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Major-ion chemistry and ground-water salinization in ephemeral floodplains in some arid regions of Namibia

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Abstract

Ground-water quality in drinking water sources within ephemeral flood plains in the Namib Desert and north central Namibia displays seasonal and spatial variations. The monthly variation in total dissolved solids (TDS) in individual sources ranges between 5% and 65% in north central Namibia and between 0.5% and 85% in the Namib Desert. A higher monthly TDS variation, close to 500%, is recorded in slightly deeper as well as over-pumped freshwater sources in both study sites. The lowest TDS values are recorded after the rains for north central Namibia sources and only after flood events for sources in the lower rainfall Namib Desert. Ground-water salinization in both sites is generally characterized by a shift from 'fresh' to 'very saline' ground-water, and a chemical evolution from Na and Ca–HCO_3 waters towards Na–Cl ones. The dominant processes that determine these hydrochemical shifts are refreshing by recharge waters, concentration by evaporation, dissolution of saline sediments (mainly evaporites), and mixing with older and more saline ground-water.

Keywords: Namibia; Arid regions; Ephemeral floodplain; Hydrochemistry; Salinization

1. Introduction

Fresh ground-water in most of Namibia is minimal and is found mainly in sedimentary terrain along ephemeral river flood plains (DWA, 1990). Many rural

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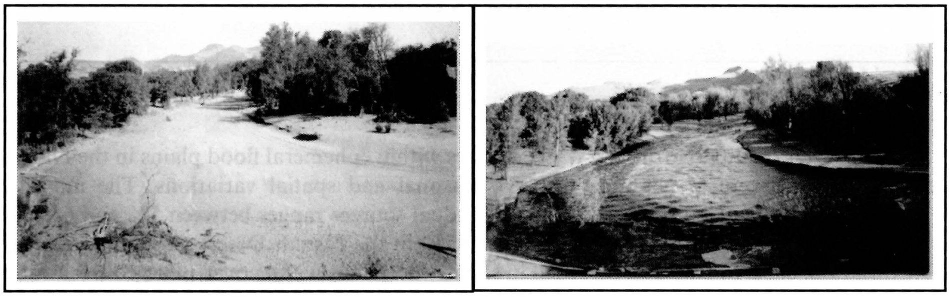
and urban centers rely on these ephemeral river-based ground-water sources for their water supply (Jacobson et al., 1995). However, these water sources display seasonal salinization and, as a result, people in these areas are subject to a seasonal shortage of potable water (Shanyengana, 1997).

A few publications e.g., Day (1993) and Grobelaar and Seely (1980) present the major-ion chemistry of some water systems in the Namib Desert. Others such as GCS (1992) and Hugo (1970) discuss general ground-water investigations and brine explorations in north central Namibia, respectively. However, ground-water salinization in both areas, particularly its seasonal trends and processes of salinization, are poorly understood.

This study investigates the hydrochemistry in drinking water sources of parts of north central Namibia and the Namib Desert where ground-water is accessed mainly through hand-dug wells and boreholes that are sunk along ephemeral river basins. The paper discusses the processes and mechanisms of ground-water salinization as well as chemical evolution of ground-water in these sources.



Fixed-point photographs of the Kuiseb River, in the Namib Desert, showing the dry river bed as it can be found during most of the year and seasonal flooding which only lasts for a few days to weeks during the rainy season.

2. Material and methods

2.1. Study area

2.1.1. Water resources in Namibia

Ninety seven per cent of Namibia is arid to semi-arid (Hutchinson, 1995). Rainfall is low and highly variable and, as a consequence, no perennial rivers originate from within the country's borders (Fig. 1).

Most urban and rural centers rely on ephemeral rivers for water supply. Water for urban areas is mainly supplied from surface dams while rural areas and a few urban centers such as in the Namib Desert are dependent on boreholes that are sunk within the river basins. Fig. 2 is a simplified cross-section of typical alluvial aquifers that are found in these ephemeral rivers.

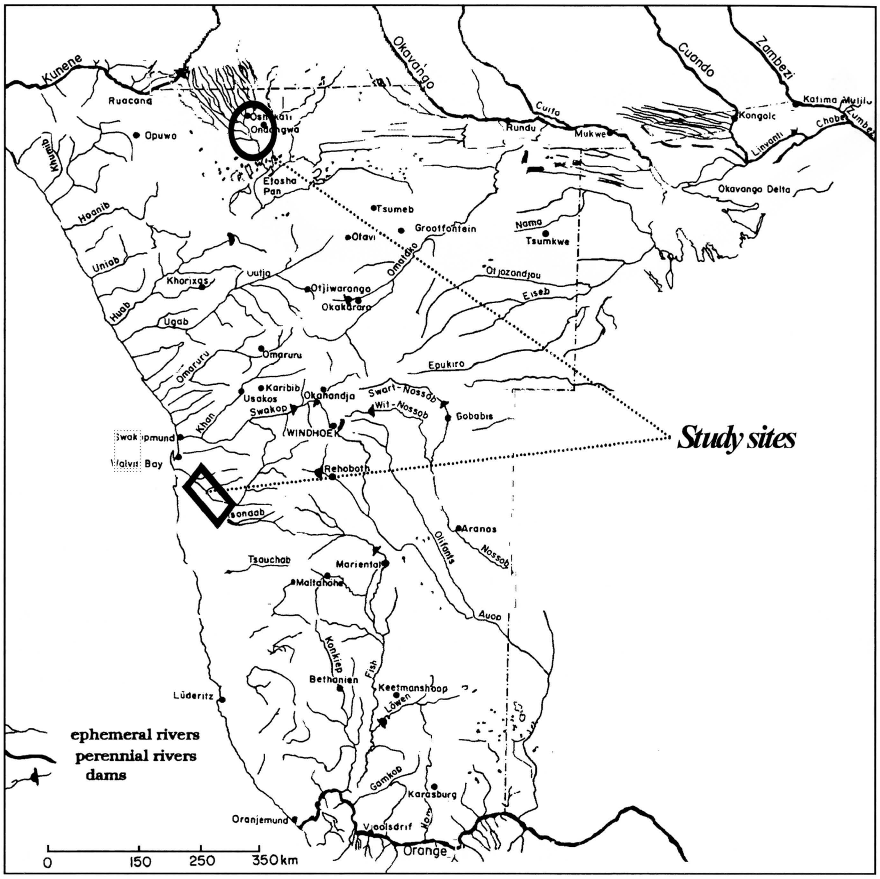


Fig. 1. Perennial (bold-lines) and ephemeral rivers in Namibia (source: Ward, 1994).

2.1.2. North central Namibia

North central Namibia is semi-arid. Rainfall averages about 400 mm per year at the study site, however, it is irregular and exhibits high temporal variability (DWA, 1990). A 79-year record at the nearest long-term weather station at Ondangua indicates an absolute maximum and minimum of 982 and 184 mm per year, respectively. The area has an average potential evaporation of 2600 mm per year and its annual water balance shows a water deficit in eleven out of twelve months (DWA, 1990; Hutchinson, 1995).

This site comprises of ephemeral rivers and pans that are locally known as *oshana* and *eendobe*, respectively. Oshanas are a series of ephemeral inland drainage channels whilst pans are shallow depressions that are found within the oshana flood plain. The flood plain is linked to an inland salt lake, Etosha, at its terminus.

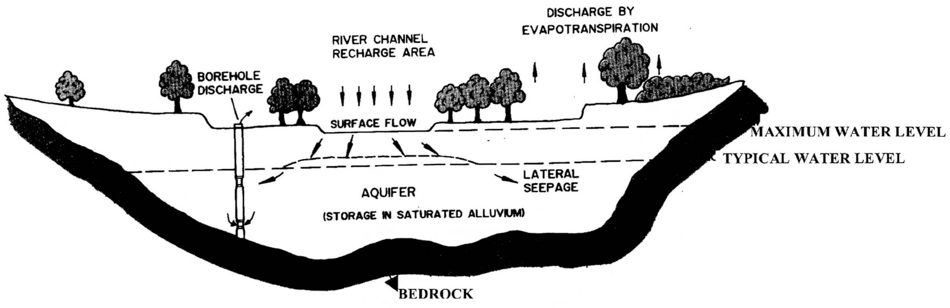


Fig. 2. A generalized sketch of alluvial aquifers found in ephemeral rivers of Namibia (source: Jacobson et al., 1995).

Ground-water in the area occurs in shallow phreatic aquifers and deeper, in confined systems that yield artesian water. Shallow ground-water in this area is generally saline owing to dissolution of evaporites (evaporitic precipitates) and saline lacustrine sediments that are found on the oshana and pan floors (GCS, 1992). The artesian sources represent long-resident waters from karst areas in the Southeast, which are even more saline (DWA, 1990). Water samples were collected from the artesian sources at Oshivelo and from hand-dug wells in the neighboring villages.

2.2. Central Namib Desert

The central Namib is an arid region. Rainfall is low and highly variable and averages about 27 mm at Gobabeb (Lancaster et al., 1984). The area has an average potential evaporation of about 3000 mm per year and its annual water balance shows a water deficit throughout the year (Lancaster et al., 1984).

Ground-water is generally saline and, as a result, freshwater availability restricts development activities in the area. Water samples were obtained from boreholes along the Kuiseb River, at rural settlements and at the Gobabeb Training & Research Center (GTRC).

2.2.1. Sample collection and analysis

Some 80 water samples with ion balances of less than 5% were obtained from shallow boreholes and wells (water level = less than 23 m) in north central Namibia and the central Namib Desert on a monthly basis, from September 1998–2000. All samples were analysed for major ions, total dissolved solids (TDS) and electrical conductivity (EC). Major ions were determined by Atomic Absorption—direct flame and with a Skalar San Plus automatic analyser. TDS was determined by evaporating the sample and drying it at 180°C while EC was measured with a Crison Micro CN 2200 electrode.

3. Results

3.1. TDS and major ions

Ground-water in water sources (depth = 10–23 m) of the Namib Desert and north central Namibia displays seasonal variation in TDS (Fig. 3). The variation is characterized by low TDS ground-water at the beginning of the rainy season and a higher and increasing TDS most of the year until the next rainy season. TDS values in water sources of north central Namibia range from 148 to 10,300 mg/l and 239 to 10,888 mg/l in the Namib Desert. Monthly TDS variation in individual sources is between 5% and 65% in north central Namibia and 0.5% and 85% in the Namib Desert sources.

Both study sites also have water sources that display much higher TDS and TDS variation, particularly during the later part of the dry season (Fig. 4).

This situation is typically observed in slightly deeper water sources (water level = 19–23 m) in north central Namibia, and in over-pumped ones in the Namib Desert. Maximum TDS and monthly TDS variation in these sources is about 11,000 mg/l and 500%, respectively.

3.2. Chemical evolution

Piper plots of water from the study sites are presented below, Fig. 5(a)–(c). Fig. 5(a) presents data from fresh and saline water sources in north central Namibia and (b) from the Namib Desert. Fig. (5c) displays the distribution of fresh and saline water end-members (the observed hydrochemical extremes) in both study areas. Rainfall analytical data from the Namib Desert was not available at the time of publishing.

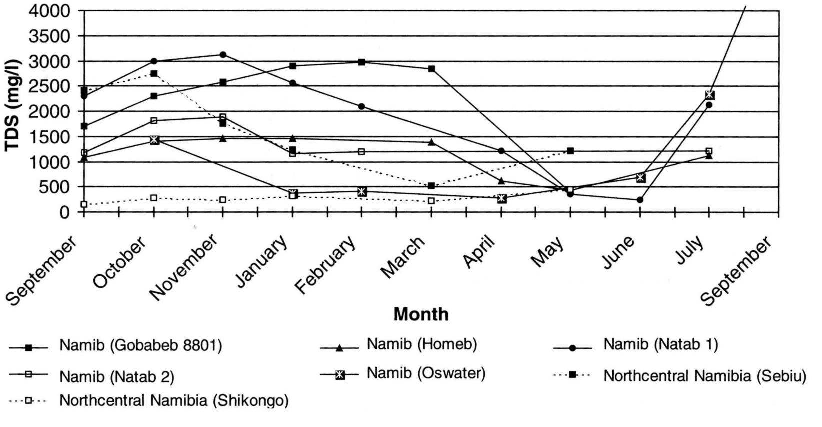


Fig. 3. Total dissolved solids (TDS) in ground-water sources of the Namib Desert and north central Namibia.

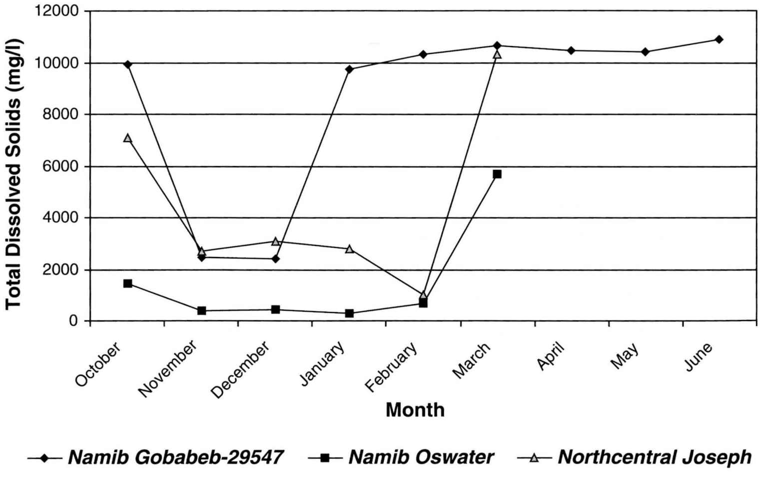


Fig. 4. Total dissolved solids (TDS) in over-pumped and slightly deeper ground-water sources of the Namib Desert and north central Namibia.

4. Discussion

4.1. Salinization

Water salinization refers to an increase in TDS and overall chemical content of water (Richter and Kreitler, 1993). Ground-water salinity in this paper is presented according to the classification of Robinove et al. (1958) (Table 1).

The ground-water quality in most shallow water sources changes from fresh to slightly saline and finally to moderately saline in response to recharge by rainfall and floods, and salinization during the latter part of the year.

Water in the deeper and over-pumped sources varies between moderately saline to very saline (Fig. 4). The deeper wells are possibly drilled past the freshwater section into the saline water ones, permitting upward migration of saline ground-water while the high ground-water TDS in over-pumped sources can be attributed to pumping-induced intrusion by deeper, more saline waters. Both these cases are reported in other arid areas, and indeed, they agree with earlier findings that arid regions often have saline ground-water underlying the fresh water resources (e.g., Kelly, 1974; Newport, 1977; Richter and Kreitler, 1993).

4.2. Process of salinization

Changes in ground-water salinity and overall chemical composition occur along flow paths from recharge to discharge areas due to either natural and/or anthropogenic causes (Richter and Kreitler, 1993). Raindrops interact with

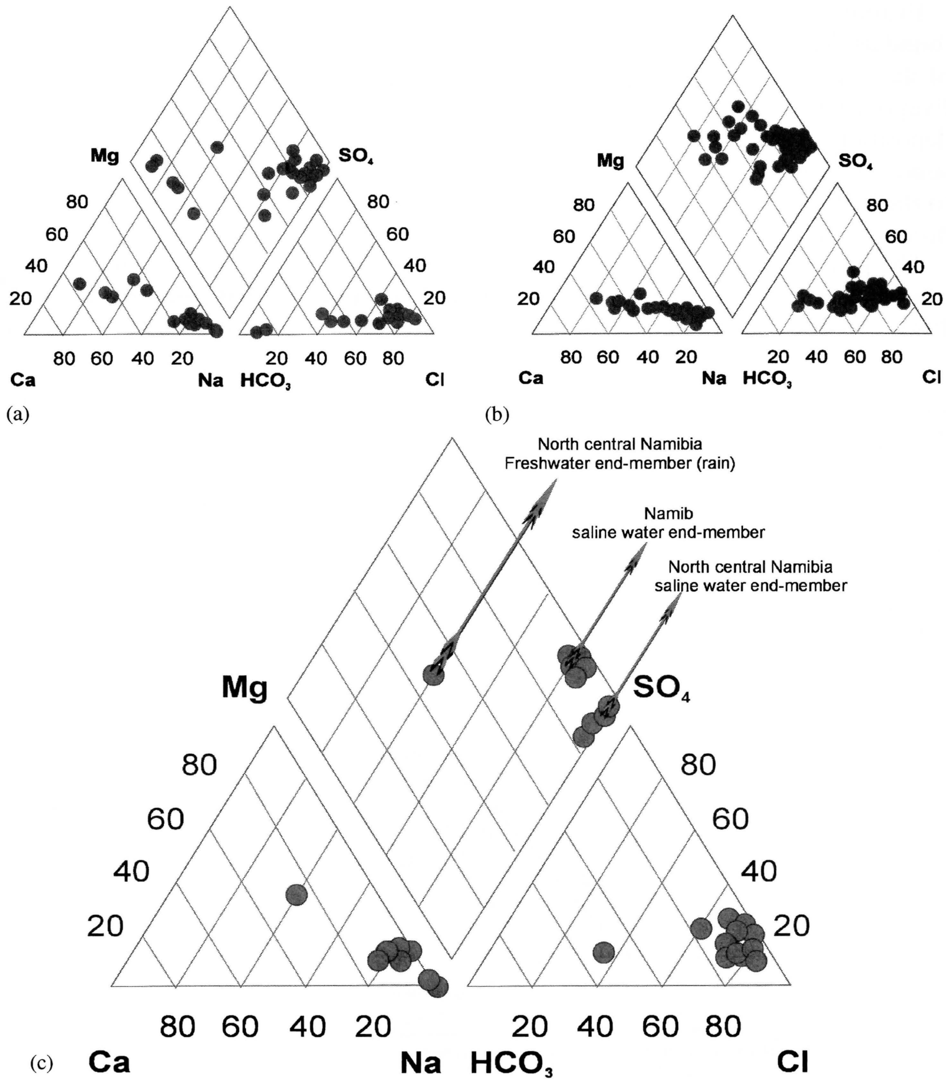


Fig. 5. (a) A Piper plot of water from north central Namibia. (b) Namib Desert. (c) Freshwater and saline water end-members of each site.

atmospheric gases and particles whilst surface runoff interacts with mineral matter on its way to surface-water bodies, where it mixes with water of different chemical composition (Richter and Kreitler, 1993). Water that enters the soil is subject to chemical, physical and biological changes due to processes such as evapotranspiration, mineral solution, precipitation, solution of gases and mixing with resident waters.

Evaporation of surface water and moisture in the unsaturated zone has been found as the most influential process in the development of the chemical composition of shallow ground-water (e.g., Boyd and Kreitler, 1986; Richter and Kreitler, 1993). Evaporation concentrates the remaining water and leads to precipitation and deposition of evaporites that are eventually leached into the saturated zone. This source of ground-water salinity is amplified in arid lands, such as the study sites, due to the high evaporation rate and low rainfall which encourage the above-mentioned processes and also lower flushing of saline water.

The processes and mechanisms that determine the composition of a water body can be identified from plots of ionic ratios such as Gibbs plot (Richter and Kreitler, 1993). A Gibbs plot of data from both study sites (Fig. 6) indicates that evaporation

Table 1
Water quality classification based on Robinove et al. (1958)

Class	TDS range (mg/l)
Fresh	0–1000
Slightly saline	1000–3000
Moderately saline	3000–10,000
Very saline	10,000–35,000
Briny	> 35,000

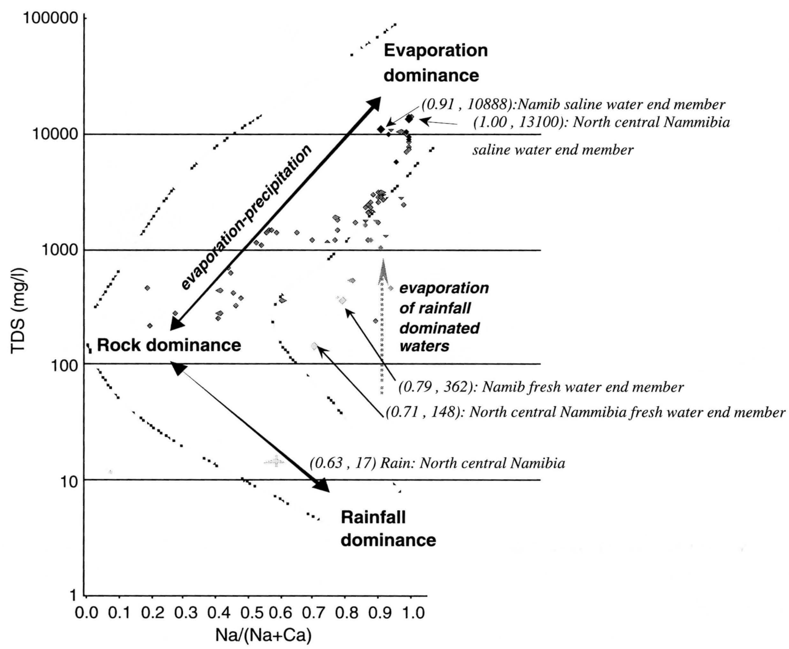


Fig. 6. A Gibbs plot indicating the mechanisms that determine the major ion composition of ground-water in ephemeral river sources in north central Namibia and the Namib Desert.

and precipitation are the dominant processes controlling the major-ion composition of ground-water in both sites. This is supported by earlier work for instance, Grobelaar and Seely (1980) and Day (1993) in the Namib Desert, and Shaw (1988) and GCS (1992) in north central Namibia.

The major-ion chemistry of fresh to slightly saline water sources in both study sites is controlled by evaporation of rainfall dominated waters while the Namib Desert's moderately saline to very saline ground-water shows evaporation and mineral precipitation as the dominant factors controlling composition. Waters from the artesian sources only plot in the evaporation dominance area and do not indicate any seasonal fluctuations. Indeed, this water is too deep to show any response to the local hydro-climatic conditions including local recharge.

The processes of ground-water salinization are often identified from ionic vs TDS plots such as Na/Cl vs TDS or Cl (e.g. Mercado, 1985; Jacks and Rajagopalan, 1996). Chloride is chemically conservative, that is, once in solution it is not easily removed by most processes other than precipitation at very late stages of salinization and, as a result, it is often used to monitor water quality changes and their sources (Hem, 1985; Richter and Kreitler, 1993).

Fresh to slightly saline ground-water sources in both study sites are refreshed by recharge water towards the freshwater end-members during the rainy season either by direct rainfall or flooding. Thereafter, they are subject to mixing and at times intrusion by underlying saline water and, salinize towards the saline water end-members of each site (Fig. 7(b)).

The refreshing phase in freshwater sources of north central Namibia starts at the beginning of the rainy season (September/October) and lasts until May. In the Namib Desert this phase only begins after flood events which normally occur between December and March.

The moderately saline to very saline Sources show a short-lived refreshing phase that is followed by a mixing phase towards the saline water end-members. Most of these water sources, particularly the deeper sources, are very saline during most of the year except during parts of the rainy season and during flood events when less saline recharge waters refresh them. However, even the recharge water is soon encroached by the surrounding saline water. This process is gradual, as well as season-dependent in well-utilized and non-pumped sources, and more rapid in cases where the water sources are pumped extensively (pumping-induced salinization).

4.3. Major ions and chemical evolution

Recharge ground-water in both study sites displays a lower major-ion concentration than that found in longer resident waters. Major-ion concentrations increase gradually from the end of the rainy season towards the next, except in cases of intrusion where the increase is exponential. This change is characterized by an increase, in order of increasing magnitude of concentrations of cations–anions, in Na, Mg, K–Cl, HCO_3 and SO_4 and Na, Ca, Mg, K–Cl, SO_4 and HCO_3 in freshwater sources of north central Namibia and the Namib Desert, respectively.

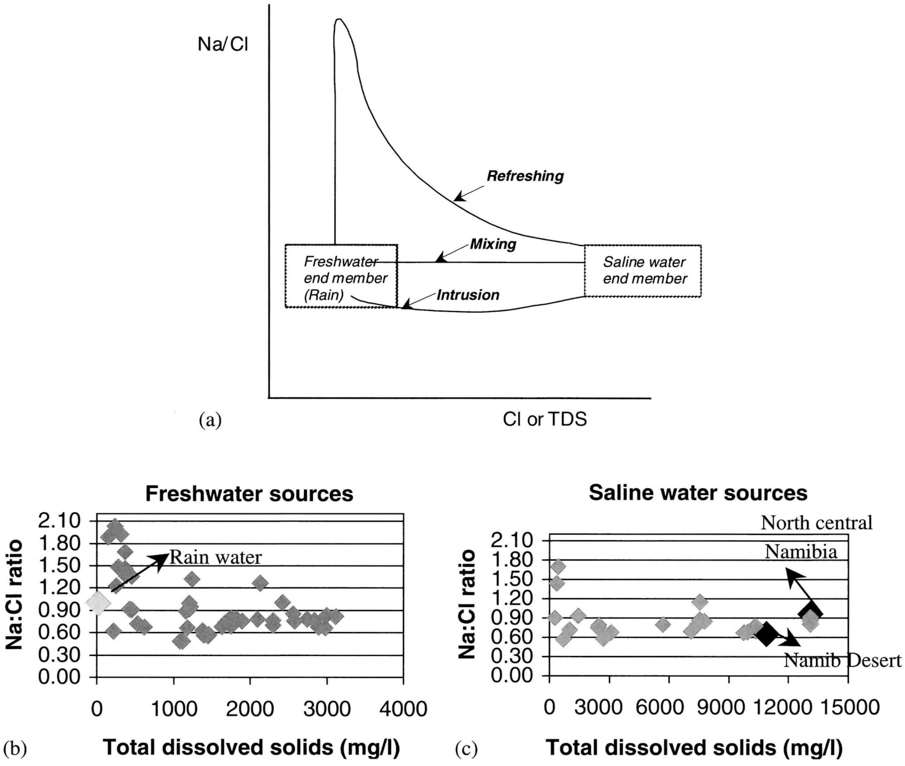


Fig. 7. (a) Mechanisms of salinization that can be determined from Na/Cl ratio vs Cl or TDS plots (after, Jacks and Rajagopalan, 1996). (b) North central Namibia water sources. (c) Namib Desert water sources.

Modified Piper diagrams (rotated axes) can be used to identify relations between ground-water sources as well as their chemical evolution and the processes responsible for the observed water quality changes (e.g., Richter and Kreitler, 1993). Below (Fig. 8), an altered Piper diagram of water sources in the study areas shows that fresh ground-water evolves towards the chemistry of the saline water end-members found in each area.

Chemical evolution in freshwater sources of north central Namibia is generally from Na–HCO_3–Cl to Na–Cl waters, while in the Namib Desert it is from Na–Ca–Cl–HCO_3 and Na–Cl–SO_4 to a Na–Ca–Cl one. This evolution is gradual in more shallow and well-utilized water sources, and rapid in water sources that are earlier reported as slightly deeper or ones that record extensive pumping.

Dissolution of gases and minerals, particularly CO_2 and CO_3-related compounds in the atmosphere and in the unsaturated zone during precipitation and infiltration, would impart the observed HCO_3 water type. The dissolution of evaporites and saline lacustrine sediments such as halite (NaCl) and soda ash (Na_2CO_3) that are found on pan floors in north central Namibia (e.g. Hugo, 1970; GCS, 1992) account for the dominant cation being Na in these sources. Dissolution of gypsum and halite

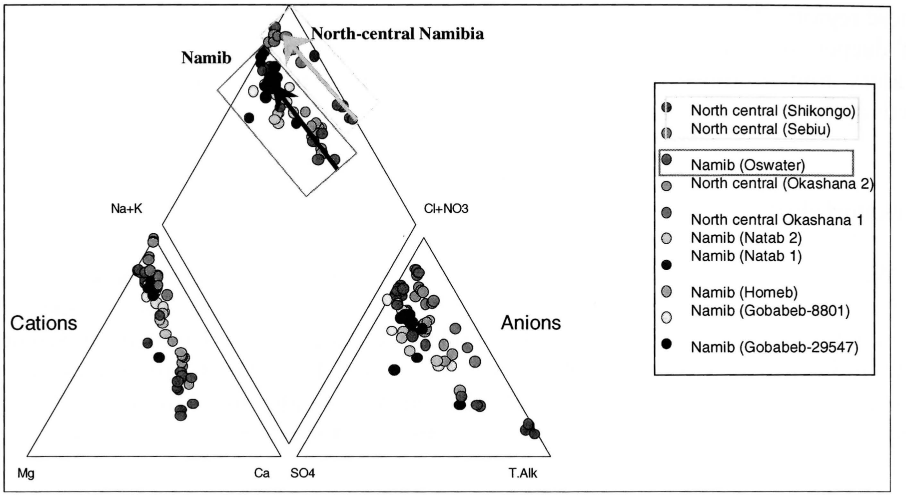


Fig. 8. A modified Piper plot indicating chemical evolution of fresh ground-water, in some of the water sources, towards the saline water end-members found in each study site.

in the Namib Desert sources would account for Ca and Na being the dominant cations in this area (e.g. Eckhardt and Spiro, 1999). The loss of Ca- and HCO_3-related minerals through precipitation of minerals such as $CaCO_3$, and the conservative nature of Chloride favors formation of the Na–Cl water type that is observed in long resident waters of both study sites.

5. Conclusions

Shallow ground-water in Ephemeral River sources in some arid parts of Namibia display high seasonal TDS and major-ion variation. The variation is a function of direct recharge by rainfall in relatively high rainfall areas such as semi arid regions, and mainly surface runoff in the lower rainfall arid and hyper-arid areas. It appears that in low rainfall areas such as the Namib Desert, the local rainfall does not effect any significant recharge and thus, no appreciable change in ground-water quality is recorded until after a flood event.

The ground-water quality regime is characterized by refreshing during the rainy season and salinization during the remainder of the year. The water displays a chemical evolution from low TDS, $CaHCO_3$ recharge waters towards the chemistry of underlying saline water end-members which are typically of a Na–Cl or X–Cl water type (X being the dominant cation (s) in the local soil media).

Evaporation of recharge waters and dissolution of evaporites appear to be the dominant processes that determine the major ion composition in ephemeral river sources of arid lands. Consequently the local hydro-climatic conditions, namely rainfall and evaporation rate, are the primary determinants of ground-water quality and can thus be used to estimate ground-water salinity in shallow water sources of these regions. However, these estimates would be lower than the actual values in case of deeper and over-pumped water sources due to intrusion by older, more saline waters, and in areas that have experienced other significant geochemistry-altering activity such as volcanism.

Acknowledgements

We are grateful to Namwater, particularly to Mrs. Merylinda Conradie for the water chemistry analysis. The following water chemists are also thanked for reviewing the manuscript namely, Dr. Gideon Tredoux of the Council for Scientific and Industrial Research (CSIR), South Africa and Prof. Dr. Gunnar Jacks of the Royal Institute of Technology (KTH) Sweden. We are also thankful to Ms. Annabel Smith of the Royal Holloway University (Britain) for editing the manuscript.

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Major-ion chemistry and groundwater salinization in ephemeral floodplains in some arid regions of Namibia

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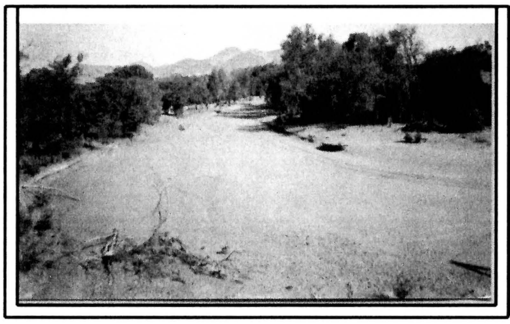
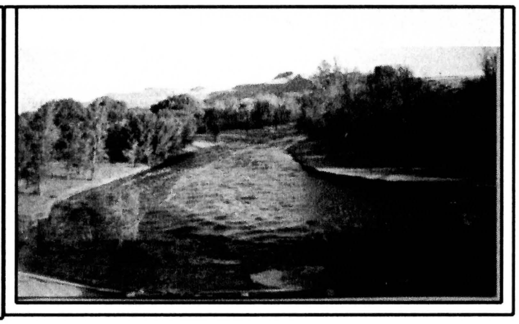

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Keywords: Namibia; arid regions; ephemeral floodplain; hydrochemistry; salinization

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Introduction

Fresh groundwater in most of Namibia is minimal and is found mainly along ephemeral river flood plains (DWA, 1995). Many rural and urban centers rely on these ephemeral river-based groundwater sources for their water supply (Jacobson et al., 1995). However, these water sources are subject to seasonal salinization and, as a result, are often too saline for general domestic purposes (Shanyengana, 1997).

A few publications report on the hydrochemistry in both study areas. GCS (1991 & 1992) discusses general groundwater investigations in north central Namibia while others such as Hugo (1968 & 1970) report on brine explorations in this area. Day (1993) and Grobelaar & Seely (1980) present the major-ion chemistry of some water systems in the Namib Desert. However, groundwater salinization in both areas, particularly its seasonal trends and processes of salinization, are poorly understood.

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Material and Methods

Study area

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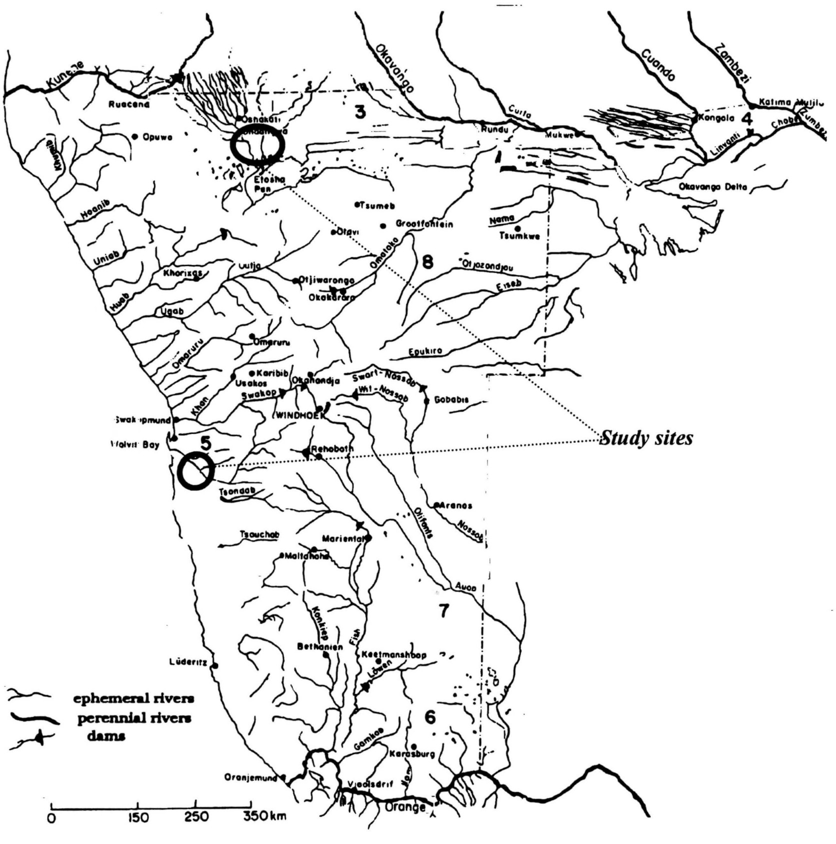

Figure 1 Perennial (bold-lines) and ephemeral rivers in Namibia (source: Ward, 1994).

Most urban and rural centres rely on ephemeral rivers for water supply. The water is accessed either through surface dams or boreholes that are sunk within the river basins. Fig. 2 is a simplified cross section of typical alluvial aquifers that are found in these ephemeral rivers.

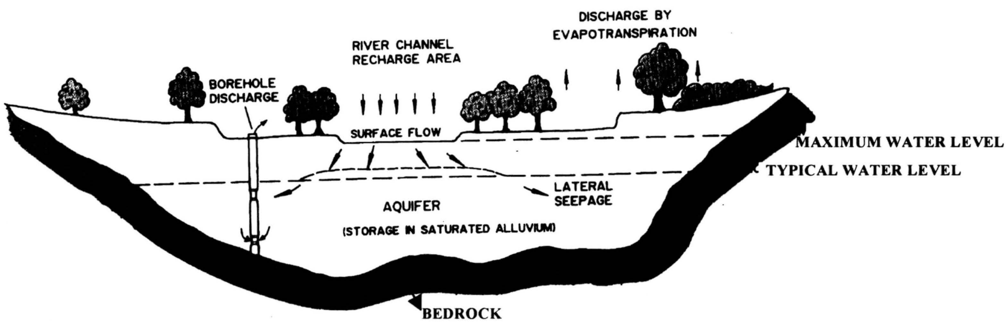

Figure 2 A generalized sketch of alluvial aquifers found in ephemeral rivers of Namibia (Source: Jacobson et al., 1995).

North central Namibia

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This site comprises of ephemeral rivers and pans that are locally known as <u>oshana</u> and <u>eendobe</u>, respectively. Oshanas are a series of ephemeral inland drainage channels whilst pans are shallow depressions that are found within the oshana flood plain. The flood plain is linked to an inland salt lake, Etosha, at its terminus.

Groundwater in the area is generally saline owing to dissolution of evaporites (evaporitic precipitates) and saline lacustrine sediments that are found on the oshana and pan floors (GCS, 1992). The artesian sources are linked to saline artesian groundwater sources (DWA, 1995). Water samples were collected from the artesian sources at Oshivelo and from hand-dug wells in the neighboring villages.

Central Namib desert

The central Namib is an arid region. Rainfall is low and highly variable and averages about 27 mm at Gobabeb (Lancaster *et al.*, 1984). The area has an average potential evaporation of about 3 000 mm per year and its annual water balance shows a water deficit throughout the year (Lancaster *et al.*, 1984).

Groundwater is generally saline and, as a result, freshwater availability restricts both small and large-scale development activities in the area. Water samples were obtained from boreholes along the Kuiseb river, at settlements of the local inhabitants and at the Gobabeb Training & Research Centre (GTRC).

Sample collection and analysis

A total of Eighty water samples were obtained from shallow boreholes and wells (water level = less than 10 - 23 meters) in north central Namibia and the central Namib Desert on a monthly basis, from September 1998 to September 2000.

All samples were analyzed for major ions, TDS and Electrical Conductivity (EC). Major ions were determined by Atomic Absorption- direct flame and with a Skalar San Plus automatic analyzer. TDS was determined by evaporating the sample and drying it at 180° C while EC was measured with a Crison Micro CN 2200 electrode.

Results

TDS and major ions

Groundwater in water sources (depth = 10 -20 meters) of the Namib and north central Namibia displays seasonal variation in Total Dissolved Solids (Fig. 3). The variation is characterized by low TDS groundwater at the beginning of the rain season and a higher and increasing TDS most of the year until the next rain season. TDS values in sources of north central Namibia range from 148 to 10 300 mg/l and 239 to 10 888 mg/l in the Namib. Monthly TDS variation in individual sources is between 5% and 65% in north central Namibia and 0.5 and 85% in the Namib sources.

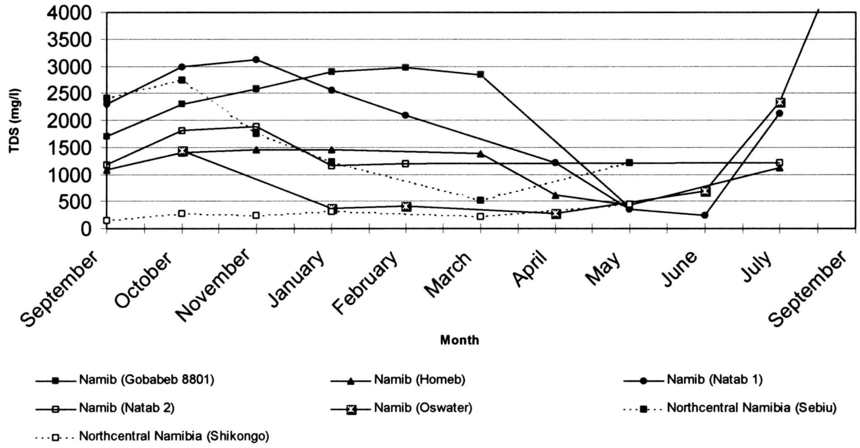


Figure 3 Total Dissolved Solids (TDS) in groundwater sources of the Namib Desert and north central Namibia

Both study sites also have water sources that display much higher TDS and TDS variation, particularly during the later part of the dry season, Fig. 4. This situation is observed in slightly deeper water sources (water level = 19 - 23 metres) in north central Namibia, and in over-pumped ones in the Namib. Maximum TDS and monthly TDS variation in these sources is about 11 000 mg/l and 500%, respectively.

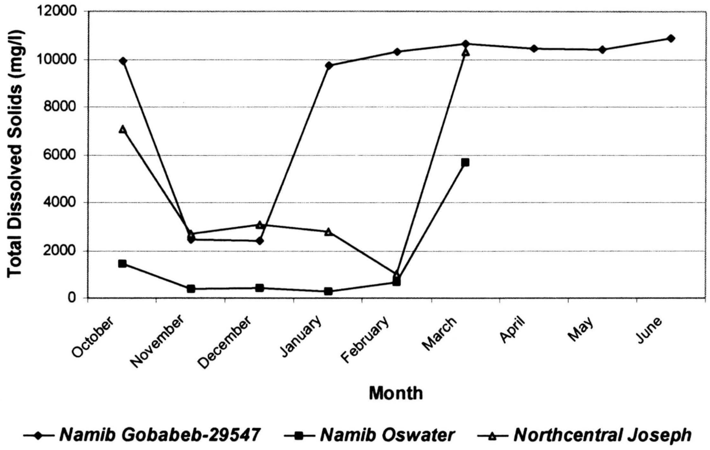
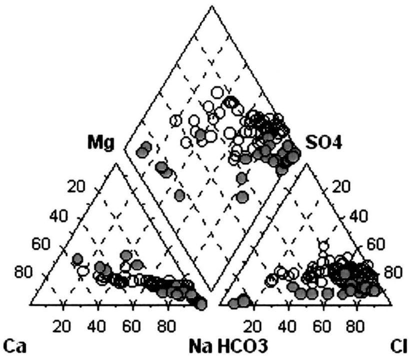


Figure 4 Total Dissolved Solids (TDS) in over-pumped and slightly deeper groundwater sources of the Namib Desert and north central Namibia.

Chemical evolution

Piper plots of water from the study sites are presented below, Fig. 5 (a) - (c). Figure 5 (a) presents data from fresh and saline water sources in north central Namibia and b) from the Namib. Figure (5c) displays the distribution of fresh and saline water end-members (the observed hydrochemical extremes) in both study areas. Rainfall data from the Namib was not available at time of publishing.



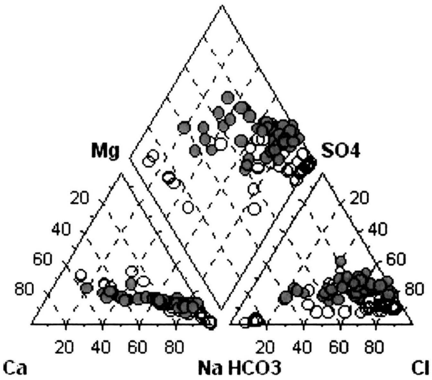


Figure 5 (a) Piper plot of water from north central Namibia 5 (b) Namib Desert

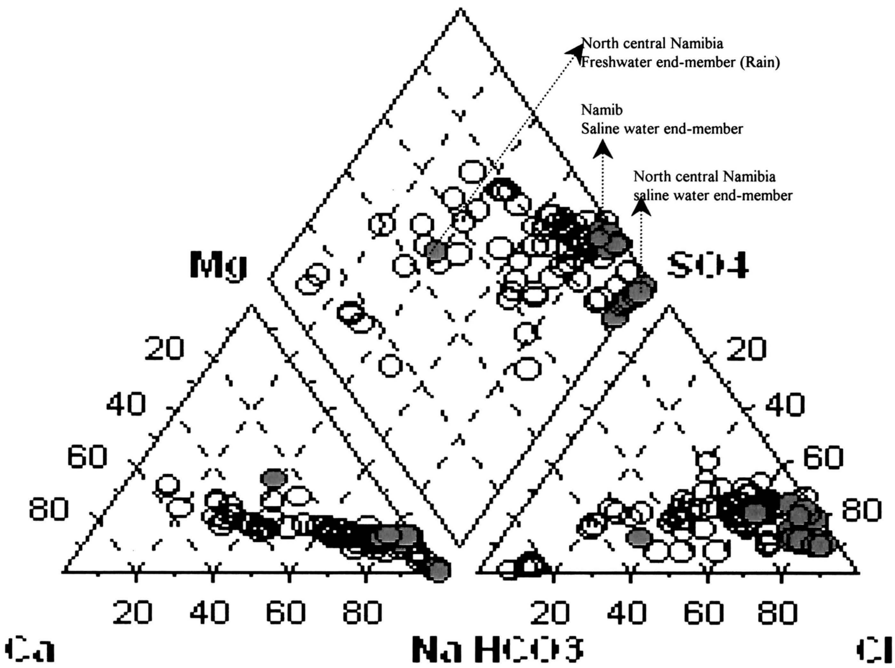


Figure 5 (c) freshwater and saline water-end embers of each site

Discussion

Salinization

Water salinization refers to an increase in TDS and overall chemical content of water (Richter & Kreitler, 1993). Groundwater salinity in this paper is presented according to the classification of Robinove et al. (1958), Table 1.

Table 1. Water quality classification based on Robinove et al. (1958)

Class	TDS range (mg/l)
Fresh	0 - 1 000
Slightly saline	1 000 - 3 000
Moderately saline	3 000 - 10 000
Very saline	10 000 - 35 000
Briny	> 35 000

The groundwater quality in most shallow water sources changes from fresh to slightly saline and finally to moderately saline in response to recharge by rainfall and floods, and then salinization during the latter part of the year.

Water in slightly deeper and over-pumped sources varies between moderately saline to very saline (Fig. 4). The deeper sources are possibly drilled past the freshwater section into the saline water ones, permitting upward migration of saline groundwater. The high groundwater TDS in over-pumped sources can be attributed to pumping-induced intrusion by deeper, more saline waters. Both these cases are reported in other arid areas (e.g., Kelly, 1974; Newport, 1977; Atkinson et al., 1986; Waddel & Maxwell, 1988; Richter & Kreitler, 1993). Indeed, they agree with earlier findings that arid regions often have saline groundwater underlying the fresh water resources (e.g. Wilmoth, 1972; Scalf et al., 1973; Newport 1977; Bednar, 1988;).

Process of salinization

Changes in groundwater salinity and overall chemical composition occur along flow paths from recharge to discharge areas due to either natural and/or anthropogenic causes (Richter & Kreitler, 1993). Raindrops interact with atmospheric gases and particles whilst surface runoff interacts with mineral matter on its way to surface-water bodies, where it mixes with water of different chemical composition (Richter & Kreitler, 1993). Water that enters the soil is subject to chemical, physical and biological changes due to processes such as evapotranspiration, mineral solution, precipitation, solution of gases and mixing with resident waters.

Evaporation of surface water and moisture in the unsaturated zone has been found as the most influential process in the development of the chemical composition of shallow groundwater (e.g., Boyd & Kreitler 1986; Richter & Kreitler, 1993). Evaporation concentrates the remaining water and leads to precipitation and deposition of evaporites that are eventually leached into the saturated zone. This source of groundwater salinity is amplified in arid lands, such as the study sites, due to the high evaporation rate and low rainfall which encourage the above-mentioned processes and also lower flushing of saline water.

The processes and mechanisms that determine the composition of a water body can be identified from plots of ionic ratios, e.g., the Na/(Na + Ca) ratio vs TDS plot proposed by Gibbs (1970).

A Gibbs plot of data from both study sites (Fig. 6) indicates that evaporation and precipitation are the dominant processes controlling the major-ion composition of groundwater in both sites. This is supported by earlier work for instance, Grobelaar & Seely (1980) and Day (1993) in the Namib, and Shaw (1988) and GCS (1992) in north central Namibia.

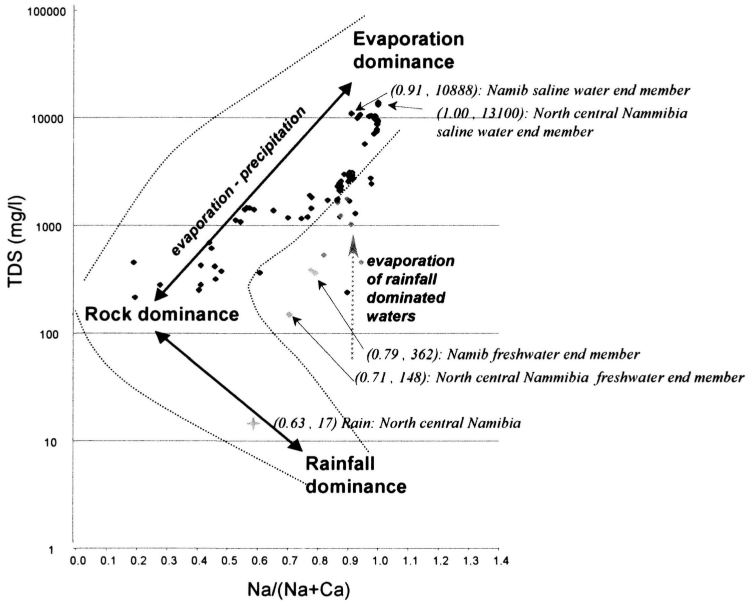


Figure 6 Gibbs (1970) plot indicating the mechanisms that determine the major-ion composition of groundwater in ephemeral river sources in north central Namibia and the Namib Desert.

The major-ion chemistry of fresh to slightly saline water sources in both study sites is controlled by evaporation of rainfall dominated waters while the Namib moderately saline to very saline groundwater shows evaporation and mineral precipitation as the dominant factors controlling composition. Waters from the artesian sources only plot in the evaporation dominance area and do not indicate any seasonal fluctuations. Indeed, this water is too deep to show any response to the local hydro-climatic conditions including local recharge.

The processes of groundwater salinization are often identified from ionic Vs TDS plots such as Na/Cl Vs TDS or Cl as by e.g. Jacks & Rajagopalan (1996) and Shanyengana (1997). Chlorine is chemically conservative, that is, once in solution it is not easily removed by most processes other than precipitaion at very late stages (Hem, 1985) and, as a result, it is often used to monitor water quality changes and their sources (Morton, 1986; Richter et al., 1990).

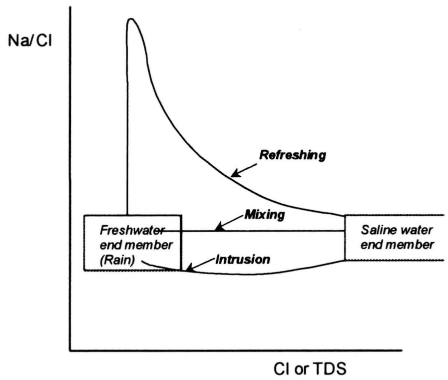
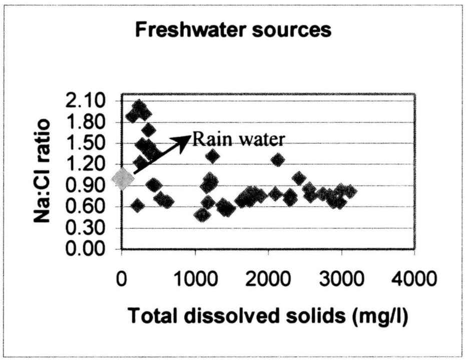


Figure 7 (a) Mechanisms of salinization that can be determined from Na/Cl ratio Vs Cl or TDS plots (after, Jacks & Rajagopalan, 1996).



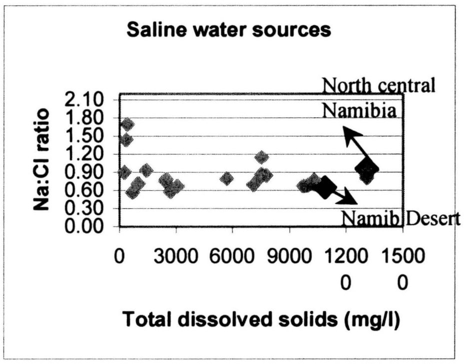


Figure 7 (b). North central Namibia water sources Figure 7 (c). Namib Desert water sources

Fresh to slightly saline groundwater sources in both study sites are refreshed by recharge water towards the freshwater end-members during the rain season either by direct rainfall or flooding. Thereafter, they are subject to mixing and at times intrusion by underlying saline water and, salinize towards the saline water end-members of each site, Fig. 7 (b).

The refreshing phase in freshwater sources of north central Namibia starts at the beginning of the rain season (September/October) and lasts until May. In the Namib this phase only begins after flood events which normally occur between December and March.

The moderately saline to very saline Sources show a short-lived refreshing phase that is followed by a mixing phase towards the saline water end-members. Most of these water sources, particularly the deeper sources, are very saline during most of the year except during parts of the rain season and during flood events when less saline recharge waters refresh them. However, even the recharge water is soon encroached by the surrounding saline water. This process is gradual, as well as season-dependent in well-utilized and non-pumped sources, and more rapid in cases where the water sources are pumped extensively- pumping-induced salinization.

Major ions and chemical evolution

Recharge groundwater in both study sites displays a lower major-ion concentration than that found in longer resident waters. Major-ion concentrations increase gradually from the end of the rain season towards the next, except in cases of intrusion where the increase is exponential. This change is characterized by an increase, in order of increasing magnitude of concentrations of cations - anions, in Na, Mg, K - Cl, HCO3 & SO4 and Na, Ca, Mg, K - Cl, SO4 & HCO3 in freshwater sources of north central Namibia and the Namib, respectively.

Modified piper diagrams (rotated axes) can be used to identify relations between groundwater sources as well as their chemical evolution and the processes responsible for the observed water quality changes (e.g., Richter & Kreitler, 1993). Below (Fig. 8), an altered piper diagram of water sources in the study areas shows that fresh groundwater evolves towards the chemistry of the saline water end-members found in each area.

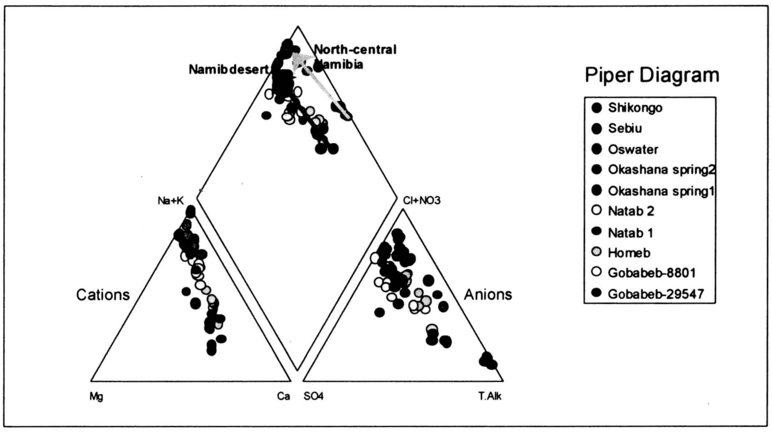


Figure 8 A modified piper plot indicating chemical evolution of fresh groundwater, in some of the water sources, towards the saline water end-members found in each study site.

Chemical evolution in freshwater sources of north central Namibia is generally from Na-HCO3-Cl to Na-Cl waters, while in the Namib it is from Na-Ca-Cl-HCO3 and Na-Cl-SO4 to a Na-Ca-Cl one. This evolution is gradual in more shallow and well-utilized water sources, and rapid in water sources that are earlier reported as slightly deeper or ones that record extensive pumping.

Dissolution of gases and minerals, particularly CO2 and CO3-related compounds in the atmosphere and in the unsaturated zone during precipitation and infiltration, would impart the observed HCO3 water type. The dissolution of evaporites and saline lacustrine sediments such as Halite (NaCl) and soda ash (Na_2CO_3) that are found on pan floors in north central Namibia (e.g. Hugo, 1968; GCS, 1992) account for the dominant cation being Na in these sources. Dissolution of gypsum and halite in the Namib sources would account for Ca and Na being the dominant cations in this area (e.g. Eckardt & Spiro, 1998).

The loss of Ca- and HCO3- related minerals through precipitation of minerals such as CaCO3, and the conservative nature of Chlorine favors formation of the Na-Cl water type that is observed in long resident waters of both study sites.

Summary

Shallow groundwater in Ephemeral River sources of arid lands display high seasonal and spatial TDS and major-ion variation. The variation is a function of direct recharge by rainfall in relatively high rainfall areas such as semi arid regions, and mainly surface runoff in the lower rainfall arid and hyper-arid areas. It appears that in low rainfall areas such as the Namib, the local rainfall does not effect any significant recharge and thus, no appreciable change in groundwater quality is recorded until after a flood event.

Refreshing during the rain season and salinization during the remainder of the year characterize the groundwater quality regime. The water displays a chemical evolution from low TDS CaHCO3 recharge waters towards the chemistry of underlying saline water end-members which are typically of a Na-Cl or **X**-Cl water type (**X** being the dominant cation (s) in the local soil media).

Evaporation of recharge waters and dissolution of evaporites appear to be the dominant processes that determine the major ion composition in ephemeral river sources of arid lands. Consequently the local hydro-climatic conditions, namely rainfall and evaporation rate, are the primary determinants of groundwater quality and can thus be used to estimate groundwater salinity in shallow water sources of these regions. However, these estimates would be lower than the actual values in case of deeper and over-pumped water sources due to intrusion by older, more saline waters, and in areas that have experienced other significant geochemistry-altering activity e.g. volcanism.

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