Frank Leon Lehmann

Water quality of the Swakoppoort Dam, Namibia

Master's Thesis under supervision of Dr. Christoph Külls

Freiburg im Breisgau, December 2010

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Co-Supervisor: Prof. Dr. Klaus Kümmerer

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Declaration of Authorship

I, Frank Leon Lehmann, declare that this thesis titled, “Water Quality of the Swakoppoort Dam, Namibia” and the work presented in it are my own.

I confirm that the work was made independently and only on the use of indicated resources.

(Frank Lehmann)

Freiburg im Breisgau, 15th of December 2010

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Abbreviations

KWR	**K**lein **W**indhoek **R**evier
NGRP	**N**ew **G**oreangab **R**eclamation **P**lant
OGRP	**O**ld **G**orengab **R**eclamation **P**lant
VBD	**V**an **B**ach **D**am
SWPD	**Sw**akop**p**oort **D**am
UWWTW	**U**jams **W**astewater **T**reatment **W**orks
OWWTW	**O**tjomuize **W**astewater **T**reatment **W**orks
GWWTW	**G**ammans **W**astewater **T**reatment **W**orks
GGD	**G**orean**g**ab **D**am
PAC	**P**owdered **a**ctivated **c**arbon
GAC	**G**ranular **a**ctivated **c**arbon
OTD	**O**ma**t**ako **D**am
SgKW	**S**ampling **g**roup "**K**lein **W**indhoek"
NGS	**N**amibian **G**eneral **S**tandard
SgOS	**S**ampling **g**roup "**O**tjiserva **s**urface"
SgOW	**S**ampling **g**roup "**O**tjiserva **w**ells"
SgSD	**S**ampling **g**roup "**S**wakoppoort **D**am"
SgBH	**S**ampling **g**roup "**B**ore**h**oles"
CONC	**Conc**entration
GMWT	**G**lobal **m**eteoric **w**ater **l**ine

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Abstract

Namibia has no perennial rivers, except at its borders in the North and South. Like in many arid to semi-arid regions the country is highly reliant on ephemeral streams.

This is especially true for the capital of Windhoek which is highly dependent on a system of three surface water dams. Those are providing about 70% of the potable water to around 300 000 inhabitants. In the recent past one of the dams, the Swakoppoort Dam, got eutrophicated so badly that it had to be excluded from the water supply system. This left Windhoek with only small water reserves.

This study aims at identifying potential pollutions and their source and tries to find out the actual status of the lake. A strategic sampling plan was designed including river, well, borehole and lake water samples. With the help of this plan it could be shown that both ephemeral rivers leaving Windhoek towards the Swakoppoort Dam are transporting intense loads of pollutants like heavy metals, Phenol, Formaldehyde and nutrients. In particular, the Klein Windhoek River was polluted by the Ujams waste water treatment works which is mainly treating industrial waste waters. Because of the dry season the effluent streams of both investigated rivers dried up before reaching the Swakoppoort Dam. In the rainy season the rivers will reach the Dam again and a washout of accumulated pollutions is presumable.

The Swakoppoort Dam was found with all signs of a highly eutrophic lake. Next to low oxygen and high phosphor concentrations also Nickel was found which could be a sign of influence Ujamns wastewater treatment plant.

Keywords: *Namibia, Windhoek, Swakoppoort, eutrophication, wastewater*

Zusammenfassung

Außer an seiner nördlichen und südlichen Grenze hat Namibia keine perennierenden Flüsse. Wie viele andere aride oder semi aride Regionen ist das Land sehr auf seine ephemeren Flüsse angewiesen.

Dies gilt besonders für die Hauptstadt Windhoek, deren Wasserversorgung weitgehend auf einem System aus drei Talsperren aufbaut. Diese liefern etwa 70% des Trinkwassers an die etwa 300 000 Einwohner. Erst kürzlich war einer der Stauseen, der Swakoppoort Dam, derart eutrophiert, dass er vom Wasserversorgungssystem abgekoppelt werden musste. Dies führte zu einer drastischen Reduzierung der Wasserreserven von Windhoek.

Das Ziel dieser Arbeit war potentielle Verschmutzungen und ihre Ursachen zu identifizieren. Außerdem sollte der Zustand des Sees analysiert werden. Ein strategischer Probenahmeplan wurde entworfen. Diesem Plan folgend wurde Wasser aus Flüssen, Brunnen, Bohrlöchern und aus dem Swakoppoort Dam beprobt. Es konnte gezeigt werden, dass beide ephemeren Flüsse die Windhoek verlassen und in Richtung Swakoppoort Dam fließen eine hohe Fracht an Schwermetallen, Phenol, Formaldehyd und Nährstoffen mit sich führen. Speziell das Klein Windhoek Revier war stark von der Kläranlage in Ujams belastet, die hauptsächlich industrielle Abwässer klärt. Aufgrund der Trockenzeit versickerten beide Ströme noch bevor sie den Swakoppoort Dam erreichten. In Regenzeiten werden die Flüsse den Dam wieder erreichen und die Auswaschung von akkumulierten Verschmutzungen ist sehr wahrscheinlich.

Der Swakoppoort Dam wies alle Anzeichen einer starken Eutrophierung auf. Neben niedrigen Sauerstoff- und hohen Phosphorkonzentrationen wurde auch Nickel gefunden. Dies deutet auf eine mögliche Beeinflussung durch die Ujams Kläranlage hin.

1 Introduction

Namibia is characterized by a semi arid to arid climate and desert landscapes therefore no perennial rivers are existent upcountry. With it being one of the driest sub-saharan countries it is heavily dependent on the few rainfall events in the summer months. Namibia's capital, Windhoek, lies nearly in the center of the country. It is the economical and societal center of Namibia and its 270,000 inhabitants consume about 21,000 Mm^3 of water per day. To collect most of the sparse precipitation, surface dams were constructed in the 70ies, which nowadays build an interconnected scheme supporting the out maxed groundwater boreholes. Still today, where state of the art techniques like direct water reclamation and artificial aquifer recharge are in charge, the dams represent the foundation of Windhoek's water supply.

The Swakoppoort Dam (SWPD) is a very important part of this complex water supply system. Together with the Omatako Dam (OMTD) it delivers water to the Van Bach Dam (VBD), which builds the backbone of Windhoek's water supply. With covering up to 75% of the capital's demand it is crucial that the surface water supply scheme stays intact. Windhoek, and hence all the related pollutions are lying in the catchment of two rivers feeding the Swakop River: The Otjiseru River situated in the South-West and the Klein Windhoek Revier in the North of Windhoek. Therefore all effluents leaving Windhoek stand a chance to reach the SWPD ultimately. Its role as an Achilles' heel of Windhoek's water supply system was exposed lately by a recent newspaper article. It stated that the pumping from SWPD to VBD had to be stopped because of serious eutrophication of the reservoir. Back then the reserves would have been enough to supply Windhoek with water till January 2012 (Heinrich 2010a). This is a dangerously small buffer for such a vital source. Even though the situation has relaxed by now, mainly because of the beginning rainy season and the subsequent dilution, it is important to look into the problem.

1.1 Objectives

1.1.1 Research question

The objectives of this thesis are to contribute answers to the following questions:

- What is the current status of the SWPD in terms of water quality?
- What and where are possible sources of pollution?
- What kinds of polluting substances can be found at the different sources?

The focus will be set on two rivers: Otjiseru and Klein Windhoek which are leaving Windhoek and flowing into the Swakop River feeding the SWPD.

1.1.2 Research needed

To get insight into the emerging problems of the SWPD it is necessary to investigate the water quality of the Otjiseru and the Klein Windhoek Rivers in order to understand the connection between the dam water quality and possible polluters. To identify a potential pollution and maximize the chance of classifying its source the samples will be taken in a strategical pattern and analyzed for a variety of water quality parameters.

Considering the timetable with only three weeks of fieldwork, the goal of this thesis is to show a “snapshot” of the water quality issues around the Swakoppoort Dam.

1.2 State of the Art

The wide multitude of studies about the water quality of surface and the associated problems shows the topicality of this subject around the world.

A lot of research was done to develop methods to get the status or to predict future conditions of dams.

Wang et al. (2004) explored a fast way of monitoring the chemical and biochemical water quality of reservoirs in China. They calibrated LANDSAT satellite data with in situ measurements and found high correlations to organic pollutions. They also stated that the water quality had become worse. In another study artificial neural network techniques were used by Elhatip & Kömür (2008) to model dissolved oxygen and conductivity values in recharge and discharge areas of a dam in Turkey. They found results which agreed with the in situ measured parameters. A dynamic numerical model (DYRESM-CAEDYM) was used by Marcé et al. (2010) to simulate the potential development of anoxic layers in a future reservoir. The model simulated the development of the hypolimnetic oxygen content during the maturation stage after the first filling, also taking into account the degradation of terrestrial organic matter flooded. The results showed that the withdrawal from deep hypolimnetic outlets and the removal of all valuable terrestrial biomass before flooding resulted in the best water quality scenario. In Taiwan a two-dimensional, laterally averaged, finite difference hydrodynamic and water quality model was used by Kuo et al. (2003) to simulate algal biomass levels under various wasteload reduction scenarios. They calculated that a 50% reduction of the total phosphorus load will improve the existing water quality, shifting the trophic state of the dam from eutrophic to mesotrophic.

Much research was done to describe the actual status of reservoirs and lakes. Oberholster & Ashton (2008) gave an overview of the current status of water quality and eutrophication in South African rivers and reservoirs. They reported of cyanobacterial blooms in many river and reservoir systems because of prevailing high levels of eutrophication caused by inadequate treatment of domestic and industrial effluents that are discharged in their catchments. They also stated the urgent need to radically improve the eutrophication management and water treatment technologies and demand a throughout review and revision of the country’s effluent quality standards. Nyenje et al. (2010) reviewed the eutrophication of surface waters and the nutrient release in urban areas of sub-Saharan Africa. They stated that eutrophication, including the extinct of fish populations and toxic cyanobacterial blooms, are an increasing problem in the area. They show that this is connected to the huge amount of waste water of which

70% is not treated. They also suggest measures to take, like e. g. to fill knowledge gaps like the fate of nutrients in soils and aquifers.

There was also research done to find solutions to already adverse water quality situation. In Cape Town an assessment survey was done by Quick & Johansson (1992) to find out what users of lakes think about its water quality. They stated that 69% of all residents expressed the willingness to pay an entry fee, should the water quality be improved. More environmental scientific solutions were reviewed by Hart (2007) who reviewed the possibility of food web (bio-) manipulations of South African reservoirs. He concluded that much more research has to be done to understand the nutrient cycles before adequate manipulations with birds, insects, fishes, or viruses can be applied. The national revitalization of reservoir limnology should remain paramount.

It is shown that the water quality problems of surface water bodies is widespread and that there exist several methods to monitor an amend the quality of surface water bodies which are not only important to be protected for drinking water purposes, but also for ecological reasons and groundwater protection. The close proximity of the Swakoppoort Dam as part of Windhoek's water supply and the city's effluents make water quality issues and a sound monitoring strategy highly important.

2 Theoretical background

2.1 Physical and physio-chemical water Parameters

2.1.1 Temperature and lake stratification

The temperature regimes in flowing waters are very complex and its importance for the ecosystem is hard to interpret. Anyhow a simple rule can be stated:

- The mean annual temperature of flowing water rises downstream and reaches a plateau at its middle to lower course. In the winter month the temperature can drop a little downstream, often superimposed by daily changes.

(Schönborn 2003)

In lakes or reservoirs the parameter temperature is often associated with stratification. Most of the solar radiation is entering a surface water gets absorbed and transformed into heat. Because of the low thermal conductivity the warmed water is transported solely by wind induced frictional forces. In summer the heat transportation is limited to the warm, more or less homogeneous stratified upper layer of the lake, the epilimnion. Beneath the epilimnion there is a layer, the metalimnion, with a steep temperature gradient caused by the density anomaly of water. The metalimnion acts like a barrier to the heat transportation. Below the metalimnion there is the so called hypolimnion where water with the highest density and the corresponding temperature is found. When the water in the upper layer cools down, the wind can mix the water into deeper levels. When the water at top layer reaches the temperature of the water at the bottom the whole water body gets mixed. If the lake isn't freezing during the wintertime it stays fully mixed until the following summer stratification. This kind of lake is called warm monomictic (Schwoerbel & Brendelberger 2005; Lampert & Sommer 1993).

The bigger lakes in Namibia are all monomictic if they are deep enough to build out a hypolimnion in the summer. In very shallow surface waters the whole water body has the same temperature and can circulate fulltime. This type of lake is called polymictic.

2.1.2 Oxygen in surface waters

The oxygen budget in surface waters consists of inputs and consumptions. Inputs can come from the atmosphere, from photosynthesis or other direct inflows. Consumptive processes can be respiration, degradation of organic matter or losses to the atmosphere. Therefore flowing waters with high velocities and low depth have a higher oxygen budget than lakes or dams. Additionally inputs of organic matter have a longer lasting impact on stagnant waters than on flowing waters (Schwoerbel & Brendelberger 2005).

In lakes or dams oxygen is transported from the atmosphere into the upper layers and then during the mixing period vertically to the deeper regions. During the mixis oxygen enriched water reaches till the ground. In the epilimnon oxygen is also generated while the lake is stratified via photosynthesis. In the hypolimnion oxygen is mainly consumed. This happens primarily through degradation of organic matter. In oligotrophic lakes the oxygen consumption is low and the stratified period. Eutrophic lakes can be totally free of oxygen (Schwoerbel & Brendelberger 2005; Wetzel 2001).

In flowing waters the oxygen conditions depend on the same factors as in lakes. The enrichment via the surface is particularly high if there is an oxygen deficit e. g. at night or in rivers with a high organic pollution. At day the biogene oxygen production prevails. In smaller rivers algae and moss do the main photosynthesis while in bigger rivers it is phytoplankton. The higher the amount of biodegradable organics, the more the oxygen concentration in rivers drops. Organic waste is stressing the oxygen budget additionally (Schwoerbel & Brendelberger 2005).

2.2 Major Ions

Major ions are generally measured to get information about the geogenic origin of waters. Basically the ions characterizing a natural water are the anions HCO_3^-, CO_3^{2-},Cl^- SO_4^- and the cations K^+, Na^+ Ca^{2+} and Mg^{2+}. The ion balance of waters which are externally influenced can be very hard to calculate because of unknown substances which had been not detected. External influences can be cultivation of alluvial land, spill from dams or the discharge of waste water (Schönborn 2003).

2.3 Iron and Manganese

Iron (Fe) and Manganese (Mn) show many similarities in the context of water chemistry. Two of them are (Koelle 2009):

- They are often both present in waters at the same time
- Both are water soluble in their reduced bivalent form and nearly insoluble in their oxidized form (Fe^{3+}, Mn $^{4+}$).

Besides of groundwater Fe and Mn can be found only in small amounts in water. Because of the bad solubility of the oxidized form only the reduced forms are found in waters. Conditions where reduced Iron and Manganese compounds stay solute in water are:

- Oxygen concentration below 50%,
- the presence of degradable organic matter,
- high CO_2 concentrations and
- pH values of below 7.5.

This can also happen during the stratification period in the hypolimnion of eutrhophic lakes. In all Iron and Manganese related precipitation and sedimentation processes bacteria are involved. Iron is also a trace element for plants (Schwoerbel & Brendelberger 2005; Schönborn 2003).

2.4 Dissolved organic carbon (DOC)

Dissolved organic carbon is a mixture of different substances. Most of them are highly biodegradable. They get into water through inflows like moor catchments outflows, waste water, or excretion of organisms. The microbiological degradation of organic matter is another source. Especially communal waste waters or waste water from food manufactures have a high DOC concentration. In surface waters DOCs lead to an increased bacterial metabolism and a corresponding reduction of the oxygen concentration. Algae also emit up to 5% of their photo assimilated carbon as DOC back to the water. Typical concentrations are 0.65 mg/l in groundwater, 10.3 mg/l in eutrophic lakes and around 5 mg/l in rivers (Wetzel 2001; Schwoerbel & Brendelberger 2005).

UV256 is a common parameter to determine organic pollutions. It is measured in abs/cm it indicates the absorption of light at the wavelength of 256 nm which is highly correlative to DOC concentration.

2.5 Anorganic nutrients

2.5.1 Nitrogen compounds

Nitrogen is present in water in many different forms. The inorganic forms are Nitrate, Nitrite and Ammonium. Nitrate and Ammonium deliver Nitrogen to photoautotrophic plants. In oligotrophic waters Nitrate is always present in high concentrations. In highly productive lakes it can be completely used up in the epilimnion. In this case Ammonia from the decomposition of organic material delivers Nitrogen to the plants. Because of annual fluctuations of the productivity in lakes the Nitrate concentrations at the epilimnion differs seasonally. Many algae can ingest Ammonium directly. Aerobic bacteria oxidize Ammonium to Nitrit and further to Nitrate. Because these bacteria are strictly aerobic a nitrification of ammonium is not possible in the hypolimnion of eutrophic lakes during the stratification. Therefore Ammonium is accumulating in the deeper parts of the lake. This accumulation gets intensified by anaerobic processes which transform Nitrit to Ammonium (Wetzel 2001; Schwoerbel & Brendelberger 2005).

In flowing water with a big organic load high Ammonium concentrations can be seen in close proximity to the pollution inflow. Along the flow path the Ammonium gets quickly oxidized to Nitrit and then to Nitrate. High Nitrit values after a pollution are a sign for a good self healing effect of river (Schwoerbel & Brendelberger 2005; Schönborn 2003).

2.5.2 Phosphate

Anorganic Phosphor compounds in surface waters which are under no anthropogenic influence are only present on little µg/l concentrations. They originate from atmospheric input or have geogenic origins. As an essential nutrient, Phosphate (PO_4) is therefore more often the limiting factor of the primary production and eutrophication in lakes than Nitrogen. Most of the input of Phosphor to lakes comes through anthropogenic sources like fertilizer from agriculture or waste water. Those can accumulate to more than 90% of the Phosphor input. In the upper layer of the lake the phosphor gets absorbed by organisms and integrated in the food chain. This organic Phosphate (in form of dead organisms) sinks down to deeper levels of the lake, where some get absorbed again by other organism and some sediment at the lake bottom. At the lake bottom phosphate binds to the sediment at aerobic conditions. If the oxygen concentrations are below 10% the phosphate gets mobilized again. At oxygen concentrations of less than 0.5 mg/l this mobilization can be suddenly and very violent. In eutrophic lakes the emitted phosphate amount can reach up to 12 mg per m^2 and day. The Phosphate can get up to lower levels through diffusion, circulation, bioturbation or raising gas bubbles. In the summer month this "intern" phosphate pollution can reach the same concentrations as external inflows trough waste water.

Flowing waters with no pollution have PO_4-P concentration of < 0.005 mg/l, medium stressed water can have around 0.02 mg/l, while 1 mg/l PO_4-P is considered as extreme (Schönborn 2003).

2.5.3 Sulphate

Sulphate in surface water acts as nutrient and gets assimilated by photoautotrophic organisms. The most important Sulphate realted processes in a lake are the transformation to Hydrogen Sulfide (H_2S), Sulphide and a considerable amount of organic bound Sulphur which is stored in the sediment. Microbiological degradation of proteins also produces H_2S which is than oxidized back back to Sulphate.

2.6 Eutrophication and algal blooms in lakes

Europhication is defined as the increase of primary production because of raising nutrient concentrations in surface waters. Although it can be a natural slow ageing process of lakes it is often greatly accelerated and modified by human intervention in the natural biochemical cycling of nutrients within a watershed. The supplied nutrients are mostly Phosphate from precipitation, waste waters and agriculture. Phosphate surplus leads to an accelerated primary production and the increased use of other nutrients like Nitrogen and Silicon. While lakes as closed systems accumulate the nutrients, flowing waters have generally less problems with eutrophication because of the short retention time (Schwoerbel & Brendelberger 2005; Rast & Thornton 1996)

A different situation occurs if rivers are draining away from metropolitan areas. They often have the dual burden of providing water supplies and transporting waste material, most of which enters downstream water storage reservoirs (Oberholster & Ashton 2008).

The Phosphate pollution first leads to an increased production of vegan biomass in the upper parts of the lake and through the food chain to an increased biomass of consumers and reducers. This leads to a high sedimentation rate of organic remains to the lake bottom where their microbiological degradation consumes Oxygen. If the Oxygen concentration sinks below 1 mg/l additional Phosphate can be mobilized from the sediments and lead to a self-amplification of the eutrophication (Schwoerbel & Brendelberger 2005)

There are many different definitions which try to quantify the term eutrophication. The OECD defines a total phosphorus concentration higher than 30 µg/l during the mixing period (Lampert & Sommer 1993). Another example is the trophic state index (TSI) after Carlson. This index can be calculated from several parameter like total phosphorous (TP), chlorophyll a concentration (CHL) or Secchi depth (SD). Also an equation for total nitrogen (TN) was added.

The empirical equations are:

$$TSI(TP) = 14.42 \ln(TP) + 4.15$$

$$TSI(CHL) = 9.81 \ln(CHL) + 30.6$$

$$TSI(SD) = 60 - 14.41 \ln(SD)$$

$$TSI(TN) = 54.45 - 14.43 \ln(TN)$$

Simplified a TSI value above 50 means eutrophication, no matter which parameter is used. Still priority is given to CHL, because this variable is the most accurate in predicting algal biomass, while SD gives the opportunity to define the trophic state in situ. (Carlson & Simpson 1996; Carlson 1977; Kratzer & Brezonik 1981).

In many eutrophicated river or lake systems cyanobacterial blooms, also called blue-green algae, are a side effects. The high nutrient concentration in the upper water level, often caused by inadequate treated domestic or industrial effluents, can evoke an explosive bacteria growth. Especially in dams or lakes in arid to semi-arid climates, the high evaporation as well as the long periods of no in- and outflows can lead to a rapid eutrophication and cyanobacterial algal blooms. Not only can cyanobacterias cause serious problems for the water treatment, they often produce neurotoxins which are dangerous to humans and animals (Du Preez & Van Baalen 2006; Oberholster & Ashton 2008; Codd 2000).

2.7 Heavy metals

Heavy metals are present as trace elements in natural waters. Their concentrations in [µg/l] are around:

- Pb, Cu	< 4.0
- Cd, Cr, Co	< 0.8
- Hg	< 0.03
- Ni	< 2.0
- Zn	< 50

In this thesis Cadmium, Nickel, Lead and Chromium-VI concentrations have been analyzed.

The natural concentration of heavy metals depends mostly on the geology of the catchment. While Cadmium and Nickel mostly occur dissolved in water, Lead and Chromium are commonly bound to suspended solids. That’s why Pb and Cr are often found in sediments. Heavy metals can bind to organic or inorganic particles. In small rivers the dissolved form of heavy metals often dominates. Heavy metals can generally be toxic to humans and animals. The grade of toxicity depends highly on the type of chemical compound and the chemical environment. High temperature, low pH and the presence of other metals generally heightens the toxicity. The presence of heavy metals harms most bacteria and can therefore interfere with the self healing processes of surface waters. Heavy metals have a high bioaccumulation potential in plants and animals (Schönborn 2003).

2.8 Phenol and Formaldehyde

Phenol (C_6H_5OH) is an organic complex and a derivate of Benzene. It is used in the production of many other organic compounds inter alia plasticizers. It is also used as a solvent. Occasionally it is found in disinfectants and in small concentration in soaps and shampoos. Phenol is toxic to humans. It burns skin on contact and can travel through skin into the blood. High concentrations (10 – 30g) can lead to respiratory paralysis and death.

Formaldehyde (CH_2O) is a toxic aldehyde. It is used in the production of plastics, fertilizer and many organic compounds. It is also used as preservative in shampoos. It occurs in industrial effluents and is emitted into the air from plastic materials. Together with phenol it is used for the production of resin glues. In drinking waters Formaldehyde can result from oxidation of natural organic matter during ozonation and chlorination. The International agency for research on cancer (IARC) has classified Formaldehyde as carcinogenic to humans (WHO 2010; Seilnacht 2010).

2.9 Excursion: Isotopes of H_2O

Isotopes are nuclides of a certain element containing the same number of electrons and protons but a different number of neutrons. Thus isotopes have a different atomic weight. Their chemical behavior is mostly the same.

As addition to chemical investigations the stable isotopes of water, ^{18}O and ^{2}H, are often used to study the origin and history of waters. Through different meteorological processes, like e.g. evaporation, the composition and relation of isotopes are changing and as a result giving very specific signatures to waters (Clark & Fritz 1997).

For further information please refer to (Clark & Fritz 1997) or (Kendall & McDonnell 1999).

3 Study area

Namibia is one of the most arid countries in the world with more than 80% of the country being desert or semi-desert (Lahnsteiner et al. 2007a). Only five rivers, situated along its northern and southern borders, are perennial. Within the country the numerous rivers are all ephemeral and only flow after intense rainfall. With its total length of about 460 km the Swakop River is one of the biggest ephemeral rivers of Namibia, rising at the Khomas Highland and draining westwards into the Atlantic Ocean, south of Swakopmund. The Swakop catchment has an area of 30,100 km^2 and has the most developed infrastructure in Namibia (CSIR 1997). Along many mines and farms it also comprises numerous towns including the capital of Namibia, Windhoek.

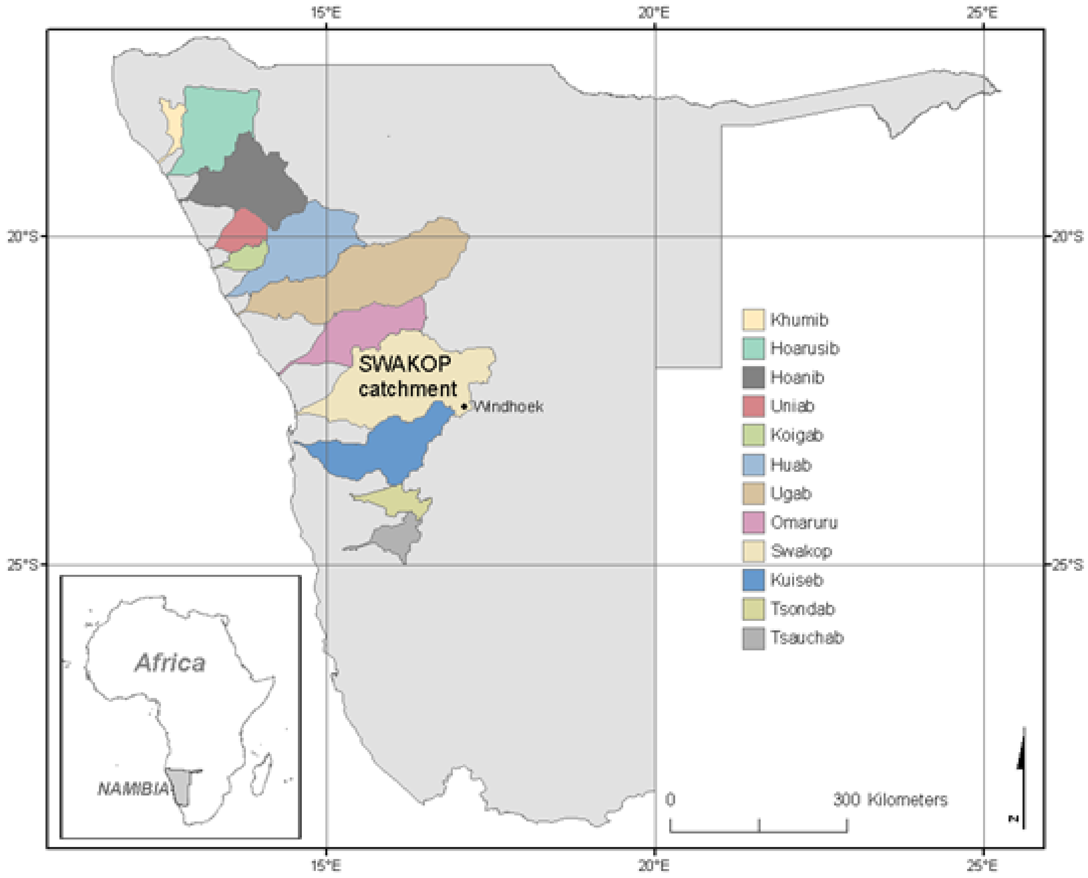

Figure 1: The location of Namibia in Africa and the westwards draining ephemeral rivers in Namibia (Marx 2009 based on (P. J. Jacobson et al. 1995))

The Swakoppoort Dam is located in the upper part of the Swakop catchment. Together with the Van Bach and Omatako Dam it constitutes an interconnected water supply system for the region. The Van Bach dam is situated east and upstream the Swakopoort Dam, close to Okahandja. The Omatako Dam is located in the northern neighboring Omatako catchment.

The Swakoppoort Dam, the focus of this thesis, is fed mainly by the Swakop river from the east. Additionally a small part of the inflow comes from the Sney river from the North. From Windhoek two small rivers are heading north. The Otjiseru, leaving the capital in the West and the Klein Windhoek River, leaving Windhoek at its northern end. The Klein Windhoek River eventually flows into the Otjiseru which later reaches the Swakop River between Okahandja and the Swakoppoort Dam.

3.1 Climate

Namibia’s climate is characterized by low annual rainfall and relatively high temperatures during the rainy season. The huge evaporation losses cause an almost continuous water deficit. Classified by Köppen the Namibian climate is arid. The rainfall events are unreliable, variable and unevenly distributed (Winker 2010). Most of the precipitation is falling in heavy thunderstorms between October and May, following a steep rainfall gradient from east to west. The variability of rainfall increases towards the Atlantic Sea where the cold sea water (Benguela current) creates a permanent temperature inversion resulting in extreme aridity. At Swakopmund, located directly at the coast, the annual rainfall does not exceed 15 mm. Average maximum temperatures reach 20 – 22 °C and average minimum temperatures 10 – 12 °C.

In Windhoek, situated in the Central Highlands at approximately 1,700 m above sea level (m a. s. l.), the annual rainfall is approximately 370 mm. The average annual temperature is approximately 20 °C while the average maximum temperature reaches 30 – 32 °C and the average minimum temperature during the coldest month is 4 – 6 °C. The potential surface evaporation rate is in the range of 3,200 to 3,400 mm/a (Atlas of Namibia 2002).

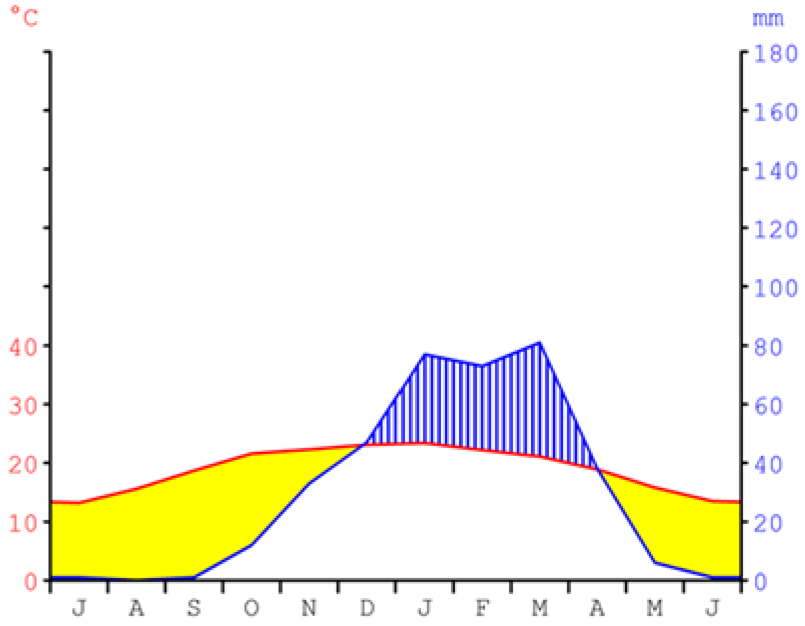

Figure 2: Climate diagram of Windhoek, Namibia (chart in the format by Walther ans Lieth, metric, °Celsius ans millimeters, made with Geoklima 2.1: www.wikipedia.com)

3.2 Geology and soils

Namibia's Geology covers a time span of more than 2,600 million years, reaching from Archean to Phanerozoic times. Nearly 50% of the land surface consists of exposed bedrock. The other half is covered by surficial deposits of the Kalahari and Namib Deserts. The oldest rocks, methamorphic inliers from the Palaeoproterozoic age (2,200 to 1,800 Ma), are found in the central and northern parts of the country. They consist of highly deformed gneisses, amphibolites, metasediments and associated intrusive rocks. Granitic gneisses, metasediments and granictic/metabasic intrusions from the Mesoproterozoic (1800 to 1000 Ma) represent the Namaqua Metamorphic Complex. The volcano sedimentary Sinclair Sequence with its associated granites was build in the same period. Large parts of central and north-western Namibia are composed of a variety of metasedimentary rocks. All these rock types, especially those of the Swakop River basin located within the Damara Orogen were liable to extensive folding, faulting and erosion before being covered by sedimentary deposits, followed by another long time of erosion.

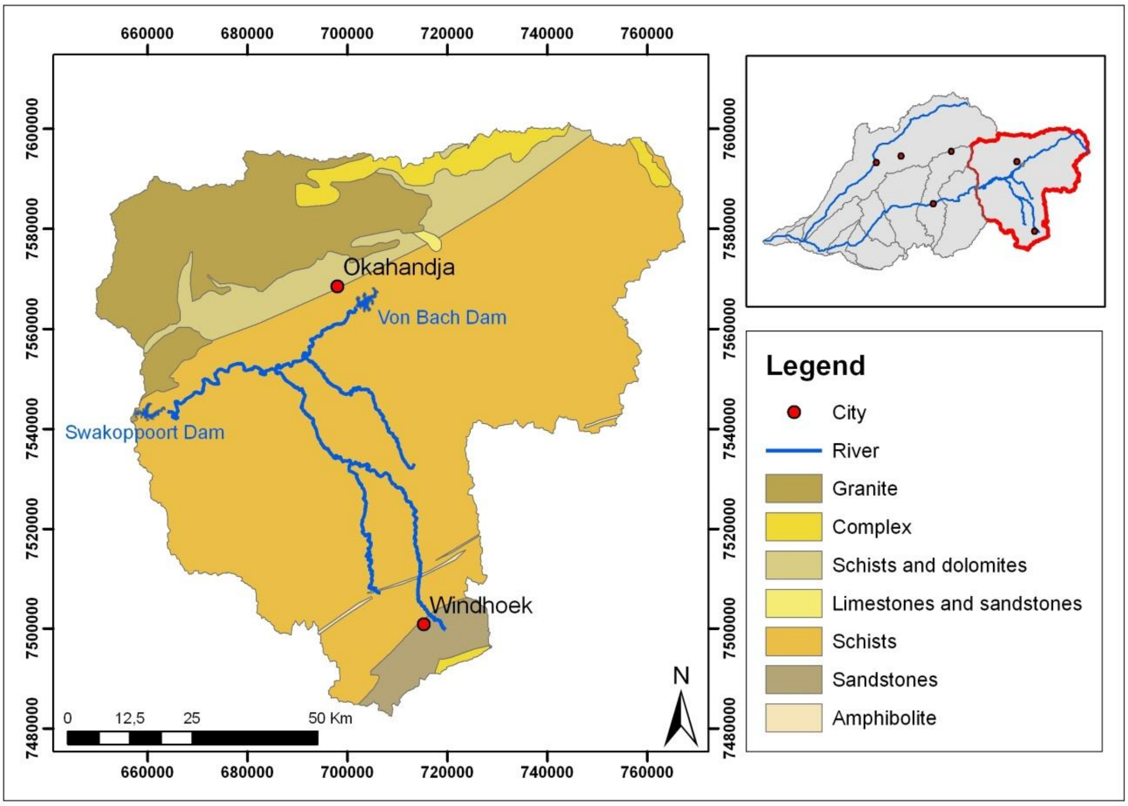

Figure 3: Geology of the study area (Source: DEA, Atlas of Namibia, 2002)

Figure 3 shows the surface geology, particulary the rock types in the study area as well as the location of the "Swakoppoort subcatchment" within the Swakop River basin. The detailed geology, i.e. the stratigraphic units and associated lithologies of the study area are listed in Table 1.

Table 1: Stratigraphic succession of the study area

Group	Subgroup	Formation	Maximum Thickness [m]	Lithology
Swakop	Khomas	Kuiseb	>3000	Pelitic and semi-pelitic schist and gneiss, migmatite, calc-silicate rock, quartzite. Tinkas member: Pelitic and semi-pelitic schist, calc-silicate rock, marble, para-amphibolite.
		Karibib	1000	Marble, calc-silicate rock, pelitic and semi-pelitic schist and gneiss, biotite amphibolites schist, quartz schist, migmatite.
		Chuos	700	Diamictite, calc-silicate rock, pebbly schist, quartzite, ferruginous quartzite, migmatite
	Discordance			
	Ugab	Rössing	200	Marble, pelitic schist and gneiss, biotite-horneblende schist, migmatite, calc-silicate rock, quartzite, metaconglomerate.
Discordance				
Nosib		Khan	1100	Migmatic, banded and mottled quartzo feldspathic clinopyroxene-amphibolite gneiss, hornblende-biotite schist, biotite schist and gneiss, migmatite, pyroxene-garnet gneiss, amphibolites, quartzite, metaconglomerate.
		Etusis	3000	Quartzite, metaconglomerate, pelitic and semi-pelitic schist and gneiss migmatite, quartzo-feldspathic clinopyroxene-amphibolite gneiss, calc-silicate rock, metaphyolite.
Major unconformity				
Abbabis Complex				Gneissic granite, augen gneiss, quartzo-feldspathic gneiss, pelitic schist and gneiss, migmatite, quartzite, marble, calc-silicate rock, amphibolite

The geology of the study area, the triangle between Windhoek in the South, the Van Bach Dam in the North-East and the Swakoppoort Dam in the North-West, is mainly represented by mica schists of the Khomas Group. The southern part of

Windhoek itself dips into sandstones while the northern end of Windhoek is underlain by amphibolites in the so called Matchless Belt (Schneider & Becker 2004).

Within the mica schists between Windhoek and Okahandja the Windhoek Graben is located. It is a fractured aquifer with moderate to high yields and represents the major water conductor in the area. Water pumped from Windhoek boreholes has a mean age of 12,000 a (Müller 2001, pp.77-85)

The soils of Namibia are, due to the arid climate, mostly thin and poorly developed. The relatively slow rates of weathering make them generally thin, and very rocky. Close to the coast, the dune fields consist of littoral sands while further inland the soils are general halomorphic, often consisting Gypsum and salt deposits.

The soils of the study area mainly consist of lithic leptosols with some additional eutric leptosols in the northern catchment of the Klein Windhoek Revier. The Swakop River between Van Bach Dam and Swakopoort Dam is flowing along a transition zone of lithic leptosols and eutric regosols (Atlas of Namibia 2002).

3.3 Windhoek's water supply

The city of Windhoek has a population of approximately 270,000 with a average growth rate of 5% over the last 19 years. To meet the demand of a total annual water consumption of approximately 21 Mm^3 per year the city uses a combination of three supply sources. With the closest perennial rivers situated more than 700 km away to the North or South, Windhoek is highly dependent on groundwater and three surface dams in ephemeral rivers. The third source of water is reclaimed water from the New Goreangab Reclamation Plant (NGRP). To each of these sources an annual production quota is allocated.

The usage of the three different sources is prioritized:

- First the maximum daily demand from surface water is predicted, which can be variable because of seasonal or operational factors.
- Second, a fixed daily maximum demand from reclaimed water is predicted
- Third, any shortages in a specific network section are covered from a variable amount of borehole water.

(du Pisani 2005; Jürgen Menge 2010)

3.3.1 Groundwater supply

Groundwater is abstracted from the Windhoek aquifer at 60 boreholes in and around Windhoek, categorized into three groups. The water is not separately treated but chlorinated before it is stored in a reservoir. (Jürgen Menge 2010). About 12% of Windhoek's annual maximum water demand can be met by groundwater (Lahnsteiner et al. 2007b).

3.3.2 Surface water supply

The surface water supply of Windhoek is coming from three surface dams. In the upper part of the Swakop catchment there are the Van Bach Dam, close to Okahandja and the Swakoppoort Dam further downstream of the Swakop. The third dam, Omatako Dam, is situated in the neighboring Omatako catchment 170 km north of Windhoek (Namwater 2010). Both, water from Swakoppoort Dam and Omatako dam is transferred via pipelines to the Van Bach Dam. Water from Van Bach Dam is then treated by the Van Bach water treatment plant, owned and run by Namwater, and then delivered to the water distribution system of Windhoek. Today the three dams deliver about 15 Mm^3 per year of water. A maximum of 78% of Windhoek's water consumption can be covered by surface water (J. Menge et al. 2009)

Because of the unreliable rainfalls the SWPD and the VBD are not overflowing regulary. Actually, in 2006, a very rainy year in Namibia, the VBD has first spilled after a period of 30 years. Due to the very high rate of evaporation in central Namibia the dams evaporate far more water per year than Windhoek is consuming. To reduce the evaporation it is planned to apply aquifer storage techniques. In Table 2 basic data of the three surface dams are shown. At the 16th November of 2010 the Omatako dam was filled to 5.3%, the SWPD to 76.5% and the VBD to 42.1% (Heinrich 2010b).

Table 2: Characteristics of the three surface water dams situated close to Windhoek.

	Otamako Dam	Swakoppoort Dam	Van Bach Dam
Capacity [Mm^3]	43,5	63,5	48,6
Surface area [km^2] (when full)	12,5	7,8	4,9
Construcion year	1981	1978	1970
Structure	Earth filled embarkment	Concrete arch	Rock fill with concrete outlet and gate
Location	170 km north of Windhoek	50 km east of Okahandja	Next to Okahandja

3.3.3 Reclaimed water supply

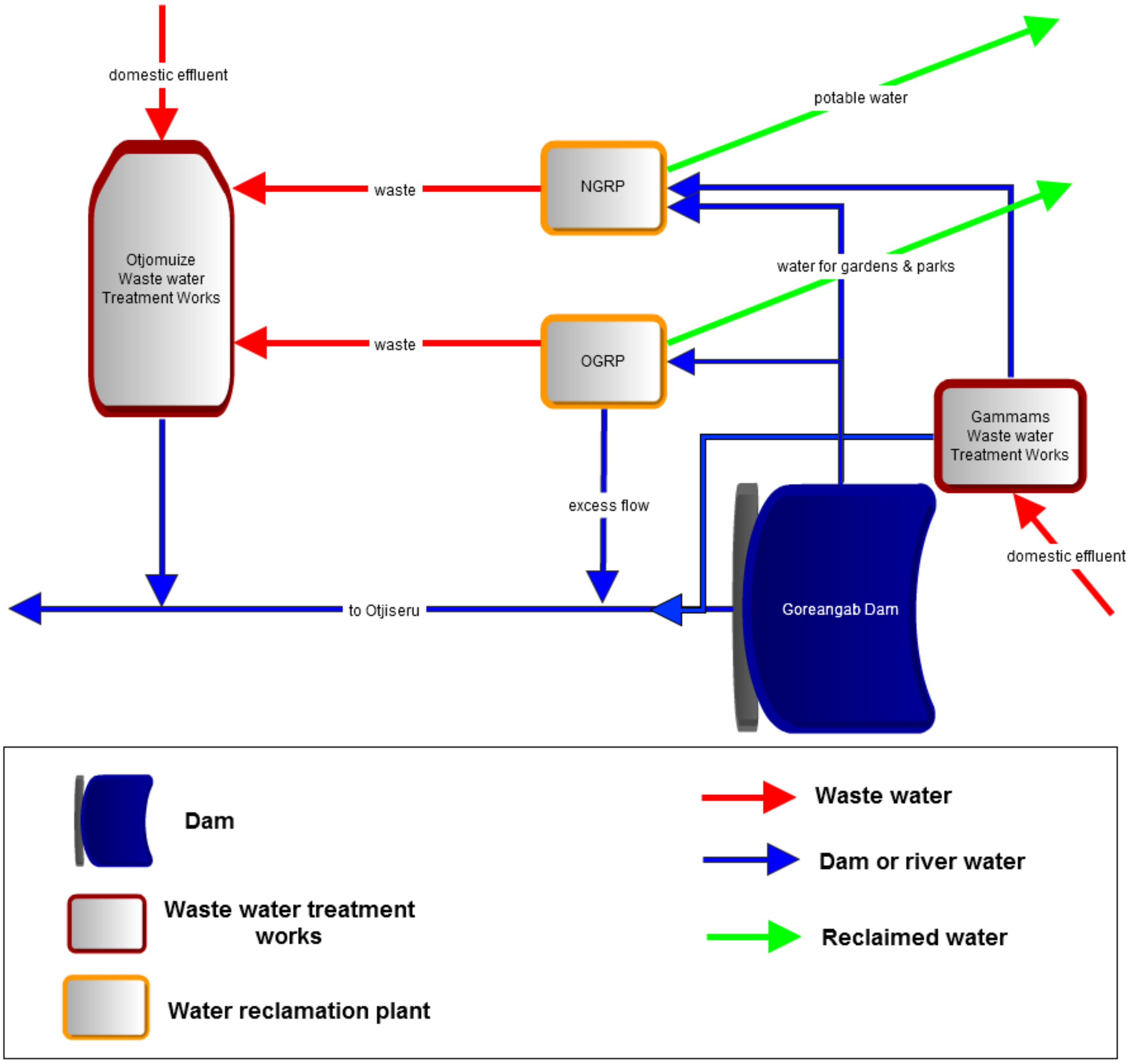

Figure 4: Flowchart of the different water treatment and reclamation plants in Windhoek. The arrow color is symbolizing the water type. Red: wastewater, blue: dam, stream or treated water and green: reclaimed water.

Since 1969 and still today Windhoek is the only city in the world which is using direct reclaimed water as potable water source in commercial scale (Asano 2007a; du Pisani 2005). Domestic and industrial effluents are treated separately in Windhoek. The industrial effluents are treated by the Ujams Wastewater Treatment Works (UWWTW) in the northern part of the city. The municipal effluents are treated by the Otjomuize Wastewater Treatment Works (OWWTW) and by the Gammans Wastewater Treatment Works (GWWTW), the latter receiving the bulk of the load. Both are situated in the south-west of Windhoek, close to the Goreangab dam (GGD). This separation of effluent treatment builds a cornerstone for the reclamation process by excluding industrial wastes from the procedure. The initial reclamation plant (now called Old Goreangab Reclamation Plant (OGRP)), build in 1969, was situated next to the GGD and fed by water from the dam itself and treated water of the GWWTW. Because the whole city and all of its informal settlements lie within the catchment of the GGD, its water quality was often worse than the treated wastewater from the GWWTW. Therefore the two sources were mixed at a desired ratio (Asano 2007b) . The initial capacity was 4,300 m^3 of potable water per day and the reclaimed water was blended with water from a well field before transferred to the distribution system(du Pisani 2005). After a series of upgrades, the latest installed in 1997, the OGRP has reached an ultimate capacity of 7,500 m^3 of reclaimed water per day. Today this water is used solely for irrigational purposes of parks and gardens.

Nowadays the production of potable water is done by a new treatment plant called New Goreangab Reclamation Plant (NGRP). It started operating in 2002 and has a potential maximum capacity of 21,000 m^3 per day. Today it delivers about one third of Windhoek's potable water. A maximum of 33% of the total water demand of Windhoek can be covered by reclaimed water (Jürgen Menge 2010). The plant is based on a multiple barrier system, composed of three different types of safety barriers: non-treatment, treatment or operational.

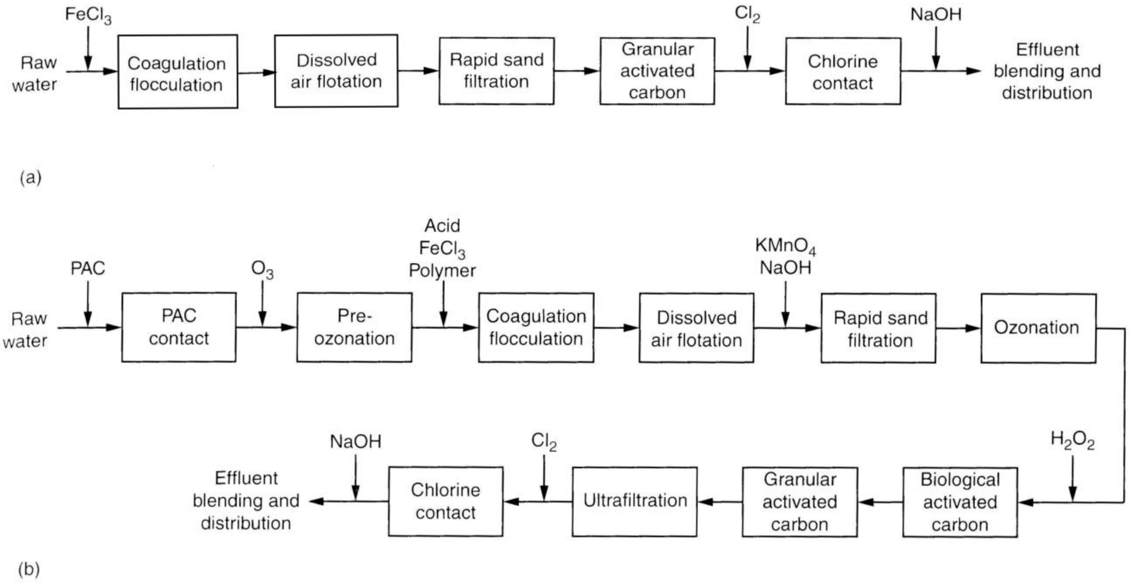

Figure 5: Water reclamation process flow diagrams for the Goreangab Reclamation Plants in Windhoek. (a) 1997 update of the Old Goreangab Reclamation Plant process train. (b) The New Goreangab Reclamation Plan process train. (Asano 2007a, p.1355)

Examples of non-treatment barriers are:

- Separate treatment of industrial and municipal wastewater, including different drainage areas
- Intensive on-line and laboratory monitoring of the raw and the treated water to protect the consumer.
- Blending the reclaimed water with conventional sources up to an maximum of 35% to reduce risks.

Treatment barriers are:

- Hardware barriers of the reclamation plant which are always in use to reduce specific contaminants.

Operational barriers are:

- Techniques to provide backup or additional capacity to an existing process. An example is the use of powdered activated carbon (PAC) instead of granular activated carbon (GAC) if the adsorption activity drops too low, or the organic loading in the raw water is too high(J. Menge et al. 2009).

The different treatment barriers used in the the OGRP and the NGRP are shown in Figure 5.

The effluent of the OWWTW and the excess flow of the GWWTW and the two reclamation plants are drained to the Otjiseru revier, which leads north, eventually flowing into the Swakop river (Figure 4).

3.4 The Swakoppoort Dam

The SWPD is situated at the Swakop River, about 50 km downstream of Okahandja. It was built in 1978, nine years after the VBD was finished. Its concrete arch dam wall impounds a water body with the surface area of approximately 7.8 km^2 and a capacity of 63.5 Mm^3 when full (Namwater 2010). Its main task is to store water for the city of Karibib and its mine and the city of Windhoek. For the latter, the water is pumped through a pipeline to the VBD.

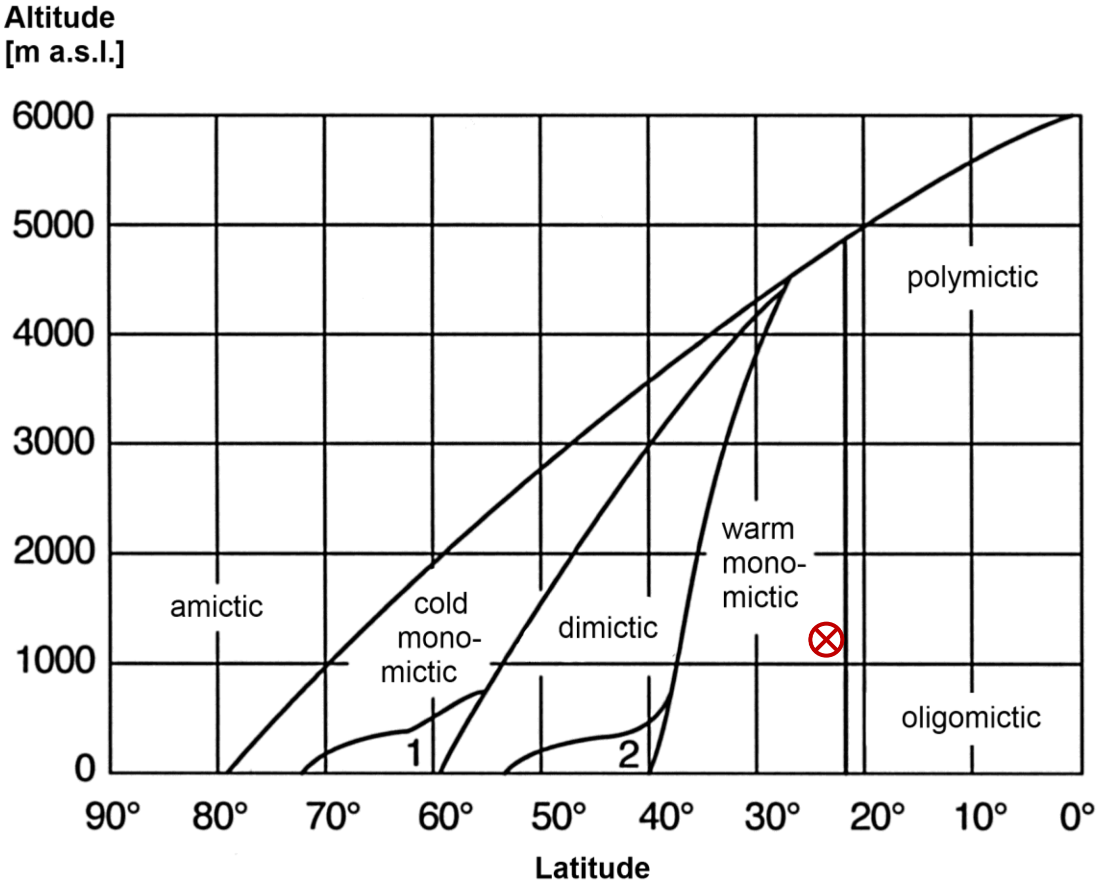

Figure 6: Mixing types of lakes in different geographic latitudes and heights. The red circle with cross symbolizes the Swakoppoort Dam (Latitude: ~ 22°12' S, high: ~ 1230 m.a.s.l.), modified from (Schwoerbel & Brendelberger 2005, p.38).

The SWPD is of the warm monomictic type. The mixing starts in April and reaches a complete mix in winter, around August. From October till end of March the lake is stratified (de Wet 1988). This concurs with the chart from (Schwoerbel & Brendelberger 2005) (Figure 6). This chart classifies lakes according to their altitude [m a. s. l.] and their geographic latitude [°].

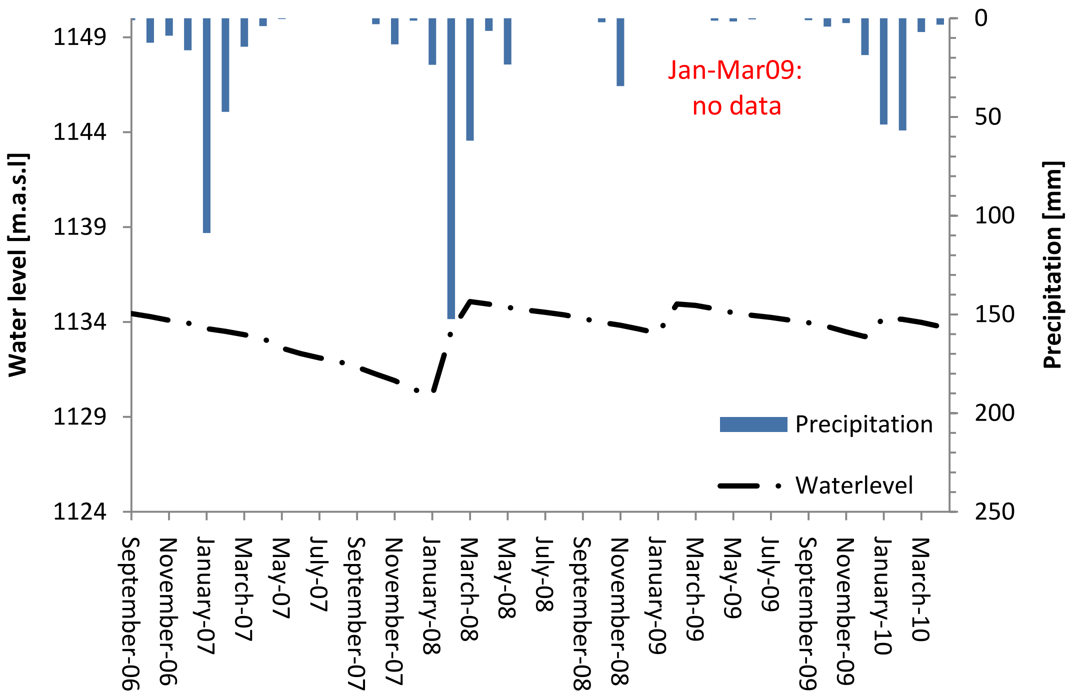

Figure 7: Accumulated monthly precipitation and water levels as a function of time (data from Namwater).

In Figure 7 the precipitation and the water level of the SWPD between September 2008 and April 2010 is plotted. Except of 2007, the rainy seasons in the winter and the correlating water level rise of the SWPD can be seen clearly. According to Namwater (2010) the mean annual precipitation is about 390 mm.

The maximum annual inflow from the Swakop River to the SWPD between 1977 and 2009 was 58.58 Mm^3 (2005/2006) while the minimum was 0.15 Mm^3 (1978/1979). Further data about abstraction, evaporation, inflow, spill and water level is given in Figure 8.

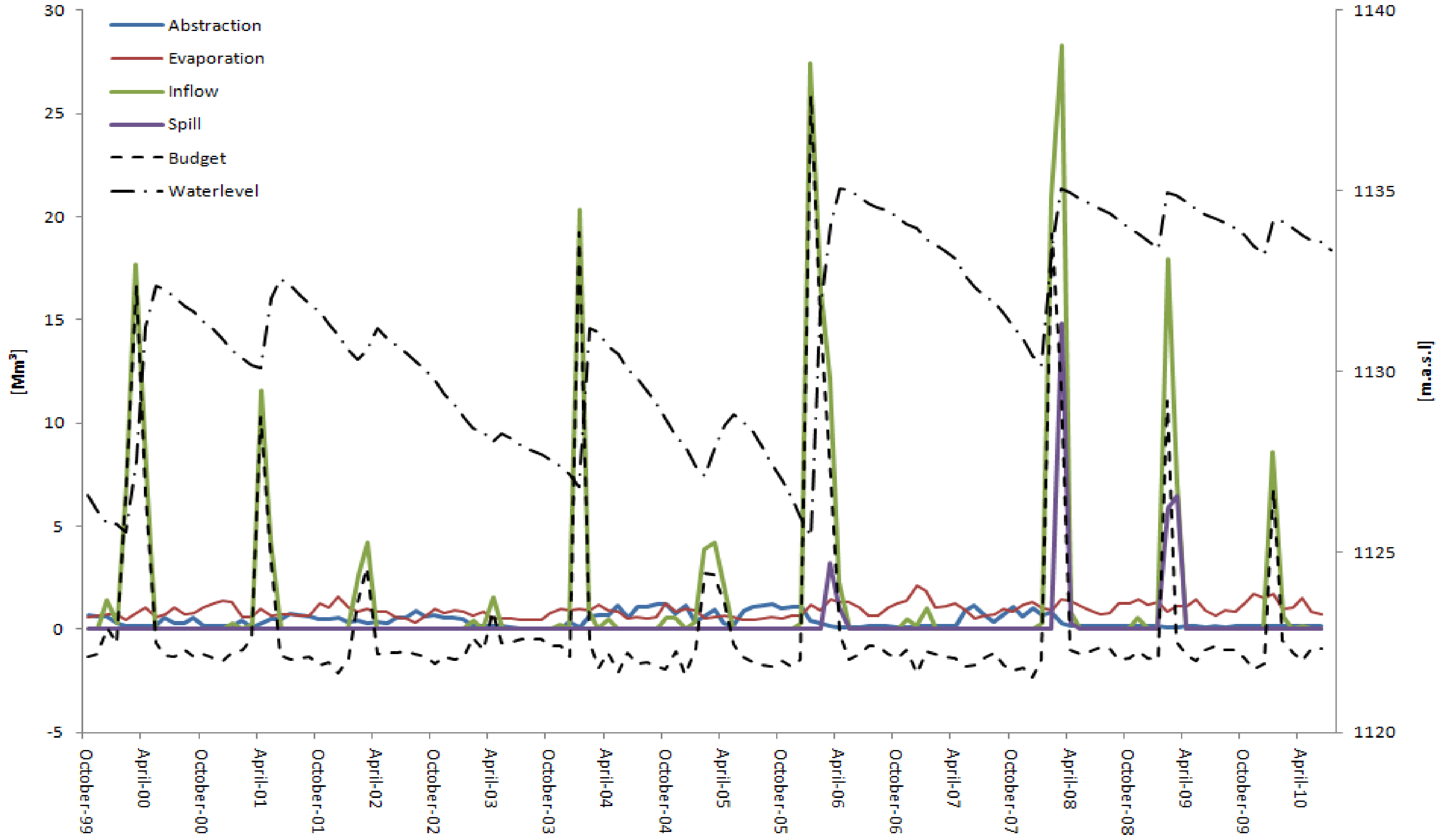

Figure 8: Abstraction, Evaporation, Inflow, Spill, Water budget and Water level as a function of time (data from Namwater).

4 Methods

4.1 Field Methods

All field work was done during a three week long field trip to Windhoek, Namibia. The field methods included the design process of a sampling plan, the sampling itself, and the application of a series of hydrological gear, including multiprobes.

4.1.1 Sampling plan

In the course of designing the sampling plan intensive study of maps and satellite imagery of the countryside has been done. Supported by advisory meetings with employees from Namwater and The Department of Water Affairs (City of Windhoek) the plan was conceptualized to capture the main pollution sources and give the opportunity to discover potential effects along the flow paths. The position of all the sampling points can be seen in Figure 9.

From the design process five different sampling groups evolved:

Sampling group "Klein Windhoek" (SgKW), covers the flow path of potential industrial pollutants, leaving the UWWTW via treated wastewater in Windhoek's North. Initially SgKW consisted of four sample points (7, 11, 12 and 1) following the Klein Windhoek Revier. Later five more samples (M1, M2, M3, M5 and M6) were taken by employees of City of Windhoek and the analysis results were sent to the University of Freiburg.

M1 was taken directly after the last pond (pond 15) of the UWWTW. M2 is situated approximately 1 km downstream, where the effluent reaches the Klein Windhoek Revier. M3, 7, 11 and 12 were located further downstream alongside the riverbed in short distances (100 – 500 m). M5 was taken close to Döbra some 8 km north of the UWWTW. Another 3.5 km further downstream, close to a small informal settlement, M6 was taken. The last sample point of SgKW was 1, in close proximity to the Okapuka Tennery. All samples were taken from flowing surface water.

Sampling group “Otjiserva surface” (SgOS) is focused around the water treatment facilities at the western end of Windhoek and the associated Goreangab Dam. Sample points 2, 3 and 4 are situated at a small stream heading from the concrete dam of the Goreangab Dam to the Otjiseru River. The water consists of spill water from the Dam as well as excess water from the OGRP. Sample 5 was taken from the stream of treated wastewater originating from the OWWTW. Sample point 6 was positioned right after the mixing of the OWWTW stream and the stream coming from the Goreangab Dam. After the confluence the Otjiseru flows northwards and traverses the Ongos farm. Sample 8 was taken right next to a farm building approximately 13 km downstream of sample point 6. Again all samples were taken from flowing surface waters.

At the Swakoppoort Dam itself six sample points were defined. These sample points (13, 15, 16, 17, 18 and 19) build the sample group “Swakoppoort Dam” (SgSD). At point 13 a sample was taken in very shallow water, close to the inlet of the Swakop River. The points 15 and 16 represent the center of the Dam and where extracted from 1 and 5 m depth respectively. Another triplet of samples was taken right next to the extraction tower. Sample 17 in 1 m, sample 18 in 5 m and sample 19 in 10 m depth.

Sampling group “Otjiserva wells” (SgOW) consists of three samples taken of wells. Sample point 10 is located at a well on Ongos Farm, right next to the Otjiseru River. It was approximately 4 m deep. Following the dry streambed further north sample point 20 was sited at a well at Düsternbrock Farm. The last sample point of this group, 21, was situated at another well at a farm further north (Frankenhof Farm). The well was approximately 6 m deep.

The last sampling group consists of two sample points (9 and 22). Sample 9 was taken from a borehole in the eastern part of the Ongos Farm. The borehole is located around 2.6 km east of the well sample point 10. The borehole was around 60 m deep, with a water level of 45 m. The second borehole sample, 22, was taken at the Osana Farm right next where the Otjiseru River flows into the Swakop River. It was taken from a water reservoir which is fed by a borehole next to the Swakop River. This borehole sampling group is labeled SgBH.

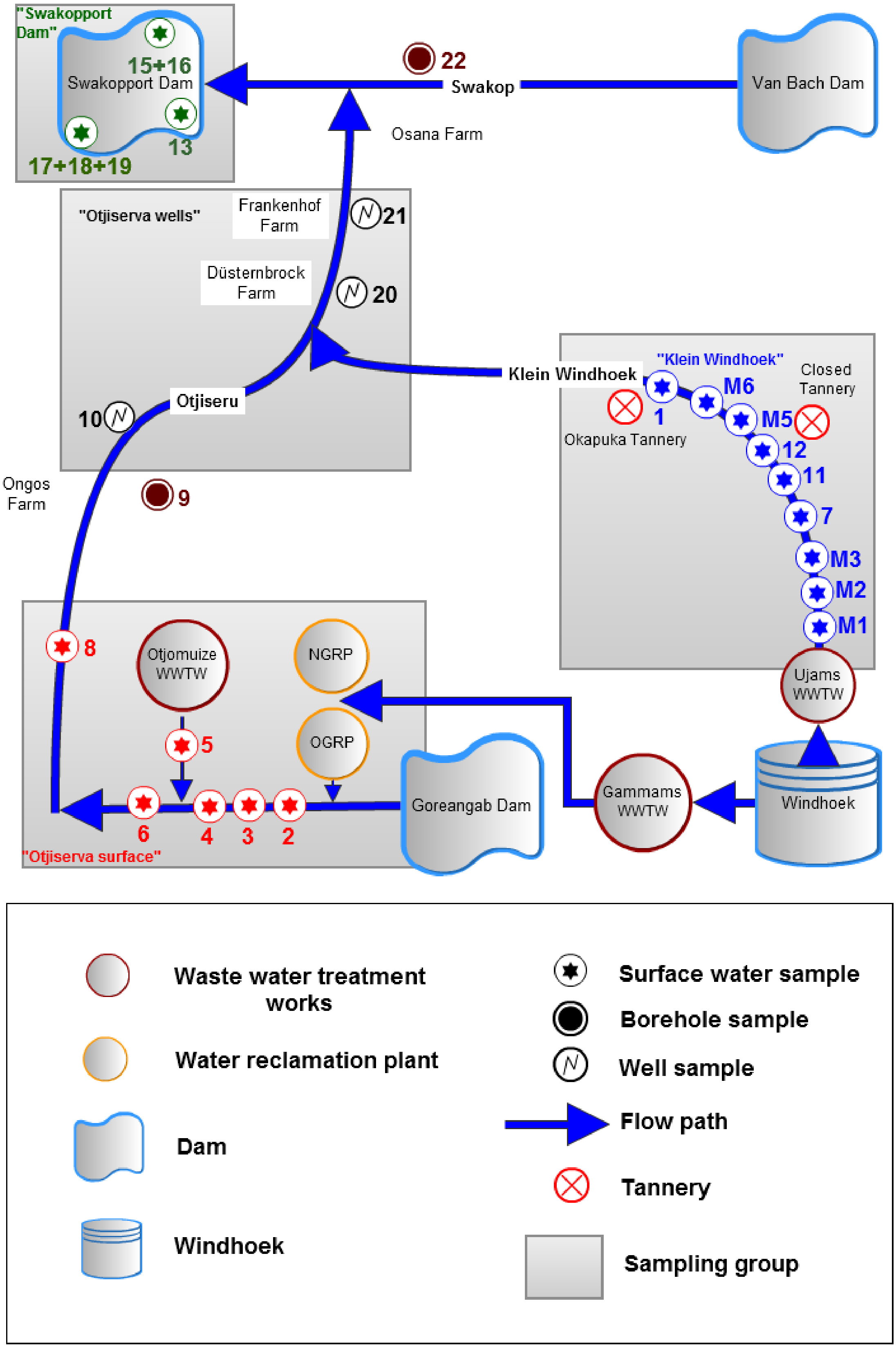

Figure 9: Sampling plan in form of a flowchart. Each sample group is displayed in a different color, correspondingly displayed in all following charts. The "Otjiserva surface" sampling group is shown in greater detail in Figure 4.

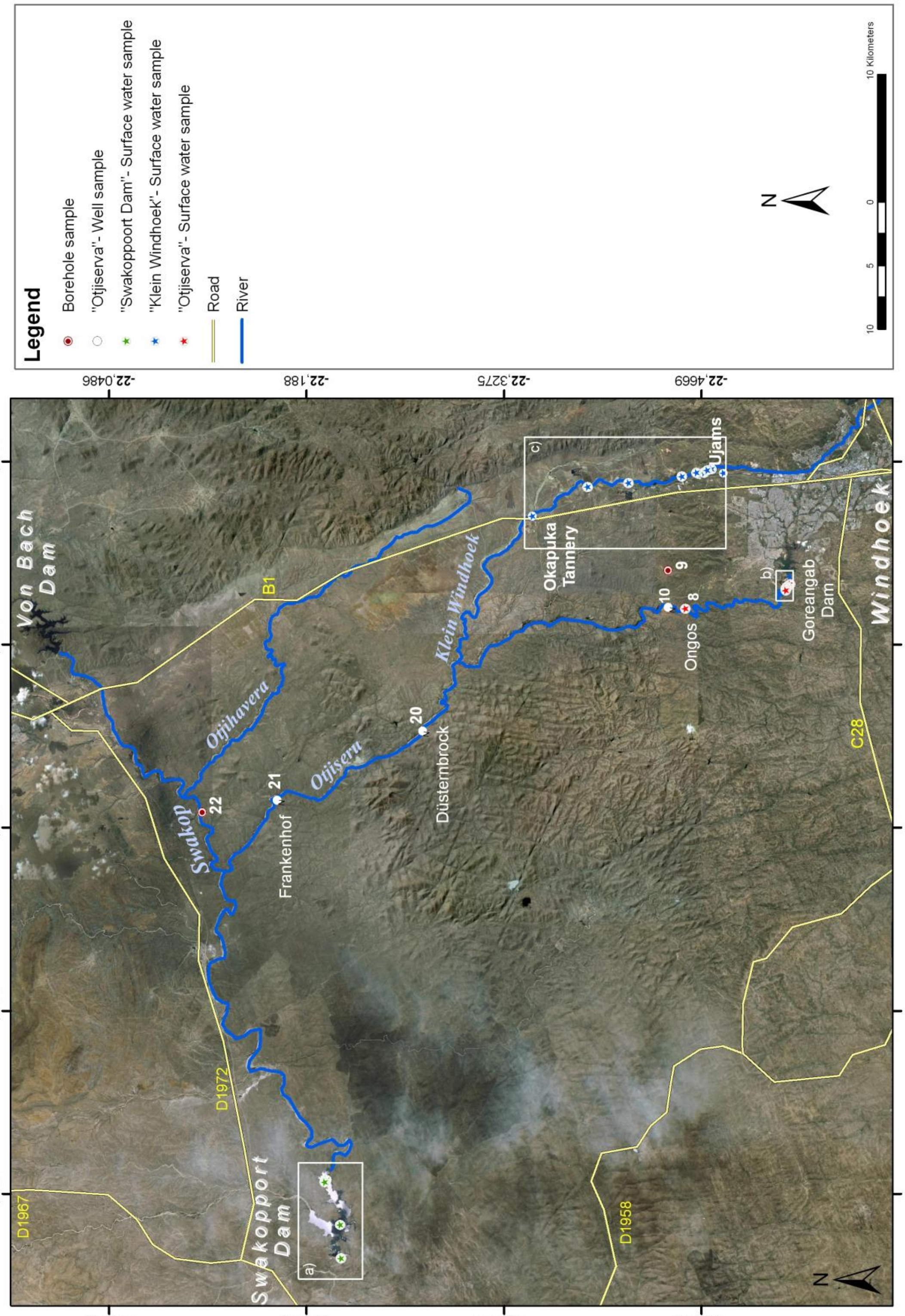

Figure 10: Overview of the study area with the different sampling groups. Details in the rectangles can be seen in Figure 11. Satellite imagery is property of Google Inc..

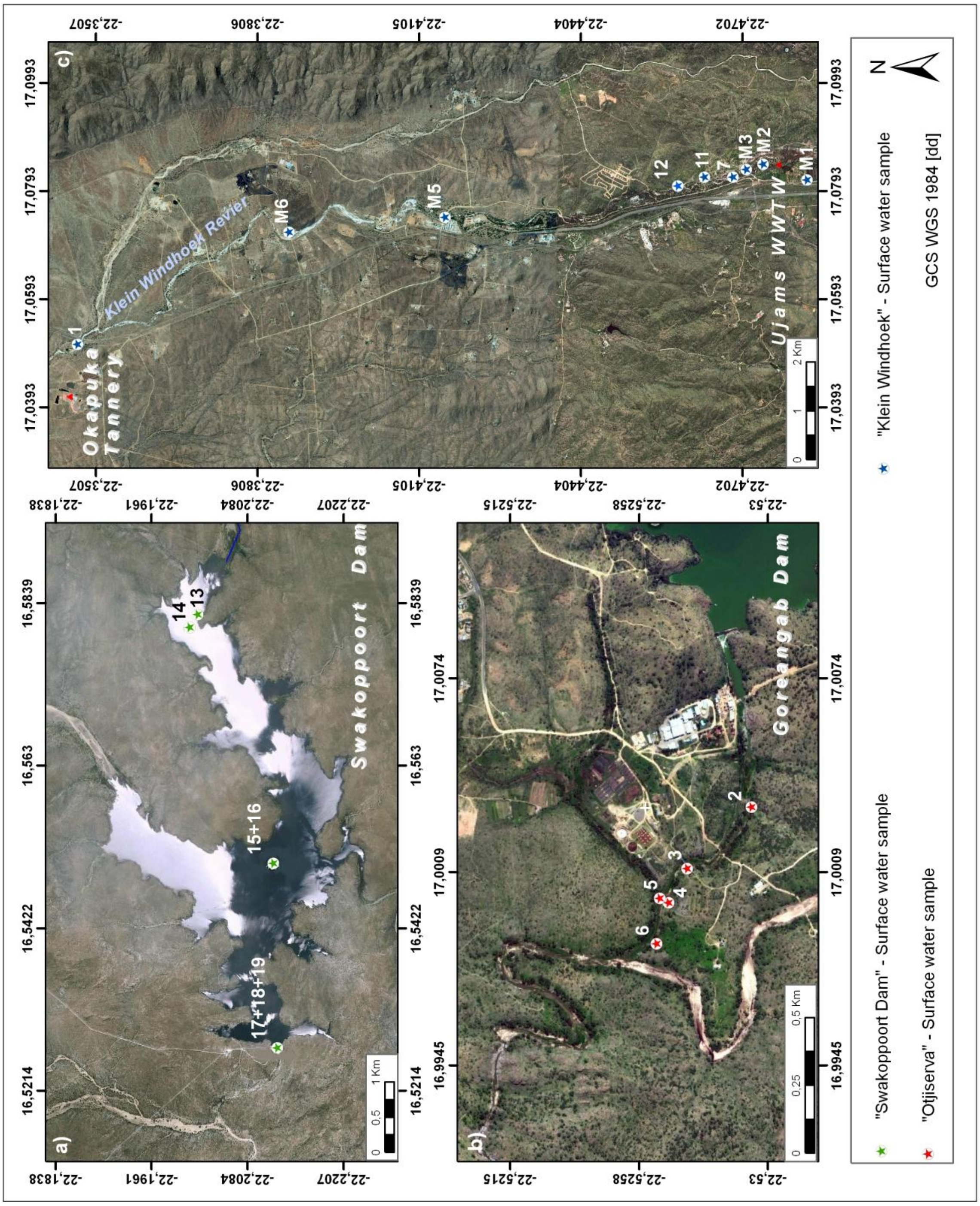

Figure 11: Details of the three surface water sampling groups. Satellite imagery is property of Google Inc..

4.1.2 Sampling and equipment

At each sample point a sample consisting of two liters of water, split to three 0.5 l plastic bottles and one 0.5 l glass bottle was taken. These two liters were for the Gammans laboratory in Windhoek. Additionally a 50 ml bottle was filled at each sample point for transportation to Germany in the case additionally analysis were needed. The surface water samples were taken by hand, directly from the stream. The well and borehole samples were pumped into a bucket and then filled into the sampling bottles. At the Swakopport Dam the samples were taken from a boat.

All samples from the Swakopport Dam itself have been taken with a Ruttner sampling device, except of 13 which was taken by hand. The Ruttner sampling device is a cylindrical tube with openings on both top and bottom. Through this openings water can enter the tube during the descent. The device is lowered into the water with a wire. The wire is marked to allow sampling at a given depth. When the device reaches the designated depth a drop weight is lowered along the wire. When the weight is reaching the tube it triggers a mechanism which closes the tube. The filled device is then lifted by hand or with a hand crane. Additionally two Secchi disc measurements have been done. One at sample point 13, close to the inlet of the Swakop River and one at the middle of the dam (15, 16). At the extraction tower Secchi Disc measurements are done on a regular basis by Namwater.

At each sampling point physical parameters where measured with a “MS-5” Multisonde from HACH-Hydromet®. The “MS-5” can be lowered to depths up to 15 meters. It was equipped with a probe configuration to measure Oxygen (O_2) in mg and %, Temperature, ph, Conductivity, Salinity and Total Dissolved Solids (TDS). In this fieldwork the probe was connected directly to a Laptop with the Hydras 3LT software to log the measured data. Additionally an “Oximeter 330” from WTW® was used for control measurements of Oxygen (O_2) and Temperature. The exact geographic location was logged witch a “eTrex Vista® HCx” mobile GPS device from Garmin. The geographic coordinates can be seen in the Appendix Table 5.

4.2 Analytical methods

All water samples were analyzed by the City of Windhoek in the laboratory of the GWWTW. The samples were examined for pH, conductivity, total dissolved solids (TDS), turbidity, total alkalinity, total hardness, Chloride (Cl^-), Sulfate (SO_4^{2-}), Fluoride (F^-), Nitrate (NO_3), Nitrite (NO_2), Sulphide (S^{2-}), Potassium (K^+), Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Ammonia (NH_3), Orthophosphate, Iron, Aluminum, Manganese, Total Kjeldahl Nitrogen (TKN), Dissolved organic carbon (DOC), UV 254, Phenol, Formaldehyde, Cadmium, Nickel, Lead and Chromium VI. The results were later send to Freiburg.

The 50 ml bottle samples were used to carry out an H_2O isotope analysis in the Institute of Hydrology of the Albert-Ludwigs University in Freiburg, Germany.

The analysis of the stable isotopes ^{18}O and ^{2}H were conducted with a “1102-i isotopic water vapour analyzer” from PICARO®. ^{18}O and ^{2}H were measured simultaneously. The precision of the 1102-i is 0.1 ‰ for ^{18}O and 0.5 ‰ for $\delta^{2}H$ according to the manufacturer (Picarro, 2008).

A series of additional data was provided by Namwater and The Department of Water affairs. These included, inter alia, Secchi Disc measurements in [m] and total phosphorus (TP), total nitrogen (TN) and Chlorophyl a concentrations (CHL), all in [µg/l]. To evaluate the condition of the Swakopport Dam the Trophic State Index after Carlson was calculated.

5 Results

All results from the laboratory analysis are given in Table 4 in the appendix. There was no clear information about the limits of detection given. So the limits of detection mentioned in this chapter are assumed based on the laboratory results.

5.1 Oxygen and Temperature

The complete values of all temperature and oxygen readings can be found in Figure 12. For the samples (M1), (M2), (M3), (M5), (M6), (15) and (19) no data is available. Furthermore the readings of oxygen and temperature at sample (17) were recorded at a depth of 3 m.

5.1.1 Sampling group "Klein Windhoek"

The temperature rises along the stream from 16.1 °C at (11) to 22.4 °C at (1).

The oxygen concentration also is increasing along the flow path from 0.2 mg/l at (7) up to 13.2 mg/l at (1).

5.1.2 Sampling group "Otjiserva surface"

The temperature of this group rises from around 17 °C near the facilities to 22.23 °C 13 km downstream at (8).

Oxygen is at 6.51 mg/l close to the dam wall and rises along the flowpath to 10.59 mg/l at (4). After the confluence the concentration drops to 6.18 mg/l and rises to 7.06 mg/l at (8).

5.1.3 Sampling group "Otjiserva wells"

In (20) and (21) the temperature is about 25 °C, while at (10) it is 17.17 °C.

The oxygen concentration is below 5 mg/l in all three well samples. The maximum is 3.34 mg/l at (20), the minimum is 2 mg/l at (10).

5.1.4 Sampling group “Boreholes”

Temperature readings were at 25.97 °C in (9) and 28.81 °c in (22).

The oxygen concentration is 1.98 mg/l at (9) and 5.16 mg/l at (22).

5.1.5 Sampling group “Swakoppoort Dam”

The Temperature readings at the SWPD drop from 22 °C at the inlet (13) to 18.04 °C at the middle of the lake (15). The temperature drops only about 0.21 °C per meter depth at the extraction tower.

The oxygen concentration has its maximum at (13) close to the inlet with 11.4 mg/l. At 5 m depth at the middle of the dam (16) it drops to 8.97 mg/l. At the extraction tower the concentration decreases further to 4.5 mg/l in 1 m and 3.67 mg/l in 5 m depth.

5.1.6 Summary

The water temperature in the upper part of the sampling groups “Klein Windhoek” and “Otjiserva surface” is between 16 °C and 18 °C. Further downstream at (1) and in the SgKW and (8) in the SgOS the temperature rises to 22.39 °C and 22.23 °C respectively. The temperature in the SWPD is also around 17 °C with the exception of the shallow inlet with 22 °C. The temperature of the groundwater from the boreholes ranges from 17.7 °C at (10) to 28.81 °C at (22).

The oxygen concentration rises along the flow path at the sampling group “Klein Windhoek”. At the sampling group “Otjiserva surface” the concentration first increases until the mixing at (5) from where it rises again further downstream. In the groundwater samples the maximum concentration of oxygen was 5.16 mg/l in (22). In the SWPD samples the concentration is decreasing with the depth, but in a much higher degree from the inlet to the extraction tower.

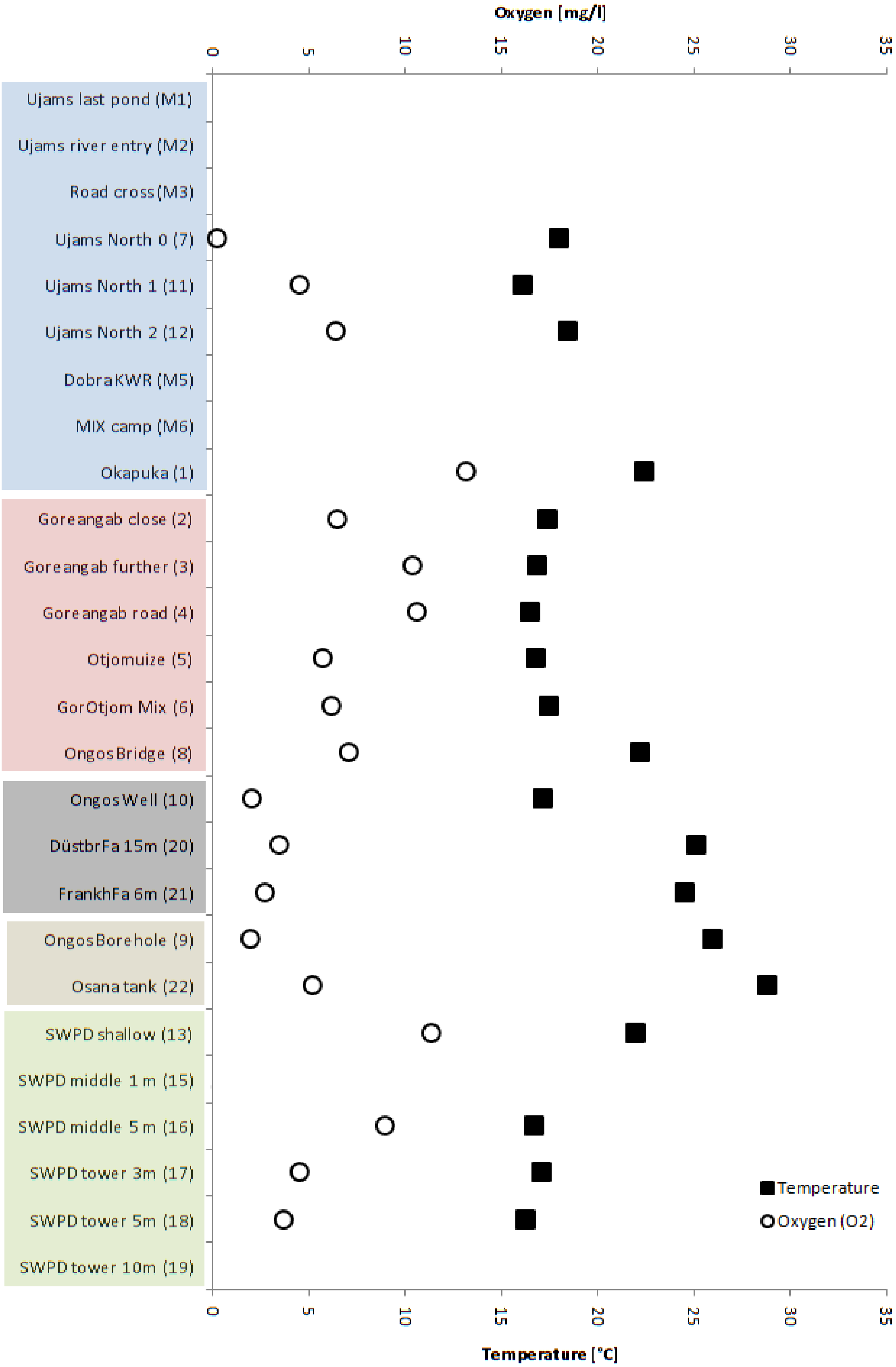

Figure 12: Temperature und Oxygen values of all samples.

5.2 pH and Conductivity

The results of all pH and conductivity readings can be found in Figure 13.

5.2.1 Sampling group “Klein Windhoek”

The ph values of all M samples are around 8. At (7) the minimum of the group with 7.4 was analyzed, while at (8) an above average maximum of 8.9 was detected.

The conductivity values up to (12) are all between 200 and 300 mS/cm with a local maximum of 340 mS/cm at (M3). At (M5) and (M6) the values get as high as 475 and 520 mS/cm respectively. Further downstream the maximum of this group was detected at (8) with 690 mS/cm.

5.2.2 Sampling group “Otjiserva surface”

pH values rise from 7 next to the dam wall at (2) up to 7.8 at (8). A local minimum is observed at the steam leaving the OWWTW at (5) with 7.

The conductivity values show hardly any variation with an average of 89.33 mS/cm, a maximum of 97 mS/cm and a minimum of 84 mS/cm.

5.2.3 Sampling group “Otjiserva wells”

The pH values of the wells do not show greater differences. They range from 7.3 at (10) to 7.5 at (21).

The maximum conductivity value of the wells is 215 mS/cm at (20). The minimum lies at 130 mS/cm at (10). (21) has a conductivity of 155 mS/cm.

5.2.4 Sampling group “Boreholes”

The borehole samples show pH values of 7.4 at (9) and 7.6 at (22).

The conductivity lies at 100 mS/cm at (9) and 146 mS/cm at (22).

5.2.5 Sampling group “Swakoppoort Dam”

The pH values are all around 8 at the SWPD. The maximum was at (16) with 8.3, the minimum at (19) with 7.8.

The conductivity do not show any bigger variation at the SWKP. The values range from 64 to 66 mS/cm.

5.2.6 Summary

The pH values range between 7.04 at (5) and 8.34 at (16) with one outlier at (1) with 8.9.

The highest conductivity values lie in the sampling group “Klein Windhoek”. They can be divided in a first part from (M1) to (M12) with values around 300 mS/cm and a second part consisting of (M5), (M6) and (1) with values more than two times as high. At the “Otjiserva surface” group and at the “Swakoppoort” group the values are relatively constant at around 90 mS/cm and 65 mS/cm respectively. The groundwater results vary between 100 mS/cm at (9) and 200 mS/cm at (20).

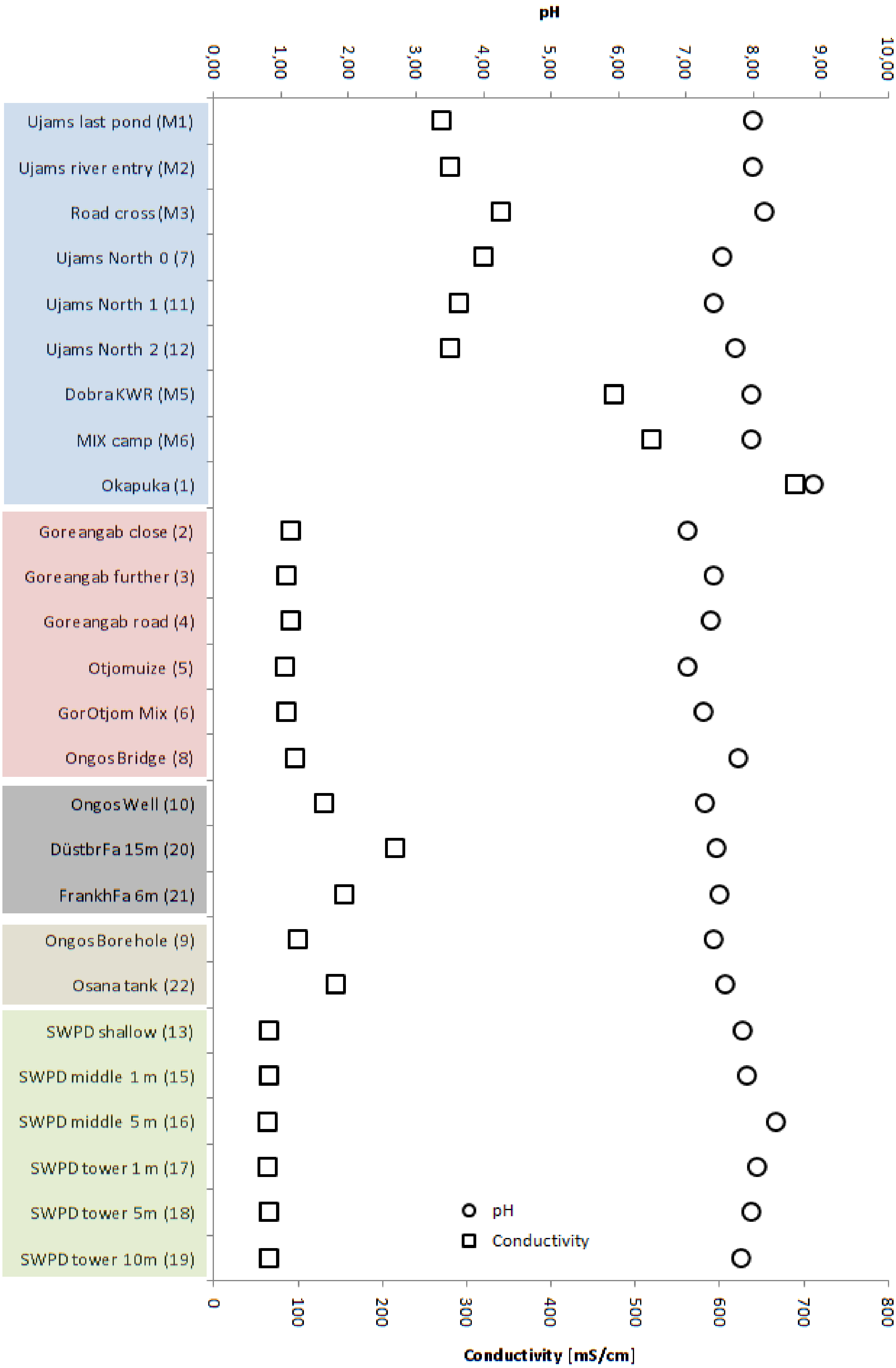

Figure 13: pH and Conductivity values of all samples.

5.3 Major ions

Major ions were analyzed in the 26 samples and the results from the laboratory analysis are given in Table 6 in the Appendix.

The major ion balance was calculated as follows:

$$\frac{(\sum cations - \sum anions)}{\sum ions * 100}$$

The results show, that cations and anions are hardly balanced at any sampling location. At three locations, (7), (3) and (4), the calculated ion balance error is larger than 10%.

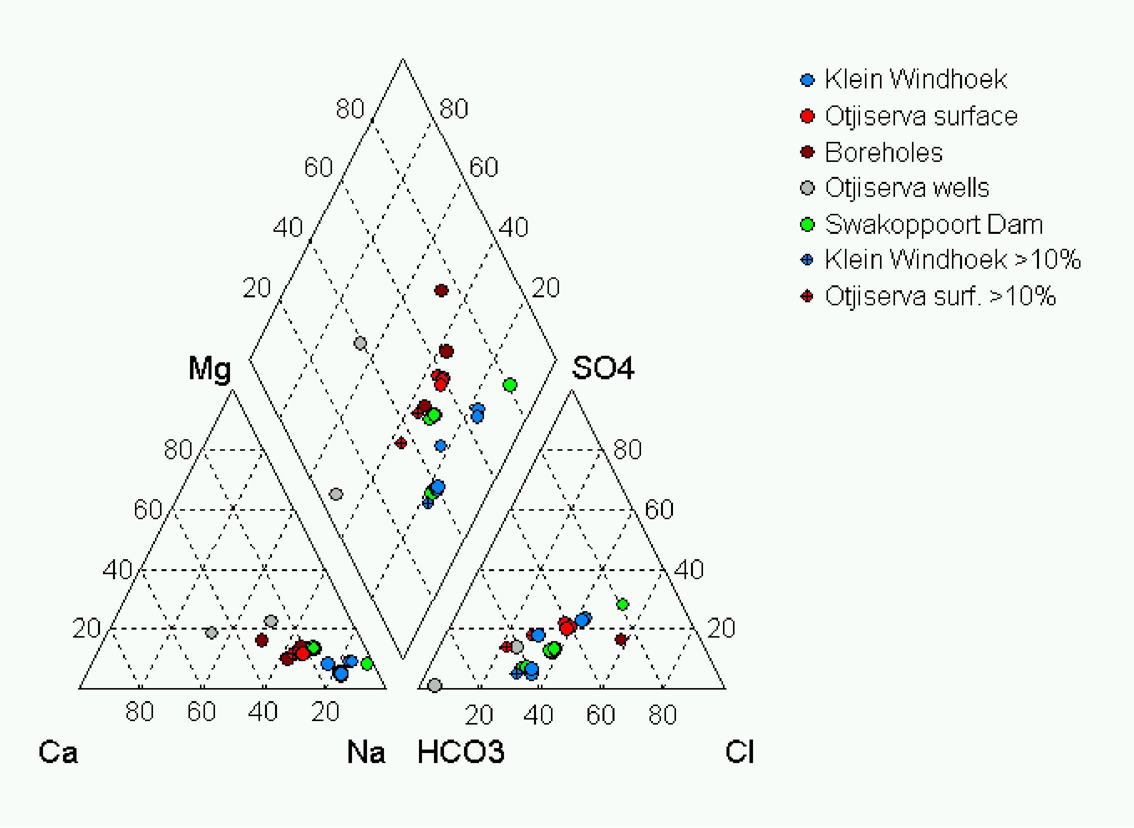

Figure 14: Piper diagram for all samples.

The cations show a trend from Na to Ca-Mg waters whereas the Otjiserva wells constitute the Ca-Mg extreme and the SgKW the Na endmember. In the anion diagram the delineation of endmembers is not that clear. The wells represent the HCO_3 waters while the Cl-SO_4 group is formed by samples from Swakoppoort Dam, boreholes and SgKW.

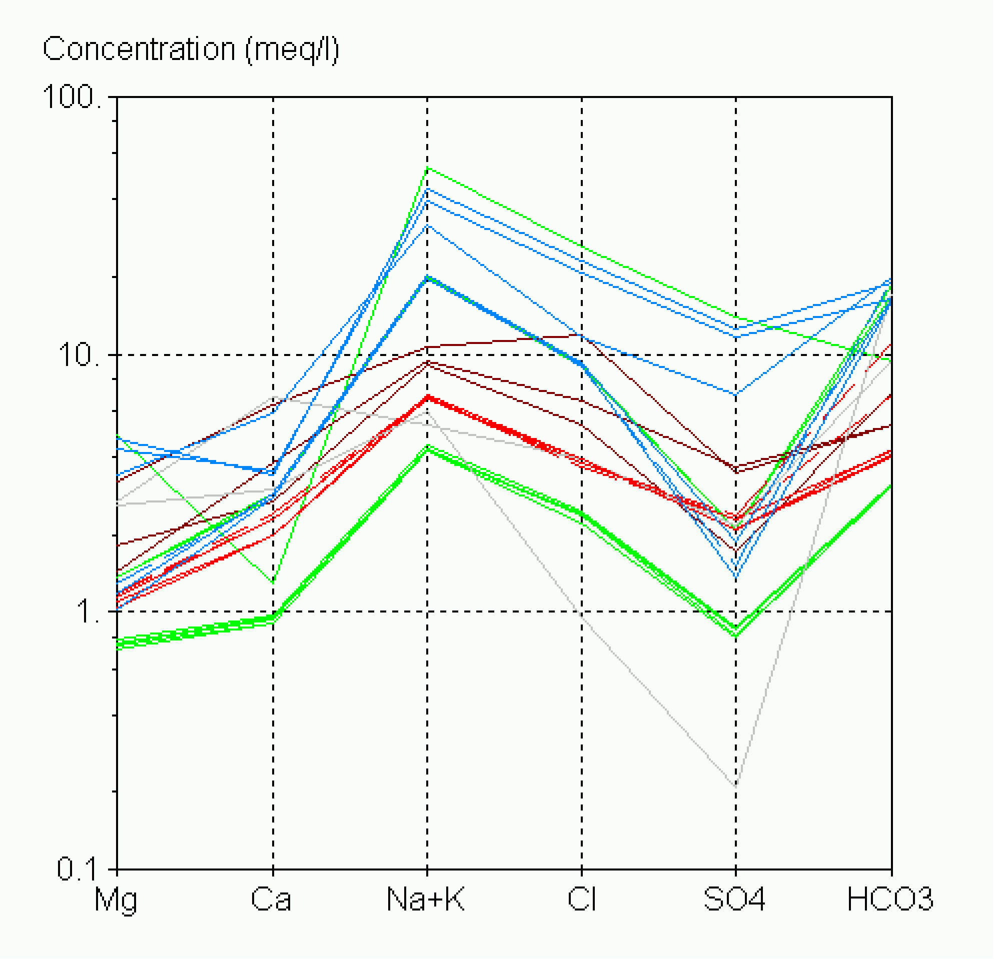

Figure 15: Schöller diagram for all samples

The Schoeller diagram shows that the dam waters are the least enriched waters. For most ions, especially Na+K, the SgKW has the highest concentrations.

5.4 Iron (Fe) and Manganese (Mn)

The thresholds described in this part are the Namibian general standards (NGS) for effluent. They are defined as follows:

- Fe: 0.05 mg/l
- Mn: 0.3 mg/l

All measured concentrations can be seen in Figure 16.

5.4.1 Sampling group “Klein Windhoek”

The Fe concentrations have their maximum at (M1) with 2.3 mg/l. From there on the values drop slightly until (12) with a Fe concentration of 1.6 mg/l. They are all above the NGS of 1 mg/l. (M3) is an outlier with 0.12 mg/l. Further downstream the Fe values fall down to 0.04 mg/l at (1).

Mn concentrations have not been analyzed for the samples (M1), (M2),(M3), (M5) and (M6). In the samples (7), (11) and (12) the Mn concentrations are far above the NGS, with a maximum of 5.3 mg/l at (12). Again the last sample point of the SgKW, (1), has a very low concentration of 0.07 mg/l.

5.4.2 Sampling group “Otjiserva Surface”

At the first the sample points of the SgOS, (2), (3) and (4), only 0.01 mg/l of Fe were detected. At the OWWTW outlet the concentration rises to 0.31 mg/l and then climbs up to 0.47 mg/l at (8). All values are below the NGS.

All Mn concentrations are at the likely detection limit of 0.01 mg/l.

5.4.3 Sampling group “Otjiserva wells”

All Fe concentrations are below the NGS. Only at (10) the concentration exceeds the likely detection limit with a value of 0.25 mg/l.

The Mn concentrations show a high variation in the three examined well samples. At (10) the concentration overshoots the NGS with 1 mg/l while (20) has a tenfold lower concentration of 0.1 mg/l. At (21) the Mn concentration was at the likely detection limit of 0.01 mg/l.

5.4.4 Sampling group “Boreholes”

At (9) the Fe concentration exceeds the NGS with 1.2 mg/l while at (22) the concentration is 0.04 mg/l.

The Mn concentrations at the SgBH show a similar picture. While (22) has a concentration of 0.01 mg/l which seems to be the detection limit, (9) shows a value of 0.14 mg/l, this time below the NGS.

5.4.5 Sampling group “Swakoppoort Dam”

At the SWPD Fe and Mn concentrations are all at the likely detection limits of 0.04 mg/l and 0.01 mg/l respectively. One exception is the sample from the middle of the lake in 1 m depth (15). There a Fe concentration of 0.08 mg/l was detected.

5.4.6 Summary

The highest Fe concentrations were detected in the SgKW. They reach values up to 2.3 mg/l. From all six samples which exceed the NGS, five are from the SgKW. The other is from the borehole sample (9).

The results of the Mn analysis reveal the highest concentration in the SgKW too. They reach values with a maximum of 5.3 mg/l, way above the NGS of 0.4 mg/l. In the other sampling groups Mn was only sparsely detected above the likely detection limit of 0.01 mg/l. Only at two well samples, one borehole sample and at the inlet of the SWPD low concentrations were detected. Those were all below the NGS.

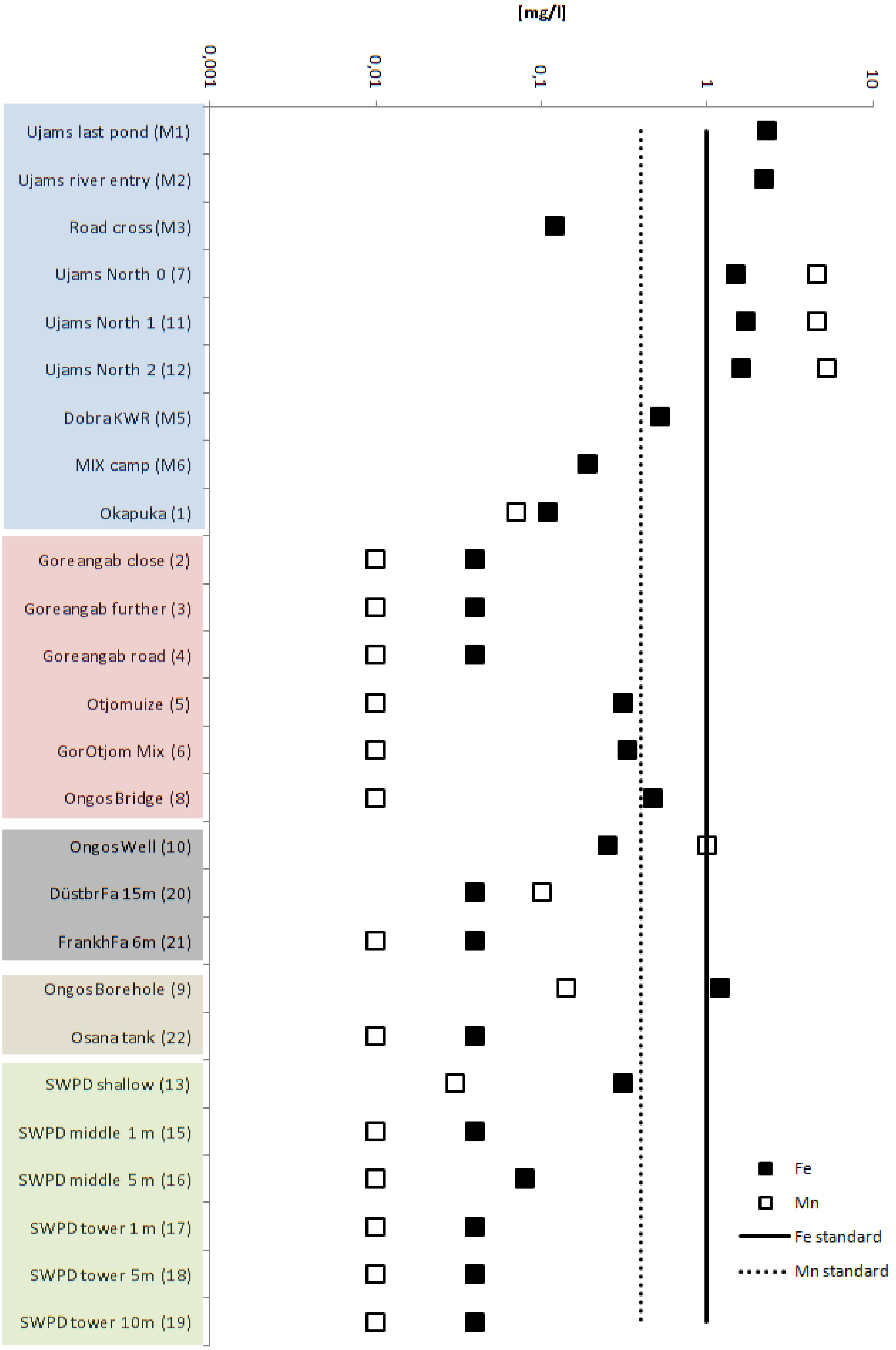

Figure 16: Iron and Manganese concentration of all samples and their corresponding standards.

5.5 TKN, DOC, UV254 (Nutrients)

The thresholds described in this part are the Namibian general standards (NGS) for effluent. They are defined as follows:

- TKN: 33 mg/l
- DOC: 15 mg/l
- UV254: 0.25 abs/cm

All measured concentrations can be seen in Figure 17

5.5.1 Sampling group "Klein Windhoek"

The TKN values start at a high level at (M1) with 105 mg/l and even rise to a plateau level around 140 mg/l at (7), (11) and (12). The maximum of 145 mg/l at (7) is more than 4 times the NGS. From (12) on the concentration drops rapidly below the NGS and reaches its minimum at (1) with a value of 3.1 mg/l.

The DOC values were not analyzed in (M1), (M2), (M3), (M5) and (M6). At (7) the maximum concentration is found with 81 mg/l. (11) and (12) show values of 57.3 mg/l and 56.1 mg/l which are also above the NGS. After (12) the concentration sinks along the flow path and reaches 7.72 mg/l at (1).

The values of UV 254 also have not been analyzed for the (M) sample points. The gradient generally follows the DOC values. The highest values are found at (7), (11) and (12) with readings of about 2 abs/cm and a maximum of 2.18 abs/cm. All three values lie way above the NGS. After (12) the values drop down below the NGO to the minimum of 0.145 abs/cm at (1).

5.5.2 Sampling group "Otjiserva surface"

The TKN readings in this sampling group are all below the NGS. The minimum concentration is found at (4) with 2.4 mg/l which then rises to 3.8 mg/l at (6) after the mixing with the OWWTW effluent of (5). The concentration then rises to a maximum of 6.7 mg/l at the downstream sample point (8).

The DOC concentrations steadily goes up from its minimum at (2) with 7.72 mg/l to its maximum at 11.1 mg/l at (8). All readings are below the NGS.

The UV254 values behave quite similar so the DOC concentrations again. The minimum is right behind the dam wall at (2) with a value of 0.145 abs/cm which then rises to the maximum of 0.232 abs/cm at (8). All values are below the NGS, whereby (8) is only slightly below the 0.25 abs/cm threshold.

5.5.3 Sampling group "Otjiserva wells"

All TKN concentrations in this group are below the NGS of 33 mg/l. The measured maximum is 3.3 mg/l at (21). The minimum is 0.5 mg/l at (20).

The DOC readings of the SgOW are all below the NGS of 15 mg/l. The maximum of 7.64 mg/l was detected at (10), the minimum of 2.02 mg/l at (21).

No measured value of UV254 is exceeding the NGS of 0.25 abs/cm in this group either. Again the maximum value was found at (10). Its value of 0.215 abs/cm only barely lies below the NGS. The minimum was measured at (21) with a value of 0.027 abs/cm.

5.5.4 Sampling group "Boreholes"

In the two borehole samples the NGS of TKN concentration was not exceeded. 1.1 mg/l was found in (9) and 1.9 mg/l in (22).

The DOC did not exceed the NGS either, but shows a huge difference in concentration. (9) has a value of 0.54 mg/l while 4.63 mg/l were detected in (22).

The UV254 concentrations of the two borehole samples show an immense difference too. While (22) has a value of 0.116 abs/cm, (9) lies on the supposed detection limit of 0.003 abs/cm.

5.5.5 Sampling group "Swakoppoort Dam"

The TKN concentration shows only little variation in this group. The mean value is 5.53 mg/l. The detected maximum at (13) is 6.2 mg/l, the minimum at (16) is 5 mg/l.

The DOC concentrations of all samples from the lake show minimal variation. Their mean value is 11.6 mg/l. The maximum lies at (15) with 11.9 mg/l and the minimum at (13) and (17), both with 11.4 mg/l.

In the values of the UV254 analysis a light descent can be seen. The maximum of 0.216 abs/cm lies at (13), the shallow inlet of the lake. The minimum of 0.176 abs/cm was detected at in 10 m depth at the extraction tower (19).

5.5.6 Summary

The only cases where TKN, DOC or UV254 are above the NGS are in the upper part of the Sampling group “Klein Windhoek”, close to the UWWTW. At sample point (11) the maxima of all three parameters have been recorded: A TKN concentration of 145 mg/l, a DOC concentration of 81 mg/l and a UV254 value of 2.18 abs/cm. In sampling group “Otjiserva surface” and in sampling group “Swakoppoort Dam” the DOC and UV254 values are quite alike, while the TKN concentrations in the dam water are higher. The lowest values are found in the two groundwater sampling groups.

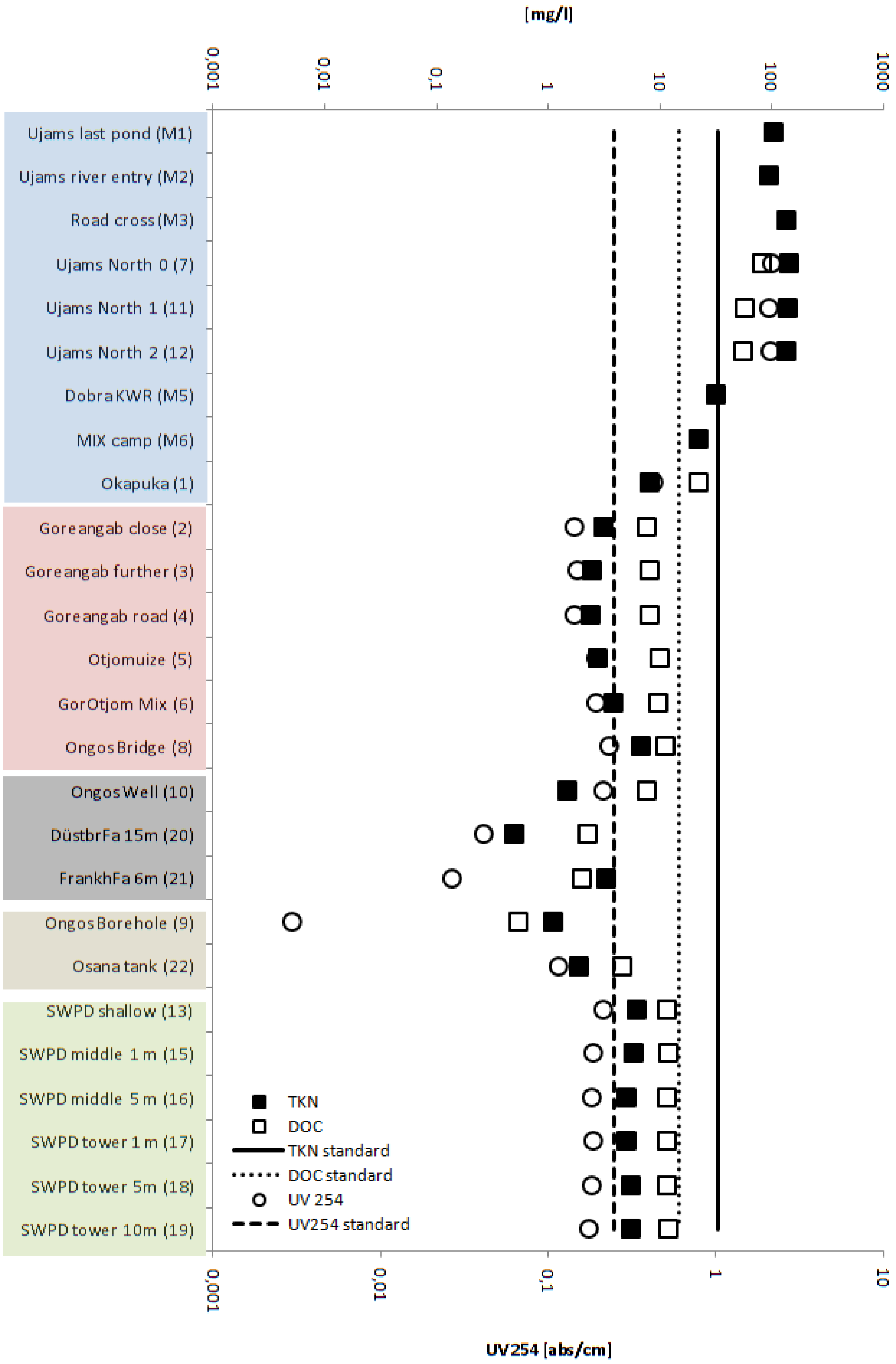

Figure 17: TKN, DOC and UV254 values of all samples and their corresponding standards.

5.6 Nitrogen compounds

The examined nitrogen compounds are Nitrate (NO_3), Nitrite (NO_2) and Ammonia (NH_3).

The thresholds are the Namibian general standards (NGS) for effluent. They are defined as follows:

- Nitrate:	20 mg/l
- Nitrite:	3 mg/l
- Ammonia:	10 mg/l

All measured concentrations can be seen in Figure 18.

5.6.1 Sampling group “Klein Windhoek”

In SgKW all Nitrate concentrations from (M1) to (12) match the supposed detection limit of 0.5 mg/l. Only at (M5) and (M6) concentrations of 1.2 mg/l and 1.6 mg/l were detected.

The Nitrite concentration starts at around 0.5 mg/l at (M1) and (M2), then drops to 0.12 mg/l at (M3). From there the concentration rises until 0.76 mg/l at (M6) and drops again to 0.15 mg/l at (1).

The results of the Ammonia analysis show very high concentrations above the limit from (M1) until (12) with a maximum of 61 mg/l at (7). After (12) the concentrations sink below the NGS until 0.15 mg/l at (1), the presumed detection limit of Ammonia.

5.6.2 Sampling group “Otjiserva surface”

From the Dam wall at (2) down to (4) the Nitrate concentrations are about 7 mg/l. The concentration of the OWWTW effluent at (5) lies on the supposed detection limit of 0.5 mg/l. After the confluence the value rises up to 3.8 mg/l at (8).

The Nitrite concentration is 0.17 mg/l at (4). All other samples show concentrations of 0.05 mg/l, which seems to be the detection limit.

All Ammonia values in this group show concentrations of 0.15 mg/l which is supposed to be the detection limit.

5.6.3 Sampling group "Otjiserva wells"

The maximum of the Nitrate concentration in this group is at (20) with 4.8 mg/l. (10) shows a value of 1.9 mg/l and 0.5 was detected at (21).

Nitrite was only detected in considerable amounts at (10) with a concentration of 1.1 mg/l. (20) and (21) are at 0.05 mg/l.

Ammonia concentrations not lying on the probable detection limit of 0.15 mg/l were only detected at (10) with 0.66 mg/l.

5.6.4 Sampling group "Boreholes"

The Nitrate concentration of (9) is 0.5 mg/l and of (22) is 3.3 mg/l.

All Nitrite concentrations lie on the suspected detection limit of 0.05 mg/l.

All Ammonia concentrations show values of 0.15 mg/l, which is the supposed detection limit.

5.6.5 Sampling group "Swakoppoort Dam"

In sample (13) from the shallow inlet of the SWPD a Nitrate concentration of 3.3 mg/l was analyzed. All other samples show concentrations of 0.5 mg/l.

Nitrite values above 0.05 mg/l are only to be found at the extraction tower in a depth of 10 meters (19), where the concentration reaches 0.14 mg/l.

Ammonia concentrations at the inlet (13) are at 0.15 mg/l. In the middle of the dam they reach 0.59 mg/l in a depth of 5 m (16). The highest concentrations in this group are found at the extraction tower in a depth of 10 m (19). There the value reaches 0.95 mg/l.

5.6.6 Summary

The highest values of Nitrate are found in the "Otjiserva surface" group with a maximum of 7.4 mg/l at (2), close to the dam. The Nitrate concentrations never exceed the NGS.

Nitrite is mainly found downstream of the sampling group "Klein Windhoek", while the maximum is at a well (10) with 1.1 mg/l. Nitrite never exceeds the NGS either.

Ammonia is the only parameter of the three nitrogen compounds of which concentrations above the NGS were detected. These were all in the upper part of the “Klein Windhoek” group. The maximum concentration was 61 mg/l at (7). Other concentrations above 0.15 mg/ are in a well (10) and in the SWPD.

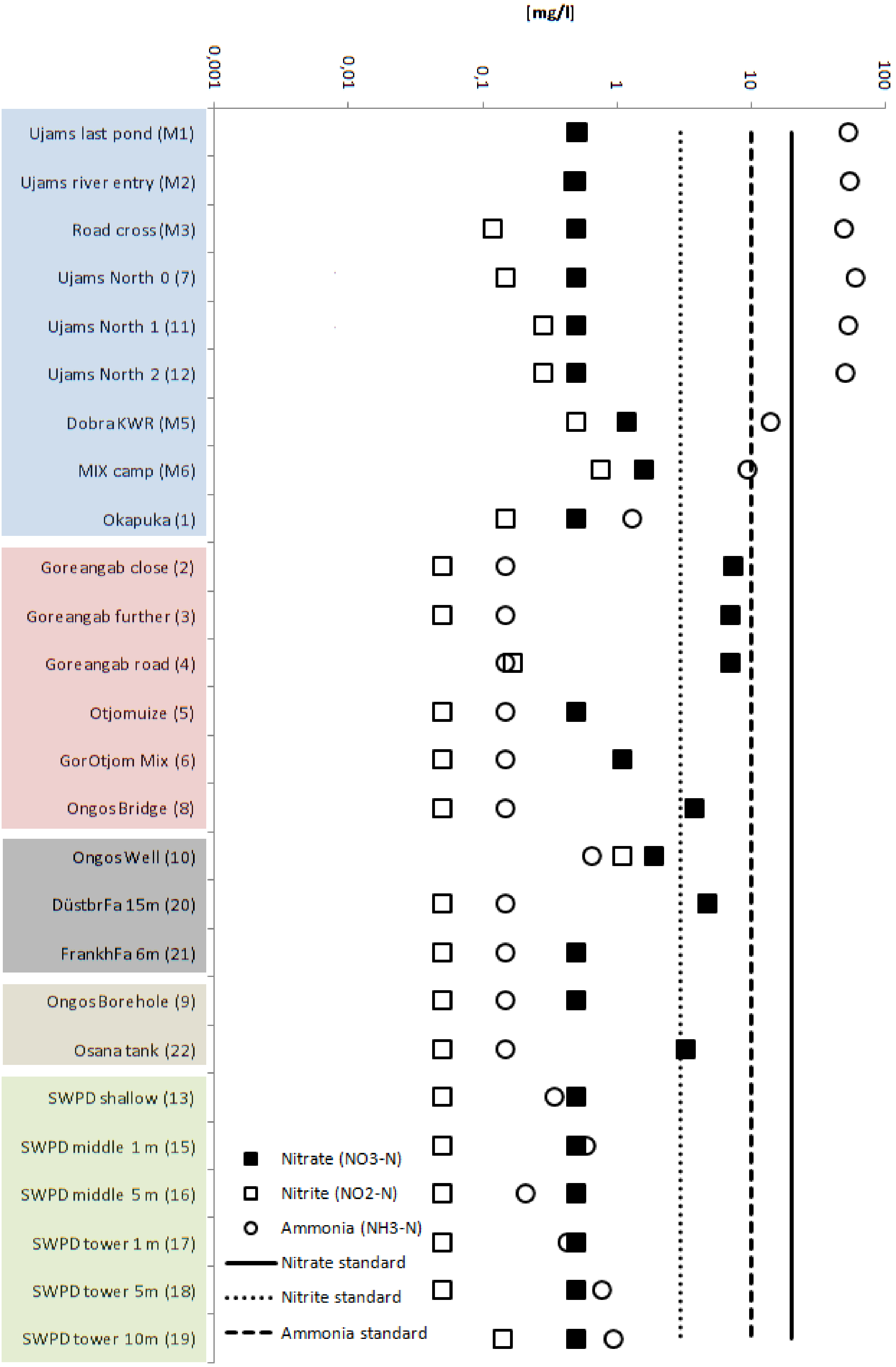

Figure 18: Nitrate, nitrite and ammonia concentrations and their corresponding standards.

5.7 Orthophosphate

The threshold for Orthophosphate described in this part is the Namibian general standard (NGS) for effluent. It is defined as follows:

- Orthophosphate: 3 mg/l

All measured concentrations can be found in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

5.7.1 Sampling group "Klein Windhoek"

The Orthophosphate values in this group are relatively steady around 20 mg/l from (M1) to (12).which is far above the NGS of 3 mg/l. The maximum is reached at (7) with 21 mg/l. Further down the flow path the concentrations drop to 2.6 mg/l at (1).

5.7.2 Sampling group "Otjiserva surface"

The Orthophosphate concentrations in the waters coming from the dam and the OGRP, (2) to (4), show values of 1.7 mg/l to 1.8 mg/l. The effluent from the OWWTW at (5) shows an Orthophosphate concentration of 0.39 mg/l. After the confluence of (4) and (5) the concentration rises to 0.72 mg/l further downstream at (8).

5.7.3 Sampling group "Otjiserva wells"

Only one well sample shows a concentration above the presumed detection limit of 0.23 mg/l. The value is 2.5 mg/l at (10).

5.7.4 Sampling group "Boreholes"

The Orthophosphate concentration in both borehole samples is 0.23 mg/l

5.7.5 Sampling group "Swankoppoort Dam"

All samples of the SWPD have an Orthophosphate concentration of 0.23 mg/l. This seems to be the detection limit of the analysis.

5.7.6 Summary

Orthophosphate concentrations above the NGS are only present in the sampling group "Klein Windhoek". There, except of the most downstream sample (1), all values are above the NGS. The maximum is at (7) with 21 mg/l. In the sampling group "Otjiserva surface" the concentration is about 2 mg/l right behind the dam wall and drops to 0.51 mg/l after the confluence of the OWWTW stream. From there is rises downstream to 0.72 mg/l at (8). One well sample has a concentration of 2.5 mg/l. All other well, borehole and SWPD samples have an Ortophosphate concentration of 0.23 mg/l, which is suspected to be the detection limit.

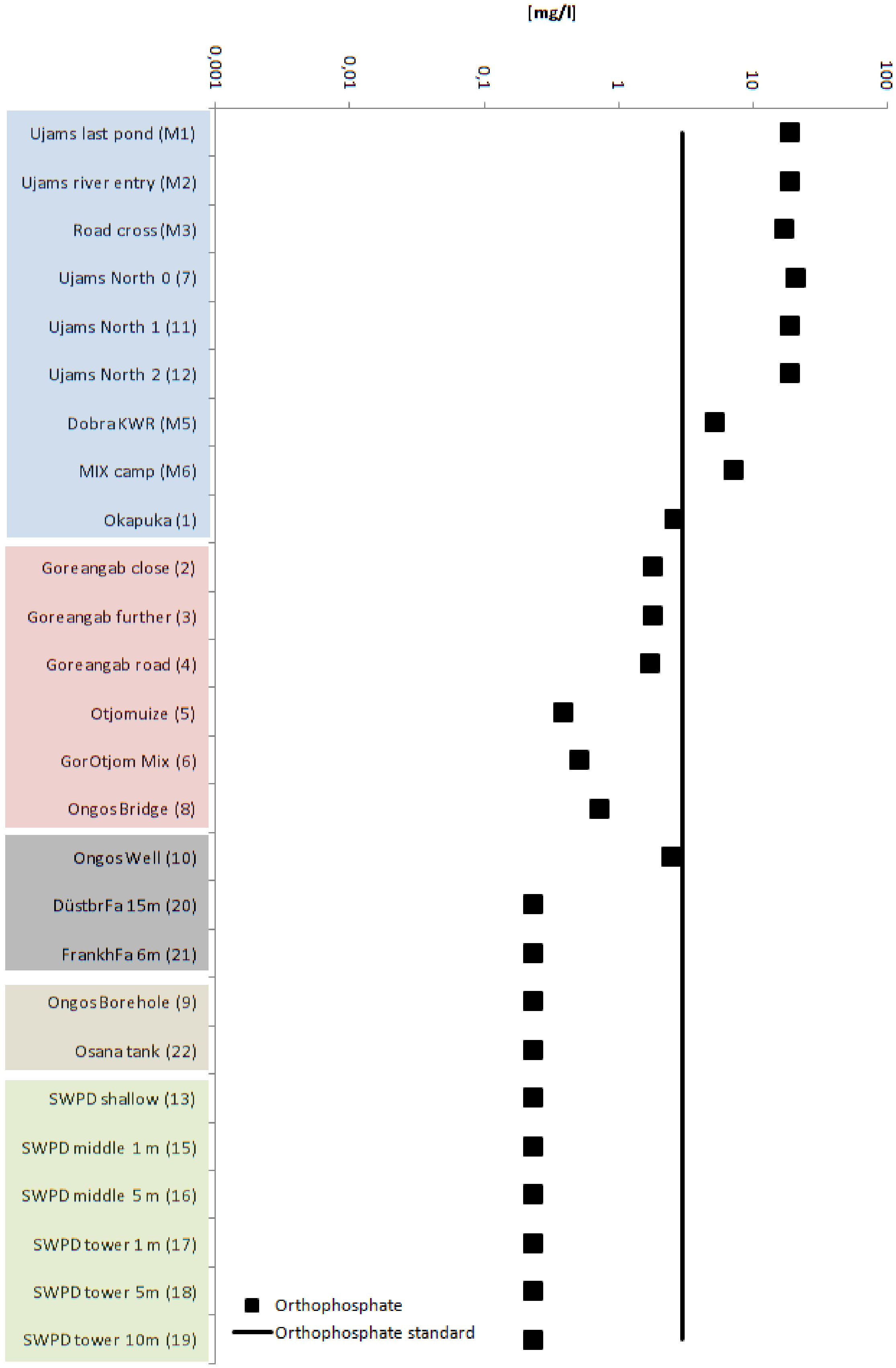

Figure 19: Orthophosphate concentration in all samples and the corresponding standard.

5.8 Sulphate and Sulphide

The threshold for Sulphide described in this part is the Namibian general standard (NGS) for effluent. It is defined as follows:

- Sulphide: 0.5 mg/l

All measured concentrations can be seen in Figure 20.

5.8.1 Sampling group "Klein Windhoek"

Sulphate concentrations from (M1) to (12) range from 65 mg/l at (M1) to 100 mg/l at (12), with (M3) as an outlier with a concentration of 335 mg/l. (M5), (M6) and (1) have high concentrations of 560 mg/l, 600 mg/l and 670 mg/l respectively.

The Sulphide concentrations are decreasing from 1 mg/l at (M1) to 0.51 mg/l at (12). Again (M3) is an outlier with a concentration of 0.02 mg/l, what seems to be the detection limit of the M samples. From (M5) to (1) the Sulphide concentration is 0.1 mg/l.

5.8.2 Sampling group "Otjiserva surface"

The Sulphate concentration in the SgOS declines from a 110 mg/l at (2) to 82 mg/l at (8). The mean concentration is 105.83 mg/l.

All Sulphide values are at 0.1 mg/l which seems to be the detection limit.

5.8.3 Sampling group "Otjiserva wells"

The minimum Sulphate concentration of this group lies at (10) with 82 mg/l. The maximum concentration was measured in well (21) with a concentration of 175 mg/l.

All Sulphide concentrations in the well group are at 0.1 mg/l.

5.8.4 Sampling group "Boreholes"

The Sulphate concentrations in the two borehole samples differ highly. In (10) 10 mg/l were detected while in (22) 105 mg/l were analyzed

Both samples had Sulphide concentrations of 0.1 mg/l.

5.8.5 Sampling group “Swakoppoort Dam”

In the SWPD the Sulphate concentrations scatter around 40 mg/l. The mean concentration is 40.33 mg/l, while the maximum is 42 mg/l at the inlet (13) and the minimum is 38 mg/l at (16).

All SWPD samples have a Sulphide concentration of 0.1 mg/l, the supposed detection limit.

5.8.6 Summary

The Sulphate concentrations are group wise relatively steady. Exceptions are the sampling group “Klein Windhoek”, where the concentration rises to a 5- to tenfold higher level further downstream, and the borehole sample group. The sampling group “Otjiserva surface” has concentrations around 100 mg/l and the samples from the SWPS are around 40 mg/l.

The Sulphide concentration only varies in the first six samples of the “Klein Windhoek” sampling group, where it reaches a maximum of 1 mg/l at (M1). All other samples show a concentration of 0.1 mg/l.

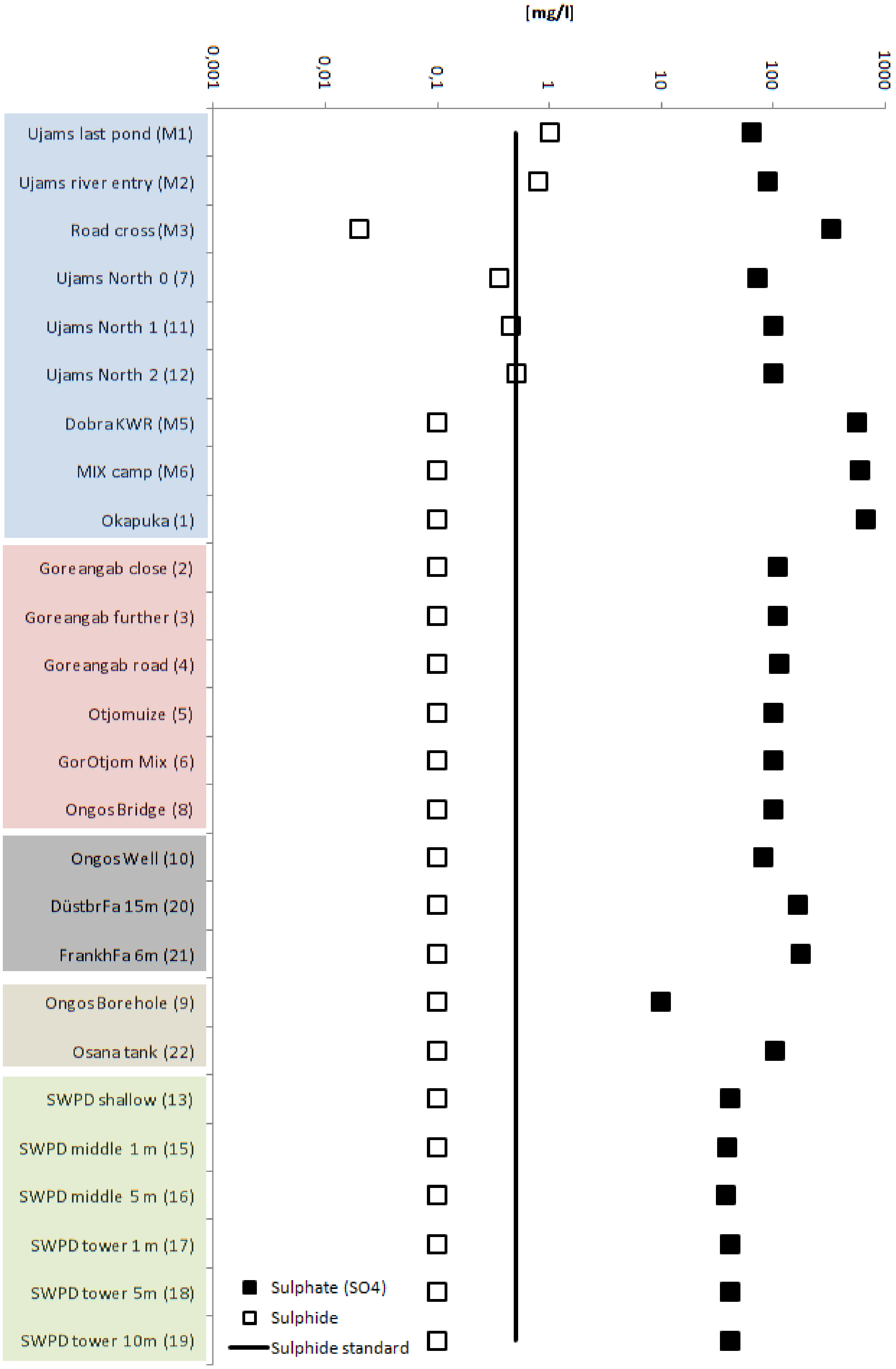

Figure 20: Sulphate and Sulphide concentrations and the standard of Sulphide.

5.9 Heavy metals

The analyzed heavy metals are: Cadmium (Cd), Nickel (Ni), Lead (Pb) and Chromium VI (CrVI). The thresholds are the Namibian general standards (NGS) for effluent. They are defined as follows:

Cd:	0.05 mg/l
Ni:	0.3 mg/l
Pb:	0.1 mg/l
CrVI	0.05 mg/l

All measured concentrations can be seen in Figure 21. Please keep in mind that the y-axis is logarithmic.

5.9.1 Sampling group "Klein Windhoek"

The Cd concentration of 0.75 mg/l at (M1) is the maximum in this sampling group. From there on the concentrations drop slowly along the flow path to (7). The exception is (M3) with its relatively low concentration of 0.04 mg/l. From (7) on the concentration rises slowly from 0.35 mg/l to 0.48 mg/l at (12) and then falls down to 0.07 mg/l at (M5). The last two sample points both have concentrations of 0.0125 mg/l which seems to be the detection limit of Cd.

The Ni concentrations behave quite similar to Cd. They start with a maximum of 23.20 mg/l right next to the last pond of the UWWTW at (M1) and 20.7 mg/l at the following sample point (M2). Then the concentration sinks to 0.35 mg/l at (7). Again (M3) is an exemption with a concentration of 0.01 mg/l. This is well below the NGS and seems to be the detection limit of Ni. The concentration of Ni then follows the same trend as Cd. It rises from 04.94 mg/l at (7) to 8.64 mg/l at (12) and then decreases to 0.51 mg/l at (1).

The result of the Pb concentrations analysis shows a different distribution than Cd and Ni. At (M1) and (M2) the concentration is 0.10 mg/l, right on the NGS. (M3) shows a relatively small Pb concentration of 0.01 mg/l, which rises to 0.03 mg/l at (7) and drops back to 0.01 mg/l at (11). From (11) the concentration rises abruptly to 0.08 mg/l at (M12) and then to its maximum of 0.39 mg/l at (M5). At the last two sample points (M5) and (1) values of 0.001 mg/l indicate the detection limit of Pb and therefore none or very little Pb is found-.

CrVI concentrations perform again in a comparable kind as Cd and Ni. The maximum concentration of 1.19 mg/l was measured right next to the last pond of the UWWTW at (M1). 1 km further downstream (M2) also shows high concentrations with 1.09 mg/l. At (M3) the concentration drops radically to 0.13 mg/l and even further to 0.066 mg/l at (7). (11) and (12) have high concentrations of 0.7 mg/l and 0.81 mg/l respectively. After (12) the concentration of CrVI falls down again to 0.15 mg/l at (M5) and 0.05 mg/l at (M6). Unlike Cd and Ni, (1) doesn't form the bottom of the descending curve. Instead CrVI is rising to 0.09 mg/l at the sample point (1), close to the Okapuka Tannery.

5.9.2 Sampling group "Otjiserva surface"

All samples except of (4) have Cd concentrations of 0.01 mg/l which seems to be the detection limit. The concentration at (4) was 0.03 mg/l and lies below the NGS.

In contrast to Cd the Ni concentrations in this group are all above the NGS. Close to the Dam, at (2) the concentration is 0.51 mg/l. It then rises to the maximum of 0.7 mg/l in this group at (3) and falls rapidly to 0.31 mg/l at (8).

All Pb concentrations were at 0.001 mg/l, which is most probably the detection limit of Pb.

The concentrations of CrVI are about a tenth lower than in the SgKW with a maximum of 0.13 mg/l at (2). From the sample close to the dam (2) to the last sample of this group at Ongos farm (8) the concentration is falling to 0.03 mg/l which is below the NGS. It is also noticeable, that the effluent from the OWWTW has low concentrations of CrVI: 0.05 mg/l has been measured in (5).

5.9.3 Sampling group "Otjiserva wells"

The Cd concentrations in the three well samples are all 0.0125 mg/l. That is below the NGS and is also the potential detection limit of Cd.

Ni is present in all three wells. With a maximum of 0.45 mg/l at (10) and a minimum of 0.28 mg/l at (21) a mean Ni concentration of 0.32 mg/l is found in the examined wells. The Ni concentration of (20) is 0.24 mg/l. Except of (10) all well Ni concentrations are below the NGS.

Pb concentrations of 0.1 mg/l and 0.07 mg/l have been detected at (10) and (20) respectively. The third sample at (21) has a Pb concentration of 0.001 mg/l. All three wells therefore have Pb concentration below the NGS.

The CrVI levels in the wells are all below the NGS. At (10) and (21) the concentration is 0.03 mg/l, at (20) the concentration is 0.01 mg/l.

5.9.4 Sampling group "Boreholes"

The Cd concentrations in both examined boreholes samples are below the NGS. In (22) the Cd level is at 0.01 mg/l, at (9) at 0.03 mg/l.

In contrast to Cd the Ni levels are above the NGS in (9) and (22). In the approximately 60 m deep borehole (9) concentrations of 0.43 mg/l are found. At (22) the concentration is 0.33 mg/l.

Pb concentrations are below the NGS in both boreholes: 0.05 mg/l in (9) and 0.001 mg/l in (22).

The CrVI concentration of 0.06 mg/l in (9) is above the NGS. In (22) the concentration is 0.01 mg/l which is most likely below the detection limit of CrVI.

5.9.5 Sampling group "Swakoppoort Dam"

No significant Cd concentrations are found at the SWPD. All samples show a value of 0.01 mg/l Cd, which seems to be the detection limit.

The Ni concentrations are all above the NGS. From the shallow inlet (13) with 0.65 mg/l Ni values rise towards the middle of the lake with concentrations of 0.77 mg/l and 0.78 mg/l in 1m (15) and 5 m (16) depth respectively. At the extraction tower the Ni concentration drops with the depth. At 1 m depth (17) the concentration is 0.65 mg/l and at 10 m depth (19) the concentration is close to the NGS with 0.36 mg/l.

No considerable Pb concentrations are detected at the SWPD. All samples have a concentration of 0.001 mg/l Pb.

CrVI in a concentration above the NGS is detected in the sample from the shallow inlet of the dam (13) with 0.07 mg/l. Furthermore in the samples from the middle of the dam, (16) and (17), and at the extraction tower in a depth of 10 m (19) the concentration was 0.02 mg/l.

5.9.6 Summary

Cd concentrations above the NGS were only found in the Sampling group “Klein Windhoek”, but those are very high. All other Cd concentrations are below the NGS and only two, (5) and (9) are above the assumed detection limit of 0.01 mg/l.

Ni concentrations are, except of two well samples, all above the NGS. The by far highest concentrations are found in the Sampling group “Klein Windhoek” with a maximum of 23.2 mg/l. This is nearly the 80-fold of the NGS.

Pb is only once detected in concentrations above the NGS (M5). Apart from the Sampling group “Klein Windhoek” and three samples from wells and boreholes nearly no Pb was found.

CrVI is mainly identified in the two rivers of the Sampling group “Klein Windhoek” and Sampling group “Otjiserva surface”. Most of the detected concentrations in these two groups are above the NGS. Most of the samples from the wells, the boreholes and the SWPD have low concentrations of CrVI.

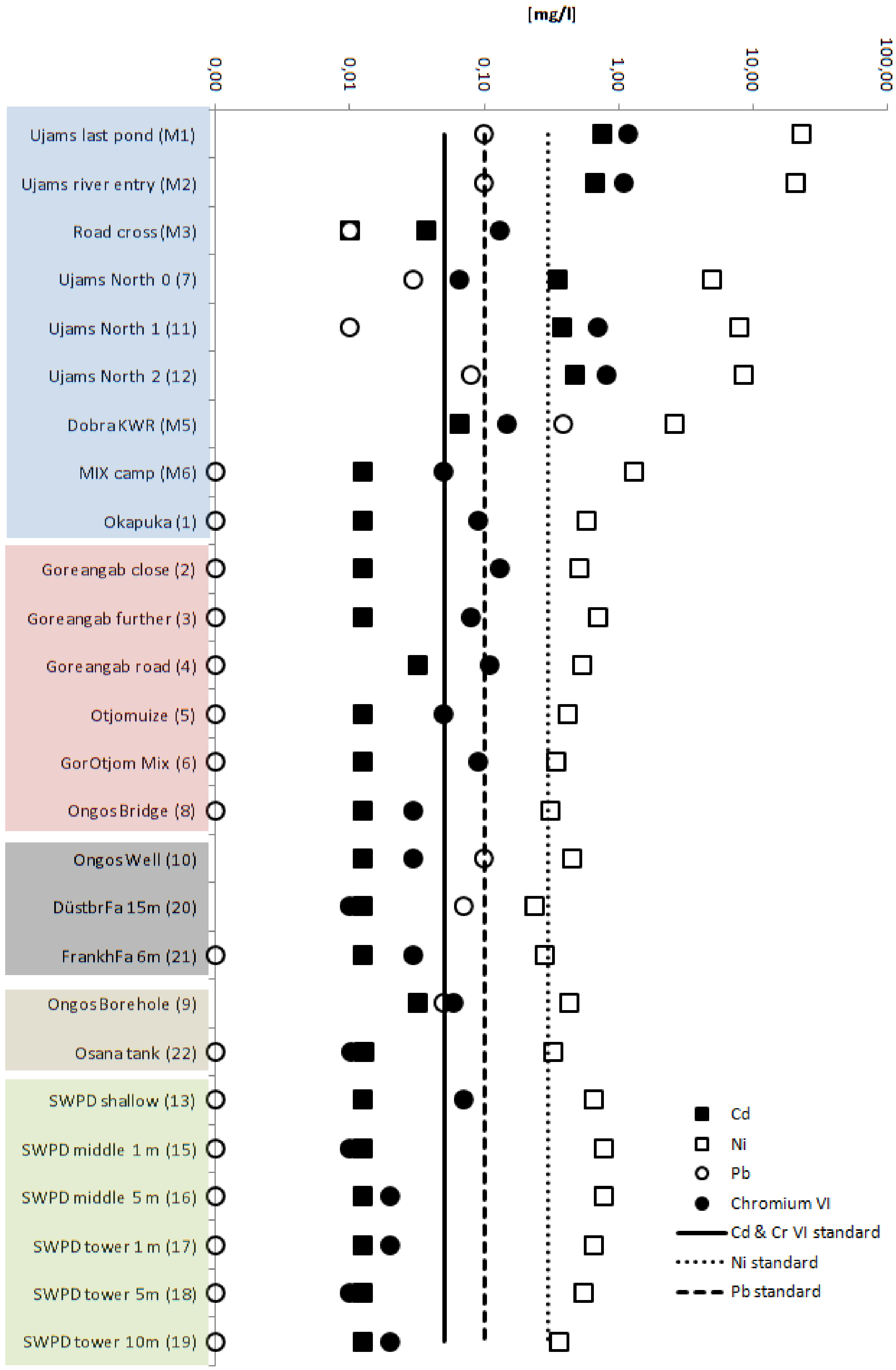

Figure 21: Heavy metal concentration of all samples and their corresponding standards.

5.10 Phenol and Formaldehyde

The threshold for Phenol and Formaldehyde described in this part are the Namibian general standards (NGS) for effluent. They are defined as follows:

- Phenols:	0,1 mg/l
- Formaldehyde	0,1 mg/l.

All measured concentrations can be found in Figure 22.

5.10.1Sampling group "Klein Windhoek"

The phenol concentration in this group is above the NGS in all samples. The maximum lies directly after the last pond of the UWWTW (M1) with 7.8 mg/l and from there on the concentrations drop to 5.5 mg/l at (12). (M3) seems to be an outlier with a value of 2.67 mg/l. Further downstream the decrease of the concentration continues and reaches its minimum at (1) with 0.44 mg/l.

The Formaldehyde concentration is above the NGS in al samples of this group, too. After (M1), (M2) and (M3) have concentrations around 0.3 mg/l the value rises to 0.67 mg/l at (7). From this maximum the concentration decreases down to 0.15 mg/l at (1).

5.10.2Sampling group "Otjiserva surface"

Phenol is present at (2) with the minimum concentration of 0.1 mg/l. Along the flow path the concentration rises first to 0.18 mg/l at (6) and reaches its maximum 0.21 mg/l some 13 km downstream. Except of (2) all concentrations are above the NGS.

All Formaldehyde concentrations have a value of 0.05 mg/l, which seems to be the detection limit.

5.10.3Sampling point "Otjiserva wells"

Phenol concentrations above 0.05 mg/l were only detected in (10) with 0.38 mg/l.

All Formaldehyde concentrations in this group are at 0.05 mg/l, which is assumed to be the detection limit.

5.10.4Sampling point “Boreholes”

No Phenol above 0.05 mg/l was detected in the borehole samples.

No Formaldehyde concentration above 0.05 mg/l was found in this group either.

5.10.5Sampling point “Swakoppoort Dam”

The highest Phenol concentrations have been detected at (13), near the inlet, with 0.2 mg/l. The two samples from the middle of the lake have values of 0.1 mg/l. At the extraction tower the concentrations are 0.13 mg/l, 0.16 mg/ and 0.14 mg/l at (17), (18) and (19) in that order.

Formaldehyde concentrations above 0.05 mg/l were only found at the extraction tower in a depth of 10m. There, at (19), the concentration is 0.12 mg/l.

5.10.6Summary

In the sampling group “Klein Windhoek” all measured concentrations of Phenol and Formaldehyde lie above the NGS. Phenol reaches its maximum at (M1) with 7.8 mg/l, which is the 78-fold of the standard. The concentration drops further downstream. In the sampling group “Otjiserva surface” the phenol concentration is also above the NGS. The values range from 0.1 mg/l to 0.21 mg/l. Except of one well sample no Phenol concentration is above 0.1 mg/l in the groundwater. In the SWPD Phenol concentrations exceed the NGS at the inlet and at the extraction tower.

All Formaldehyde values in sampling group “Klein Windhoek” are above the NGS. The maximum lies at (7) with 0.67 mg/l, which is nearly the seven-fold of the standard. The only other sample where the Formaldehyde concentration is higher than 0.1 mg/l is at the extraction tower at the SWPK in 10 m depth, (19). There the concentration is 0.12 mg/l.

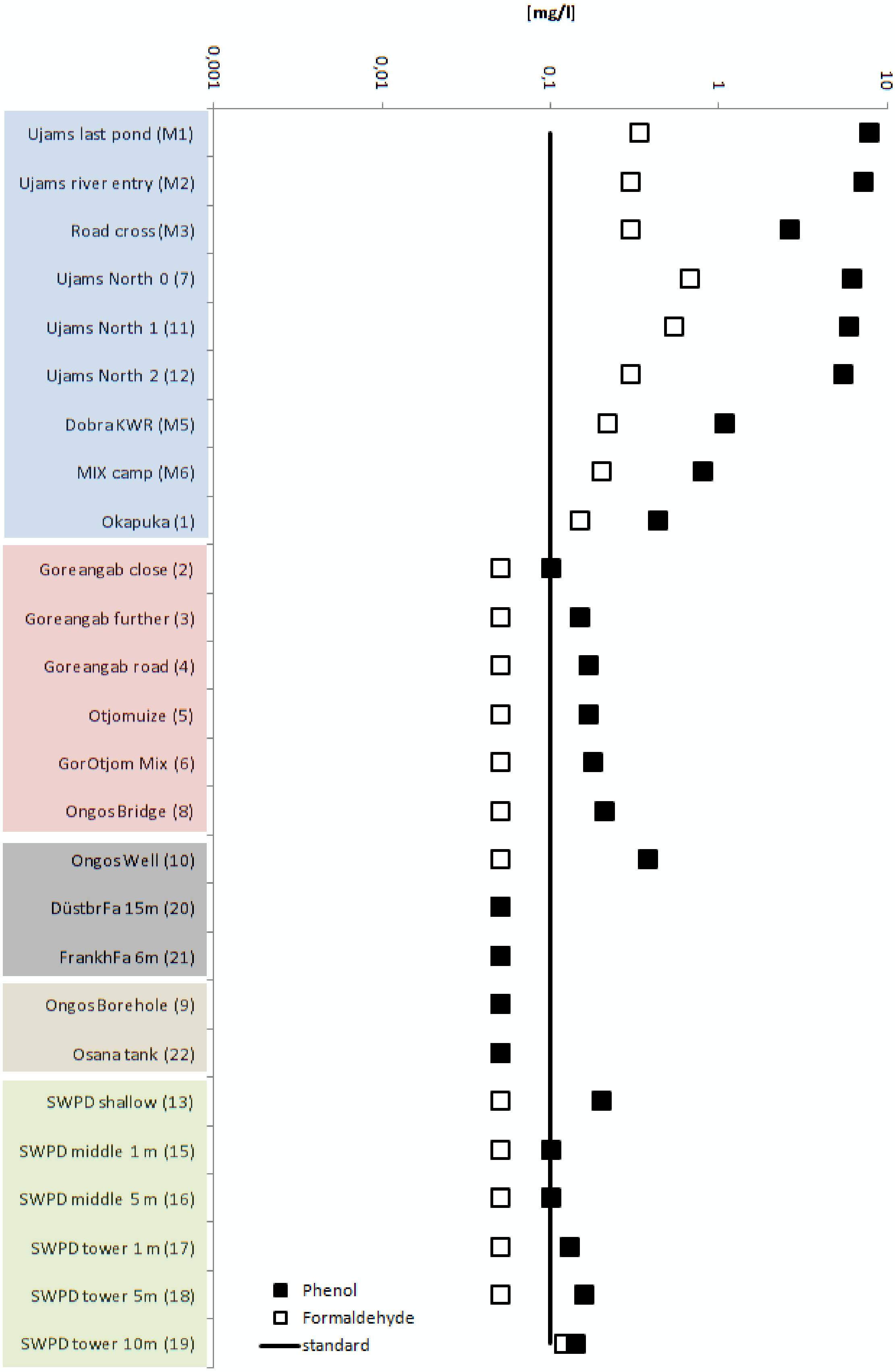

Figure 22: Phenol and Formaldehyde concentrations and their corresponding standard.

5.11 Secchi depth and lake status of the Swakoppoort Dam

Secchi disc measurement data was provided by Namwater. 144 measurements were conducted between May 1997 and October 2010, approximately one per month, while 2009 just one measurement was taken in June.

Figure 23 shows, that the annual variation of the Secchi disc depth is decreasing from 1997 to 2010. While 1997 Secchi disc values ranged from 0.30 m to 2.35 m in 2008 the range has reduced to 0.45 m to 0.89 m.

Despite the decreasing range of the secchi depth the mean annual depth is also reducing which can be seen in Figure 24.

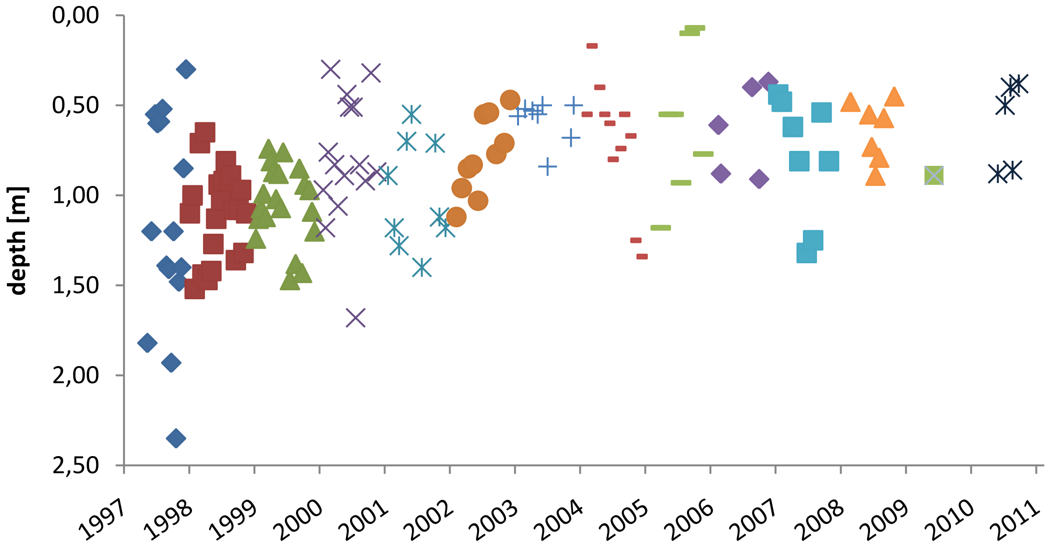

Figure 23: Secchi disc readings from 1997 to 2010.

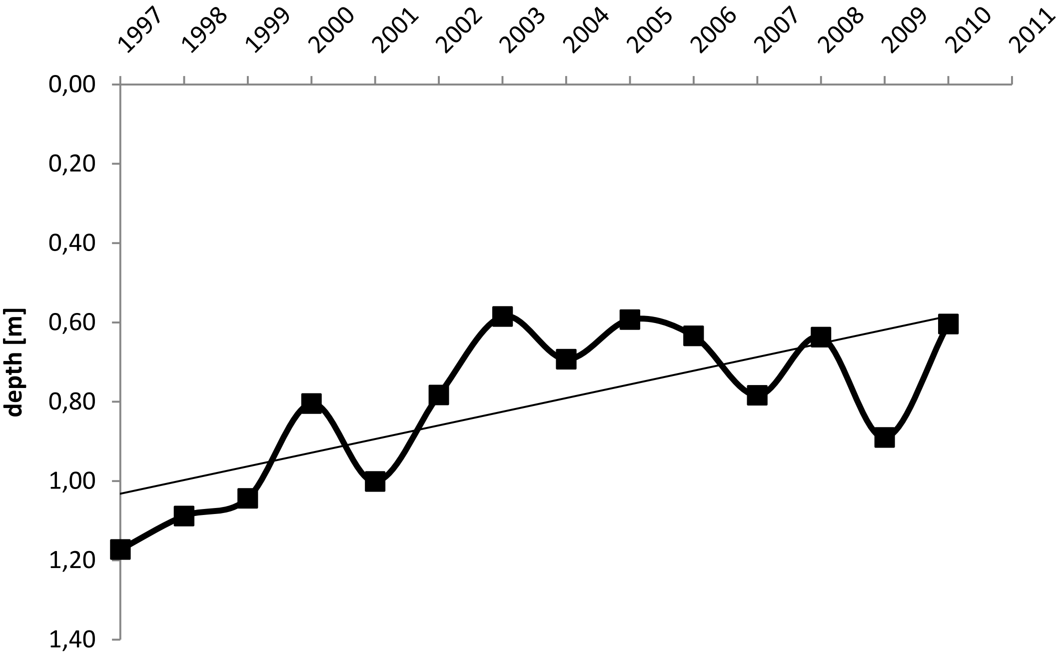

Figure 24: Mean annual Secchi disc readings from 1997 to 2010 with trend.

The lake status of the SWPD was analyzed with the help of a Tropic State Index (TSI) calculation after Carlson. To comply with the "snapshot" idea of this thesis, one day as closely as possible to the sampling dates was chosen. The most closely date where all needed data was available was the 21.07.2010. The values can be found in Table 3.

Table 3: Total phosphor, total nitrogen, chlorophyll a and Secchi depth values at the extraction tower of the Swakoppoort Dam. Sampling date: 21.07.2010. Source: Namwater.

Sampling depth *m*	TP *µg/l*	TN *µg/l*	CHL *µg/*	SD *m*
2,5	1010	3400	502	0,5
6,5	200	1800	194	
10,5	170	1600	80,9	
14,5	420	1700	23,4	

The TSI was calculated with the concentrations at 2.5 m depth. The four calculated TSIs are:

TSI(TP): 104

TSI(TN): 72

TSI(CHL): 92

TSI(SD): 70.

TSI values above 70 imply hypereutrophic conditions and high algae concentrations, while at values over 80 algal scums are forming. The visual impressions from the lake support this result.

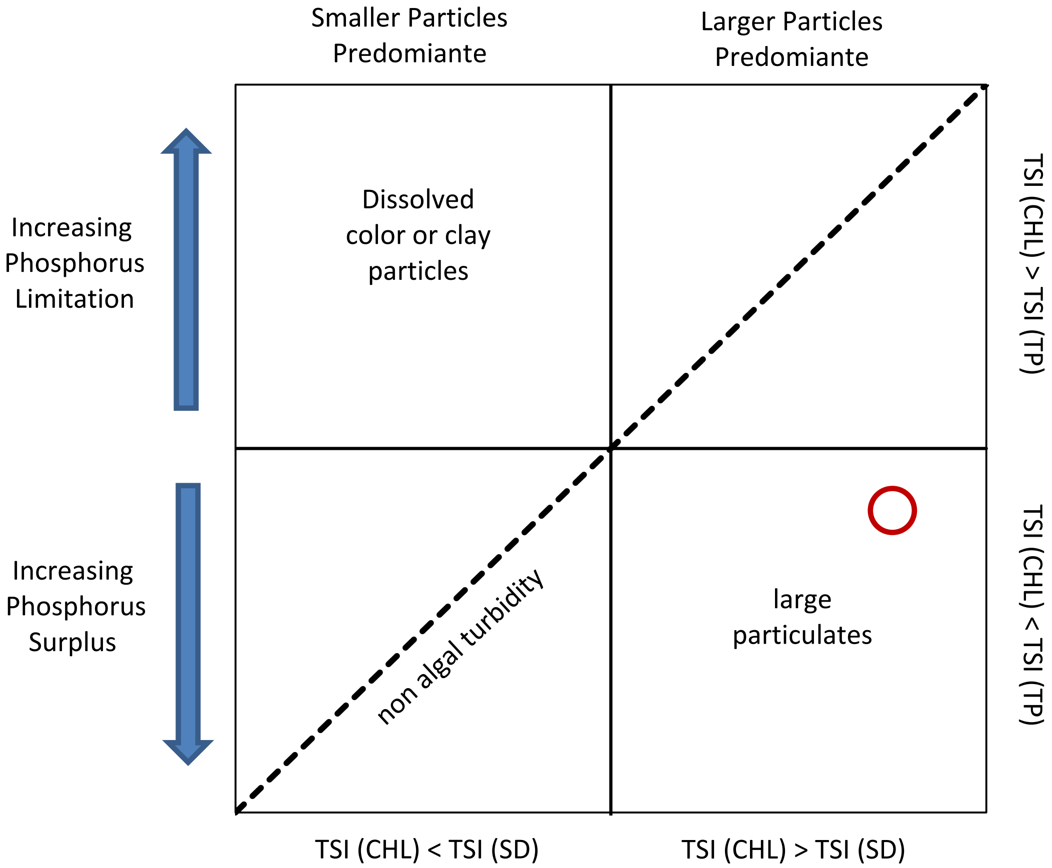

Figure 25: Interpretation of Trophic State Indices relations of Carlson (1977). Red circle symbolized the SWPD at the 07.21.10. Modified by (Carlson & Simpson 1996).

5.12 Stable isotopes of H_2O

In the results of the ^{18}O and ^{2}H isotope analysis the five sampling groups are visibly separated as can be seen in Figure 26. In a ranking from a lighter to a heavier isotope distribution the following order can be seen: SgBH, SgOW, SgOS, SgKW and SgSD. The constructed evaporation line with a slope of 5.3 cuts the GMWT close to borehole sample (9) at -7.44 [^{18}O ‰] to -50,31 [^{2}H ‰].

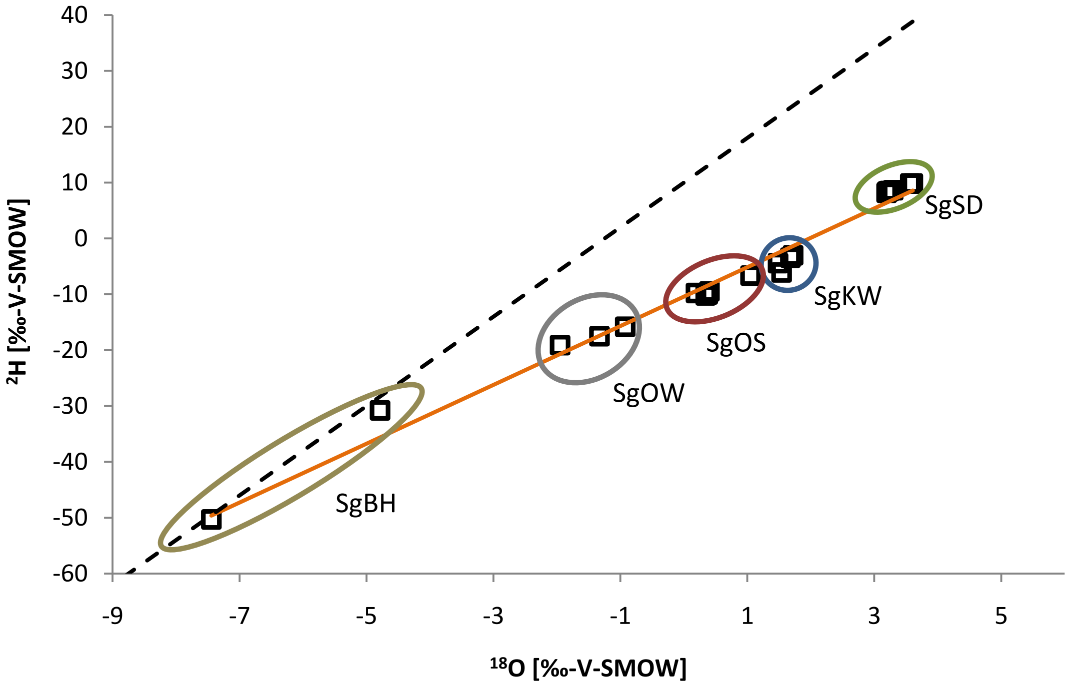

Figure 26: Stable isotope analysis of all samples. The dashed line is the GMWL, the orange line represents the evaporation line of all samples. Circles show sampling groups.

6 Discussion

In this chapter the different parameters are not interpreted separately to be able to describe interactions between them. Instead the different sampling groups are examined individually.

6.1 Discussion of individual groups

6.1.1 Sampling group "Klein Windhoek"

The results of the SgKW show clear signs of pollution by the effluent of the UWWTW.

The sample points close to the treatment plant show very low oxygen concentrations with a minium of 0.2 mg/l which indicate reducing conditions obvouisly coming from the degradation of organic waste which is indicated by extremely high DOC concentrations of up to 81 mg/l. The low oxygen concentrations seem to lead to a mobilization of Fe and Mn from the sediment which is indicated by high values of up to 2.3 mg/l and 5.3 mg/l respectively (Schönborn 2003).

The high Phosphate levels close to the UWWTW could point to problems with the precipitation techniques in the plant. As micronutrient orthophosphate in higher concentrations is one of the main reasons for eutrophication (Asano 2007a).

Low levels of The Nitrate values close to the UWWTW could indicate that the Nitrate removal at the plant is working. Eye-catching are the Ammonia values. With up to 61 mg/l they are far above the NGS. The high concentration was also noticeable through an intensive smell during the sampling process. High Ammonia concentrations are a sign of a current heavy pollution further upstream.

Because the UWWTW is mainly treating industrial waste waters from the northern industrial area of Windhoek one is not excepting so high concentrations of organic pollution. The fact that a big abattoir is also situated in Windhoek's north could eventually be the source of nutrient concentrations.

Ammonia is known to be obstructive in the treatment process of heavy metals in industrial wastewaters. This could be a reason for the exceptional high values of Ni, Cd and CrVI close to the UWWTW. The Ni maximum concentration of 23.2 mg/l is nearly eighty times higher than the NGS which indicates a total failure of the relevant cleaning process. The Cd and CrVI concentrations are also far above the NGS.

The presence of high concentrations of Phenol and Formaldehyde in the upper part of the Klein Windhoek River also indicate industrial pollution and unsufficient treatment.

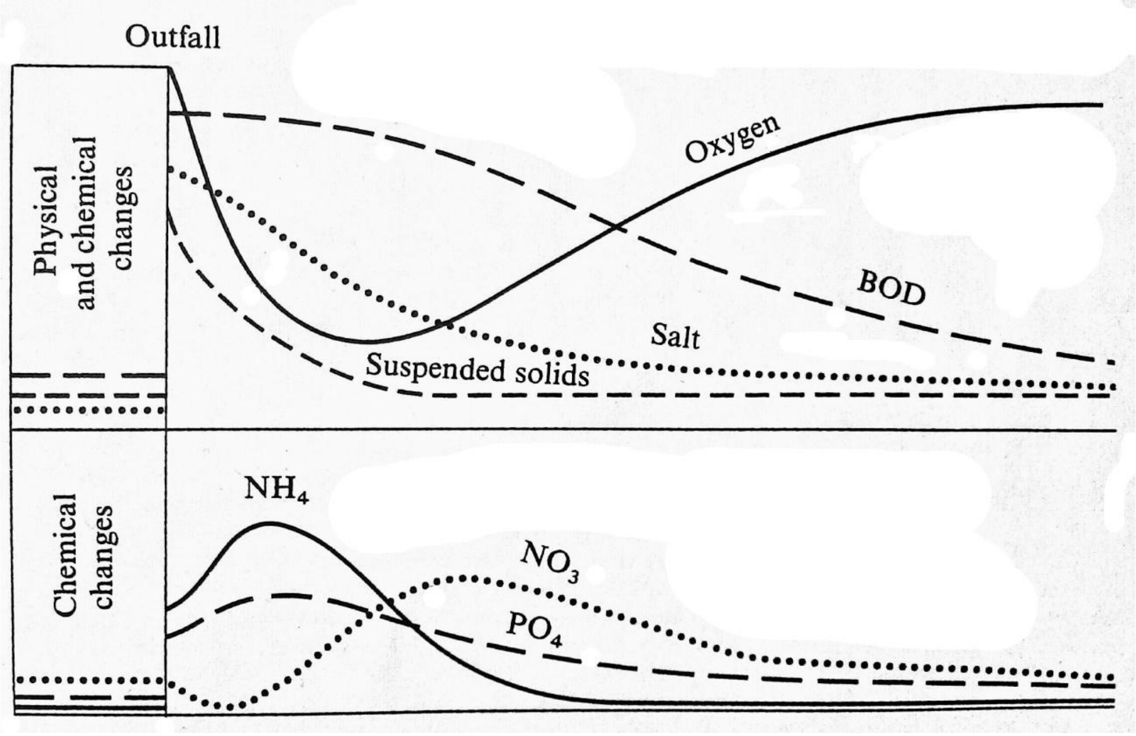

Figure 27: Diagram of typical changes in water chemistry in a river below a source of organic pollution. (Modified from Hynes 1963)

Further downstream the oxgen concentrations are rising again and with it the DOC values drop. At the same time the Fe and Mn concentrations are decreasing which indicated their oxidation to immobile forms. The falling Ammonia concentrations together with rising Nitrate and Nitite values along the flowpath show a natural cleaning effect of the river which is illustrated in Figure 27. Phosphate is also decreasing which indicates its biodegradation. The concentration of Ni, CrVI and Cd also drops along the flow path. Because heavy metals are normally not degraded this means probably that they are accumulating in the sediment of the river. Despite the decrease of most parameters in the direction of the flow path the concentrations of DOC, Ni, Cr, Phenol and Formaldehyde are still above the NGS at the last sampling point of this group close to the Okapuka tannery. The high conductivity reading at this point was most probably because the river was crossing the access road to the tannery. The rise of Cr from the supposed detection limit of 0.05 mg/l to 0.09 mg/l at this sample point could relate to the use of Cr in the tanning process.

6.1.2 Sampling group “Otjiserva surface”

The SgOS is consisting of two flow paths which confluence and then flow northwards into the Otjiseru River. One is coming from the dam wall of the GGD and consists of spilled lake water and excess flow of the OGRP. The other is coming from the OWWTW and consists mainly of treated effluent. If the parameter of both are compared the source of some pollutions can be explained.

The oxygen concentration of the water from the dam is much higher than the OWWTW water. This is most likely because of degrading processes of nutrients like DOC. The lower oxygen concentrations are also reflected in the higher values of Fe. Mn is not yet detected because it gets mobilized later than Fe.

From the dam water Nitrate and Phosphate are coming in higher concentrations, most likely from the eutrophicated dam water of the GGD but even after mixing with the water from the OWWTW they start to rise again which could be a sign of more pollution sources along the flow path. The rising of Phenols along the stream could also be a sign for another pollution source.

Cr and Ni are coming most probably from the dam water in concentrations slightly above the NGS. They decrease along the flow path supposedly by accumulating in the sediment.

It can stated, that the water quality of the SgOS which is affected by the effluents of the domestic treatment plants is much better than of the SgKW. Except of Nitrate, Phenol, Nickel and Cr all values are below the NGS. Even the concentrations which exceed the NGS are much lower than at the SgKW.

6.1.3 Sampling group "Otjiserva wells"

Sample (10) from the Ongos Farm has a significantly lower temperature than the other two wells which could be a sign of exchange with water of the nearby stream All three well samples show low oxygen concentrations most likely because of oxygen consuming degradation processes. Another sign for reducing conditions are Fe and Mn which have been found in sample (10) and (20). In sample (10) it exceeded the NGS. Another sign for a possible influence from the nearby Otjiseru River are high concentrations of Phosphor, Phenols and Ni which the other two well samples lack. Ni is even above the NGS at the well sample (10). It is important to know that of the time of the sampling only at Ongos farm (10) the Otjiseru River was still slowing. At the other two farms the pollution could come from the last rainy season, alluvium influences or local sources. The owner the Düsternbrock Farm stated that his animals prefer water from another source, further away from the Otjiserva River. This may be because of the high conductivity value of the well water.

6.1.4 Sampling group "Boreholes"

The only sample which was taken close to the Swakop River was (22) at a water tank which was filled from a borehole in the alluvium. The fact that it was stored in a tank is reflected in its high temperature. All parameters are below the NGS except of Ni which is also present in concentrations higher than the NGS in the other borehole (9), located at Ongos farm (9). At (9) the Fe concentration was also above the NGS which may come from the borehole casing. The concentration of Cd is also higher than the NGS at the Ongos borehole.

6.1.5 Sampling group "Swakopport Dam"

The Swakopport Dam showed obvious signs of eutrophication which were already at the process of sampling. The water was green and algae particles were clearly visible. On some occasions also algae scum layers were drifting on the water.

The oxygen concentration is decreasing from to inlet to the extraction tower and with the depth. This correlates with the visible impression of the concentration of algae. This may be because the water flow is transporting and accumulating the algae to the dam wall, the former outlet. The Ammonia concentrations are increasing opposed to the oxygen concentration. This is a sign anaerobic degradation of nutrients in the deeper layers of the lake.

The high DOC values could come from Algaes producing DOC or from waste waters (Schwoerbel & Brendelberger 2005).

High Phosphate inputs are mostly the reason for eutrophication in lakes. The analysis results from the Gammans laboratory show Orthophosphate values of 0.23 mg/l which seems to be the detection limit of this analytical method. To identify the trophic state of the dam results from Namwater measurments of Total Phosphorus, Chlophyll a, Total Nitrogen and Secchi depth of the 07.21.2010 were used to calculate the Trophic State Index of Carlson (1977). The results are all larger than 70 which means the lake is hypereutrophic. The relation of the different TSIs can be used to further interpret the status of the lake (Figure 25). The TSI(CHL) is with 104 much higher than the TSI(SD) with 70. This means the transparency of the lake is greater than expected from the chlorophyll a values. These deviations may occur if large particles like blue-green algae (Cyanobactercia), dominate and transparency is less affected by the particulates. This fits to the large algae particles which have been seen during the sampling Photo 1. Because the TSI(TP) is larger than the TSI(CHL) something else than Phosphorus may be limiting chlorophyll.

Ni concentrations above the NGS are in all samples of the lake which may be an indicator that the effluents from Windhoek are somehow reaching the Swakopport dam if other sources can be excluded. Cd and Phenol is found in concentrations higher than the NGS close to the shallow inlet. Both have concentrations higher than the NGS.

6.2 General discussion

For the interpretation some points have to be kept in mind:

- The possibility of dilutional effects in the flowpath of SgKW and SgOS was mostly excluded because of in the time when the sampling was done it was not raining and all ephemeral rivers were dry. There is however the possibility of dilution from groundwater and anthropogenic inputs cannot be ruled out too.
- It also has to be stated that the samples were taken on different days which could lead to misinterpretations of e. g. degradation processes along flow paths. Obvious outliers like the sample point (M3), which was taken two month before the other (M) samples make this noticeable. The fact that the waste water treatment plants are constantly emitting effluents does not mean that the emmited pollutants are always the same.
- The thresholds used in this thesis are the Namibian General Standard for effluents. These may be significantly higher than thresholds for natural or drinking waters.

The major ions analysis is normally used to identify the geogenic origin of natural waters. The high grade of pollution may be the source of the high ion balance errors in some samples. Since the sampled surface waters are mixtures of different waters (rain, surface, underground, dam) an interpretation of the piper diagram is fairly difficult. The Schoeller diagram confirmed the extent of pollution in the different groups.

In the isotope analysis the fractionating effect of the evaporation can be clearly seen. The most evaporated waters were in the lake water of SWPD (SgSD) followed by the surface water groups SgKW and SgOS. Of the groundwater samples the SgOW, being groundwater with access to the atmosphere and therefore evaporation showed lighter values than the borehole samples from SgBH. They both lie close to the GMWL indicating recharge from rainwater.

7 Conclusion

The aim of this thesis was to determine the current status of the Swakoppoort Dam and to identify possible sources of pollution and polluting substances.

A strategic sampling plan consisting samples from of two rivers, three wells, two boreholes and the dam itself was designed to investigate these questions.

Two pollution sources which have been identified are the ephemeral rivers Klein Windhoek and Otjiseru which transport effluent from different water treatment plants from the city of Windhoek to the north. Because this work was done in the dry season the effluent streams seeped away before it could reach the Swakopport Dam. During the rainy season the ephemeral rivers are flowing and the chance is high, that pollutants which may have accumulated in the streambed get washed out and transported to the Sawakoppoort Dam.

The pollutants found were high concentrations of heavy metals like Cadmium, Nickel and Chromium, Phenol, Formaldehyde and Ammonia as well as high loads of nutrients like Phosphate and DOC. Especially the effluents leaving the UWWTW to the Klein Windhoek river showed alarmingly high pollutant concentrations, often multiple times exceeding the Namibian Standard for Effluents: in case of Nickel nearly 80-fold. Nickel was also found in the Swakopport Dam in high concentrations. The UWWTW is treating mainly industrial effluents and investigations should be done to find the source in the defective cleaning process.

The Swakoppoort Dam itself was highly eutrophicated. On parts of the lake and along the shore algae scum was drifting. If the high nutrient load of the Klein Windhoek River is the reason for the eutrophication could not be clarified. The fact is that the Phosphor concentrations are much too high. Not only do the high algae concentrations hinder the treatment process of the water for potable uses, many blue-green algae emit dangerous neurotoxins. No analysis was done to determine if toxins are present, but high concentrations of Phenol and Formaldehyde were detected right next to the extraction tower, which is pumping the water to Karabib and the Van Bach Dam. If these pollutants are from the UWWTW in Windhoek this means a new industrial waste water cycle is present and would highly endanger the innovative and unique waste water reclamation process of Windhoek.

For further investigations the surface water sampling should be done during the rainy season when all ephemeral rivers are flowing. Additionally alluvium samples should be taken during the dry season to find out if the pollutants move through the alluvium also ending in the Swakoppoort Dam. There should also be a monitoring at the Swakop River which is coming from the Van Bach Dam. The creation of a detailed map of possible polluters, qualitatively, quantitatively and also seasonally and daily would help to find meaningful sampling locations. A sediment probe of the Swakopport Dam could help to identify the status of the lake and find accumulated pollutants. A pharmaceutical analysis would help to identify less known and heavy to treat pollutants like hormones before they could accumulate. This is especially important in system where water reclamation is practiced.

In a semi-closed system of waste water and potable water like in Windhoek there should be strict effluent standards and controls. The cooperation between all the parties concerned has to be maximized. Higher prices for water like they have been decided recently (Hofmann 2010) , after the Swakopport Dam was excluded from the water supply because of eutrophication will help to conserve water, but the only long-term solution is to find the source of the problem.

Windhoek will continue its path of responsible water use and will find a solution, like they always did, being the one and only city using reclaimed water as potable water since nearly 33 years.

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Appendix

Photos

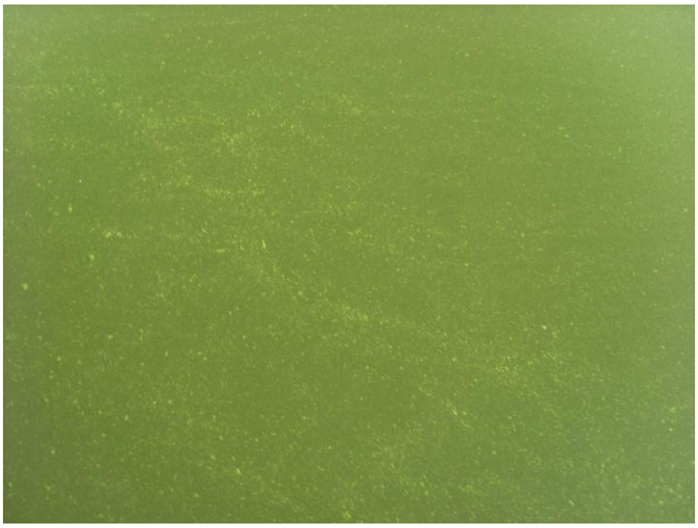

Photo 1: Large algae particles at the Swakopport Dam.

Photo 2: Otjiseru River close to Ongos farm at (8)

Photo 3: Algae scum floating at the Swakoppoort Dam.

Photo 4: Algae scum at the Swakoppoort Dam.

Tables

Table 4: Results of the laboratory analysis.

sample No.	Laboratory No.	Location	Date	pH	Conductivity	TDS calc
				-	mS/m 25°C	mg/l
Klein Windhoek						
M1	CO0144_S1	Ujams last pond (M1)	22.09.2010	8,00	270	
M2	CO0144_S2	Ujams river entry (M2)	22.09.2010	8,00	280	
M3	CO0144_S3	Road cross (M3)	01.07.2009	8,17	340	
7	RE0012_S07	Ujams North 0 (7)	19.08.2010	7,54	320	2144
11	RE0012_S11	Ujams North 1 (11)	21.08.2010	7,41	290	1943
12	RE0012_S12	Ujams North 2 (12)	22.08.2010	7,73	280	1876
M5	CO0132_S5	Dobra KWR (M5)	22.09.2010	7,98	475	
M6	CO0132_S8	MIX camp (M6)	22.09.2010	7,97	520	
1	RE0012_S01	Okapuka (1)	18.08.2010	8,9	690	4623
Otjiseru surface						
2	RE0012_S02	Goreangab close (2)	19.08.2010	7,02	92	616
3	RE0012_S03	Goreangab further (3)	19.08.2010	7,41	86	576
4	RE0012_S04	Goreangab road (4)	19.08.2010	7,37	91	610
5	RE0012_S05	Otjomuize (5)	19.08.2010	7,04	84	563
6	RE0012_S06	GorOtjom Mix (6)	19.08.2010	7,27	86	576
8	RE0012_S08	Ongos Bridge (8)	20.08.2010	7,78	97	650
Otjiseru wells						
10	RE0012_S10	Ongos Well (10)	20.08.2010	7,29	130	871
20	RE0012_S20	DüstbrFa 15m (20)	25.08.2010	7,45	215	1441
21	RE0012_S21	FrankhFa 6m (21)	25.08.2010	7,5	155	1039
Boreholes						
9	RE0012_S09	Ongos Borehole (9)	20.08.2010	7,42	100	670
22	RE0012_S22	Osana tank (22)	25.08.2010	7,59	145	972
Swakopporte Dam						
13	RE0012_S13	SWPD shallow (13)	23.08.2010	7,84	66	442
15	RE0012_S15	SWPD middle 1 m (15)	23.08.2010	7,91	66	442
16	RE0012_S16	SWPD middle 5 m (16)	23.08.2010	8,34	64	429
17	RE0012_S17	SWPD tower 1m (17)	23.08.2010	8,07	64	429
18	RE0012_S18	SWPD tower 5m (18)	23.08.2010	7,97	65	436
19	RE0012_S19	SWPD tower 10m (19)	23.08.2010	7,83	65	436

sample No.	Location	Turbidity NTU	Total alkalinity mg/l CaCO3	Total hardness mg/l CaCO3	Cl mg/l	Sulphate (SO4) mg/l
Klein Windhoek						
M1	Ujams last pond (M1)		799,36	190	325	65
M2	Ujams river entry (M2)		820,87	205	330	90
M3	Road cross (M3)		1002,32	465	415	335
7	Ujams North 0 (7)	97	979,47	205	315	73
11	Ujams North 1 (11)	85	921,8	215	315	100
12	Ujams North 2 (12)	105	856,3	210	320	100
M5	Dobra KWR (M5)		813,54	390	740	560
M6	MIX camp (M6)		947,95	405	810	600
1	Okapuka (1)	17,6	467,64	310	920	670
Otjiseru surface						
2	Goreangab close (2)	1,13	212,12	170	135	110
3	Goreangab further (3)	2	347,41	175	130	110
4	Goreangab road (4)	1,53	556,99	180	135	115
5	Otjomuize (5)	2,86	198,04	150	140	100
6	GorOtjom Mix (6)	10,3	202,35	150	140	100
8	Ongos Bridge (8)	34,3	213,69	155	140	100
Otjiseru wells						
10	Ongos Well (10)	2,26	356,01	225	190	82
20	DüstbrFa 15m (20)	0,91	263,34	480	425	165
21	FrankhFa 6m (21)	1,46	264,91	260	235	175
Boreholes						
9	Ongos Borehole (9)	13,2	868,23	280	34	10
22	Osana tank (22)	0,648	474,49	475	140	105
Swakopporte Dam						
13	SWPD shallow (13)	99,5	159,53	88	87	42
15	SWPD middle 1 m (15)	10,6	154,06	86	85	39
16	SWPD middle 5 m (16)	8,01	155,82	85	79	38
17	SWPD tower 1m (17)	7,88	154,45	81	86	41
18	SWPD tower 5m (18)	13,9	154,84	82	86	41
19	SWPD tower 10m (19)	7,81	155,62	82	85	41

sample No.	Location	F	Nitrate (NO3-N)	Nitrate standard	Nitrite (NO2-N)	Nitrite strandard
		mg/l	mg/l as N	mg/l as N	mg/l as N	mg/l as N
Klein Windhoek						
M1	Ujams last pond (M1)		0,5	20	0,51	3
M2	Ujams river entry (M2)		0,5	20	0,48	3
M3	Road cross (M3)		0,5	20	0,12	3
7	Ujams North 0 (7)	0,43	0,5	20	0,15	3
11	Ujams North 1 (11)	0,38	0,5	20	0,28	3
12	Ujams North 2 (12)	0,39	0,5	20	0,28	3
M5	Dobra KWR (M5)		1,2	20	0,5	3
M6	MIX camp (M6)		1,6	20	0,76	3
1	Okapuka (1)	1,2	0,5	20	0,15	3
Otjiseru surface						
2	Goreangab close (2)	0,44	7,4	20	0,05	3
3	Goreangab further (3)	0,41	7	20	0,05	3
4	Goreangab road (4)	0,38	7	20	0,17	3
5	Otjomuize (5)	0,38	0,5	20	0,05	3
6	GorOtjom Mix (6)	0,46	1,1	20	0,05	3
8	Ongos Bridge (8)	0,47	3,8	20	0,05	3
Otjiseru wells						
10	Ongos Well (10)	0,59	1,9	20	1,1	3
20	DüstbrFa 15m (20)	0,17	4,8	20	0,05	3
21	FrankhFa 6m (21)	0,3	0,5	20	0,05	3
Boreholes						
9	Ongos Borehole (9)	0,31	0,5	20	0,05	3
22	Osana tank (22)	0,55	3,3	20	0,05	3
Swakopporte Dam						
13	SWPD shallow (13)	0,28	0,5	20	0,05	3
15	SWPD middle 1 m (15)	0,35	0,5	20	0,05	3
16	SWPD middle 5 m (16)	0,23	0,5	20	0,05	3
17	SWPD tower 1m (17)	0,31	0,5	20	0,05	3
18	SWPD tower 5m (18)	0,27	0,5	20	0,05	3
19	SWPD tower 10m (19)	0,27	0,5	20	0,14	3

sample No.	Location	Sulphide mg/l S	Sulphide standard mg/l S	K mg/l	Na mg/l	Calcium hardness mg/l CaCO3
Klein Windhoek						
M1	Ujams last pond (M1)	1	0,5	33,04	429,5	140
M2	Ujams river entry (M2)	0,8	0,5	33,37	446,04	145
M3	Road cross (M3)	0,02	0,5	49,47	703,65	295
7	Ujams North 0 (7)	0,36	0,5	33,45	443,29	140
11	Ujams North 1 (11)	0,45	0,5	33,31	439,36	145
12	Ujams North 2 (12)	0,51	0,5	32,53	441,06	140
M5	Dobra KWR (M5)	0,1	0,5	46,96	874,17	175
M6	MIX camp (M6)	0,1	0,5	51,62	970,72	170
1	Okapuka (1)	0,1	0,5	60,97	1185,4	65
Otjiseru surface						
2	Goreangab close (2)	0,1	0,5	24,53	140,69	115
3	Goreangab further (3)	0,1	0,5	24,78	142,53	115
4	Goreangab road (4)	0,1	0,5	24,68	141,52	120
5	Otjomuize (5)	0,1	0,5	27,19	138,02	100
6	GorOtjom Mix (6)	0,1	0,5	27,21	138,03	100
8	Ongos Bridge (8)	0,1	0,5	31,54	142,25	100
Otjiseru wells						
10	Ongos Well (10)	0,1	0,5	27,05	192,22	135
20	DüstbrFa 15m (20)	0,1	0,5	23,44	230,79	320
21	FrankhFa 6m (21)	0,1	0,5	19,61	203,44	190
Boreholes						
9	Ongos Borehole (9)	0,1	0,5	9,02	134,04	150
22	Osana tank (22)	0,1	0,5	18,99	110,22	340
Swakopporte Dam						
13	SWPD shallow (13)	0,1	0,5	19,69	91,02	49
15	SWPD middle 1 m (15)	0,1	0,5	19,75	87,55	48
16	SWPD middle 5 m (16)	0,1	0,5	19,06	86,26	47
17	SWPD tower 1m (17)	0,1	0,5	19,26	86,22	45
18	SWPD tower 5m (18)	0,1	0,5	18,96	85,48	45
19	SWPD tower 10m (19)	0,1	0,5	18,95	85,39	45

sample No.	Location	Magnesium hardness mg/l CaCO3	Ammonia (NH3-N) mg/l as N	Ammonia standard mg/l as N	Ortho phosphate (P) mg/l	Fe mg/l
Klein Windhoek						
M1	Ujams last pond (M1)	51	54	10	19	2,3
M2	Ujams river entry (M2)	59	55	10	19	2,2
M3	Road cross (M3)	170	50	10	17	0,12
7	Ujams North 0 (7)	65	61	10	21	1,5
11	Ujams North 1 (11)	68	53	10	19	1,7
12	Ujams North 2 (12)	68	51	10	19	1,6
M5	Dobra KWR (M5)	215	14	10	5,2	0,52
M6	MIX camp (M6)	235	9,6	10	7,2	0,19
1	Okapuka (1)	245	1,3	10	2,6	0,11
Otjiseru surface						
2	Goreangab close (2)	57	0,15	10	1,8	0,04
3	Goreangab further (3)	59	0,15	10	1,8	0,04
4	Goreangab road (4)	59	0,15	10	1,7	0,04
5	Otjomuize (5)	52	0,15	10	0,39	0,31
6	GorOtjom Mix (6)	52	0,15	10	0,51	0,33
8	Ongos Bridge (8)	55	0,15	10	0,72	0,47
Otjiseru wells						
10	Ongos Well (10)	91	0,66	10	2,5	0,25
20	DüstbrFa 15m (20)	160	0,15	10	0,23	0,04
21	FrankhFa 6m (21)	72	0,15	10	0,23	0,04
Boreholes						
9	Ongos Borehole (9)	130	0,15	10	0,23	1,2
22	Osana tank (22)	135	0,15	10	0,23	0,04
Swakopporte Dam						
13	SWPD shallow (13)	39	0,34	10	0,23	0,31
15	SWPD middle 1 m (15)	38	0,59	10	0,23	0,04
16	SWPD middle 5 m (16)	38	0,21	10	0,23	0,08
17	SWPD tower 1m (17)	36	0,43	10	0,23	0,04
18	SWPD tower 5m (18)	37	0,77	10	0,23	0,04
19	SWPD tower 10m (19)	37	0,95	10	0,23	0,04

sample No.	Location	Al mg/l	Mn mg/l	TKN mg/l as N	DOC mg/l	UV 254 abs/cm
Klein Windhoek						
M1	Ujams last pond (M1)			105		
M2	Ujams river entry (M2)			95		
M3	Road cross (M3)			135		
7	Ujams North 0 (7)	0,26	4,6	145	81	2,181
11	Ujams North 1 (11)	0,34	4,6	140	57,3	2,087
12	Ujams North 2 (12)	0,42	5,3	135	56,1	2,13
M5	Dobra KWR (M5)			32		
M6	MIX camp (M6)			22		
1	Okapuka (1)		0,07	8,2	22,2	0,432
Otjiseru surface						
2	Goreangab close (2)		0,01	3,1	7,72	0,145
3	Goreangab further (3)		0,01	2,5	8,04	0,151
4	Goreangab road (4)		0,01	2,4	8,18	0,145
5	Otjomuize (5)		0,01	2,8	9,93	0,195
6	GorOtjom Mix (6)		0,01	3,8	9,77	0,194
8	Ongos Bridge (8)		0,01	6,7	11,1	0,232
Otjiseru wells						
10	Ongos Well (10)		1	1,5	7,64	0,215
20	DüstbrFa 15m (20)		0,1	0,5	2,28	0,041
21	FrankhFa 6m (21)		0,01	3,3	2,02	0,027
Boreholes						
9	Ongos Borehole (9)		0,14	1,1	0,54	0,003
22	Osana tank (22)		0,01	1,9	4,63	0,116
Swakopporte Dam						
13	SWPD shallow (13)		0,03	6,2	11,4	0,216
15	SWPD middle 1 m (15)		0,01	5,9	11,9	0,187
16	SWPD middle 5 m (16)		0,01	5	11,5	0,182
17	SWPD tower 1m (17)		0,01	5,1	11,4	0,185
18	SWPD tower 5m (18)		0,01	5,5	11,5	0,181
19	SWPD tower 10m (19)		0,01	5,5	11,8	0,176

sample No.	Location	Phenol mg/l	Formaldehyde mg/l	Cd mg/l	Ni mg/l	Pb mg/l
Klein Windhoek						
M1	Ujams last pond (M1)	7,8	0,34	0,75	23,2	0,1
M2	Ujams river entry (M2)	7,2	0,3	0,68	20,7	0,1
M3	Road cross (M3)	2,67	0,3	0,04	0,01	0,01
7	Ujams North 0 (7)	6,2	0,67	0,35	4,94	0,03
11	Ujams North 1 (11)	5,9	0,54	0,38	7,88	0,01
12	Ujams North 2 (12)	5,5	0,3	0,48	8,64	0,08
M5	Dobra KWR (M5)	1,09	0,22	0,07	2,65	0,39
M6	MIX camp (M6)	0,8	0,2	0,0125	1,31	0,001
1	Okapuka (1)	0,44	0,15	0,0125	0,58	0,001
Otjiseru surface						
2	Goreangab close (2)	0,1	0,05	0,0125	0,51	0,001
3	Goreangab further (3)	0,15	0,05	0,0125	0,7	0,001
4	Goreangab road (4)	0,17	0,05	0,032	0,54	0,001
5	Otjomuize (5)	0,17	0,05	0,0125	0,42	0,001
6	GorOtjom Mix (6)	0,18	0,05	0,0125	0,34	0,001
8	Ongos Bridge (8)	0,21	0,05	0,0125	0,31	0,001
Otjiseru wells						
10	Ongos Well (10)	0,38	0,05	0,0125	0,45	0,1
20	DüstbrFa 15m (20)	0,05	0,05	0,0125	0,24	0,07
21	FrankhFa 6m (21)	0,05	0,05	0,0125	0,28	0,001
Boreholes						
9	Ongos Borehole (9)	0,05	0,05	0,032	0,43	0,05
22	Osana tank (22)	0,05	0,05	0,0125	0,33	0,001
Swakopporte Dam						
13	SWPD shallow (13)	0,2	0,05	0,0125	0,65	0,001
15	SWPD middle 1 m (15)	0,1	0,05	0,0125	0,77	0,001
16	SWPD middle 5 m (16)	0,1	0,05	0,0125	0,78	0,001
17	SWPD tower 1m (17)	0,13	0,05	0,0125	0,65	0,001
18	SWPD tower 5m (18)	0,16	0,05	0,0125	0,55	0,001
19	SWPD tower 10m (19)	0,14	0,12	0,0125	0,36	0,001

sample No.	Location	O2hand %	Temphand °C	ph	Cond µS/cm	Sal	TDS
Klein Windhoek							
M1	Ujams last pond (M1)						
M2	Ujams river entry (M2)						
M3	Road cross (M3)						
7	Ujams North 0 (7)	4,3	18,8	7,87	2619	1,4	1,7
11	Ujams North 1 (11)	60	16,5	8,61	2598	1,34	1,7
12	Ujams North 2 (12)	106	18,4	8,4	2595	1,4	1,7
M5	Dobra KWR (M5)						
M6	MIX camp (M6)						
1	Okapuka (1)	163		9,84	5324	2,93	3,4
Otjiseru surface							
2	Goreangab close (2)	123		8,11	878	0,51	0,6
3	Goreangab further (3)	190	17,8	8,78	887	0,52	0,6
4	Goreangab road (4)	166	16,4	8,69	983	0,51	
5	Otjomuize (5)	93		7,89	938	0,49	0,6
6	GorOtjom Mix (6)	108	17,5	7,89	946	0,49	0,6
8	Ongos Bridge (8)	124	22,2	8,85	955	0,52	0,6
Otjiseru wells							
10	Ongos Well (10)			7,54	1271	0,67	0,8
20	DüstbrFa 15m (20)	46	24,5	7,92	2014	1,08	1,3
21	FrankhFa 6m (21)	48	23,7	7,15	1407	0,75	0,9
Boreholes							
9	Ongos Borehole (9)	27	26,1	7,15	1021	0,53	0,7
22	Osana tank (22)	78	29,5	7,56	1367	0,72	0,9
Swakopporte Dam							
13	SWPD shallow (13)						
15	SWPD middle 1 m (15)						
16	SWPD middle 5 m (16)			9,28	576	0,29	0,4
17	SWPD tower 1m (17)			8,7	579	0,3	0,4
18	SWPD tower 5m (18)			8,6	582	0,3	0,4
19	SWPD tower 10m (19)						

sample No.	Location	Chromium VI mg/l Cr	Oxygen mg/l	Oxygen %	Temp °C	O2hand mg/l
Klein Windhoek						
M1	Ujams last pond (M1)	1,19				
M2	Ujams river entry (M2)	1,09				
M3	Road cross (M3)	0,13				
7	Ujams North 0 (7)	0,066	0,2	2,4	18,01	0,3
11	Ujams North 1 (11)	0,7	4,5	53,4	16,1	5,1
12	Ujams North 2 (12)	0,81	6,4	78,5	18,4	8,4
M5	Dobra KWR (M5)	0,15				
M6	MIX camp (M6)	0,05				
1	Okapuka (1)	0,09	13,2	175	22,39	12
Otjiseru surface						
2	Goreangab close (2)	0,13	6,51	77,2	17,36	9,6
3	Goreangab further (3)	0,08	10,39	125,3	16,86	14,3
4	Goreangab road (4)	0,11	10,59	123,5	16,46	13,87
5	Otjomuize (5)	0,05	5,73	67	16,8	7,7
6	GorOtjom Mix (6)	0,09	6,18	74	17,48	8,81
8	Ongos Bridge (8)	0,03	7,06	95,3	22,23	9,1
Otjiseru wells						
10	Ongos Well (10)	0,03	2	0,61	17,17	
20	DüstbrFa 15m (20)	0,01	3,43	48	25,11	3,5
21	FrankhFa 6m (21)	0,03	2,7	36,9	24,51	3,5
Boreholes						
9	Ongos Borehole (9)	0,06	1,98	27,9	25,97	1,8
22	Osana tank (22)	0,01	5,16	77	28,81	5
Swakopporte Dam						
13	SWPD shallow (13)	0,07	11,4	150	22	
15	SWPD middle 1 m (15)	0,01				
16	SWPD middle 5 m (16)	0,02	8,97		16,68	
17	SWPD tower 1m (17)	0,02	4,5	104	17,1	
18	SWPD tower 5m (18)	0,01	3,67	54,4	16,27	
19	SWPD tower 10m (19)	0,02		42,8		

Table 5: Coordinates of all sample points.

Sampling Group	Sample ID	WGS 1984 UTM Zone 33S	
		Easting	Northing
Klein Windhoek	M1	714142,37	7512318,25
	M2	714450,48	7513215,91
	M3	714358,61	7513562,18
	M5	713534,76	7519738,01
	M6	713290,96	7522934,92
	7	714215,04	7513829,73
	11	714221,33	7514418,49
	12	714064,24	7514959,42
Otjiserva Surface	2	706014,62	7507185,13
	3	705808,89	7507423,95
	4	705693,13	7507493,55
	5	705708,95	7507525,38
	6	705553,84	7507539,46
	8	704334,28	7515395,87
Otjiserva Wells	10	704467,41	7516766,84
	20	695729,41	7536079,52
	21	690820,65	7547519,87
Boreholes	9	707151,83	7516728,80
	22	689993,91	7553370,66
Swakoppoort Dam	13	663124,91	7543962,40
	14	662954,11	7544080,36
	15+16	659824,05	7542924,21
	17+18+19	657381,29	7542890,75

Location	Date	CATIONS									ANIONS									Sum ions	Ion balance error
		Na mg/l	K mg/l	Mg mg/l	Ca mg/l	Na meq/l	K meq/l	Mg meq/l	Ca meq/l	Sum cations meq/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l as N	Total alkalinity mg/l CaCO3	Cl meq/l	SO_4 meq/l	NO_3 meq/l	HCO_3 meq/l	Sum anions meq/l	meq/l	%
Ujams last pond (M1)	22.09.2010	429,5	33,0	12,4	56	18,7	0,8	1,0	2,8	*23,3*	325	65	0,5	799,4	9,2	1,4	0,04	16,0	*26,5*	*49,87*	*-6,4*
Ujams river entry (M2)	22.09.2010	446,0	33,4	14,3	58	19,4	0,9	1,2	2,9	*24,3*	330	90	0,5	820,9	9,3	1,9	0,04	16,4	*27,6*	*51,95*	*-6,3*
Road cross (M3)	01.07.2009	703,7	49,5	41,3	118	30,6	1,3	3,4	5,9	*41,2*	415	335	0,5	1002,3	11,7	7,0	0,04	20,0	*38,8*	*79,91*	*3,0*
Ujams North 0 (7)	19.08.2010	443,3	33,5	15,8	56	19,3	0,9	1,3	2,8	*24,2*	315	73	0,5	979,5	8,9	1,5	0,04	19,6	*30,0*	*54,25*	***-10,7***
Ujams North 1 (11)	21.08.2010	439,4	33,3	16,5	58	19,1	0,9	1,4	2,9	*24,2*	315	100	0,5	921,8	8,9	2,1	0,04	18,4	*29,4*	*53,64*	*-9,7*
Ujams North 2 (12)	22.08.2010	441,1	32,5	16,5	56	19,2	0,8	1,4	2,8	*24,2*	320	100	0,5	856,3	9,0	2,1	0,04	17,1	*28,3*	*52,43*	*-7,8*
Dobra KWR (M5)	22.09.2010	874,2	47,0	52,2	70	38,0	1,2	4,3	3,5	*47,0*	740	560	1,2	813,5	20,8	11,7	0,09	16,3	*48,9*	*95,87*	*-1,9*
MIX camp (M6)	22.09.2010	970,7	51,6	57,0	68	42,2	1,3	4,7	3,4	*51,6*	810	600	1,6	948,0	22,8	12,5	0,11	19,0	*54,4*	*106,01*	*-2,6*
Okapuka (1)	18.08.2010	1185,4	61,0	59,5	26	51,5	1,6	4,9	1,3	*59,3*	920	670	0,5	467,6	25,9	14,0	0,04	9,4	*49,3*	*108,56*	*9,2*
Goreangab close (2)	19.08.2010	140,7	24,5	13,8	46	6,1	0,6	1,1	2,3	*10,2*	135	110	7,4	212,1	3,8	2,3	0,53	4,2	*10,9*	*21,05*	*-3,2*
Goreangab further (3)	19.08.2010	142,5	24,8	14,3	46	6,2	0,6	1,2	2,3	*10,3*	130	110	7,0	347,4	3,7	2,3	0,50	6,9	*13,4*	*23,71*	***-13,0***
Goreangab road (4)	19.08.2010	141,5	24,7	14,3	48	6,2	0,6	1,2	2,4	*10,4*	135	115	7,0	557,0	3,8	2,4	0,50	11,1	*17,8*	*28,20*	***-26,5***
Otjomuize (5)	19.08.2010	138,0	27,2	12,6	40	6,0	0,7	1,0	2,0	*9,7*	140	100	0,5	198,0	3,9	2,1	0,04	4,0	*10,0*	*19,76*	*-1,5*
GorOtjom Mix (6)	19.08.2010	138,0	27,2	12,6	40	6,0	0,7	1,0	2,0	*9,7*	140	100	1,1	202,4	3,9	2,1	0,08	4,0	*10,2*	*19,89*	*-2,1*
Ongos Bridge (8)	20.08.2010	142,3	31,5	13,3	40	6,2	0,8	1,1	2,0	*10,1*	140	100	3,8	213,7	3,9	2,1	0,27	4,3	*10,6*	*20,66*	*-2,3*
Ongos Well (10)	20.08.2010	192,2	27,1	22,1	54	8,4	0,7	1,8	2,7	*13,6*	190	82	1,9	356,0	5,4	1,7	0,14	7,1	*14,3*	*27,88*	*-2,7*
DüstbrFa 15m (20)	25.08.2010	230,8	23,4	38,8	128	10,0	0,6	3,2	6,4	*20,2*	425	165	4,8	263,3	12,0	3,4	0,34	5,3	*21,0*	*41,25*	*-1,9*
FrankhFa 6m (21)	25.08.2010	203,4	19,6	17,5	76	8,8	0,5	1,4	3,8	*14,6*	235	175	0,5	264,9	6,6	3,6	0,04	5,3	*15,6*	*30,18*	*-3,4*
Ongos Borehole (9)	20.08.2010	134,0	9,0	31,6	60	5,8	0,2	2,6	3,0	*11,7*	34	10	0,5	868,2	1,0	0,2	0,04	17,4	*18,6*	*30,22*	***-22,9***
Osana tank (22)	25.08.2010	110,2	19,0	32,8	136	4,8	0,5	2,7	6,8	*14,8*	140	105	3,3	474,5	3,9	2,2	0,24	9,5	*15,9*	*30,63*	*-3,5*
SWPD shallow (13)	23.08.2010	91,0	19,7	9,5	20	4,0	0,5	0,8	1,0	*6,2*	87	42	0,5	159,5	2,5	0,9	0,04	3,2	*6,6*	*12,77*	*-2,6*
SWPD middle 1 m (15)	23.08.2010	87,6	19,8	9,2	19	3,8	0,5	0,8	1,0	*6,0*	85	39	0,5	154,1	2,4	0,8	0,04	3,1	*6,3*	*12,35*	*-2,4*
SWPD middle 5 m (16)	23.08.2010	86,3	19,1	9,2	19	3,8	0,5	0,8	0,9	*5,9*	79	38	0,5	155,8	2,2	0,8	0,04	3,1	*6,2*	*12,11*	*-1,9*
SWPD tower 1m (17)	23.08.2010	86,2	19,3	8,7	18	3,7	0,5	0,7	0,9	*5,9*	86	41	0,5	154,5	2,4	0,9	0,04	3,1	*6,4*	*12,26*	*-4,4*
SWPD tower 5m (18)	23.08.2010	85,5	19,0	9,0	18	3,7	0,5	0,7	0,9	*5,8*	86	41	0,5	154,8	2,4	0,9	0,04	3,1	*6,4*	*12,25*	*-4,6*
SWPD tower 10m (19)	23.08.2010	85,4	19,0	9,0	18	3,7	0,5	0,7	0,9	*5,8*	85	41	0,5	155,6	2,4	0,9	0,04	3,1	*6,4*	*12,23*	*-4,6*

Table 6: Major ions