Chapter 8

Managed Aquifer Recharge in Atlantis, South Africa

Gideon Tredoux, Bettina Genthe, Maronel Steyn and~~,~~ Jason Germanis ~~and Bettina Genthe~~

8.1 INTRODUCTION

8.1.1 Historical background

The town of Atlantis with a population exceeding 60,000 is located 50 km north of the centre of the City of Cape Town and presently forms part of the metropolitan area. Previously, the area resorted under the authority of the Cape Divisional Council and in 1976, the new Atlantis development was declared a National Growth Point, under the government's "decentralisation initiative". As it was planned to become an industrial growth point various incentives were introduced for attracting industries to the area. As the west coast is semiarid, the importation of surface water from the Berg River system, located some 70km distant, was planned as the permanent water supply source. However, in 1972 the Department of Water Affairs and Forestry started developing local groundwater as an interim measure allowing for the postponement of the pipeline construction. In the early phases of development all water supply was provided by the perennial springs at Silwerstroom. These produced an average flow of about 1 x 10^6 m^3 per year. A weir was constructed to capture the spring flow in a small dam, from which it was pumped to the growing town. Subsequently two wellfields were developed and over the next 25 years the local groundwater proved itself as a sustainable water resource providing the bulk of the water demand. Only in 2000 limited augmentation of the water supply by surface water was introduced via an alternative route.

More than three decades ago, at the time the Atlantis water resource management scheme was developed the Water Act No 54 of 1956 was in force in South Africa. That act did not have any sections dealing with the authorisation and regulation of artificial groundwater recharge nor with the recycling of water. In 1979 the CSIR concluded pilot scale artificial recharge studies using treated wastewater in the Cape Flats (Tredoux *et al.*, 1980). Hence the Regional Office of the Department of Water Affairs and Forestry requested the local authority to set up a monitoring programme for the Atlantis water supply scheme in collaboration with the CSIR.

The National Water Act (Act No 36 of 1998) replaced the Water Act of 1956 and this act specifically controlled artificial groundwater recharge through a permitting system. However, it is a gradual process, and whereas new systems will only be permitted once pilot studies are completed and strict requirements are met, the permitting of existing operations has not been completed. Nevertheless, in 2002 an audit was recommended covering all legal compliances, licences, and authorisations required to legalise the Atlantis water system (Tredoux and Cavé, 2002).

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Artificial recharge has played a key role in the augmentation of the groundwater supplies at Atlantis. Initially, indirect recycling of wastewater and urban stormwater was considered an economic means of wastewater disposal as it eliminated the need for a marine outfall for such discharges. Soon water conservation became a key feature of the scheme and various combinations of urban stormwater and treated wastewater from sources in the town have been infiltrated into the aquifer over the years to maximise the amount of available groundwater. At the same time, several refinements have been made to the artificial recharge system to ensure that any potential deterioration of water quality does not jeopardise the scheme. In this way the Atlantis Water Resource Management Scheme has pioneered the application of artificial groundwater recharge as a water management tool for bulk water supply in southern Africa.

8.1.2 Motivations for recharge and use of abstracted water

In the South African coastal areas marine discharge of wastewater used to be the preferred disposal option. Strict marine water quality criteria promulgated by the Department of Water Affairs and Forestry in the 1980s and enforced by means of a permitting process required detailed monitoring programmes for marine water quality and filter feeders near such marine outfalls. The associated costs gradually became prohibitive and outfall designs had to be refined to ensure thorough blending and dilution with seawater to achieve the microbiological criteria within a set distance from the outfall. Therefore, the initial motivation for managed aquifer recharge at Atlantis was to obviate a marine outfall for wastewater disposal. Recycling of the water was, however, a secondary objective. Similarly the case was made to add the urban stormwater runoff to the wastewater recharge system instead of disposal into the ocean.

Once the aquifer was studied more intensively, it emerged that the natural yield of the aquifer is too little to sustain the water supply to Atlantis. This need for water recycling introduced a new perspective to the water management system at Atlantis and the management of water quality throughout the system became a key issue from that time. Domestic and industrial wastewater is treated separately and only the domestic wastewater is recycled. Similarly the peak flow and base flow in the stormwater system are channelled to different recharge basins to maintain good quality water in selected areas of the aquifer. Summarizing the MAR scheme in Atlantis serves several purposes:

- Augment local groundwater supplies by recycling (about 25 - 30% of current water demand)
- Prevent seawater intrusion into the aquifer
- Sensible stormwater and treated wastewater disposal, obviating need for costly marine discharge

8.1.3 Authorisation procedure

More than three decades ago, at the time the Atlantis water resource management scheme was developed, the Water Act No 54 of 1956 was still in force in South Africa. The act did not have any sections dealing with the authorisation and regulation of artificial groundwater recharge or the recycling of water, and all the Regional Offices of the Department of Water Affairs required was a general monitoring programme for the water supply scheme. The standard requirements for a potable water supply (SANS-241:2006) were applied to the water distributed in the town of Atlantis.

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8.2 DESCRIPTION OF THE TEST SITE

8.2.1 Study area

Atlantis is located along the semiarid to arid west coast of South Africa (Figure 8.1) and has a Mediterranean climate, with most of the 450 mm mean annual rainfall received from April to September. As a result of the sandy surface over most of the area, recharge percentages of 15 to 30% of the annual rainfall are generally experienced, the higher recharge occurring in the unvegetated dune area.

The aquifer covers an area of about 130 km^2, stretching inland from the Atlantic Ocean to the town itself in the east. It pinches out against the Malmesbury Group shales and Cape granite outcrops to the north and east. The thin aquifer slopes steeply in a southwesterly direction from a maximum elevation of about 160 m in the north down to sea level in the west. A small part of the aquifer extends below sea level in the Witzand and Silwerstroom areas. The granite outcrops of Dassenberg, Kanonkop and Mamre-Darling near Mamre form the highest points in the area, at heights of 210 to 410 m above sea level (van der Merwe, 1983).

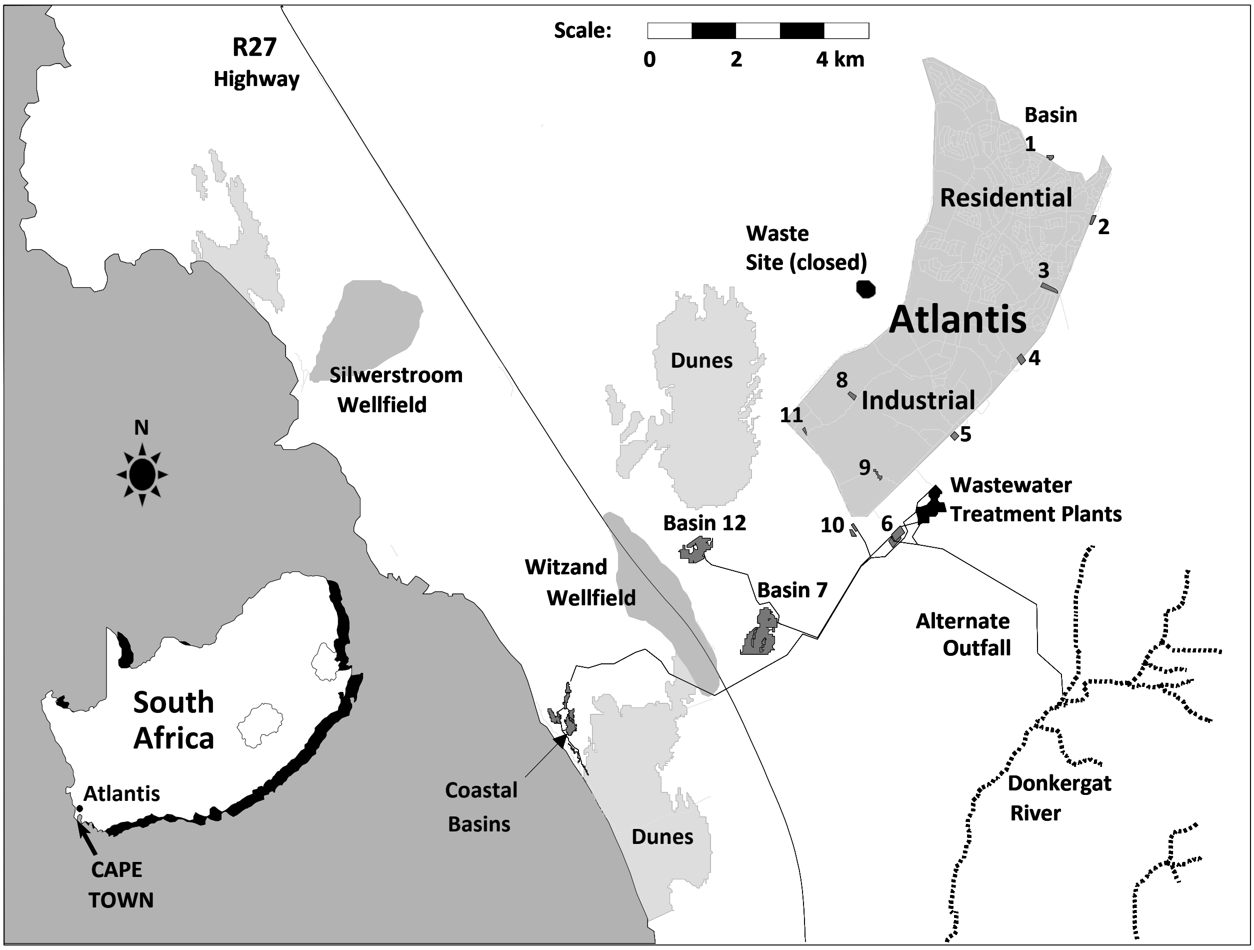

Figure 8.1: Location and layout of Atlantis water supply system

8.2.2 Hydrogeology

The primary coastal aquifer system in the Atlantis area is formed of unconsolidated Cenozoic sediments of tertiary to recent age, overlying Malmesbury Group bedrock consisting of greywacke and phyllitic shale (Van der Merwe, 1983). Granite plutons have intruded the bedrock. The Cenozoic successions in the area consist of quartz sands belonging to the Sandveld Group. These comprise a lower unit of shallow marine origin, the Varswater Formation, and an upper, primarily aeolian unit, the Bredasdorp Formation (Rogers, 1980). The Bredasdorp Formation is subdivided into the Springfontein, Mamre and Witzand Members. The base of the Springfontein Member is a peaty sand bed, while the rest of the member consists of relatively well-sorted quartz sand, free of shelly material, ranging from fine- to coarse-grained. The Witzand Member overlies the central part of the area and consists of calcareous quartz sand, shell fragments and discontinuous calcrete layers (Figure 8.2 and 8.3). The total sand cover reaches a thickness of 60 m in the central area, with an average thickness of 25 m (Van der Merwe, 1983).

The bedrock also contains groundwater, but the weathered upper zone of the shale forms an impervious clay layer preventing any exchange of groundwater. Sandy-peat layers of varying thickness and calcrete lenses are often interbedded in the aquifer or interfinger laterally with clean sands, producing local heterogeneities in aquifer properties.

Groundwater flows westwards to southwestwards and discharges along the coast in areas where the aquifer dips below sea level. The groundwater table has a relatively steep gradient (approximately 1:58) towards the coast. The saturated thickness varies considerably, but seldom exceeds 35 m. Groundwater is abstracted in two wellfields, Silwerstroom in the north and Witzand in the south (Figure 8.1). Due to topographic constraints, artificial recharge is only practised near the Witzand wellfield in the south. The overlying Witzand Member is a calcareous quartz sand succession containing shell fragments and cemented calcrete horizons.

The Atlantis area is practically devoid of surface drainage features, with the exception of the Buffels River at Silwerstroom. The Donkergat and Sout rivers flow to the south of the Atlantis area in winter, while surface drainage to the north and east of Atlantis contributes to the catchment areas of the Modder and Diep rivers respectively. All these rivers are non-perennial, drying up in summer.

Perennial springs feeding the Buffels River near the coast at Silwerstroom have been used for water supply since 1976. There is also a spring at Mamre and a minor spring at Groot Springfontein.

Figure 8.2: Geology of the Atlantis area

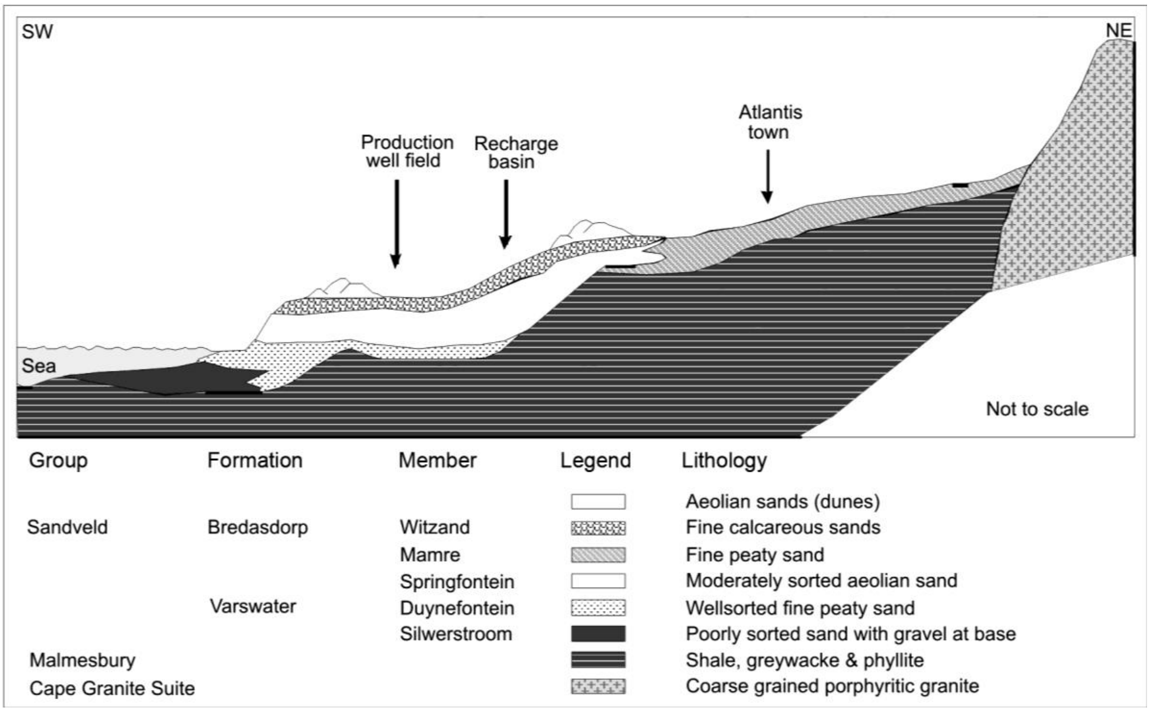

Figure 8.3: Geological cross section through the Atlantis aquifer

8.2.3 Process design and operation

The various components of the Atlantis Water Resources Management System are shown schematically in Figure 8.4. The natural characteristics of the aquifer material affect the groundwater quality, e.g. imparting high hardness to the water, significant dissolved organic carbon and, in certain parts, measurable dissolved iron, or high salinity to the water. The hardness is reduced by ion exchange softening part of the flow. In the process iron is also partly removed but the organic carbon remains in solution.

The large volumes of stormwater runoff that would be generated after urbanisation and the associated hardening of surfaces was seen as a valuable water source for augmenting water supplies and it prompted the construction of an appropriate stormwater collection system. This consists of twelve detention and retention basins and the necessary interconnecting pipelines with peak flow reduction features (Liebenberg and Stander, 1976). The stormwater system at Atlantis was redesigned to allow flexibility for controlling water flows of differing salinity and to collect the best quality water for infiltration into the aquifer. Low salinity flows are channelled into two large spreading basins, Basin #7 and Basin #12, for artificial recharge up-gradient of the Witzand wellfield. Higher salinity baseflow is diverted to the coastal basins or to the Donkergat River in the south (Figure 8.1). Discharges during storm events can reach up to 72 000 m^3/d at Atlantis, while summer baseflow, averages 2160 m^3/d (Wright, 1994). The baseflow is mostly groundwater entering the stormwater pipelines in areas where these are below the water table.

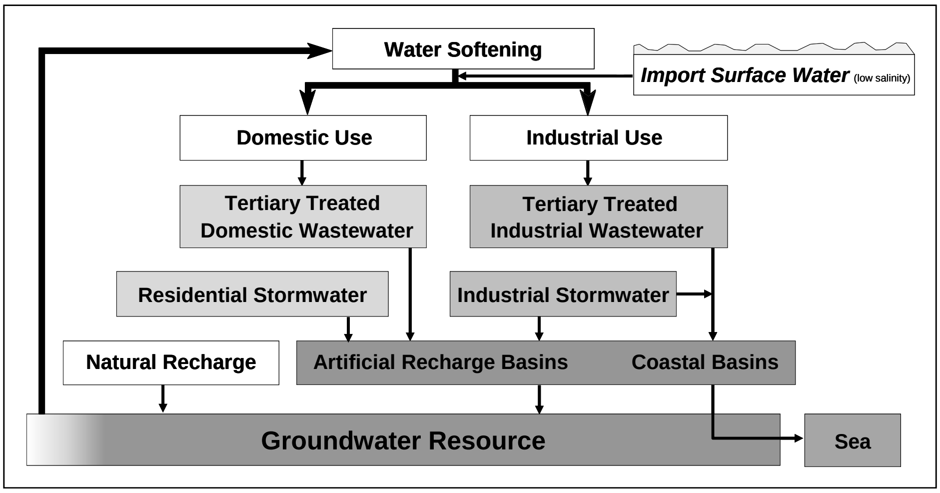

Figure 8.4: Components of the Atlantis Water Resource Management System

Initially all wastewater was treated in a single wastewater treatment plant and all the treated effluent used for artificial recharge. In 1986 this practice was discontinued due to water quality considerations and a separate treatment plant was constructed for domestic wastewater treatment. This came on line in the mid 1990s. The domestic wastewater undergoes full secondary treatment with nitrification-denitrification steps (anaerobic-anoxic-aerobic). The effluent from the secondary settling tanks is polished in a series of maturation ponds (Figure 8.5). The maturation pond effluent is blended with the urban stormwater runoff before discharge into the main recharge basins #7 and #12. The more saline treated industrial wastewater is discharged into the coastal recharge basins and seeps into the ocean through the subsurface.

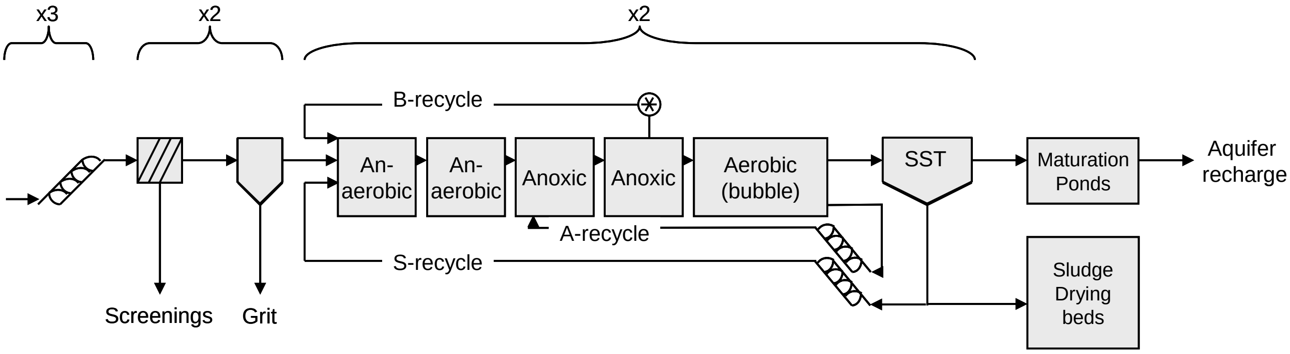

Figure 8.5: Schematic diagram of domestic wastewater treatment plant at Atlantis

The characteristics of the recharge facilities consisting of various large basins are shown in Table 1. Basin 7 is the largest and is mostly wet due to the larger volume of water reaching this basin, the shallow groundwater table, and the low infiltration rate. Basin 12 is mostly dry as it receives predominantly peak flow stormwater, has a deeper water table, and a higher infiltration rate. The three coastal basins operate in series with the primary basin always full and some overflow in one secondary basin. It is estimated that on average approximately 7500 m^3/d of stormwater and wastewater is recharged up-gradient of the well field (Basins 7 and 12, Figure 8.6) augmenting the water supply by more than

2.7 Mm^3/a. Some 4000 m^3/d higher salinity industrial wastewater is treated and discharged into the coastal basins down gradient of the well field close to the ocean.

Table 8.1 Recharge facility characteristics (average values)

Facility	Area (ha)*	Unsaturated zone (m)	Infiltration rate (m/day)**
Basin 7	28.3	1.5	0.01
Basin 12	16.8	4.5	0.16
Coastal Basins	12.5	10.5	0.11

* Total basin area when full; Basin 12 mostly dry

** Rate based on total basin area

8.3 TECHNOLOGY PERFORMANCE AND CONTAMINANT MONITORING

The Atlantis water resource management scheme has been fully operational for nearly three decades and during that time several upgrades and modifications were implemented. In 2006 a number of further improvements and modifications were identified. However, due to the participation of the CSIR in the Reclaim Water Project and the selection of the scheme as a study site for the project it was decided not to implement any modifications for the duration of the project and only to carry out the routine maintenance and monitoring.

The CSIR joined the Reclaim Water Project in January 2007 (*i.e.* month 16) which is during summer in the southern hemisphere. For the case study at Atlantis the key aspect was the evaluation of the performance of the system from a water quality perspective, *i.e.* the removal of nutrients, heavy metals, endocrine disruptors and other organic micro-components such as pharmaceuticals, but also bacteria, viruses and other micro-organisms. These data were needed for determining the efficiency of removal of the various pollutants and the health risks related to the remaining contaminants. Hazard mitigation is envisaged for ensuring the longer term viability of the system. A mass balance-based sustainability analysis for the Atlantis artificial groundwater recharge system was attempted.

For determining the efficiency of removal of the contaminants listed above the following groups of samples were taken at the indicated points, *i.e.* the input, in the aquifer, and product. The sampling points are shown schematically in Figure 6.

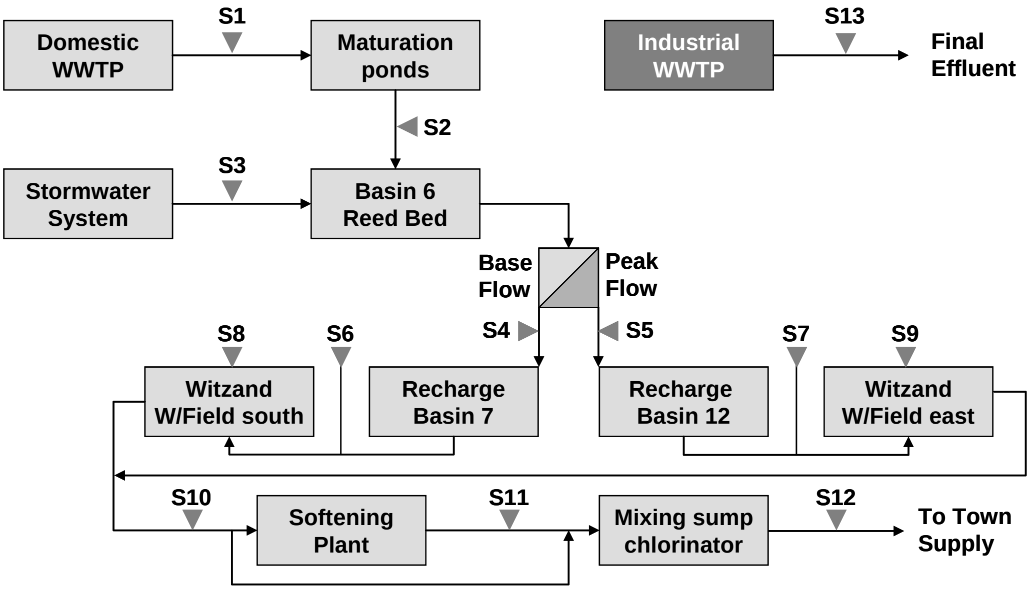

Figure 8.6: Schematic layout of the Atlantis system showing the monitoring points

i) Sampling points 1 to 5: The feed water sources are: secondary treated domestic wastewater, before and after the maturation ponds, the final stormwater, as well as the blend after passing through the reed bed that is used for recharging the aquifer, both at peak flow and base flow.

ii) Sampling points 6 to 10: The groundwater blend was sampled down gradient of each of the recharge Basins #7 and #12, approximately halfway to the production well field. Groundwater was sampled at two production boreholes influenced by the respective recharge operations at the two basins. Finally, the groundwater blend from all production boreholes was sampled immediately before the softening process.

iii) Sampling points 11 to 12: The product water after softening was sampled in order to determine the effect of softening on the general water quality. The last sample represented the final chlorinated water before pumping to the town for determining the effect of the chlorination on the overall water quality.

iv) Sampling point 13: The treated industrial wastewater which has a higher salinity and is discharged into the coastal recharge basins, *i.e.* which does not form part of the recycling system. Sampling recorded the composition of the industrial wastewater for providing an indication of the possibility to make better use of this source instead of being discharged into basins in the coastal dunes and seeping into the ocean.

Sampling at Atlantis followed the Reclaim Water standardised Protocol 1 and Protocol 2 (cf. chapter 2). Sampling according to Protocol 1 was completed four times while Protocol 2 sampling was completed twice (Table 8.2). The testing programme also included characterisation of natural organic matter and effluent organic matter. This was done together with the partners at TUB and IHE UNESCO due to a lack of suitable local facilities and expertise. Sampling for pharmaceuticals and contrast media took place in June 2008 in collaboration with the project partners of BfG. A second sampling using the SPE method was completed in October 2008 to confirm the results of the first survey.

Table 8.2: Sampling programme completed at Atlantis

Sampling	Season / Basin	Dates
Protocol 1	Autumn	May 2007
	Winter	August 2007
	Spring	October 2007
	Summer	February 2008
Protocol 2	Winter	August 2007
	Summer	March 2008
Pharmaceuticals and contrast media	Winter	August 2008
	Spring	October 2008
Soil sampling	Basin #12	July 2008
	Basin #7	September 2008

The soil and unsaturated zone sampling in the two recharge basins, #7 and #12 took place in July and September 2008 as shown in the site schedule (Table 8.2). This was not ideal due to the fact that it was in the midst of the rainy season but it had to be organised when the auger drill was available for the unsaturated zone sampling (Figure 8.7). For this purpose all recharge water was at first diverted to Basin #7. Afterwards, all the water was diverted to Basin #12 for sampling in Basin #7. In the case of Basin #7 only soil sampling was possible due to the shallow groundwater table. The main purpose of the soil sampling was to attempt a mass balance for the various constituents (contaminants) in the recharged water. The soil sample of the first 50 cm seen in the split spoon sampling unit in Figure 8.7 (right), clearly shows the filtering effect of the infiltration surface in the basin.

Figure 8.7: Auger drilling for unsaturated zone sampling in Basin #12; split spoon core (right)

The four sets of results for Protocol 1 (standard parameters) and two sets for Protocol 2 (micro-contaminants) presented in Table 8.4 allows a qualitative evaluation of the overall performance of the water recycling scheme with regard to chemistry and microbiology. The Protocol 1 sampling results are discussed below. From a water supply point of view the general inorganic chemistry of the water supply at Atlantis is of key importance due to the salinity and hardness of the groundwater. The average values of the macro chemical results at the different sampling points are illustrated by means of Stiff diagrams in Figure 8.8. In each diagram the cations are shown on the left and the anions on the right. For direct comparison the concentrations of the parameters are presented in milliequivalents per litre (meq/L).

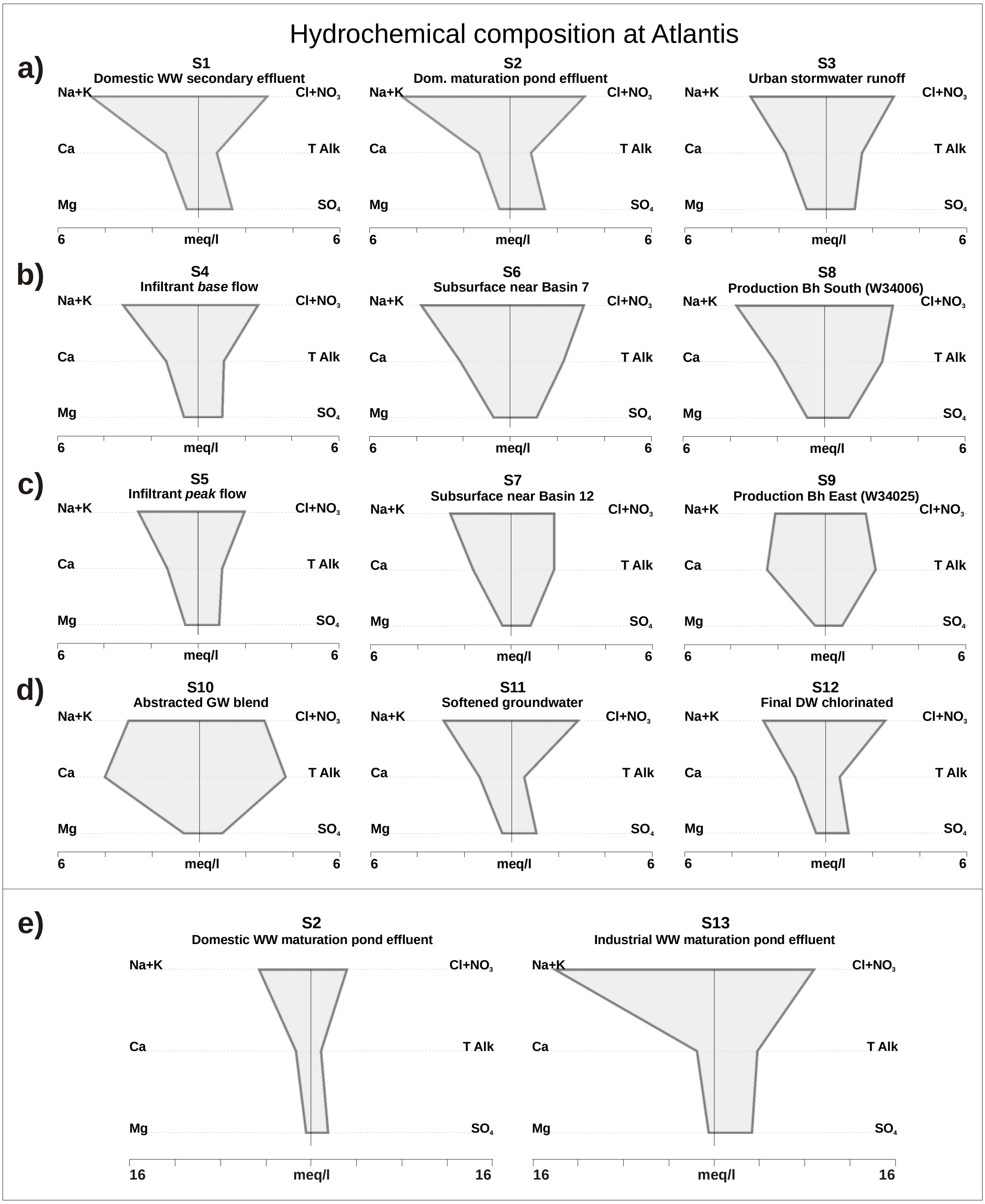

Figure 8.8: Hydrochemistry and salinity in the Atlantis recycling system (concentration scale is different in Series (e))

In the case of the first four sets of diagrams a) to d) the full scales for the cations and anions are both 6 meq/L while for the last set of two diagrams e) the full scale is 16 meq/L. On the top axis of each diagram, sodium and potassium are shown opposite chloride and nitrate, in the middle calcium opposite total alkalinity, and on the bottom axis magnesium opposite sulphate.

The series a) to d) in Figure 8.8 shows the sampling points S1 to S12 which represent the various stages in the recycling. Series a) represents the source water and it is evident that the maturation pond effluent (S2) is a sodium chloride water which is chemically very similar to the secondary effluent (S1). Inspection of the data shows that only the nitrate decreased slightly during the residence in the maturation ponds. The urban stormwater (S3) has a slightly different composition with a little less sodium and chloride but slightly higher calcium, magnesium, and bicarbonate (total alkalinity).

In series b) the blend of maturation pond effluent and stormwater used for recharge in Basin #7 is shown at S4. As the water progresses through the subsurface past sampling point S6 to the nearest production borehole (W34006, sampling point S8) both calcium and bicarbonate increase to some extent. These changes together with the slight increase in sodium and chloride are ascribed to the dissolution of calcium carbonate from the aquifer and blending with slightly more saline groundwater. Series c) represents the lower salinity parallel flow path from Basin #12 past observation point S7 to the closest production borehole (W34025, sampling point S9) in the wellfield. In this case calcium and bicarbonate also increase but both sodium and chloride decrease due to blending with low salinity natural groundwater. The impact of the lower salinity groundwater is clearly visible by comparison of the two production boreholes at S8 and S9.

Series d) shows the groundwater blend from the whole wellfield (S10), the softened water (S11) and the final chlorinated water (S12). It is evident that sodium and chloride levels in the blend (S10) are similar to those at the production borehole S8 but higher than at production borehole S9. The blend also has a significantly higher calcium and bicarbonate content and this represents the impact of the natural groundwater in the aquifer which is unaffected by artificial groundwater recharge and relatively hard. After softening, calcium, magnesium, and particularly bicarbonate are significantly lower (S11) and the composition remains the same after chlorination (S12). During use in the town the sodium, chloride and sulphate concentrations increase notably when considering the treated domestic effluent (S1) and comparing it with the final chlorinated water (S12).

In series e) the domestic and industrial wastewater are compared after the maturation ponds (S2 and S13). The diagrams in series e) were redrawn on a different scale to accommodate the higher salinity of the industrial wastewater hence the diagram for S2 in series e) looks different to that in series a). The large increase in most parameters (compare S13 with S12) during use in the industries is noteworthy and underlines the necessity from a salinity viewpoint to divert the industrial wastewater from the recycling system.

8.3.1 Dissolved organic carbon

Dissolved organic carbon (DOC) levels are relatively high both in the treated wastewater and in the stormwater (Figure 8.9). The stormwater shows the largest variation in DOC levels at S3, the outlet from the stormwater system and before the reed bed, possibly due at times to intensive wash-off from roads and other surfaces in town.

Via both recharge basins (S6 and S8 representing the Basin #7 route, and S7 and S9 representing the Basin #12 route) there is a significant reduction in DOC but the level in the abstracted groundwater is still approximately 4 mg/L. In the case of Basin #12 receiving mainly peak flow stormwater and a thicker unsaturated zone the resultant groundwater has a lower DOC when comparing production borehole S9 with S8. The presence of natural organic matter in the groundwater elevates the DOC level in the final water. The DOC is of concern due to the potential mobilization of iron from the geological material which causes clogging of the production boreholes. Furthermore, the final product water is chlorinated leading to the formation of trihalomethane compounds. The much higher DOC level in the industrial wastewater (S13) is noteworthy and supports the decision to exclude the industrial wastewater from recycling.

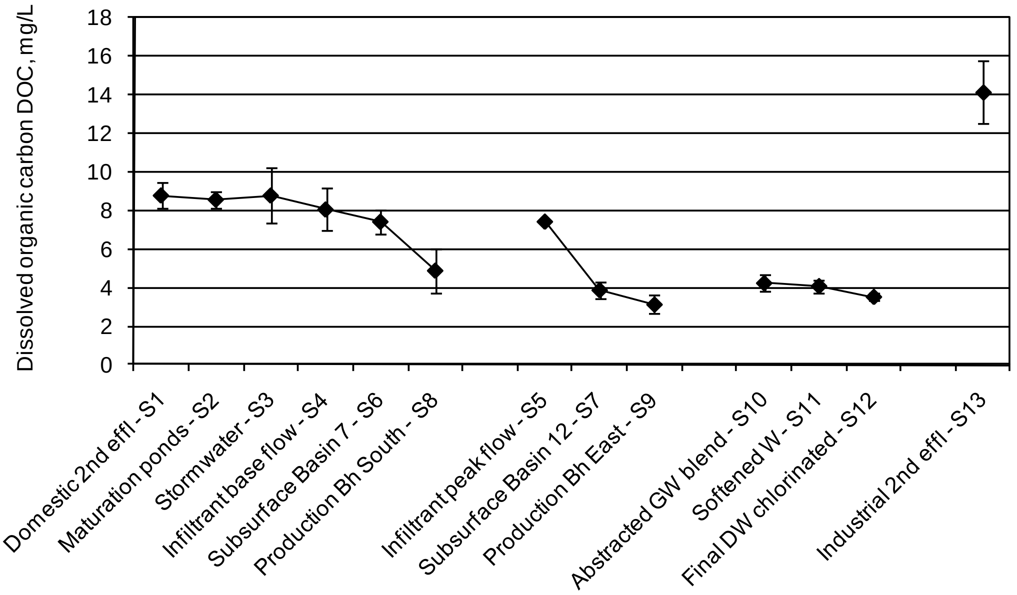

Figure 8.9: Dissolved organic carbon levels at various points in the system at Atlantis

The Technical University in Berlin, Germany, analysed the dissolved organic carbon by means of liquid chromatography and the results are shown in Table 8.3. These sampling runs took place after the data series shown in Figure 8.9. In broad terms the results in Table 8.3 support the earlier conclusions but also add perspective with regard to the reduction in dissolved organic carbon during domestic wastewater treatment. The DOC results for the production boreholes in the Silwerstroom wellfield shows the background level of natural organic matter in groundwater which is unaffected by artificial recharge of treated wastewater and storrnwater runoff.

Table 8.3: Dissolved organic carbon results by passive LC-OCD (DOC in mg/L)

Sampling point	June 2008 (Winter)	October 2008 (Spring)
S0 Raw domestic wastewater	-	17.8
S1 Domestic wastewater secondary effluent	7.7	7.7
S2 Maturation pond effluent	7.3	8.1
S3 Urban stormwater runoff	6.5	-
S4 Infiltrant blend	6.4	6.0
S8 Production borehole near Basin 7	4.7	5.0
S9 Production borehole near Basin 12	2.9	3.0
S11 Softened groundwater blend	-	4.0
S12 Chlorinated drinking water from reservoir	-	2.1
Silwerstroom production bh W34018 (no recycled water)	1.9	-
Silwerstroom production bh G29757 (no recycled water)	2.6	-

8.3.2 Electrical conductivity

The salinity of the groundwater is of importance for the Atlantis Water Resource Management Scheme as the aim is to keep the electrical conductivity (EC) of the town water supply below 700 µS/cm. This is generally achieved (Figure 8.10).

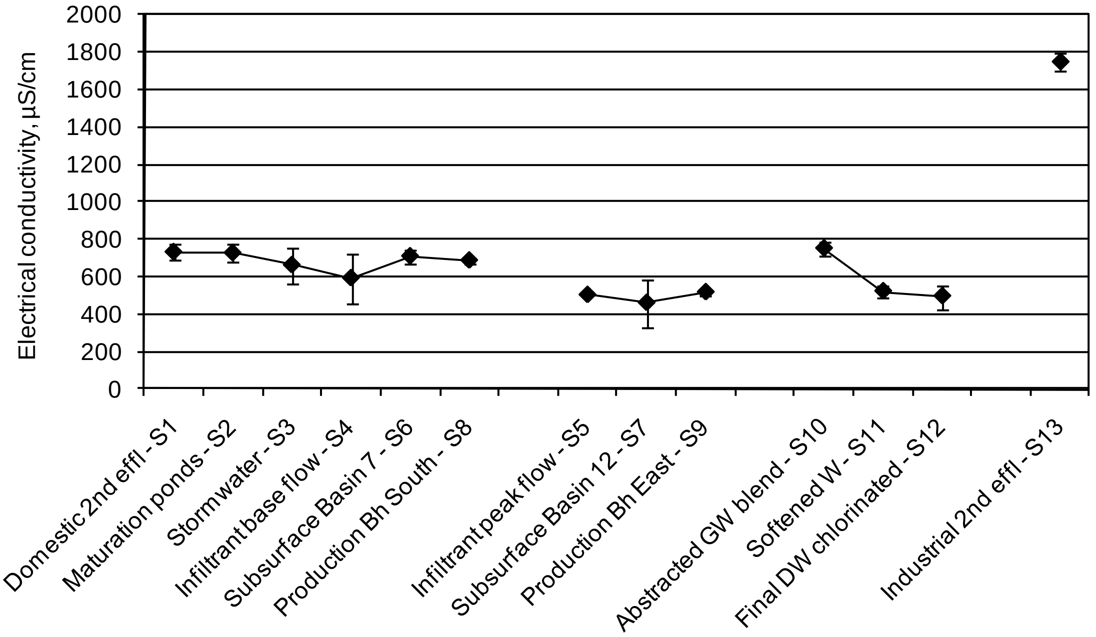

Figure 8.10: Electrical conductivity at various points in the Atlantis water recycling system

The salinity of the domestic wastewater is generally slightly above 700 µS/cm compared to the average of the water supply which is just below 500 µS/cm. On average the salinity of the stormwater runoff is lower than that of the wastewater and this helps to offset the increase in salinity in the subsurface. The salinity difference between Basin #7 (sampling points S6 and S8) and the low salinity Basin #12 (sampling points S7 and S9) is evident from the graph (Figure 8.10). The effect of the low salinity peak flow water recharged in Basin #12 during winter is clearly visible at the monitoring point (S7) down gradient of the basin. The wellfield include boreholes outside the influence of the recharge basins and hence the overall EC of the abstracted groundwater blend (S10) is higher than the two production boreholes (S8 and S9) shown in the graph. This is mainly due to the increase in calcium (bicarbonate) (Figure 8.13) but by ion exchange softening both calcium and bicarbonate is removed. Sampling point S13 shows that the treated industrial wastewater has EC levels of the order of 1700 to 1800 µS/cm which would make treatment for recycling for potable purposes very costly.

8.3.3 Sulphate

The sulphate concentration in the water recycling system at Atlantis is shown in Figure 8.11. The domestic wastewater has a sulphate concentration of between 70 and 80 mg/L while that of the stormwater is sometimes significantly lower. Sulphate reduction in the deeper layers of the aquifer is a natural phenomenon and this together with dilution with natural groundwater lower in sulphate helps to reduce the sulphate concentration at the production boreholes. The effect of the input of low salinity stormwater into Basin #12 is clearly evident at sampling point S7. The treated industrial wastewater has significantly higher sulphate concentrations (S13).

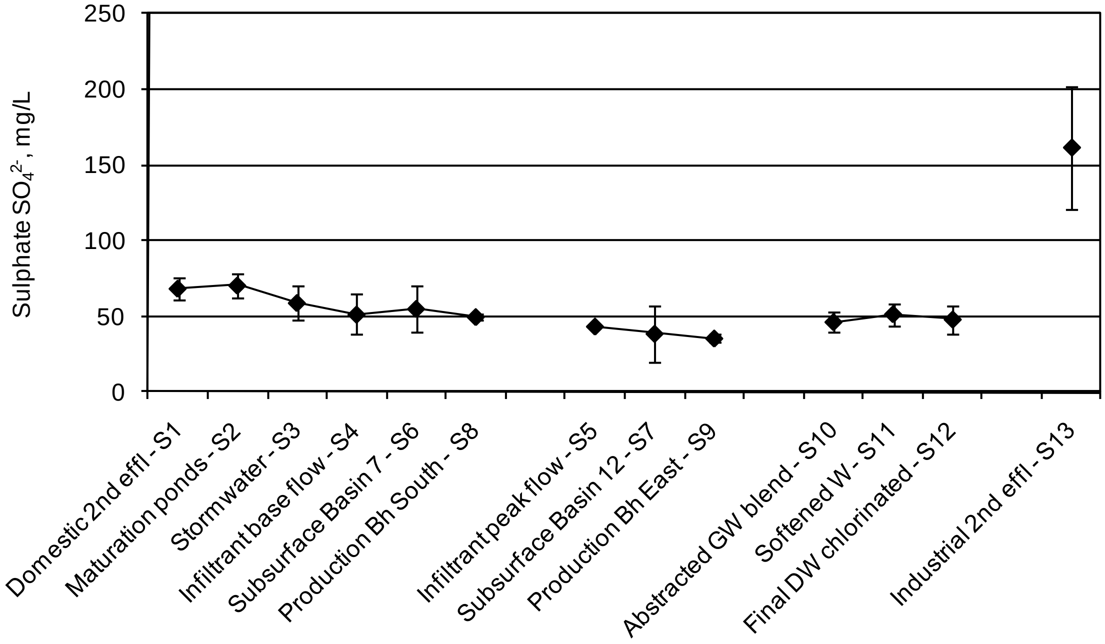

Figure 8.11: Sulphate concentrations at various points in the Atlantis water recycling system

8.3.4 Potassium and calcium

The usefulness of potassium as a tracer for wastewater is shown by the high levels for this parameter in the treated domestic and industrial wastewater (Figure 8.12). Stormwater also contains potassium but only slightly above background levels. In the subsurface potassium is removed by ion exchange on clay particles and the abstracted water has low potassium levels approaching the natural background in the aquifer. As the clay content of the aquifer material is very low, it is expected that potassium will break through eventually and reach higher levels in the boreholes affected by the recycling.

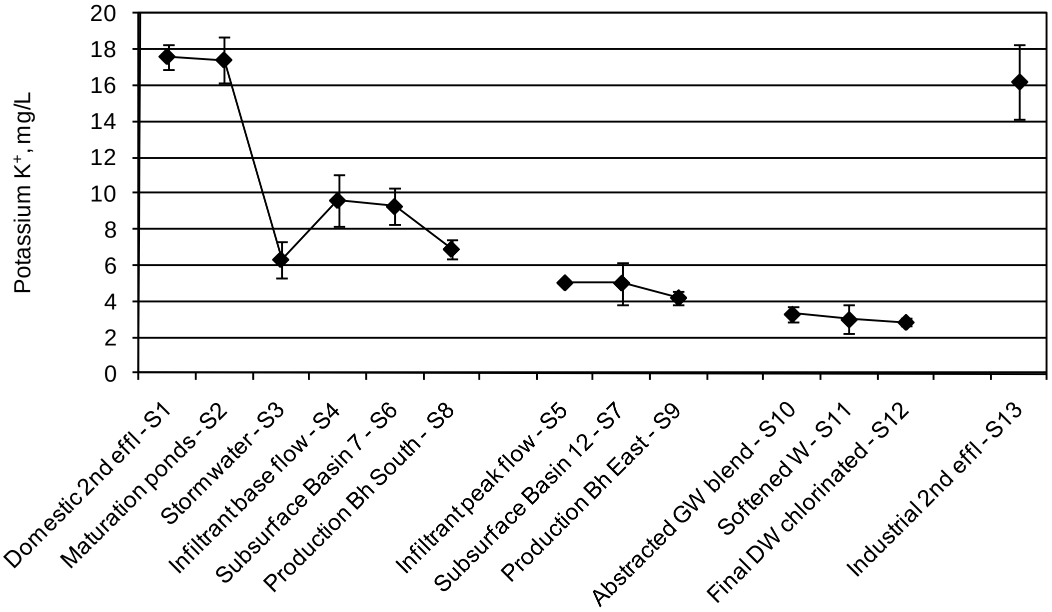

Figure 8.12: Potassium concentrations at various points in the Atlantis water recycling system

The calcium concentration is shown in Figure 8.13. In contrast to salinity, the water supply and the domestic wastewater have very similar calcium concentrations. Also, the industrial wastewater does not show any significant increase in calcium during use in the various industries. However, even the stormwater has a higher calcium content, perhaps caused by leaching of the cement pipes conducting the stormwater. The calcium increases significantly in the subsurface from the input values (S4) to the production boreholes (S8 and S9) due to leaching of calcium carbonate from the aquifer. At this stage leaching down-gradient of Basin 12 is more pronounced than at Basin 7 which has been in operation for much longer. The levels at these production boreholes are still lower than the mean value for the wellfield as the abstracted groundwater blend (S10) is significantly higher confirming the need for softening.

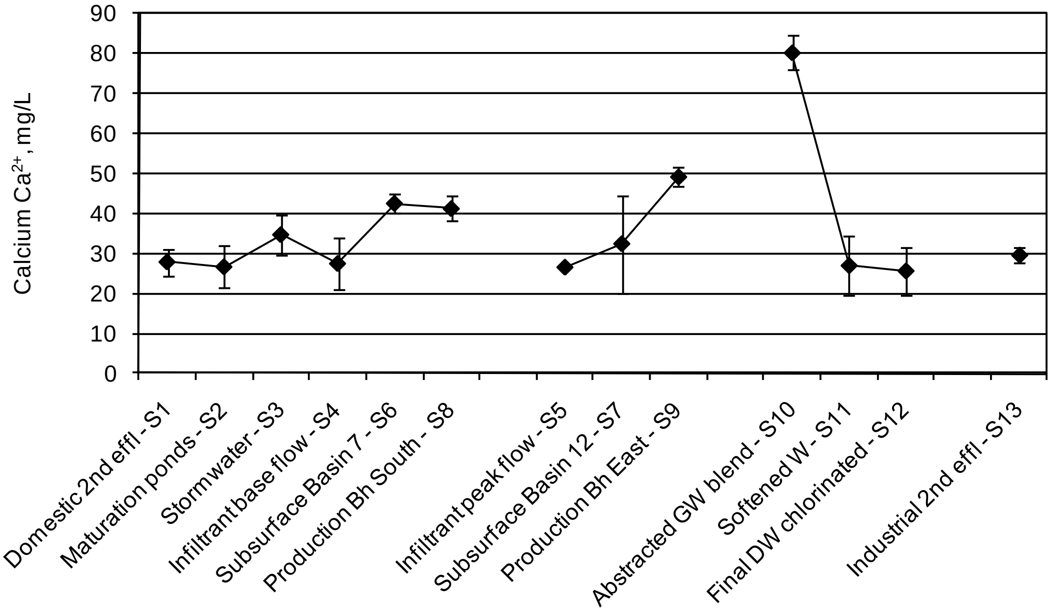

Figure 8.13: Calcium concentrations at various points in the Atlantis water recycling system

8.3.5 Boron

The boron values measured at Atlantis were generally close to the detection limit of 25 µg/L reported by the laboratory that carried out the analyses. Nevertheless, it was evident that the wastewater contained traces of boron originating from detergents. The industrial wastewater contained higher levels of boron (Figure 8.14). It is noteworthy that the boron was not removed in the subsurface but only diluted by blending with the natural groundwater.

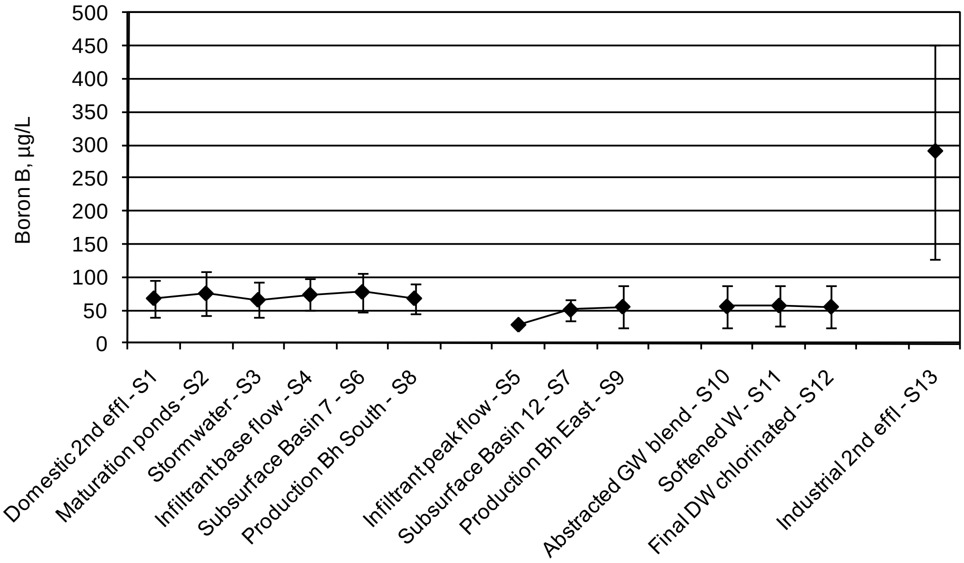

Figure 8.14: Boron concentrations at various points in the Atlantis water recycling system

8.3.6 Redox conditions

The concentrations of certain chemical species affected by oxidation-reduction conditions in the aquifer are shown in Figure 8.15. Both the domestic and industrial effluent contain nitrate and after circulation through the maturation ponds (S2 and S13) the mean nitrate-N concentrations in the two effluents are very similar at about 8 mg/L. The nitrate concentration in the stormwater (S3) is much lower and the blend with treated domestic wastewater after the reed bed at Basin 6 (S4 and S5) is even lower. This means that the input into the recharge basins was only in the order of 3.5 to 4.5 mg/L as NO_3-N. In the subsurface (S6) between Basin 7 and the wellfield nitrate decreased significantly and by the time groundwater reached the wellfield nitrate had virtually disappeared (S8). Although the exact redox potentials were not determined, it is evident that reducing conditions prevailed in the subsurface and that denitrification took place. Considering the situation at Basin 12 it is evident that nitrate reduction was also taking place in that part of the aquifer (S5 to S7) but to a lesser extent as even at the production borehole (S9) nitrate was still present. This would imply that compared to Basin 7the redox potential was not as low in the area down-gradient of Basin 12. This also relates to DOC levels that are higher in the area down-gradient of Basin 7 (S6).

Ammonium-N concentrations were generally at or just above detection levels except in the stormwater system (S3) where the mean concentration was 2.2 mg/L (Table 8.4). Together with other forms of nitrogen as measured by Total Kjeldahl Nitrogen (TKN) significant oxidation to nitrate and removal took place during the passage through the reedbed (between S3 to S4 and to S5). In the subsurface near Basin 7 (S6) there was a slight increase in ammonium but by the time the water reached the wellfield (S8) the ammonium had disappeared. This may relate to the presence of higher levels of oxygen and variable redox conditions near the wellfield due to the ingress of oxygenated water from shallow depth.

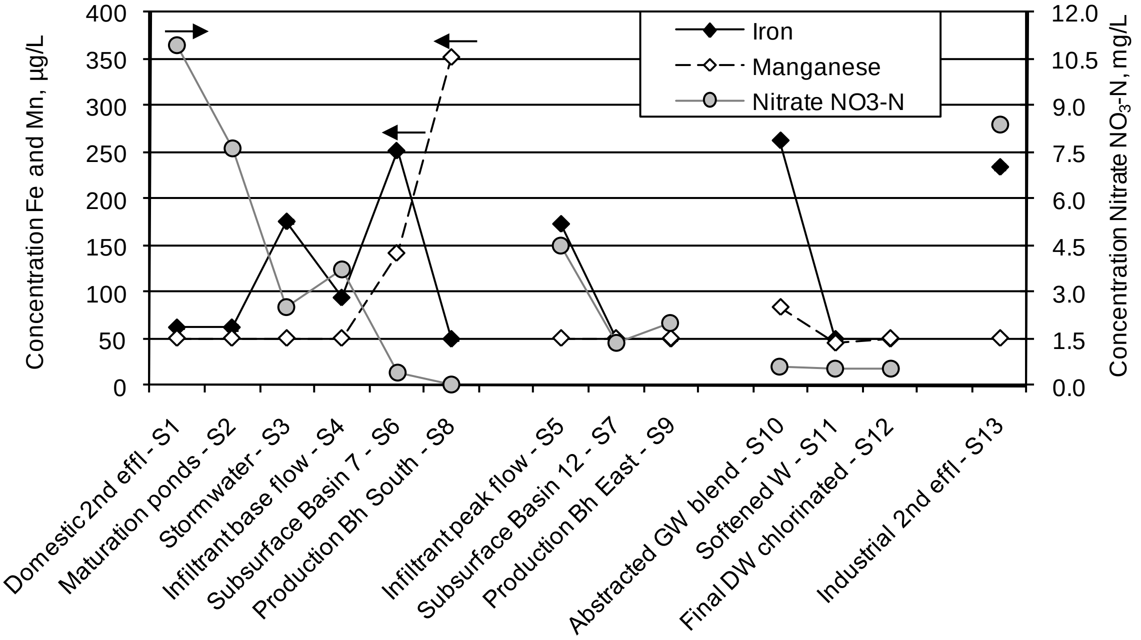

Figure 8.15: Iron, manganese and nitrate as indicator of Redox conditions along the recycling system at Atlantis

The presence of iron in the groundwater at Atlantis causes significant production borehole clogging problems in all areas, not only where artificial groundwater recharge is practised. During the initial stage of aquifer development at Atlantis the presence of hydrogen sulphide indicated that sulphate reduction occurred in the deeper layers of the aquifer, generally at a depth greater than 20 m. At the low redox potential in this part of the aquifer Fe^{2+} concentrations would also seem to be stable. From Figure 15 it is evident that stormwater (S3) is the main source contributing iron to the feedwater. In the subsurface (S6) down-gradient of Basin 7 the iron concentration was at its highest while manganese was also being mobilised. For manganese this process continued up to the production borehole (S8) while the iron concentration decreased at the production borehole. This may imply that the soluble Fe^{2+} was converted to insoluble Fe^{+3} at the production borehole (S8) while manganese remained in solution in the reduced form despite the likely increase in the redox potential. Down-gradient of the peak flow recharge basin (S7) denitrification takes place but the redox potential is not low enough to keep iron and manganese in solution. The lower concentration of organic compounds in the form of DOC in this part of the aquifer also favours less reducing conditions. It was evident that the blend of abstracted groundwater originating from a large number of production boreholes included several others (not covered by the graph in Figure 8.15) with higher iron concentrations indicating stronger reducing conditions at production boreholes in certain parts of the aquifer. Both iron and manganese are removed in the ion exchange softening process (S11).

8.3.7 Microbiological parameters

The bacterial counts at the various points in the system illustrate the importance of the subsurface passage as a safety barrier in the system (Figure 8.16). It was found that not only the indicator organisms follow this pattern but also the pathogens, including viruses follow a similar pattern of log-reductions to provide the necessary safety margins for the recycling system.

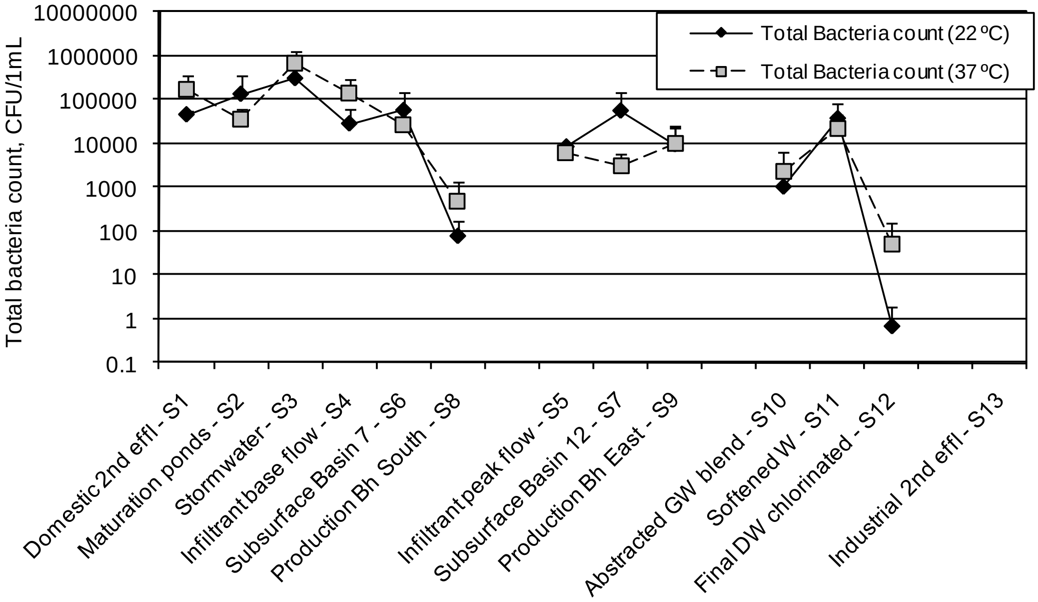

Figure 8.16: Bacteria removal in the recycling system at Atlantis

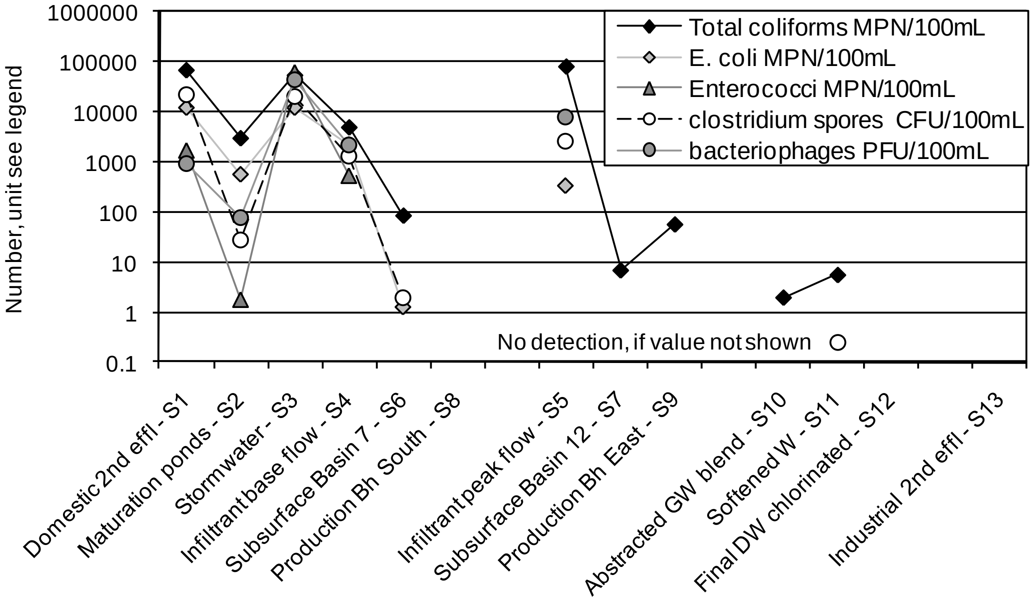

Figure 8.17: Bacterial counts for all sampling protocols

As expected, following the total general bacterial numbers, total coliforms were found in the highest numbers (except for enterococci once during winter), followed by *E. coli*, *Clostridium*, enterococci and lastly coliphage (Figures 8.16 and 8.17). The most notable factor observed is the low level of bacteria, if any, and surrogate pathogens (*Clostridium* and bacteriophages) in the groundwater and the final water before distribution to the town, *i.e.*, sampling points S6-S12. The highest counts in the infiltrant (S4 and S5) were observed in the winter which is the rainy season in Atlantis. Maximum total coliforms were in the order of 10^5/100mL. The absence of microbes or low microbial numbers found in the groundwater may be a result of filtration of the poorer quality recharge water. It may also be a result of natural die-off of the microorganisms.

Another important factor is that the stormwater (S3) tended to have higher microbial counts than the treated wastewater effluent. This has implications for the management of the water scheme.

These results were used in a human health risk assessment and management programme within RECLAIM WATER to further understand how to best manage the recharge scheme to protect human health. Results are given in chapter 20 Surrogate pathogen counts, namely E. coli representing bacterial pathogens, Clostridium representing parasite pathogens and coliphages representing viral pathogens, were used in addition to the protocol 2 parameters for the risk assessment.

8.3.9 Organic micropollutants

With the assistance of the Bundesanstalt für Gewässerkunde tests were carried out for a wide range of about forty trace organic compounds known to occur in domestic wastewater. Two sampling campaigns were organised in winter (June 2008) and spring (October 2008). At first the wastewater and stormwater inputs to the system were sampled as well as the production boreholes nearest to the recharge basins. A total of twelve of these compounds were detected in the domestic wastewater secondary effluent while nine were detected in at least one of the production boreholes at nanogram per litre levels. In the wastewater some compounds reached the microgram per litre level (Figure 8.18a and b). The compounds included antibiotics, antiepileptic and psychoactive drugs, compounds used as contrast media, and anti-inflammatory medication in the group of “acidic compounds”. As these compounds occur at very low levels triplicate samples were taken but this limited the number of sampling points as four SPE extractions are required on each sample plus blanks and spiked samples to increase confidence limits. For the second round it was considered important to extend the range of samples by including the raw domestic sewage and the final drinking water after softening and chlorination. This was achieved by taking only duplicate samples. By including the raw wastewater the number of compounds detected in the second round increased to fifteen. This time a total of eight compounds were detected in at least one of the production boreholes (Figure 8.18a and b). Traces of only two compounds were detected at nanogram level in the final chlorinated drinking water. These were the antiepileptic medication carbamazepine and its metabolite dihydrodihydroxycarbamazepine with concentrations between 10x10-9 and 20x10-9 g/L. Such very low concentrations are well within the Australian National Guidelines for Water Recycling (2006) and can be considered as being safe for human consumption.

The highest concentrations of the trace organic compounds occurred in the wastewater and sometimes the treated effluent. In four cases the wastewater treatment effected a reduction in the levels as shown by sulphamethoxazole, diclofenac, ibuprofen and iopromide (Figure 8.18). In the case of some of the other compounds it would seem that the concentrations detected in the raw wastewater was lower than in the treated water. This may be correct but it is also possible that the grab samples were taken at a time when the concentrations in the wastewater were actually lower. During the wastewater treatment process the water is mixed well, also due to the various recycling loops. Comparing the maturation pond effluent (S2) to the domestic wastewater secondary effluent (S1) shows that the concentrations generally remain largely unaltered during the fourteen day residence time in the maturation ponds although carbamazepine, dihydrodihydroxycarbamazepine, and ibuprofen showed a decrease. The concentrations of the trace organic compounds were generally low in the urban stormwater runoff (S3) with the exception of carbamazepine, dihydrodihydroxycarbamazepine, and ibuprofen. The ibuprofen concentration in the stormwater is even higher than in the secondary effluent as it would seem that the wastewater treatment significantly reduces the ibuprofen concentration. Blending the secondary effluent with the stormwater causes a reduction in the concentration of the trace organic compounds in the feed water (S4) to the recharge basins. In the subsurface further decomposition and dilution with natural groundwater take place and very low concentrations of most of the eight compounds shown were found in the production boreholes.

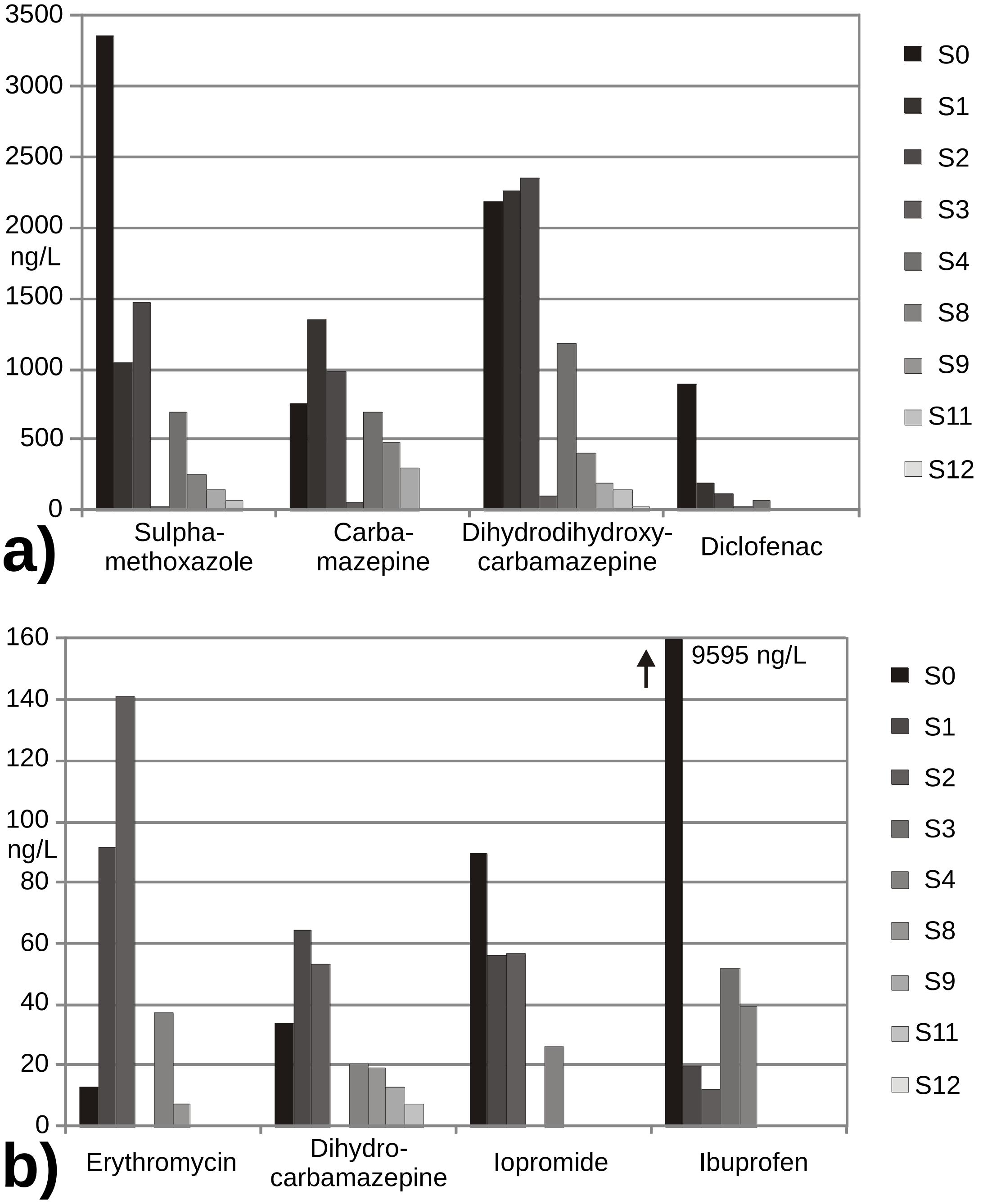

Figure 8.18: Occurrence of trace organic compounds in various parts of the water recycling system (S0 represents raw domestic wastewater, other sampling points as before)

8.3.10 Summary of water quality monitoring

The following table 8.4 presents an overview of the monitoring results at Atlantis during the years 2007 and 2008with the mean values of the main quality parameters and the measured ranges.

Table 8.4: Overview of the water quality monitoring results at Atlantis (mean values, followed by the range)

Sampling point description		Domestic 2nd effl	Maturation ponds	Stromwater	Infiltrant base flow	Subsurface Basin 7	Production Bh South	Infiltrant peak flow	Subsurface Basin 12	Production Bh East	Abstracted GW	Softened W	Final DW chlorinated	DWG SANS 241 2006	Industrial WW - S13
Number		SA1	SA2	SA3	SA4	SA6	SA8	SA5	SA7	SA9	SA10	SA11	SA12		SA13
Basic WW analysis															
Suspended Solids	$mg.L^{-1}$	<4.0	5.1	5.7	5.7	<4.0	4.3	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	-	4
		<4.0	<4.0-6.4	<4.0-8.0	<4.0-8.0	<4.0	<4.0-5.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0		4
COD Total	$mg.L^{-1}$	38	31	28	27	19	18	26	15	12	11	14	11	-	53
		29-48	21-41	19-35	18-36	<10-25	<10-23	26	<10-24	<10-15	<10-14	<10-18	<10-13		35-82
COD Soluble	$mg.L^{-1}$	53	26	24	26	39	12	23	12	9	9	11	11	-	40
		23-105	21-29	17-29	23-29	18-67	<5-18	23	6-21	<5-12	<5-13	<5-14	9-13		7-73
DOC	$mg.L^{-1}$	8.8	8.6	8.8	8.1	7.4	4.9	7.4	3.9	3.1	4.2	4.1	3.5	<10	14
		7.8-9.4	8.0-9.1	7.7-10.7	6.9-9.1	6.6-7.9	3.3-5.9	7.4	3.5-4.4	2.7-3.6	3.7-4.7	3.7-4.4	3.3-3.8		13-16
Ammonia (NH_4-N)	$mg.L^{-1}$	0.2	0.2	2.2	0.1	0.4	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<1.0	0.5
		<0.1-0.5	0.1-0.2	0.1-6.9	<0.1	0.1-0.6	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1		<0.1-1
Nitrate NO_3-N	$mg.L^{-1}$	11	7.6	2.5	3.7	0.4	<0.1	4.5	1.4	2.0	0.6	0.6	0.6	<10	8
		9.4-12.8	4.7-10.6	<0.1-4.9	2.9-5.1	<0.1-1.3	<0.1	4.5	0.7-2.0	1.9-2.1	0.5-0.7	0.5-0.7	0.5-0.7		6.4-12.2
Total Nitrogen (TKN)	$mg.L^{-1}$	2.3	4.4	4.7	1.1	1.0	0.8	1.9	0.8	0.7	0.8	0.8	0.8	-	3
		1.2-4.1	1.3-13.0	1.5-14.0	1.0-1.3	0.6-1.5	<0.3-1.3	1.9	<0.3-1.3	<0.3-1.2	<0.3-1.3	<0.3-1.2	<0.3-1.2		2.2-4.2
Total Phosphorus	$mg.L^{-1}$	8.6	5.9	1.0	2.5	1.3	0.2	2.7	<0.2	0.4	0.2	<0.2	<0.2	-	2
		7.8-9.4	2.6-7.8	<0.3-2.8	2.2-3.2	0.8-2.2	<0.2-0.3	2.7	<0.2	0.3-0.5	<0.2-0.3	<0.2	<0.2		1.4-3.2
Alkalinity	$mg.L^{-1}$	40	45	77	57	113	123	53	91	107	184	28	30	-	190
		35-52	37-54	60-115	49-65	92-137	119-128	53	78-106	97-118	182-185	27-30	20-41		165-204
pH	unit	7.0	7.6	7.4	7.6	7.9	8.0	7.2	7.9	7.8	7.8	7.6	7.3	5.0-9.5	7.8
		6.5-7.2	7.1-8.1	7.2-7.7	7.4-7.8	7.4-8.2	7.7-8.2	7.2	7.4-8.2	7.5-8.1	7.2-8.4	7.4-7.7	6.8-7.8		7.8-8.0
Turbidity	NTU	8.4	1.5	7.4	2.5	1.0	0.2	12.8	1.6	0.3	1.5	0.2	0.2	<1	5
		1.9-18	0.5-3.4	4.3-11.1	1.0-3.8	0.1-2.2	0.1-0.3	12.8	0.4-2.8	0.0-0.7	0.3-3.9	0.1-0.5	0.2-0.3		3-8
detergents	PPB	293	180	840	170	135	175	400	180	133	128	150	113	-	167
		<100-600	<100-300	<100-1600	<100-310	<100-240	<100-400	400	<100-400	<100-230	<100-210	<100-200	<100-150		<100-200

mineral oils	PPB	<200	<200	<200	<200	<200	<200	-	<200	<200	<200	<200	<200	-	265
		<200	<200	<200	<200	<200	<200		<200	<200	<200	<200	<200		<200-330
phenols	PPB	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<10	<4
		<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0	<4.0		<4
Microbiological															
Total Bacteria count (22 ºC)	CFU/1mL	$4.5 x 10^{4}$	$1.3 x10^{5}$	$3.0x10^{5}$	$2.8x10^{4}$	$5.6x10^{4}$	76	8300	$5.5x10^{4}$	9400	1000	$3.7x10^{4}$	0.67		-
		32000-58000)	1100-390000	3.3x10^4-4.8x10^5	4800-51000	27-160000	13-200	8300	97-160000	0-28000	6-3000	28000-82000	0-2		
Total Bacteria count (37 ºC)	CFU/1mL	$1.7X10^{5}$ 11	$3.6X10^{4}$	$6.8X10^{5}$	$1.4X10^{5}$	$2.5X10^{4}$	500	6200	3100	$1.0X10^{4}$	2400	$2.2X10^{4}$	50	<100	-
Total coliforms	MPN/100mL	$6.9X10^{4}$	$3.0X10^{3}$	$5.5X10^{4}$	5000	87	0	$8.2X10^{4}$	7.0	58	2	5.7	0	<5 95% of samples	-
		5000-130000	1100-5000	5000-100000	5000	0-170	0	$8.2X10^{4}$	0-14	0-120	0-4	5-6.3	0		
E. coli	MPN/100mL	$1.2X10^{4}$	550	$1.2X10^{4}$	2 200	1.3	0	327	0	0	0	0	0	<1	-
		3500-25000	10-2000	1400-41000	52-3500	0-5	0	327	0	0	0	0	0		
Enterococci	MPN/100mL	1700	1.8	$6.3X10^{4}$	538	0	0	0	0	0	0	0	0	<1	-
		0-2900	0-3.1	0-240000	41-1300	0	0	0	0	0	0	0	0		
clostridium spores	CFU/100mL	$2.3X10^{4}$	28.5	$2.1X10^{4}$	1250	2	0	2600	0	0	0	0.25	0	<1	-
		9800-41000	11-48	850-73000	110-2600	0-7	0	2600	0	0	0	0-1	0		
bacteriophages	PFU/100mL	910	75	$4.5X10^{4}$	2140	0	0	7900	0	0	0	0	0	<1	-
		440-1800	0-150	50-150000	30-3300	0	0	7900	0	0	0	0	0		
Trace elements															
Boron	PPB	68.3	75.7	65.9	73.8	77.9	68.2	28.5	51.1	55.6	56.0	57.3	55.5	-	291
		36.9-93.8	38.3-105	39.9-100.8	54.2-100.8	46.7-114.6	40.1-93.7	28.5	29.7-65.8	27.1-100	29.7-100	29-100	25.1-100		190-478
Cadmium	PPB	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<5	<10
		<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10		<10
fluoride	PPB	154	130	102	119	198	299	<100	206	146	202	206	179	<1000	392
		<100-255	<100-199	<100-108	<100-158	<100-317	266-339	<100	162-291	121-199	147-304	162-304	121-291		307-449
Iron	PPB	63	63	177	95	253	<50	174	<50	<50	264	<50	<50	<200	235
		<50-100	<50-100	112-230	51-174	<50-618	<50	174	<50	<50	<50-606	<50	<50		172-325
lead	PPB	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	<20	50
															50
Manganese	PPB	<50	<50	<50	<50	141	352	<50	<50	<50	83	<50	<50	<100	<50
		<50	<50	<50	<50	<50-338	245-443	<50	<50	<50	69-99	<50	<50		<50

barium	PPB	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	-	<50
		<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50		<50
Sampling point description		Domestic 2nd effl	Maturation ponds	Strom water	Infiltrant base flow	Subsurface Basin 7	Production Bh South	Infiltrant peak flow	Subsurface Basin 12	Production Bh East	Abstracted GW	Softened W	Final DW chlorinated	DWG SANS 241 2006	Industrial WW - S13
Number		SA1	SA2	SA3	SA4	SA6	SA8	SA5	SA7	SA9	SA10	SA11	SA12		SA13
Zinc	PPB	55	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<5000	111
		<50-66	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50		93-125
Salinity															
Chloride	$mg.L^{-1}$	104	112	102	97	112	104	72	64	62	98	100	90	<200	313
		101-108	100-135	95-114	70-112	106-119	94-110	72	36-93	56-69	95-101	93-109	72-109		286-333
Electrical conductivity	$\mu S/cm^{-1}$	730	725	660	590	708	685	500	458	515	750	520	494	<1500	1750
		680-780	660-760	580-780	440-700	680-760	660-700	500	340-620	500-530	720-800	490-560	425-580		1700-1800
sodium	$mg.L^{-1}$	95	96	70	72	82	82	57	56	46	67	64	59	<200	313
		90-102	92-99	65-79	53-84	75-96	78-86	57	41-69	43-52	62-72	59-74	53-67		298-322
potassium	$mg.L^{-1}$	18	17	6.3	9.6	9.3	6.9	5.1	5.0	4.2	3.3	3.0	2.9	<50	16
		17-19	16-19	5.5-7.7	8.2-11.1	8.3-10.4	6.5-7.7	5.1	4.0-6.5	3.7-4.5	2.8-3.7	2.0-3.8	2.7-3.1		14-17
calcium	$mg.L^{-1}$	28	27	35	28	43	41	27	32	49	80	27	26	<150	30
		24-31	19-31	28-39	24-35	41-46	38-44	27	23-48	46-51	76-86	20-37	19-33		28-32
magnesium	$mg.L^{-1}$	5.9	5.7	10.0	7.0	8.6	8.8	6.8	4.2	5.1	7.7	4.8	4.9	<70	6
		4.9-6.8	5.0-6.4	8.3-11.2	4.8-9.6	7.1-9.8	8.6-9.0	6.8	2.7-5.9	4.9-5.4	6.8-8.2	3.6-6.3	4.1-5.5		5-6
bicarbonate	$mg.L^{-1}$	49	54	94	70	138	150	64	111	131	224	35	37	-	232
		42-63	45-66	73-141	59-79	112-167	146-156	64	95-129	118-144	222-226	33-37	25-49		201-249
sulphate	$mg.L^{-1}$	69	71	59	51	55	50	44	39	36	47	52	48	<400	162
		58-75	61-80	48-74	37-64	42-76	48-53	44	20-56	33-38	39-53	45-60	37-57		128-207

8.3.11 Operational feedback

The water reclamation scheme at Atlantis is operated by the City of Cape Town and the CSIR is involved in an advisory capacity. An important feature incorporated into the Atlantis recharge system is the separation of the runoff and wastewater into components with different qualities, mainly with respect to salinity (Tredoux and Cavé, 2002). This allows the recharge of lower salinity water in parts of the aquifer where the natural groundwater salinity is lower. Hence two recharge basins were constructed with Basin #7 intended for higher salinity water and Basin #12 for lower salinity water. The more saline industrial wastewater and high salinity stormwater is diverted to the coastal recharge basins and is not used for recycling. During the water quality monitoring and inspection visits the operational performance of the various units were observed and several matters noted for improvement. The main difficulty experienced in the operation is the borehole clogging ascribed to biofouling and the natural occurrence of iron in the groundwater. This seriously affects the well field production capacity and borehole rehabilitation is being planned. However, no modifications to the system were implemented during the Reclaim Water Project period in order not to complicate the interpretation of the results. One result is that larger volumes of surface water from other water resources of the City of Cape Town are being imported. Hence the groundwater (and recycled water) content of the final water supply may be as low as 50% at this stage. It means that the aquifer is not optimally utilised but an important spin off is the decrease in overall salinity of the system. This is brought about by the imported surface water of low salinity which is recharged into the aquifer after use and which blends with or even displaces more saline groundwater.

The Atlantis scheme faces several water quality management challenges, ranging from the control of saline water encroachment to industrial pollution threats and biofouling of production boreholes. The relatively thin unsaturated zone limits the attenuation capacity of the soil-aquifer system during basin recharge

8.4 CONCLUSIONS

Managed aquifer recharge ensured the sustainability of the Atlantis groundwater supply over more than two decades and will continue to play a key role.

- Indirect recycling of stormwater and treated domestic wastewater via the aquifer as a means to augment supplies found public acceptance.
- Water quality management is the dominant issue regarding water supply at Atlantis. Separation of source water into different quality fractions allowed recharge of the highest quality water in the areas of importance for the production wellfield.
- Diverting the industrial wastewater from the recycling system has been shown to be the correct approach considering its high salinity and organic carbon content.
- When managed carefully the wastewater and stormwater recycling system is robust with regard to consistent water quality.
- While the importation of low salinity surface water lowered the overall salinity in the system calcium carbonate is gradually leached from the aquifer matrix.
- The presence of iron in the groundwater causes clogging of the production boreholes and although the deeper groundwater is naturally reducing organic carbon added through recycling may be contributing to the intensity of such conditions.
- The heavy metal concentrations in the system are low and in the abstracted water the heavy metal content is negligible.
- Microbiologically the subsurface passage plays a decisive role as a safety barrier. The presence of organic carbon needs to be controlled as this may affect the bacteria removal in the subsurface.
- Trace organic carbon compounds are effectively removed and diluted to such an extent that the nanogram levels remaining are well within internationally accepted norms.

The Atlantis groundwater scheme provides a cost-effective water supply option when coupled with strict management of the resource. The importation of limited quantities of low salinity surface water has enhanced the viability of the recharge scheme and also allows the utilisation of slightly more saline groundwater. The future introduction of membrane processes for water softening and partial desalination will further enhance the scheme, even allowing the possible export of potable water to other residential areas.

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REFERENCES

Australian Guidelines (2006). Australian National Guidelines for Water Recycling: Managing Health and Environmental Risks

Department of Water Affairs (2007) South Africa's Artificial Recharge Strategy Accessed August 2011. http://www.artificialrecharge.co.za/03strategy.html

Department of Water Affairs (2010a) The Atlantis Water Resource Management Scheme : 30 years of artificial ground water recharge

Department of Water Affairs (2010b) Strategy and Guideline Development for National Groundwater Planning Requirements. Water Banking: A practical guide to using Artificial Groundwater Recharge, dated November 2010.

Liebenberg and Stander (1976) Planning and Masterplan for the Stormwater Network, Outfall and Disposal System. Report GW/EduT/1961 PC. Cape Town: Liebenberg and Stander Consulting Engineers.

Rogers, J. (1980) First report on the Cenozoic sediments between Cape Town and Elandsbay. Open File Report 1980 – 0249. Pretoria: Geological Survey of South Africa.

SANS 241-1 (South African National Standard. Drinking Water). (2011) Part 1: Microbiological, physical, aesthetic and chemical determinants. 1st Edition. SABS Standards Division, Pretoria.

Siebe C. (1994) Heavy metal accumulation in soils from the irrigation District 03, in Tula, Hidalgo irrigated with wastewater. International Magazine of Environmental Pollution. 10: 15-21 (in Spanish).

Smith, K. (2003) Hydrogeologische studie te Koksijde : Kunstmatige infiltratie als bijdrage tot duurzame waterwinning in kustgebieden. Faculteit Wetenschappen, Vakgroep Geologie en Hydrogeologie, Universiteit Gent. Licentiaatsverhandeling. (in Dutch)

Spanish Official Bulletin (BOE). Royal Decree 1620/2007 of December 7, setting rules and regulations for treated wastewater reuse.

Swierc, J., Page, D., van Leeuwen, J. and Dillon, P. (2005). Preliminary Hazard Analysis and Critical Control Points Plan (HACCP) – Salisbury Stormwater to Drinking Water Aquifer Storage Transfer and Recovery (ASTR) Project. CSIRO Land and Water Technical Report 20/05.

Toze, S. (2006) Reuse of effluent water – benefits and risks. Agricultural Water Management, 80, 147-159.

Toze, S., Sidhu, J., Shackleton, M. and Hodgers, L. (2009). Decay of Enteric Pathogens in Urban Stormwater Recharged to an Aquifer using Aquifer Storage, Transfer and Recovery. CSIRO Water for a Healthy Country Flagship Report.

Toze, S., Sidhu, J., Shackleton, M., Hodgers, L. and Gama, S. (2008). Decay of Microbial Pathogens in Wetlands Receiving Storm Water for Pre-Treatment Prior to Aquifer Storage, Transfer and Recovery. CSIRO Water for a Healthy Country Flagship Report.

Tredoux G, Ross W R and Gerber A, (1980) The potential of the Cape Flats aquifer for the storage and abstraction of reclaimed effluent (South Africa). Z. dt. geol. Ges., 131, 23 - 43

Tredoux, G and Cavé, L C, (2002) Atlantis Aquifer: A Status Report on 20 Years of Groundwater Management at Atlantis. Report submitted to the City of Cape Town. CSIR Report No ENV-S-C 2002-069.

Van der Merwe, A.J. (1983) Exploration, development and evaluation of groundwater in the sand deposits in the Atlantis area for water supply to the Atlantis growth point. M.Sc thesis. Bloemfontein: University of the Orange Free State.

Wright, A. (1994) Artificial recharge of urban wastewater, the key component in the development of an industrial town on the arid west coast of South Africa. In: Water Down Under '94. Proceedings of the IAH Congress: Vol.2, Part A, 39 - 41. Adelaide: International Association of Hydrogeologists.