight the vast improvement accomplished by additional treatment barriers. The Performance Target and Maximum Allowable limit and the amount of data (n) are shown at the bottom of the table

	Old Plant Turbidity (NTU)	New Plant Turbidity (NTU)	Old Plant COD (mg/l)	New Plant COD (mg/l)	Old Plant DOC (mg/l)	New Plant DOC (mg/l)	Old Plant UV_{254} (abs/m)	New Plant UV_{254} (abs/m)	Old Plant HPC (cfu/1 ml)	New Plant HPC (cfu/1 ml)
50%P	0.65	0.06	12.0	5.70	3.82	1.60	5.44	1.25	1.00	0.00
85%P	1.10	0.07	17.3	10.4	5.78	2.31	7.38	1.85	5.00	0.40
95%P	1.62	0.08	20.3	14.8	6.79	2.60	8.41	2.23	16.0	1.15
99%P	2.52	0.13	22.6	19.5	8.37	3.00	11.11	2.83	134	5.83
Target	0.10	0.10	10.0	10.0	3.00	3.00	5.00	5.00	80	80
Max	0.20	0.20	15.0	15.0	5.00	5.00	6.00	6.00	100	100
(n)	314	363	301	368	212	367	312	369	308	366

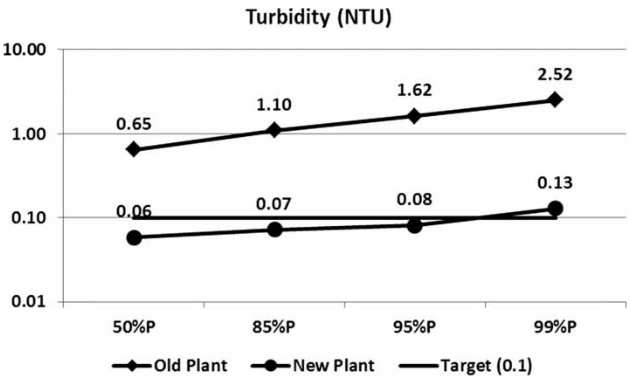

Figure 3 | Turbidity Old Plant and New Plant.

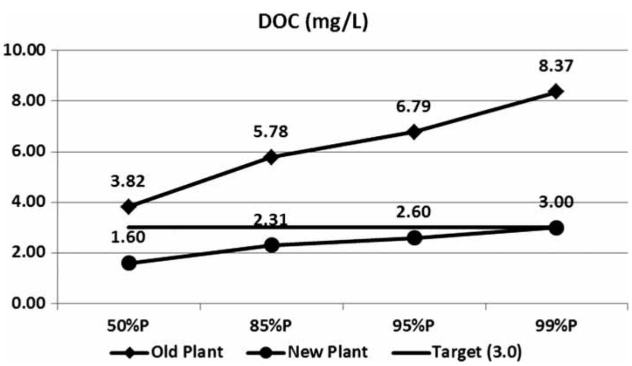

Figure 4 | DOC Old Plant and New Plant.

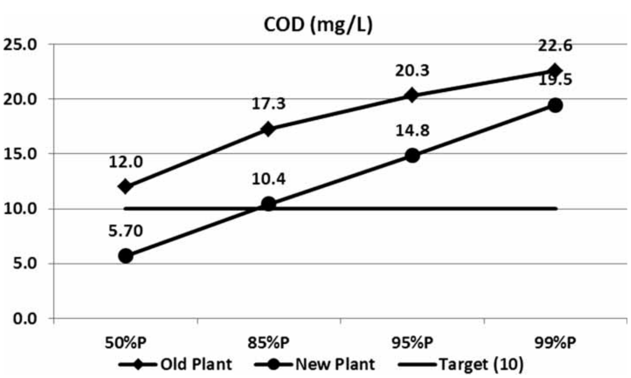

Figure 5 | COD Old Plant and New Plant.

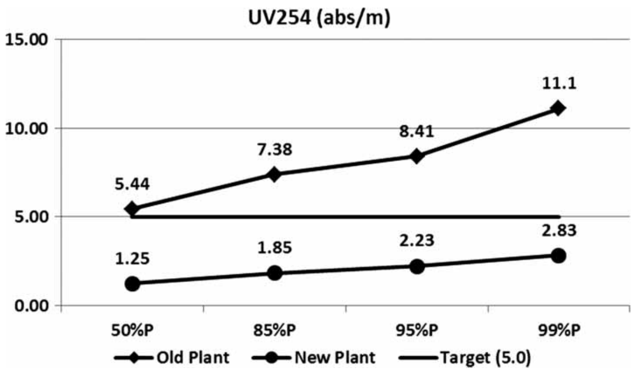

Figure 6 | UV254 Old Plant and New Plant.

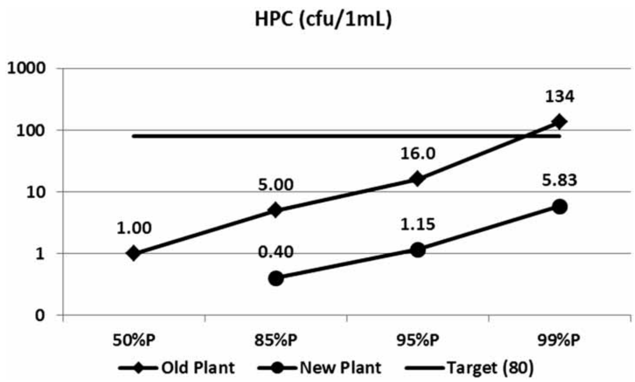

Figure 7 | HPC Old Plant and New Plant.

reduced with 1 log by comparing the final water quality data of Old Plant and New Plant. In addition, the organic composite parameters DOC, COD and UV_{254} indicate a considerable reduction and improvement in concentration levels.

Figure 4 (DOC), Figure 5 (COD) and Figure 6 (UV_{254}) are a proof that the additional barriers, namely pre-ozonation, EC, ozonation and BAC followed by GAC in the New Plant compared with normal coagulation, and carbon adsorption without any oxidation in the Old Plant vastly enhanced the organic removal. COD is the parameter that did not follow this pattern. There could be two reasons for this. Firstly, the COD method is not accurate lower than 12 mg/l. Secondly, the COD seems to contain a dissolved fraction of inert material (most probably organic and inorganic material) which is not removed by the treatment steps described above. This is also evident when one compares the percentage hypothetical fractions of DOC and COD during the operational period (values based on 95^{th} percentile) of the New Plant, where the biodegradable fractions are 27 versus 10%, the non-biodegradable-adsorbable fractions are 33 versus 22% and the non-biodegradable-non-adsorbable fractions are 40 versus 68%. This

Table 5 | Macro elements which are important in water supply which are not removed by the New Plant and bromate in final water and distribution system (values with* are raw design values and NS = not specified)

	New Plant-IN TKN (mg/l-N)	New Plant-OUT TKN (mg/l-N)	New Plant-IN NH_4 (mg/l-N)	New Plant-OUT NH_4 (mg/l-N)	New Plant-IN NO_3 (mg/l-N)	New Plant-OUT NO_3 (mg/l-N)	New Plant-IN TDS (mg/l)	New Plant-OUT TDS (mg/l)	New Plant-OUT BrO_3 (mg/l)	Distribution system BrO_3 (mg/l)
50%P	1.90	0.25	0.35	0.05	10.00	10.00	737	858	0.08	0.02
85%P	3.30	0.51	0.98	0.15	16.00	16.00	858	973	.011	0.02
95%P	4.39	1.19	1.80	0.15	20.45	21.00	931	1,039	0.12	0.03
99%P	7.79	2.30	3.01	0.26	27.45	26.88	1,005	1,126	0.13	0.03
Target	3.31*	1.56	2.30*	NS	7.71*	NS	563*	1,000	0.01	0.01
Max	NS	1.95	NS	0.10	NS	10.00	NS	1,200	0.025	0.025
(n)	344	343	363	361	352	353	369	368	17	40

observation was already reported during the pilot studies (Miecznic 1998). The 95th percentile of COD was within the maximum allowable target of 15 mg/l. PAC was recommended as an additional operational safety barrier in the event that another barrier should fail. During an ozone failure PAC was dosed. Increased fouling of the UF membranes resulted in an increase in backwash cycles. PAC dosing was discontinued and the flow through the plant was reduced to the point that the backwash cycles could be managed. No tests were run to see if the addition of powder activated carbon would have had a positive influence on the COD removal. It is clear that DOC and UV_{254} are more sensitive methods to measure the presence of organic carbon than the COD method. Further investigations into the fractionation of DOC have revealed that the different DOC fractions react differently to different treatment steps (Jacquemet *et al.* 2007). The COD will be phased out as surrogate parameter for drinking water treatment.

As mentioned earlier, direct potable reclamation was also pioneered in Southern Africa since the 1950s. Each treatment step was rigorously researched and tested under extreme conditions. Full scale operation added further confidence. An epidemiological study was conducted (Isaäcson *et al.* 1987) over a period of ten years and concluded that no correlation could be found between the consumption of reclaimed water, natural water and disease patterns recorded. Diseases were rather related to cultural differences in lifestyles. Although proposed, such a study was not conducted prior or during the operation of the New Plant, for the following reasons: the sample group would be too small and diverse, the control would be too small, enormous movement of people from one township to another, questionable medical records and finally the cost would be too high for an effort that would likely have a similar conclusion as the first study. The focus was rather to concentrate on rigorous monitoring, implementing ISO and HACCP certification and conducting a risk assessment (Ander & Forss 2011) for the whole treatment process, following a ranking approach as suggested in Water Safety Plans (WHO 2009). Vigilance, training and motivation of the operational staff play a major part of the operational success of the reclamation scheme in Windhoek. Continued research is part of the agreement with the private operator of the plant. A steering committee suggests new research projects and reviews all the research work on an annual basis. In this way students are exposed to the field of water reuse (Menge *et al.* 2007). A special monitoring programme for the distribution is followed, which is described in detail by Iiputa *et al.* 2008.

In addition to routine monitoring, a separate health research programme is conducted in parallel, which covers virus testing for cytopathogenic effect and polymerase chain reaction toxicity (waterflea lethality and urease enzyme), as well as Ames *Salmonella* mutagenicity testing. These tests are negative for the water sources providing Windhoek with treated drinking water. A special programme to trace the removal of endocrine disrupting compounds (EDCs) and medical substances has until now, not shown that these compounds are present in the final water of the New Plant.

The final water quality impact of the New Plant on the distribution system is twofold. The parameters mentioned earlier have a positive influence on the distribution system and

Table 6 | Comparison of the water quality in the distribution system with that of underground, surface sources and reclaimed water with the Namibian Guideline Group A quality over the period January 2006 to June 2007 (all values are based the 95th% percentile)

Parameters		**Units**	**Borehole KA**	**Borehole KK**	**Borehole PQ**	**Borehole ALL**	**Surface Water**	**Reclaimed Water**	**Reservoirs**	**Consumer**	**Nam Group A**
Aesthetic	pH	–	7.74	7.93	8.01	7.90	8.02	8.4	7.94	8.01	6,0-9,0
	Conductivity	mS/m 25°C	130	68	**165**	108	29	**160**	75	67	150
	TDS calc	mg/l	871	457	**1106**	722	194	**1072**	503	449	1000
	Turbidity	NTU	5.27	4.64	8.08	4.88	1.1	0.082	1.2	1.5	1.0
	Total alkalinity	mg/l $CaCO_3$	513	237	246	334	111	237	283	228	–
	Total hardness	mg/l $CaCO_3$	350	252	281	281	110	242	229	226	300
	Calcium hardness	mg/l $CaCO_3$	220	112	93	158	71	153	145	140	375
	Magnesium hardness	mg/l $CaCO_3$	125	69	85	87	29	87	85	83	290
	Chlorophyll A	μg/l	–	–	–	–	1.02	0.95	–		–
	Temperature	°C	28	25	58.5	34.1	27	25.8	27	27	–
Bacteria and viruses	HPC	per 1 ml	**10000**	152	**10000**	**5076**	**10000**	1	**232**	**295**	100
	Total coliform	per 100 ml	**10**	0	**45**	**13.8**	**0**	0	0	0	0
	Faecal coliform	per 100 ml	–	–	–	–	–	0	–		0
	E. coli Tryptone	per 100 ml	**57**	0	**48**	**35**	-	0	0	**1.9**	0
	Faecal streptococci	per 100 ml	–	–	–	–	–	0	–	–	–
	Pseudomonas	per 100 ml	–	–	–	–	–	0	–	–	–
	Clostridium spores	cfu 100 ml	–	–	–	–	–	0	–	–	–
	Clostridium viable	cfu 100 ml	–	–	–	–	–	0	–	–	–
	Som. coliphage 100 ml	PFU/100 ml	–	–	–	–	–	0	–	–	–
Protozoa	*Giardia*		–	–	–	–	0	0	0	–	–
	Cryptosporidium		–	–	–	–	0	0	0	–	–
Organics and micropollutants	DOC	mg/l	1.39	3.15	1.5	2.29	4.77	2.64	4.2	4.5	–
	COD dis	mg/l	–	–	–	–	–	17.2	–	–	–
	UV 254 dis	abs/cm	0.0691	0.0649	0.0582	0.0618	0.0759	0.0197	0.0707	0.0662	–
Disinfection byproducts	Free chlorine	mg/l	2.2	2.2	–	1.95	1.26	1.72	2.2	2.2	0,1–5,0
	Total chlorine	mg/l	2.2	2.2	–	2.07	1.68	–	2.2	2.2	0,1–5,0
	Total trihalomethane	μg/l	30	147	18	38	96	26	107	107	–
	Chloroform	μg/l	10	73	6	16	54	3	57	57	–
	Dichloromonobromoform	μg/l	9	43	7	13	26	4	27	27	–
	Monochlorodibromoform	μg/l	9	21	4	6	11	9	16	16	–
	Bromoform	μg/l	2	10	1	3	5	10	7	7	-
Stability	$CaCO_3$ precipitation pot.	mg/l $CaCO_3$	–	–	–	–	–	–	–	–	–

(*Continued*)

Table 6 | Continued

Parameters		Units	Borehole KA	Borehole KK	Borehole PQ	Borehole ALL	Surface Water	Reclaimed Water	Reservoirs	Consumer	Nam Group A
Natural and effluent organic matter	TKN	mg/l as N	–	–	–	–	–	4.37	–	–	–
	Ammonia (NH_3-N)	mg/l as N	0.27	0.16	0.27	0.215	0.27	0.09	0.1595	0.27	1.0
	Ortho phosphate (P)	mg/l	0.9	0.91	0.9	0.9	0.9	0.9	0.9	0.9	–
	Nitrate (HO_3-N)	mg/l as N	1	4.76	1.79	3.07	1	22	5.84	5.72	10
	Nitrite (NQ_2-N)	mg/l as N	0.5	0.345	0.5	0.42	0.5	0l5	0.5	0.5	–
Inorganics	K	mg/l	24.7	10.74	36.9	20.8	9.3	39.57	16.7	15.8	200
	Na	mg/l	**101**	57	**158**	93	18.5	**266**	96	97	100
	CI	mg/l	42	66	71	61	23.6	**277**	118	110	250
	SO_4	mg/l	**265**	CO	**496**	**224**	20	187	101	85	200
	F	mg/l	**2.10**	0.36	**4.37**	1.79	0.33	0.61	0.45	0.48	1,5
	Br	mg/l	0.20	0.10	0.30	0.11	0.127	0.14	0.15	0.11	1.0
	Mn	mg/l	–	–	–	**0.38**	0.02	0.01	0.03	0.03	0.05
	Fe	mg/l	**0.55**	**0.62**	**0.35**	**0.54**	0.06	0.02	0.08	0.1	0.1

improve the quality. The DOC of the surface water that is blended with the potable reclaimed water is between 2.5 after a good rainy season and 8.0 mg/l during times of drought. The high nitrates released from the wastewater treatment plant, entering the New Plant, are diluted by the natural water and raise the level in the distribution system slightly. The 95% probability is 5.3 mg/l-N (guideline value 10). The TDSs are raised considerably due to the higher percentage of recycling, especially during low rainfall periods, but have not exceeded the maximum guideline of 800 mg/l. During the design stage the WHO bromate guideline was 0.025 mg/l (WHO 1993), which was then changed to 0.01 mg/l (WHO 2003). Due to high bromide levels in the wastewater, it is very difficult to reach the 0.01 mg/l guideline target, without compromising the purpose of the ozonation step. For this reason partial treatment with RO is considered, which will reduce the concentration well within guideline levels. RO is considered and pilot testing has started in the second half of 2011. The operational results are currently being evaluated to calculate the operating cost. The quality results are well within expected limits. It can be argued that in an inland situation, with extreme water shortages, that RO would not be a preferred option, as the water losses can amount to between 10 and 15% and the removal of brine would also be a cost factor to be considered.

The reclamation scheme has operated reliably and has saved Windhoek numerous times from severe water restrictions and in this way potable reclamation in Windhoek has contributed to a stable economy despite severe droughts and water shortages.

CONCLUSIONS

Were design expectations met?

The final water quality targets set out in the design were achieved by adding:

1. UF as an additional barrier for turbidity, microorganism and protozoa removal.
2. Ozonation as treatment step to reduce organic precursors for THM and effectively deal with EDCs and to reduce the NOM content of the water.

From the data analysed and reported, it is concluded, that the multiple barrier system as incorporated in the New Plant has indeed achieved the water quality as set out in the design criteria of the plant.

What would be done differently if we were to design a new plant?

During the design phase in 1996 it was obvious that membranes would be preferred as a primary treatment step to remove suspended matter. At that time, the cost of membranes was too high and there was no track record available on membrane life over an extended period in wastewater treatment. The ozone, BAC and GAC combination proved in numerous international studies to be effective in reducing organic compounds, especially EDCs and pharmaceuticals. A possible combination of treatment steps could be:

1. Membrane technology, which would replace a clarifier at the biological treatment plant, chemical addition, flocculation, DAF and RSF.
2. An oxidation and biological adsorption (BAC) and adsorption (GAC) step would be maintained, to provide an additional safety barrier against fluctuations in wastewater effluent DOC and N concentrations.
3. Partial or full RO (depending on the situation) would be considered as a polishing step to reduce DBPs, the salt concentration and remove the refractive or non-biodegradable non-absorbable organic portion of DOC to lower than 0.1 mg/l.
4. Ultraviolet as final disinfection with the addition of a chlorine residual of 0.4 mg/l to protect the water in the distribution system in a warm climate with temperatures between 15 and 32 °C.

Does direct potable reclamation have a future?

Windhoek's residents have been supplied with directly reclaimed water for nearly 43 years. The additional treatment barriers discussed, have added an additional margin of safety, shown by the data. With a proposed treatment train of a membrane-ozone-BAC-GAC-RO-UV the bacteria, virus and protozoa should be completely removed, even at very high fluctuating concentrations. Organic substances, measured as DOC concentration would be below 0.01 mg/l. Variations in raw water ammonia concentrations would also be reduced.

The Windhoek experience has proven that direct potable reclamation indeed has a future in areas where alternatives are not available.

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