Management of City aquifers from anthropogenic activities, soil dynamics and challenges for the future: An example of the Windhoek aquifer, Namibia

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Abstract

As the city of Windhoek is growing rapidly, it has become increasingly obvious that dangers to the underlying groundwater aquifer have become imminent and need addressing immediately. The Windhoek aquifer is large and is used both as a storage facility and as a source of clean drinking water for the expanding city. The abstraction rate is about 15 000 000 m^3 per year, out of which 11 000 000 m^3 is pumped into the aquifer from reclamation and Grootfontein aquifers some 500 km north of Windhoek. The natural recharge is very minimal, under 350 mm per year in good rainfall years and way below this figure in dry years. The recharge areas of the aquifer lie to the east and south east of the city in the vicinity of the suburb of Kleine Kuppe and Cimbebasia. The soil horizon over the Windhoek schist is very thin; most areas of the city are built directly on bed-rock, making the aquifer vulnerable. The use of pesticides for weed control, oil spills, toxic chemical spills and high fertilizer application rates can lead to the contamination of ground water. The hydrochemistry of these pesticides and fertilizers can cause severe pollution to the ground water if the practice is not carefully monitored. The Windhoek aquifer is supplemented by water pumped from Grootfontein, some 500 km north of Windhoek, a costly expense for the nation. The geology of the city of Windhoek consists of the Kuiseb Schist, locally known as the “Windhoek Schist” and amphibolites. The Kuiseb schist possesses pervasive cleavage that renders the underlying lithology to be permeable to percolating water and fluids from the surface into the aquifer. The Pahl fault, which is a major structure in the Suiderhoff area is a major conduit of surface water to groundwater, especially in the rainy season. The fissility and fracture density of the schist imply that leakage of surface waters, phenols, septic tank spills and industrial contaminants than may reach the aquifer in unusually high rainfall years. Organic fuels and oils are much more adverse, as they are able to be resident in soils for long periods of time. Thus the close monitoring of all sewage pipes, filling stations, dump sites including cemeteries preferably on a GIS based model is the best way possible to save the aquifer from future pollution. The weathering of soils in humid climes, produces silicic acid, which has an effect in sealing the conduits due to soil generation from rocks. In dry climates however, the action of this acid, with a very small equilibrium constant, implies that, soil formation is very limited, and pollutants can easily reach the aquifer below. These concerns apply to the location of new suburbs and cemeteries in the city. The water used in the city of Windhoek is sourced some 500 km away, in the Berg Aukas area of Namibia. The Windhoek aquifer supplies about 10% of the water needs. The city of Windhoek is underlain by the Kuiseb Schist, locally known as the “Windhoek Schist” and amphibolites. These rocks are not very good aquifers, but can be used as storage facilities in a dry and high evaporation environment. In the low places of the Windhoek valley, gravels and sands are present. The schist has several

lithologies, dominated by garnet-muscovite-chlorite-biotite schist, with distinctive cleavage. This pervasive cleavage renders the underlying lithology to be permeable to percolating water and fluids from the surface into the aquifer. Other minor lithologies are trachytes, metarhyolites and quartzites found to the east of the city. The amphibolites are part of the Matchless belt, and traverse the city in a NE-SW fashion. When weathered, the Matchless belt it forms a perfect aquiclude. North south and northeast-south west trending faults with a few splays cut across the Kuiseb Schist. The faults play a significant role in increasing the fracture density of the fissile schist. The faults are the major link that form channel ways between the surface and the aquifer below. The city of Windhoek uses the aquifer both as a source of fresh water and as a storage facility. The recharge areas of the aquifer lie to the east and south to south east of the city in the vicinity of the suburb of Kleine Kuppe. The soil horizon over the Windhoek schist is very small; most areas of the city are built directly on bedrock. The thin soil horizon makes the aquifer to be easily amenable to pollution, either caused by accidents such as spills or carelessness due to unsupervised dumping. The fissility and fracture density of the schist imply that leakage of surface waters, phenols, septic tank spills, chemical and industrial contaminants and other such materials can reach the aquifer in unusually high rainfall years. The case of organic fuels and oils is much more adverse, as they are able to be resident in soils for long periods of time. Thus the close monitoring of all sewage pipes, filling stations, dump sites including cemeteries preferably on a GIS based model is the best way possible to save the aquifer from future pollution.

Key words: Groundwater, pollution, fractured aquifer, mitigation, reclamation scheme, leakage.

1. Introduction

Arid regions require special education of the population in water usage. Water is much more difficult to obtain and store. In areas where rainfall is high, dams can be built; however in arid regions evapotranspiration from water bodies with surface areas is very high, and the stored water has to be used quickly before it is lost to the atmosphere. Oceans occupy large areas on the globe, precipitation is skewed towards oceans that account for 77%, whereas on land it is only 23%. In a country like Namibia, only a fraction of that 23% is received as rainfall.

Namibia is a water stressed country, except for the northern part of the country and the large Tsumeb-Otavi-Grootfontein groundwater carbonate aquifer (Figure 1). On average, Namibia is a country that is deficient in surface water, as all but four major rivers namely the Zambezi, Kunene, Kavango and Orange are ephemeral streams. In the inland large dams, evaporation rates are quite high averaging about 3200mm per annum (GTZ-DWA, 1993). Precipitation on the other hand around Windhoek averages 370 mm per year, and the highest rainfall recorded has been 766 mm in 1936 (Crerar and Church, 1988; Colvin, 1994). The lowest rainfall recorded was in 1944-1945 rainy season of 112 mm. Namibia is divided into distinct zones according the amount of rainfall received and catchment geometry (Arnestrand and Hansen, 1993). Windhoek lies in the 200-400 mm category, with exceptional years when precipitation reached 700 mm (Arnestrand and Hansen, 1993; van Wyk et al., 2001). Those precipitation levels are not sufficient to stave off drought in a rapid growing city like Windhoek.

Historically Windhoek was water sufficient due to its springs, and became the site of original white settlement around 1890 (GTZ-DWA, 1993). As the population of the city was growing, notably in the 1920-1940's, its groundwater became inadequate and new sources of water were required (GTZ-DWA, 1993). Prior to 1942, all of Windhoek's water resources were from boreholes drilled in the aquifer (Kirchner and van Wyk, 2001). Increased pumping from the aquifer increased also in tandem the water demand in the city leading to a drastic lowering of the water table in 1942 (GTZ-DWA). As precipitation was not sufficient to replenish the aquifer, water schemes were put in place. By 1942, the aquifer had become depleted (Kirchner, 2001), and surface water from Avis Dam on the Avis River that runs through Windhoek, became the main source for the city in that year (1942) as precipitation levels were very low as well. In 1958, both the Avis and Goreangab Dam (situated west of the city) water schemes were in operation to ease the pressure on the Windhoek aquifer (Christelis and Struickermeir, 2001). In the years 1966-1969, abstraction from the Windhoek aquifer reached 4.28 million cubic metres per annum (Christelis and Struickermeir, 2001, Kirchner, 1981; 2001), at which time it became clear that the aquifer would not be sustainable. Reclamation of sewage water was then introduced in 1968 (Kirchner and van Wyk, 2001), to supplement the water from the aquifer. Water demand rose exponentially in the years 1969-1970 to a level of 11 500 000 m^3, which event necessitated the initiation of transferring water from other parts of the country to Windhoek (GTZ-DWA, 1993, Kirchner, 1981). The Department of Water Affairs (DWA) in the Ministry of Agriculture and Desert Research Foundation conducted a study on water management in the city in conjunction with the City Council. The study has showed that, water usage can increase if they are no tariffs that encourage savings (Heyns et.al., 1988).

Windhoek is the capital city and administrative and industrial centre of Namibia. Since independence in 1990, the population of the city has grown so fast that water demand is now between 18.5-20 million cubic metres per annum (Christelis and Struickermeir, 2001; Kirchner, 1981). The aquifer only supplies 4 million cubic metres of water by 2003, the remainder being the combined artificial recharge and state water transfer scheme from the Tsumeb-Grootfontein-Otavi aquifer (Mapani, 2005). In 1990 this constituted 25% of the total needs of Windhoek, but today, it represents 10%, showing that external sources of water for the city are becoming more and more important with time. As such huge amounts of money are spent by NAMWATER (Namibia Water Corporation) in pumping water from the Tsumeb-Grootfontein-Berg Aukas aquifer (Fig. 1) to the intermediate dams in the Omatako region near Otjiwarongo and von Bach near Okahandja (Fig. 1), before pumping it to Windhoek, the largest city in the country, it becomes obvious why water management strategies have to be put into place to protect this resource. It is evident that the Windhoek aquifer is not only a source of freshwater for the city, but also a most convenient natural storage facility for the city (Fig. 2). Water in the aquifer is relatively unaffected by evaporation than that stored in dams around the city, such as Avis Dam to east and Goreagab Dam to the west. This scenario all the more serves the importance of jealously protecting the Windhoek aquifer.

In this paper we discuss the nature of the aquifer, highlighting its weaknesses and how new management systems can be introduced that can help to mitigate dangers to the aquifer in the face of rapid industrial growth coupled with an increase in the number of unplanned settlements. Thus issues of policy, climate, relief, population distribution and density, lack of water supply and sanitation services all affect the evolution of the aquifer.

2. Geology of Windhoek aquifer

2.1 Geomorphology

Windhoek lies about 1800 m above sea level, situated in a broad valley that opens to the north and flanked by the Auas mountains to the south, east and west. The Eros and Otjihavera mountains occur to the north and north –east of the city. The elevation to the east of Windhoek is about 1900-2000 m above sea level. The high elevation of Windhoek also makes it the central watershed area. Five big ephemeral rivers have their origin around Windhoek, the Kuiseb flows to the west to southwesterly, until it enters the Atlantic Ocean; the Swakop flows northwards from Windhoek, then turns in a westerly direction until it also enters the Ocean. The Oanob River flows to the south, the Olifants flows eastwards out of the city and then turns in a south-easterly direction and the Nossob flows easterly and then south easterly, more or less parallel to the Olifants River.

2.2 Geology of the Windhoek Aquifer

The geology of the region around Windhoek is dominated by the Neoproterozoic Damara sequence, that underlies most of central and northern Namibia (Fig. 1). The basal succession of the Damara Sequence is underlain by the Nossib Group arenites, that formed between 850-700 million years (Ma) (Miller, 1983). The Nossib Group is overlain by the Swakop Group metasedimentary units, composed of carbonates interbedded with graphite mica schists, quartzites, mass flow deposits, lavas, iron formations, until the platform became stable to allow the Otavi carbonate platform development (Miller and Grote, 1988). To the south, the Damara Orogen is marked by deep-water fans of the Auas Mountains Formation around Windhoek. Above the Auas Formation is the Kuiseb Formation, that consists of metamorphosed greywackes and ocean floor basalts in a 350 km long zone trending east-west. The Kuiseb formation was deformed and metamorphosed to lower Amphibolite facies, to form the currently observed Kuiseb Schist during the Damara Orogeny at 650 Ma (Miller, 1983). This metamorphism, gave way to well defined schistosity and cleavage in the rocks (Fig 3). Post deformation trachytes occur in the Auas Mountains that further induced fracturing in the Kuiseb schist and enhanced its aquifer potential.

The Kuiseb formation underlies the whole area covered by the Windhoek aquifer (Fig. 2). The other lithologies are highly dissected quartzites, which are generally interbedded with schists mainly to the south, that strike west to south west and east to north east, dipping at moderate 30-40 to the north. The Kuiseb schist is in certain zones, as south of the city interbedded with arenites, but make up a small proportion in the sequence. On the extreme southern part of the city (Fig. 2), the Auas Mountan Quartzite Formation is encountered, and forms the extreme southern limit of the aquifer and an important recharge zone. The Kuiseb Schist is highly fractured (Fig. 4) as is observed in the vicinity of the Pahl fault in the city. In places the Kuiseb schist is weathered due to faulting near the surface, producing brittle structures (Fig. 4), although even when this is the case, there is a very small soil horizon developed. Above the aquifer there is a thin soil cover, generally 1 cm to about 20 cm thick, and in places there is virtually no soil at all even when weathering has occurred in the underlying rocks (Fig. 3A). This disposition of the pedological evolution supports acacia savanna woodland, with little grass and humus horizon in the soil.

3. Nature of the Windhoek Aquifer and its potential

3.1 Aquifer evolution with increasing water demand

Vertical primary porosity and permeability in the schist is quite low, what enhances porosity and permeability is the fracture pattern of the rock units and the schistosity that is pervassive. Groundwater is stored and transmitted along the north-south trending faults of the city, and fracture zones generated (Fig. 4). The Auas quartzites are the main principal aquifers, with the Kuiseb schist being secondary in nature. The natural recharge to the aquifer is principally through the Auas quartzites to the south of the city. Precipitation by rainfall is deemed not significant (GTZ-DWA, 1993), and this is generally observed each rainy season; for instance in the 2006-2007 season, Windhoek received way below 297 mm. Water levels in the Windhoek aquifer are generally between 70 m and 110 m below the surface (GTZ-DWA, 1993). This property has for years protected the aquifer, as the water level is quite low. However fracture zones do reach this water table due to continuity of fractures and consistency. The water demand curve for Windhoek (Fig. 6) shows a consistent pattern of a sinusoidal curve for groundwater levels (Kirchner, 2001). Following excessive years of abstraction from the aquifer (Fig. 6, dark bars), the aquifer levels drop, for instance, from 1945 to 1949, was followed by 1950 when aquifer levels were low, similarly the period1957-1962, 1969-1970, when the aquifer was reduced to very low levels. The pattern was repeated in the years 1977-1982 and 1990-1997 (Fig. 6). The water demand curve also shows that the Windhoek aquifer has principally evolved from being a principal source of water to a principal storage aquifer. This evolution must also be reflected in the style of management of the aquifers' unique location, emphasis must shift more to protection and sustainable usage, than just storage of water. The figures also over a long period of time of 78 years (1920-1998) have shown that an average abstraction of 2.34 million m^3 per annum does not exceed the mean natural recharge for the aquifer, but those above 2.79 million m^3/year, exceed the sustainable yield of the aquifer (GTZ-DWA, 1993). High abstraction rates (e.g., 1965-1970) lower the water table, and if the water table is lowered to very low levels, without corresponding artificial recharge to equate equilibrium volume occupancy of fluid, collapse structures may occur within the aquifer, thus reducing the storage capacity. Storage capacity in the aquifer can reach up to 18 million m^3/year, although GTZ-DWA (1993) study suggests 14.64 million m^3/annum as the average figure. More pumping tests are however recommended to actually ascertain the exact storativity of the aquifer. It is evident that the City of Windhoek is growing rapidly, and its population will continue to increase, that will in turn put pressure on the aquifer as a storage facility of clean water.

Production boreholes are currently about 50 in number, all drilled to intersect the north-south trending fault zones such as that of the Pahl fault (Fig. 4) and managed by the City of Windhoek. Supply from the boreholes now (2004) account for only 10% of the water supply, another 10% is from the reclamation of wastewater from Goreangab dam, and 80% from water transfer schemes. Windhoek was one of the first cities in Africa to introduce wastewater reclamation for domestic consumption in 1968 (Murray and Tredoux, 2000). The quality of the groundwater supplied from the production boreholes from the aquifer is very good, with Total Dissolved Solids contents averaging 600 mg/l, sulphate, nitrate and fluoride are all well below the WHO limits.

3.2 City water supply and access to piped water

Of the 250 000 -270 000 inhabitants (estimates as of 2006) of Windhoek, 95% of them have access to Municipal water network, the other 12 500-14 000 live in informal or unplanned settlements in the city such as Babylon. The city supplies about 48 000-50 000 cubic metres per day (van der Merwe, 1988, Windhoek Customer Care) with about 38 200 water points to households (Goldblatt, et. al., 2000, WRP, 2001) accounting for 74% of the usage whereas the other 24% of the water served is to companies and industry. The water supply revenue base for the city council is in the order of N$45 million per annum (US$ 7.5 million/annum). Gumbo (2004) has shown that in most African cities such as Mutare (Zimbabwe), Maputo (Mozambique), Lusaka (Zambia), Maseru (Swaziland) there exists no policy on water demand management, whereas in others such as Windhoek and Johannesburg, a water strategy does exist, but does not extend to aquifer protection and is not legislated. The major problems related to water supply that occur in a city as Windhoek are related to pipe bursts, sewer bursts and illegal dumping of waste (Fig. 5). As has been outlined above, such sewer bursts can leak into the groundwater system if they occur in unfavourable zones, as the soil cover over the city is very thin. The city however has been working hard to reduce gross uncounted for water losses in the system. Windhoek has reduced this value to about 20 % of the total supply volume.

4. Vulnerability of the Windhoek aquifer.

4.1 Groundwater vulnerability and risks

Cities are unique, in that a large number of people have to be supplied with water, this in itself is a challenge, and to do better is yet another formidable challenge as some studies do show (Gumbo, 2004, Turton, 2002). The cities bring together a large group of people who have to share, use, and dispose water as either sewage or factory effluent, all with consequences that require specific management styles.

Groundwater resources in Namibia are classified according to risk in four (4) categories, very high risk (VHR), high risk (HR), moderate risk (MR) and rather low risk (LR) (Struikmeier and van Wyk, 2001). The city of Windhoek is currently classed as a HR city. This study highlights the fact that if the population increase rate in Windhoek continues at current levels, in consort with the rapid growth of light industries, such as plastic manufacturing, will require increasing the risk scale for the Windhoek aquifer at least to the VHR level. For example, between 2000 and 2004, new suburbs have sprung up in the south of the city, in the areas of Kleine Kuppe, Cimbebasia, and Prosperita, a light industrial zone and to the east of the city, Rocky Crest. These developments have all taken place within the boundary of the Windhoek aquifer (Fig. 2). The other corollary is that the recharge area has also been encroached upon. The phrase "every drop is precious" by Umgeni Water of South Africa, applies in this case. The locality and resources required to bring water to Windhoek (Fig. 6), imply that a more stringent code of water management be enforced.

Windhoek is growing at quite a rapid pace, with new industries being opened up such as the Ramatex Textile Factory. This has also introduced a new type of factory textile effluent from dyes and associated processes. This effluent is pumped to the Goreangab dam to the west of the city. The danger posed by these effluents to groundwater is not as yet well studied, as the bulk water is recycled. The aspect that is expected to be of concern, are the unauthorized dye spills within the Ramatex Complex. Such spills are expected to percolate to the groundwater, much more easily if they happen during the rainy season. Dyes are commonly organo-metallic compounds, that are likely to have long lived half lives as herbicides and pesticides (Chilton, et al., 2000). These developments around Windhoek that was once a light industry city are likely to increase the risks to the groundwater resource.

One aspect often overlooked is the case and location of cemeteries. By nature cemeteries are a special of case of "dump sites", that require careful study before land is allocated in the city environment. In the case of Windhoek, the cemetery is located on the edge of the aquifer, and not directly above the aquifer. The cemeteries, especially the 'old location cemetery' is located in low-lying valley floor area, close to the 100-year flood line. However the flooding in 2002-2003 rain season encroached the cemetery, though no graves were submerged. The water that flows once a year, in most cases, ends up in the groundwater aquifers. In most cases, politicians, rather than water and geological experts locate these special sites for disposal of organic remains. It is hoped that future planning of cemeteries will encompass a multidiscipline team, to avoid such risks for future generations.

4.2 Geology, soil and vulnerability of groundwater.

The effect of sewage pipe bursts, chemical spillage by industry, oil spills and filling stations can be deleterious to a fractured aquifer and its groundwater resources such as Windhoek. Sewage is a source of nitrate, and in semi-desert conditions, nitrate levels from natural sources are rarely diluted. The greatest risks are likely to occur in fractured and carbonate aquifers with potential for very rapid water flow (Chilton et al., 2000) as water percolates in pre-existing fracture zones and schistosity. In regions where a thick soil cover occurs on top of the overlying aquifer, transport of contaminants to the water table may be slow. Each rock type yields a specific soil horizon, which in turn will have a specific number of clay minerals with high or low adsorptive properties. Granites develop kaolinites, basalts develop montmorillonites, and schists, develop smectites, and illites (a clay mineral between montmorillonite and muscovite), depending on the amount of chlorite present. Kaolinites have lower adsorptive properties than montmorillonites or smectites. The schists of Windhoek yield a small volume of montmorillonites and smectites. These clays have the capacity to absorb cations on their surfaces, such as Mg^{2+}, Fe^{2+}, Zn^{2+}, Cd^{2+}, Ni^{2+}, Cr^{3+} and a horde of others that can substitute for Si^{4+} and

Al^{4+} in silicate structures (Krauskopf, 1979). Thus a soil cover helps to retard the flow of effluents to the aquifer due to cation exchange and silicic acid reactions. Windhoek for the most part has a very thin soil cover, mainly due its semi-desert climate with little rainfall. This scenario renders the aquifer to be very vulnerable to any accidents that may be generated by anthropogenic activities, such location of factories, homes, hospitals, sporting facilities and schools. Most buildings are built on bare rock, exposing the aquifer to any accidents that may arise from sewer bursts or industrial waste spillages. In addition, unplanned settlements such as Babylon, to the north of the city are not connected to the central sewage system, and rely on pit latrines. This arrangement is unfortunate as the toilets are directly in contact with the Kuiseb schist (Fig. 3) and therefore in contact with pathways to the aquifer, especially in times of the rainy season. The relief of the city is such that these unplanned settlements are situated on high ground, making them sources of high run-off during the rainy season. At present this is not seen as a danger, because the number of informal settlements is relatively small, however there is no guarantee that the status quo will be maintained as other cities in Southern Africa evolved on a similar pattern (Nyambe and Maseka, 2000). In fact, it is expected that more people will flock to Windhoek from the rural areas, thus exacerbating the situation. This state of affairs, if the problem is not now tackled now, will create a crisis in the near future.

4.3 Leakage of petroleum and pesticides into the aquifer

Field observations around Windhoek riverine systems have shown that fossil fuels like diesel, petrol and oil, do seep into the ground at rather fast rates. In the vicinity of the Windhoek Mosque, in Klein Windhoek, around the Avis River banks, phenol oils derived from the nearby filling stations are observed to be seeping into the riverbed. This observation serves to indicate that travel rates of contaminants into the Windhoek Schist are rather fast, collaborating the absence of clay minerals in the weathered schist which would other wise bind the petroleum products. When petroleum products are introduced into the soil, before they breach the aquifer surface, their behaviour will depend on the *field forces* (i.e., gravity, electric field and magnetic field); *stochastic parameters* (i.e., diffusion, difusiophoresis and thermal gradient); *fluid mechanics* ((inertial drag, centrifugal, turbulence, shear gradient and coriolis (mainly in rivers)), and other minor ones such as photoionic and sonic. Hence before the aquifer surface is breached, and passage through soil and faults, we are more concerned with stochastic and gravity field force. For petroleum, thermal gradient is important especially every hot season, as particles or fluid will flow from a hotter to a colder region, in our case down towards the aquifer surface. Its effect is to reduce the viscosity and slowly aid its migration downwards into the aquifer. Salama and Mikula (1996) have modeled this flow in considerable detail, and will not be discussed any further here, save to point out petroleum products, petrol, diesel, paraffin and oils can all potentially travel with relative ease in soils that lack montmorillonites.

The Windhoek City council through their public relations newsletter the “Aloe”, (Aloe, August, 2004) have raised these concerns and requested Filling Stations to regularly inspect their storage tanks. Such a move would be efficient if it were legislated, and fines imposed on those who do not replace their corroded or damaged storage tanks as they have done for the dumping of vehicle tyres (Aloe, September, 2004).

Pesticides used in gardens and other applications such as fertilisers are major threats to the aquifer, due to the breakdown products that are liberated when they are applied to gardens and crops. Most pesticides and herbicides in Windhoek are applied for weed removal in paved areas, car parks, airfields, road pavements, and railway lines and sports grounds. These sources of pesticides are of serious concern, given the fact that the Windhoek aquifer is currently also used as a major storage facility of fresh water (Fig. 6). As indicated by Chilton et al. (2000) this type of usage posses a constant threat to groundwater, as it is continuous, and is not restricted to a particular season, ultimately having a cumulative effect on the aquifer. The motion of the pollutants is by field forces, stochastic and fluid mechanics. These herbicides are generally washed into soak-aways, and drains, and finally enter the groundwater system via fractures and secondary fault systems. Of the common pesticides and herbicides, Carbofuran, Alachlor, and Ametryn have been studied to see how they degrade in agricultural uses (e.g., Agrawal, 1999, Chilton et al., 1995). Carbofuran breaks down to a 3-OH-7-phenol group when quantities of 12 kg per hectare are applied, with groundwater analyses picking up concentrations of 10-60 µg/l (Chilton et. al., 2000). Alachlor is detected at the water table level, without much breakdown, together with Ametryn, when both are applied at a rate of 4 kg/hectare. Atrazine on the other hand may not be detected in wells, but will be detected in abstracted drinking water in the range 0.2-3 µg/l, implying that, it has a less resident time at the water surface (Chilton et. al., 2000). This behaviour of pesticides and common herbicides shows that these complex compounds pose a threat to all groundwater resources. In the United Kingdom, Atrazine was banned for non-agricultural use (Chilton et al., 2000) because of its persistence in groundwater, and its effects on human health.

5. Discussion and Conclusions

5.1 Discussion

The Windhoek aquifer is highly fractured; faults and their secondary splays make up the fault zones around Windhoek. In zones where the faults are exposed, and where seepage from the surface can be modeled, nitrate precipitation has been found (Fig. 4). Fertilisers and sewage are the largest sources of nitrate in groundwater and can be toxic to humans even when levels are as low as 10-15 ppm (Press and Siever, 1986). Nitrates are very soluble and they easily leak into the groundwater resources. Similar studies in fractured aquifers, e.g., Stadler et. al. (2004), have shown that surface to ground inflows of water into the aquifer does introduce nitrates.

In Windhoek, hydrogeological observations show that nitrate percolation is active (Fig. 4), from secondary recrystallisation that produces sodic to aluminium nitrate deposits on fault surfaces. These can be seen as whitish colouration on the sides of the faults (Fig. 4). The geology of the aquifer then shows that leakage is constantly occurring from surface into the ground water in times of high rainfall seasons. This may not be the general case, but is a warning to what hydrogeological processes are taking place in the Windhoek aquifer. The dry weather conditions around Windhoek are a blessing in that most nitrates may recrystallise before hitting the 70 m level below the surface. All manner of nitrate and pesticides are detrimental to the safety of the groundwater resource. Continuous seepage of nitrates into ground water gradually does change the water chemistry from (Ca-Na)HCO_3 to mainly $NaHCO_3$. Nitrates in groundwater are common (Heaton et al., 1983), but highly elevated levels are not pleasant for consumption. The problem is less acute for the Windhoek aquifer because the artificial recharge water exceed the aquifer volumes by a ratio of approximately 1:5, should suffice for maintaining aquifer chemistry (Figure 6) if no further leakage of these substances occur or if they are controlled.

Humic soils are excellent retainers of heavy metal elements that stem from spillages on the surface, and act as barriers to the underlying groundwater resources. They also are able to buffer certain concentrations of organic contaminants such as diesel and paraffin. Petrol degenerates quickly than other high viscosity oils that are more of a concern in an environment as Windhoek. Around Windhoek however, soil cover is very thin, and its soil composition is mostly kaolinite, montmorillonite and minor smectites, and lacks the critical humus layer. The thin soil cover would not be able to contain a large factory spillage, as observations in the Avis River bed have shown, implying that this remains a major threat for Windhoek. The advantage for the Windhoek aquifer is the depth to the water table, being at level of 70 m below the surface. This scenario suggests that, the probability of dilution, reaction and attenuation, will increase directly proportional to increase in travel time. Transport of contaminants to the 70 m depth would have sufficient time to allow cation exchange between inorganic substances such as paints, to effect an effective dilution, though not completely attenuated. If spillages continue to occur, this barrier will not be helpful, infact we will be creating a dangerous situation for posterity, as some of these pollutants are cumulative. Organic contaminants would be difficult to dilute, due to the fact that the gibbsite layers of montmorillonite ($Al_2 (OH)_6$), does not posses enough charges to bind a whole organic molecule, even the simple one as CH_4. As the alkane series progresses to large molecules such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and pentane (C_5H_{12}), their boiling points increase from –162 °C for methane up to 36°C for pentane. Their melting points also increase, but in less drastic fashion, from -182°C for methane to -130°C for pentane. Beyond pentane, we get petroleum (ether, C_6H_{14}-$C_{12}H_{26}$) with a range of 20°C to 70°C, then Petrol, Paraffin, oil ($C_{16}H_{26}$). At standard temperature and pressure conditions (STP), most of these are gases and liquids and use the route of diffusion, diffusiophoresis and thermal gradient to reach the water table.. These are the most difficult pollutants as they do not degenerate easily with time when they reach the ground water table. Since they are lighter than water, they will always form a thin film coat on the water table. This progression is also proportional to the difficulty with which they can be removed from groundwater. The other main reason is that, the principal acids formed during weathering of schists is silicic acid (H_4SiO_4), for which an equilibrium constant of:

$$\frac{[\mathrm{K+}]^2[\mathrm{H_4SiO_4}]^6}{[\mathrm{H^+}]^2} = 10^{-13.4} \qquad (1)$$

Is known, and is very small and therefore the reaction to reduce the contaminants is very slow, requiring, thousands of years. Equation (1) can be simplified to:

$$\frac{2\log[K+]}{[H+]} + 6\log[H_2SiO_4] = -13.4 \qquad (2)$$

implying that at standard temperature and pressure (25º C, 1 atmosphere pressure, STP) this reaction is slow, and hence the rate at which nature will return to equilibrium, i.e., cleaning up the inorganic contaminants is extremely slow, but is effective with cations of valence 2+ in alkaline conditions. The equilibrium constant in equation (1) is derived indirectly using the silica solubility data of Siever (1962), and then working backwards using the van't Hoff equation:

$$\frac{d\ln K}{dT} = \frac{\Delta H}{RT^2} \qquad (3)$$

from which we obtain ΔH in thermodynamic tables at 25° C (298 K). The relevant silica equilibrium used is:

$$SiO_{2qtz} + H_2O_{aq} \Leftrightarrow H_4SiO_{4aq} \qquad (4)$$

For which K = a_{H4SiO4aq}. With increasing alkalinity, you are more likely to dilute the inorganic contaminants, but acidity, decreases the rate at which that dilution occurs, inducing more contaminants. However for some inorganic substances, for which a reaction with silicic acid is possible, the aquifer may be able to dilute them to very low levels that are not detected. Silicic acid is the natural product from the weathering of soils as such it will be present nearly in all aquifers, except those that are wholly made of carbonate rocks as the ones in Tsumeb-Grootfontein-Berg Aukas areas. The concentrations of silicic acid are only expected to be high during the periods when the soil cover is wet, i.e., the rainy season for a town in the climatic zones of Windhoek, the case differs in high rainfall areas together with increasing *log* $[K^+]/[H^+]$, which aids soil formation, by decreasing the stability of silicate minerals such as feldspars and micas (biotite, muscovite and chlorite) found in the Windhoek Schist. As Windhoek is semi-arid, soil formation occurs only for short periods, not sufficient enough to protect the aquifer. Porous sand on the hand may have significant storativity, but very low dilution factors, as quartz (SiO_2), the main component of sand is very stable at STP conditions. Natural attenuation of contaminants has been reported by Lerner et al. (2000), where intrinsic bio-remediation is emphasised. It is also called monitored natural attenuation (MNA), a concept that emphasises continuous monitoring of groundwater and systematic recording of the decrease/increase of pollutants with time. Once this data has been collected, a groundwater aquifer can be modeled on how long it will attenuate a specific contaminant. Such an action plan is being advocated for the Windhoek aquifer as a possible co-mitigation measure.

Once polluted, cleaning up a groundwater aquifer is very expensive, as it will involve significant pumping of water reserves even when they are not being used, until, contaminants reach an acceptable level for human consumption. The alternative is to change the purpose of the aquifer, say from domestic to industrial use only. This option is a luxury for a water stressed country such as Namibia, and Windhoek in particular.

The current policy of discouraging very large *erven* or plots for domestic housing around the city must be encouraged. Further an educational campaign must be introduced to highlight the problems that Windhoek faces. This policy can be spear headed by both the Ministry of Local Government and Housing an the Windhoek City council, with technical help from the ministry of Agriculture, under which the Department of water Affairs falls under. The educational campaign must include gender and development, especially in low income areas of the city and unplanned settlements.

5.2 Conclusions

Windhoek is built on a thin soil cover, and its groundwater resource is vulnerable. As observed in the fault systems around Windhoek, such as the Pahl Fault, nitrate leakage is occurring in these fractured zones. Planned soil covers are likely to help reduce the seepage to groundwater sources. Phenol oils have been observed in the Avis River in Kleine Windhoek, indicating that this is a source of undesirable liquid fossil fuels that are likely to seep into the aquifer. Protection of the aquifer is more desirable, to ensure that the resource is safe. Dangers will always be present due to sewer pipe bursts, for a quick reaction time from the City Council will be needed. Leakages from septic tanks in un-planned settlements are likely to become the next major source of contamination for the Windhoek aquifer.

The best mitigation measure at present is to carry out a consistent monitoring of all sewage pipes, filling stations, dump sites including cemeteries preferably on a GIS based model, is the best way possible to save the aquifer from future pollution.

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Figure Captions

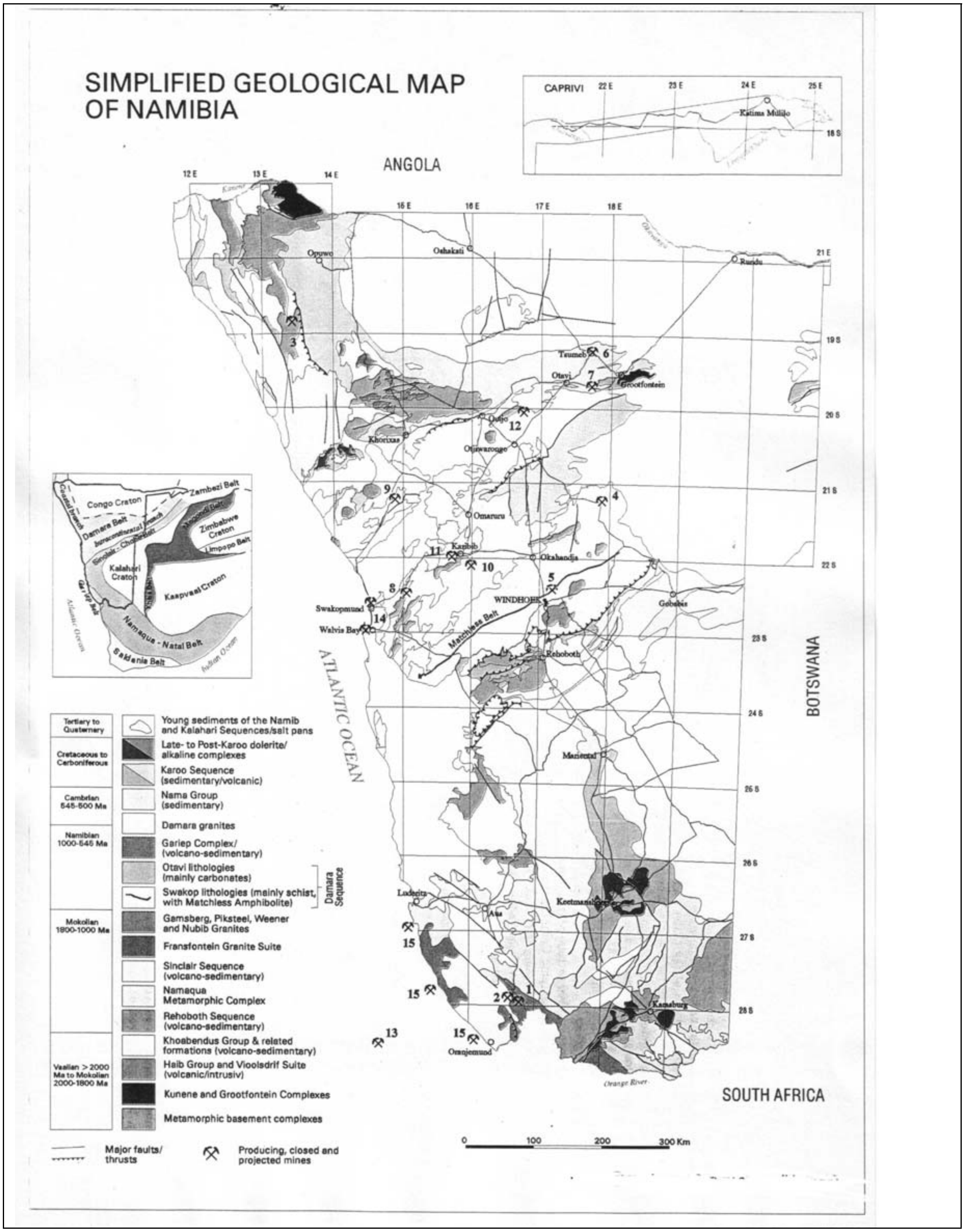


Figure 1. Geological Map of Namibia, showing the main lithological units associated with groundwater.(Geological Survey of Namibia, 2000)

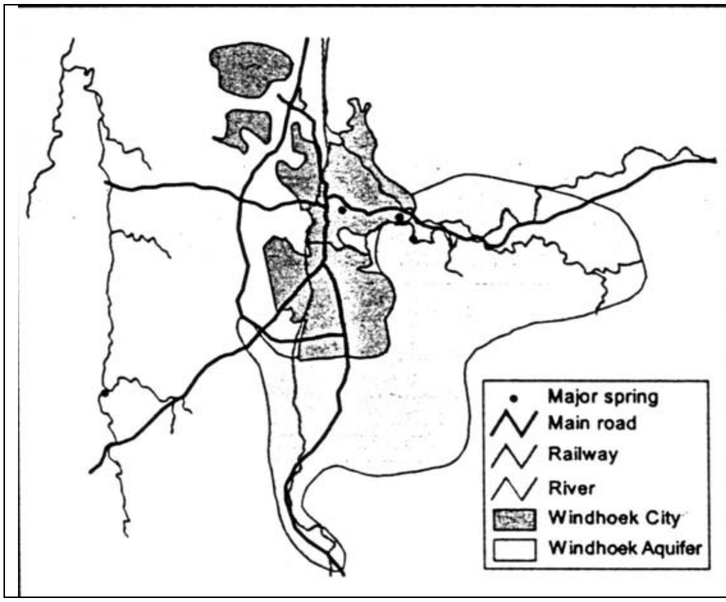
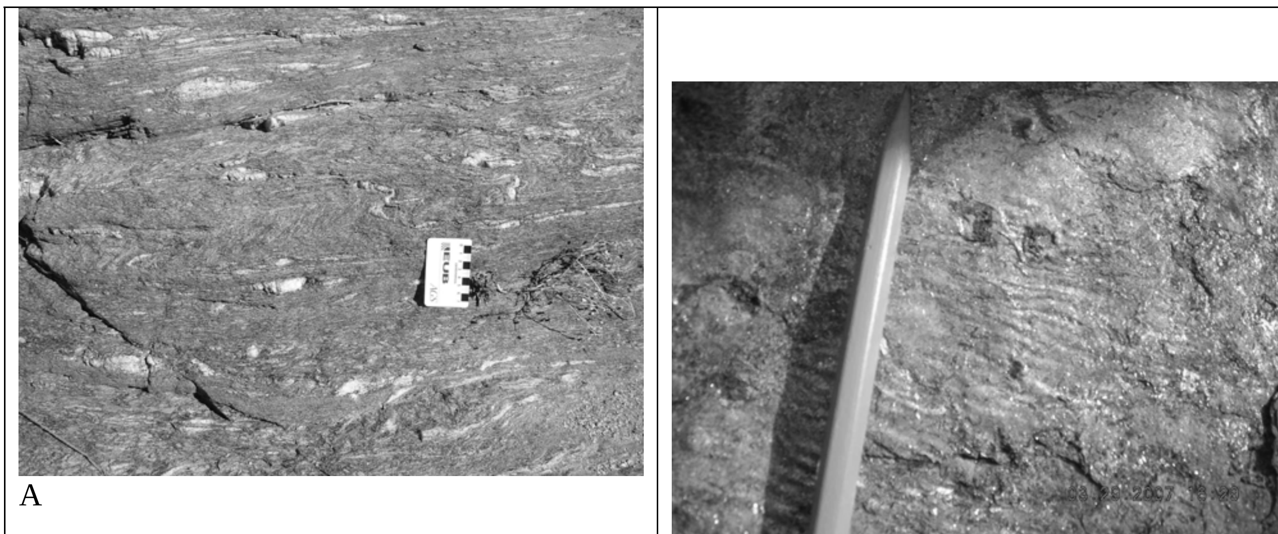


Figure 2. Outline of the Windhoek Aquifer. (after Kirchner, 2001)



A

B

Figure 3. Kuiseb Schist, showing schistosity and fissility in an unweathered disposition in plate A and a weathered example in B. The soil yield from weathered rocks is generally very little.

Figure 4. The Pahl fault, Windhoek, showing a highly fractured disposition that characterises the Windhoek aquifer.

Figure 5. Dumping in the Avis stream bed

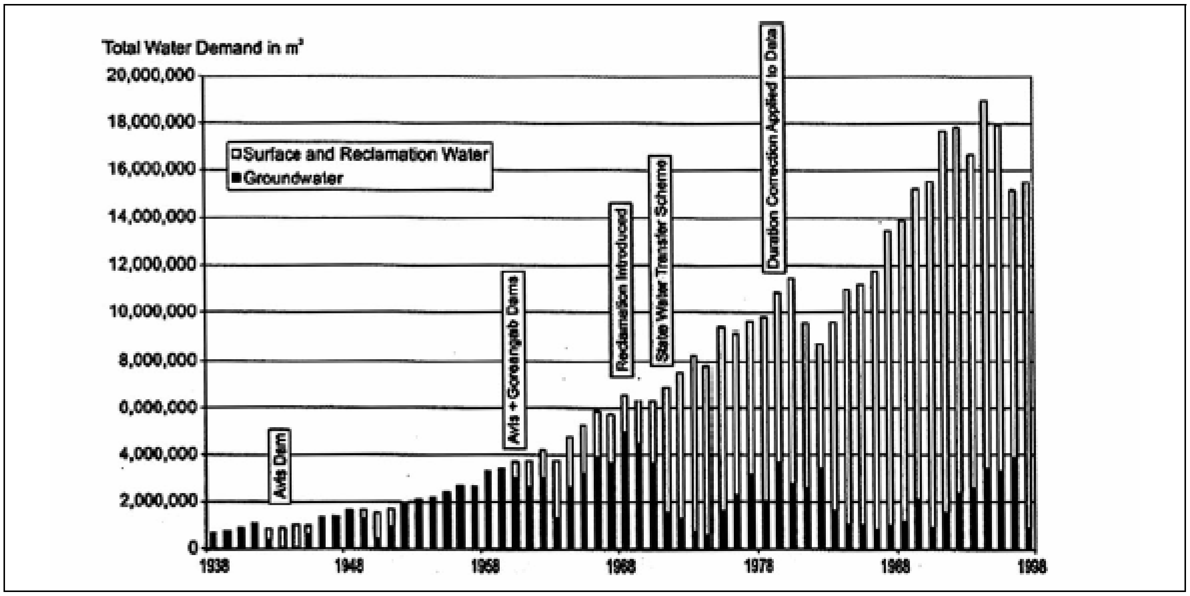


Figure 6. Water demand curve for Windhoek (after Kirchner, 2001).