Okavango River Basin Transboundary Diagnostic Analysis Technical Report

OKACOM

The Permanent Okavango River Basin Water Commission

The Groundwater Hydrology of the Okavango Basin

FAO (2010) Internal Report prepared by MJ Jones (Consultant) for FAO

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Environmental protection and sustainable management of the Okavango River Basin

EPSMO

BIOPHYSICAL SERIES

TOC

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1 INTRODUCTION

Faced with the problems of scale and disparities in the quality and quantity of available databases, a strategic groundwater assessment of large river basins must go back to basic principles where the key objectives are to establish the resources in terms of a) their occurrence b) their chemical quality and c) the periodic changes in groundwater storage.

In the Okavango Basin, circumstances have resulted in a very unequal spatial distribution of sound geological and other essential environmental data. While the available topographic, climatic, soil, vegetation and hydrological information is sufficient to achieve a broad appreciation of the groundwater processes within the Okavango Basin, quantifying the resources is constrained by the lack of geological and hydrogeological data in the Cubango and Cuito catchments.

The overview of the resources and definition of the groundwater circulation are partially simplified by the fact that large areas of the basin receive little, if any, modern recharge and can, therefore, be considered as inactive. Very limited geological and hydrogeological data is available for the Cubango and Cuito catchments where active groundwater recharge supports the essential baseflow to the Okavango River runoff. The hydrological and climate data needed to establish aquifer recharge is available but information on the nature of the groundwater occurrences, the depth to water and the yield of wells usually available from the records of previous well drilling and testing programmes has not been located. Without this supporting field verification, geophysical survey, aerial photography and remote sensing interpretations have a limited application. This poses a major constraint to developing the necessary understanding of these two significant and potentially under-utilised basins. Against this background, judgement has been used to select and cite what appears to be the most realistic and representational of the available data.

This review broadly follows a hydrogeological terrain concept that combines classification of groundwater occurrences and their tectonic and geomorphological setting with specific climatic zones as this approach conveys an idea of what type of groundwater system or occurrence to expect. Thus the term “large sedimentary basin and arid” conveys the prospect of extensive stratiform sandstone aquifers largely containing “fossil water” and that only receives modern recharge along the mountainous rim of the basin. Similarly “Basement complex and arid zone” conveys a mountainous terrain with widespread exposures of crystalline metamorphic and batholithic rocks that are cut by numerous faults, fissures and stress joints. Preferentially erosion along these lines of weakness results in a heavily incised surface water drainage pattern with the fissure and fault zones below the valley floors are ideally located to receive indirect recharge as are the large tracts of outwash deposits (colluvial deposits) along the mountain front piedmont.

2 GEOLOGICAL SETTING

2.1 Tectonic Background

The main groundwater occurrences in the Okavango Basin are found in the Basement rocks, the Karoo System formations and the Kalahari Group formations and minor, but locally important occurrences, exist in the lightly metamorphosed Late Pre-Cambrian – Palaeozoic sediments. Given the importance of the Karoo System and Kalahari Group aquifers it is necessary to develop a clear understanding of the geological setting of the Basin.

An almost ubiquitous cover of Kalahari Group formations hides the complex underlying geological structure of the Okavango Basin that is enclosed by ancient tectonic cratons (Figure 1) that apatite fission track dating shows to have been land since 300 to 450Ma (M. Raab et al. 2005).

The cratons are coherent relics of previous continental breakup and drift episodes and comprise batholith cores and intensely metamorphosed crystalline rocks. The cratons were conjoined by later Precambrian and Early Palaeozoic metamorphic sedimentary sequences of the Limpopo, Namaqua and Demara Belts and the Lufilian Arc to form the southern extremity of the Pangaea supercontinent by Mid to Late-Carboniferous (ca 320-330Ma). The southern margin of Pangaea was an active convergent, low-angle, continental and oceanic plate subduction zone. The resulting compressional forces created an extended coastal mountainous range. The South African Cape Fold Belt is a remnant of these mountains.

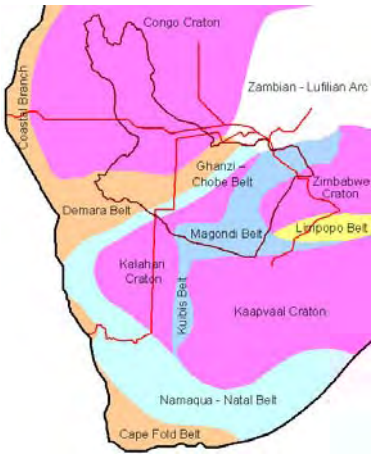


Figure 1:

Figure 1: Provisional simplified schematic of the Basement structure of the Okavango Basin. Dated between 3.6 and 2.5Ga, the Zimbabwe and Kaapvaal Cratons became attached by the Limpopo Mobile Belt around 2.0Ga. The collision of these cratons with 1.8-1.6Ga Congo Craton between 500 and 550Ma saw the deformation of the island arc sediments of the Demara and Lufilian belts (adapted from Geological Survey of Namibia, 2005).

Extensional forces and hot spots (Figure 2) associated with superplume activity initiated the breakup of the Pangaea super-continent into first, the Gondwana and Laurasia supercontinents in the Permian Period (230 Ma) and then, the breakup of Gondwana in to Africa, South America, Madagascar, India, Australia and Antarctica in the Late Jurassic and Cretaceous (130 and 100Ma).

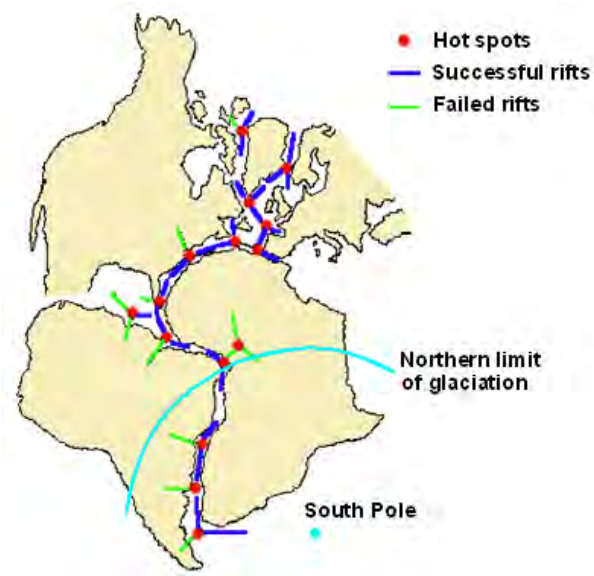


Figure 2

Figure 2: Pangaea prior to the ca 230Ma separation of Laurasia and Gondwana due to mantle plume initiated rifting. The hot spots shown now lie along or near to the mid-Atlantic ridge.

Shows location of South Pole ca 300Ma and north limit of recognised lower Karoo glacial deposits (Adapted from Earle, S., 2001).

Each tectonic development left regional structural trends in the fabric of the underlying Basement. Figure 3 shows the deep geological structure under the Kalahari Group cover in northern Botswana. This has been established from detailed geophysical surveys and from various mineral exploration programmes coupled with the geological mapping of the outcrops of the Demara folded quartzites and intercalated limestones in the bed of the Okavango River at the Popa Falls on the Angola-Namibia border and of the Pre-Cambrian felsic granitoid gneiss outcrops in the Tsoilo Hills to the west of the Okavango Delta. The degree of Basement complexity under the Namibia and Angolan areas of the Okavango Basin remains to be established but will have impacted on the deposition of later Karoo and Kalahari sediments as will the impact of renewed tectonic activity as typified by the current movements along the Okavango graben faults.

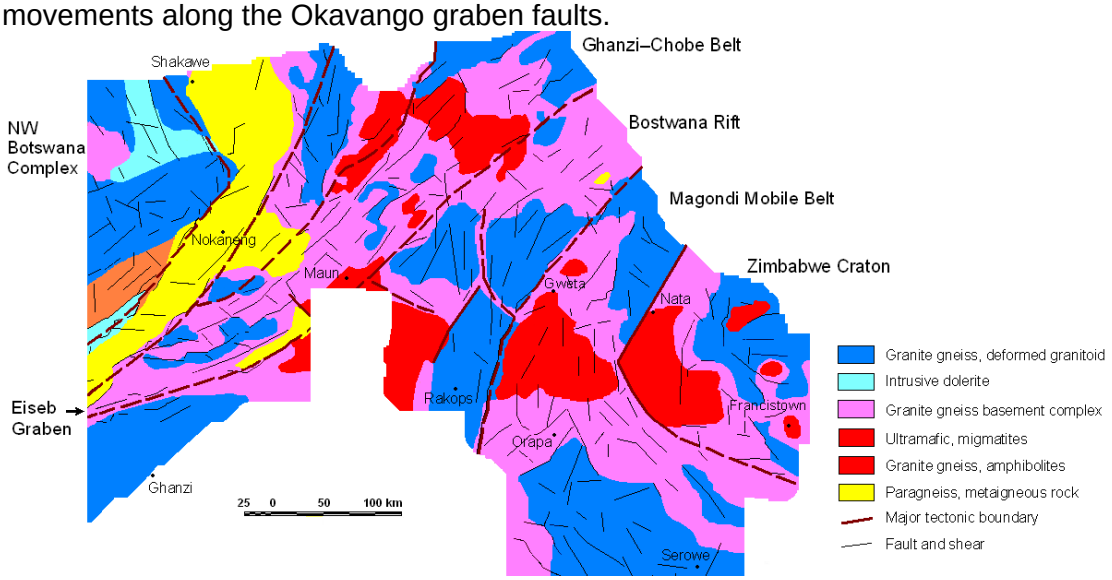


Figure 3

Figure 3: Northern Botswana, Basement geology and tectonic elements (redrawn from S. Yawsangratt, 2002)

2.2 The Karoo System

The start of the deposition of the Karoo System sediments in the Late Carboniferous and Permian (300Ma) coincided with an intra-cratonic sag (S. Lawrence and I. Hutchinson, 2009) or the flexural subsidence of the back-bulge to the Cape Fold Belt (O. Catuneanu et al., 2005) prior to the breakup of Pangaea. Figure 4 shows the regional tectonic setting during the deposition of the Ecca Sandstone in the Central Botswana and the Great Karoo. Compression forces in the western half of southern Africa saw uplift and erosion of the Karoo Basin margins with a north-eastward focused drainage pattern. To the east and north, extensional forces and rifting controlled the tectonic development of linear Karoo basins typified by the Luangwa and central Zambezi Valleys.

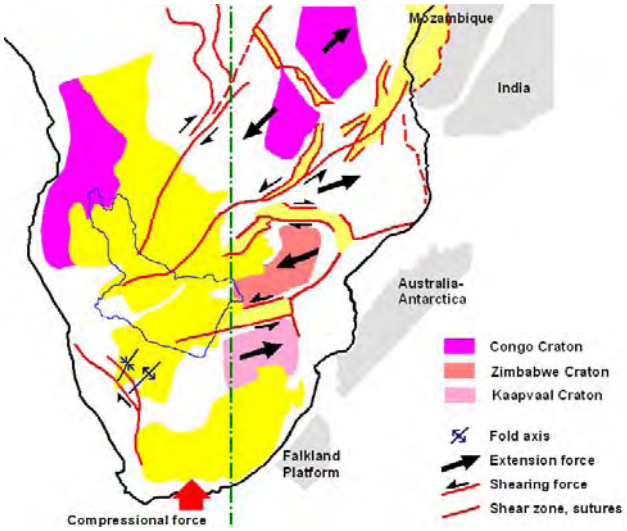


Figure 4: Inferred Permian tectonic setting during the deposition the Karoo in southern Africa (adapted from S. Lawrence and I. Hutchinson, 2009).

Figure 4

A NE-SW trending shear zone approximating to the northern margin of the Caprivi Strip delineates boundary between the Central Kalahari Karoo Basin and the Angolan Karoo sequence to the North as shown on Figure 5.

During the deposition of the Early Karoo formations around 300Ma, southern Africa lay close to the southern pole and under the influence of glaciation that extended northwards to the Gulf of Guinea and central Sudan (Figures 2 and 7). Subsequently as plate movement drifted the African continent to the north and slowly rotated it counter-clockwise, as the deposition of the Karoo sequence progressed the prevailing palaeo-climate changed of from cold and semi-arid to hot and humid although there were considerable temporal and spatial fluctuations.

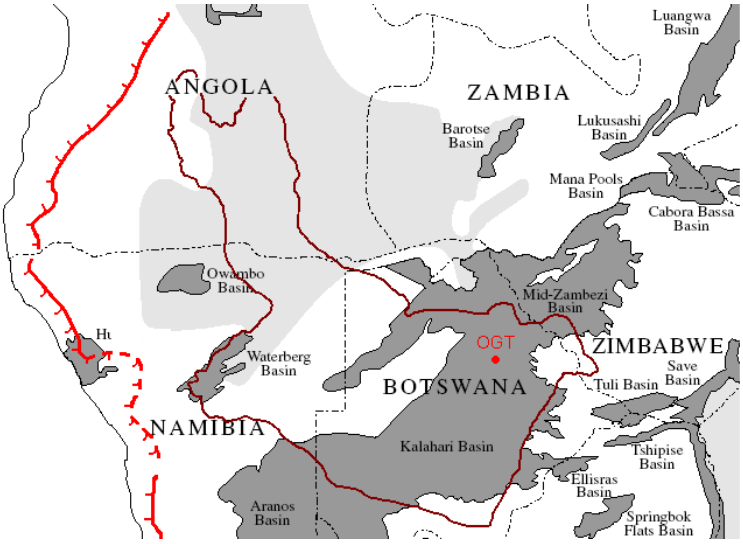


Figure 5

Figure 5: The Okavango Basin - distribution of main Karoo occurrences (extracted from O. Catuneanu et al., 2005)

Light grey shading indicates Karoo subcrop under Kalahari Group formations. Coastal escarpment marking regional water divide indicated in red.

OGT – approximate site of cored BH shown on Figure 11.

The established Karoo System stratigraphy in the Kalahari Basin and the more provisional Angolan sequence are shown on Figure 6. The dating and regional correlation of the formations is being established but significant gaps still exist (B. N. Modie and A. Le Herisse, 2009)

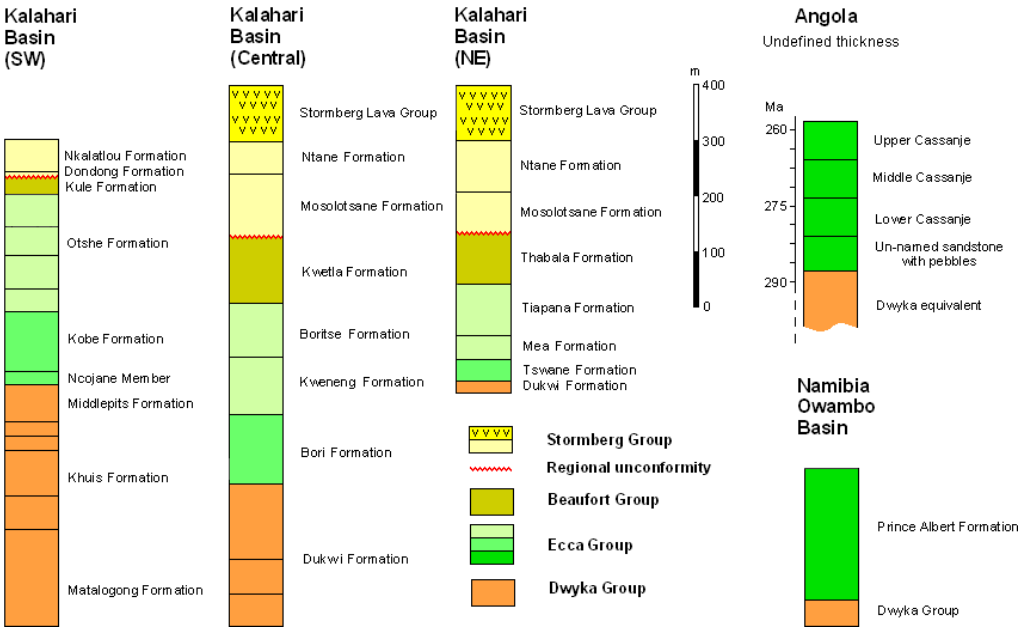


Figure 6

Figure 6: Okavango Basin – Karoo System stratigraphy with indicative thicknesses, adapted from O. Catuneanu et al. (2005).

In depth studies of the main South African Karoo Basin and the Kalahari Basin have established the prevailing palaeo-geographical and palaeo-climatic conditions during the deposition of the Karoo formations as shown on Figures 7 and 8. Most of the clastic sediments have an arkosic composition that reflects rapid denudation, transportation and deposition.

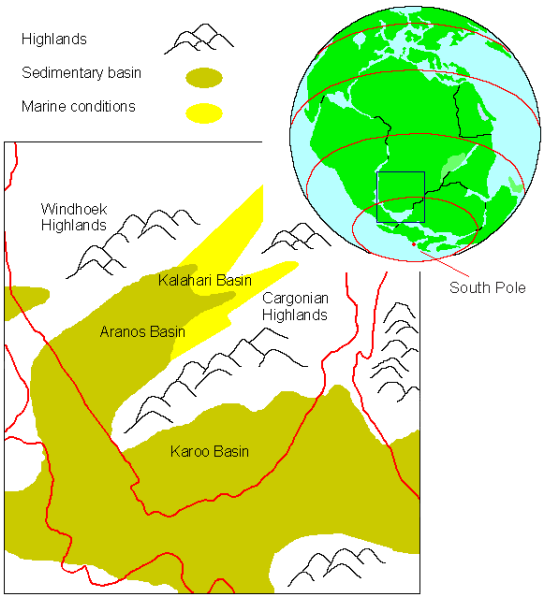


Figure 7

Figure 7: Central Kalahari and main South African Karoo Basins, palaeogeography during the deposition of the Ecca Group sediments ca. 275Ma (abstracted from K. Scheffler, D. Buehmann and L.Schwarkm, 2006). Inset shows the configuration of Pangaea prior to breakup.

The Karoo formations of the Okavango Basin have all been subject to deep weathering both during and after deposition as shown on Figure 9. This weathering profile, determined by detailed examination, including analysis of 34 samples taken from a 340m cored borehole drilled near Orapa (see approximate site on Figure 5): It is interpreted as establishing the changing sedimentary and climatic environment during the deposition of the Karoo formations (K. Scheffler, D. Buehmann and L.Schwark, 2006). The profile reflects the key factors that impacted the formations during deposition, the changing climate, the marine retreat and changes in the sediment sources. These sources were firstly from the southern Cargonian highlands and then during the deposition of the largely lacustrine Tihabala Formation from the northern Windhoek highlands before finally reverting to the southern sources again during the deposition of the continental arkoses of Ntane Formation.

The distribution of 1:1 kaolin clays and 1:2 smectite clays is attributed to changing redox conditions in the profile shown on Figure 9. From the groundwater resources perspective the clay distribution coincides with the view of open and closed weathering profiles as applied to the formation of weathered Basement complex aquifers. Following this view suggests that some of the weathering of the profile could have developed during the subsequent denudation processes associated with the formation of the African erosion surface.

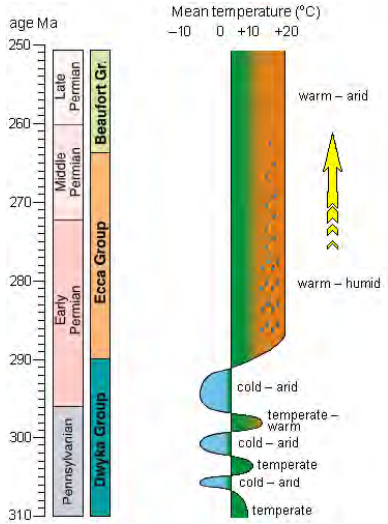


Figure 8

Figure 8: Southern Africa, palaeoclimate changes during the deposition of the Dwyka, Ecca and Beaufort Groups (abstracted from K. Scheffler, D. Buehmann and L.Schwark, 2006).

The maximum thickness of the Karoo formations in the South African Karoo Basin is around 1500m and, in the Kalahari Basin 800m. This points to a low energy environment and relatively stable long-term tectonic conditions compared to the accelerated denudation and sedimentation conditions of the eastern rifted basins in Zambia and Tanzania (the Luangwa and Ruhuhu basins) where 3 to 5km of the truncated Karoo System formations remain.

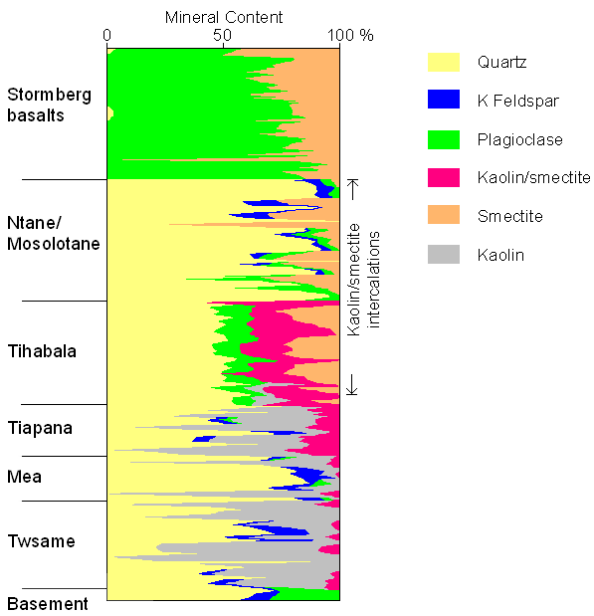


Figure 9

Figure 9: Karoo formation weathering profile from borehole OGT (Figure5) showing influence of climate and mineralogical changes notably in the K feldspar (Orthoclase) content in the arkoses derived from a southern sources in Cargonian highlands. K. Scheffler, D. Buehmann and L.Schwark, 2006

The deltaic environment for the deposition of the Ecca formations in the central Kalahari Basin comprises an upward-coarsening, lower delta-front member marking the final marine retreat that is followed by a series of upward-fining deltaic and fluvitile members (T. Segwabe1 and E. Bordy, 2009) as shown on the fence diagram (Figures 10). The withdrawal of the Early Ecca sea to the west largely separated the central Kalahari Basin from the Aranos Basin in Namibia. Figure 10 shows the configuration of the pre-Karoo landsurface, the Dwyka glacial deposits, the deltatic-fluvitule Ecca formations and the Beaufort floodplain sediments. It is apparent that the regional palaeo-water divides approximately followed the modern geography (Figure 5).

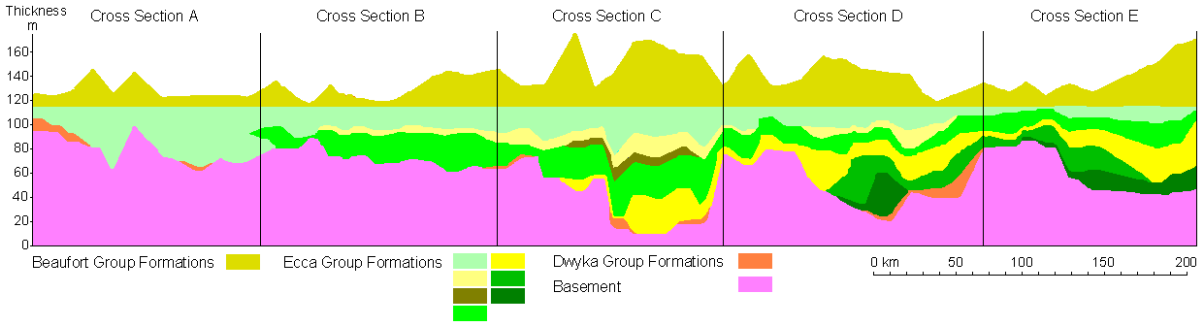


Figure 10

Figure 10: Distribution of Karoo formations across the central Kalahari Basin along the cross sections marked on Figure 10 (adapted from (T. Segwabe1 and E. Bordy, 2009). The depths are centred on top of the Ecca Formation and not relative to ground level.

The distribution and thickness of the Karoo Dwyka, Ecca and Beaufort Groups across the Kalahari Basin (Figure 11) reflects the active control imparted by the deep tectonic structure with the cratonic core of the Ghanzi Ridge and Magondi Belt forming a mark northern boundary to the central Kalahari Karoo Basin. The southern margin of the Ghanzi Ridge is labelled the Makgadikgadi Line (L. V. Ramokate, 1997 and T. B. Rahube, 2003) and incorporates the Tsau normal fault zone. The Kunyere – Thamalakane Fault line defines the northern margin of the Ghanzi Ridge and the southern limit to the Okavango Delta graben. It is not certain that the basin configuration shown on Figure 11 is the result of the palaeo-geomorphology or, as is more likely, due to intra-depositional sag possibly related to a pre-Karoo rift branch that is on nearly the same alignment as, and followed by, the Okavango dyke swarm.

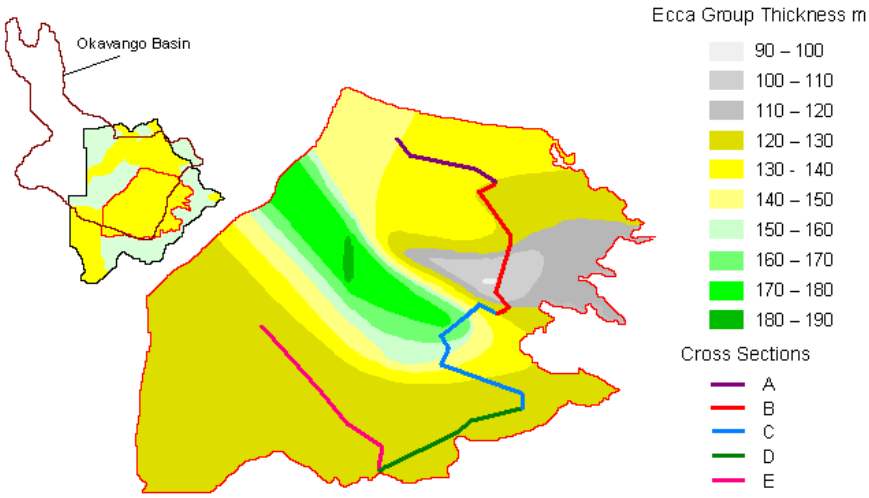


Figure 11: Thickness of the Ecca Group in the Central Kalahari Basin (adapted from T. Segwabe and E. Bordy, 2009)

Figure 11

North of the Ghanzi Ridge, the Dwyka, Ecca and Beaufort Group formations are less well defined and where present, they appear less well developed as shown on Figure 6: Information for the Angolan and Namibian areas of the Okavango Basin is limited. The imprint of the deep geological structure, however, is expected to be repeated but remains to be established. A break in main intra-continental water divide in Namibia saw the deposition of shallow and deep marine shales in the Price Albert Formation of the Ovambo Basin.

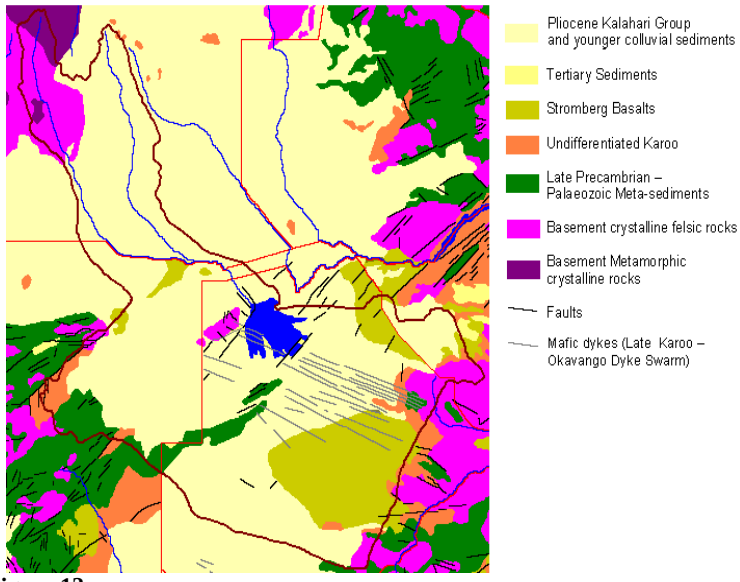


Figure 12: Okavango Basin - regional superficial geological map (extracted from E. G. Purday, 1989).

Figure 12

The persistent unconformity between the Beaufort and Stormberg Groups point to widespread Triassic tectonic events that culminated with the extrusion of the Stormberg (Drakensberg) trap basalts associated with the relatively short-lived Karoo large igneous province (LIP) that was active between 180 and 190Ma.

The sandstones and arkoses of the Ntane formation and Stormberg Basalt lavas are the main potential aquifers and in the Okavango Basin. They are well exposed in eastern and northern Botswana and at places in Namibia as shown on the superficial geological map, Figure 12 and the geological map of Botswana showing the solid geology below the Kalahari Group sediments, Figure 13.

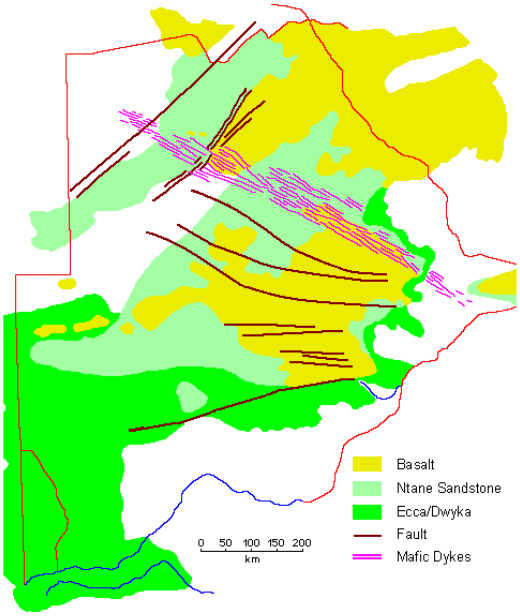


Figure13: Geological map of Botswana showing the Karoo Group solid geology below the Kalahari Group sediments (adapted from J. L. Farr et al. 1981)

Figure 13

The intrusion of the Okavango mafic dyke swarm ca 179Ma in the Jurassic marked the end of the Karoo System deposition. Extending on a N110°E trend for some 1500km and with a width of some 100km, this dyke swarm is considered to be aligned on a branch of the pre-

Cambrian triple rift junction that was weakly active during the deposition of the Karoo System (B. Le Gall, et al., 2005 and F. Jourdana, G. Férauda and H. Bertrand, 2006).

2.3 Post Karoo Geological Events

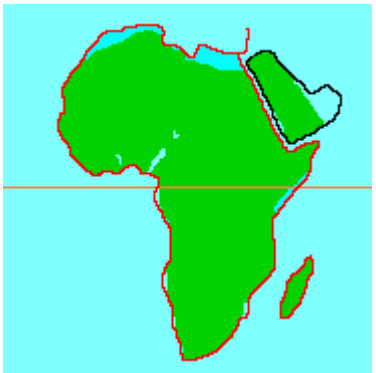
Two significant global changes and two major continental scale changes impacted on the present Okavango Basin.

The first global change is the northern drift of the African continent and anticlockwise rotation as shown on Figure 14. This transit has resulted in regional climate shifts that saw the Okavango Basin enter the southern latitudinal arid belt during the Eocene-Tertiary (ca. 50Ma).

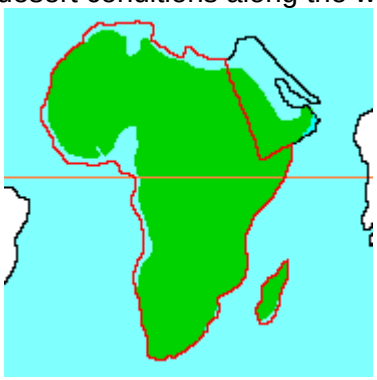
Deep geophysical investigations have shown the geographical stability of the African plate for at least 300Ma to be due to tectonic inertia caused by a large low shear velocity province in the mantle under much of the African continent (E. J. Garnero, T. Lay, and A. McNamara, 2007). The presence of this mantle structure and two phases of superplume activity along the margins of this structure (T. H. Torsvik, et al. 2006, 2008 and K. Burke and Y. Gunnell, 2008) are indirectly responsible for the African Plateaus. The first superplume activity started in the Jurassic (ca. 225Ma) with the breakup of the Pangaea super-continent into Gondwana and Laurasia to form the North Atlantic and culminated in the Cretaceous (ca. 130Ma) when the Tristan superplume triggered the separation of the African and South American plates to form the South Atlantic. By this time the separation of the African and Indo-Antarctic-Australian tectonic plates had already occurred. This phase of continental separation resulted in passive margins to the southern African plate.

The second phase is associated with the Afar superplume that saw the separation of the African and Arabian plates. Incidental with these events were the crustal extensions responsible for the formation of the East African Rift systems.

The second global change that impacted on the palaeo-climate was the global decline in sea levels and the creation of the modern oceanic circulation pattern that followed the formation of the Antarctic Ice Sheet around 34Ma. This occurred after the breaching of the land links between Antarctica and Australia and South America (K. Burke and Y. Gunnell, 2008) that opened the Southern Ocean. The subsequent influence of the cold Benguela Current compounded the hot semi-arid desert conditions along the western half of southern Africa.

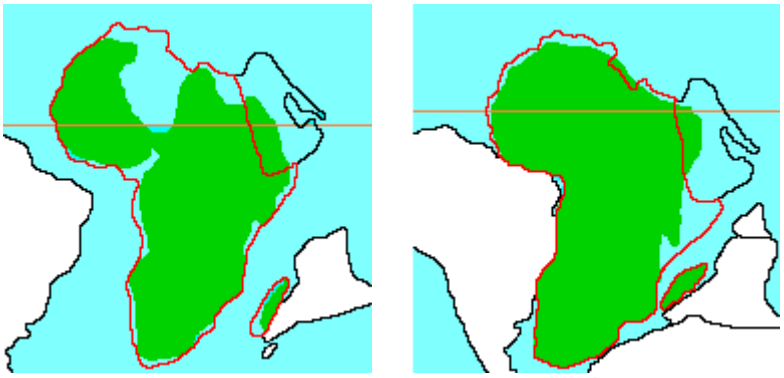


14Ma Miocene



50Ma Eocene

65Ma end of Cretaceous



95Ma Cretaceous 150Ma Jurassic

Figure 14

Figure 14: Palaeo-geographic maps showing rotational and northern drift of the African Continent.

The continental changes covered the interplay between tectonic events and denudation the moulded the African landscape.

The first continental change was the formation of the African erosion surface. This surface was
formed in the Mid-Cretaceous following the breakup of the South American and African continents around 130 Ma. Closely following this separation, was the elevation of the Kalahari High Plateau (M. de Wit, 2007) that triggered two denudation cycles that lowered much of the African continent to a low-relief, peneplaned landsurface (P. van der Beek, et al., 2002 and A. Moore, T. Blenkinsop and F. Cotterill, 2009, M. D. Rowberry, T. S. McCarthy & S. Tooth, 2009). Apatite fission track analysis dates the two phases of shoulder uplift that occurred between 138 and 160Ma and between 90 and 115Ma (F. Guillocheau, et al., 2009). While the tectonic mechanism responsible for the uplift of the Kalahari Plateau has yet to be identified, the dates correspond with the two phases of kimberlite emplacement.

Offshore lithological and stratigraphical evidence from oil exploration studies confirms the denudation of the Kalahari plateau in the Late Cretaceous as the main source of sediments (F. Guillocheau, et al., 2009).

The denudation process started at the coastline between 95 and 115Ma and culminated in a final pulse around 80Ma across most of the interior. By this stage many of the main water divides found in modern southern Africa were established. At least 5km of rocks are estimated to have been eroded during this phase of accelerated denudation that averaged ≈ 40m/Ma. After 80Ma, the offshore deposition record shows a sharp decline in sediment transportation from the main basins of the pre-Limpopo and pre-Orange Rivers as denudation dropped to ≈ 5m/Ma (M. Séranne and Z. Zanka, 2005). This leads to conclusion that much of the southern African topography was of low relief and lay close to the prevailing sea level after 80Ma (see Figure 15).

The second regional change was the uplift of these low-lying peneplains from 30Ma onwards to form the characteristic, modern high African plateau landscape.

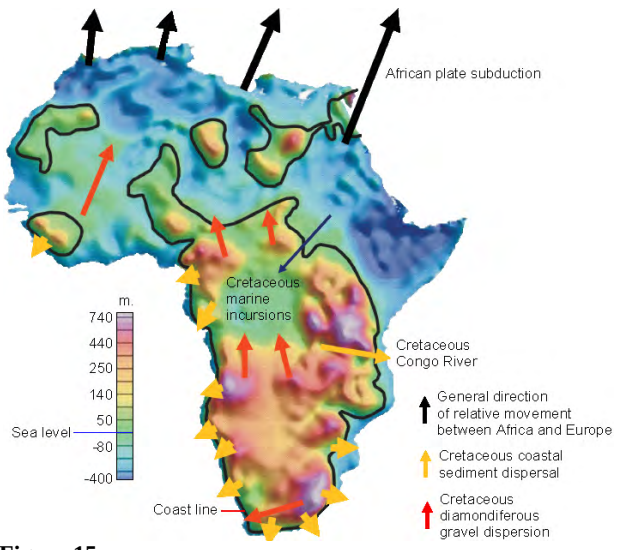


Figure 15

Figure 15: Palaeo-topography of Africa in the Mid to Late Cretaceous ca.100-90Ma (adapted from M. de Wit, 2007)

These African plateaus were first described and attributed to erosion by E. J. Wayland (1934) , B. Willis (1936), F. Dixey (1946, 1956) and L. C. King (1962).They postulated structural unloading due to denudation and periodic isostatic uplift as the trigger for a succession of peneplanation cycles. A major objection to this concept of periodic isostatic uplift is that the unloading rebound is seen as a continuous process: Subsequently, superplume activity was proposed as the driving mechanism for regional periodic uplift (G. C. Bond 1979). This mechanism, however, is not supported by deep geophysical investigations that identify the large low shear velocity province in the mantle underlying much of the African continent as the source of the tectonic buoyancy (E. J. Garnero, T. Lay, and A. McNamara, 2007).

The noted geographical stability of the African plate for at least 300Ma due to this mantle structure and two phases of superplume activity are indirectly responsible for the African Plateaus ((T. H. Torsvik, et al. 2006, 2008 and K. Burke and Y. Gunnell, 2008).

While still contested by other workers (A. Moore, T. Blenkinsop and F. Cotterill, 2009), K. Burke and Y. Gunnell (2008) present a coherent interpretation of the geological processes behind the African erosion surfaces. Of relevance to the Okavango Basin, their main findings are:

- the African continental plate has remained close to its present geographical position for at least 200 million years with only latitudinal and minor rotational drifting taking place (Figure 14);
- two deep seated tectonic events have shaped the landsurface, these were the eruption of the Karoo (225 -130Ma) and Afar (30Ma) large igneous provinces (LIPs) that arrested or pinned the slow movement of the African plate;
- the plate-pinning event caused by the Afar superplume coupled with shallow mantle convection resulted in the formation of the characteristic swells and basins found across the Continent: These regional uplifts had previously been ascribed to isostatic movements and then large mantle plumes;
- the African erosion surface developed during the 100Ma interval between the end of 130 Ma Karoo and the 30Ma Afar events when tectonic activity was largely quiescent;
- between 80Ma and 30Ma much of Africa had a low relief and lay close to the prevailing sea level;

- the present large-scale geomorphological features of the African landscape have taken shape since 30Ma and local tectonic movements, however, make the African surface appear polycyclic.

K. Burke and Y. Gunnell (2008) reassign many of the plateaux in southern and central Africa previously considered to be post-Gondwana or Gondwana as part of a polycyclic African surface that has been differentially uplifted by movements associated with regional rifting and shallow mantle convection driven swells. They find there are unlikely to be any continuously exposed African land surfaces much older than 40Ma. They cite the P. van der Beek, et al. (1998) maximum apatite fission track (AFT) ages of 40Ma for the landsurface on Kipengere and Livingstone Mountains in south west Tanzania and for the topographically lower Lupa and Ufipa plateau each side of Lake Rukwa. Landsurfaces older than 40Ma, however, are preserved where buried under younger sedimentary formations and subsequently exhumed as described in Namibia by M. J. Raab, et al. (2002, 2005)

The distribution of the post 30Ma basin and swell structures that moulded the landscape of southern Africa is shown on Figure 16. The scale of the regional uplifts is in the order of 2 to 5km as determined for the Biè Swell in Angola shown on Figure 17. Consideration of accelerated post-uplift denudation and isostatic balancing, however, suggests that actual land levels did not vary greatly from their current elevations.

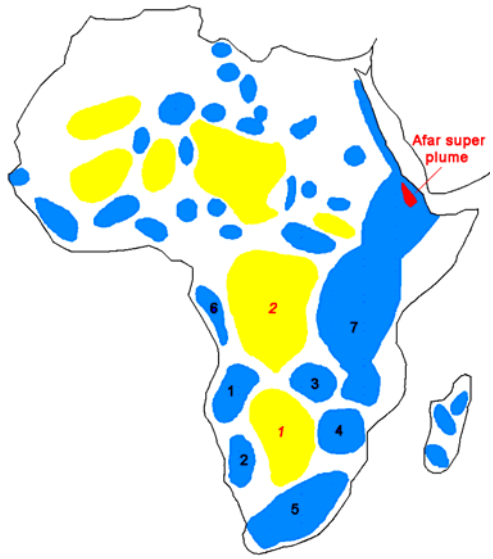


Figure 16

Figure 16: Distribution of the post 30Ma basin and swell structures (adapted from K. Burke and Y. Gunnell, 2008)

Key:

Swells (blue)
1- Biè (Angola);
2- Namibia;
3- North Zambia;
4 – Zimbabwe;
5- South Africa;
6- Mayombe;
7- East African;
Basins (yellow)
1- Kalahari
2- Congo

The Kalahari Basin shares a similar inter cratonic location to the Congo Basin and there is no clear tectonic mechanism for their formation. They may occupy a region where the shallow mantle convection rotated and sunk rather than a tectonic downthrown rifted zone as typified by the Sudd Basin. For the Congo Basin, S. Buiter and B. Steinberger (2009), however, suggest a deep seated gravity anomaly as exerting a downward pull under the basin.

Irrespective of the tectonic mechanism involved, the formation of the Kalahari Basin disrupted the regional drainage basins and impacted of the deposition of the Kalahari Group formations.

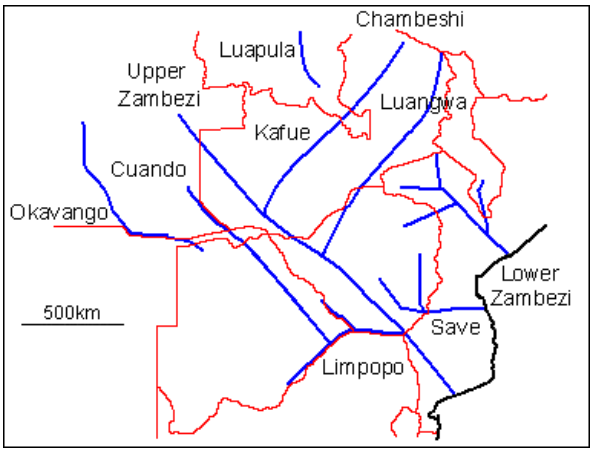
Figure 17: The Neogene (ca 30Ma) Biè Swell in Angola from M. P. Jackson and M. Hudec, 2009

Figure 17

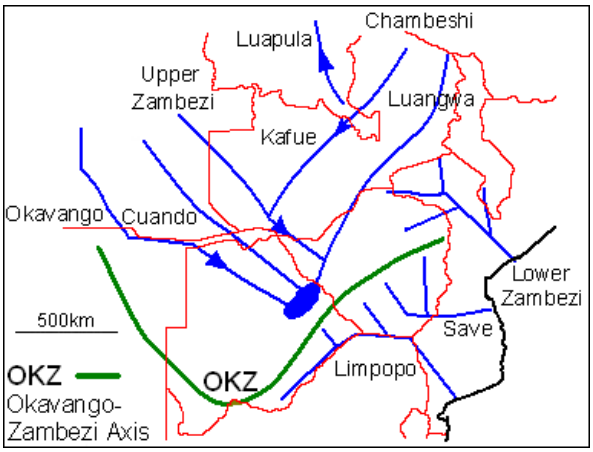
2.4 The Post-Cretaceous development of the Okavango Basin

As the palaeo-geomorphological development of the Okavango Basin had key control over the distribution of the Kalahari Group formations that contain some of the locally important aquifer horizons in the region, consideration must be given to the environmental changes that occurred during their deposition.

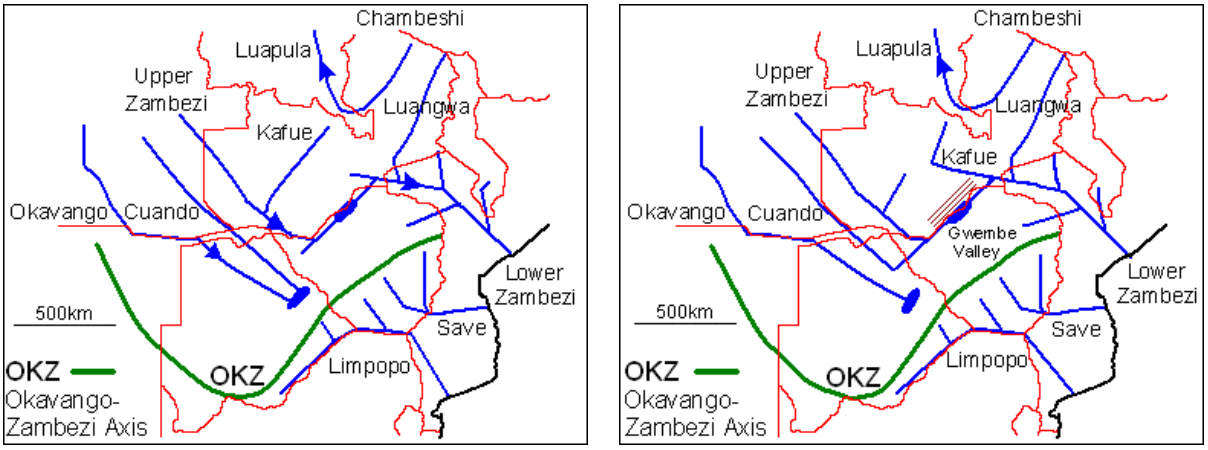
Two main reconstructions of the post-Karoo drainage systems of central and southern Africa have been proposed. The first is largely based on the interpretation of persistent tectonic uplift along three concentric horseshoe shaped sets of flexural axes (Moore, A.E. & P.A. Larkin, 2001, A. T. Moore, A., T. Blenkinsop and F. Cotterill, 2009 and J. Stankiewicz and M. J. de Wit, 2006). This model proposes that the palaeo-Okavango River was part of the Limpopo River system that also included the upper Zambezi catchment until around the end of the Cretaceous (Figure 18A). From the end of the Cretaceous 34Ma to the Mid-Pleistocene (2.5Ma) these combined catchments were cut-off from the Limpopo are considered to have formed the closed Kalahari basin where the fluvitile and lacustrine Kalahari Group formations were deposited (Figure 18B). In the Pleistocene, the Okavango Basin was detached from Zambezi River as the influence of the East African Rift System (EARS) spread westwards (Figure 18C).



A: The Late Cretaceous (65Ma)



B: Palaeocene to Mid Pleistocene (65-1.5Ma)



C: Mid-Late Pleistocene (~ 1Ma) D: Present

Figure 18A-D: The post Cretaceous development of the drainage system in Southern Africa (modified from A. E. Moore and P. A. Larkin, 2001 and J. Stankiewicz and M. J. de Wit, 2006).
Figure 18

No stratigraphic record in the east coast delta sediments of the Limpopo and Zambezi between 65 and 30Ma is preserved to provide ancillary evidence on the denudation and eastward sediment transfer history during this interval.
The alternative models (K. Burke and Y. Gunnell, 2008) for the development of the palaeo-drainage system of the southern Africa between 80 and 15Ma are shown on Figure 19A, B and C and are supported by the stratigraphy and lithology of the off-shore sediments of the deltas of the main rivers as shown. Subsequent to uplift of the South African swell ca. 30Ma, the regional drainage was disrupted and Transtswana River was cut off from the Kalahari (Orange) River. Flow in the proto-Okavango River was further impounded by the rising Zimbabwe and North Zambian swell.

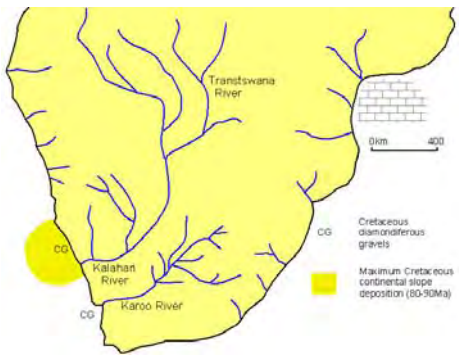


Figure 19A: The palaeo-drainage system of southern Africa ca. 70-30Ma (adapted from K. Burke and Y. Gunnell, 2008). Pre 30Ma Kalahari River and Karoo River (Orange River Delta) peak deposition between 122 and 95Ma with pulse at 80Ma. Little deposition since 30Ma

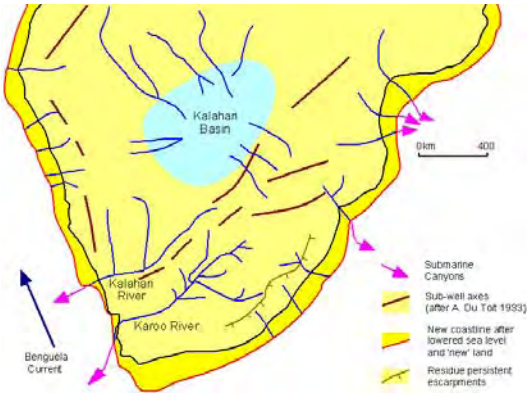


Figure 19B: The palaeo-drainage system of southern Africa ca. 30Ma. Uplift of South African swell reverses flow of the upper course of the Transtswana River.

Renewed accelerated denudation triggered in the Zambezi Basin associated with activity along the East African Rift System.

Figure 19C: The palaeo-drainage system of southern Africa ca. 15Ma.

Limpopo River captures headwaters of the Orange (Vaal) River and potentially the Proto-Okavango River.

Rifting continues to dominate the development of the Zambezi-Shire River basin.

Figure 19 A - C

As the outwash fan and terminal lakes in the Okavango expanded during the Tertiary, the deposition of the Kalahari Group formations merged with the Owambo-Cuvelai-Cunene River system fans and lakes. Intermittent tectonic movements and climate fluctuations resulted in expansion and contraction of the lakes surrounding pans throughout the Tertiary.

2.5 The Kalahari Group

The main subdivisions of Kalahari Group are the pre-Pleistocene Lower Kalahari fluvial and lacustrine formations and the upper Pleistocene-Holocene aeolian Kalahari Sands.

2.6 The Lower Kalahari Group Formations

The hidden begrock geology of palaeo-African Erosion Surface below the Kalahari Group includes the topographically higher areas underlain by Pre-Cambrian and Early Palaeozoic crystalline and the topogarphically lower sedimentary basins occupied by various Karoo Group formations.

Figure 20 shows the thickness and distribution of the Kalahari Group formations. The basal members of the Lower Kalahari Group must incorporate and preserve the imprint of the palaeo-African Erosion Surface drainage pattern and the associated alluvial and colluvial deposits.

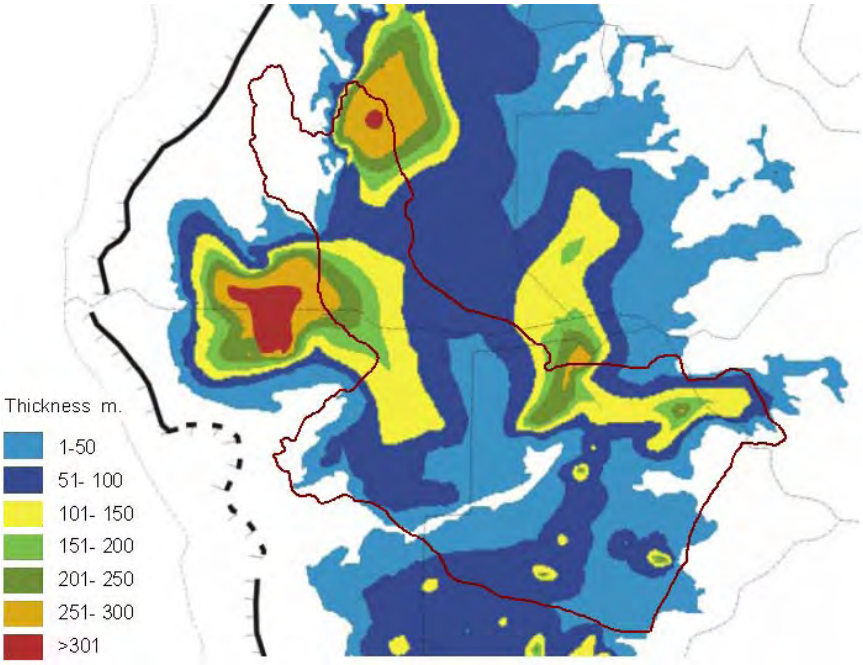


Figure 20: Distribution and thickness of the Kalahari Group formations in southern Africa (adapted from M. H. T. Hipondoka, 2005 and based on data from D. S. G. Thomas, 1988, D. S. G. Thomas and P. A. Shaw 1991 and I. G. Haddon, 2000).

Some further certainty to dating the base of the Lower Kalahari Group formations in the Okavango Basin is provided by the Kimberlite pipe intrusion phases in the Mid to Late Cretaceous (120 - 80Ma). After intrusion, these were subject to denudation and laterisation before being covered by the Kalahari Group sediments. The presence of laterites points to humid conditions continuing sometime after 80Ma (F. Guillocheau, et al., 2009). As regional denudation became subdued at around 4m/Ma between 80 and 30Ma and the hydrological regime became strongly seasonal, it is reasonable to envisage that large parts of the palaeo-drainage system became ephemeral and that possibly in places fragmented into a series of closed (endorheic) basins (Figures 19A - 19C).

T. C. Partridge and R. R. Maud (1987) concluded that the widespread fluvitile and lacustrine Kalahari sediments were deposited between the Mid-Palaeocene (ca. 60Ma) and the Pliocene (ca. 2.5). They consider that the extensive calcrete and silcrete deposits formed from the Mid-Pliocene onwards as the result of increasing aridity. Adding detail, I. G. Haddon and T. S. McCarthy (2005) assign a Late Cretaceous date to the river gravels and outwash deposits found at the base of the Kalahari Group. They envisage Early Palaeocene tectonic block faulting, tilting and down-warping of the Kalahari Basin as leading to the merging of colluvial tracts and the spread of shallow lakes that were infilled by lacustrine clays and marls. The denudation of the Basement rocks and Karoo Group formations over surrounding uplifted swells was the source of the sediments but there was considerable re-working of the sediments. There is agreement that the formation of extensive calcrete and less extensive silcrete beds reflects more arid periods but generally, the palaeo-climate comprised clearly defined wet and dry seasons in-line with the modern climate.

Two approaches are taken to defining the geology of the Lower Kalahari Group Formations. The first categorises the formations by lithology and the second attempts to apply a more rigorous time base stratigraphical classification. The lithological approach is dictated by a lack of exposed sections and a consistently datable fossil or mineralogical record.

D.S.G. Thomas and P. P. Shaw (1991) adopt the lithological approach and recognise four main units in the Lower Kalahari Group succession:

- conglomerate and gravel units that sporadically occur at the base of the Lower Kalahari Group and occasionally within the other units;

- pink to red, fine-grained, homogenous marls;
- varicoloured, sandstones;
- calcretes, silcretes and other duricrusts.

Given much of the Kalahari Group occurrence is less than 100m thick in the Okavango Basin (Figure 19), this lithological classification has been widely applied to hydrogeological investigations in central and southern Botswana where the focus is largely on recharge studies. It is also appropriately applied to the thick, rapidly-infill stratigraphy of the Okavango Delta proper. Here the Lower and Upper Kalahari Group reach a maximum thickness of over 400m (Figure 21).

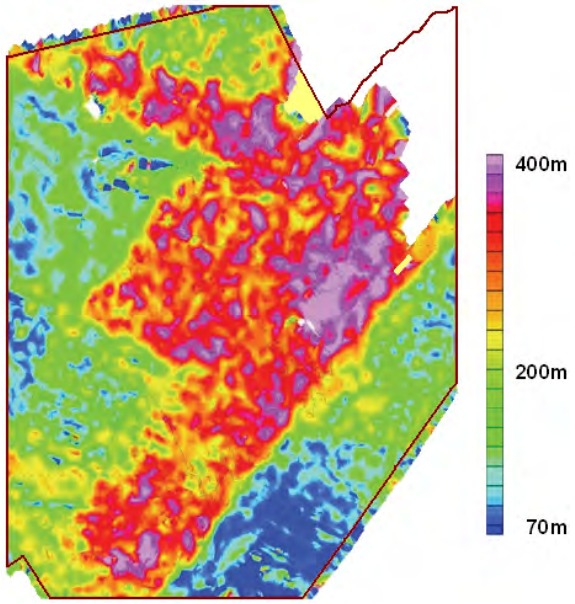


Figure 21: Thickness of Kalahari Group formations under the Okavango Delta (from W. Kinzelbach 2006).

Figure 20

In the Ovambo Basin in Namibia, the Kalahari Group occurrence is thicker than 100m and a formal lithostratigraphic succession has been established as shown in Figure 22. This succession recognises sub-divisions that are largely based on palaeo-environmental factors revolving around low-energy deltas and shallow, ephemeral lakes under arid and semi-arid climatic conditions.

How this lithostratigraphy applies to the Namibian and Angolan parts of the Okavango Basin remains to be confirmed but I. G. Haddon and T. S. McCarthy (2005) propose a provisional cross correlation for the entire Kalahari Group occurrence. As the Kalahari Group occurrence in Namibia and Angola are relevant to the groundwater resources of the Okavango Basin, the Ombalantu Formation and part of the Belseb Formation in the Ovambo Basin are correlated with the clayey Tsumkwe Formation in Eiseb Graben adjacent to the Botswana border (Figure 23).

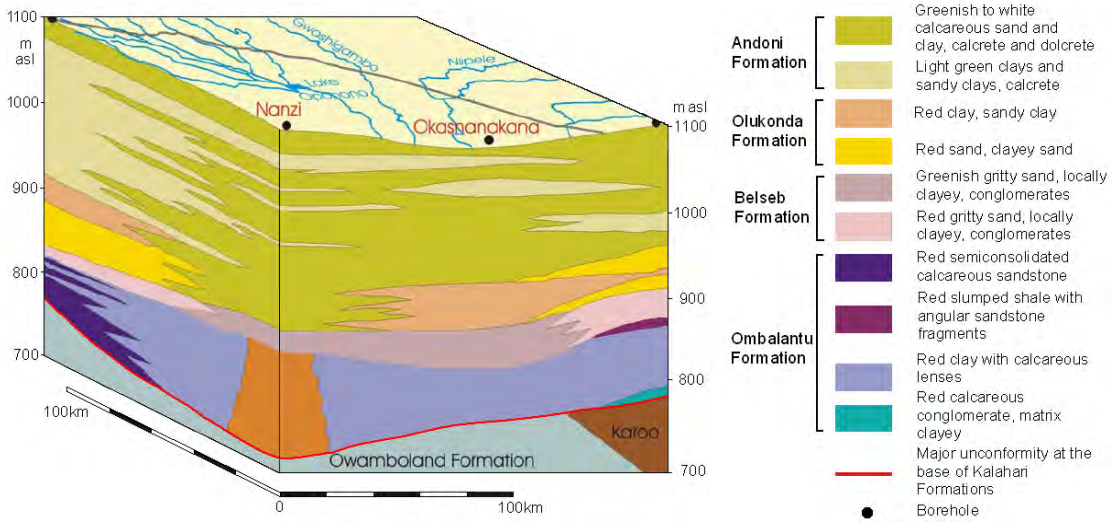


Figure 21

Figure 22: The Kalahari Group stratigraphy of the Ovambo Basin, Namibia (redrawn based on M. H. T. Hipondoka, 2005).

Although more remote from the East African Rift System from where these tectonic features are widely assumed to be propagated, the Eiseb Graben (Figure 3) is identified as a south-western extension of the Okavango Graben (H. Wanke, 2005) and the currently unconfirmed stratigraphy of the Lower Kalahari Group under the Okavango Delta may share a similar correlation to that of the Eiseb Graben.

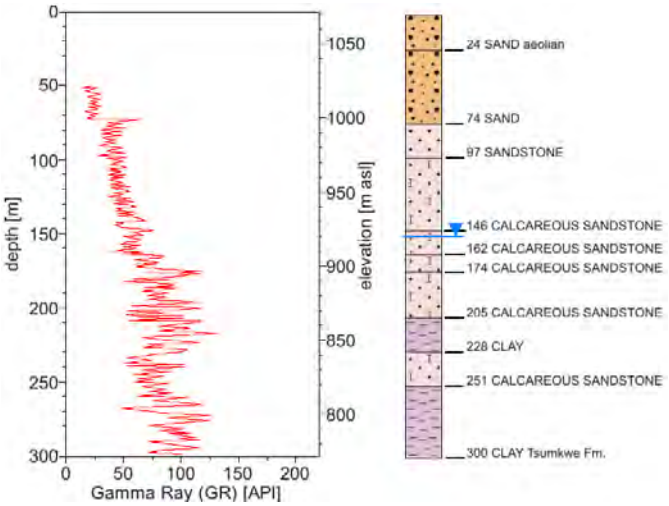


Figure 22

Figure 23: Log for Borehole WW41024 drilled in the Eiseb Graben (adapted from C. Stadtler et al. 2005).

The map of Kalahari Group thickness (Figure 20) shows the lower Cubango and Cuito Rivers in southern Angola and along the Angola-Namibia border is clearly cross the NE extension of the Ovambo Basin were at least the upper part of the Lower Kalahari Group will closely correlate with the succession shown on Figure 22. The same assumption, however, may not apply to the virtually unreported Kalahari Group occurrence in the upper catchment of the Cuito River where over 300m of the Group sediments underlie the water divide between Cuito and Kasai River Basins. The surface water drainage pattern is very linear and sub-parallel with strongly meandering consequent tributaries running SSE off the shoulder of the Biè swell. The tributary lateral valleys are wide with poorly defined drainage channels and the hydrogeological indications are that aquifer horizons of the Kalahari Group are effectively absorbing the majority of the annual precipitation. In view of the geomorphological

setting it is likely that the Kalahari Group in this area contains considerably more coarse clastic material in the succession than found downstream. Future investigations will establish if there are significant calcretes and silcretes in the northern Kalahari Group formations. While the more humid, long term, prevailing climate could be against the formation of these secondary deposits, if they are found to be extensive the role of groundwater circulation in their formation will require investigation.

2.7 The Kalahari Sands

Up to 50m thick, the Kalahari Sands extend over entire Okavango Basin and much of the more extensive Kalahari Basin in Namibia, Angola, DR Congo, Zambia, Zimbabwe and South Africa: The thickness may exceed 200m in northern Namibia. Largely derived from the Lower Kalahari Group and Karoo System formations, the Sands show typical aeolian landforms including dune fields. In the lower Cuito Basin and around the Okavango Delta the dunes have a uniform E-W orientation. In detail, however, the finer individual sand grains show less rounding and the deposits are less well-sorted than normally associated with purely aeolian deposits (B. M. Savory, 1965).

Although the deposition of the aeolian Kalahari Sands in the Pliocene and Pleistocene are largely linked to climate changes, continuing tectonic movements changed the geometry of the drainage system. The climate changes were associated with northern hemisphere glacial events as shown by the analysis of recent scientific core drilling of sediments at the bottom of Lake Malawi. These have provided a detailed climatic record dating back to around 1.0Ma (R. P. Lyons et al., 2009, C. A. Scholz, et al., in press). This record shows the region to have experienced to two relatively recent mega-droughts between 70,000 and 135,000 Ka (thousand years before present) when Lake Malawi dropped to more than 550m below current levels. The 135 Ka drought lasted 20,000 to 30,000 years and the 70 Ka drought ca 5,000 years. These mega-droughts were more severe than those associated with the last glacial maximum. Since 70Ka, the Lake Malawi has stabilised around the current level but significant precipitation fluctuations have occurred in parallel with Holocene climate changes in the northern hemisphere.

Possibly as early as the Pliocene (ca. 5Ma) tectonic shifts formed the Palaeo-Makgadikgadi Lake Basin (D. R. C. Grey and H. J. Cooke 1977 and T. C. Partridge and L. Scott, 2000). Evidence of the Pliocene and Pleistocene geomorphology and extent of the Palaeo-Makgadikgadi Lake during the pluvial periods has not been established: And it may not exist due to subsequent re-working and re-deposition of the Pleistocene alluvium during the last high lake level stands as shown on Figure 24.

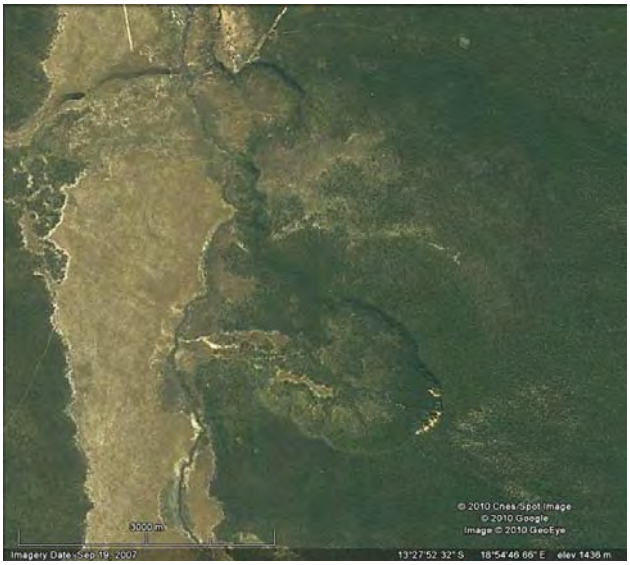


Figure 23

Image 1: Kalahari Sands, slump and slip features in the Upper Cuito Catchment (Google Earth Image centred on 13^0 27' 52" S, 18^0 54' 46" E, ground elevation 1436m).

The ferrasols developed on the Kalahari Sands have very high infiltration capacity and effective porosity: When saturated the soils and Kalahari Sand profiles have a low structural strength giving rise to frequent rotational and slump slips on even moderate slopes (Image 1).

2.8 The Tectonic Development of the Okavango Graben

Figure 24 shows the proven and inferred distribution of the main faults associated with the Okavango Graben.

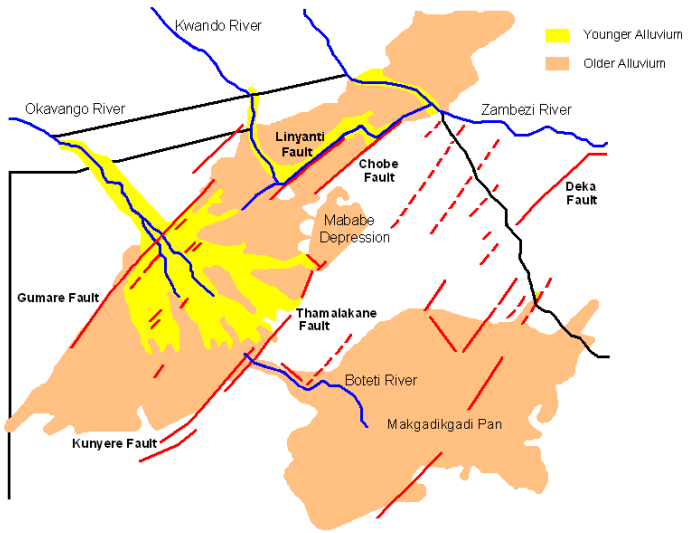


Figure 24

Figure 24: The proven and inferred faults associated with the Okavango Delta and distribution of the Pleistocene and Recent alluvial tracts (adapted from I. G. Haddon and T. S. McCarthy, 2005).

Despite unresolved views as to the exact nature of the Okavango Graben as shown on Figure 25, the Basement bedrock geology and structural features shown on Figure 3 clearly have had a long term control over tectonic development of the modern grabens and fault blocks as highlighted by M.P. Modisi, et al. (2000), E. A. Atekwana, et al. (2005) and H. Wanke (2005). The currently dominant NE-SW structural trends aligned with the East African Rift System are superimposed on older rifts termed the NW Botswana rift system that was

initiated around 1100Ma: That is prior to the formation of the Pangaea supercontinent (R. Key and R. Mapeo, 1999). This rift system was active again during the break-up of Pangaea and Gondwana and the deposition of the Karoo Group. The separate phase of pre-Karoo rifting on a NW-SE trend is less well defined but is reflected in the interpreted bedrock structure as shown on the block diagram Figure 26, and as previously noted, is followed by the Okavango mafic dyke swarm.

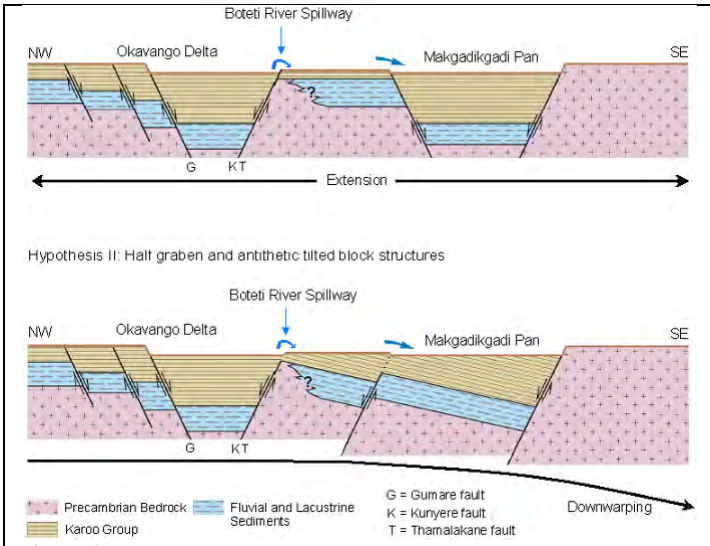


Figure 25

Figure 25: NW-SE schematic section through the Okavanga Delta area showing possible interpretations of the graben structure (from J. T. Meier, T. Himmelsbach and J, Böttcher, 2008).

Gravity, airborne and surface magnetic geophysical surveys (C.V. Reeves and D. G. Hutchins, 1976, M. P. Modisi, et al., 2000 and S. Yawsangratt, 2002) have supplemented the limited information available from deep boreholes drilled in the Delta area shown on Figure 27. M.P. Modisi, et al. (2000) considered the structure to be a half graben with late Tertiary to Recent down throws ranging from 200 to 300m. E. A. Atekwana, et al. (2005), however, consider it to be a full graben (Figure 25) with downthrow of 400 to 700 m. The intra-Karoo and post-Karoo downthrows are unknown.

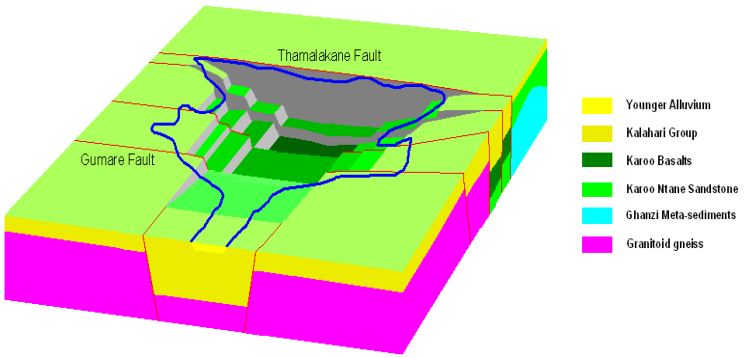


Figure 26

Figure 26: Simplified block diagram showing the graben faulted structure underlying the Okavango Delta based on geophysical data and borehole information as indicated on Figure 26 (based on W. Kinzelbach, et al., 2006 and C. Milzow, et al., 2009)

H. Wanke (2005) traces the Okavango rift faults into the Eiseb Graben and confirms the rift system as actively controlling the deposition of the Karoo Group as well as the Kalahari Group. He also notes very recent displacement (post 38Ka) of the Pleistocene dunes by the movements along the faults.

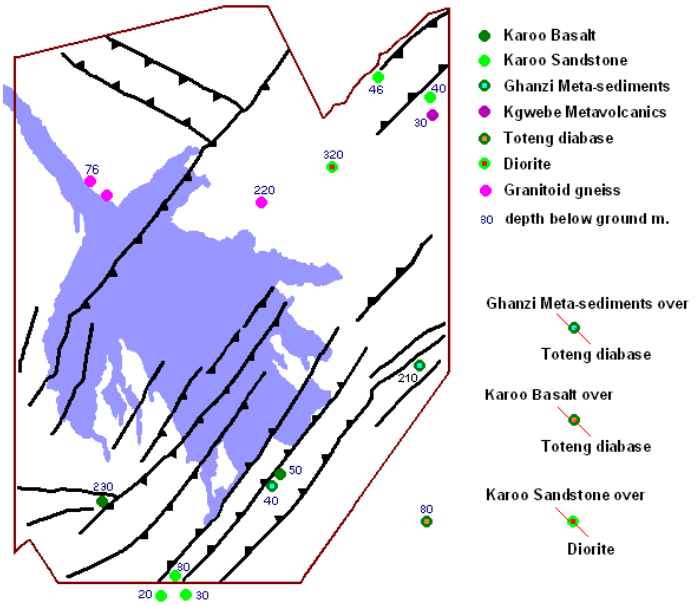


Figure 27

Figure 27: The Okavango Delta, bedrocks underlying the Kalahari Group formations, depths based on borehole data (from UNESCO, 2007).

2.9 Impact of the Palaeo-geomorphological Legacy in the Okavango Basin

Given the key factors in soil formation are parent material, climate, topography, soil biota (vegetation and organisms) and time, the most obvious palaeo-geomorphological legacy is the prevalence of predominantly loose arenaceous soils that cover around 90% of the Basin: Figure 28 shows the distribution of the main soil groups in the catchment and their characteristics. The classification system used is largely based on how the soil was formed (pedogenesis).

Since the start of the Karoo Group deposition around 310-300Ma, all the soil forming materials have been derived from within the Okavango Basin by the mechanical and chemical weathering of Basement rocks apart from the Stormberg Basalts, the mafic dyke swarm, the dacite sills and the two phases of Kimberlite pipe intrusion. The Karoo Group sediments can be considered as a mechnaical and chemical transition stage (as can the Lower Kalahari Group) as the continental weathering, transportation and deposition processes continued to mould the landscape and create the soils of the Basin.

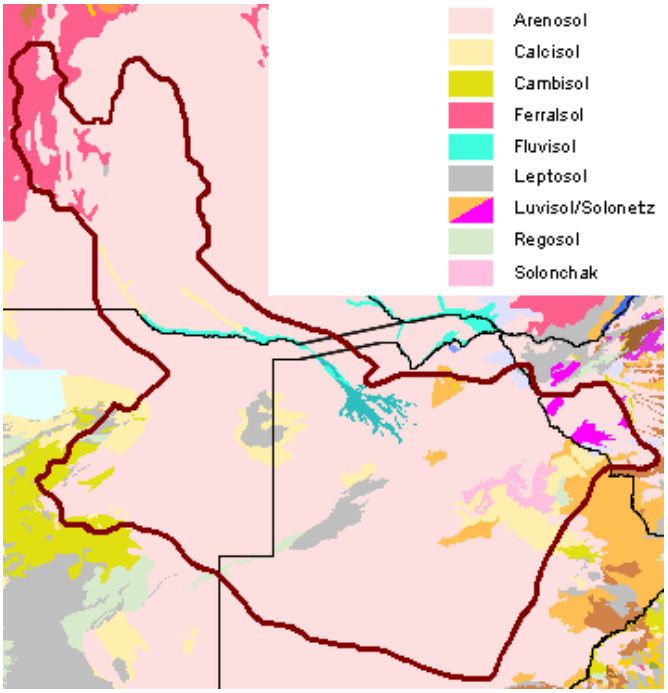


Figure 28

Figure 28: Soils map - Okavango Basin, (extracted from HWSD,2009 - Harmonized World Soil Database Viewer, FAO/IIASA/ISRIC/JRC by L. Verelst, IIASA).

Main soil characteristics:

Arenosols (AR)**:** Sandy soils featuring very weak
or no soil development
Calcisols (CL)**:** Soils with accumulation of
secondary calcium carbonates
Cambisols (CM)**:** Weakly to moderately
developed soils
Ferralsols (FR)**:** Deep, strongly weathered soils
with a chemically poor, but physically stable subsoil
Fluvisols (FL)**:** Young soils in alluvial deposits
Leptosols (LP)**:** Very shallow soils over hard rock
or over unconsolidated very gravelly material
Luvisols (LV)/Solonetz (SN)**:** Soils with subsurface accumulation of high activit
clays and high base saturation
Regosols (RG)**:** Soils with very limited soil development
Solonchaks (SC)**:** Strongly saline soils

The relationship between the modern soils and the geology of the bedrock outcrops shown on Figure 12 is clear.

The predominance of ferrasols in the headwater catchment of the Cubango River conforms to the expected chemical and mechanical weathering products derived from felsic crystalline rocks under a warm humid to sub-humid climate (mean annual precipitation ca 600-1200mm) and with freely draining (open) and closed dual groundwater flow systems.

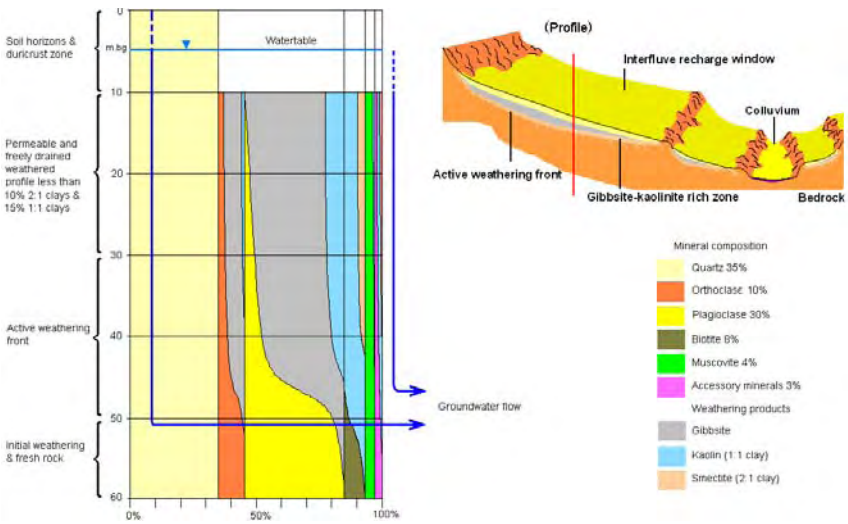


Figure 29

Figure 29: Approximations of the progressive open weathering profile and main secondary mineral products for a generic felsic granite.

Based on numerous published studies, the accepted weathering profile over a freely drained felsic Basement rock mainly comprises unaltered quartz grains, gibbsite ($Al_2Si_2O_5(OH)_4$– or more rarely halloysite ($Al_2Si_2O_5(OH)_4.2H_2O$) derived from the plagioclase feldspars, kaolinite ($Al_4Si_4O_{10}(OH)_2$) and minor amounts of smectite: Figure 29 illustrates an empirical distribution of the mineral fractions down such a profile. The weathered zone has a high micro-porosity and retains sufficient permeability for to allow recharge and drainage of weathering products.

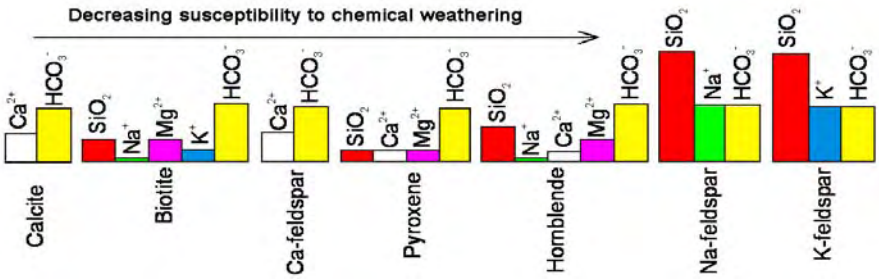


Figure 30

Figure 30: Calculated stripped ion content ratio derived form typical silicate minerals. The compositions are expressed as mole ratios relative to HCO3- (after R. Garrels, 1967).

With the objective of predicting water quality, R. Garrels (1967) calculated the proportions of ions in waters resulting from the weathering of the indicated silicate minerals to kaolinite as shown on Figure 30. The compositions employed for biotite, pyroxene and hornblende are typical those of igneous rocks. Thus, the major ion hydrochemistry of groundwater flowing through the weathering front is largely predictable with high concentration of calcium, magnesium and sodium as the main cations and a low concentration of iron and aluminium. Bicarbonate is the dominant anion: The draining groundwater will have a pH in the range of 6.5 to 8.5 with a higher pH capable of supporting higher dissolved amorphous silica levels (M. L. L. Formoso, 2006).

Image 1: Dambo landforms in the headwaters of the Cubango River – located ca 8km South of Chinhama, Angola (Google Earth Image centred on 13^0 09' 33" S, 16^0 27' 40" E, elevation 1624m).

Characteristic dambo landforms on the African Erosion Surface underlain by granitic Basement rocks are shown on Image 1. The term dambo is restrictively used to describe open, treeless, grass-floored, seasonally flooded valleys that lack of a clearly defined flow channel or gully. Hydrogeologically, dambos are associated with confined or closed weathering front aquifer and deep groundwater flow as shown on Figure 31.

The chemical weathering processes associated with the formation of dambos is focused on the removal of the most mobile cations, calcium, magnesium and sodium from the bottom of the saprolite profile by the deep groundwater flow.

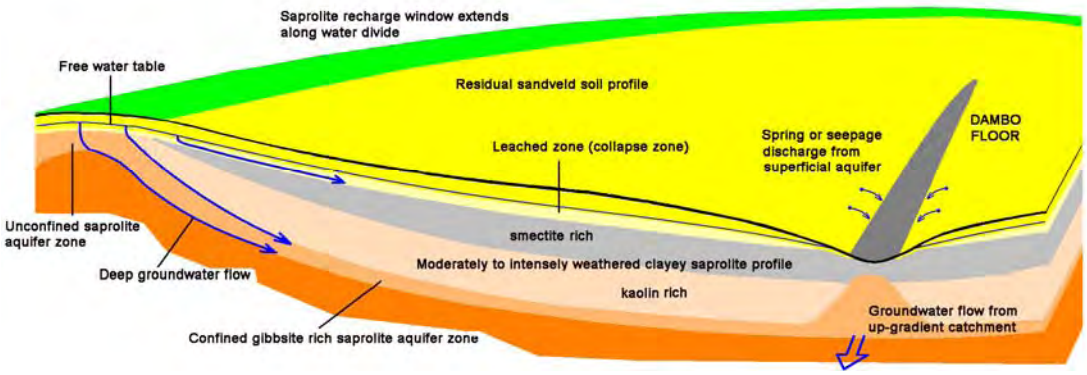


Figure 31

Figure 31: Schematic section of the integrated dambo model showing the three main morphological components, the recharge window, the confined saprolite aquifer zone under the interfluve and the dambo with the underlying gibbsite rich flow artery. Also shown are the geometry of the collapse zone and the springs discharging from the superficial aquifer. Grey saprolite zone indicative of high smectite content and very restricted water movement. The deep groundwater flow under the dambo floor discharges at a terminal dambo spring.

The soils overlying the water divides and interfluves of weathered crystalline Basement are dominantly free-draining ferrasols with an effective porosity of around 40%, a field capacity of 250 to 330mm/m and a wilting point of 165 to 210mm/m. They have a high infiltration capacity, often over 75mm/hr (NCSR 1971) and resist erosion other than the etchiplanation processes as described by E. J. Wayland (1933), B. Willis (1936) and J. Büdel (1982). This process allows for slow slope wash of sands down the interfluve towards the dambo floor where they form a wedge of residual colluvium along the break of slope. Geomorphologically, therefore, denudation from dambos catchments is less than 4m/Ma.

The distribution of the leptosols is limited to the crystalline felsic Basement outcrop in the Tsoilo Hills west of the Delta and over the Demara meta-sediment outcrops of the Ghanzi Ridge. This distribution reflects the more arid prevailing climate conditions. The mean annual precipitation is less than 600mm. The Ghanzi Ridge is a topographic high standing around 300m above the surrounding plains. The leptosols are the product of mechanical weathering processes with only superficial chemical weathering of the feldspars and ferro-magnesium silicate accessory mineral surfaces. Transported under arid and semi-arid conditions, these mechanically derived soils provide the source of future arkosic sandstones.

Apart from minor intercalated carbonate horizons, the moderately metamorphosed arkoses and shales of the Demara Group shared a similar depositional environment to the Karoo Group and under humid or sub-humid conditions could be expected to be subject similar chemical weathering to that shown for the sedimentary formations of the Karoo Group shown on Figure 9.

Active recharge and groundwater flow promoted by free drainage of the geological formations are essential for chemical weathering to be effective over extended periods of time. This implies that the weathering of the Karoo Group formations shown on Figure 9 must have occurred during intervals when these conditions were met. Despite the Ecca and the Beaufort formations being laid down under deltaic, fluvial and lacustrine conditions, the survival of the minerals susceptible to chemical alteration (Figure 30) points to limited chemical weathering during and immediately after the deposition of these formations. The Ntane formation comprises largely continental arkosic sandstone and is buried under the sub-aerially extruded Stormberg basalt flows. These two formations have been substantially, but not completely chemically weathered.

The weathering of the Karoo formations must have taken place during the last accelerated denudation phase in the late Cretaceous that led to the formation of the African Erosion Surface and prior to the deposition of the first Kalahari Group formations. The groundwaters circulating in the Ecca, Beaufort and Ntane formations would have been essentially calcium, magnesium and sodium cation and bicarbonate anion rich, and could provide the main source of the calcrete forming minerals. Likewise secondary weathering of the smectites means circulating groundwaters exposed to the Stormberg Basalts would have been silica rich and could provide the source of the silcrete forming minerals.

Remote from the modern Basement outcrops, the re-working and deposition of material from the older formations as the Kalahari Group, has eliminated the bulk of the minerals susceptible to chemical weathering. The resulting weakly developed quartz rich, base-ion and nutrient poor sandy arenosols are, therefore, the dominant soils in the Okavango Basin.

Surveys of natural vegetation cover in Central and Southern Africa show a close correlation between the occurrence of the arenosols, ferralsols and leptosols soils and the distribution of characteristic “miombo” woodland (Figure 32). The typical grasses and trees of the miombo woodland are totally adapted to the base-poor, residual sandy soils developed by the in-situ weathering over the crystalline Basement or derived from clastic sediments sourced from the crystalline Basement and the certain Karoo sedimentary formations.

That the deeply rooted miombo woodlands and the sandy soils of the Okavango Basin evolved together over a significant period of geological time when climatic conditions have fluctuated within the broad range is a major factor in their current distribution. The long-term climate has, and does, range from semi-arid to humid with precipitation varying between 550mm and 1,500mm and an annual temperature fluctuating between 15°C and 25° C. More significantly has been the long-term division of the annual climate into clear cut wet and dry seasons. Variations in the density and prevalence of the deeply rooted miombo woodlands under present climatic conditions are subject to investigation under the International Geosphere-Biosphere Programme (IGBP) Kalahari Transect Project (K. K. Caylor and I. Rodriguez-Iturbe, 2004 and R. J. Scholes, P. G. H. Frost and Y. Uhong Tian, 2004). Below an elevation of around 1000m, the miombo woodlands give way to “mopane” woodlands across the sandy Karoo and Kalahari soils where groundwater levels are closer to the surface.

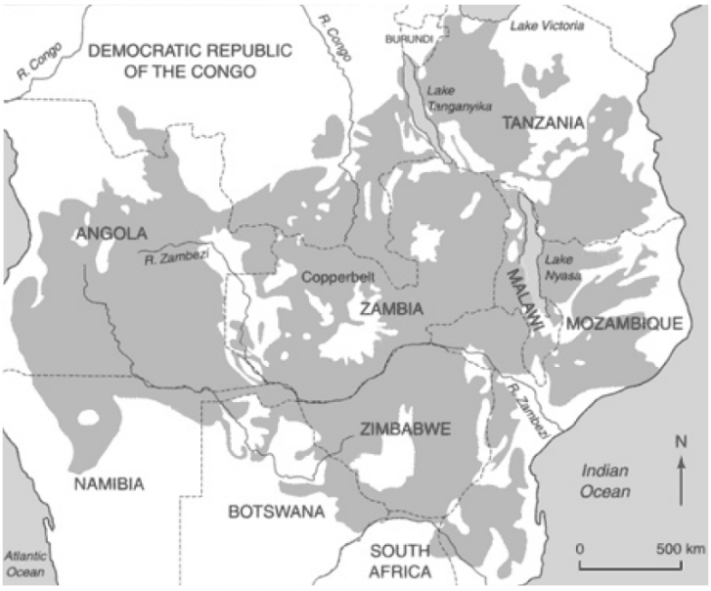


Figure 32: Distribution of Miombo Woodlands in Central and Southern Africa, from F White (1983) quoted in A. Malmer and G. Nyberg (2008)

Figure 32

The remaining soil classes have much more restricted occurrences closely tied to their geological or geomorphological setting as follows:

- Calcisols are associated with the extensive calcrete occurrences along the margins of the pans or “dry or fossil” river valleys;
- Cambisols are thin residual restricted to the Demara Group outcrops on the arid Botswana-Namibia border;
- Fluvisols occur along the course of the perennial surface water courses in the middle Cubango and Cuito Rivers and in the Okavango Delta;
- Luvisols are associated with the chemical weathering of the surface outcrops of Stormberg Basalts and are rich in 2:1 clays.
- Regosols are poorly developed and occur over the colluvial material found along the courses of the ephemeral rivers draining the high ground on the Botswana-Namibia border.
- Solonchaks are the strongly saline soils associated with the Makgadikgadi Pan.

3 THE GROUNDWATER OCCURRENCES AND QUALITY IN THE OKAVANGO BASIN

The tectonic framework, the distribution of the broad lithological divisions set out in Box 1 and the description of the late Tertiary and Quaternary evolution provide most of the necessary geological background required for the definition of the main hydrogeological provinces found within the Okavango Basin.

The main aquifers are clastic consolidated and unconsolidated formations with high primary, inter-granular porosity in the Karoo System and Kalahari Group formations. In addition, there are locally important aquifers in the Demara metasediments typified by the karst dolomites around Grootfontein, the Tosoilo and Aha Hills and in the colluvial outwash aprons and valleys fronting the crystalline Basement highlands.

In line with the surface water division of the Okavango Basin in to active and inactive hydrological systems based on the whether the sub-basins support perennial or non-perennial river flows, the first order division of the groundwater occurrences is based on the link between recharge potential and depth to groundwater plus consideration of the groundwater quality.

3.1 Potential Aquifer Recharge

Aquifer recharge is the net infiltrating water that moves from the land surface or the unsaturated zone to the saturated zone. Recharge can be expressed as a millimetre equivalent of precipitation or as cubic metres of flow. There are three main natural aquifer recharge mechanisms – “Direct” or diffuse recharge, “Indirect” or concentrated recharge and “Underflow”.

The four environmental factors controlling aquifer recharge are:

- Climate that includes the intensity, duration and volume of the precipitation;
- The hydrogeological influences that include the geomorphology, geology and pedology of the land surface;
- The surface water run-off regime and ;
- The vegetation cover/land use.

Direct or diffuse recharge describes the process where precipitation passes vertically from the ground surface through the unsaturated zone to the water table. Direct annual recharge mirrors the rainfall pattern and is very variable. Based on mean annual values, in the tropics the cut-off value for meaningful direct recharge is 600mm. Below this mean value, direct recharge is erratic and unpredictable. Above 600mm recharge can be expected to rise exponentially, become predictable and above around 1200mm, the available aquifer storage can become a factor as to whether recharge is accepted or rejected.

Indirect aquifer recharge occurs wherever runoff takes place. This runoff can be generated locally or come from a remote upstream source. Indirect infiltration of runoff is the dominant recharge mechanisms in semi-arid and arid regions where rainfall is limited to three to five storms a year with individual storms lasting only few hours. In addition, it has been

recognised that 5 per cent of the storms cause over 50 per cent of the stream flow and that approximately 15 per cent of the floods produce 90 per cent of the total stream flow.

Underflow recharge is used to describe large-scale lateral groundwater transfers between regional aquifers.

The scope for the aquifer recharge in the Okavango Basin, therefore, revolves around the distribution and amount of precipitation, the infiltration capacity of the soils and the geological setting of the aquifers. The annual rainfall is generally limited to a few months and the year is divided into clearly defined wet and dry seasons. Under the prevailing arid and semi-arid climate across much of the Okavango Basin, the main differences in the rainy season are its duration and the number of rain days. As the climate becomes drier, rainfall in the wet seasons tends to become more variable in both quantity and distribution. Many of the rainfall events are of relatively short duration and highly localised making it inherently difficult to sensibly quantifying any hydrologically response particularly when the analysis is based on mean daily, monthly or annual data. This particularly applies when trying to establish aquifer recharge.

As the need to monitor the hydrochemistry of precipitation has emerged to help elucidate infiltration and aquifer recharge, differentiation between the cyclonic or convection origin of the rainfall becomes particularly relevant in the semi-arid zones that receive storms spilling over from neighbouring humid zones. In these zones, frequently less than 25 percent of the rainfall may come directly from the oceans. The remaining 80 percent of the precipitation originates as recycled evapo-transpiration.

Figure 33 shows a preliminary distribution of aquifer recharge mechanisms and potential for recharge events to occur based on a subjective appreciation of numerous worldwide recharge assessments: The exceptional recharge to the karstic dolomite aquifers in the Otavi Mountains around Grootfontein is has not been incorporated in this Figure.

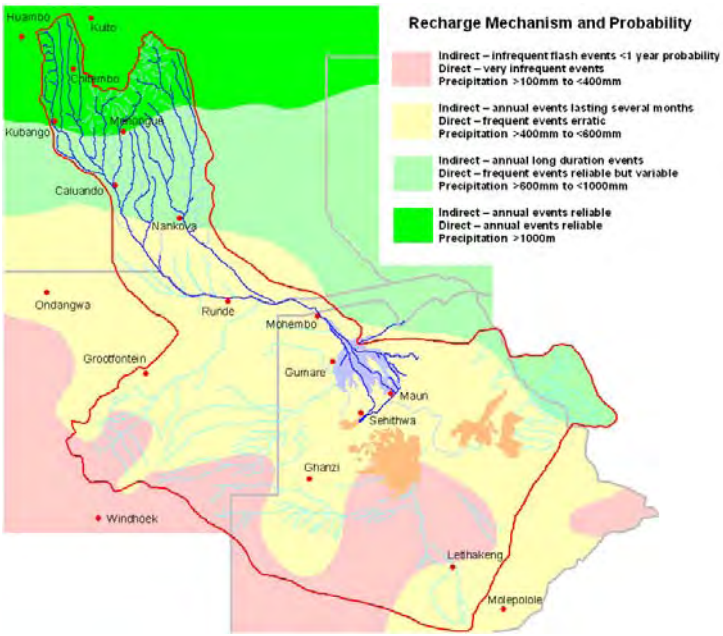


Figure 33: Preliminary distribution of potential aquifer recharge in the Okavango Basin based on subjective consideration of mean annual precipitation. No allowance is made for influent seepage from the main rivers (based on Department of Environmental Affairs (Botswana), 2006). Perennial rivers in mid blue, seasonal and ephemeral in light blue.

Figure 33

Box 1: Okavango Basin - simplified hydrogeological classification of with basic properties and characteristics

Geological Formation	Water bearing properties	Aquifer Characteristics	Geomorphological setting	Dominant recharge mechanism	Large (L), medium (M) and (S) small (localised) scale examples
Unconsolidated					
Colluvial outwash deposits , mountain front scree, talus.	Primary, inter-granular porosity and permeability	Poor - excellent	Mountain front	Indirect >> direct	(S)
Alluvial sand, deltaic sand		Fair – moderate	Deltas, valley floor floodplains	Indirect (~influent)	(L) Okavango Delta (M) Cubango and Cuito River Valleys
Interbedded alluvium, sand, silt, clay		Poor – fair	Valley floor floodplains	Indirect (~influent)	(M) Cubango and Cuito River Valleys
Aeolian sand, loess		Fair – good	Dunes, blanket cover	Direct > indirect	(M) Northern basin areas
Aquicludes, clay, clayey sands & silts, marls, calcareous mud.		Very poor – poor	River backwater, flood plain, lagoon	None	
Consolidated					
Conglomerate, arkose		Poor – fair		Direct – indirect	(M) Ntane and Ecca Group
Sandstone	Primary ≤ secondary		Sedimentary basin	Direct – indirect	(M) Ntane and Ecca Group
Interbedded sandstone, siltstone and mudstones	Secondary		Sedimentary basin, rift valley floor (E and S Africa)	Direct – indirect	(M) Ecca, Beaufort Group
Siltstone	Secondary	Poor – fair			(M) Ecca, Beaufort Group
Limestone and Dolomite (marble)	Secondary , Karst		Sedimentary basins, elevated massifs	Direct - indirect	(S) Calcretes, Transvaal Group (L) Otavi Mts., Grootfontein
Crystalline Rocks					
Extrusive basalt, lava flows	Primary ≥	Fair to	Incised plateau,	Direct ≥	(L) Stormberg Basalts

	secondary	excellent		indirect	
Granites, Basement Complex (fissured), low and medium grade metamorphic Palaeozoic rocks	Secondary	Poor – moderate	Mountain, erosion scrap	Indirect ≥ direct	Localised across Basement outcrop
Basement Complex Weathering Front	Secondary	Fair - moderate	Continental peneplain	Indirect ≥ direct	(S) Upper Cubango Basin
Aquicludes					
Unweathered, massive Basement	Secondary	Very poor			Throughout Basement outcrop
Mafic dyke swarms	Secondary	Very poor			Okavango Dyke Swarm

3.2 Depth to Groundwater

Figure 34 shows the depth below ground of the groundwater rest water level for the main aquifer horizons in the Okavango Basin. The broad configuration of the deep groundwater levels mirrors the potential recharge and suggests a first order hydrogeological division of the Basin based on a line following the southern margin of the Ghanzi Ridge that extends eastwards to the south of the Makgadikgadi Pan as shown on Figure 35.

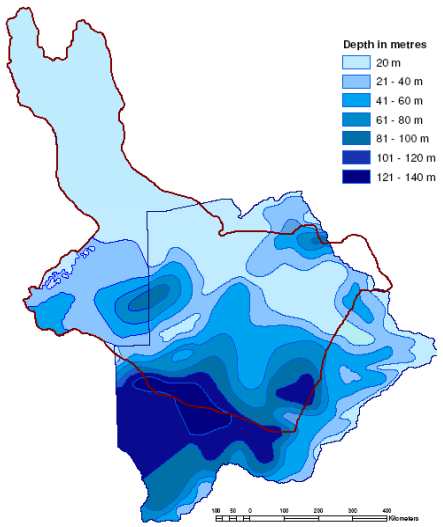


Figure 34

Figure 34: Depth below ground level to the groundwater rest water level for the main aquifer horizons in the Okavango Basin (adapted from Department of Environmental Affairs (Botswana), 2006 and Mendelsohn, J.M. & el Obeid, S. 2004 with additional extrapolated data for Namibia from H. Klock and P. Udluft, 2002).

Apart from under the Eiseb Graben, to the north of this line the depth to groundwater is less than 40m and there is a potential for aquifer recharge that points to active groundwater circulation. South of this line, the depth to groundwater is predominantly over 60m and, under current climatic conditions the aquifers receive little or no recharge.

3.3 Groundwater Quality

As a virtually closed drainage system and with high evaporation losses, the ground and surface waters of the Okavango Basin will be steadily accumulating dissolved solids as they move downstream.

The natural sources of dissolved solids in the ground and surface waters are entirely from the weathering of the exposed and buried bedrock formations and from the mineral content of the rainfall. There are no hydrothermal springs recorded within the Basin that could supply deep, mineralised, juvenile groundwater. (There are hot springs outside the Basin near Huambo and at Kasane.)

Given an expected annual chemical weathering denudation rate of the open groundwater flow system defined in Figure 28 of around 0.02 to 0.04mm for the Pre-Cambrian crystalline Basement occurrences in upper Cubango headwaters the resulting groundwater baseflow total dissolved solid (TDS) content will be in the order of 300 to 400mgl. The lower calculated denudation rate is not entirely outside the ranges modelled for silicate chemical weathering by C. S. Riebe, et al. (2001). The higher rate conforms with the 0.04 mm/year measured in Puerto Rico by B. F. Turner, R. F. Stallard and S. L. Brantley, (2003), R. C. Fletcher, H. L. Buss and S. L. Brantley (2006), S Brantley, et al., (2006), M.I. Lebedeva, R.C. Fletcher, V.N. Balashov and S.L. Brantley, (2007) H. L. Buss, et al., (2008) and S. Brantley (2008). The pH of the groundwater increases from around a pH5 where the recharge enters the aquifer to a pH over 8.5 as the weathering processes reach a chemical equilibrium.

Provisional modelling of the closed dambo landforms shown on Figure 30 point to a lower annual denudation rate of 0.017 to 0.034mm from the shallow groundwater flow system that discharges onto the dambo floor from the interfluves: This points to a shallow interfluves groundwater TDS content of around 100 to 200mgl. The deep weathering front groundwater flow will have a similar TDS content to the open system. These chemically weathering denudation-rates align with the 0.01– 0.5 mm/year as calculated from the silica fluxes in the world's ten largest rivers by G. E. Hilley and S. Porder (2008).
As indicated, the Karoo and Kalahari sedimentary formations are largely derived from denuded Pre-Cambrian Basement rocks and the metasediments of the Demara Group that were chemically weathered to a greater or lesser extent depending on the prevailing climatic conditions during transportation and deposition. The under humid conditions, the chemical weathering processes steadily released the more active metallic elements and anions as indicated in Figure 30. Rapid mechanical and fluvial transportation associated with the humid to and semi-arid conditions prevailing during the deposition of the Karoo Group formations, notably the Ecca and the Ntane Formations, allowed for the survival of the more chemically resistant sodium and potassium feldspars that characterise arkosic sandstones. These arkosic sandstones have been deeply weathered since deposition as shown on Figure 9. Across much of Kwenang in the Ecca formations contain unconfined groundwater with TDS in the order of 400 to 600mgl (J. L. Farr and S. S. D. Foster, 1978, B. Th. Verhagen,1995 and A. A. Aganga, C. M. Tsopito and K. More, 1997). Although this is slightly higher than that expected from weathered crystalline Basement rocks, the Ecca groundwaters receive little if any modern recharge and are considered to date back to ca 12,000 years BP (J. J. De Vries, J. J. and M. Von Hoyer, 1988). Experience elsewhere of modern Karoo groundwater quality under humid conditions suggest lower groundwater TDS with values often well below 100mgl (CCKK, 1982).

The weathering and depositional history of the Kalahari Group stripped of the most mobile ions and left the formations composed of essentially inert residue quartz, gibbsite and goethite. The very low active mineral content results in groundwater TDS values of less than 100mgl. At Mongu in Zambia, the TDS levels recorded from the Kalahari Sands of the Zambezi floodplain are less than 50mgl.

The igneous Stormberg Basalts, the mafic dyke swarm and the kimberlite pipes, however, are highly susceptible to chemical weathering. This is reflected by the distribution of the base rich luvisols and solonetz soils associated with the Stormberg Basalt occurrences in eastern and central Botswana and the strongly saline solonchaks in and around the Makgadikgadi Pan that is terminal drainage point for the runoff from these occurrences. Chemical weathering of the Stormberg Basalts strips the ultramafic biotites, pyroxenes and hornblendes of the mobile ions that are transported by ground and surface water flow to the Pan leaving the residual of active smectite clays to accumulate in the soils. As no well- developed groundwater occurrences are associated with these igneous rocks, the bulk of the chemical weathering products accumulate at the surface and are removed by surface runoff and interflow.

4 HYDROGEOLOGICAL PROVINCES OF THE OKAVANGO BASIN

Figure 35 shows a provisional distribution of main hydrogeological provinces identified using the proceeding criteria. The Cubango-Cuito Basin, the Omatako and Eiseb Basins and the Ghanzi Block are upstream of the Okavango Delta and the Makgadikgadi and Central Kalahari Blocks lie downstream of the Delta.

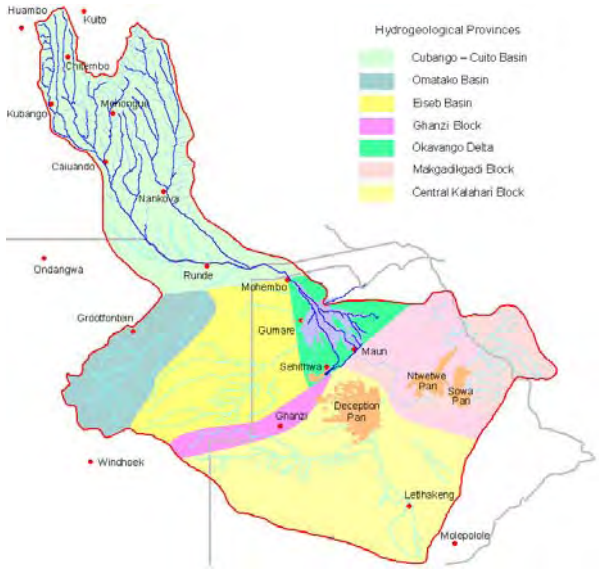


Figure 35: The Okavango Basin hydrogeological provinces. Perennial rivers in mid blue, seasonal and ephemeral in light blue.

Figure 35

4.1 The Cubango-Cuito Basin[1]

The lack of most forms of groundwater data means the resource assessment of these catchments has to be subjectively based on experience from similar hydrogeological provinces. Figure 36 shows the superficial geology of the Basins with the crystalline Basement outcrops underlying the almost the entire headwaters and upper basin of the River Cubango as far downstream as Caiundo and forming a clearly defined hydrogeological terrain. The lower Cubango and the the Cuito Basins are dominated by Kalahari Group formations. While ample examples of Basement groundwater occurrences are available from Zambia, Zimbabwe, Malawi and Tanzania, the only comparable Kalahari basins with a similar climate are in Western Zambia, northern Angola and DR Congo but these again lack groundwater data.

[1] Unless otherwise noted basin areas and mean runoff values for this section are taken for the FAO *Okavango River Basin Transboundary Diagnostic Analysis (TD)* Final Draft Report prepared in 1999.

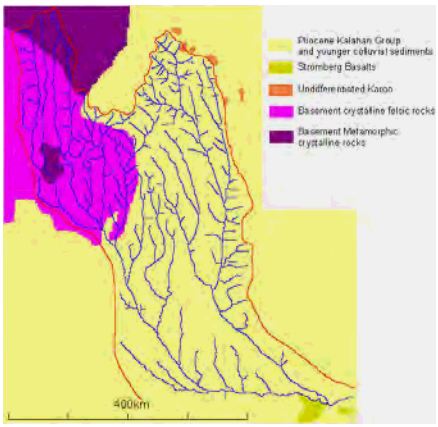


Figure 36: The superficial geology of the Cubango and Cuito Basin.

Figure 36

The Groundwater Resources of the Basement in the Upper Cubango Basin

Despite the lack of factual groundwater data, the surface water flow record for the River Cubango at Caiundo (Figure 37) coupled with satellite imagery enables a number of pertinent observations to be made regarding the groundwater occurrences in the crystalline Basement:

- With a catchment area of 38,486km^2, the mean 8 year (1963-1970) annual runoff of 5.716km^3 or 148mm is equivalent to 13.4% of the mean annual catchment rainfall of 1106mm (OKACOM, 2009). The basic graphical quantification (Appendix 1) of baseflow contribution from the 11 year record shown on Figure 37 varies from a low of 0.75 km^3 in 1972 to a high of 3.09 km^3 in 1969. The mean 11 year baseflow represents around 37.5% of the total mean annual catchment runoff and 5% of the OKACOM (2009) mean annual rainfall.

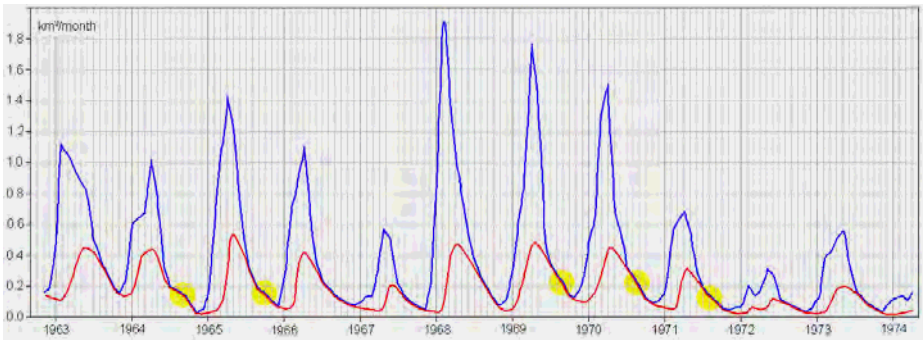


Figure 37

Figure 37: Hydrograph for the River Cubango at Caiundo with baseflow separation shown in red and dry season anomaly highlighted in yellow (adapted from D.A. Hughes, et al., 2004).

- Direct translation of the baseflow to recharge gives the following annual values:

Year	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Baseflow km^3/a	3.08	2.56	2.55	2.28	0.98	2.76	3.09	2.88	1.52	0.75	1.15
Baseflow/ recharge mm	80	67	66	59	25	72	80	75	39	19	30

- Although these recharge values are low compared to the regional estimates with similar annual rainfall as shown on Table 1, this comparison is of limited validity as

most of the values cited in this Table are for very small experimental catchments of less than 20km^2. However, there is scope for similar empirical analysis of the flow records from upstream hydrographic stations. These analyses would also benefit from acceptable estimates of mean precipitation over the associated catchment areas.

- The groundwater hydrographs for 1966-1971 from observation wells at Kabwe, Central Zambia (Figure 38) indicate how recharge is more dependent on the rainfall distribution and antecedent soil moisture conditions than the absolute seasonal total. M. Owor, et al. (2009) demonstrate in more detail this correlation between rainfall intensity and Basement aquifer recharge in Uganda.

Location	Rainfall mean mm	Estimated recharge mm	% of mean rainfall	Method	Reference
Aroca Catchment, Uganda	1400	200	14.2	Soil moisture balance	R. G. Taylor and K. W. F. Howard, (1996)
Livulezi, Malawi	~ 1140	145 114 234	12.7 10 20	Baseflow separation Chloride balance Chloride balance	E. P. Wright (1992)
Bua, Malawi	~ 940	14 188	1.5 20	Baseflow separation Chloride balance	E. P. Wright (1992)
Diamphe, Malawi	~ 850	75 97 152	8 11.4 17.9	Baseflow separation Chloride balance Chloride balance	E. P. Wright (1992)
D28, Zimbabwe	~ 890	80 80 115	9 9 14	Baseflow separation Chloride balance Chloride balance	E. P. Wright (1992)
Kabwe, Zambia					
Miombo woodland	924	80 281	8.7 30.0	Soil moisture balance Soil moisture balance	J. F. T. Huston (1982)
Cropped farm land					
Nyatsime catchment, Zimbabwe	~ 799 ~ 795 ~ 796 ~ 900	131 130 74 162	16.4 16.3 9.3 18.0	GW level data Chloride balance Reservoir method Flux analysis	B. Mudzingwa* (1999)
Marondera Grassland	~ 900	136	15.1	Chloride balance	M. P. McCartney* (1998)
Research Catchment, Zimbabwe	~ 900 ~ 863	185 190	20.5 22.0	Chloride balance GW level data	M. Jarawaza (1999)
Chiweshe, Mazowe, Zimbabwe	~ 900	71.6	4.1-7.9	Baseflow separation	R. Mjanja* (2000)

Table 1: Published recharged estimates for weathered Basement aquifers in southern and central Africa (* Source K. M. Sankwe, 2001).

- The baseflow separation shown on Figure 37 and the hydrograph for observation well ‘T’ on Figure 38 shows river flow and groundwater levels rising (highlighted in yellow) in response to reduced evapotranspiration losses in the cooler dry season.

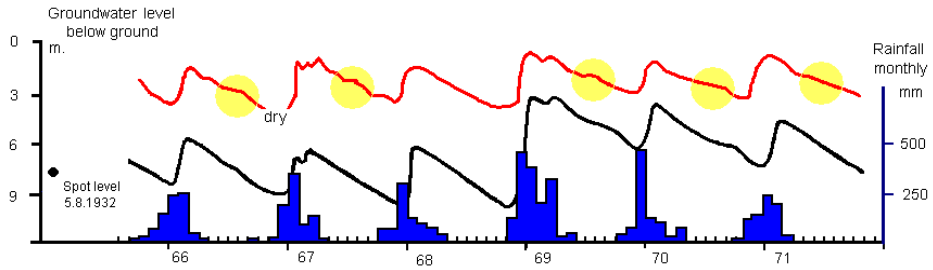


Figure 38

Figure 38: Groundwater levels recorded in Observation Borehole A – blue (Water Affairs Department, 47K-1) and Well 'T' – red. Weathered Schist and monthly rainfall between 1966 and 1971 at Kabwe, Zambia (re-drawn from M. J. Jones and K. D. Töpfer 1972).

The early vegetation flush of the miombo woodland is considered to reduce the soil moisture levels close to wilting point towards the end of the dry season (September-October). Depending on the temporal and intensity distribution of the precipitation, there can be a six to twelve week delay after the wet season starts before recharge is registered across the weathered crystalline Basement aquifers.

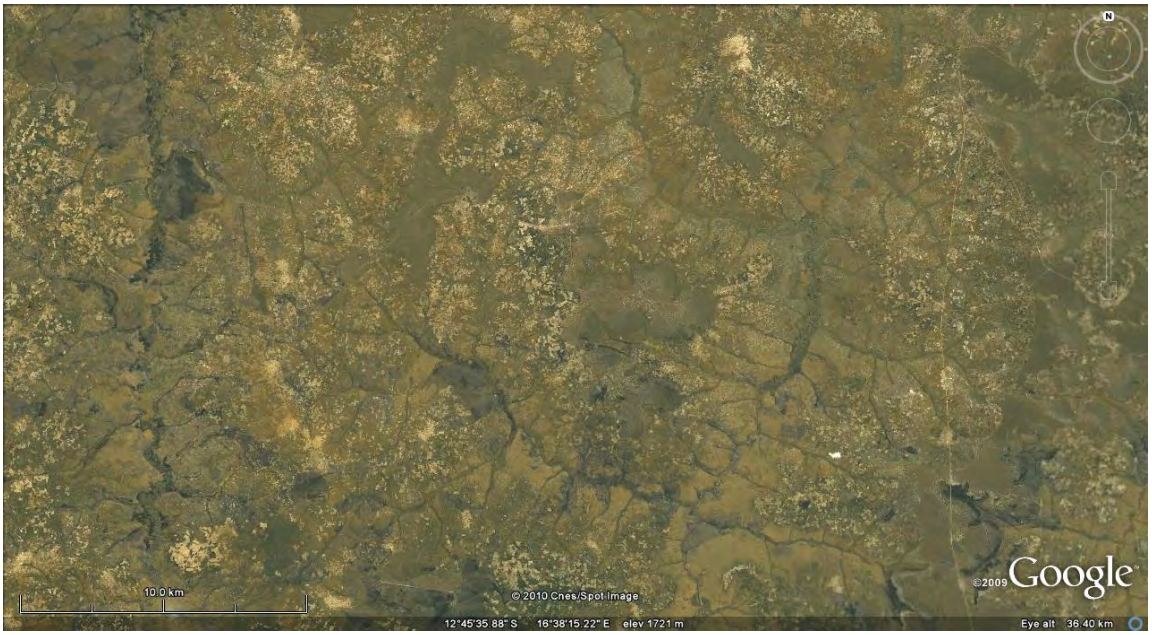


Image 2: Crystalline Basement terrain in the Upper Cubango showing the juxtaposition of dambo and normal headwater drainage basins across the African Erosion Surface west of Chinhama (Google Earth Image centred on 12^0 45' 35" S, 16^0 38' 22" E, elevation 1721m).

Image 2 typifies the crystalline Basement terrain in the upper Cubango Basin and points to a fairly uniform distribution of the weathered profile aquifers. Groundwater should be reliably available within the normal constraints associated with these aquifers. The productive weathered profiles should be less than 70m thick and the optimum well depth should be less than 100m. Rest water levels should be within 20m of the surface and well yields will be in the 2-10m^3/hour range. The groundwater quality will be generally potable with an EC of less than 750 µSm although the local geology may result in limited occurrences of unacceptable iron, manganese and fluoride levels.

The humid climate of the Upper Cubango Basin should be taken into account when seeking comparisons from similar weathered zone Basement aquifers: This makes northern Zambian and Malawi data more appropriate for comparison than examples from Zimbabwe. In addition, when assessing climate change impacts, it should be noted that the weathered profile aquifers remain robust and productive under the sub-humid and semi-arid climate of southern Zambia and Zimbabwe.

Hydrologically, the surface water runoff regime will be largely predictable from the weathered Basement terrain. The high infiltration capacity (>75mm/hr) of the soils over the recharge windows and interfluves means very little, if any, runoff is generated over these area during most storm events. The main sources of surface runoff from normal storm events will be generated over rock outcrops and the clayey dambo and regular valley floors.

The Groundwater Resources of the Kalahari and Karoo Groups in the Lower Cubango and the Cuito Basins above the Mukwe Hydrographic Station

The six year surface water flow record (1966-71) for the River Cuito at Cuito Cuanavale (Figure 39) shows the high baseflow contribution to the total flow. The River Cuito is clearly strongly effluent and is support by continuous groundwater inflow above and downstream of Cuanavale. Although a number of abstraction boreholes exist within the catchment, no hydrogeological information is available to assist with an assessment of the groundwater resources. However, the following observations can be made:

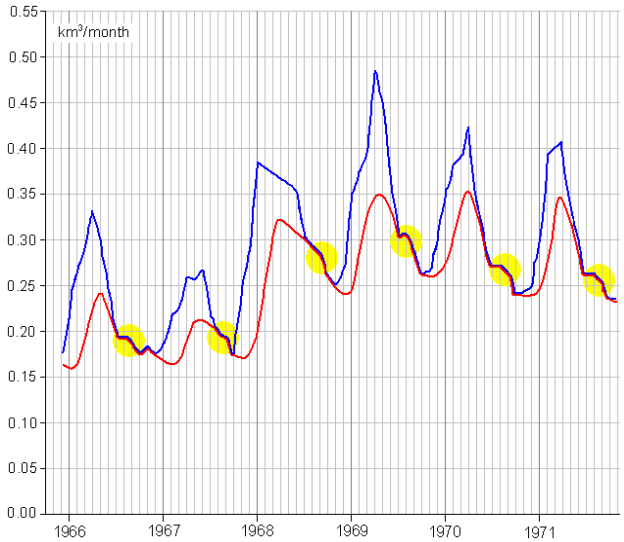


Figure 39

Figure 39: Hydrograph for the River Cuito at Cuito Cuanavale with baseflow separation shown in red and dry season anomaly highlighted in yellow (adapted from D.A. Hughes, et al., 2004).

- With a catchment area of 15,857km^2 (TWINBAS, 2007), the 5 year (1966-1970) mean annual runoff of 3.162km^3 or 199mm is equivalent to 18.5% of the mean annual catchment rainfall of 1073mm (OKACOM, 2009). The basic graphical quantification of the baseflow contribution for the 5 year record shown on Figure 39 varies from a low of 2.23km^3 in 1967 to a high of 3.395 km^3 in 1970. The mean 5 year baseflow represents around 73% of the total mean annual catchment runoff and 17.4% of the OKACOM (2009) mean annual catchment rainfall.

- The subdued wet season surface flood flows reflect low topographic gradients and high retention of rainfall in the soil, subsoil and the underlying geological formations.

- Direct translation of the baseflow to recharge gives the following annual values:

Year	1966	1967	1968	1969	1970

Baseflow km^3/a	2.305	2.23	3.415	3.475	3.395
Baseflow/ recharge mm	145	141	215	219	214

- The impact of the lowering of the cooler dry season evapotranspiration losses in the baseflow recession is clearer than that seen in the hydrograph for the upper Cubango at Caiundo. This indicates increased dry season groundwater flow from the interfluves to the rivers and illustrates vigorous groundwater circulation. The predominance of miombo woodland cover on the interfluves indicates that the top few metres of the soil and subsoil profiles will be at, or close to, wilting point and will be receptive to infiltration at the beginning of the wet season.

- The rapid throughput of groundwater under the interfluves can clearly seen on Image 3. This shows large areas of apparently natural open grassland straddling or close to the main surface water divides in the upper catchments of the Cuito Basin and the spring fed ponding of groundwater in the valley floor: Box 2 sets describes these geomorphological features and it distribution in some detail.

The main unknowns in this hydrogeological province hinge on the limited geological and hydrogeological data that is available for the Lower Cubango and Cuito catchments where active groundwater recharge supports the essential baseflow to the Okavango River runoff. Information on the nature of the groundwater occurrences, the depth to water and the yield of wells from the records of previous well drilling and testing programmes has not been located.

Karoo System formations outcrop to the north and northeast of the Upper Cuito-Kasai-Kwando water divides but the stratigraphy and lithology are largely undefined (Figure 6). The assumption, however, must be that aquifer horizons similar to those found in the other Karoo Basins will be present: Even if this is prove the case, the quality of the deeper groundwaters may be unacceptable.

Image 2: Open grassed areas straddling the Cuito-Kasai Basin water divide with groundwater fed lake at the head of a Cuito tributary valley – Google Earth Image from August 2007 centred on 12^0 39' 55"S, 18^0 21' 28"E, ground elevation 1493m asl.

The Kalahari Group sediments are reportedly over 300m thick but again stratigraphic and lithological details are poorly reported and again it must be assumed that the groundwater bearing properties of the formations must be similar to those reported from the Ovambo Basin in Namibia.

As a potential aggregate groundwater resource, the Karoo and Kalahari Group formations are expected to be reasonable rather than prolific. Groundwater should be widely available but individual well yields are expected to be in the range of 2 to 10 l/sec.

The strongly effluent rivers that drain the Kalahari Group and Karoo System in the Lower Cubango and the Cuito Basins indicate the groundwater storage of the aquifer formations will be fully saturated for most of the water year. The rainfall-infiltration-recharge balance suggests that given heavy groundwater abstraction, the hydrologic system would replenish the aquifers. Equally, downstream where the effluent groundwater discharge to the rivers reverses and the river becomes influent, groundwater abstraction close to the rivers will induce artificial recharge from the river to the wells.

A further outstanding question concerns the thickness of the active groundwater flow zones: It is possible that it extends less than 100m below the ground surface under the river beds. It could extend down to more than 250m if there are well developed Karoo System sandstone aquifers running under the basins. If this is the case, there is a slight potential for artesian groundwater to occur in the lower reaches of both basins. The trellis drainage pattern will capture groundwater under the interfluves that flow laterally parallel to the main river valley. A comprehensive regression analysis of the baseflow hydrograph recorded at Mukwe would provide approximate estimation of the volume of groundwater held in storage in the Cubango and Cuito Basins.

The longitudinal profiles for the Cubango and Cuito Rivers (Figure 40) provide geomorphological evidence of the past tectonic history of the basins. The three breaks in the Cubango profile above Caiundo point to base level changes since the uplift of the Biè swell around 30Ma. While the convex profiles of the intervening reaches are similar to dambo interfluve profiles, the convex nature could be a function of the drainage pattern and accelerated erosion as tributary rivers join the main valley. Further research should enable correlation between the dating of the triggering of the base level changes and depositional changes in the Kalahari Group sedimentation.

The upper Cuito profile mirrors the Cubango but the nick point some 40km upstream of the confluence of the two rivers suggests Late Pliocene – Pleistocene capture of the Cuito by the Cubango.

The suggestion that the trellis drainage pattern is a sign of a youthful Cuito drainage system (page 37 - J.M. Mendelsohn and S. el Obeid, 2004) breaks down when viewed against trellis drainage pattern seen around Katako Kombi in the DR Congo (Box 2, Image B2-1) and nick points along the Cuito profile. The trellis pattern could be a residual following the E-W dune lines seen around Vila Nova da Amada or function of the low structural strength of the soil and Kalahari Sand profiles (Image 1).

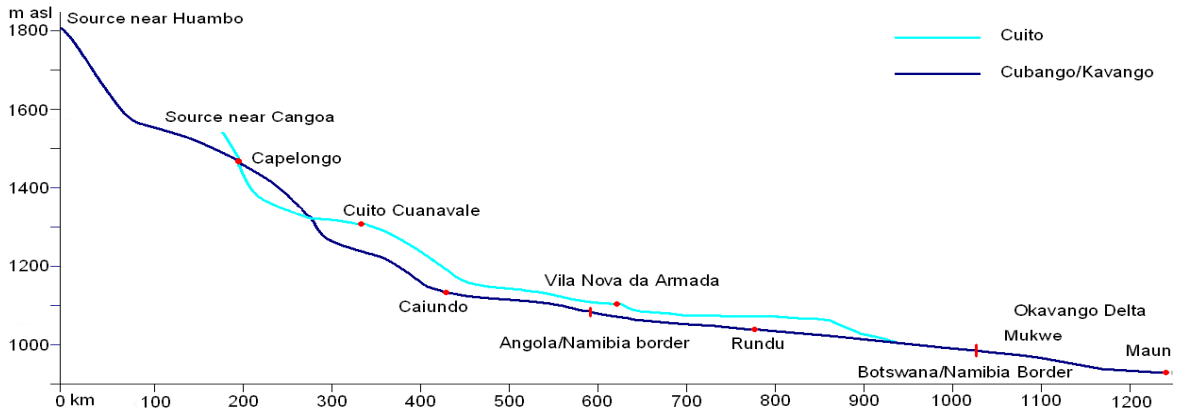


Figure 40

Figure 40: Longitudinal profiles of the Cubango and Cuito Rivers (based on J.M. Mendelsohn and S. el Obeid, 2004).

While some groundwater data is available for the Lower Cubango Basin below the Cubango, equivalent data from the Lower Cuito Basin remains to be established but there is every reason for assuming close similarities between these two areas. The merged flow from the two Basins forms the Okavango River above the Dealta and is measured at several sites. The 1960-1974 record of flow Mukwe is shown on Figure 41.

Box 2: Hydrological-land cover-soil configurations associated with Basement Complex rocks in the Congo Pedicle (DRC) to the east of Ndola (Zambia)

The following are extreme examples in the debate whether groundwater recharge is greater under forested or open grassland areas. Both examples have a significant spatial distribution across Central and Southern Africa. Geology, geomorphology and, to a lesser extent climate have a key role in their distribution.

Photo B2-1, Landscape near Katako Kombi, Kasai Oriental, DR Congo, 1983

The extensive open grasslands cover of the Pleistocene superficial alluvial deposits along the water divides near Katako Kombi (Photo B2-1) in Kasai-Oriental Region (DRC) have a very high infiltration capacity capable of adsorbing daily rainfalls in excess of 70mm without water-logging. In common with many land-cover units, these open grasslands are readily mapped using satellite imagery (Image 3-1). The superficial deposits are several tens of metres thick and are freely draining. The water table is deep despite mean monthly rainfall totals between 45mm and 200mm. The sandy soils are sufficiently fine to support a good perennial grass cover. As can be seen in Photo 3-1, tree cover on the water divides is limited to a few scatter clumps of acacia. In contrast the sharply incised valleys are densely forested. The alluvial deposits are underlain by less permeable Karoo and Cretaceous formations and the contact between the formations is marked by a well defined line of perennial springs. Further south and into Angola, the Kalahari Beds replace the superficial alluvial cover along the water divides but the extensive geographical distribution of nearly identical open grasslands and heavily forested valleys persists.

In contrast (Image B2-2) shows a reversal in the hydrological-land cover-soil configuration associated with the Basement Complex rocks in the Congo Pedicle (DRC) to the east of Ndola (Zambia). The water divides are moderately forested and the valley floors are characteristically wide open dambos. The heavy black expansive clay vertisols of the dambo floors are completely treeless, and despite relatively steep longitudinal gradients, they have no, or only a poorly defined water course for much of their length. Readily water logged during the rainy season, sheet flow is the dominant runoff mechanism. The valley slopes have characteristic heavily-leached, sandveld soil profiles with a shallow, perched water table that discharges by slow seepage along the dambo margins. The deeper groundwater flow through the weathered Basement Complex aquifer zone that underlies both the dambo and the valley slopes, discharges at lower end of the dambo and is marked by the emergence of a clearly defined stream channel. The geographical distribution of dambos is exclusively associated with crystalline Basement Complex rocks, the well established peneplain erosion surfaces and a humid tropical climate with a mean annual rainfall in excess of about 450mm. The term dambo, however, is frequent misapplied to waterlogged topographic lows associated with limestone and dolomite outcrops like the Itawa Dambo (near Ndola) and the

Chambishi examples in Zambia (P. Hadwen and M. J. Jones 1971, C. van der Heyden and New, M. G., 2003). In Tanzania the term mbuga is used to describe not only true dambos but almost all occurrences of black expansive clay vertisols and low-lying, swampy valleys.

Image B2-1, Satellite Image (Google Earth) West of Katako Kombe, DR Congo

Zambia
DCR

Image B2-2, Dambos in Congo Pedicle, DCR, due East of Ndola, Zambia, (Google Earth).

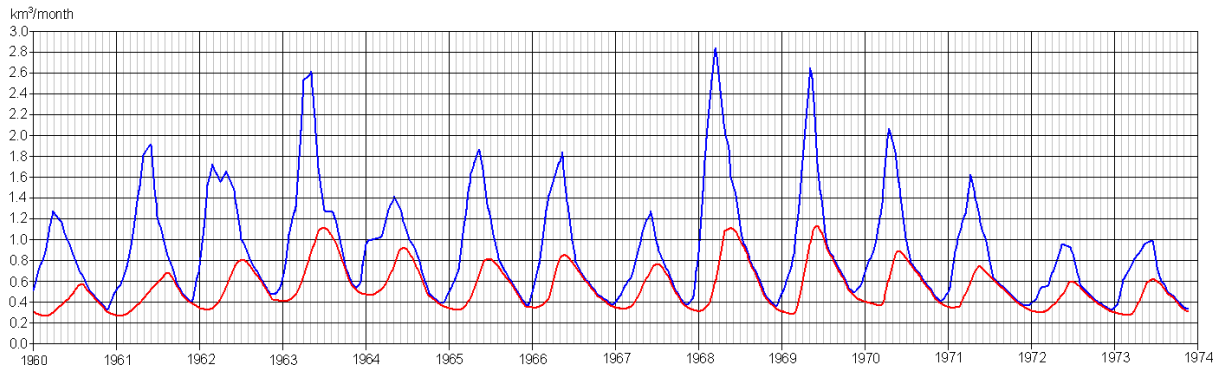


Figure 41

Figure 41: Hydrograph for the Okavango River at Mukwe with baseflow separation shown in red (adapted from D.A. Hughes, et al., 2004).

The following observations can be made regarding the Mukwe hydrographic record:

- With a catchment area of 226,236km^2 (TWINBAS, 2007), the 13 year (1960-1973) mean annual runoff is 9.5843km^3 or 42mm rainfall equivalent (TWINBAS, 2007). The basic graphical quantification of the baseflow contribution for the 13 year record shown on Figure 41 varies from a low of 4.58km^3 in 1960 and to a high of 8.73km^3 in 1963.

- Direct translation of the baseflow to recharge gives the following annual values:

Year	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Baseflow km^3	4.58	5.43	6.5	8.73	7.22	6.42	6.65	5.93	7.9	7.74	6.89	6.05	4.95
Baseflow recharge mm	20	24	29	39	32	28	29	26	35	34	30	27	22

- The strong baseflow component of the Okavango River as recorded at Mukwe below the Cubango-Cuito confluence is shown on Figure 41. Comparison of the combined annual baseflows in the River Cubango at Caiundo and the River at Cuito Cuanavale with the River Okavango baseflow at Mukwe suggests that the groundwater throughput across the lower reaches of the Cubango and Cuito is largely in balance.

The continual reworking of the geological formations in the basin accounts for the low mineral content of the active groundwater flows in the Cubango-Cuito Basin sediments. The geological history of the clastic sediments of multiphase re-working has stripped the mobile metallic ions from the mineral assemblage and this has virtually removed the possibility of active 2:1 clays from the unconsolidated alluvium, colluvium and soils. The major environmental and development issues with the groundwater occurrences are their high susceptibility to anthropogenic contamination and their high contribution to the surface water flows in to the Delta.

4.2 The Omatako and Eiseb Basins

Although topographically separate river basins with different discharge points, for the purposes of this hydrogeological report the Omatako and Eiseb Basins are considered together. Basement felsic cratonic rocks and metasediments belonging to the Demara Group

outcrop along the northern regional water divide. East-west trending outcrops of the Karoo System occupy the Waterberg and Eiseb Basins that disrupt the Basement and Demara outcrops along the western and southern water regional divides. Eastwards, the Basement, Demara and Karoo rock outcrops pass under thickening sediments of the Kalahari Group except where isolated Basement and Demara outliers form the Tsoilo and Aha Hills.

The crystalline Basement and Demara metasediments do not have a thick weathered mantle cover and the groundwater occurrences are limited to the mountain front and valley-fill, colluvial, outwash sediments and the fissure and fracture zones in the underlying bedrocks. The depth to groundwater in these areas is generally less than 40m below ground. Where well-developed, the limestone and dolomite formations in the Demara metasediments form important local groundwater occurrences around Grootfontein and in the Tsoilo and Aha Hills areas.

The nature of groundwater occurrences in the Karoo System in the Waterberg Basin are large unrecorded but the depth to groundwater near the regional water divide is deep (>40m) but becomes shallower (<40m) eastwards. The hydrogeological mapping of the area (Hydrogeological Map of Namibia, 2001) indicates the Karoo formations along the northern side of the Waterberg Basin have a high inter-granular aquifer potential. Due to the thick Kalahari Group cover (<up to 300m) the Karoo System in the Eiseb Basin has not been investigated.

Apart from the Tsoilo and Aha bedrock outliers, the entire central and eastern areas of the Omatako and Eiseb Basins are underlain by a continuous blanket of Kalahari Group sediments that are from 50m to over 300m thick. The groundwater potential over most of the Eiseb Basin is mapped as very limited and away from the ephemeral water courses, the groundwaters are essentially saline (C. Stadtler, et al., 2005). The prevailing depth to groundwater reflects the topography. The groundwater levels are deeper under the high ground in the western half of the Basins and shallower approaching the Okavango River and the Delta. Similar hydrogeological conditions are considered to extend to the east of the Namibia-Botswana border towards the Delta.

The groundwater under the interfluves of the Omatako River and tributaries is reported as saline.

Although the Basement rock outcrops and the storm intensities and frequency in the upper catchment of the Omatako River are sufficient to support runoff events to support urban water supplies from Omatako Dam, there is no record of any surface water flows from either basin reaching the main Okavango River or the Delta. Similarly there are no indications of significant groundwater underflow from the Basins to the Okavango River or Delta.

The distribution of potable groundwater reflected by the distribution of rural and urban water supply boreholes in the Namibian catchment areas (Figure 42), however, points to the importance of indirect recharge from storm flood events in the surface water courses in the middle and lower catchments. H. Wanke (2005) reports on the use of the chloride balance method to investigate diffuse recharge across the Omatako and Eiseb Basins as tabulated on Figure 42. The validity of the low diffuse recharge rates where groundwater levels are more than 10 to 15m below ground is examined in the section on the Central Kalahari Block.

Recharge to the limestones and dolomites around Grootfontein is reported on by G. Schmidt & D. Plöthner (2000) and H. Klock and P. Udluft (2002) used remote sensing to augment recharge evaluations to provisionally quantify the regional aquifer recharge and the groundwater balance for the Omatako and Eiseb Basins. They estimate an annual abstraction of 50 to 100Mm^3 from the approximate 1230 water supply boreholes shown on Figure 42 and calculate the annual regional recharge to be in the order of 140 to 730Mm^3. This is equivalent to an annual recharge of 0.9 to 4.5 mm assuming uniform distribution.

As the main focus of future water resource developments will be concentrated along the Okavango River between Katwitwi on the Angola-Namibia Border and Mohembo at the head of the Delta, the groundwater occurrences in part of the Okavango Basin should be closely monitored and investigated due to the vulnerability of the Kalahari Group aquifers to over-exploitation and susceptibility to contamination.

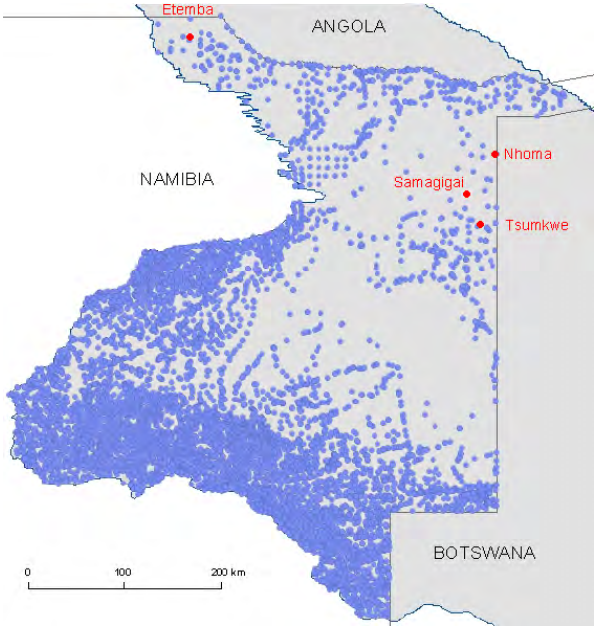


Figure 42

Figure 42: Distribution of water supply boreholes in the Okavango Basin within Namibia (from L. Veríssimo, 2009). Shows borehole sites following river courses in the middle and lower catchments of main water courses.

Chloride mass balance diffuse recharge determinations (from H. Wanke, 2005). Sites shown in red on map.

Location	Mean rainfall mm	Diffuse recharge mm
North Omatako	420	0.42
Omatako Vlei	440	3.70
Omatako Sand	440	0.86
Etemba	410	0.33

The extension of the Eiseb Basin towards the Delta is largely dominated by saline groundwaters that make any pockets of fresh groundwater equally vulnerable and requiring careful exploitation.

4.3 Ghanzi Block

Running some 350km, the ~50 km wide SWS –ENE axis of the Ghanzi Ridge rises some 300m above the surrounding Kalahari Basin. Formed of strongly folded clastic and minor carbonate metasediments of the Demara Group, apart from the thin limestones, these formations are unlikely to contain significant deep groundwater. The exploitable groundwater storage will be restricted to the colluvial outwash aquifers deposited in local depressions in the Kalahari superficial cover or along the valley floors (Figure 43 and 44) that are likely to be underlain by fracture or fissure zones that have been accentuated by structural unloading during the denudation of the land surface. The colluvial deposits were derived by the mechanical erosion and transport of the metasediments: These will be recharged by during flood flows associated with local or more extensive, semi-annual, storm events (G. Tredoux and S. Talma, 2007).

Figure 43: A cattle-post water point sited in a loosely closed topographic depression with the corralled cattle waste clearly viable clustered around the water point. Located 25 km NE of Ghanzi, Botswana (Google Earth Image centred on 21^0 34' 22" S, 21^0 50' 29", elevation 1140m).

Figure 43

The extent of the flood recharge was highlighted by the death of some 200 head of cattle due to acute nitrate poisoning traced to the groundwater supply boreholes after an exceptional rainfall event in 2000. C. Colvin, et al. (2008) report nitrate levels of 14 to 508mgl in samples collected in October 2000 from 13 boreholes along the Ghanzi Ridge. They identify the source of the build-up of nitrates to the concentrated cattle ranching activity in the areas around the supply boreholes. They also report the decline in the nitrate levels from 509mg in October 2000 to 45mgl in November 2004. This supports a very localised pollution plume model associated with a restricted contamination source located close to the contaminated water point.

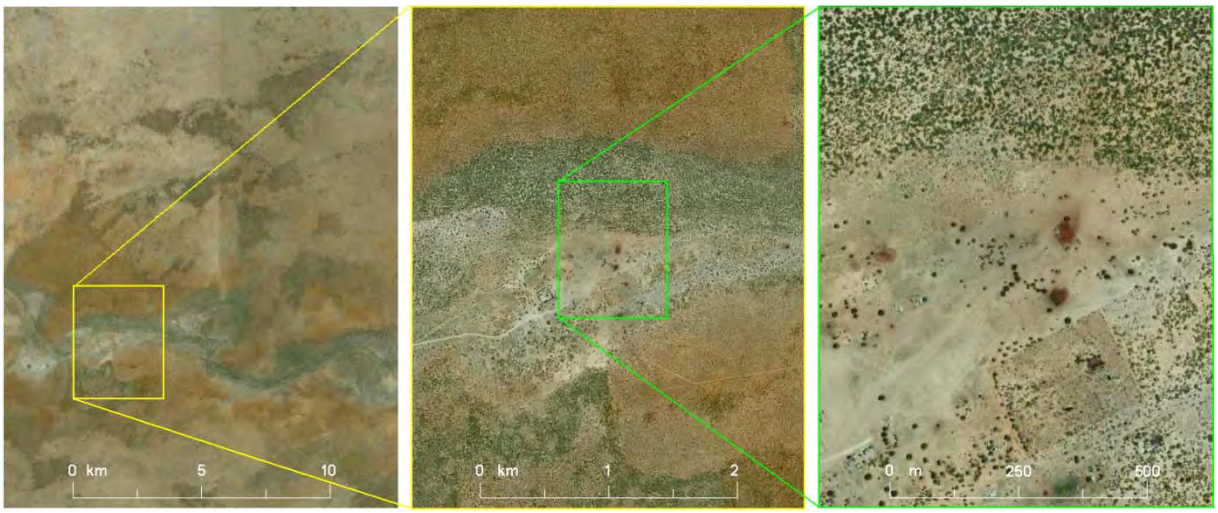


Figure 44: East Hanahai, Botswana, cattle watering points located in a well defined ephemeral river valley forming part of the Okwa drainage system. Clear surface accumulation of cattle waste visible, Google Earth Images, ground elevation of valley floor, 1077m .

Figure 44

A similar build up of nitrate levels in groundwater was noted at Lubbock, Texas where the Lubbock Land Application Sites (LLAS) was first used in 1925 to dispose of around 3,800 m^3/day of partially treated waste water over 80 ha using furrow and boarder irrigation. Lubbock is a major meat processing and packing centre. The problematical build up of nitrates in the unsaturated zone under the LLAS was first documented in 1968. The background level in groundwaters under the two sites averages 16mgl against the maximum permissible level of 10mgl. After the LLASs were formally cited by the State environmental

agency in 1989, clean up measures involving reduced irrigation applications and changes in cropping from grains to fodder marginally improved the nitrate levels but groundwater in wells to the south of the eastern LLAS was found contaminated. Direct grazing of the fodder by cattle was also found to have no or little effect on the soil nitrate levels.

C. B. Fedler, et al. (2003) report on effectiveness of the irrigation over the LLAS in the de-nitrification of the wastewater. They conclude that the de-nitrification processes are only partly understood, but consider it is highly dependent on soil moisture, temperature, soil type and carbon content. Removal rates ranged from zero to 80% of the nitrates in the applied water: The soil carbon content acts as an electron donor and significantly enhances the de-nitrification process.

The nitrate problem along the Ghanzi Ridge is focused by the valley and depression floor setting of the groundwater occurrences and is further reinforced by the low natural de-nitrification potential of the thin base ion and carbon poor soils and subsoils. Hydrogeologically the nature of the thin, poorly-developed soils and the granular nature of the colluvial aquifer makes tight sanitary sealing of the borehole annulus uncertain and it is possible that the borehole - formation interface may provide a major pathway for infiltrating surface water runoff.

C. Colvin, et al. (2008) show that the water supply borehole nitrate problem is not confined to the Ghanzi Ridge but is widespread across southern Africa where it has been investigated around Serowe (S. Stadler, 2005 and J. Meier, T. Himmelsbach and J, Böttcher, 2008). Here the source for the nitrate build up in the soil profile is concluded to be the result of natural biomass processes: An anthropogenic origin was dismissed.

Despite the topographic prominence of the Ghanzi Ridge its annual contribution to the surface and groundwater resources of the wider Okavango Basin under the current climatic regime is marginal.

4.4 The Okavango Delta

With the comprehensive records of borehole drilled in the Delta (Figure 45) and the substantial volume of surface and groundwater information, reports and publications, this report considers two main points:

- The definition of the usable aquifers and their resource potential.
- The groundwater transfer between the Okavango River input at the head of the Delta and the discharge zones to the south east along the Thamalakane Fault, towards the River Linyati and Savute Channel in the north east via the Seinda Spillway and possibly to the south west towards Lake Ngami.

Groundwater development for the Maun municipal water supply and for the towns and villages surrounding the Delta coupled with formal registration of water supply boreholes shows the fresh aquifer horizons to be unconfined or semi-confined, fine to medium grained sands lying within the top 120m of the Kalahari Group filling the Okavango Graben. The variability of the alluvial sediments can be seen on the borehole composite logs shown on Figure 46.

Depending on the topographic location, the groundwater levels lie within 3 to 20m below the ground surface. A persistent shallow sand unit lying within 18m of the surface is identified and contains good quality groundwater. Below 18m, rapid lateral and vertical changes in the alluvial fill result in a complex multilayered groundwater occurrence as shown on Figure 47. The water quality can also change rapidly from fresh to brackish to saline down to around 120m below which no fresh groundwater lenses are considered to occur.

Extensive pumping tests show borehole yields to be equally variable with a maximum of around 10l/sec and the mean to be 2 to 3l/sec: Interpreted transmissivity values range from 4 to 30m^2/day. The shallow groundwater occurrences of the Kalahari Group are reliably recharged by effluent seepage from the Okavango flows depending on the scale of the seasonal floods.

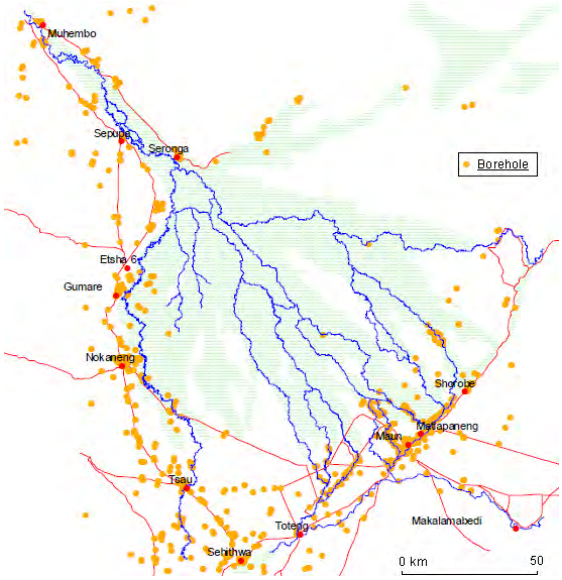


Figure 45: Okavango Delta - borehole location map of boreholes recorded by the Botswana Water Affairs Department (adapted from TWIBAS, 2007)

Figure 45

As seen in the Cubango and Cuito Basins, definition of the active groundwater flow zones under the Delta lies at the core to understanding of the groundwater circulation and resources. The geometry of the tectonic structure under the Delta dictates that all groundwater flow must take place through the Kalahari Group sediments but no well developed continuous sand horizons have been located within the multilayered formations. The ubiquitous salinity of the groundwaters below 120m points the elimination of deep groundwater circulation under the Delta.

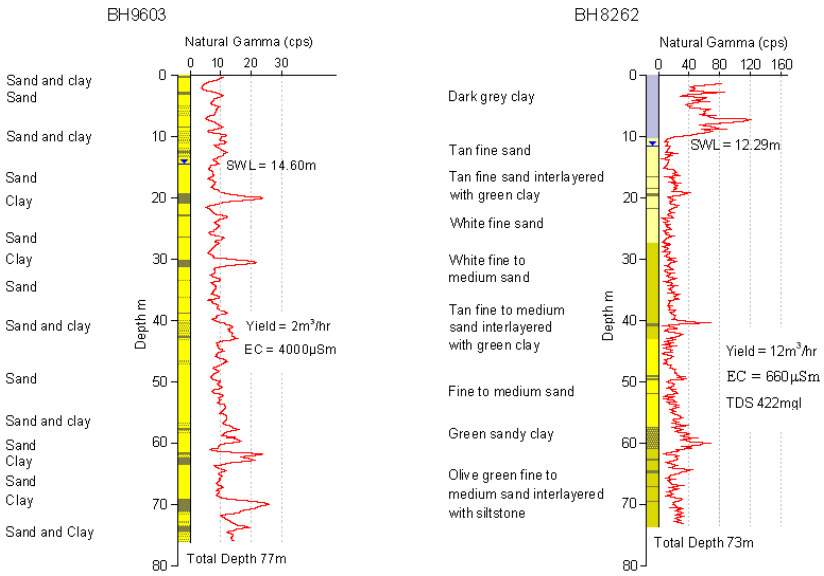


Figure 46

Figure 46: Typical composite borehole logs prepared for the Maun Water Supply study

(adapted from Mangisi, N., 2004).

The relationship between the surface water low flows in to the Delta and the groundwater regime is considered to be in broad balance. The limited aquifer storage leads to the rejection of excessive flood flows and the surface water hydrological response is an increase spill into the Boteti River with exceptional floods spreading to Lake Ngami in the west and the Mababe Basin to the east (Figure 25). The high surface water seasonal groundwater recharge is largely lost to evapotranspiration during the low flow months.

If there is large-scale transfer of groundwater towards from the head of the Delta and downstream
towards the River Linyati and Savute Channel in the north east via the Seinda Spillway it is not obvious.

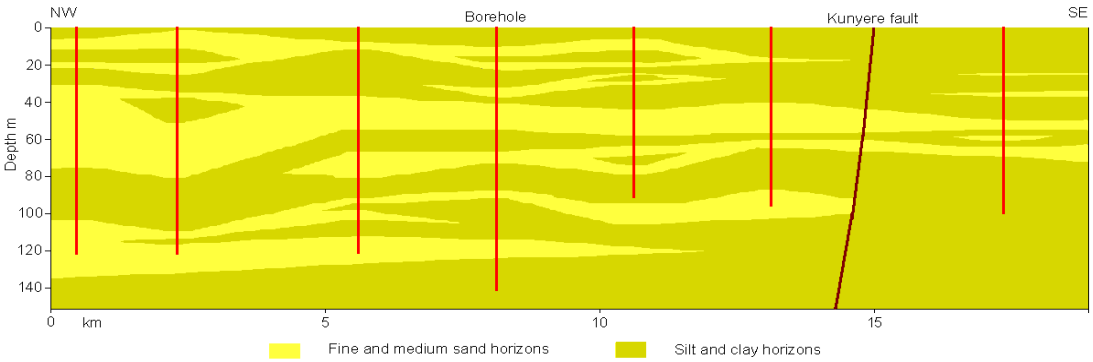


Figure 47

Figure 47: Schematic cross-section of the Kalahari Group sediments in the Okavango Graben showing the multilayered aquifer horizons (based on C. Milzow, et al., 2009 using data collected during the Department of Water Affairs investigations for the Maun Water Supply)

Equally groundwater contour mapping around the Delta has not been located. Such mapping would establish if the Delta lies at the centre of a groundwater mound with potential radial flows to the surrounding Kalahari formations and the older alluvium as suggested by T.S. McCarthy (2006) and C. Milzow, et al. (2009), or if the Delta is the focus of groundwater flow from the Eiseb Basin to the west. The latter mechanism is substantially ruled out by the depth to groundwater and the hydrochemical zoning shown on Figure 48.

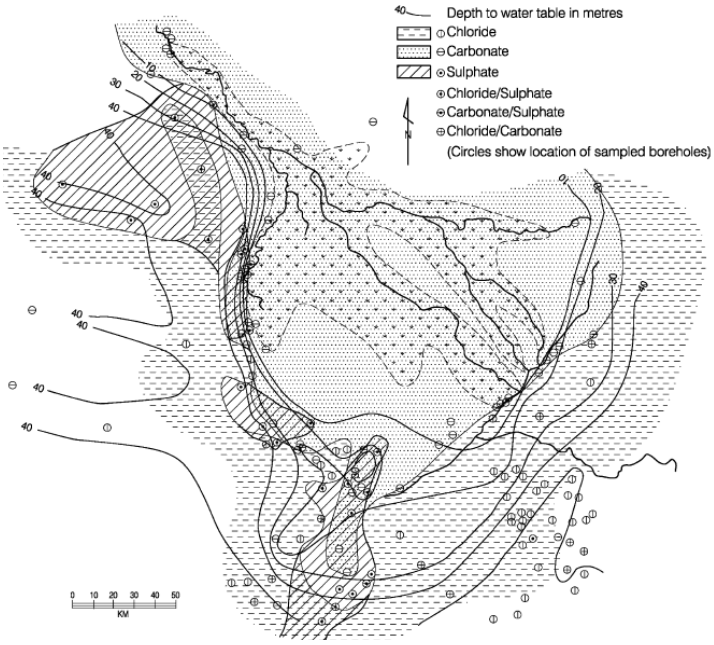


Figure 48

Figure 48: Groundwater levels and hydrochemistry around the Okavango Delta. The prevalence of sulphate rich groundwaters and the steep gradient hydraulic west of the Delta may be directly linked to the underlying bedrock surface and geology (from T.S. McCarthy, 2006).

4.5 Makgadikgadi Block

Lying to the southeast of the Thamalakane- Kunyere Faults, the centre of the Makgadikgadi Block occupies a topographic depression that holds the Ntwetwe and Sowa Pans that are the terminal drainage points for all the surface and potential groundwater flows in the Okavango Basin.

The Ntwetwe Pan is directly linked to the Okavango Delta surface water overflows via the Boteti River. The Sowa Pan is the focus of annual transient surface water flows from the Ntata River that drains the eastern water divides between the Okavango, Limpopo and Zambezi Basins. The ephemeral Letlhakane River connects the Ntwetwe and Sowa Pans.

Under current climatic conditions no distant surface water flows are expected to reach the Makgadikgadi Block from the Central Kalahari or Ghanzi Blocks. Under past more humid conditions the terminal pans merged and expanded to cover much of the older alluvial occurrences shown on Figure 24. Although the regional groundwater gradients are towards the Pans, the actual groundwater transfer appears extremely limited.

Extensive surface and airborne geophysical and geological exploration surveys have established the tectonic structure of the Makgadikgadi Block. Narrow outcrops of crystalline Basement and Karoo System formations form the regional water divide between the Okavango and Limpopo Basins and the centre of Makgadikgadi Basin is underlain by up to 300m of Kalahari Group sediments. The Basement and Karoo formations are cut by the closely spaced 179Ma Jurassic Okavango dyke swarm that follows pre-existing rift structure trends. Subsequent movements associated with the formation of the 30Ma swells and basins and the East African Rift System have broken the underlying geology into a series of faulted blocks that follow the same structural weaknesses as shown on Figure 49. The Karoo surface was clearly heavily eroded prior to the deposition of the Kalahari Group formations and the modern groundwater chemistry has been closely linked to the underlying Karoo formation (S. Stadler, 2005).

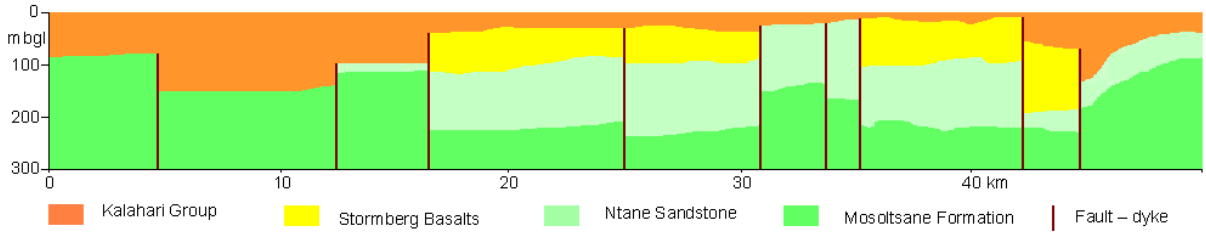


Figure 49

Figure 49: Schematic E-W geological section in the Orapa Area (adapted from I.F. Blecher and R. A. Bush,1993 quoted in B. Th. Verhagen, 2003).

Away from the regional interfluves, the top of the saturated groundwater horizons lie within the Kalahari Group formations. Along the Boteti River and around the Ntwetwe and Sowa Pans where groundwater occurrences are within 20m of the surface, evapotranspiration losses can be expected to be high.

To varying degrees, the deeper groundwater south of the Thamalakane- Kunyere Faults is saline except where seasonal recharge events associated with the Delta overflows takes place along the Boteti River as illustrated on Figure 50. Further airborne EM surveys along the Boteti River (D. Sattel and L. Kgotlhang, 2004) indentify low conductivity signature zones between Rakops and Lake Zau as shallow sand lenses containing fresh groundwater within the Kalahari Group formations.

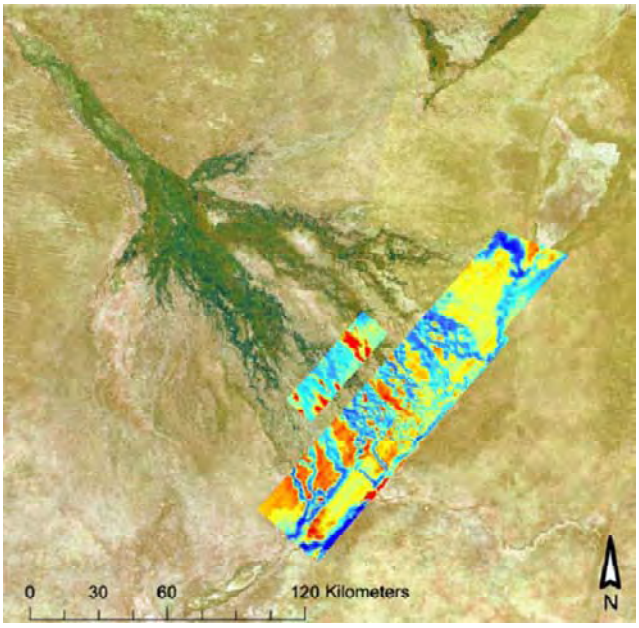


Figure 50

Figure 50: Airborne electromagnetic (AEM) map superimposed on Landsat view of the Okavango Delta. Red and yellow tones indicate high salinity groundwater and blue and green tones represent fresh groundwater (From C. Milzow, et al., 2009 and data from Campbell et al., 2006)

Similar localised fresh groundwater lenses occur along the main ephemeral water courses that drain to the Ntwetwe and Sowa Pans. The fresh groundwater lenses frequently occur as perched aquifers within the Kalahari Group formations (S. Stadler, 2005) and are exploited in the dry valleys by hand-dug wells. The main groundwater developments, however, are centred on the Orapa and Letlhakane Diamond Mines and on scattered cattle watering points.

Wellfield abstraction for the Orapa and Letlhakane water supplies and the dewatering operations at the mines began in 1960 and have modified the regional SE-NW groundwater

flow as shown on Figure 51. The 2003 wellfield abstraction was 8.9Mm^3 and the dewatering 4.1 Mm^3. The wellfields large draw groundwater from the Ntane Sandstone that is considered locally to be in hydraulic continuity with the overlying Stormberg Basalts and the Kalahari Group formations (B. Th. Verhagen, 2003).

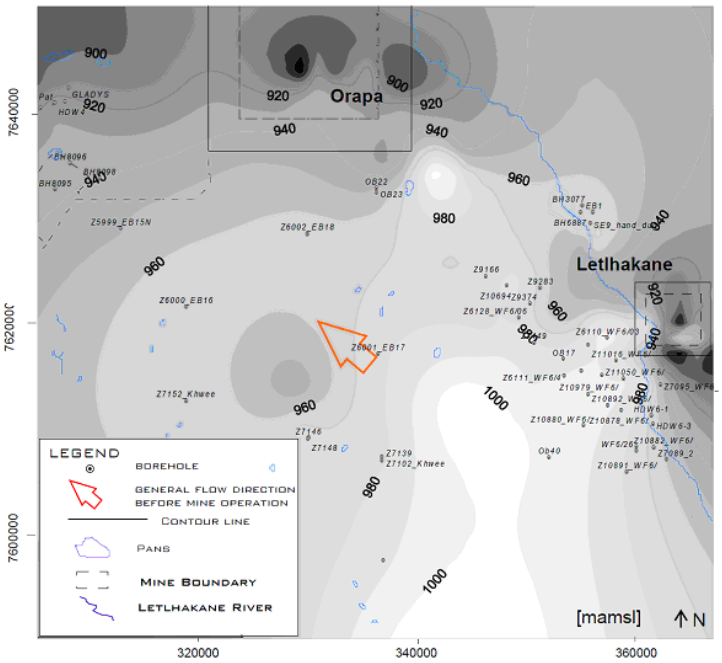


Figure 51: Groundwater contours (m asl) of the Orapa and Letlhakane are for 2002 (from S. Stadler, 2005).

Figure 51

Although the groundwater contours shown on Figure 51 do not reflect the complex block faulting of the Karoo Group formations, S. Stadler (2005) characterizes the groundwater chemistry on the basis of the bedrock geology with sulphate rich groundwaters associated with the chemical weathering of the Stormberg Basalts and withy the siltstones and clays of the Mosoltsane formation. This implies a degree of differential groundwater flow and compartmental groundwater occurrences. The sulphate rich waters associated with the Stormberg Basalts also provide the source of the sodium carbonate deposits mined from the Sowa Pan.

The hydrogeological investigations undertaken to support Orapa and Letlhakane water supplies include evaluations of recharge and chemical quality (B. Th. Verhagen, 2003 and S. Stadler, 2005). Little consensus exists over the role of direct diffuse recharge to the main Ntane Sandstone aquifer zones but the potential for annual indirect recharge from ephemeral stream flow is high given a mean annual rainfall of between 400 and 600mm. The fractured and fissured nature of the Stormberg Basalts is generally considered to provide preferential flow paths for infiltration and isotope and water balance studies indicate the global recharge reaching the regional water table at around 2% of the annual rainfall.

The impact of this volume of recharge may be enough to sustain regional groundwater flow as indicated on Figure 52. The on-going groundwater level monitoring may well show the validity of this possibility. However, for current groundwater resource planning purposes, even the highest recharge estimates are considerably below the gross groundwater abstraction.

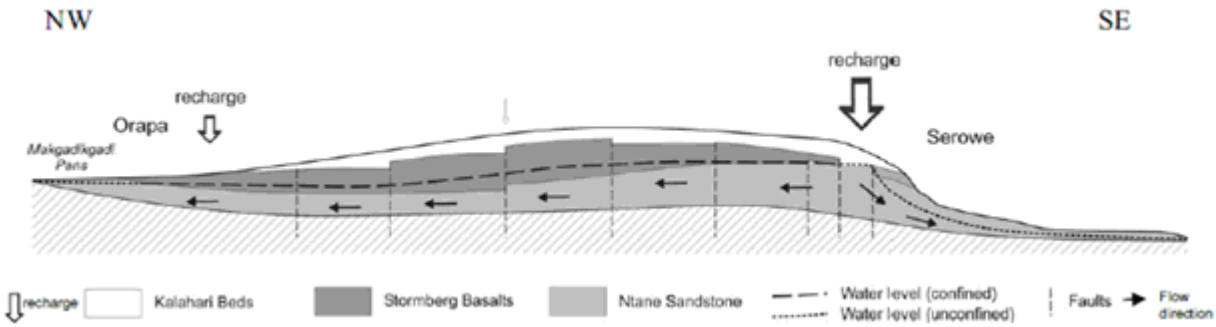


Figure 52

Figure 52: Schematic hydrogeological section from Serowe to Orapa showing potential for groundwater flow and relative recharge (from S. Stadler, 2005).

Groundwater developments in the Ntane Basin and eastwards from the Sowa Pan are currently limited to cattle posts and rural communities and the priority for systematic study of the groundwater resources is low compared to the priorities driven by the development demands elsewhere in the Makgadikgadi Block.

4.6 Central Kalahari Block

In contrast to the other groundwater provinces within the Okavango Basin, the semi-arid climate and relatively deep groundwater levels means the Kalahari Group formations lie above the regional water table across most of the Central Kalahari Block. The main groundwater occurrences are found in the Ecca Group Kweneng Sandstone, the Ntane Sandstone and the Stormberg Basalt belonging to the Karoo System: These formations provide the sole source of water for the economically important cattle ranching industry.

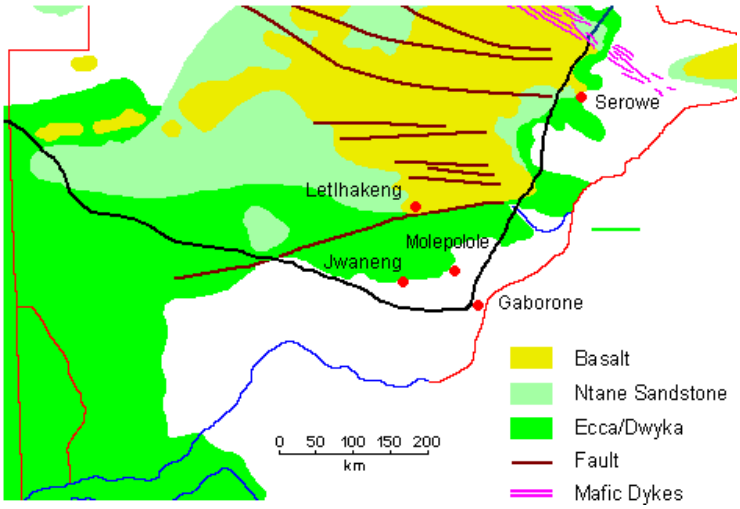


Figure 53

Figure 53: The distribution of the main Karoo System fromations in Central Southern Baotswana (adapted from J. L. Farr et al. 1981).

In line with the depth to the water table, there are no visible groundwater discharges at the surface from these aquifer formations across this groundwater province. The groundwater quality in these formations varies from good close to the past recharge areas to saline where the aquifers are totally confined. Figure 53 shows the Karoo System subcrop under the Central Kalahari Block.

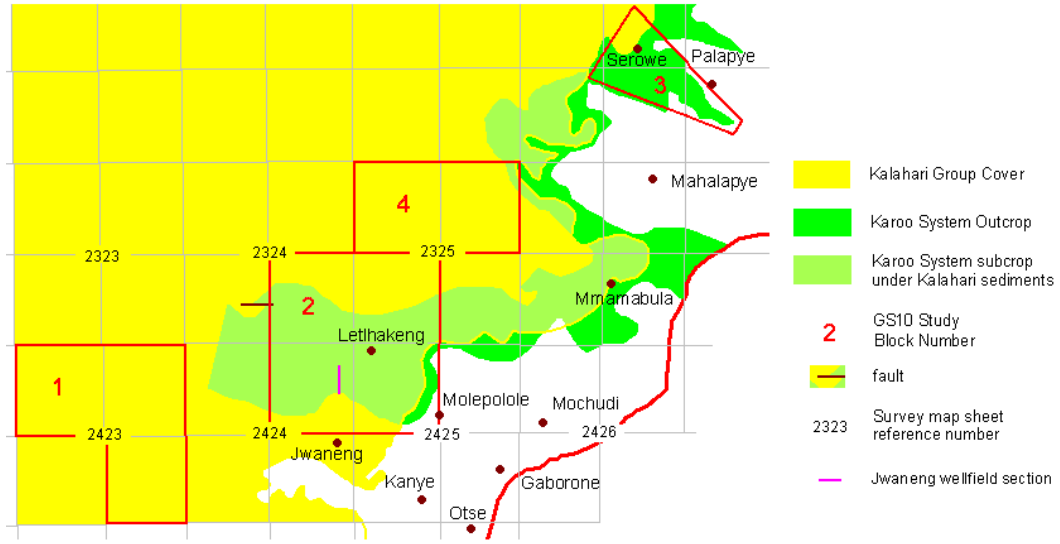


Figure 54

Figure 54: Botswana Geological Survey GS10 study blocks. Jwaneng wellfield section shown on Figure 58 (adapted from J. H. Whitelaw, J. L. Farr and S. S. D. Foster, 1977).

Between 1976 and 1981, the UK funded Geological Survey of Botswana GS10 project undertook an assessment of the groundwater resources that largely concentrated on the Karoo System aquifers within the Central Kalahari Block. The main area covered for detailed study was a 11,300km^2 Block 2 to the west south of Letlhakeng were the geological results from a 70 hole coal exploration drilling programme were augmented by the GS10 well drilling and testing (Figure54). The Geological Survey held records of some 220 water supply wells drilled in the area: At the time of the GS10 survey, only 120 wells were located on the ground and were in use for watering cattle. The GS10 project proved the Ecca Group Kweneng Sandstone to be the main aquifer in Block 2.

Since 1980, significant urban and mining groundwater supplies have been developed within Block 2. The Molepolole urban water supply is taken from a wellfield located around Matlagatse to the northwest on the Letlhakeng Road. The geological cross-section (Figure 55) shows the favourable geometry of the Kweneng Formation subcrop to maximise storage and recharge under more humid conditions with the less permeable shales and siltstones of the Beaufort Kwetla formation probably in position to force excess groundwater flow into the surface water drainage system.

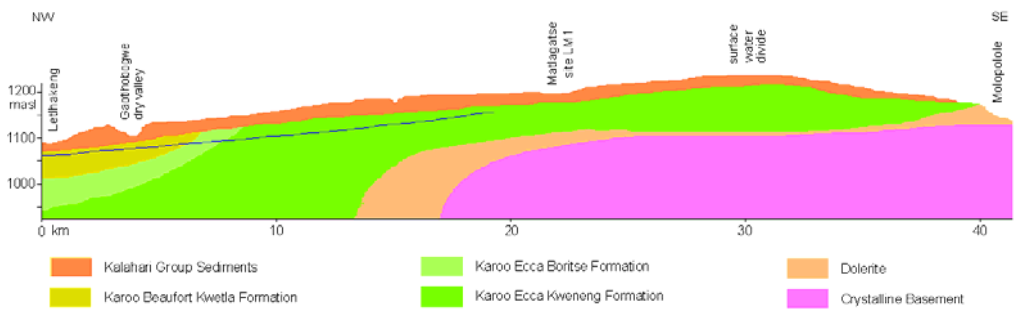


Figure 55

Figure 55: Geological cross section along Molopole-Letlhakeng Road (adapted from A. Gieske, E. T. Selaolo and H. E. Beekman, 1995 with additional data from R. T. Chaoka, et al, 2006).

Under present climatic conditions, however, the potential and processes of aquifer recharge are limited. Attempts to quantify diffuse recharge using rigorous hydrochemical and isotope investigations have produced conflicting results as can be seen from the studies in the Matlagatse and Letlhakeng areas by the GS10 project (S. S. D. Foster, 1978) and the follow-up Groundwater Resources Monitoring and Recharge Study (GRES) reported on by A. Gieske, E. T. Selaolo and H. E. Beekman (1995) and E. T. Selaolo, et al., (2003).

Figure 56 shows seasonal changes in soil moisture determine by neutron probe logging by the GRES project in the Letlhakeng area. The GS10 conclusion was that diffuse recharge was undetectable while the GRES project identified diffuse recharge rates of a few millimetres. Allowing for the adaption of the natural Kalahari vegetation to the semi-arid climate and the high percentage of fine silty sand in the soil profile, the wilting point saturation level will be towards or even below the low end of the accepted normal range of 5 to 16% by volume (see Box 3).

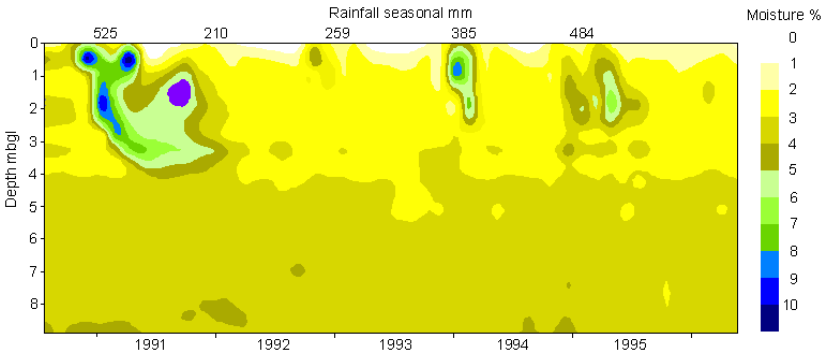


Figure 56

Figure 56: GRES temporal soil moisture changes at the Maipatlelo site (redrawn from E. T. Selaolo, et al., 2003).

The results from multiple parameter analysis of samples from a 41.7m deep, augered hole at Maipatlelo near Letlhakeng are shown on Figure 57. Assuming a mean density of 1.9 to 2.2 for the soil column, the soil moisture values by weight can be adjusted to volumetric values in the range of 2 to 25%: The saturation levels shown on Figure 56, therefore, are at, or below wilting point from 5m downwards. The parameter profiles, however, do show anomalies that indicate past recharge events. Although these anomalies can be tied to lithological variations in the geological profile it is felt that more consideration should be given to the periodic floods that occur in the “fossil” valleys.

At Letlhakeng in 1978 a maximum flood level during the 1967 flood down the Meratswe and Gaotlhobogwe Valleys (Figure 55) was marked some 40cm up the Post Office Wall: This was several metres above the nearby valley floors. A similar flood effecting over 120 households occurred in June 2009 after storm event with over 100m of rain falling within 24 hours. D. J. Nash (1996) records various qualitative descriptions of historic floods that can be considered potential aquifer recharge events. The fate of the flood waters is seldom reported, but they are dispersed by infiltration in to the unsaturated soils and subsoil zones with some runoff ultimately reaching the local unconfined water table, if it exists, and the rest being returned to the atmosphere by evapotranspiration. Excess flood waters may reach the terminal Deception Pan that forms the focus of the Central Kalahari drainage system but most is expected to be temporarily ponded and lost by open-water evaporation along the course of the dry valleys.

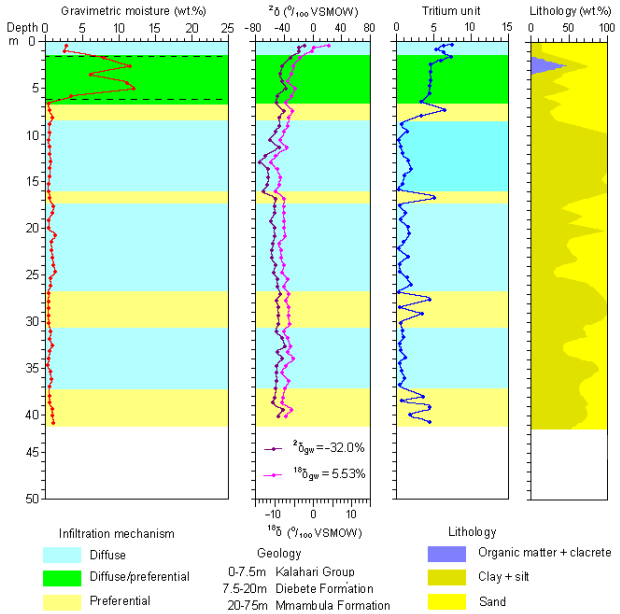


Figure 57: Composite multiple parameter log for the 41.7m deep, augered hole at Maipatlelo near Letlhakeng (redrawn from E. T. Selaolo, et al., 2003).

Figure 57

The complex dynamics of the three phase (gas, fluid and solid) nature of the unsaturated zone suggest a more active role for preferential flow paths than diffuse mechanisms for the downward transmission of recharge through the profile. On this basis the limited recent recharge identified by B. T. Verhagen (1995) in the Jwaneng Wellfield area SW of Letlhakeng is possibly feasible.

The absence of groundwater discharge coupled with the limited recent recharge means the evaporation and transpiration losses from the top of the saturated formations as the driving mechanism accounting for the depth of the groundwater levels. Determined using lithium chloride as a tracer, tree rooting depths are reported to reach below 53m by M. Keeletsang (2004) and 70m by O T Obakeng 2007. As is seems unlikely that the roots would extend downwards through an unsaturated formation with only hydroscopic water available, its seems probable they follow preferential recharge pathways that given the reported solution effects (J. L. Farr and S. S. D. Foster, 1978) could be could be enhanced by precipitation stem flow. If the net annual evapotranspiration losses are in the order of 2 to 4mm, they would be sufficient to account for a 30 to 50m decline in groundwater levels over a period in excess 10,000 years. As these losses will be fairly uniform over the entire Kalahari Karoo subcrop, the pre-existing groundwater gradients could be preserved although possibly in a modulated form.

BOX 3: Soil Moisture, Infiltration and Recharge under Arid and Semi-arid Conditions

Within a porous soil profile four theoretic steady-state conditions can be reached. First total dryness (inherently requires zero atmospheric humidity), second hydroscopic saturation (water trapped by molecular attraction to soil particles – requires soil gas to be at 100 percent humidity), thirdly field capacity and fourthly fully saturated (all pore space saturated). The capillary fringe above a water table occupies a relatively stable status between the third and fourth steady state conditions. Between the total dryness and hydroscopic saturation all water movement in the soil profile must be as vapour. The water can only be removed by evaporation. The percentage volume of hydroscopic moisture is very small and relates to the soil grain size distribution and the moisture film thickness is < 0.5 x 10^{-3} mm (Fig 1).

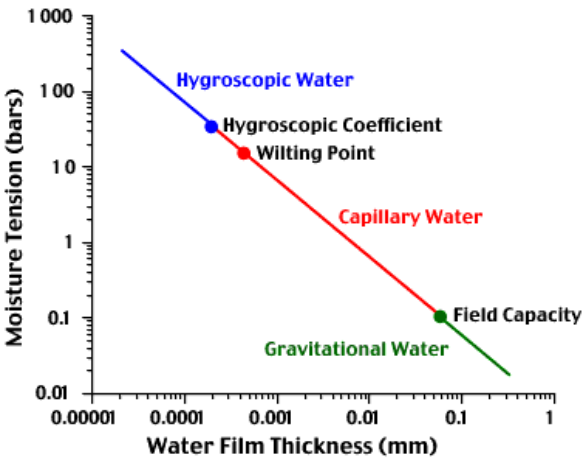


Figure 1: Relationship between soil water film thickness and moisture tension. (Source: PhysicalGeography.net)

Between the hydroscopic and field capacity states, the water may move through the soil profile as vapour or as a liquid with capillary tension acting as the main driving potential and gravity only playing a minor role. The capillary forces may be exerted in any direction and water may be removed by both evaporation and transpiration. There is, however, a bottom limit (wilting point) to the ability of plants to suck water from the soil; nominally this corresponds to a moisture content of between 5% and 16% by volume. The moisture content of soils at field capacity ranges from 2% to over 70%. In general the coarser grained and better sorted the soil, the lower the field capacity. Soils with field capacities over 55% generally have a high humus content. Between field capacity and full saturation, only the largest pores are likely to contain soil gas and these may be discontinuous, therefore the movement of water vapour is very much curtailed and gravity controls the main movement of water as a liquid. Water, however, may be removed from the profile by evaporation, transpiration and gravity drainage. Below the water table, gravity dominates all movement although density differences cause by thermal gradients can distort the flow pattern. Water is removed by evaporation, transpiration, and lateral outflow.

The movement and volume of both water vapour and liquid in unsaturated profile is subject to physical size and shape of pore openings and the presence of preferential flow paths. The same physical properties control the water bearing properties below the water table. Experimental work in southern France by Chaptal (1932) quoted by Gottman (1942) and Hills (1966) was modelled on the traditional Middle Eastern air well system for atmospheric water harvesting. This system and the "solar-still" survival technique rely on temperature differentials and relative humidity to achieve the condensation of water. The basic maximum water availability can be calculated from the simplified values given below:

Ambient Air Temperature ^{o}C	Saturated Humidity (*RH Relative Humidity = 100%) Partial Pressure (mb)	g/m^3
10	11.97	9.6
20	22.89	18.4
30	41.58	33.4

Thus cooling one cubic metre of saturated air from 30° C to 20° C will yield 15 gram of water and from 20° C to 10° C will yield 8.8 gram. Extracting water from a soil profile will obviously have a lower yield as only the void spaces will contain air and the air is not necessary completely saturated if the profile is below the hydroscopic saturation point. Soil microclimate measurements under desert

conditions, however, indicate that the top of the mid-day fully saturated soil atmosphere (and hence the hydroscopic saturation point) is usually found at < 2.0m below ground.

Much field, laboratory and mathematical research has been undertaken to quantify all aspects of the proceeding observations as part of investigations in to infiltration and aquifer recharge. For example, Kitchen et al. (1980) report on a project in Cyprus that successfully employed physical soil moisture determinations, lysimeters, chloride balance and isotope profiling investigations to determine recharge to coastal aquifers. The recommendation concerning the appropriateness of the chloride balance profiling technique for investigations in remote semi-arid regions with deep watertables and thick arenaceous cover, has lead to its widespread application across the Kalahari in Southern Africa: Foster, et al. (1982), Gieske (1992), Beekman, et al. (1994, 1996, 1997 and 1999), Selaolo (1998) and Selaolo, et al. (1994 and 1995) report on various recharge research projects undertaken in Botswana while similar projects elsewhere in Africa, Australia, SE and E Asia, and the US have been reviewed to develop a global synthesis of groundwater recharge in arid and semi-arid regions (Scanlon, et al. 2005). The African recharge estimates are from 1mm to 20mm. with the lowest rates recorded in areas with deep watertables (>25m.).

The validity of recharge estimates below 5mm and possible as high as 20mm is speculative as no account appears to be given to the upward movement of water vapour through the profile to replace the evaporation losses from the top 2m of the profile. The mobility of soil gases associated with hydrocarbon pollution plumes has been extensive studied (Scanlon, 2002) and the seasonal desiccation to depths of more than 6m of stiff bentonite clays have been recorded in Texas (Simpson, 1934 quoted in Meinzer, 1942). Without considerably more data to prove the contrary, it is felt that there is a significant movement of water vapour up the unsaturated profile to replace the evaporation water losses at the landsurface even over a deep watertable. The potential for the evaporation loss is borne out by the effectiveness of the solar still and comparison of the air relative humidity (ca. 30% at 30°C dew point* 11° C) and soil gas humidity a few centimetres below the surface (ca 90% at 25°C dew point*
18° C).

*RH = 100%

Reported absolute isotope values and ratios largely support the proceeding observations.

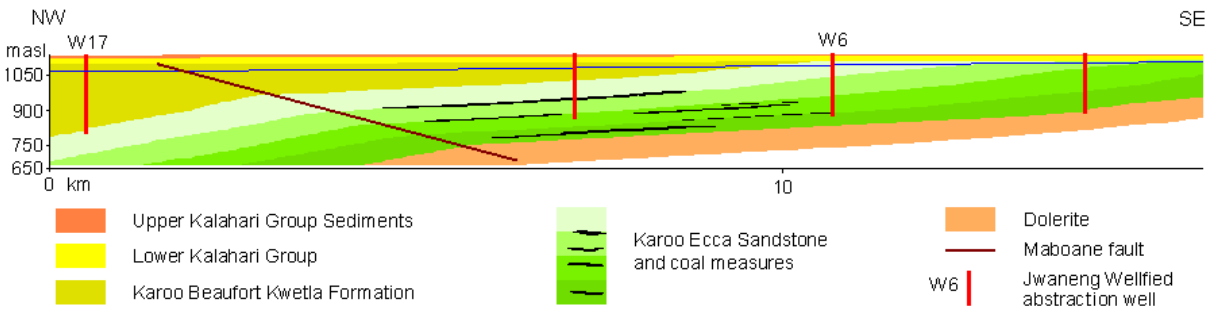


Figure 58

Figure 58: Jwaneng Wellfield geological section (adapted from D. Buckley, 1984 and J. H. Whitelaw, 1978)

The aquifer properties determined for the Ecca Group formations in the Jwaneng wellfield area are shown on Table 2 and imply that the groundwater occurrence ranges from unconfined at site W6 on Figure 58 to totally confined by the overlying Beaufort Group sediments at site W17. Elsewhere in study block 2 the Ecca Sandstone is largely semi-confined: This again restricts the opportunity for recharge to reach the aquifer horizons in the Ecca Group subcrop.

Site	Rest water level m bgl	Water inflows	Test yield (Q) l/sec	Transmissivity (T) m^2day	Storage (S)	*Permeability K mday^{-1}*	*Effective porosity %*
W6	65	75-90	7.5	490	$2x10^{-3}$	*0.59*	*n.a.*
			9.1	620	$1x10^{-2}$		
W13	60	95-115	10.5	680	$3x10^{-4}$	*0.09*	*13.3*
W14	68	95-115	5.1	320	$3x10^{-4}$		
W16	59	80-100	10.5	190	$6x10^{-5}$		
W17	51	80-115	19.0	1100+	$3x10^{-4}$	*0.14*	*18.6*
			7.0	620	$7x10^{-4}$		
W18	50	135-160	12.8	450	$1x10^{-4}$		
W20	56	90-110	10.5	130			
			7.2	100	$1x10^{-3}$		
Permeability and effective porosity values - laboratory determinations for core samples.						*0.02*	*12.4*

Table 2: Jwaneng Wellfield well testing and aquifer properties (adapted from J. L. Farr and S. S. D. Foster, 1978).

Annual abstraction from the Jwaneng wellfield in 2008 was reported around 5.5Mm^3, dewatering at the mine extracts 3.7Mm^3 and drainage from the slimes dams yields a further 3.6Mm^3 (M.C. Brook, 2009). Maximum drawdowns of 5m across the wellfield after 14 year abstarction were considerably less than the 30m predicted by the initial aquifer model (M.C. Brook, 1990 and B. T. Verhagen, 1995). Subsequent modelling calibration incorporated increased leakage and recharge rather than increasing storage on the basis of isotope data that was interpreted to indicate significant modern recharge. The hydrochemical analyses used, however, were from stratigraphically mixed pumped samples from abstraction wells and this may affect the integrity of the isotope findings.

Investigation of the Ecca Group aquifers in the GS10 study blocks 1 and 4 remains limited but in Block 1 the water quality is known to deteriorate as the aquifer horizons become increasingly

confined and groundwater flows stagnate under the younger formations (C. Cheney, et al., 2006). Below the Kalahari Group cover, much of Block 4 is underlain by the Stormberg Basalts that forms provides unpredictable groundwater yields (J. H. Whitelaw, J. L. Farr and S. S. D. Foster, 1977).

The demand for increased raw sources for the Serowe urban water supply and for the Morupule Power Station has driven hydrogeological investigation and development of the Ntane Sandstone Formation in the GS10 study Block 3.

The Block straddles the water divide between the Okavango and Limpopo Basins and the geometry of the Karoo and Kalahari formations is shown on Figures 59, 60, 61 and 62. At Serowe, the surface and groundwater divides approximately coincide with a marked groundwater mound. This points to local diffuse recharge occurring at least across the Stormberg Basalts outcrops (Figures 60 and 61). Infrared satellite images north and east of the Paje wellfield indicate widespread active seasonal groundwater seepage along the foot of the Kalahari Group escarpment (Ecosurv 2009). The Ecoserv configuration of the groundwater contours point to the area around the Serwe Pan as receiving contemporary recharge: The groundwater quality provides additional confirmation and the detailed studies around Serowe reported by J. Meier, T. Himmelsbach and J, Böttcher (2008) date the nitrate rich groundwaters in the recharge areas as younger than 1Ka. To the west, down gradient confined waters under the Stormberg Basalts are dated to +15Ka.

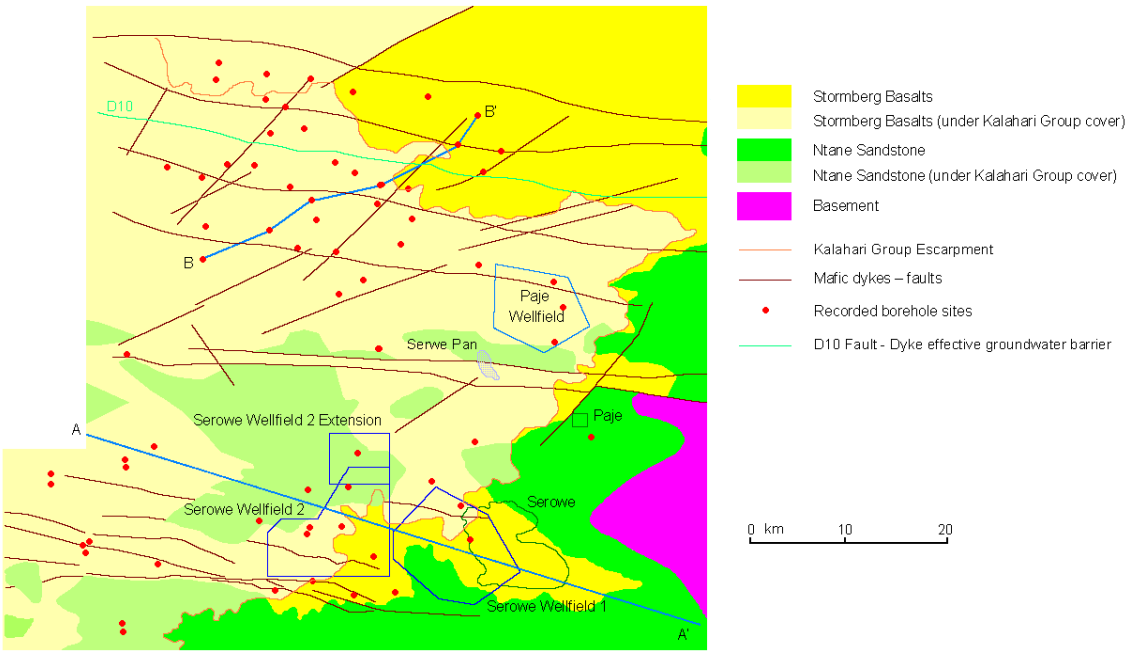


Figure 59

Figure 59: The geology, wells and wellfields in the Serowe area.. Hydrogeological sections on Figures 60 and 61 are shown in mid blue (redrawn from B. T. Verhagen, 1995 and Ecosurv, 2009).

The role of the regional fault pattern and the mafic dykes on the groundwater flow appears localised but is sufficient to break the aquifer up into a series of poorly interconnected compartments as shown on Figures 60, 61 and 62.

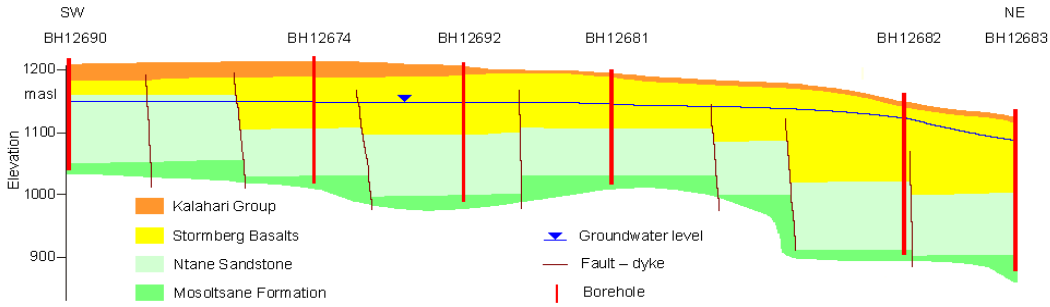


Figure 60

Figure 60: Hydrogeological section B-B' (shown on Figure 59) through the Morupule Power Station Wellfield area (redrawn from Ecosurv, 2009).
The aquifer modelling of the Morupule Power Station groundwater supply boreholes reproduces these aquifer compartments to assess impact of various abstraction scenarios on other local groundwater users. Future monitoring should validate the extent to which the faults and dykes dominate the geometry of the regional drawdowns but Ecoserv (2009) note a 40m head differential associated with the fault – dyke labelled D10 on Figure 59.

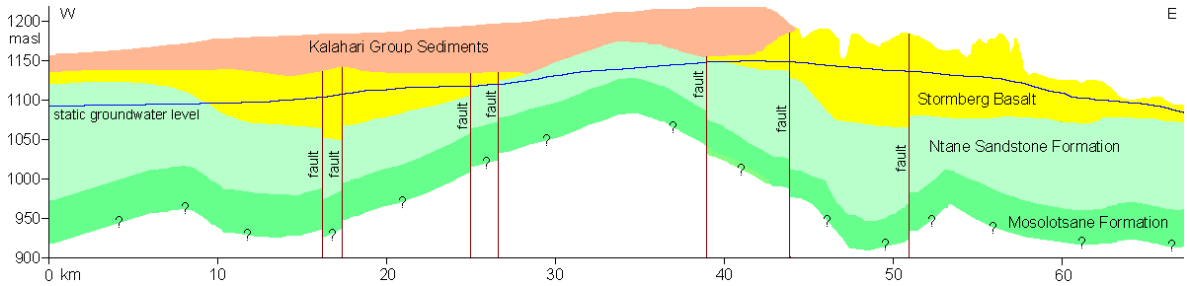


Figure 61

Figure 61: Hydrogeological section A-A' (shown on Figure 57) through the Serowe Water Supply Wellfields (adapted from Swedish Geological Company (SGC), 1988)

While the two cross-sectional interpretations of groundwater levels in the Serowe wellfields area shown on Figures 61 and 62 highlight the inferred impact of ongoing and increasing abstraction in amplifying the head differentials across the main fault and dyke groundwater barriers.

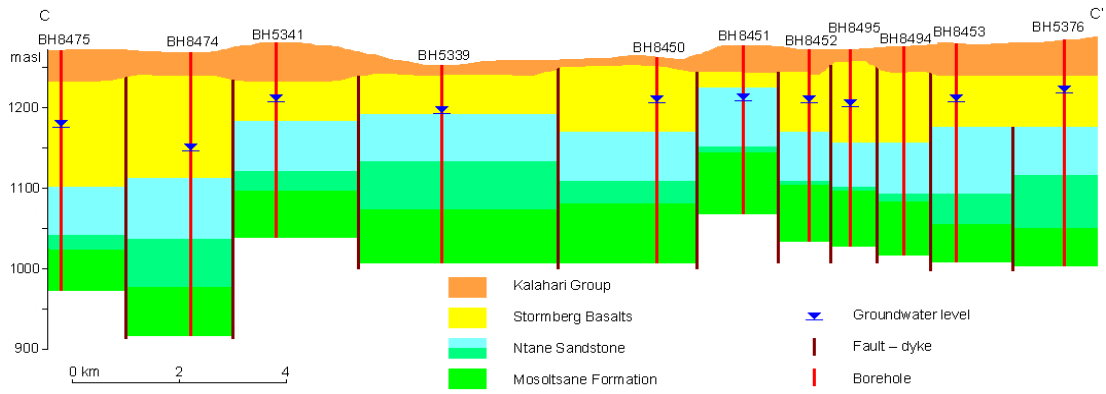


Figure 62

Figure 62: Hydrogeological section through the Serowe Water Supply Wellfield after a decade of abstraction at around 2.5Mm^3/year (adapted from J. Meier, T. Himmelsbach and J, Böttcher, 2008).

All groundwater resource studies around Block 3 agree that current abstraction greatly exceeds current recharge. At Serowe, S. Stadler (2005) illustrates the pre-development 1988 and the 2002 groundwater contours (Figure 63) and Figure 64 shows the observed shift in the groundwater divide in response to the Serowe and Paje wellfield abstraction.

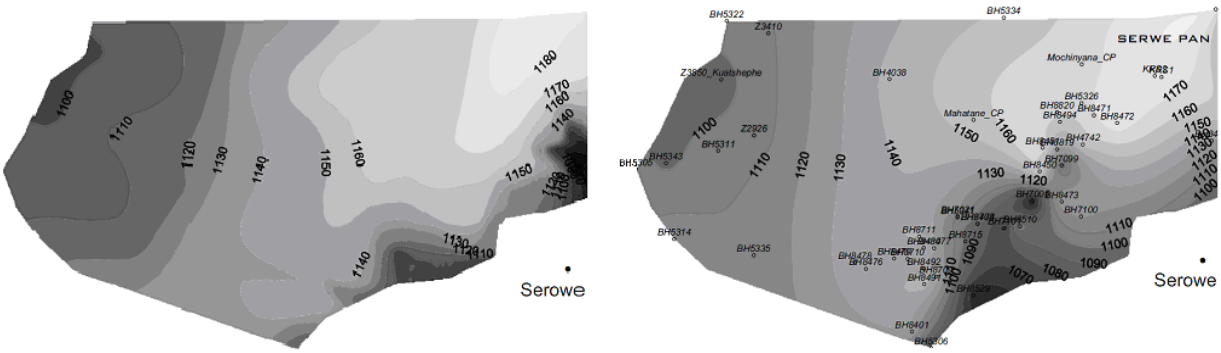


Figure 63

Figure 63: Serowe Block, groundwater contour maps for 1988 (left) and 2002 (right) showing impact of Serowe Water Supply abstraction (adapted from S. Stadler, 2005).
As the groundwater occurrences are substantially defined, current and future monitoring will enable a time-scale to be assigned to the sustainability of large-scale abstraction. The thickness of the saturated aquifer zones will be a critical to in the assessment of long term resources and demand pressures will have to be met by expansion of wellfields to new aquifer development areas.

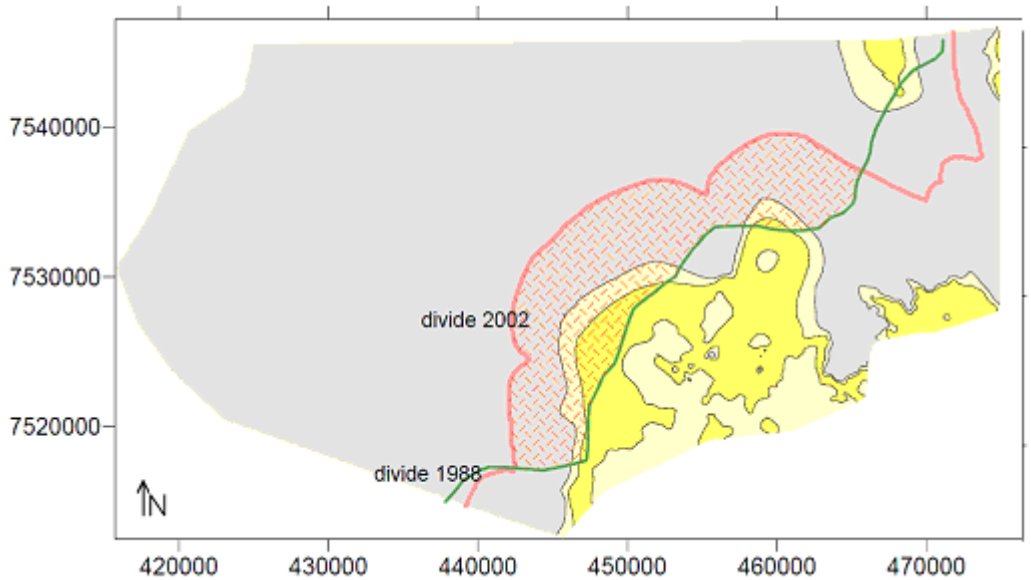


Figure 64

Figure 64: Serowe Block, 1988-2002 shift of the groundwater divide (from S. Stadler, 2005).

These new areas will undoubtedly extend in to be Central Kalahari Block where current abstraction is large limited to cattle posts and rural settlements.

5 CONCLUSIONS

The main unresolved questions in the Okavango Basin concern the geology and groundwater occurrences of the Cuito and lower Cubango Basins.

A limited, closely monitored investigation programme aimed at establishing the stratigraphy, lithology, water bearing characteristics and hydrochemistry of the Karoo System and Kalahari Group formations in these Basins should determine whether the groundwater flow system is superficial as found under the Okavango Delta; of intermediate depth as found in the Serowe and Makgadikgadi Blocks; or deep as found in Kwenang in the Central Kalahari Block. The almost complete lack of hydrogeological data for the Cuito and lower Cubango Basins requires addressing.

It is felt that the prevailing hydrology and hydrogeology of the crystalline Basement occurrences of Upper Cubango Basin is sufficiently well understood for planning purposes.

The hydrogeology and groundwater resources of the Omatako and Eiseb Basins are poorly documented. In view of likely further surface and groundwater developments close to the Okavango River between Katwitwi on the Angola-Namibia Border and Mohembo at the head of the Delta and west of the Delta in Botswana, attention should be given to expanding the groundwater database for future planning purposes.

The limited groundwater resources of the Ghanzi Block will naturally restrict future developments and the current situation is sufficiently well documented for planning purposes.

Future monitoring and investigation of the Delta should aim at completing the contouring of groundwater levels around the Delta margins.

Driven by mineral exploration and developments, the hydrogeology of the Karoo System in large areas of the Makgadikgadi and Central Kalahari Blocks has been scientifically investigated and is reasonably well understood. For future planning purposes, however, when new areas will need to be opened up for development, steps should be taken to complete groundwater inventories and to install long term monitoring points.

Finally, more hydrogeological research should be directed to evaluating the role of storm flood flows in the ephemeral rivers as the source of indirect recharge. The considerable effort that has been centred on direct, diffuse recharge has failed to distinguish indirect recharge as probably the main mechanism across the Okavango Basin.

6 REFERRENCES

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Appendix 1

Upper Cubango River at Caiundo, Monthly Baseflow Component

Year/Month	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Jan	0.12	0.16	0.03	0.06	0.05	0.03	0.10	0.14	0.05	0.04	0.03
Feb	0.13	0.22	0.06	0.15	0.04	0.20	0.23	0.24	0.05	0.07	0.05
Mar	0.22	0.40	0.18	0.37	0.03	0.44	0.39	0.37	0.20	0.06	0.13
Apr	0.36	0.42	0.45	0.40	0.06	0.48	0.49	0.46	0.30	0.05	0.18
May	0.46	0.42	0.50	0.36	0.17	0.42	0.46	0.41	0.26	0.09	0.20
Jun	0.43	0.32	0.42	0.25	0.18	0.38	0.38	0.37	0.21	0.11	0.17
Jul	0.38	0.21	0.30	0.20	0.14	0.28	0.30	0.29	0.15	0.10	0.14
Aug	0.30	0.17	0.20	0.15	0.11	0.21	0.23	0.23	0.12	0.08	0.10
Sep	0.22	0.12	0.16	0.12	0.08	0.14	0.18	0.15	0.08	0.06	0.06
Oct	0.17	0.08	0.12	0.09	0.05	0.08	0.12	0.10	0.05	0.04	0.04
Nov	0.15	0.02	0.07	0.07	0.04	0.05	0.11	0.07	0.03	0.03	0.03
Dec	0.14	0.02	0.06	0.06	0.03	0.05	0.10	0.05	0.02	0.02	0.02
Total km^3	3.08	2.56	2.55	2.28	0.98	2.76	3.09	2.88	1.52	0.75	1.15
mm	80	67	66	59	25	72	80	75	39	19	30
mean	2.15 km^3		56mm								

River Cuito at Cuito Cuanavale, Monthly Baseflow Component

Year/Month	1966	1967	1968	1969	1970
Jan	0.16	0.17	0.22	0.265	0.28
Feb	0.18	0.17	0.27	0.305	0.33
Mar	0.21	0.18	0.35	0.34	0.35
Apr	0.24	0.20	0.34	0.32	0.34
May	0.24	0.22	0.32	0.31	0.32
Jun	0.23	0.21	0.31	0.3	0.28
Jul	0.19	0.21	0.29	0.30	0.28
Aug	0.18	0.20	0.27	0.28	0.26
Sep	0.18	0.175	0.26	0.27	0.25
Oct	0.18	0.17	0.26	0.26	0.24
Nov	0.18	0.17	0.30	0.26	0.24
Dec	0.18	0.18	0.25	0.27	0.24
Total km^3	2.31	2.23	3.42	3.48	3.40
mm	145	141	215	219	214
Mean	2.96 km^3		187mm		

Okavango River at Mukwe, Monthly Baseflow Component

Year/Month	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Jan	0.28	0.26	0.34	0.41	0.47	0.34	0.35	0.35	0.34	0.30	0.40	0.34	0.32
Feb	0.26	0.28	0.34	0.45	0.50	0.33	0.38	0.34	0.39	0.28	0.37	0.36	0.30
Mar	0.28	0.33	0.39	0.55	0.55	0.39	0.50	0.37	0.61	0.47	0.41	0.49	0.35
Apr	0.34	0.41	0.50	0.76	0.68	0.50	0.72	0.49	0.97	0.78	0.65	0.65	0.40
May	0.40	0.47	0.66	0.96	0.84	0.70	0.83	0.64	1.10	1.08	0.87	0.74	0.47
Jun	0.46	0.57	0.78	1.10	0.93	0.81	0.80	0.76	1.05	1.07	0.85	0.68	0.57
Jul	0.57	0.63	0.79	1.08	0.83	0.78	0.70	0.74	0.90	0.90	0.76	0.61	0.56
Aug	0.56	0.67	0.72	0.97	0.70	0.70	0.62	0.67	0.75	0.80	0.68	0.56	0.50
Sep	0.46	0.58	0.64	0.82	0.55	0.61	0.53	0.50	0.63	0.66	0.58	0.49	0.45
Oct	0.38	0.46	0.51	0.62	0.43	0.50	0.45	0.40	0.47	0.52	0.50	0.43	0.38
Nov	0.32	0.40	0.42	0.53	0.38	0.40	0.40	0.35	0.37	0.46	0.46	0.37	0.34
Dec	0.27	0.37	0.41	0.48	0.36	0.36	0.37	0.32	0.32	0.42	0.36	0.33	0.31
Total km^3	4.58	5.43	6.5	8.73	7.22	6.42	6.65	5.93	7.9	7.74	6.89	6.05	4.95
mm	20	24	29	39	32	28	29	26	35	34	30	27	22
mean	6.54km^3		29mm										

The Okavango River Basin Transboundary Diagnostic Analysis Technical Reports

In 1994, the three riparian countries of the Okavango River Basin – Angola, Botswana and Namibia – agreed to plan for collaborative management of the natural resources of the Okavango, forming the Permanent Okavango River Basin Water Commission (OKACOM). In 2003, with funding from the Global Environment Facility, OKACOM launched the Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) Project to coordinate development and to anticipate and address threats to the river and the associated communities and environment. Implemented by the United Nations Development Program and executed by the United Nations Food and Agriculture Organization, the project produced the Transboundary Diagnostic Analysis to establish a base of available scientific evidence to guide future decision making. The study, created from inputs from multi-disciplinary teams in each country, with specialists in hydrology, hydraulics, channel form, water quality, vegetation, aquatic invertebrates, fish, birds, river-dependent terrestrial wildlife, resource economics and socio-cultural issues, was coordinated and managed by a group of specialists from the southern African region in 2008 and 2009.

The following specialist technical reports were produced as part of this process and form substantive background content for the Okavango River Basin Transboundary Diagnostic Analysis.

Final Study Reports	***Reports integrating findings from all country and background reports, and covering the entire basin.***		
		Aylward, B.	*Economic Valuation of Basin Resources: Final Report to EPSMO Project of the UN Food & Agriculture Organization as an Input to the Okavango River Basin Transboundary Diagnostic Analysis*
		Barnes, J. et al.	*Okavango River Basin Transboundary Diagnostic Analysis: Socio-Economic Assessment Final Report*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Project Initiation Report (Report No: 01/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment EFA Process Report (Report No: 02/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Guidelines for Data Collection, Analysis and Scenario Creation (Report No: 03/2009)*
		Bethune, S. Mazvimavi, D. and Quintino, M.	*Okavango River Basin Environmental Flow Assessment Delineation Report (Report No: 04/2009)*
		Beuster, H.	*Okavango River Basin Environmental Flow Assessment Hydrology Report: Data And Models(Report No: 05/2009)*
		Beuster, H.	*Okavango River Basin Environmental Flow Assessment Scenario Report : Hydrology (Report No: 06/2009)*
		Jones, M.J.	*The Groundwater Hydrology of The Okavango Basin (FAO Internal Report, April 2010)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions (Volume 1 of 4)(Report No. 07/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions (Volume 2 of 4: Indicator results) (Report No. 07/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions: Climate Change Scenarios (Volume 3 of 4) (Report No. 07/2009)*
		King, J., Brown, C.A., Joubert, A.R. and Barnes, J.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Biophysical Predictions (Volume 4 of 4: Climate Change Indicator Results) (Report No: 07/2009)*
		King, J., Brown, C.A. and Barnes, J.	*Okavango River Basin Environmental Flow Assessment Project Final Report (Report No: 08/2009)*
		Malzbender, D.	*Environmental Protection And Sustainable Management Of The Okavango River Basin (EPSMO): Governance Review*
		Vanderpost, C. and Dhliwayo, M.	*Database and GIS design for an expanded Okavango Basin Information System (OBIS)*
		Veríssimo, Luis	*GIS Database for the Environment Protection and Sustainable Management of the Okavango River Basin Project*
		Wolski, P.	*Assessment of hydrological effects of climate change in the Okavango Basin*
Country Reports Biophysical Series	***Angola***	*Andrade e Sousa, Helder André de*	*Análise Diagnóstica Transfronteiriça da Bacia do Rio Okavango: Módulo do Caudal Ambiental: Relatório do Especialista: País: Angola: Disciplina: Sedimentologia & Geomorfologia*

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