

Artificial recharge of the Windhoek aquifer, Namibia: Water quality considerations

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ABSTRACT

For managed aquifer recharge (MAR) to succeed, an aquifer is needed which allows easy access to a relatively high storage capacity. Whereas the country rock hosting the Windhoek Aquifer, consisting largely of quartzite, has no primary porosity, secondary porosity developed for several reasons. The brittle nature of the quartzite led to better secondary porosity development than in the adjacent schistose terrain. The degree and intensity of fracturing decreases as the mica content of the quartzite increases. Therefore, a larger storage capacity is found per unit volume of the fractured quartzite compared to an equal volume of fractured schist. Equally, the success of MAR depends on a thorough understanding of the ambient water quality in the various parts of the aquifer together with potential water-rock interactions. This study was aimed at developing water quality guidelines with specific management options for ensuring sustainable artificial recharge of the aquifer. Ample groundwater quality data are available for the saturated zone but a major aspect that can only be assessed to a limited extent is the water-rock interactions that will take place when the unsaturated zone becomes saturated during injection. To some extent unsaturated water-rock interaction can be inferred from the hydrochemistry of the saturated zone and its evolution in the aquifer. Water quality criteria for the recharge water are included.

Key words: artificial recharge, hydrochemistry, Namibia, quartzite, Windhoek

La recarga artificial del acuífero de Windhoek, Namibia: consideraciones sobre la calidad del agua

RESUMEN

Para que la recarga artificial de acuíferos tenga éxito, es preciso disponer de acuíferos con una capacidad de almacenamiento relativamente importante. Las rocas que conforman el acuífero de Windhoek, constituidas en gran parte por cuarcitas, no poseen porosidad primaria, pero sí secundaria, que se ha desarrollado por la acción de diferentes procesos. La frágil naturaleza de la cuarcita ha originado en esta roca un mejor desarrollo de la porosidad secundaria que en los terrenos esquistosos adyacentes. El grado de intensidad en la fracturación decrece a medida que aumenta el contenido en mica en la cuarcita. Por consiguiente, la cuarcita fracturada tiene una capacidad de almacenamiento por unidad de volumen más grande que el mismo volumen de esquisto fracturado. De igual modo, el éxito de la recarga artificial depende de la adquisición de un sólido conocimiento de la calidad del agua en diferentes zonas del acuífero, así como de las potenciales interacciones entre la roca y el agua. El propósito del estudio que se presenta ha sido desarrollar directrices relativas a la calidad del agua con distintas opciones de gestión que aseguren la recarga artificial sostenible del acuífero. Se dispone de mucha información sobre la calidad del agua en la zona saturada, pero la interacción agua-roca que se produce cuando la zona no saturada se satura como consecuencia de la inyección del agua de recarga solamente ha podido ser evaluada en extensiones limitadas del acuífero. Hasta cierto punto, la interacción agua-roca en la zona no saturada se puede inferir a partir de la hidroquímica de la zona saturada y su evolución dentro del acuífero. También se han incluido criterios de calidad para el agua de recarga.

Palabras clave: cuarcita, hidroquímica, Namibia, recarga artificial, Windhoek

Introduction

Namibia is located along the arid south-west coast of Africa. The capital, Windhoek, is situated in a semi-arid region in the central highlands of the country and river systems originating in the Auas and Eros Mountain ranges, are draining away from the city in all directions. As a result, local water resources are very limited and most of the city's water supply is

obtained from surface impoundments located at a distance of tens to hundreds of km from the city. Large fluctuations in annual rainfall aggravate the situation. The lack of water has led to direct recycling of reclaimed wastewater and the implementation of water demand management. The main local source of water is the Windhoek Aquifer found in the Auas Formation quartzite and other quartzitic formations located on the southern side of the city. The aquifer

can provide approximately nine per cent of the present demand of about 20 Mm³/a on a sustainable basis. Periods of drought have led to overexploitation and water levels in some parts of the aquifer are presently tens of metres lower than initially when the boreholes were drilled. For this reason, artificial groundwater recharge, or managed aquifer recharge (MAR), provides an attractive option for augmenting the natural groundwater recharge and subsurface storage from surplus surface water. The physical feasibility of artificial recharge by injection of surface water into boreholes was proved by four pilot scale tests, one of which extended over seven months (Murray and Tredoux, 2002). The cost of other various potential water supply schemes were compared and using artificial groundwater recharge for augmenting the water supply proved to be the most cost efficient.

Successful introduction of an MAR scheme requires a thorough understanding of the ambient water quality in the various parts of the aquifer together with potential water-rock interactions. The sources of water for injection are the Von Bach Dam and the reclaimed water. For both these sources and for the Windhoek Aquifer, considerable amounts of water quality data are available also providing trends over time. However, the expected water-rock interaction and the hydrochemical evolution have to be inferred from the groundwater data. Another important aspect relates to the inundation of at least parts of the unsaturated zone. The water-rock interactions that will take place when the present unsaturated zone becomes saturated during injection can only be assessed to a limited extent.

The conclusion from a preliminary investigation into the quality of the recharge water sources was that none of these was of sufficiently high quality to be used as such for injection into the Windhoek Aquifer (Tredoux, 2003). The presence of dissolved organic carbon (DOC) at levels often exceeding 5 mg/L in the treated Von Bach Dam water renders this source unacceptable for injection. On the other hand the salinity of the reclaimed water is such that the water would only be suitable for injection in certain parts of the aquifer. Subsequently, the issues regarding injection water quality were addressed in a report by Van der Merwe *et al.* (2005) on management options for the sustainable artificial recharge of the Windhoek Aquifer. The improvement of the source water quality was also considered in detail.

The purpose of this paper is to evaluate the impacts of full scale injection of aerated surface water on ambient groundwater chemistry in the Windhoek Aquifer. Hydrochemical results of the pilot scale injection tests are interpreted against the background of

the natural groundwater quality and give an indication of the expected impact of water-rock interaction and potential water quality deterioration. Injection water quality requirements are provided and injection practices may need to be adapted to ensure sustainable management of the aquifer in terms of water quality.

Hydrogeology

The Windhoek aquifer is located to the south of the city extending northwards from the Auas Mountains for 20 to 25 km as far as the city centre. It forms part of a highly complex metamorphic environment. The geological formations within the area were folded in the process of orogenesis, and subjected to a number of episodes of faulting including thrusting and rifting. Quartzite and schist horizons with transverse faults and fractures are prevalent throughout the aquifer. The quartzite, being brittle, is highly fractured because of folding and faulting and has developed secondary porosity and permeability. The schist on the other hand is ductile and does not have well developed secondary permeability (Murray & Tredoux, 2002; Carr Barbour & Associates, 1999). Hydrogeologically the aquifer can be divided into three main units of decreasing permeability: quartzite, micaceous quartzite, and schist. The Auas Formation quartzite in the south is relatively pure but the mica content in the quartzite horizons increases northwards and quartzite of the Kleine Kuppe Member (Kuseb Formation) in the north is highly micaceous. The degree and intensity of fracturing decreases as the mica content of the quartzite increases.

The Windhoek Aquifer is bounded by impermeable formations on all sides. In the south it is bounded by gneiss, in the north by amphibolite of the Matchless Belt, and in the east and west by low permeability formations consisting predominantly of schist. The succession hosting the aquifer dips from the Auas Mountains northwards at an angle between 15 and 30°. The water level configuration in 2001 is shown in Figure 1. Elevated water levels occur in the north at the hot springs in the centre of the city (near boreholes 4/2 and 4/3), in the central area in shallow boreholes in the schist (e.g. near borehole 9/5), and in the west around the Kaiser Wilhelm Mountain (see Figure 1). This latter area also includes the Kupferberg waste disposal site where saline water occurs at elevated topographic levels. Groundwater leakage from the aquifer is only possible along the Aretaregas River valley in the north-western part of

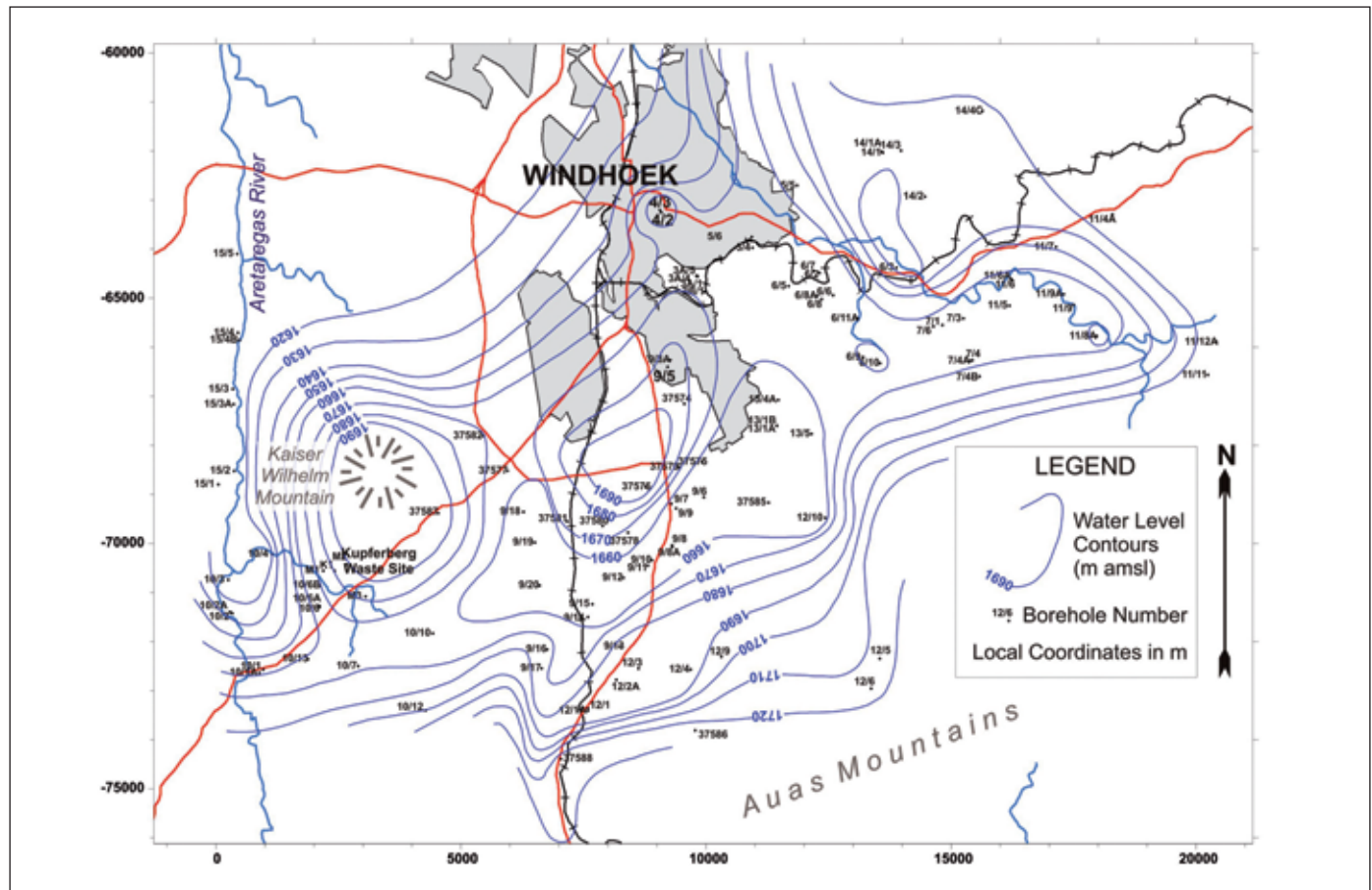


Figure 1. Water levels and piezometric heads in the Windhoek Aquifer in 2001. Contour labels are oriented to indicate higher level above the number

Figura 1. Niveles de agua y cota piezométrica en el acuífero de Windhoek en 2001

the aquifer (see Figure 1). The hydraulic relationship between the elevated levels in shallow boreholes in the schist and water levels in the main water bearing formations needs further investigation. Radiometric age determinations using ^{14}C indicate that recharge occurs in, and possibly also just south of, the Auas Mountains. The overall water level gradient indicates that water flows from the Auas Mountain range to the north and northwest. This is in general agreement with the topographic gradient and with natural recharge mainly taking place in the highly fractured Auas Formation quartzite, with limited recharge in the micaceous quartzite, and practically no recharge in the areas underlain by schist. This was also borne out by the groundwater modelling (Zhang *et al.*, 2002).

The micaceous schist is not conducive to groundwater flow. The same applies to the thin layers of amphibolite, with their orientated fabric and common association with thrusts. Secondary porosity deve-

loped for several reasons including sympathetic fracturing of the country rock flanking the tension faults (Carr Barbour & Associates, 1999). Weathering, due to the breakdown of disseminated iron sulphide (pyrite) in the quartzite, is another potential source of secondary porosity. The oxidation of the sulphide generally extends down to the lowest historic water levels, but may extend to greater depths within the fault zones.

Hydrochemistry

The hydrochemical evolution of groundwater in the aquifer takes place along the flow direction. Initially, in the Auas Formation quartzite, the water represents recently recharged water containing mainly calcium-magnesium-bicarbonate. Even in the quartzite matrix, sufficient calcium carbonate is present to allow the

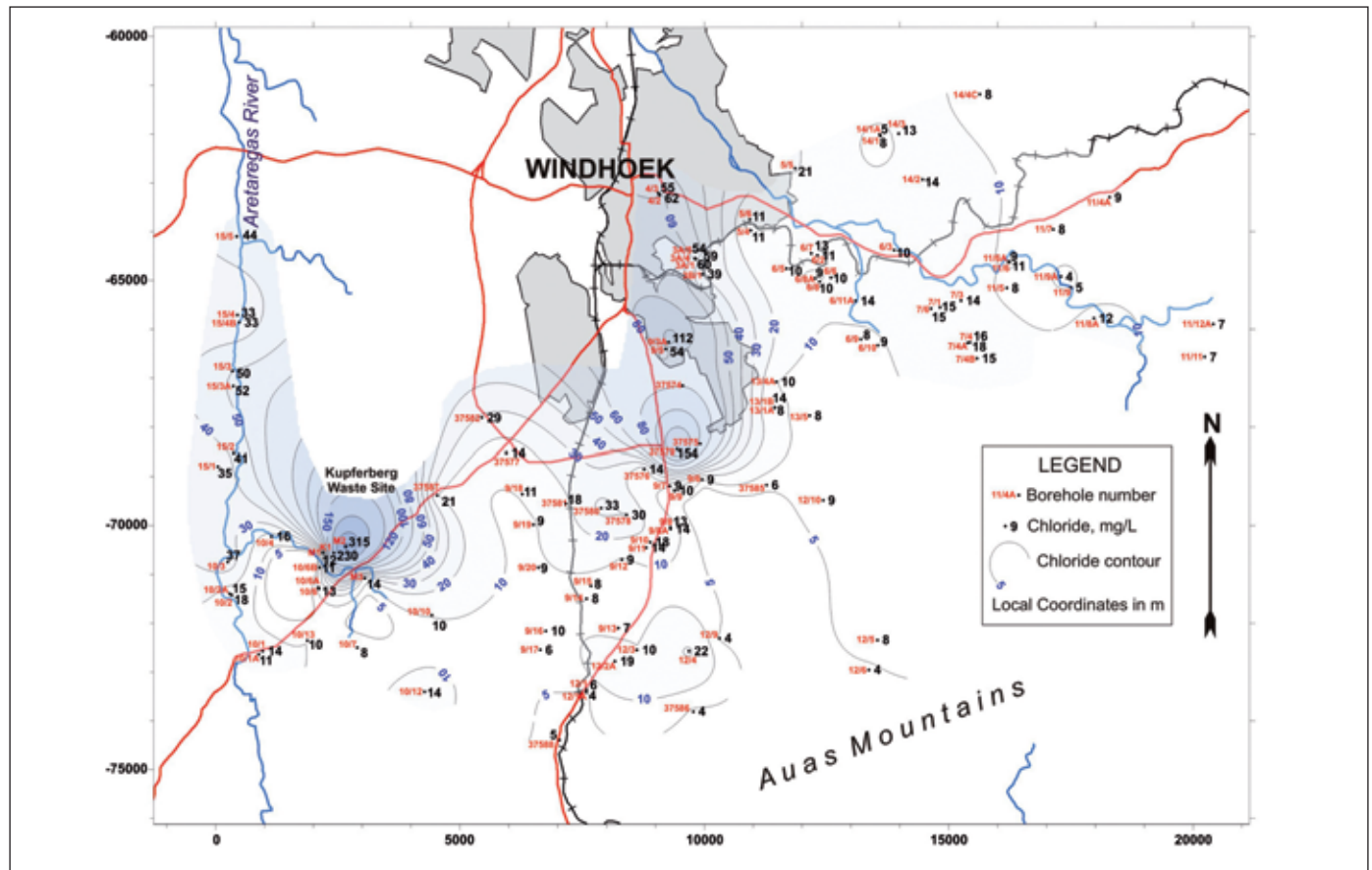


Figure 2. Chloride concentration in groundwater in the Windhoek Aquifer. Contour labels are oriented to indicate higher level above the number

Figura 2. Concentración de cloruro en el agua del acuífero de Windhoek

development of groundwater of such hydrochemical composition. Along the flow path sodium chloride dissolves from the aquifer matrix to increase the sodium content of the groundwater. In the case of the Windhoek Aquifer, shale and clay are largely absent and ion exchange plays a minor role. Only in the deep-circulating groundwater this process can progress to near completion as the residence time of the water is long enough.

The salinity distribution in the aquifer, as portrayed by the chloride distribution (Figure 2), confirms that the groundwater has a very low salinity in the Auas Formation quartzite in the south where chloride is below 10 mg/L. As part of the hydrochemical evolution in the aquifer, the salinity increases gradually in a northerly, north-westerly and westerly direction and reaches the highest levels in the mica schist underlying the southern part of the residential area, and in the west along the Aretaregas River. The

deep circulating water emanating in the city centre as hot water have a higher chloride concentration, reflecting the long residence times at depth. The highest salinities in the area occur at the Kupferberg waste disposal site (in the south-western part of the aquifer) where the chloride reached 315 mg/L. However, this might be part of a perched aquifer in the micaceous schist and at this stage, it is unknown how much, of this water will eventually reach the main aquifer, and at what rate. On this relatively coarse scale, this is the main pollution point source identified based on the hydrochemical data.

Figure 3 shows the distribution of sulphate in the aquifer and it is evident that sulphate occurs in high concentrations practically throughout the aquifer. The reason is that iron sulphide in the form of pyrite is disseminated throughout the host rocks of the Windhoek Aquifer. Dissolved oxygen entering the aquifer with the rainwater during natural recharge oxidizes the

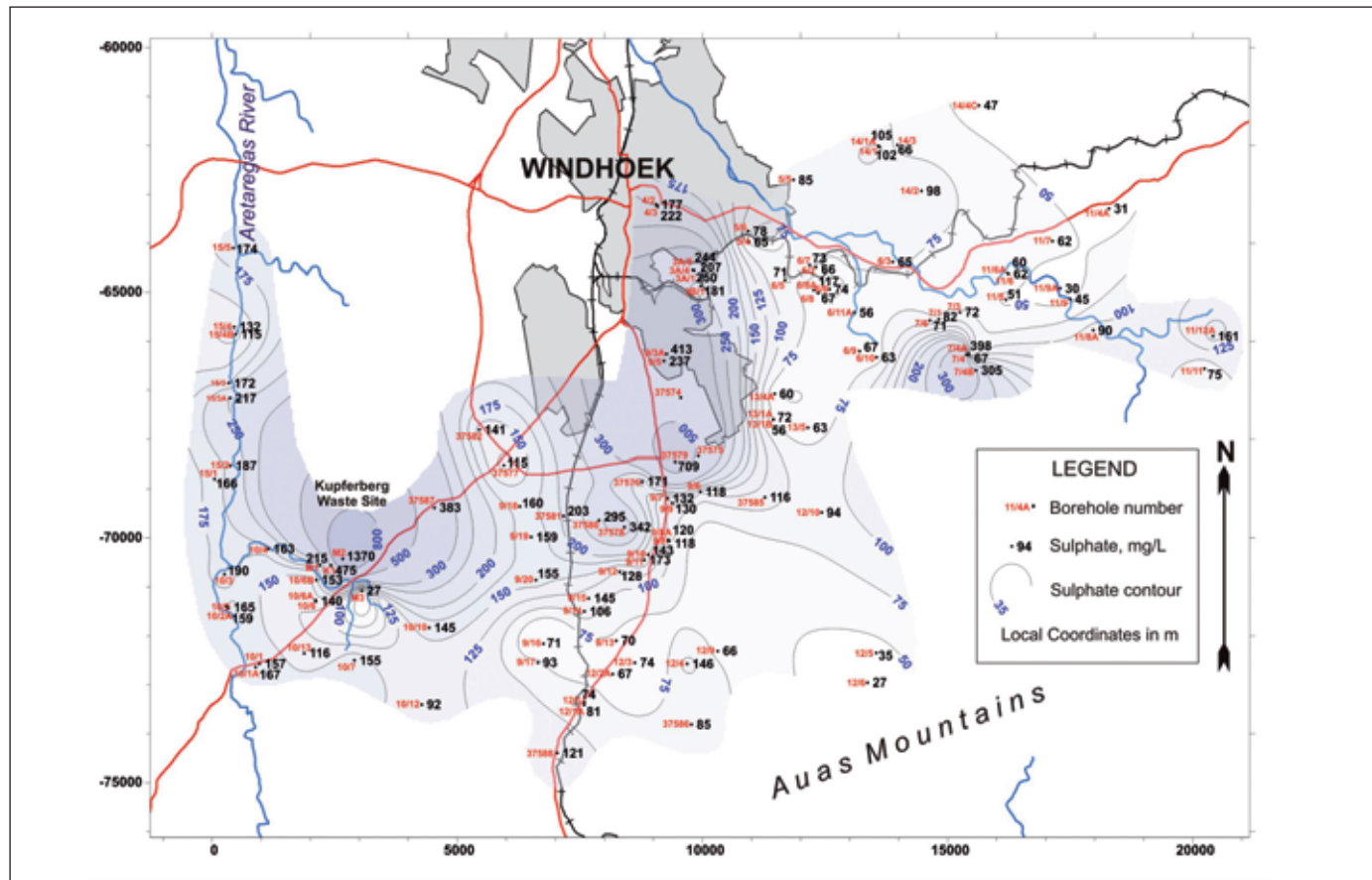


Figure 3. Sulphate concentration in groundwater in the Windhoek Aquifer. Contour labels are oriented to indicate higher level above the number

Figura 3. Concentración de sulfato en el agua del acuífero de Windhoek

sulphide to sulphate. In this way, sulphate is generated in the aquifer until the dissolved oxygen is exhausted. As a result, the groundwater is largely devoid of dissolved oxygen and high in sulphate. Under natural conditions, the groundwater easily attains sulphate concentrations of 200 to 300 mg/L. In areas where the soil has been disturbed, as in the residential area, the sulphate concentration increases as more of the pyrite is exposed to oxidation. This is the case in the central part of the area where shallow monitoring boreholes show high levels of sulphate. Also at the Kupferberg waste disposal site the natural soil and rock structure is disturbed and high concentrations of sulphate are being generated. This is reflected in the groundwater down-gradient of the site where the sulphate exceeds 1000 mg/L. However, at this stage it is evident that these high sulphate levels are not reflected in the main aquifer underlying the perched aquifer in these areas.

In view of the high sulphate levels in the aquifer, the relationship between sulphate and electrical conductivity was investigated (Figure 4). The strong correlation between sulphate and electrical conductivity suggests that the increase in the salinity is largely due to the dissolution of sulphate ions. The down-gradient observation borehole at Kupferberg, with highest sulphate is not shown in the figure. The graph also indicates that there is more than one population of points. Whereas most of the water plots near a straight diagonal a certain number of points plot below the line. These include the hot water emanating in the city, the associated wellfields, as well as boreholes in the west and northwest.

During the oxidation of iron sulphide, iron also enters into solution in the form of Fe²⁺ ions. In the unsaturated zone, sufficient oxygen may be available to oxidize the iron to the Fe³⁺ form, which is insoluble at neutral or alkaline pH. However, in the saturated

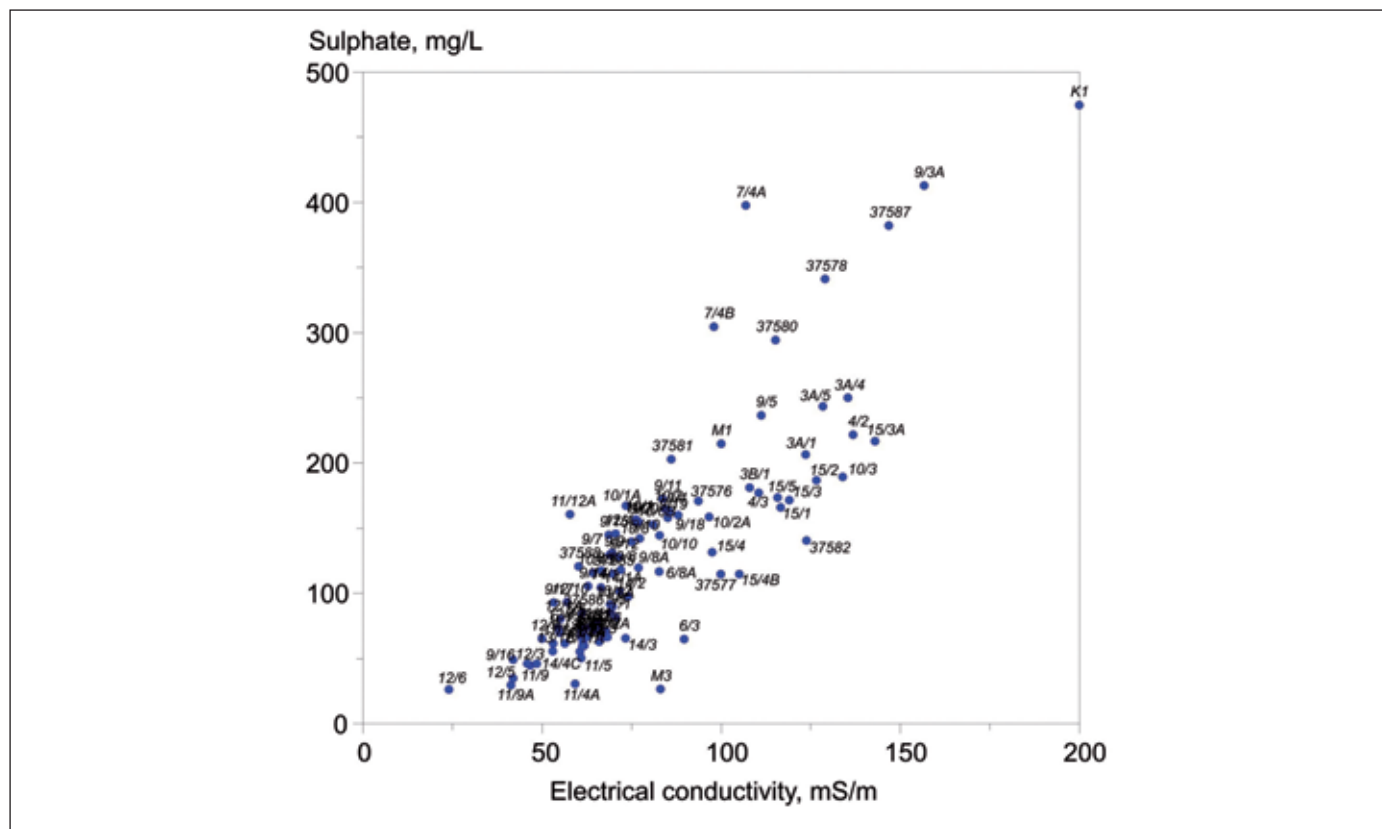


Figure 4. Relationship between sulphate and electrical conductivity in the Windhoek Aquifer
 Figura 4. Relación entre sulfatos y conductividad eléctrica en el acuífero de Windhoek

zone Fe^{+2} ion remains in solution once the dissolved oxygen is consumed. Inspection of analytical data showed that iron is widely distributed throughout the aquifer. This needs further investigation but is consistent with the high levels of iron sulphide present in the mineralised fault zones in this area. High iron concentrations occur at the Kupferberg waste disposal site and a maximum of 22 mg/L was recorded in the slightly acidic water. Both Fe^{+2} and Fe^{+3} ions are soluble in such groundwater.

Discussion

Most aspects of the hydrochemistry in the Windhoek Aquifer were discussed above using the data provided. However, little attention has been devoted to the occurrence of organic compounds. The analytical results indicate that such compounds are generally absent from the aquifer except in polluted areas such as the vicinity of the Kupferberg waste disposal site, and in shallow boreholes in the schist.

Potential hydrochemical interactions and changes in water quality during and after injection are related to a number of factors. These include chemical differences between the injected water and the ambient groundwater, e.g. oxygen content and chemical composition, which will lead to re-establishment of chemical equilibria. Other important interactions will take place between the injected water and the aquifer matrix, both in the saturated and unsaturated zones. The oxidation-reduction potential of the injected water and the groundwater as well as the carbon dioxide partial pressure will determine the extent of such reactions. From the available data, it would seem that changes in the oxidation-reduction potential in the subsurface might be the main factor affecting the hydrochemical environment of the Windhoek Aquifer.

Borehole injection is presently considered the preferential technique for applying managed aquifer recharge at Windhoek. Where pure, inert quartzite is involved, this may have little effect on the hydrochemistry but at Windhoek the quartzite contains

pyrite and graphitic schist. The aquifer is highly reducing with no dissolved oxygen in the ambient groundwater. Injection of surface water saturated with oxygen will change the redox conditions and cause interaction with the rock matrix. At Calvinia (Northern Cape, South Africa), where surface water was injected into a breccia pipe with ideal hydraulic properties for subsurface water storage, pilot studies showed that it had adverse hydrochemical effects (Cavé, 1999, 2000; Murray & Tredoux, 2002).

However, it is important to note that the abstraction of the natural groundwater from any aquifer is also accompanied by the ingress of oxygen into the reduced environment. This shifts the redox potential of the system, creating disequilibrium and promoting oxidation reactions in the subsurface. Subsequent rises in the water levels, natural or induced, will dissolve soluble chemical species and cause changes in water chemistry. At Windhoek, the widespread dissemination of iron sulphide in the aquifer affects the quality of the water stored in the aquifer. The intensity of the effects will depend on the recharge technique, method, and regime. Injection through a deep borehole at depth will be the preferred technique as cascading of the water through the unsaturated zone

will exacerbate any adverse reaction, such as the oxidation of pyrite.

Although the chemical speciation of iron is unknown, considerable information is available on the distribution of total iron in the aquifer. Manganese is also present in the aquifer but little detail is available on its distribution. However, it is also mobilized by changes in the redox potential in the aquifer and the study of the Kupferberg waste disposal site (Tredoux & Barbour, 2004) has confirmed that it is present in sufficient quantities to warrant attention.

Protection of the aquifer against pollution has to have a high priority. Once artificial recharge is fully operational, the water level will rise and the need for protection will increase.

In view of the wide distribution in the aquifer and the high iron levels, borehole clogging is a distinct possibility. For this reason, future monitoring should be designed to allow research into the concentrations of the various iron species in order to get a better understanding of the situation in the aquifer with regard to the clogging potential.

Quality guidelines for recharge water

As the recharge water will be injected directly into the aquifer without seeping through the unsaturated zone it was concluded that the injection water quality needs to conform at least to drinking water requirements. The final water quality from the Von Bach Dam Water Treatment Plant is presented in Table 1. The salinity (EC) and inorganic constituents are relatively low but the 95th percentile as well as the median of the dissolved organic carbon concentration is very high. On the other hand, the DOC values of the New Goreangab Water Reclamation Plant are relatively low, but the salinity and chloride concentrations are high (Table 2). Even a 4:1 or 5:1 blend of Von Bach with Goreangab water would produce water that is unsuitable for injection. Thus further treatment is essential, particularly better removal of DOC at Von Bach, and partial desalination as a future option at Goreangab.

Assuming that the water from the treatment plants could be improved, the quality criteria were set based on the following guiding principles (Van der Merwe *et al.*, 2005):

The recharge scheme should meet a number of demands, which are listed below:

1. No negative environmental impact of significance.
2. Sustainable use of water from the Windhoek aquifer for drinking water purposes preferably

Quality Variable	Measuring Units	Median	95%
Physical and Organoleptic			
Conductivity	mS/m	24	42
pH	pH units	7.8	8.3
pH Field Analysis	pH units	7.7	8.3
Temperature	°C	24.0	27.1
Turbidity	NTU	0.6	2.1
Total Dissolved Solids	mg/L	161	281
Dissolved Organic Carbon	mg/L	3.6	7.2
Chemical Oxygen Demand	mg/L	14	21
Total Trihalomethanes	µg/L	73	122
TOX	µg/L	51	84
UV 254	abs/cm	0.05	0.09
Macro Constituents			
Ammonia	mg/L as N	0.05	0.28
Calcium	mg/L	11	22
Chloride	mg/L as Cl	24	19
Magnesium	mg/L	11	22
Nitrate	mg/L as N	0.3	0.7
Nitrite	mg/L as N	0.01	0.05
TKN	mg/L as N	0.6	1.7
Ortho Phosphate	mg/L as P	0.04	0.07
Sulphate	mg/L as SO ₄	4.9	19.0
Biological			
Chlorophyll-A	µg/L	0.13	1.3

Table 1. Final water quality Von Bach Dam Water Treatment Plant
Tabla 1. Calidad del agua final de la planta de tratamiento de Von Bach Dam

Quality Variable	Measuring Units	Median	95%
Physical and Organoleptic			
Conductivity	mS/m	130.0	145.0
pH	pH units	7.87	8.80
Temperature	°C	20.05	25.50
Turbidity	NTU	0.06	0.13
Total Dissolved Solids	mg/L	871	972
Dissolved Organic Carbon	mg/L	1.50	2.54
Chemical Oxygen Demand	mg/L	7.3	11.0
Total Trihalomethanes	µg/L	31.5	86.0
TOX	µg/L	4.5	13.5
UV 254	abs/cm	0.01	0.03
Macro constituents			
Ammonia	mg/L as N	0.05	0.31
Calcium	mg/L as CaCO ₃	101.8	133.4
Chloride	mg/L as Cl	207.5	268.3
Magnesium	mg/L as CaCO ₃	70.0	105.0
Nitrate	mg/L as N	8.8	17.2
Nitrite	mg/L as N	0.05	0.09
TKN	mg/L as N	0.25	0.91
Ortho Phosphate	mg/L as P	0.06	0.71
Total Phosphate	mg/L as P	0.00	0.00
Sulphate	mg/L as SO ₄	110.0	155.5
Biological			
Chlorophyll-A	µg/L	0.16	1.85

Table 2. Final water quality New Goreangab Water Reclamation Plant

Tabla 2. Calidad final del agua de la planta de depuración de New Goreangab

without treatment or at most with limited treatment such as stabilisation and disinfection:

- a) The recharge water should meet modern drinking water standards (e.g. Rand Water and RSA)
 - b) No additional health risk for the residents of Windhoek as compared to present sources (2004)
3. No technical problems should arise due to injection water quality, such as clogging, corrosion and demand for extensive treatment of water before distribution.
 4. Accept a deterioration of certain quality parameters of the water within the aquifer provided that the water quality after abstraction complies with acceptable water quality guidelines (RSA & Rand Water)

Van der Merwe *et al.* (2005) also recommended that:

1. The Rand Water (95% percentile values) and South Africa (Class 0) water quality guidelines be adopted as the general guideline for the injection water.
2. The provisional guidelines as summarised in the Table 3 be accepted on an interim basis
3. The guidelines be revisited after 2 years of intensive data collection and evaluation after further pilot injection studies.

Determining the longer term water quality impact will only be possible through mass transport model-

ling and this has to be considered as a next step for predicting the sustainability of the operation. The mass transport model will be based on the existing hydraulic simulation model. The outcome will strengthen the scientific base for refining the water quality requirements.

Conclusions

The Auas Formation quartzite constitutes the most important part of the Windhoek Aquifer. This is where natural recharge is taking place, the best quality groundwater is found, and high permeability combines with high storativity. Only low salinity water free of organic compounds should be injected in this part of the aquifer.

Low salinity water occurs over most of the aquifer. Groundwater in the Auas Mountains generally has very low chloride concentrations ranging from 4 to 10 mg/L and increasing to a maximum of approximately 60 mg/L in the deep circulating hot water issuing in the city and the associated wellfield area. In contrast, the chloride concentration exceeds 300 mg/L in the polluted part of the aquifer at the Kupferberg waste disposal site. It is also high in shallow boreholes located in the schist. From the observations it would seem that these polluted parts may have limited hydraulic connection with the main aquifer.

Major changes in salinity and sulphate were associated with pilot scale injection tests, but also due to variations in the abstraction regime due to fluctuations in the water level in the aquifer, the concomitant enhanced oxidation of sulphide, and subsequent dissolution of sulphate. High intensity natural recharge events may also cause salinity fluctuations in intake areas. Such a phenomenon was observed at the Kupferberg waste site following the 1999/2000 rainy season.

The detailed water quality assessment showed that the presence of sulphate throughout the aquifer is an important characteristic of the hydrochemistry. Sulphate reaches very high concentrations of several hundred mg/L in certain areas. Its source is the iron sulphide (pyrite) which occurs widespread throughout the aquifer. Disturbing the soil and rock enhances weathering and oxidation of the sulphide. In disturbed areas, such as the Kupferberg waste disposal site, sulphate reaches several thousand mg/L.

Iron is ubiquitous in the groundwater in the Windhoek Aquifer. Similarly, manganese is present in the aquifer. The solubility of iron depends on a number of factors and data on the chemical speciation of iron are needed for a full understanding of the conditions in the aquifer.

Parameter	Rand Water / SABS Guideline Value	Proposed Injection Water Quality Values	Reason
DOC mg/L	5	4	Oxygen consumption
AOC growth rate/h	0.15	0.15	Clogging
EC (mS/m)	70	60*	Water quality
Chloride mg/L	100	100	Water quality
Sulphate mg/L	200	50	Water quality
Nitrate & Nitrite (as N) mg/L	6	5	Water quality

* The EC may be adjusted upward to a maximum of 70 mS/m in areas where the prevailing EC level in the groundwater of the injection area is above 60 mS/m.

Table 3. Provisional water quality guidelines for recharging the Windhoek Aquifer
 Tabla 3. Estándares provisionales de calidad para la recarga del acuífero de Windhoek

The presence of pyrite in the aquifer is of some concern and injection should be controlled to minimize the oxidation of pyrite. Deep injection of the water, i.e. directly into the saturated zone, would be necessary to prevent cascading of the water through the unsaturated zone. It is suggested that injection points (levels) should be determined according to the characteristics of each individual borehole but should be at least 10 metres below the rest water levels. The rapid rise and fall in the water tables during injection and abstraction over long periods would also release sulphate in the water as a result of the oxidation of pyrite as a result of the variation in the groundwater table. Where possible, the change in water table should be minimised.

Mass transport modelling will be essential for determining the longer term impact of the injected water on aquifer water quality. Managing injection water quality according to the set criteria should go a long way to maintaining the high quality of the water stored in the aquifer. It may be possible to improve the water quality in certain higher salinity areas, e.g. in the western part of the aquifer, by artificial recharge.

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