Chapter 8

Hydrogeology

October 2010

Republic of Botswana

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List of Acronyms

AVHRR	Advanced Very High Resolution Radiometer (Sensor)
ArcGIS	Arc Geographic Information System (Software)
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Sensor) Global Digital Elevation Model (30m resolution data)
CSAG	Climate Systems Analyses Group
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DWA	Department of Water Affairs (Botswana)
ENSO	El Niño-Southern Oscillation
ETM	Enhanced Thematic Mapper (Landsat Platform)
ETOPO	Global Digital Elevation Model (5km resolution data)
GLCF	Global Land Cover Facility (University of Maryland)
GTOPO	Global Digital Elevation Model (1km resolution data)
JPSS	Joint Polar Satellite System
MCM	Million Cubic Meters
MFMP	Makgadikgadi Framework Management Plan
MIR	Mid Infrared
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multispectral Scanner (Landsat Platform)
MW	Monitoring Wells (BotAsh)
MWS	Makgadikgadi Wetlands System
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration *(Agency)*
PW	Production Well (BotAsh)
SIOD	Subtropical Indian Ocean Dipole
SRTM	Shuttle Radar Topography Mission (1km resolution data)
SST	Sea Surface Temperature
TM	Thematic Mapper (Landsat Platform)
UB	University of Botswana
UCT	University of Cape Town
WMC	Water Management Consultant

Chapter details

This chapter is part of the Project Development of a Makgadikgadi Framework Management Plan (MFMP) prepared for the Government by the Department of Environmental Affairs in partnership with the Centre for Applied Research.

This chapter is authored by the Dr. Frank Eckardt.

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Acknowledgements

This work would not have been possible without my appointment to the University of Botswana between 1998-2005. It was during this time I was able to develop an interest in the Makgadikgadi. Early research efforts were supported by UB and the SAFARI 2000 campaign. I was particularly encouraged working with Graham McCulloch. Godfrey Nkala from BotAsh has also been supporting research initiatives over the years.

This report owes greatly to Rob Bryant who has been a close collaborator. Who would have thought that after working on the Chott El Djerid in Tunisia back in 1994 we would end up tackling the Makgadikgadi? His persistence and expertise have really transformed the remote sensing records for such systems. I am also deeply indebted to Marty McFarlane who has and is still teaching me a lot about Botswana. Our trips and discussions have given me some of the eyes I need to decipher the “geomonotony” of the Kalahari.

Warren W Wood was committed to come and work with me in Botswana within days of me accepting a position at UB. I owe a lot to his generous support. We also need to thank the agencies of the Botswana government in particular Met Services and the DWA as well as survey and mapping for generating and sharing valuable data with us. I would also like to thank Horst Vogel (GTZ) SADC and Water Survey Botswana for making additional data available. Their collective skills are transforming our understanding of this exciting but subtle environment.

I appreciate the feedback provided from Tim Liversedge which clarified content concerning the Boteti River and called for a more detailed treatment concerning the importance of groundwater in salt pan dynamics.

Any errors and omissions in this report are still my own. I also need to acknowledge the people who have accompanied me to the pans over the years in particular most recently Michelle Rapotsanyane, Tyrel Flügel and Kathryn Vickery who were the first students I have taken to the pans. Hopefully they are not the last.

1. Introduction

This report serves to inform the ecological, hydrological and hydrogeological components of the Makgadikgadi Management Plan. Its aim is to break the Makgadikgadi system into its lacustrine subcomponents and identify areas of surface water, their hydrological controls and potential for impact.

2. Terms of reference

Requirements from the Hydrologist

Input in the INCEPTION PHASE

1. Information (GIS remote sensing data and scientific publications) that is already acquired that will contribute to the review of the current information on the physical and hydrological background, and hydrological status of the Makgadikgadi;
2. Remote sensing GIS data of the physical and hydrological status of the pans for the GIS map layers, detailing current and historical hydrological status and analysis.

Input in the COMPONENT ACTIVITIES

Data input and analysis in the identification of flood dynamics, watershed boundaries, ground water dynamics, and geochemical inputs into ecosystem functioning during Hydrological review specifically:

1. Hydrology and hydrogeology Review:

a) Identify, using remote sensing data and analysis the watershed boundaries of the MWS, and map it on a GIS map. (2 days)
b) Identify, using remote sensing data the flood volume and seasonal dynamics on the pan surfaces of the MWS using historical data, and map them on a GIS map. (3 days)
c) Identify the relative proportions and importance of river discharge, rainfall and groundwater inputs in this flood dynamics. (3 days)
d) Identify and map the important sites/'hotspots' for water input into the MWS. (2 days)
e) Identify the linkages between geology, soils, hydrology and the geo-chemical characteristics of the aquatic ecosystem. (3 days)
f) Identify the linkages, if any between surface water, groundwater resources, and fossil water/brine within the basin of the MWS. (3 days)

2. Hydrological input and off take, and use conflict:

a) Identify and quantify anthropogenic off-take of water resources within the MWS, its uses and the methods of off take, highlighting off take 'hotspots' and mapping them on a GIS map. (3 days)
b) Identify areas of current and potential water resource use conflict. (2 days)
c) Provide relevant management interventions to current and future water resource use conflict (2 days).

Total Man Days Input Required (30)

Outputs Required:

1. ***Hydrology and hydrogeology Review:***

a) A GIS map of the watershed boundaries, identifying individual river basins.
b) A GIS map of the MWS flood spatial dynamics, based on historical seasonal data of at least 10 years, which includes a layer identifying the important input sites/‘hotspots’.
c) A report which includes the following:

- A quantitative description of flood volume and dynamics and the respective importance of river discharge, rainfall and groundwater inputs and linkages;
- The areas and relative proportions of natural water output from the system through evapo-transpiration and groundwater seepage;
- The linkages between surface water, groundwater resources, and fossil water/brine, and;
- The important of the linkages between geology, soils, hydrology and the underlying geo-chemical characteristics of the aquatic ecosystem of the MWS.

2. Hydrological input and off take, conflict and management:

a) A report on the anthropogenic off-take of water from the MWS, which includes the uses, methods of extraction and the quantities used, highlighting off-take ‘hotspots’.
b) A GIS map of water off take ‘hotspots’.
c) A report on the current and potential water resource use conflict, including relevant management interventions.

Experience Required

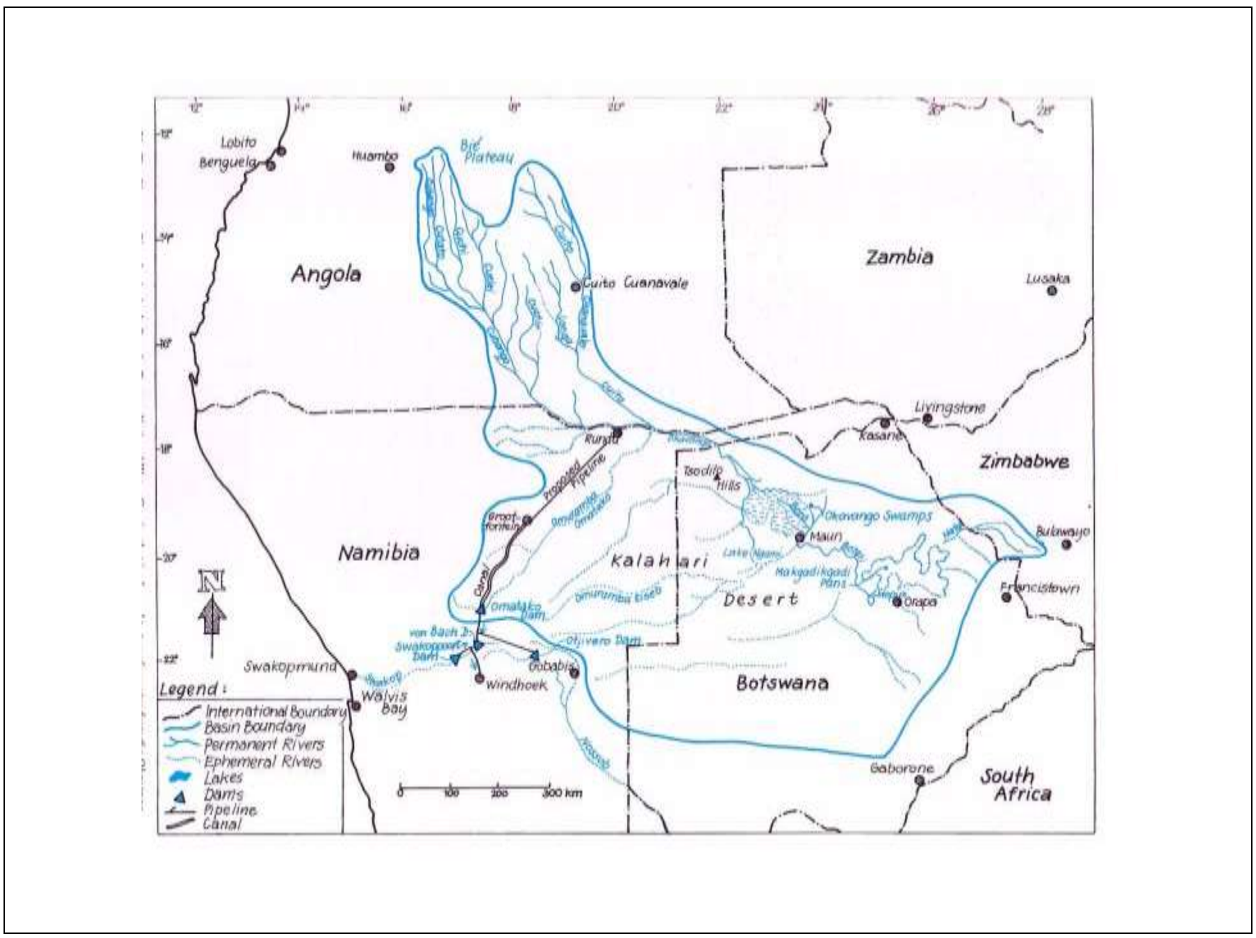
The candidate for this position requires a Masters of PhD in Hydrology or Environmental Sciences, or any topic related to this component and its activities. The candidate must also have at least 5 years of experience in work/research related to wetland hydrology or water resources in Botswana and/or the Makgadikgadi Wetlands specifically.

3. Approach-method and activities

3.1 Introduction

Playas or pans such as the Makgadikgadi occur in arid regions where average annual rainfall does not exceed 500 mm. In general pans tend to have a negative water balance for most of the year due to marginal inputs combined with excessive losses in the form of evaporation and water infiltration. Large playas such as the Makgadikgadi, occupy continental basins which represent topographic low points in often flat and featureless landscapes. They may have been subjected to modification by recent Cenozoic tectonics and witness to higher lakes levels during a wetter past. The Makgadikgadi occupies the lowest point in the endoreic Okavango catchment (Figure 1) and like most pans features no surface outflow. It may however host ephemeral surface water bodies following a short rainy season.

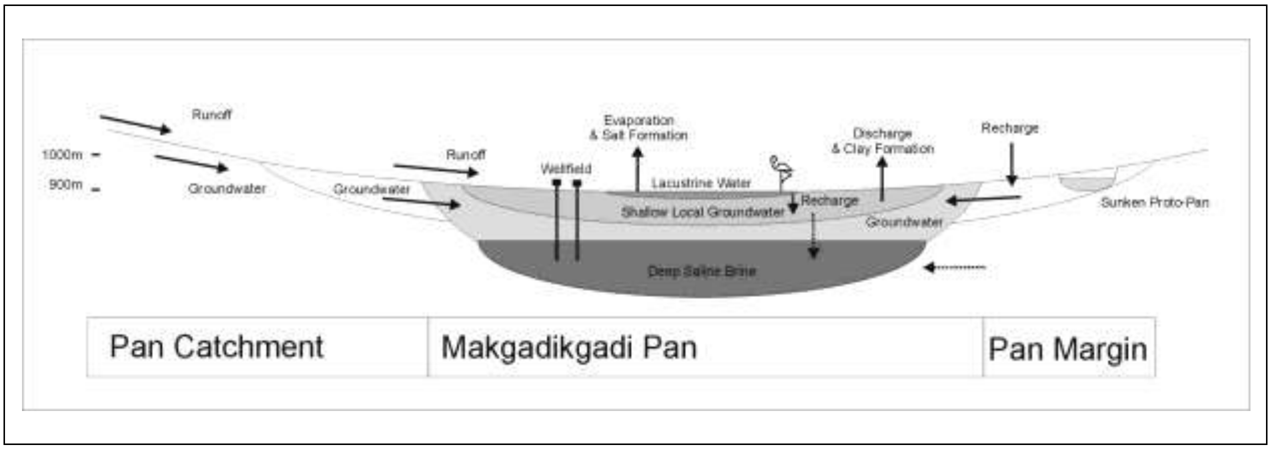
Figure 1: Okavango Catchment: Note the location of the Makgadikgadi in its eastern extension



Source: Pallet 1997.

Pans may receive water in the form of direct rain contributions and considering the overall size of the Makgadikgadi (approx 7000 km^2), this may not be insignificant. They may also receive contributions in the form of surface and subsurface flow which in total may temporarily sustain lacustrine conditions. The overall hydrological regime of a pan is thus determined by external drainage controls such as catchment configuration and climate and internal controls such as the surface and groundwater relationship. This report will in particular examine the present-day hydrology and processes which govern the Makgadikgadi with focus on controls of its ephemeral surface water. Figure 2 depicts a hydrological schematic of the pan system. It needs to be stressed that surface water in pans is not merely the result of standing rainwater but is in fact the net result between various inputs and outputs. In particular the status of the pan crusts and sediments as well as the shallow groundwater determines the amount of water present at the surface.

Figure 2: A proposed hydrological model for the Makgadikgadi



Source: Author and McFarlane (unpublished)

The various components will be examined in detail. This report aims to highlight various knowledge gaps and uncertainties.

The report aims to review, present, analyze and examine existing data and in particular highlight knowledge gaps and propose a future monitoring scheme in order to further our understanding of this system and manage the Makgadikgadi and its sub-systems effectively.

The following sections of this study will represent a systematic breakdown of the Makgadikgadi system into its hydrological sub-components which include the following. The catchment (3.2), Meteorology (3.3), Drainage hydrology (3.4) Riparian system (3.5), Lacustrine water (3.6), Pan surface morphology (3.7), Pan chemistry (3.8), Groundwater (3.9) and Mass balance (3.10)

This will be followed by dedicated sections on Water take-off (3.11), Water conflict (3.12), Monitoring (3.13) and Summary on significant pan wetspots (3.14).

3.2 Topography of the Makgadikgadi and its catchment

The main catchment features of the Makgadikgadi are well established. Ironically in a landscape that is so flat, height does become one of the most important parameters which determines the movement and storage of surface water and groundwater. Topographic maps have never fulfilled this role due to a lack of precision. This section aims to refine our understanding of this landscape drawing on the latest findings from digital terrain data and mapping.

Global topographic DEM (Digital Elevation Model) data is gradually improving and freely available (Table 1). SRTM (Shuttle Radar Topography Mission) provided the first major insight into the capability of such data for the world as well as Botswana (McFarlane and Eckardt 2008) which helped in identifying some of the highest shorelines for the Makgadikgadi. The SRTM data presented here is release version 4 (http://srtm.csi.cgiar.org) with better void filling techniques as well as coastal and lacustrine shore improvements. It has been known for some time that the relative accuracy is quite high (1-2 m) but that the absolute accuracy of this data is only around 4-5 m. In the case of Botswana and the area around Gweta in particular (Figure 3) one can clearly see an overestimation of around 5 m often attributed to vegetation. This absolute error is actually more fundamental and intrinsic than that and has been reported elsewhere (Rodriguez 2005).

Table 1: Global Digital Elevation Data

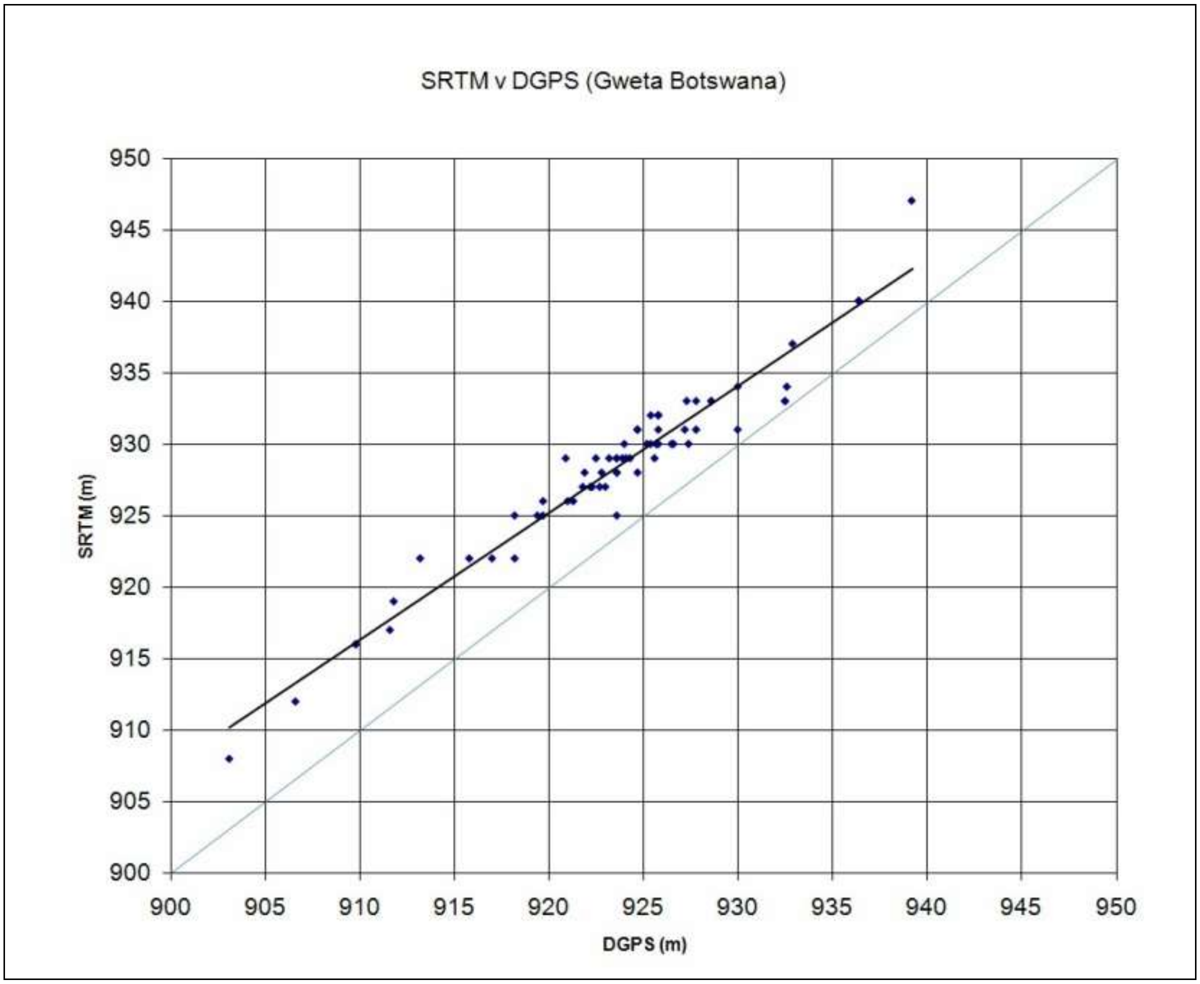
Global DEM Datasets	Data Release	Resolution	Resolution	Global Tiles	Tile Size Pixels
ETOPO5	1988	5 km	5 arc minutes	1	2160x4320
GTOPO30	1996	1 km	30 arc-second	33	6000x4800
SRTM30	2003	1 km	30 arc-second	33	6000x4800
SRTM3 *	2004	90 m	3 arc-second	14000	1201x1201
ASTER GDEM	2009	30 m	1 arc-second	22600	3601X3601

Note: SRTM3 (*) data was chosen as the most suitable DEM source for the project.

(Source: Compiled by Author)

When referring to global spot heights from the Icesat laser altimetry satellite, it is apparent that this 4-5 m shift is not vegetation dependant but actually refers to the entire Makgadikgadi basin including pan floor, grassland, savannah and mopane veld irrespective of any canopy height. This degree of error is not really significant when mapping drainage lines and watershed boundaries but does not allow for a detailed mapping of the pan surface itself. Even the most recent global follow up the, ASTER GDEM, a photogrammetrically derived elevation model, shows similar offsets and even wider random errors and noise compared to the radar derived SRTM (Figure 4) and Table 2.

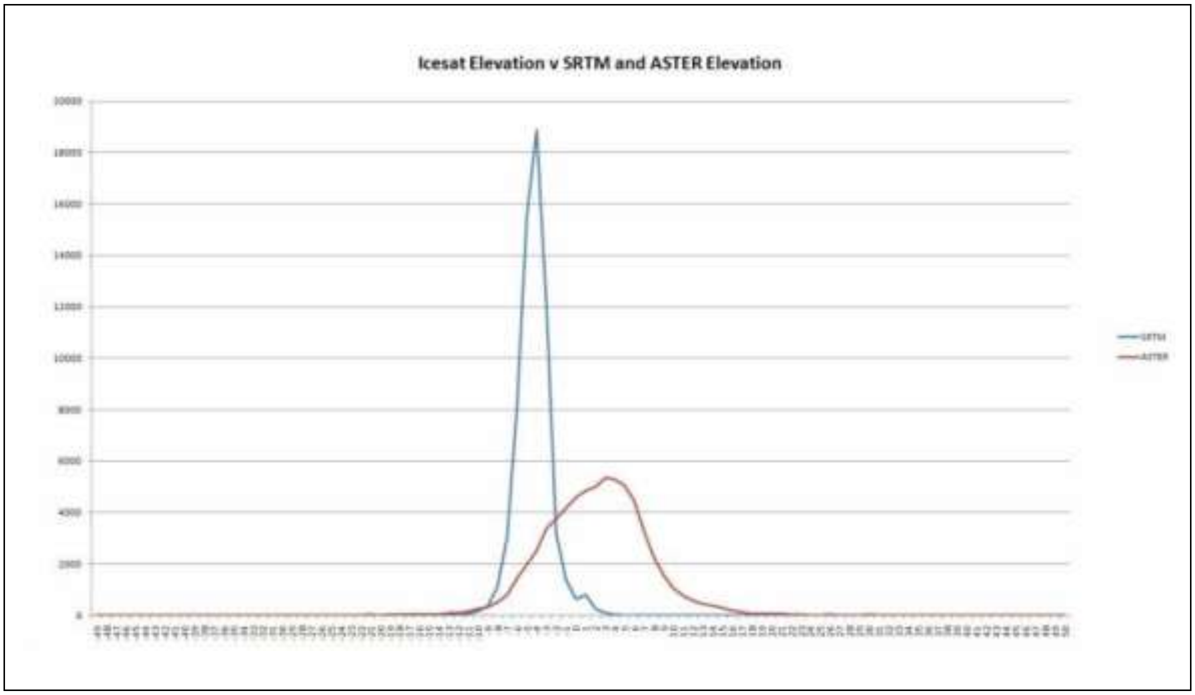
Figure 3: Quality of SRTM derived height against DGPS for the Gweta area



Note: SRTM overestimate by approximately 4-5 m.

Source: Author, DGPS data via Water Survey Botswana, (unpublished).

Figure 4: SRTM and ASTER DEM heights plotted against 65000 Icesat Point heights covering the Makgadikgadi basin.



Note: Relative over and underestimation as well as error spread. SRTM error is more consistent

Source: Author (unpublished).

Table 2: Icesat data is on average -4.8 m lower than SRTM and 1.6 m higher than ASTER

Stats	>905 m	910 m	915 m	920 m	925 m	930 m	935 m	940 m	945 m	>945 m	Icesat v SRTM	Icesat v ASTER
Mean	-3.4	-4.3	-4.9	-5.1	-4.8	-5.1	-4.9	-5.6	-5.3	-5.3	-4.8	1.6
Median	-3.7	-4.4	-4.7	-5.0	-4.6	-4.9	-4.8	-5.4	-5.2	-5.1	-4.8	1.7
Mode	-3.3	-5.5	-3.8	-5.8	-6.2	-5.3	-5.5	-5.6	-6.1	-5.9	-4.5	-0.2
Std Dev	1.9	1.7	1.2	1.4	1.2	1.4	1.2	1.6	1.4	1.5	1.7	5.2
Range	15.5	13.6	8.7	18.8	14.0	11.4	9.9	12.0	12.1	34.6	38.3	105.9
Minimum	-12.1	-9.7	-9.3	-18.2	-14.9	-11.0	-10.4	-12.3	-12.2	-14.5	-18.2	-61.2
Maximum	3.5	3.9	-0.6	0.6	-1.0	0.4	-0.6	-0.3	-0.1	20.1	20.1	44.6

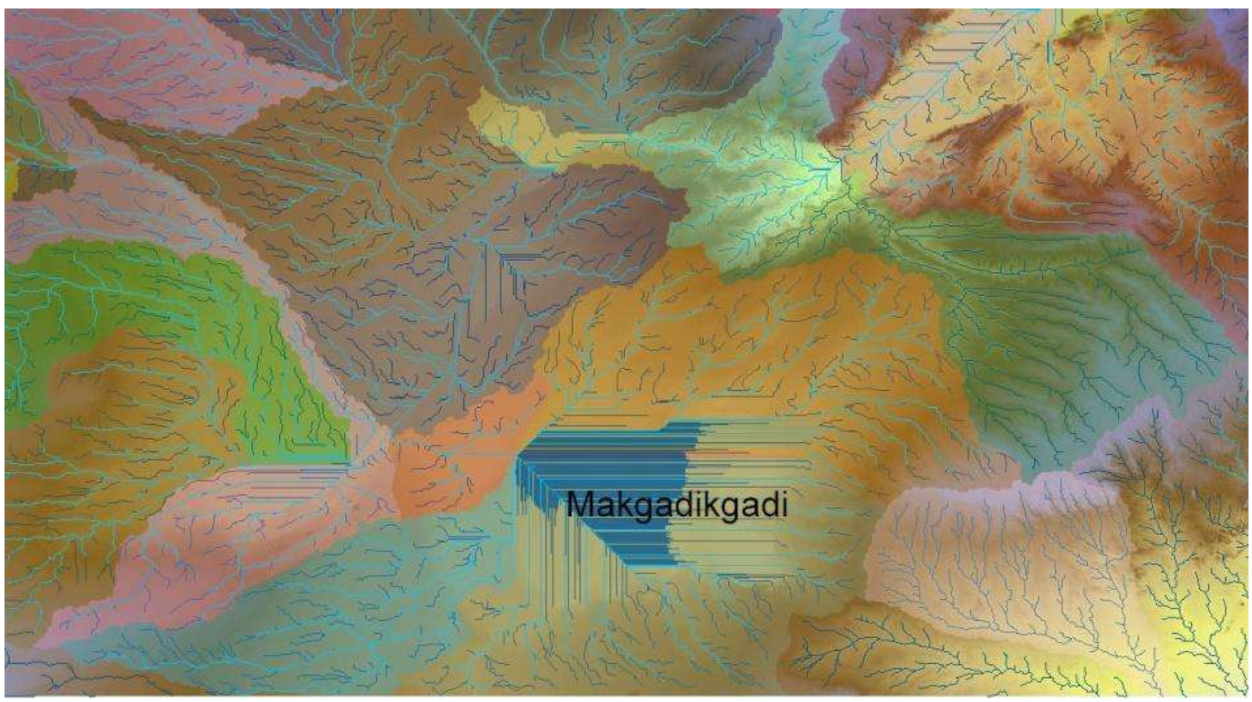
Note: ASTER underestimates height and SRTM overestimates height assuming that Icesat provides better height reference. Total sample size approximately 65000 data points. SRTM inaccuracies for different height zones in the Makgadikgadi (905-945 m) are relatively consistent. Errors appear systematic and not vegetation dependant.

Source: Author (unpublished)

Overall SRTM data appears more coherent with a greater internal consistency than ASTER data despite slightly greater error in accuracy. In a sense SRTM data is less noisy. Due to the above quality assessment this report will use rasterized 90 m resolution SRTM coverage to depict watershed boundaries as well as drainage lines which should optimize our understanding of the Makgadikgadi catchment.

Automated watershed and drainage generation was attempted but quality was sub-optimal (Figure 5) requiring significant post processing and correction. Hence an entirely manual method was considered to be the most effective for such a relatively small area. The results need major revisions and the output makes numerical sense but has no bearing on most drainage lines and watersheds found in reality. This highlights the limits of automated techniques for such flat landscapes.

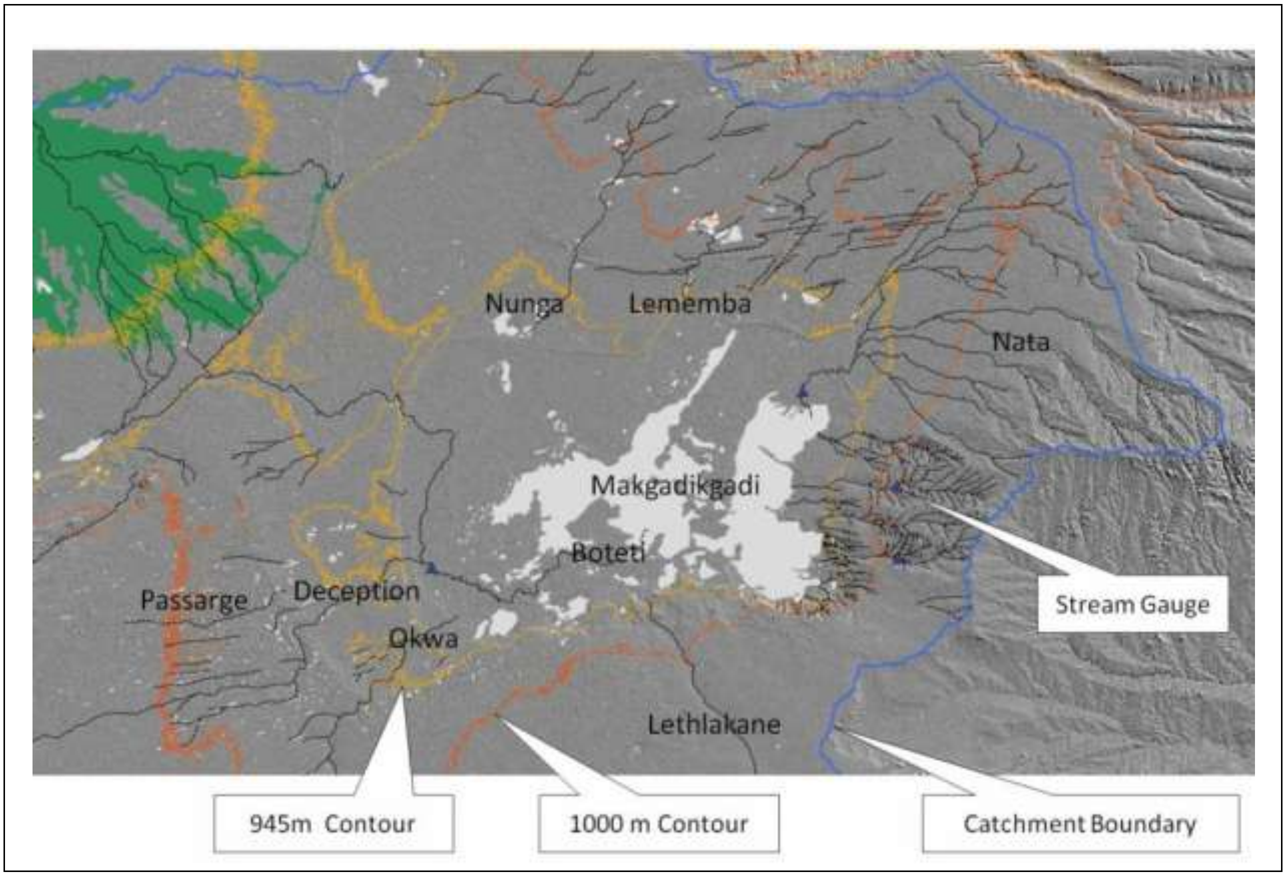
Figure 5: ArcGIS automated watershed and drainage generation for Makgadikgadi



Source: Flügel (unpublished)

Figure 6 is an overview of surface water catchment and topographic setting with special reference to the 945 m and 1000 m contours. Note not all rivers reach the pan and note pronounced incision of eastern catchments. The contours are indicative of old lake floor which may now facilitate infiltration and pan groundwater recharge. Stream Gauges are covered in Section 3.4.

Figure 6: Shaded SRTM with drainage and major contours



Source: Author (unpublished)

The Makgadikgadi Pan represents the lowest point in the Okavango catchment along with the Mababe depression and Lake Ngami. Using the entire Okavango catchment as a source region is not realistic. Establishing the exact surface as well as groundwater sources for a pan this size is difficult. Numerous drainage lines enter the basin but many of these are considered fossil stream features and have not contributed surface water during modern time. A range of surface features such as the former lake shores to the north and west act as topographic watershed boundaries but may not have an impact on the movement of groundwater. Drainage features in general are very subdued with the exception to the east of the Pans where watershed boundaries are well defined and rivers appear most active (Figure 6). The following section will focus on this area.

Depicted above (Figure 6) is the shaded view of the Pan and its surroundings, as well as a related contour product. Carefully mapping drainage lines from SRTM alongside Landsat imagery in particular to the east of the Pan margin highlights two distinct drainage patterns or zones. Above the 1000 m contour most of the rivers are well incised and portray a dendritic surface pattern. Below the 1000 m contour the Rivers (Semowane, Mosetse, Lepashe, Mosope) enter the terrain of the former lake floor which has a higher infiltration potential due to its calcareous and silica karst morphology. The watersheds between these rivers below the 1000 m contour are wide and flat and may act as direct recharge zones to the Pan basin (Figure 7). The channel flood plains widen towards the Pan and shallow discharge supports a host of riparian wetlands and delta systems. This subtle observation stresses the importance of the eastern margin in sustaining the hydrological integrity of the pan and also would explain as to why the Sua surface is generally wetter. It's not just a function of drainage such as the Nata River and runoff but also potentially significant groundwater recharge from much of the Pan margin. Runoff may add directly and relatively swiftly to lacustrine conditions whereas groundwater flow has a delayed function which may discharge through the pan floor to promote water bodies not just along the pan margin but anywhere in the Makgadikgadi sump.

In addition recent tectonic activity to the north of the Pan has resulted in fault controlled topography, and produced the potential for "channeled" groundwater flow in a number of ill defined channels such as the Nunga and Lememba (Figure 6). Surface water in these drainage features is not expected. These "channels" along with the Letlhakane River have in fact no modern record of surface flow; they might however contribute to the active lacustrine pan-environments through the movement of groundwater. Again channels lose some of the definition as they enter the karstic terrain of the former lake margin highlighting the importance of groundwater recharge.

SRTM data also depicts many of the smaller surrounding pans as elevated yet sunk into the margin of the raised perimeter of the pan. These smaller pans nested in the karstic terrain of the older lake floor below the 1000 m and 945 m contours may act as important elevated recharge points to the Makgadikgadi proper. Their hydrological function has yet not been fully explored but the role of these pans from now on referred to as 'proto–pans deserve broader consideration in future work. They include the following from west to east (area km^2 in brackets): Dzibui Pan (19), Xhorodomo Pan (30), Lake Xau (145) Tsokotshaa Pan (33), Rysana Pan (93), Guquago Pan (28), Nkokwane Pan (76), Tshitsane Pan (29) Ntsokotso Pan (46), Mea Pan (3) and Makopela Pan (3). There are other smaller Pans along the eastern margin of the Pan which do not appear to have names. These may host lacustrine environments in their own right, although most of these systems appear have no surface water input.

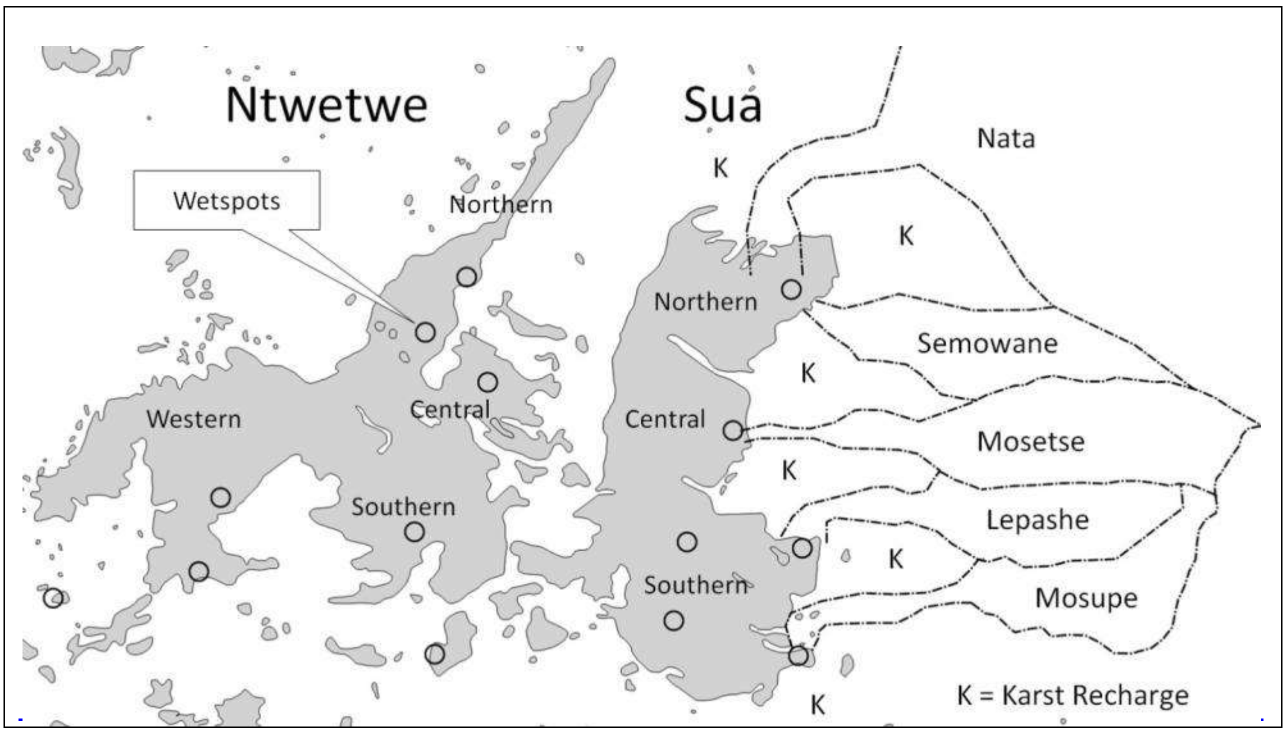
To the north-west one finds the additional Nxai Pan and Kudiakam Pan located within the confines of the Nxai Pan National Park which may contribute water to the Makgadikgadi basin. It might also be worthwhile to note that SRTM data has also been used to look at drainage long profiles for various rivers entering the Makgadikgadi (Nash and Eckardt submitted). These profiles are relatively straight, neither concave nor convex or feature excessive knickpoints. Such an apparent equilibrium and lack of geomorphic adjustment would suggest that the current pan environment is representative of longer time periods. Fault control does show up in these profiles and is taken as an indication of recent tectonic modification.

It is important to stress that the Pan only seems flat but that hydrologically it is not. Systematically mapping the topography of the pan floor is highly desirable as this will highlight sub-basins which might be prone to ponding. Pan topography may also be dynamic due to groundwater fluxes and mobile surface material. Capturing this is currently only possible with slow ground based GPS point survey techniques or the point heights produced from the Icesat laser altimeter. Neither ASTER nor SRTM are useful to map the pan in such detail. Icesat does not produce systematic raster coverage but has so far generated approximately 24000 point heights of the pan surface derived from 40 m diameter laser observation with a 200 m interval.

These Icesat point samples are on the increase as coverage improves with time. There are currently more points covering Ntwetwe than Sua Pan. Validation campaigns at the Salar de Uyuni, a large pan in Bolivia, have shown Icesat derived elevation to have an absolute accuracy of <2 cm (Fricker *et al.* 2005). The author expects the same to hold here (Figure 7) and hence this data serves as a good validation tool for ASTER and SRTM data (Figure 4 and Table 2). Icesat campaigns continue and global coverage is slowly improving. The future might even hold the promise of mapping dynamic topography in the sub-meter/cm range which might capture vertical and lateral movement of water bodies on the pan surface. This might require some validation and at this stage can only be considered experimental. However the topographic monitoring of the Pan surface is bound to improve and enhance our understanding on the pans micro-topography and lacustrine environments.

The topographic elevation data generated by the Survey and Mapping Division of the Botswana Government will soon be compared alongside ASTER and SRTM data. Note Karst recharge zones on the old lake floor of Palaeo Lake Makgadikgadi. Pan wetspots to be discussed in section 3.6.

Figure 7: Eastern Catchments and Watersheds



Source: Author (unpublished)

Box 1: Summary of the topography of the Makgadikgadi and its catchment

What we know so far:

- Raster DEM Topographic data is improving
- We have a relative accuracy of around 1 m
- We have an absolute accuracy of better than 5 m with a 90 m resolution
- This helps us identify drainage lines and watershed boundaries
- We also have laser altimetry with sub-m/cm vertical accuracy for 40 m circular footprints
- At the meter to sub meter scale the pan is most certainly NOT flat
- Icesat is ideal for mapping the topography of the pan surface

What we do not know:

- Require denser mesh of laser derived point height to improve pan surface model
- Require more repeat coverage to determine dynamic pan surface topography
- This should improve volume/depth estimates of pan water bodies
- National DEM data, generated in Botswana and handled by the Department of Survey and Mapping, has not been compared against Icesat height data.
- Differential ground based GPS surveys might be necessary to quantify bathymetry of major sub-basins during a dry spell which in turn will improve lake volume estimates

3.3 Rainfall around the Makgadikgadi

The MFMP was able to draw on weather station data covering the Makgadikgadi region. This was obtained from the Botswana Meteorological Office in Gaborone. Emphasis was on stations in the most pronounced stream catchments of the pan system in particular to the north east and east. Previously published work (Bryant *et al.,* 2007) on the hydrology of the Makgadikgadi, drew on weather station data from Gweta (044-GWET), Nata (164-NATA), Orapa (179-ORAP) and Sua (333-SUAP) and results are reviewed here.

The additional dataset presented here features monthly rainfall records in mm dating back as far as 1958 and includes records up to December 2008. There are a total of 11 stations (Figure 8 and table 3) and includes Mosu, Mopipi, and Rakops towards the west and south east of the pan, Letlhakane to the south, and Nata, Sebina, Tutume, Sua Pan, Dukwi, Maitengwe and Lepashe to the east and north east of the pan. Rainfall records for Gweta, Orapa and Mosu were not made available on this occasion.

The data coverage has several temporal gaps i.e. missing months. For the following analyses only complete annual records (i.e. 12 months) were considered. Daily data does exist but was not made available for the MFMP project.

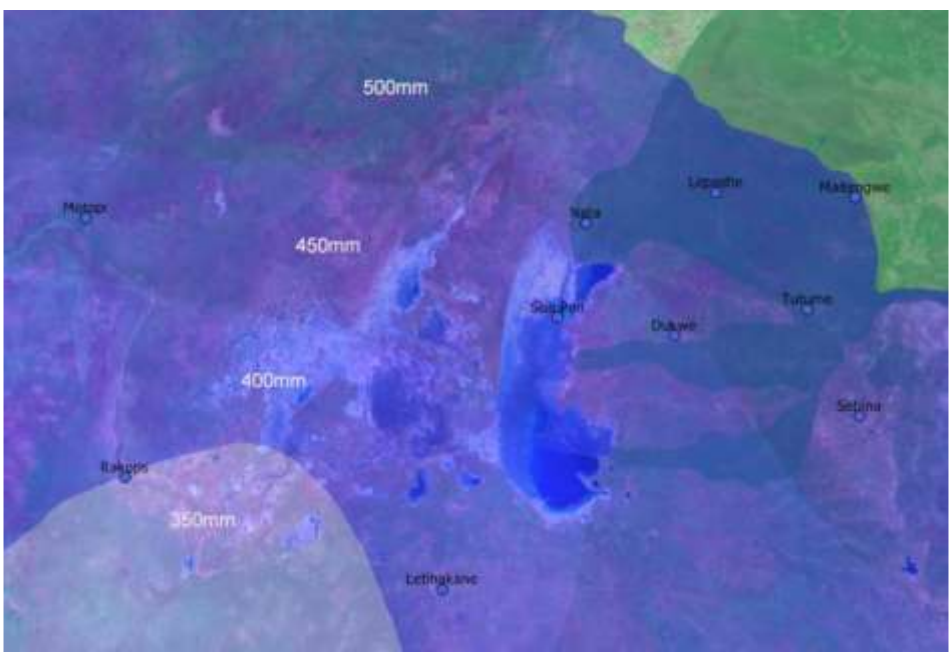
Table 3: Monthly weather station data made available to this project

Location of Met Station	MET Record	Start	Finish	Gaps	Lat	Lon
NATA POLICE STATION	164-NATA	Apr-59	Nov-05	Yes	-20.22	26.17
RAKOPS POLICE STATION	195-RAKO	Feb-59	Jul-06	Yes	-21.05	24.40
SEBINA STORE	207-SEBI	Apr-58	Jan-06	Yes	-20.85	27.22
TUTUME POLICE STATION	256-TUTU	Oct-59	Dec-08	Yes	-20.50	27.02
SUA PAN MET. STATION	333-SUAP	Aug-91	Dec-08	No	-20.53	26.06
DUKWI POLICE STATION	030-DUKW	Jan-94	Dec-08	No	-20.59	26.51
MAITENGWE PRIMARY SCHOOL	110-MAIT	Dec-59	Nov-08	Yes	-20.13	27.20
MOSHU PRISONS OFFICE	155-MOSU	Sep-79	Dec-99	Yes	-20.12	23.25
LEPASHE PRIMARY SCHOOL	468-LEPA	Nov-92	Jan-08	Yes	-20.12	26.67
MOTOPI PRIMARY SCHOOL	160-MOTP	Oct-79	Dec-06	Yes	-20.20	24.25
LETLHAKANE MET. STATION	093-LET2	Sep-92	Dec-08	Yes	-21.42	25.62

Source: Botswana Meteorological Office

The rainfall gradient from National Atlas of Botswana depicted along with some of the eastern catchments (Nata, Mosetse and Mosope River), Figure 8.

Figure 8: Location of weather station data provided to this project



Source: Author

Some preliminary observations indicate that Rakops (359 mm annual average total) appears to be the driest and Maitengwe (545 mm annual average total) the wettest place (Table 4). The data depicts the expected seasonal cycle with maximum monthly average rain in January at Dukwi (133 mm monthly average) and lower levels at Rakops and Letlhakane with 93 mm monthly average, highlighting the distinct north-east to south-west rainfall gradient across the pan. Maitengwe the eastern most location achieves peak rainfall slightly earlier in December (131 mm monthly average) and July and August appear to be the driest months throughout.

Table 4: Mean monthly and annual rainfall figures for the Makgadikgadi

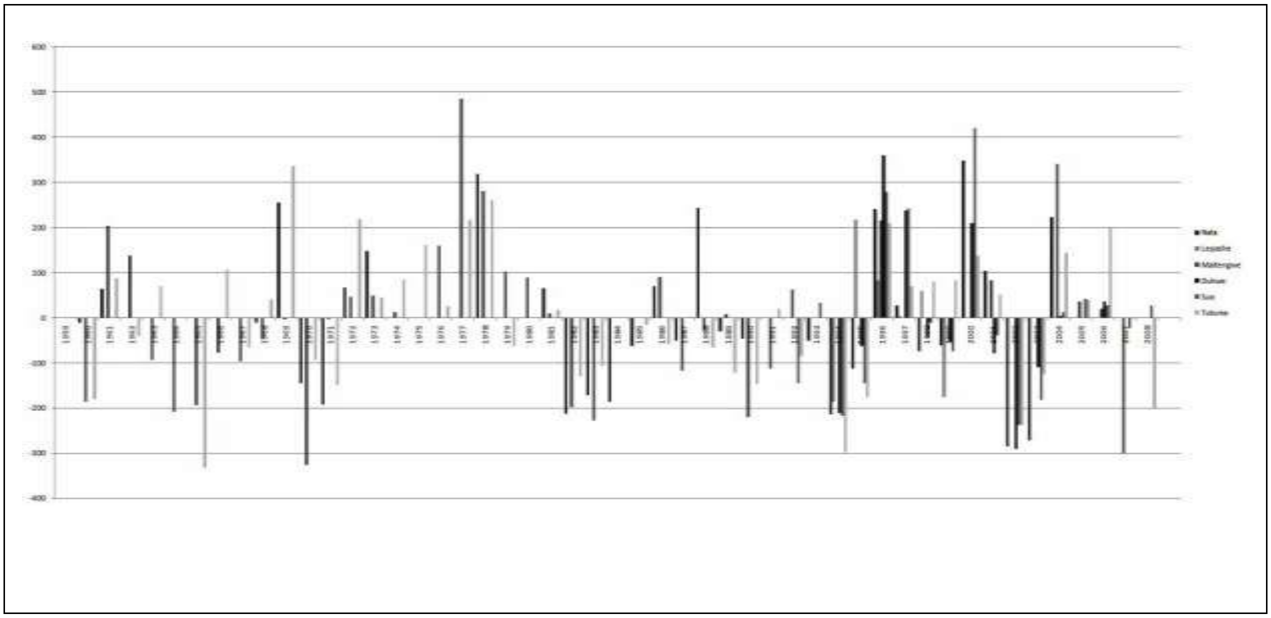
Months	Motopi	Rakops	Letlhakane	Sua	Nata	Dukwi	Lepashe	Tutume	Maitengwe	Sebina
August	0	1	0	0	0	0	0	0	0	1
September	3	3	3	4	3	2	2	5	5	7
October	21	16	12	14	20	12	16	20	23	20
November	62	44	56	56	53	69	67	69	78	75
December	60	61	77	79	83	84	89	95	131	87
January	121	93	93	123	112	133	111	116	120	109
February	87	66	87	87	96	73	72	84	93	83
March	48	49	58	53	55	58	39	68	62	44
April	12	21	11	6	25	6	11	25	26	21
May	4	3	5	5	4	7	10	4	5	3
June	0	3	3	5	1	3	12	2	3	1
July	1	0	0	2	1	0	4	0	0	0
Total	**419**	**359**	**405**	**435**	**453**	**448**	**433**	**488**	**545**	**452**

Source: Botswana Meteorological Office, compiled by Author (unpublished)

A number of rain gauges have recorded seasons with monthly rain in excess of 200 mm. This took place in Jan 1972, Dec 1977 - Jan 1978, Dec 1987 - Mar 1988, Dec 1995 - Feb 1996, Dec 1996 – Feb 1997, Jan 1998, Dec 1999 – Feb 2000, Jan 2004 - Mar 2004. Some stations even recorded more than 400 mm per month such as Sebina and Tutume in December 1972, Mosu in January 1989 and Maitengwe in December 1995 with a record of 597 mm per month.

Looking at rainfall departures from the mean and associated rainfall variability (Figure 9) it becomes apparent that inter-annual variation is as pronounced and expected for any semi-arid region. 1971-1981 features a period of distinct above average rainfall for all stations while 1982-1995 appears distinctly drier with a long spells of below average rainfall. Generally other periods of variability are apparent at shorter timescales of 2-3 years.

Figure 9: Rainfall deviation from the mean (in mm) for selected stations NE of the Makgadikgadi from 1959-2008



Notes: This depicts inter-annual variability. Note the decadal cycle for 70's and 80's.

Source: Botswana Meteorological Office, Compiled by Author (unpublished)

Previous published work (Bryant *et al.,* 2007) based on similar rainfall records as above showed that rainfall in the Makgadikgadi basin are strongly linked to El Ninõ Southern Oscillation (ENSO) cycles in the Pacific and SST (Sea Surface Temperature) anomalies in the Indian Ocean. Records for the 1980-2000 time series showed a strong correlation between wet season rain DJF (December, January, February) in the Nata River Catchment and the Subtropical Indian Ocean dipole (SIOD) values for JFM (January, February, March) of the same year. Furthermore extreme rainfall events are linked to the landfall of tropical cyclones during periods of La Ninā conditions and associated anomalous low level moisture flux into eastern southern Africa.

Data provided for this study was similar to what had been analysed previously, for full and detailed analyses of Makgadikgadi and Nata basin climatology refer to Bryant *et al.* (2007). Making a stronger connection between monthly rainfall, daily stream hydrology and pan surface dynamics is currently hampered by data gaps and temporal and spatial mismatches.

In addition higher temporal resolution daily rainfall data would be desirable. This would be indicative of the nature of single rain events, such as storm intensity and through a referral to NCAR (National Center for Atmospheric Research) reanalysis products, would place each daily event into its proper regional synoptic context. Monthly rainfall data is merely a summary and can at best be linked to slower and gradual dynamics in the remote oceans rather than the rapid changes in the nearby atmosphere. To make any headway with future climate research in the Makgadikgadi would require daily rainfall data. Furthermore measurements from the pan surface and some of the specific recharge areas are currently absent. Therefore monitoring key climate variables at or in close proximity to actual lacustrine areas on the pan surface is required.

Overall rainfall records for this area as well as most areas in Botswana have a slightly negative trend, suggesting that Botswana is becoming drier (Botswana National Atlas 2001).

Box 2: Summary of rainfall around the Makgadikgadi

What we know so far:

- Analyses on rainfall data so far is based on monthly means
- This has shown a strong connection with sea surface temperature elsewhere
- The spatial trends in this study confirm previous studies
- In light of inter annual variability and various long term cycles this negative trend may not necessarily be due to global warming

What we do not know:

- Daily rainfall data would be required if one were to examine local synoptic controls
- Daily data exists and should be subject to appropriate analyses using NCEP/NCAR reanalyses
- All existing stations focus on settlements and ignore pan surface, wetlands and specific pan recharge zones

3.4 Stream hydrographs for the Makgadikgadi catchment

Daily river flow data exists for a number of catchments in the Makgadikgadi refer to Figure 10 and Table 5 Four out of six rivers which feature current surface flow in the catchment are being gauged. The closest gauge to the pan margin is the Nata stream gauge in Nata. Other gauges are some distance from the pan. Mosetse and Mosupe gauges are about half way up the stream some 50 km from the pans edge. Lepashe and Semowane are not being gauged.

Table 5: Stream gauge record for the Makgadikgadi

Catchment	Location	DWA Code	Start	Gaps	Lat	Lon
Boteti River	Rakops	8122	Sep 1971	Yes	-20.03	24.40
Nata River	Nata Old Bridge	5311	Oct 1969	Yes	-20.20	26.18
Mosetse River	Mosetse	5211	Oct 1969	Yes	-20.65	26.63
Mosope River	Matsitama	5111	Oct 1970	Yes	-21.02	26.63

Note: Daily flood data

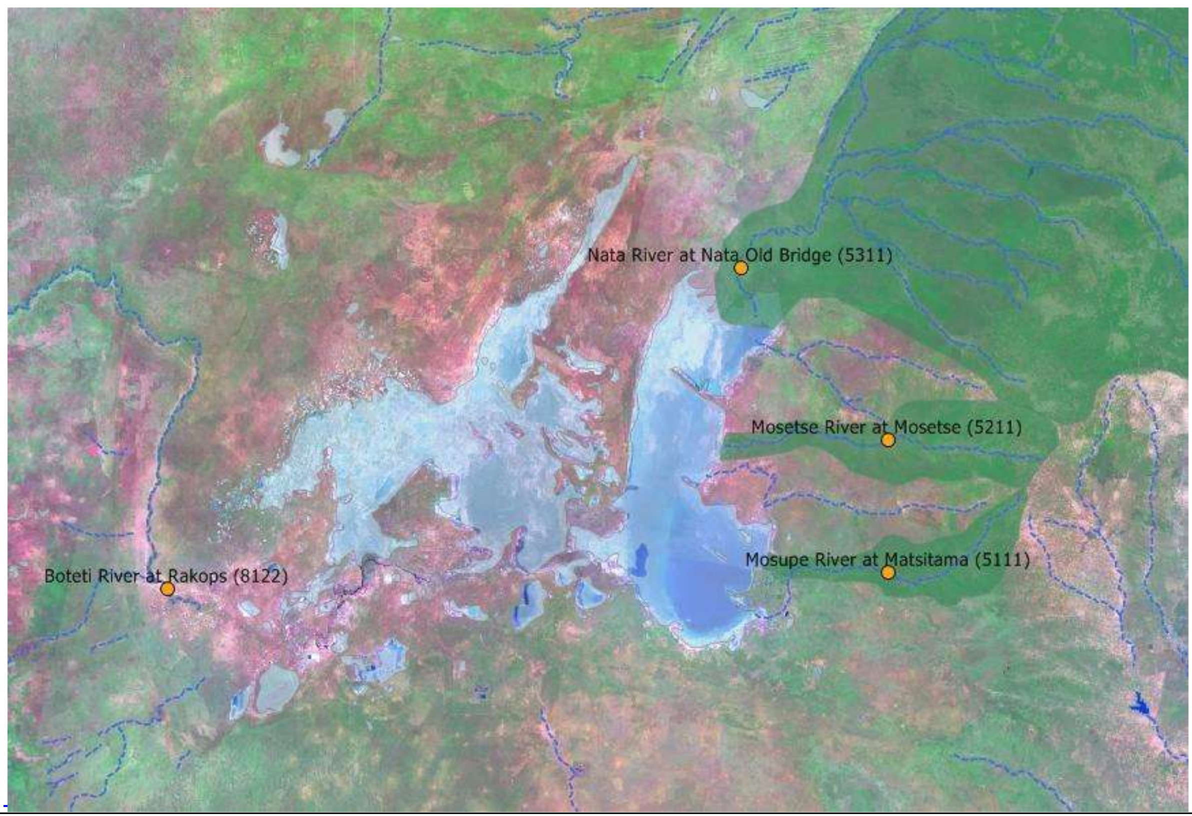
Data Source: Department of Water Affairs.

Due to data gaps, analyses and plots of the stream gauge record, focus on the 1971-1999 with emphasis on the monthly summary records. For this observation period the Nata carried most of the water (4471 MCM) total, Boteti slightly less (3274 MCM) and Mosetse (688 MCM) and Mosope (208 MCM) much less.

It is not surprising that stream flow is highly variable and that all months are able to produce zero flow records. It is also very much apparent that the nature of stream flow from the east is very different compared to the Boteti River (Figures 11 and 12). Eastern floods are short and sharp and synchronized with emphasis on the summer months with peak flow usually attained in January. The Boteti peaks much later during September as its flood waters originate from the Okavango Delta outflow. Boteti flood periods may extend over many months with noted variations being gradual. In the 1970's it did not stop flowing for several years (April 1974-March 1980) and its last recorded surface flow at Rakops occurred in February 1991. During the writing of this report the river has passed Rakops and reached Lake Xau.

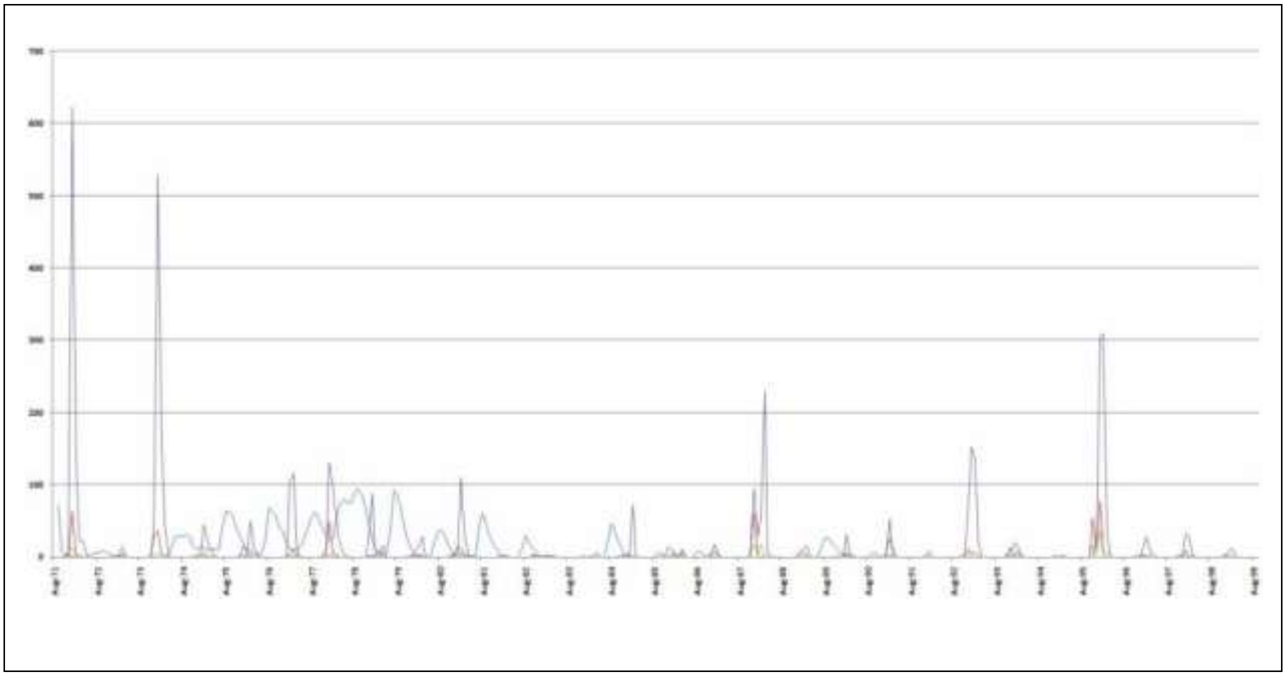
Work by Bryant *et al*. (2007) has pointed to a strong ENSO control in the Nata River stream flow and a good link to surface water conditions in the Makgadikgadi.

Figure 10: Location of Stream gauges with DWA code in the Makgadikgadi Catchment and its main contributors the Boteti , Nata , Mosetse and Mosope Rivers



Data Source: Department of Water Affairs

Figure 11: 1971-1999 Stream Records in MCM for Boteti (Blue), Mosupe (Green), Mosetse (Red) and Nata Rivers (Purple)

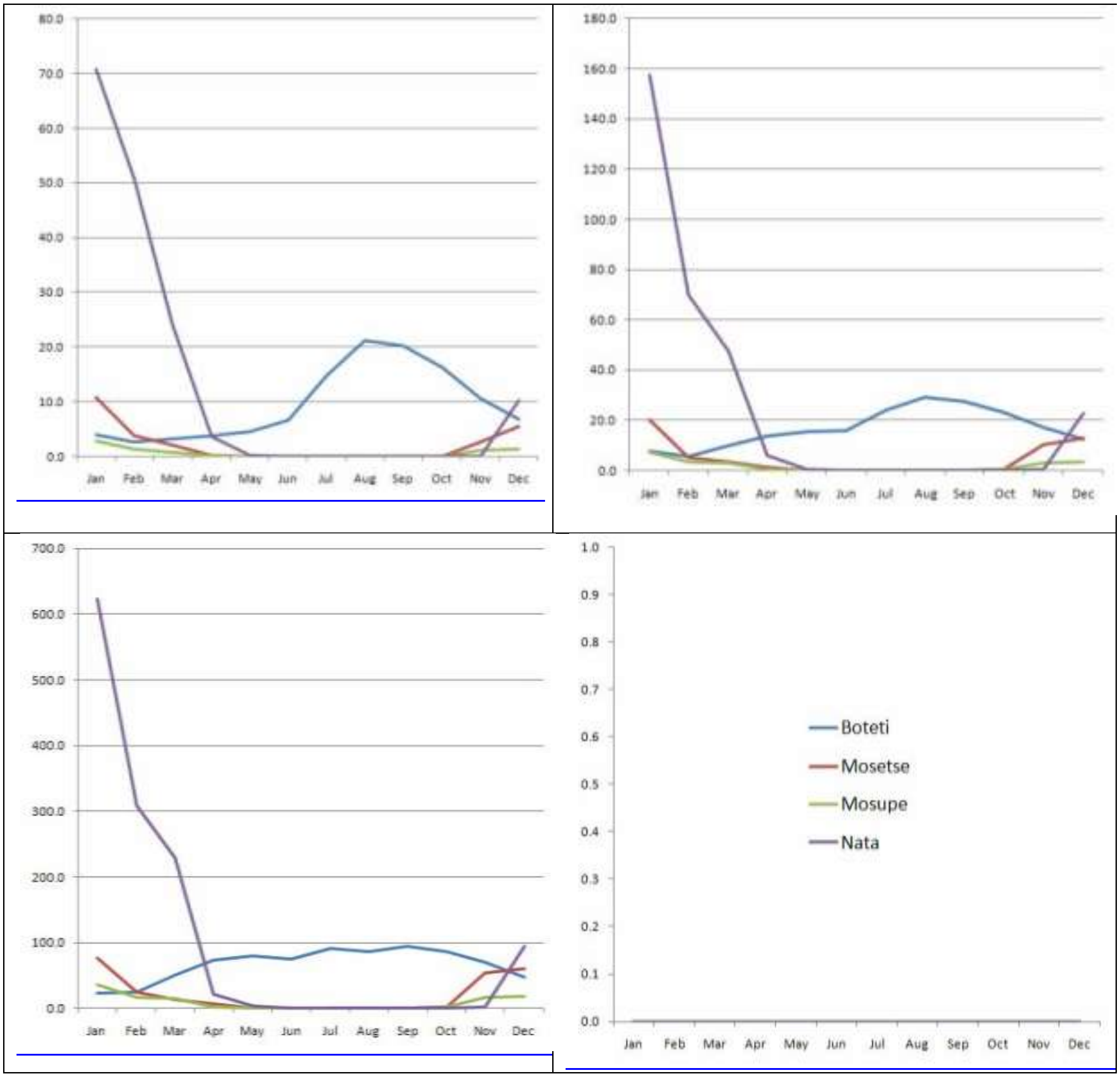


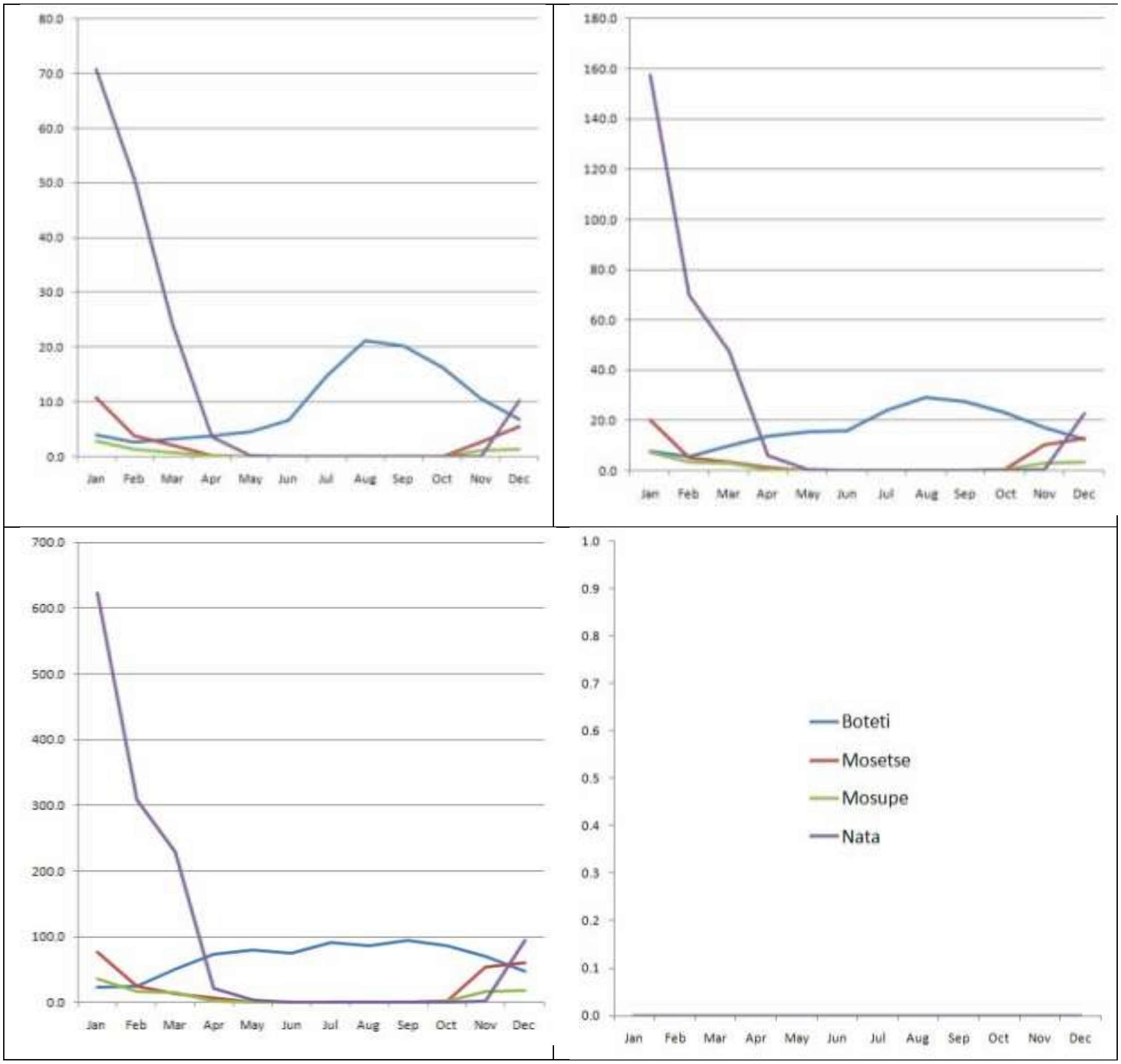
Notes: Note short spiky summer flood in eastern catchments and protracted winter peak flood in the Boteti.

Data Source: Department of Water Affairs

On Figure 12, the Mean is on (Top Left), Standard Deviation (Top Right), Max (Bottom Left) and Min (Bottom Right). Note zero flow possible in all months for all rivers.

Figure 12: Monthly Flood in MCM





Data Source: Department of Water Affairs

Box 3: Summary: Stream hydrographs for the Makgadikgadi catchment

What we know so far:

- The daily flood record for the streams entering the pans is valuable
- A strong ENSO control is evident
- In particular Nata River and Pan surface dynamics appear closely linked
- Other gauges only capture runoff at some distance from the Pan
- Surface runoff is not the only contribution to the pan environment

What we do not know:

- Exact temporal lag and link between stream flow and lacustrine response
- Contribution of stream flow to groundwater recharge of pan environment

3.5 Riparian systems and seepage points

This section depicts Landsat data from the historic archives of the GLCF (Global Land Cover Facility). This record extends back to 1973 and hosts imagery for the 1970's in the form of MSS (Multi Spectral Scanner) data (80 m resolution), TM (Thematic Mapper) data for the 1990's (30 m resolution) and ETM (Enhanced Thematic Mapper) data for the 2000 period (30 m resolution), see Table 6. In these false colour displays (Bands 4, 3, 2 RGB), green vegetation appears red.

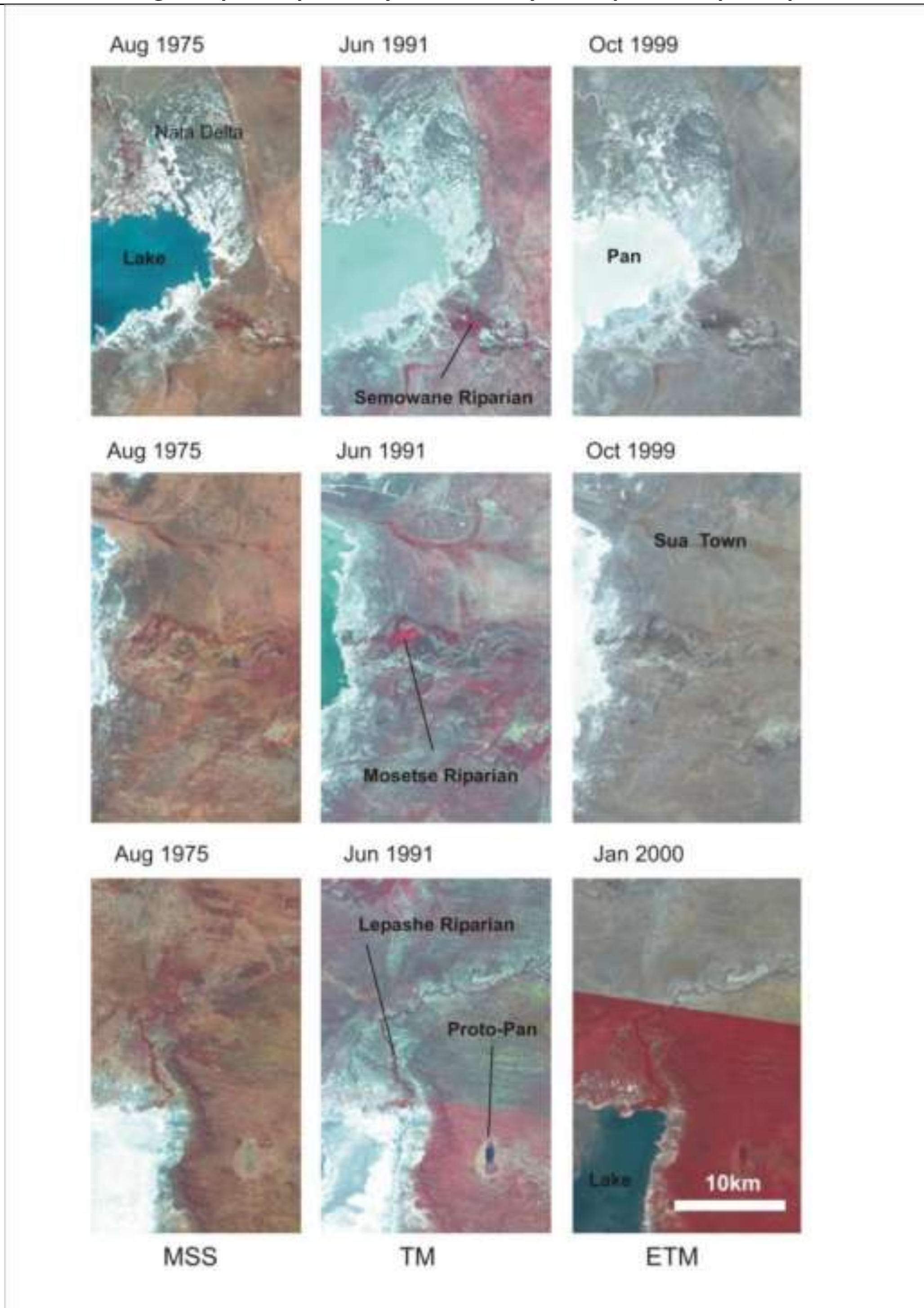
Table 6: Catalogue of Landsat Data for the Makgadikgadi.

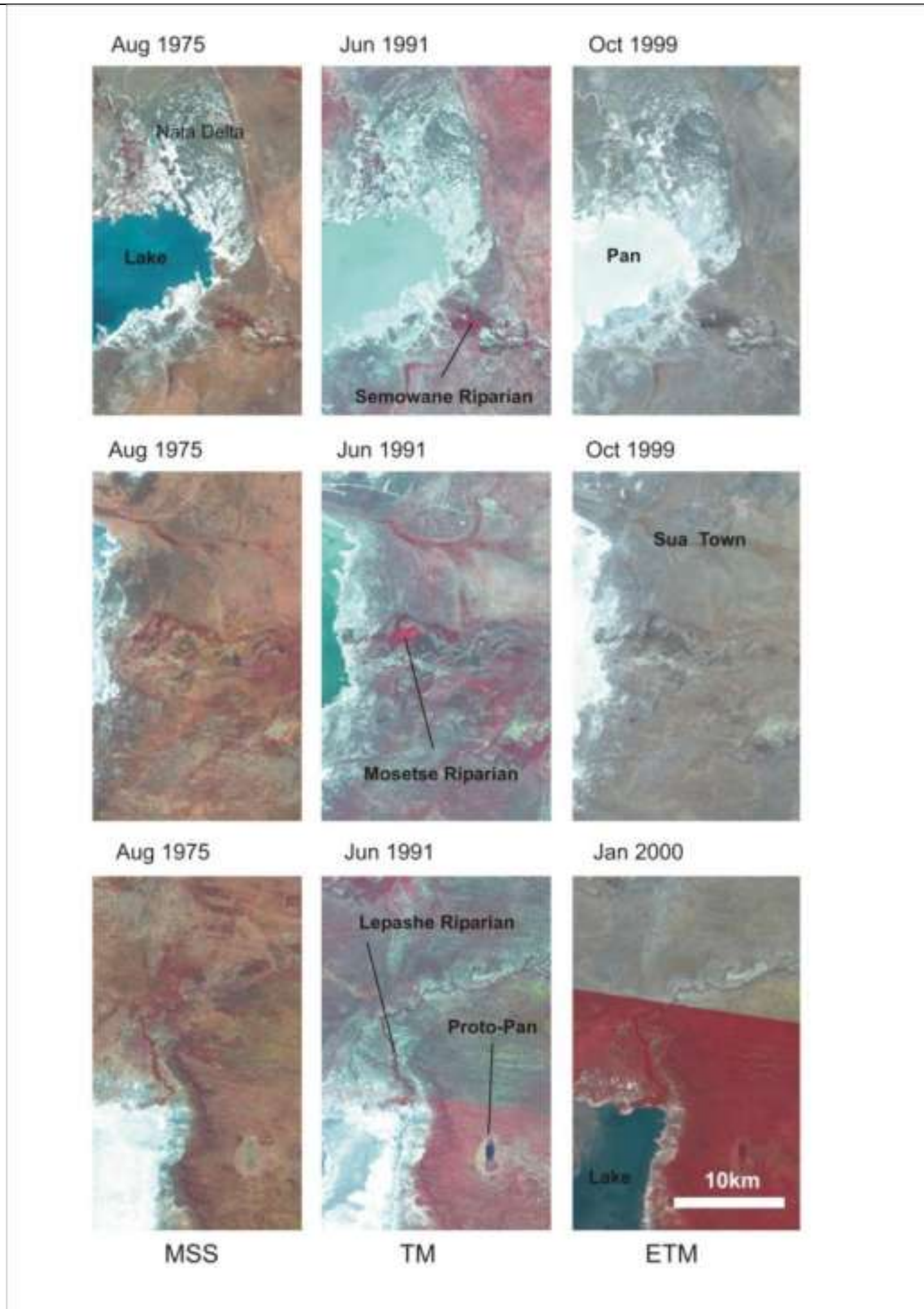
Landsat	Path	Row	Year	Month	Day
MSS	184	74	1975	Aug	19
MSS	184	75	1979	Oct	9
MSS	186	74	1975	Mar	12
MSS	186	75	1973	Feb	5
MSS	185	74	1979	Jun	6
MSS	185	75	1979	Jun	6
TM	172	75	1991	Jun	24
TM	172	74	1990	Mar	1
TM	173	75	1991	Mar	11
TM	173	74	1990	Apr	9
ETM	172	74	1999	Oct	12
ETM	172	75	2000	May	23
ETM	173	75	2001	May	17
ETM	173	74	2001	Jan	9

(Source: GLCF)

A rapid appraisal of the 14 images shows various degrees of surface change and dynamics between 1970's to 2000. (Figures 13, 14, 15, 16). A full analysis into these and other related Landsat imagery especially in the context of climatic variability is beyond the scope of this report. This would however provide a more systematic and quantifiable appraisal of change within the Makgadikgadi Basin. In addition Landsat imagery lends itself to map small seepage points and water pools as well as riparian distributions (Figure 13). MODIS will be used for a systematic pan water survey (Section 3.6).

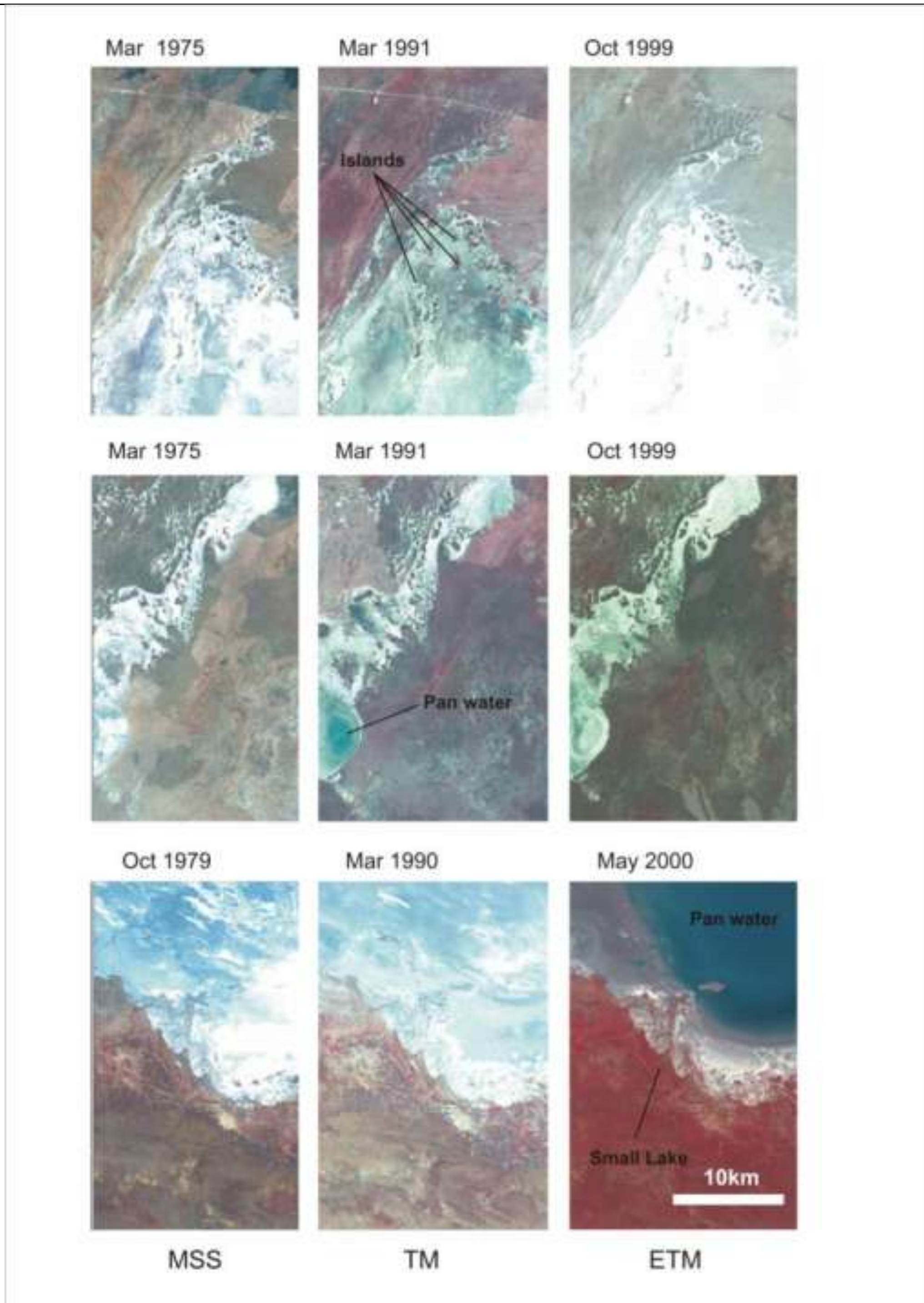
Figure 13: Eastern Margin of pan. Riparian systems and dynamic pans and proto-pans

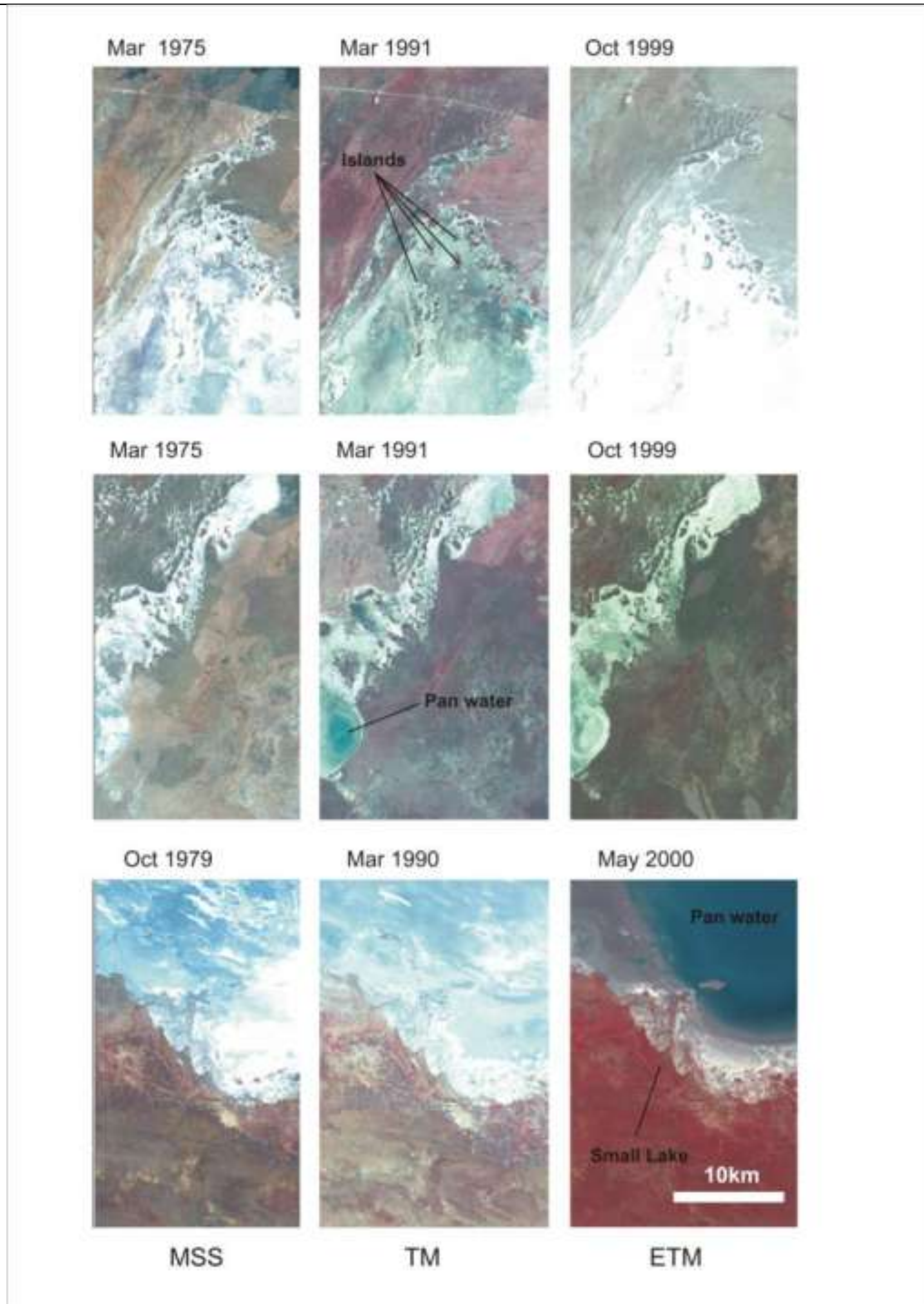




Data Source: GLCF, interpretation by author, unpublished

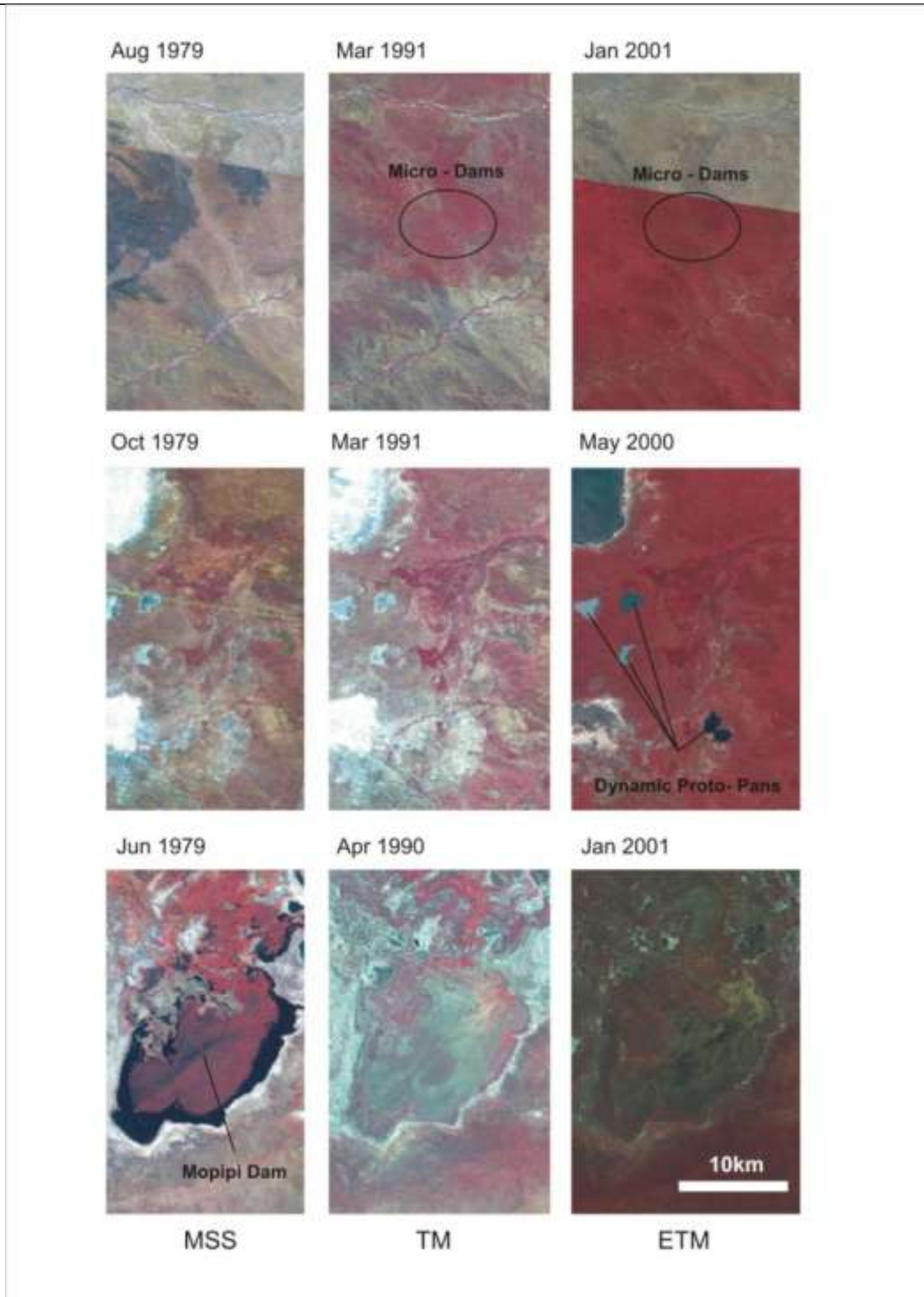
Figure 14: Surface dynamics at Nata, Ntwetwe, and Mosu Escarpment

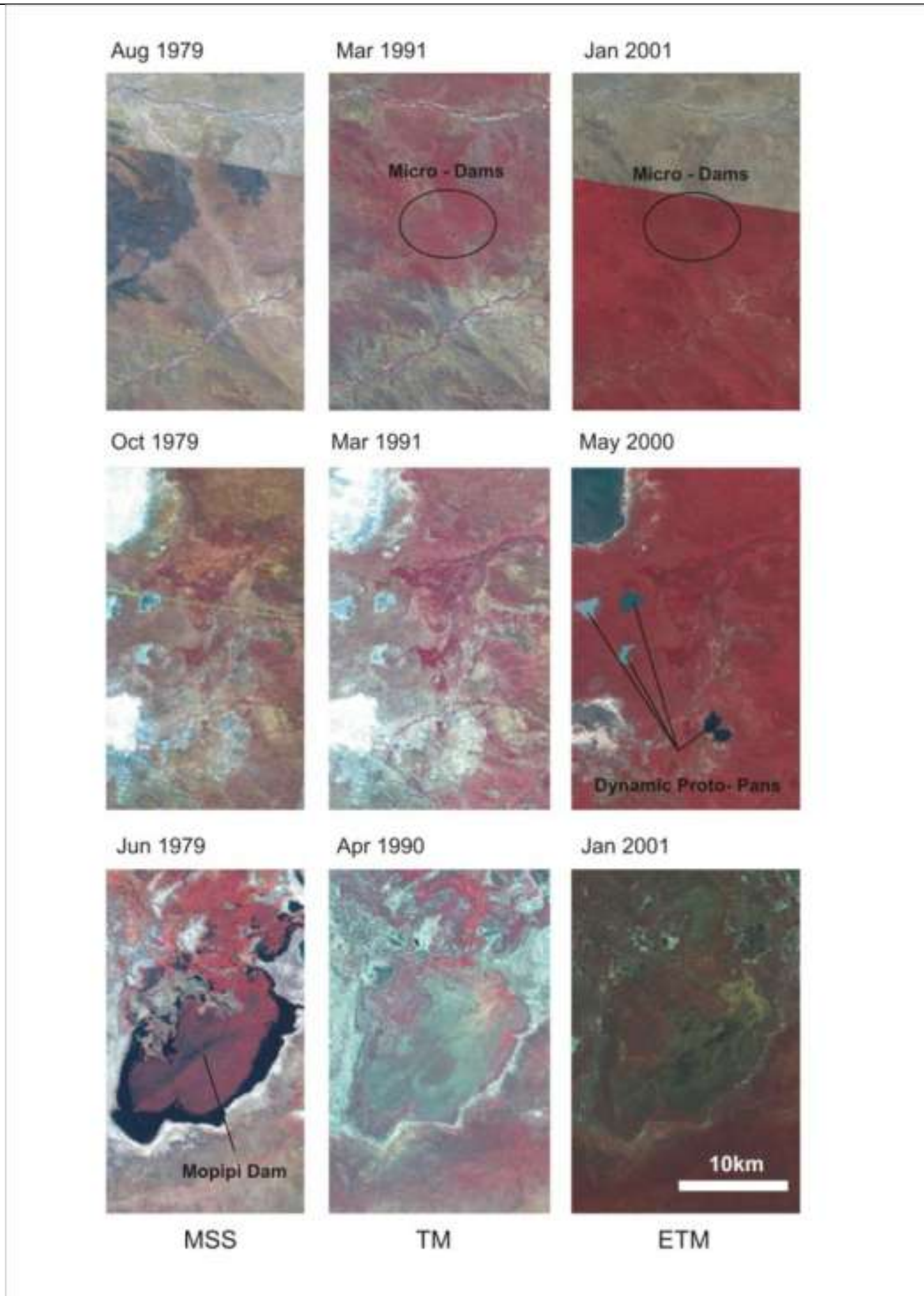




Data Source: GLCF, interpretation by author (unpublished)

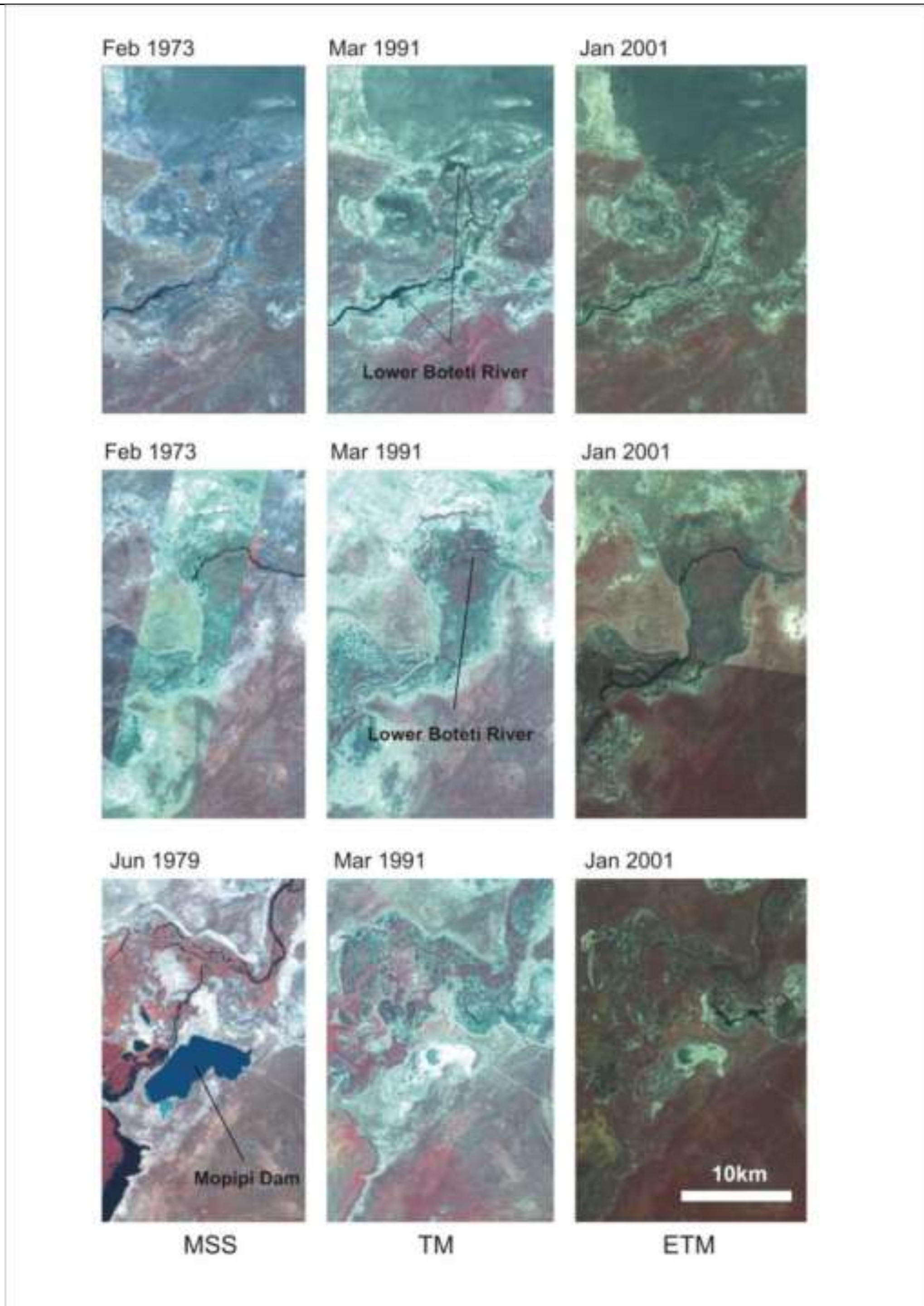
Figure 15: Micro-dams, dynamic proto pans, and Lake Xau desiccation





Data Source: GLCF, interpretation by author (unpublished)

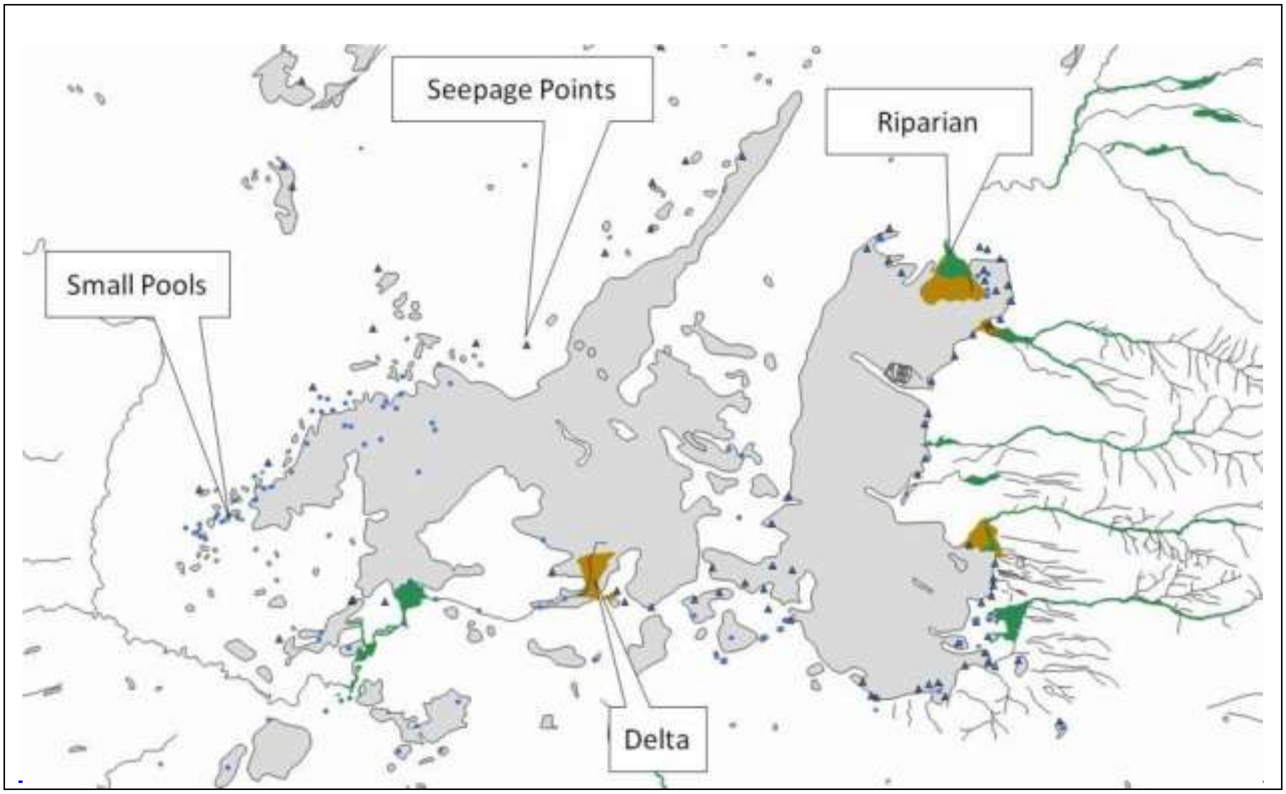
Figure 16: Persistent surface water in lower the Boteti and deactivation of Mopipi dam



Data Source: GLCF, interpretation by author (unpublished)

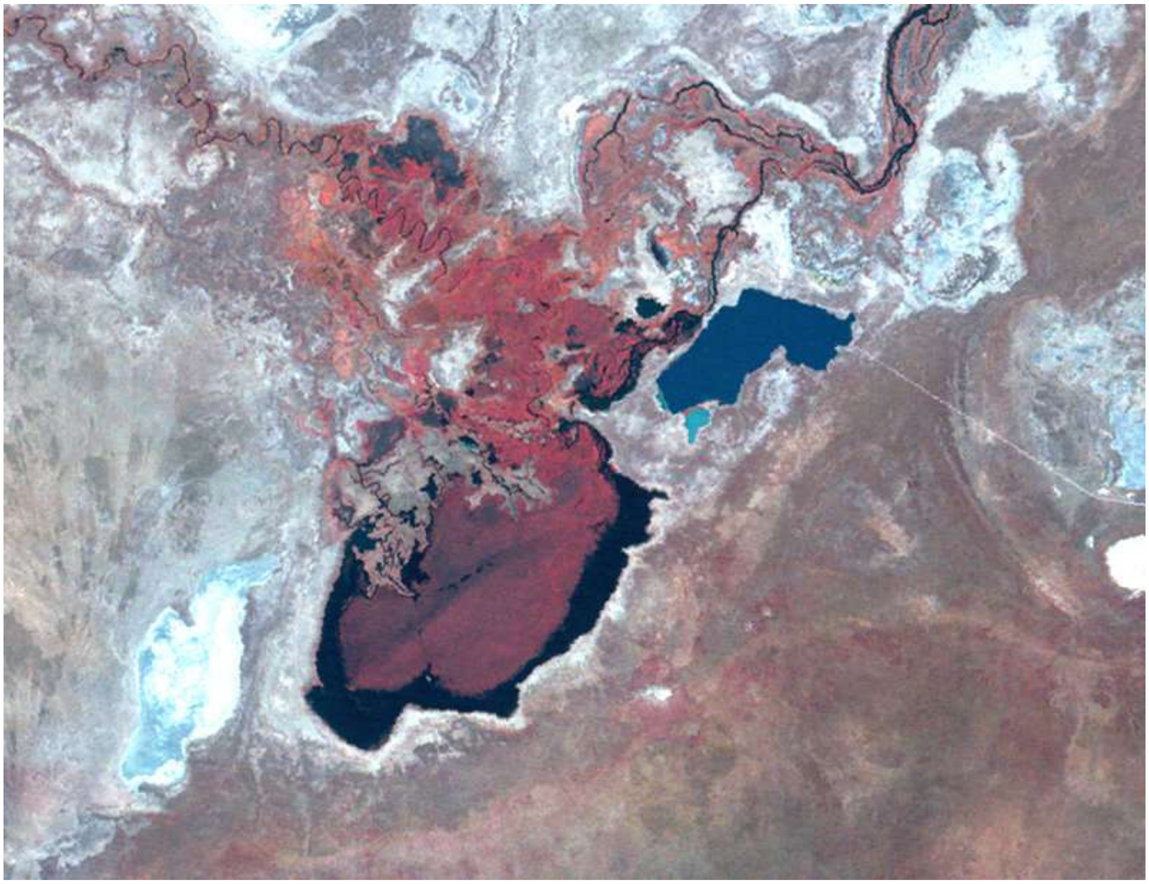
Figure 17 shows the significant and permanent riparian between 1970 and 2000 period as well as small surface pools, shallow groundwater seepage points and deltas identified in Landsat series data.

Figure 17: Significant and permanent riparian between 1970 and 2000 period



Source: Author (unpublished)

Figure 18: A flowing Lower Boteti, a filled Lake Xau and rim full Mopipi Dam in June 1979 as seen in Landsat MSS.



Data Source: GLCF

Figure 19: Lower Boteti reaches Lake Xau, September 29, 2010

(Image Source: http://earthobservatory.nasa.gov)

These observations made so far can be summarized as follows.

- Total desiccation of Lake Xau in the 80's
- Decommissioning of Mopipi Dam in the 80's
- Relatively persistent riparian ecology to the eastern margin of the Pan
- Seemingly persistent lake margins and grass islands at the depicted scale up to 2001
- Small fresh water lake below Mosu escarpment prevails (lat -21.1761° lon 25.9842)
- Numerous small proto-pans host water as part of recharge or discharge events
- No noticeable proliferation of dams or micro-dams in Pan catchments
- No massive changes in land use land cover noted
- Arable land expands mostly to the east of the Makgadikgadi watershed
- Establishment and growth of mines and associated towns including Sua Town
- Dynamic land surface response to rain and drought cycles as well as fires

Box 4: Summary of riparian systems and proto-pan wetlands

What we know so far:

- Landsat imagery can be used to examine the finer detail of landscape change
- Nested in climatic data it can capture past responses to variability and extremes
- Some of the riparian is relatively persistent suggesting healthy groundwater status
- 30-80 m resolution can be used to study some of these environments
-

What we do not know:

- We have not looked at the wider Landsat archive in more detail

National high resolution orthophotos, generated in Botswana and handled by the Department of Survey and Mapping, have not yet been used for the mapping of the study area

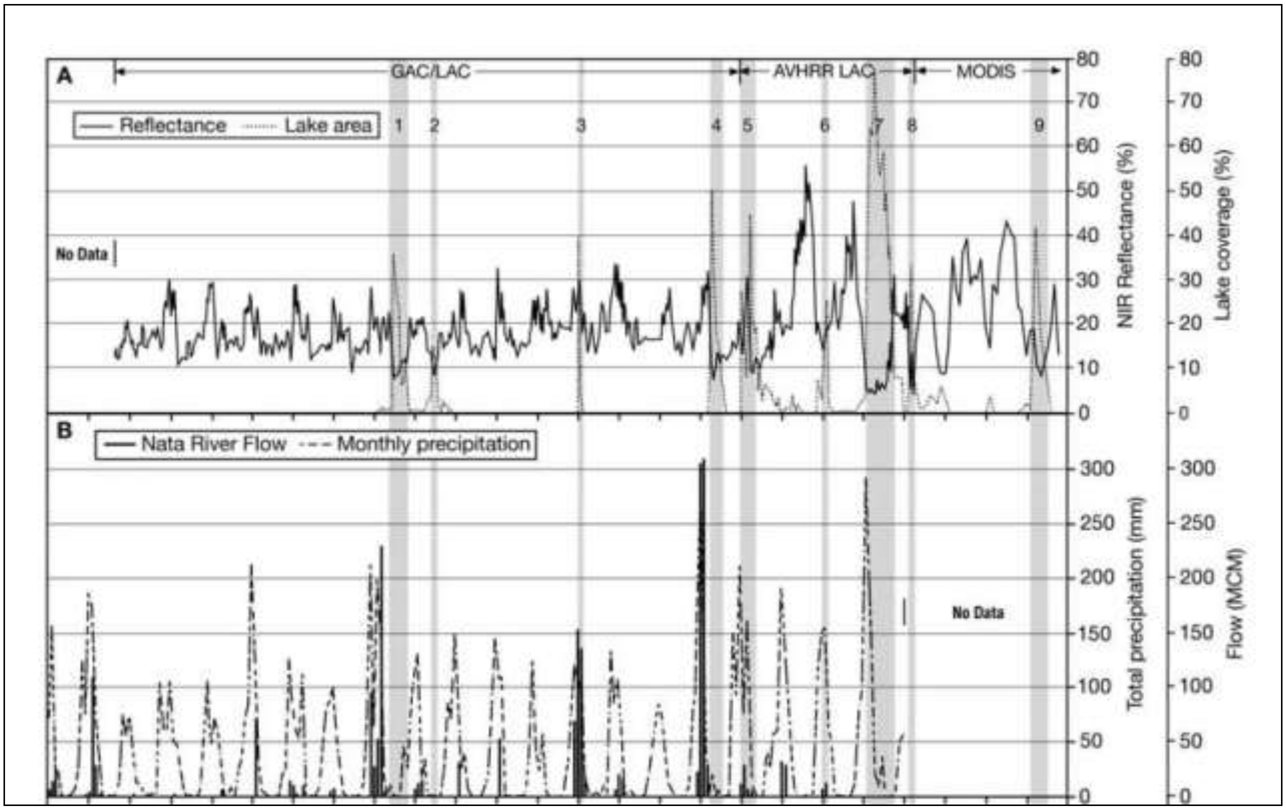
3.6 Ephemeral lacustrine surface water

There are no official records of pan surface water dynamics. The only available observation record comes in the form of remotely sensed data. In all imagery e.g. Landsat (MSS, TM and ETM) (Section 3.5), NOAA AVHRR, MODIS; the Pan surface appears dynamic and depicts lacustrine variability, with such areas having the potential for being significant wetlands.

Bryant *et al.* (2007) resorted to daily NOAA AVHRR (1980-2000) data at 5 km and 1 km resolution. This imagery, linked with other records was able to produce the lacustrine history of the Makgadikgadi at the scale of the entire basin. Several flood events are captured for this period. The following section is a detailed and direct quote from the paper. It places individual flood events into climatic and hydrological contexts. (Refer to Figure 1.6 and quote on following page)

Figure 20 shows the 1980-2005 Time series for the Makgadikgadi. This includes NIR Reflectance (%), Lake Area (%), Monthly Precipitation (mm), and Nata River Flow (MCM). Lake Events 1-8 are discussed in detail on following page.

Figure 20: 1980-2005 Time series for the Makgadikgadi



Source: (Figure 13: Bryant *et al.* 2007)

Box 5: The Summary of flood events at the Makgadikgadi

Event 1 occurred in the wet season of 1988 in which significant rainfall fell within the Nata catchment (474 mm) in the DJF period (four times the long-term average fell at both Nata and Sua) resulting in high flows on the Nata River (reaching a total of $228x10^6$ m^3 in March). This was followed by extensive inundation of both Sua and Ntwetwe Pans, beginning in late March/early May and peaking at coverage of 36% (1080 km^2) in June. This event coincided with a return to La Nina and negative ENSO 3.4 sea surface temperature anomalies.

It is likely that high water tables resulting from this event persisted into the wet season of 1989 when a small lake (**Event 2**) formed (peaking briefly at 450 km^2; 15%). Nata catchment rainfall was 315 mm in the 1989 DJF period, and flow on the Nata peaked at a modest $13.7x10^6$ m^3 (March 1989).

Event 3 occurred in January 1993 where a short-lived lake (1095 km^2; 36.5% coverage) formed after DJF rainfall within the catchment exceeded 327 mm and flow on the Nata River peaked at $152x10^6$ m^3.

Event 4 occurred in January 1996 when a lake of 1500 km^2 (50.2% coverage) formed as a result of significant DFJ rainfall (529 mm) and total Nata River flows of $300x10^6$ m^3 in both January and February (both comparable with event 1).

Again, it is assumed that high water tables resulting from this event contributed to the formation of a lake (**Event 5**) of 1300 km^2 in 1997 (44% coverage peaking in April). DJF rainfall of 378 mm coupled with a Nata flow of $28.3x10^6 m^3$ were observed.

Event 6 occurred in 1999 where DJF rainfall of 366 mm and peak flow of $11.47x10^6$ m^3 resulted in a lake of 750 km^2 (25% coverage).

Event 7 occurred in February 2000 when La Nina conditions coupled with the landfall of tropical cyclone (TC) Eline [Reason and Keibel, 2004] caused extensive flooding in Mozambique and the eastern coast of southern Africa. Its vestiges eventually traveled inland to cause further widespread damage and flooding in the eastern provinces of Botswana. Recorded February rainfalls at Nata (316 mm) and Sua (385 mm) were between three and four times the long-term average at each location and two to three times higher than the totals for any of the other recorded events. This resulted in high flows on the Nata River (no data available here) and elsewhere in eastern Botswana and one of the largest flood events recorded in recent times on Sua Pan. The lake that formed on the surface of the Makgadikgadi Pans was in excess of 4500 km^2. Sua Pan itself had a lake of approximately 2400 km^2 (peaking in April 2000) which covered approximately 78% of the entire Pan surface to a depth of 1–2 m and which only disappeared briefly in January 2001.

Event 8 followed quickly in March 2001 and can again be associated with the likelihood of high water tables remaining from event 7. The lake area peaked at 1000 km^2 (33.4%). No river flow or climate data were available for this event. The final significant event occurred in January 2004, with a lake of 1500 km^2 forming in April and drying up by September. Again, no flow or climate data are available for this event.

No ground based Nata River discharge record available to discuss **Event 9**

Source: Quoted from Bryant et al 2007.

Bryant *et al.* (2007) depicted total percentage area coverage of wet pan environment without being spatially specific. The paper also assumed that the presence of surface water is entirely dependent on the Nata River. For the purpose of wetland management one requires better spatial detail and accuracy. Such satellite data has become available and will be discussed next.

A better record for pan moisture detection can be derived from the MODIS sensor (Terra and Aqua platform) which has been in operation since 2000. It provides twice daily coverage across a range of wavebands. This data has been acquired and processed by Rob Bryant at University of Sheffield and preliminary results have been made available to the MMP and are superior to results from Bryant *et al.* (2007).

Various flood frequency map products have been generated and are presented here. The final product is still subject to continuing improvement, further validation and proper analyses in the context of rainfall and flood frequency data. This is very much work in progress.

Imagery though needs to be interpreted with caution. There are causes for “over” as well as “underestimation”. Underestimation occurs when the body of water is very shallow and sediment filled and viewed in shorter waveband region. Overestimation occur using longer waveband regions which also pick up moisture in the sediments (i.e. wet mud) and hydrated salts. Determining proper detection thresholds is required and would benefit from field validation. We still are confident that these products are a valid depiction of relative moisture and water abundance on the pan surface.

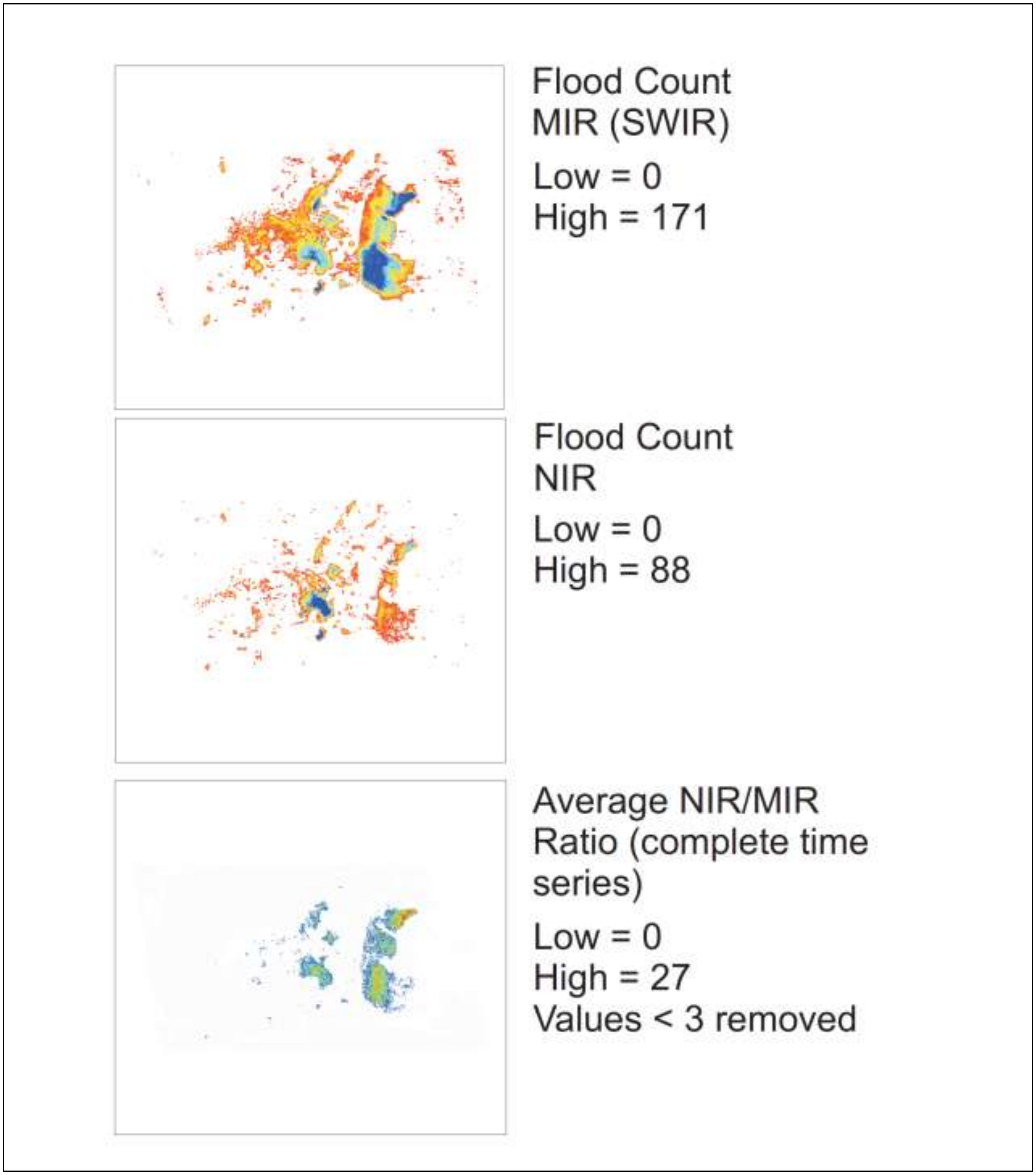
The first generated product was based on MODIS Terra using MIR bands (2.130 µm) at a 500 m resolution. This data was obtained from the GLCF and was stacked to 16 days which produced a total of 218 cloud free time slices between 2000 and 2009. Results suggest that floods of 2000/1 have the highest magnitude and longest duration, while floods in 2004/2006/2008 and 2009 are also evident. There are also dryer years 2002/3, 2005 and 2007. While trends are apparent and partly in line with what is expected, precise water body demarcation is not straight forward. In particular hydrated salts and moist mud’s are problematic. Water body overestimation is a likely outcome (Figure 21 top).

The second product was also based on MODIS, but covers shorter wavelength in NIR (0.865 µm). 500 m resolution images were also stacked to 16 days which again produced a total of 218 cloudless time slices between 2000 and 2009. The NIR wavebands only pick out deeper water and are a more conservative water detection product. Both sediment and algal blooms induce noise in the surface water regions which gives rise to an underestimation of lacustrine water bodies (Figure 21 middle).

The third product under evaluation is also MODIS Terra derived and is generated using a NIR/MIR ratio at 500 m resolution. This image ratio product is based on inputs from the above mentioned channels. It is also subject to evaluation at this moment in time (Figure 21 bottom).

Figure 21 shows 218 day image stacks of MODIS Terra. Note pallet for ratio (NIR/MIR) is reversed. Top MIR (SWIR), Middle NIR, Bottom NIR/MIR Ratio. Locations of wetspots remain relatively persistent but actual area estimates differ.

Figure 21: MODIS Terra, 218 day image stacks



Source: Bryant (Unpublished)

Precise water body and edge demarcation remains an issue. Remote sensing products depict pan wetness due to actual surface water as well as the presence of wet mud and hydrated salts. In a sense all of these combined are indicative of pan hydrology and highlight areas worthy of further examination and consideration. These areas are listed here and above all require field validation against the background of changing seasons and longer term trends. While some of these areas are directly linked to surface water inputs most of them may well show a response to short-lived groundwater pulses or even rainwater ponding depending on pan topography as well lacustrine dispersal by wind (Nkala per comm). These are the wettest portions of the Makgadikgadi wetland and are listed in Table 7. I will refer to these as “wetspots”. These have been first identified in the 2000-2009 MODIS record and were then also observed in Landsat imagery.

Table 7 is a summary of pan surface regions with detectable moisture fluxes as identified from MODIS time series. Size observations in km^2 are estimated from actual observations in Landsat data (Refer to Section 5). These estimates are subject to improvement and validation and may include wet salt and mud. (Refer to Figure 4.6 A and B).

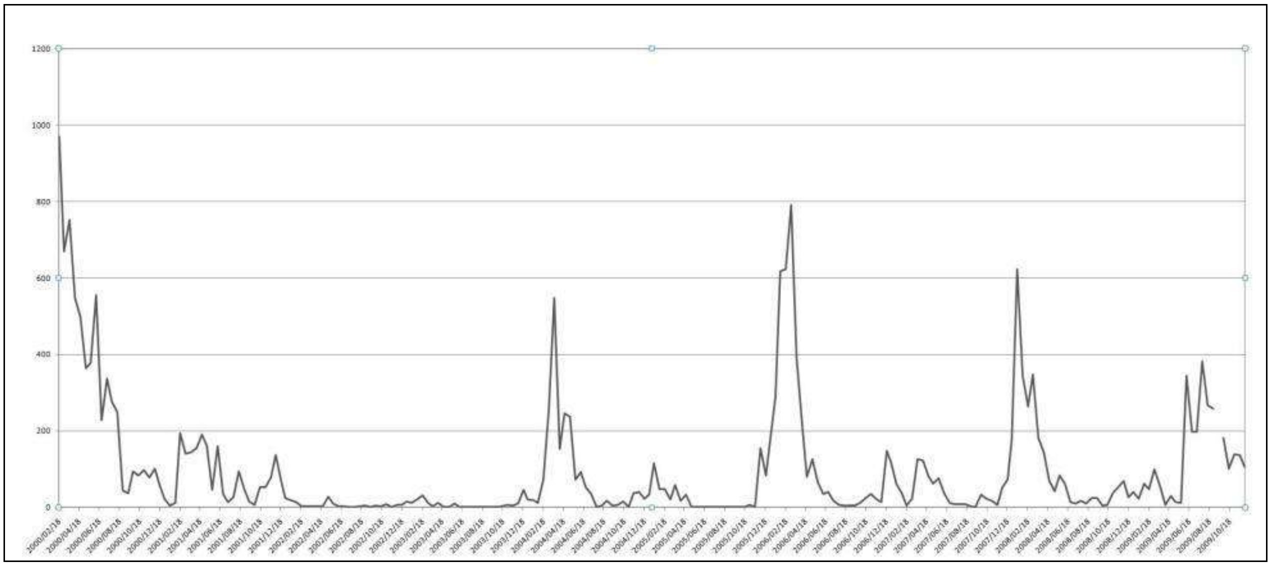
Table 7: Most persistent and dynamic Makgadikgadi wetspots

Location	**Most Likely Water Input**	**MSS** 1970’s	**TM** 1990’s	**ETM** 2000	**Lat**	**Lon**	**Map ID**
Northern Sua	Nata & Semowane River	142	118	0	-20.3	26.2	1
Central Sua	Mosetse River	0	40	0	-20.6	26.1	2
Southern Sua	Lepashe River	0	0	0	-20.8	26.2	8
Southern Sua	Mosope River	0	0	0	-21.1	26.2	11
Southern Sua	Groundwater	0	0	933	-20.8	26.0	3
Northern Ntwetwe	Groundwater	0	18	8	-20.4	25.5	5
Central Ntwetwe	Groundwater	0	0	0	-20.5	25.6	6
Southern Ntwetwe	Boteti Groundwater	0	0	0	-20.8	25.4	4
Western Ntwetwe	Groundwater	0	0	11	-20.7	25.0	9
Western Ntwetwe	Groundwater / Boteti	0	0	13	-20.9	25.0	10
No Name Pan	Groundwater	0	0	7	-20.9	24.7	12
Nkokwane Pan	Groundwater	0	23	0	-21.1	25.5	7
	Sum	142	199	968			

(Source: Eckardt and Bryant, unpublished)

Figure 22 shows the preliminary water time series 2000 to 2009 derived from MODIS NIR record. Area coverage estimate are in km^2. Results suggest that floods of 2000/1 have the highest magnitude (1000 km^2 max) and longest duration, while floods in 2004/2006/2008 and 2009 are also evident. There are also dryer years 2002/3, 2005 and 2007. Water volume estimate would require depth estimate.

Figure 22: Preliminary pan water time series 2000-2009 derived from MODIS NIR record



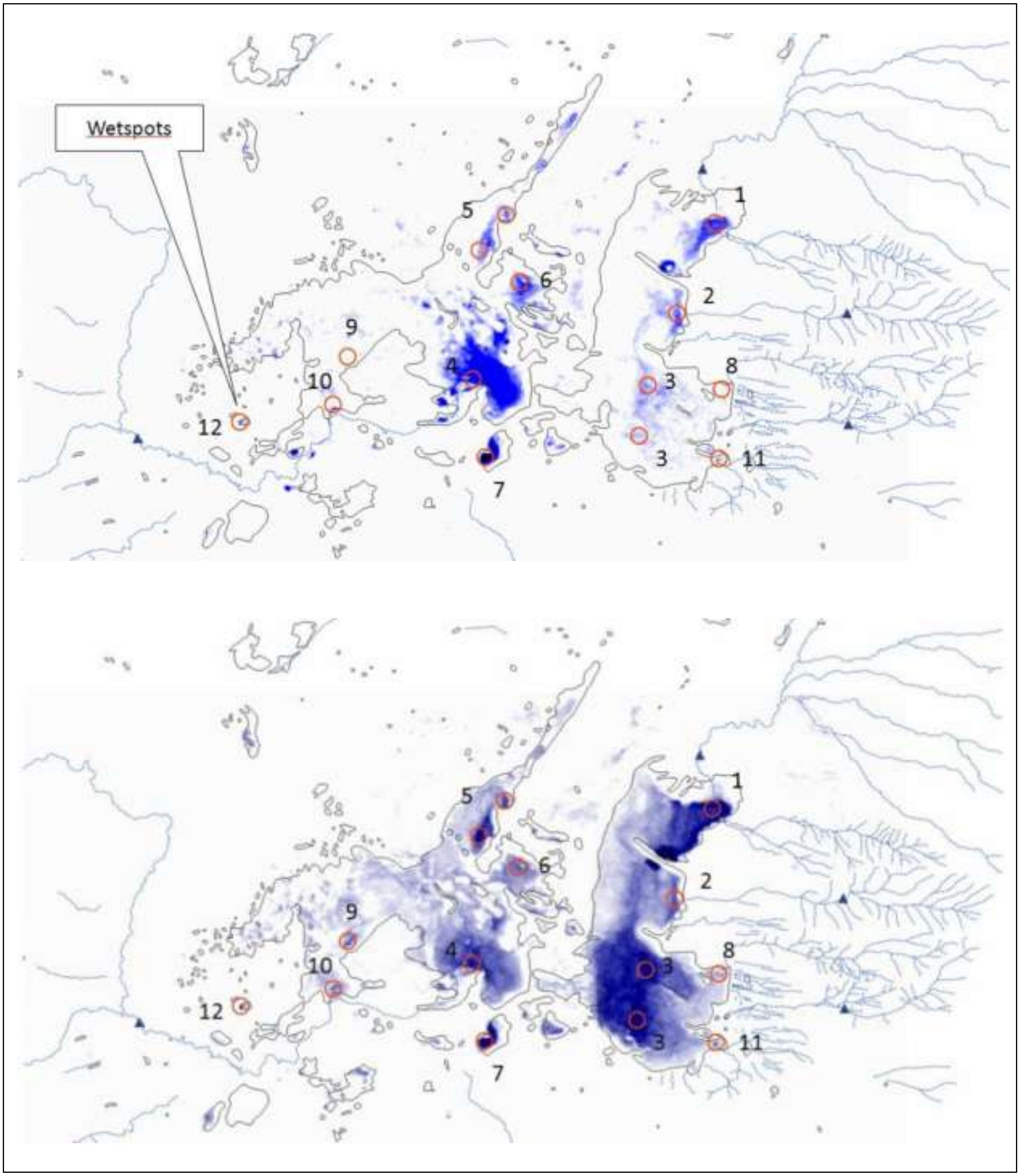
Source: Bryant (Unpublished)

Box 6: Wetspots definition

Wetspots are pan surface areas, which have the potential to support an ephemeral wetland. These areas gradually grade into wet mud, hydrated salts and during dry cycles may be reduced entirely to a bare, moisture free, pan surface. Wetspots are produced by direct rain contributions to the pan surface, water runoff from adjacent river catchments and the discharge of shallow groundwater.

Note: The extend of these features is highly variable and the exact surface area, depth and water volume of wetspots is difficult to ascertain, as shallow pan water bodies may also be filled with sediment and algae. Current identification of wetspots is based on the 10 year observation record from the MODIS sensor. Follow up instruments are to be deployed on the Joint Polar Satellite System (JPSS). Systematic space borne monitoring also needs to be accompanied by dedicated, groundbased validation, including water edge detection, pan bathymetry measurements and limnological characterisation.

Figure 23: Relative pan wetness and wetspot map as depicted in NIR (top) and MIR (Bottom) for 2000-2009 period



Notes: Note over- and under-estimate. Wetspots are listed in Table 7

Source: Bryant (Unpublished)

Numerous areas in the Makgadikgadi have the potential to host surface water and support a lacustrine environment. These locations have been selected from preliminary MODIS NIR and SWIR products described above and were validation against Landsat MSS, TM and ETM data for the 1970's, 1990's and 2000 period respectively (more on Landsat Data used in the previous section).

The first and possibly most important location is the northern Sua Pan which is subject to surface runoff from the Semowane and in particular Nata River (1). Surface water is common here and may occupy an area of up to 300 km^2 and attain depth of up to 2 m (McCulloch pers. com). The area to its west is subject to brine extraction by BotAsh Mine. Central Sua Pan also hosts near shore water bodies with the Mosetse River (2) making the most likely contribution. Total area occupied by surface water is likely to be less than 50 km^2. Southern Central Sua (3) may host some of the largest areas of surface water (up to 1 000 km^2) as was manifested clearly in 2 000 and 2009. This however does not appear to be linked directly to any direct runoff input from the Lepashe (8) or Mosope (11) Rivers but may well be due to groundwater discharge originating from the pan margin and associated rivers. The lacustrine water body is likely to be shallow and is centered on the middle of the pan framed by up to 10 km of dry pan surface. Spectral confusion with salts and wet mud is likely. This area would require further field validation.

Southern and central Sua on the whole, appear to host larger water bodies than the northern section. This is surprising when taking into account the relative size of eastern catchments and observed discharge in particular from the Mosetse, Lepashe and Mosope streams. In fact the southern water body occurs mostly in the pan centre and is not closely associated with the pan margin inputs, unlike Mosetse in the central and Nata in the northern portion. This might suggest that lacustrine water in the northern portion is largely dependent on direct river runoff while water in the southern section is perhaps more dependent on groundwater discharge.

There is scope to analyse surface and groundwater movement on the pan, however without a better handle on pan topography it is hard to validate water transfer between the northern, central and southern Sua sub-basins. In any case the link between river discharge and surface water is perhaps not quite as strong as previously estimated and that shallow groundwater contributions need to be given some further consideration.

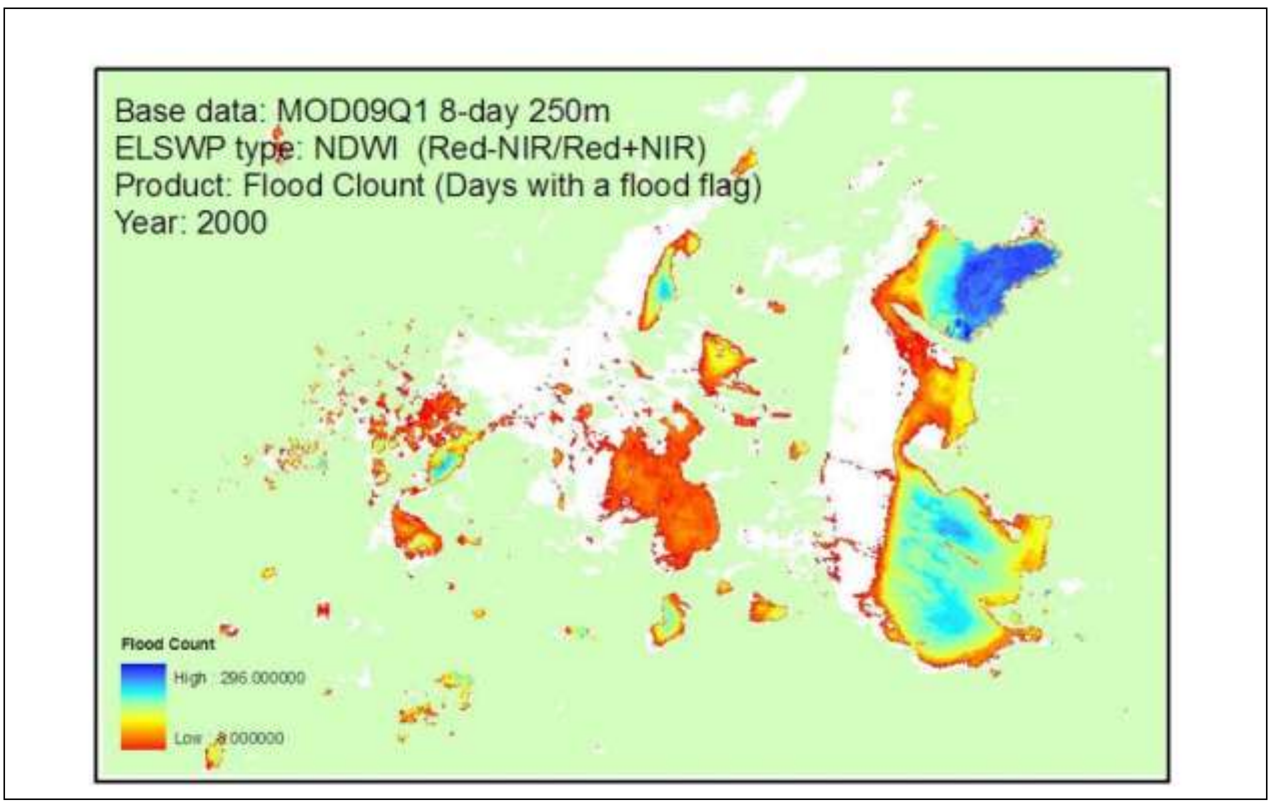
Ntwetwe appears much dryer by comparison. Northern Ntwetwe (5) may host near shore water with coverage of up to 85 km^2. No direct surface water input is associated with this portion of the Pan as is also the case in the central (6) and southern portion (4) which certainly gives credence to the importance of groundwater discharge sustaining some of the lacustrine water bodies. In particular southern Ntwetwe (4) appears wet in MODIS data but this must be validated in the field as the area in question appears rather large and is not known to host waterbodies of such size (300 km^2). Western Ntwetwe is home to a number of small and dynamic water bodies which again have no surface water origin (10, 9). These sites all appear groundwater controlled with some contributions coming from the lower Boteti. Some smaller spring type environments are located in the Makgadikgadi Park (North western Ntwetwe) (Section 3.5).

There are numerous pans on the southern margin of the Makgadikgadi, some of which often appear to host surface water. In particular a small pan apparently without a name (12) and Nkokwane Pan (7) have been highlighted here. These pans along with others could act as recharge windows to the Makgadikgadi proper. In general total surface water accumulation may be less than 100 km^2, 2000 saw up to 1000 km^2 and there might be the potential to host water of even greater extent. How this translates into actual water volume is difficult to estimate without in-situ water depth measurements. The most important wetlands appear to be linked to the eastern catchments of the Nata, Semowane, Mosetse, Lepashe and Mosope Rivers at Sua. Other lacustrine wetspots at Ntwetwe are generally smaller and may well turn out to have not much volume. A detailed biological and limnological assessment would be required to establish the value of each of these wetspots.

These above listed features are not conclusive but likely to be the most important sites. Further MODIS products are being evaluated. Rob Bryant currently draws on the original MODIS data (MOD09Q1) which is doubling the temporal resolution (8-day) and quadrupling the spatial resolution (250 m) compared to the previous products (Figure 20). Again one has to stress that ground validation is required in particular to set detection thresholds and to generate field spectra. MOD09Q1 data is currently processed for the entire time series up to 2010 and will form the basis for future research (Figure 23).

All of the above products can only estimate surface area. But with knowledge of the pan floor shape and with in situ depth observations these could be turned in actual lake volume estimates. Future results are expected to improve surface area estimates. Locations of wetspots are most likely going to remain the same.

Figure 24: Example of MODIS derived Flood Count Map for Year 2000



Notes: Note distribution of floodwater in line with previous observations.

Source: Bryant (Unpublished)

Box 7: Summary of Ephemeral surface water bodies in the Makgadikgadi from Remote Sensing

What we know so far:

- We are grateful to for Rob Bryant for sharing this data with MMP
- Only a small portion of the Pan surface appears fluvially dynamic
- Ntwetwe less so than Sua
- In some instances rain and river flood and surface water appear well connected (i.e. Nata)
- There are numerous other dynamic lacustrine active spots on the pan floor.

What we do not know:

- Spectral confusion with moist mud or hydrated salts still possible but technique improving,
- Setting proper detection thresholds is required
- Some areas appear to show consistent surface water without a direct surface water input
- This might be driven by pulses of shallow groundwater and needs to be validated in the field
- Need in situ measurements of surface water dynamics
- Parameters absence/presence of water, depth and movement need to be measured
- This would provide actually lacustrine volume estimates

3.7 Pan surface morphology

Pans can be distinguished on the basis of the prevailing hydrological regime. A system as large as the Makgadikgadi may have variable conditions in time and space however many of its geomorphic surface characteristics are indicative of the most dominant hydrological controls. One can use the pan surface and composition as an indicator of hydrological processes and trends.

In general two extreme scenarios are considered in the literature. A pan where the groundwater table is below the surface, is relatively permeable and is subject to preferential recharge and a pan where the groundwater table is close to or at the surface will preferentially discharge. The relationship between the groundwater table and the pan surface is thus one of the most important factors which governs the environmental conditions and appearance of the pan surface. In short we can use surface appearance and composition as an indicator of overarching hydrological conditions.

The Makgadikgadi can be described as a clay-rich pan with shallow groundwater and few massive salt crust accumulations when compared to discharge pans elsewhere. The absence of such massive salt with thrust polygons features would suggest that we do not have overwhelming subsurface brine evaporation near the surface. The salts that occur at the surface are often mixed into the muds and may be the product of lacustrine water evaporation and some shallow groundwater evaporation. This shallow groundwater has its source in the hinterland of the pan in particular the palaeo floor below the 1000 m contour which is home to calcareous/silica karstic recharge conditions. Its leached products provide some of the pan salt along with the clay (McFarlane pers comm). Hence much of the salt is mixed into the clay. Furthermore much of the smectite rich black cotton soil is an aluminosilicate evaporate derived from shallow groundwater discharge. Once these clays are in place recharge or discharge may be somewhat diminished. A clay rich pan will be able to support a relatively shallow ground water table and capillary fringe and during rain or runoff will quickly cause flooding on the pan surface due to reduced infiltration capacity. Pan surface lakes are sustained for many months and in some cases are known to have persisted even longer (e.g. 2000-2001). Lacustrine desiccation may be governed by evaporation as well as by infiltration. This can currently not be quantified.

The grass islands which demarcate the pan edge and form isolated clusters further away from the margin appear stable according to historic accounts (Gabasadi Island), Landsat imagery (Section 3.5), and personal observations. There have been accounts (Nkala pers comm) of grass infringement onto the pan surface at Sua in relation to pumping activity at BotAsh but this has not been adequately monitored, documented and quantified. Fields of 1 m high nebkha dunes, which form in the lee of salt bushes on the pan surface, occur in areas of available surface sands (Figure 25).

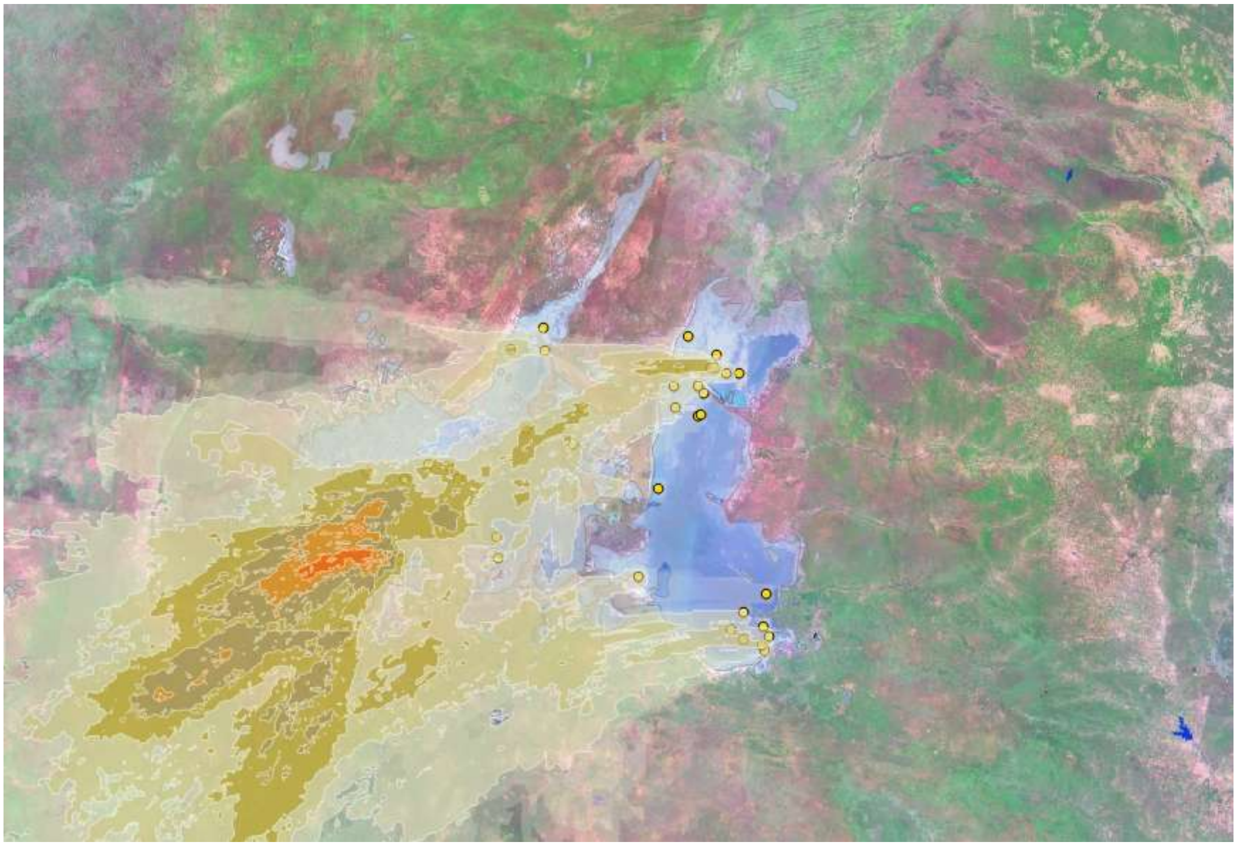
Figure 25 shows Aeolian pan environment controlled by hydrological dynamics. (Top) Deflation lag deposit indicative of past groundwater drop at Southern Sua (Middle) Nebkha and saltbush in BotAsh wellfield (bottom) Dust outbreak near Nata Delta.

Figure 25: Aeolian pan environment controlled by hydrological dynamics

Source: Author

Figure 26 shows the Hysplit model output. Net relative aeolian deposition combined for all 2007-2009 dust events. Note sources points are linked to lacustrine surface dynamics.

Figure 26: Hysplit model output



Source: Eckardt and Vickery (unpublished)

The pan surface is not only subject to fluvial processes but is subjected to deflation. Such aeolian processes are an extension of hydrological dynamics. In fact the fluvial, hydrological and aeolian environment at the Makgadikgadi are tightly interwoven (Bryant *et al.,* 2007).

It has been noted here and elsewhere that dust production is directly linked to fluvial inputs into the pans. In particular flood events provide sediments and salts for deflation. According to a global 30 year satellite based inventory, the Makgadikgadi is currently ranked within the top 10 of the world's dustiest places (Washington *et al.* 2003) and many of these sources are known to have hydrological dust production controls. Generally the Makgadikgadi has been considered a "supply limited" system. The amount of dust coming from the pan is limited by the supply of available sediment as derived by surface and groundwater controlled evaporation products and sediments as well as the state of the available surface crust.

The current hydrological state of the Makgadikgadi is difficult to quantify. The system as a whole may well appear to be in a state of equilibrium. However groundwater levels along the southern margin of Sua must have dropped in the past which produced distinct lag gravel on the pan surface (Figure 26).
The Boteti riparian and delta on the southern rim of Ntwetwe Pan has also been subject to desiccation. The causes and effects of these changes over less than 30 years are not well understood but deserve

attention in light of current and future extraction. If we do not understand the cause and effect of past and present changes we will not be able to manage the Pan in the future.

Any significant lowering of the groundwater table and capillary fringe or general desiccation of the Pan and its margin due to climate variability or any form of over-utilization or over extraction has the potential to widen the dust source areas and liberate more material for deflation. In such a state, transport could become the only limiting factor. The outcome could be a “transport limited” source, such as the Bodele depression in the Chad, which is currently the world dustiest source due to favourable winds and a limitless supply of mobile material.

It is at this point also important to refer to recent history of Owens (Dry) Lake, a pan in California. Owens Lake was subjected to extensive water extraction as part of the Los Angeles water supply scheme which draws water from the snow recharged desert of the Sierra Nevada. I quote Reheis (2006) from the USGS:

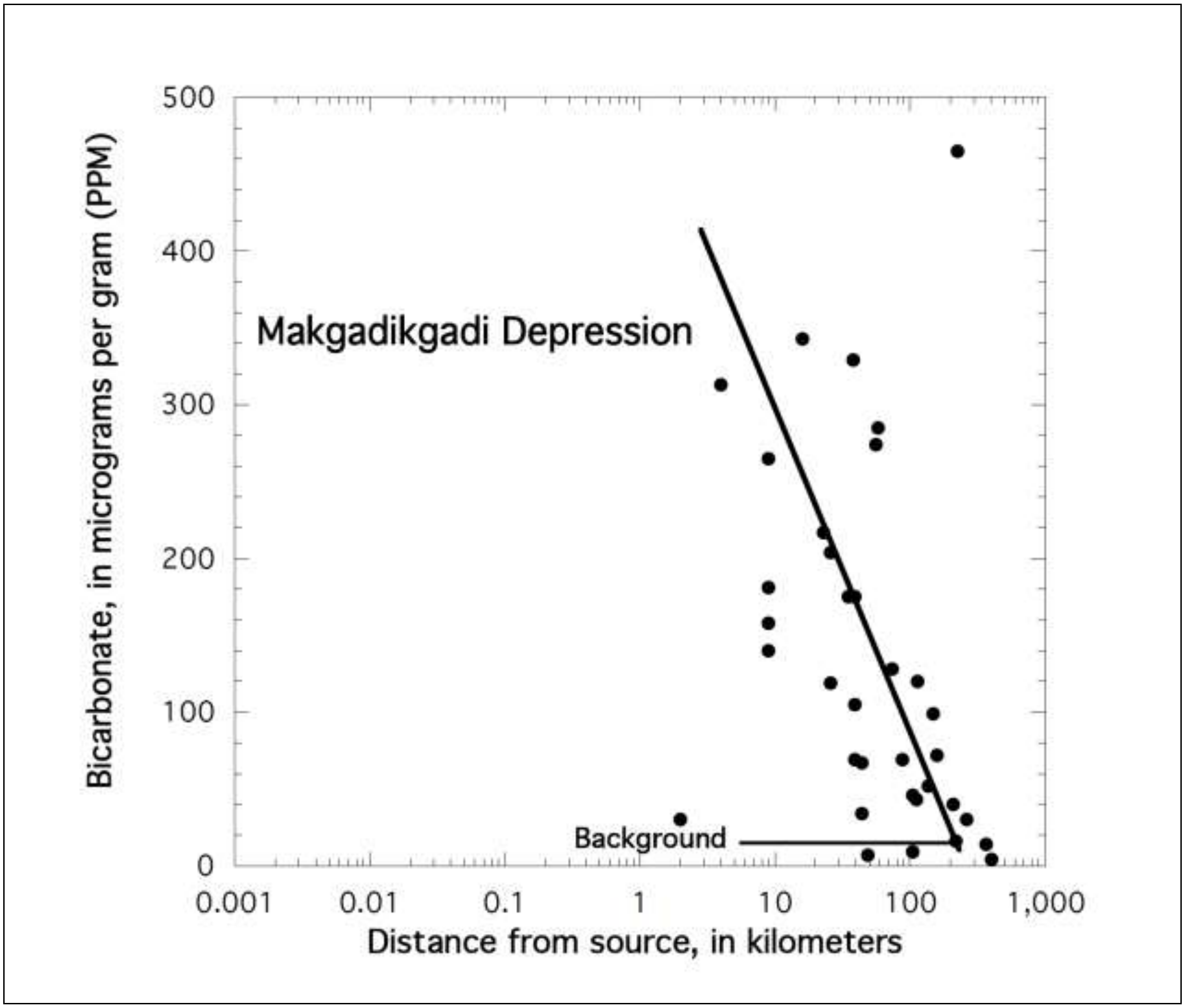
“*The artificial desiccation of Owens Lake has created the single largest source of dust in the United States. Owens Lake is an extreme example of the potentially destabilizing effect on land surfaces and vegetation by the extraction of surface and ground water in desert regions*”.

Current measures to stabilize Owens (Dry) Lake include artificial water recharge of the basin. Dust sources points have been mapped for the 2007-2009 period and are located in hydrologically dynamic areas while associated dust depositions zones have been modelled for the basin with the main impact in SW sector towards Rakops (Figure 26). The annual average chemical dust footprint is approximately 150 km long and contains three million metric tons of chloride, sodium, and bicarbonate (Wood *et al.,* 2010) which in August 2003 was traced as far as Johannesburg (Resane *et al.,* 2004). The dust also contains uranium from the weathered granites from its eastern catchments in particular the Nata River (Figure 28) (Wood *et al.,* 2010).

Dust deflation is in a sense an important indicator of hydrological dynamics as well as environmental quality. Much of what is being deflated is governed by runoff inputs and shallow groundwater levels in particular the state of the capillary fringe and surface crusts.

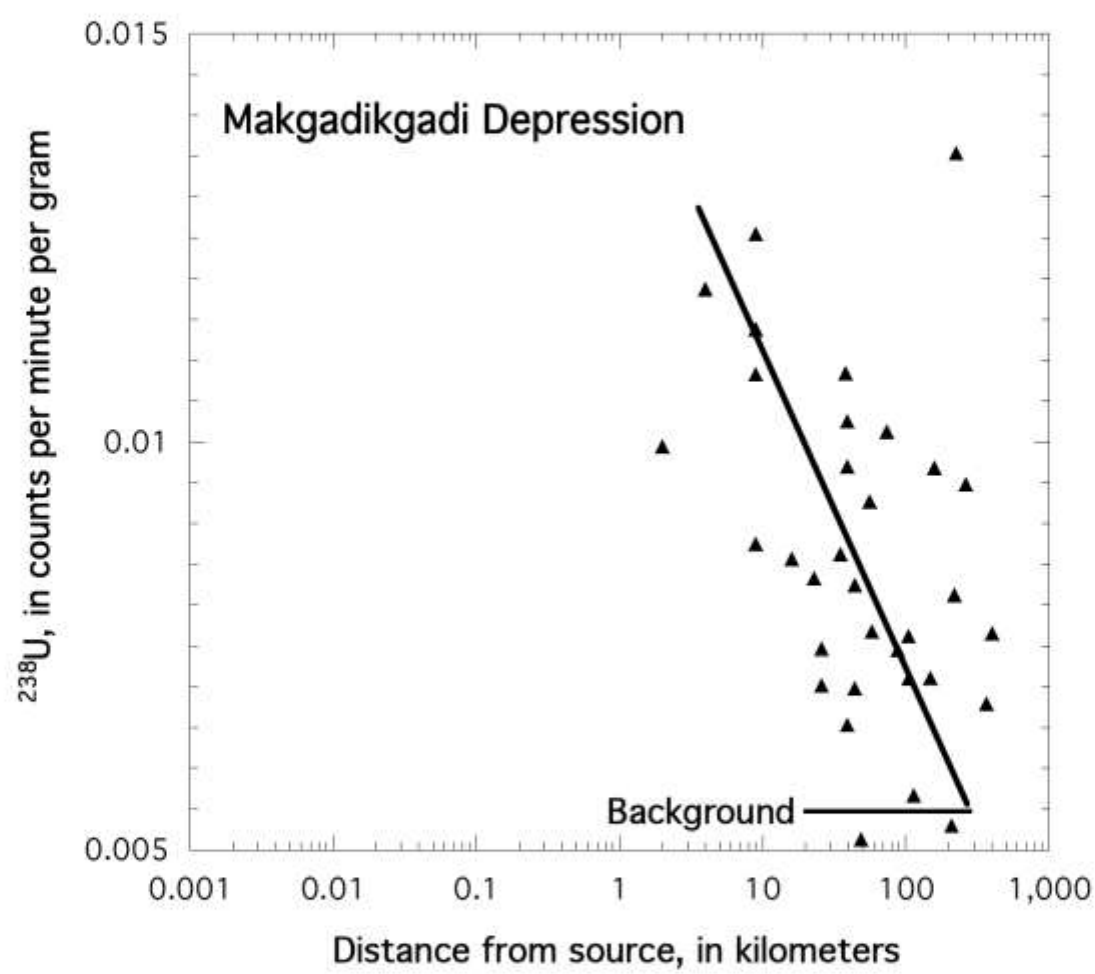
High groundwater levels produce evaporites, lowering of the groundwater table will cause surface drying and promote finer clay and silt sized dust particle. The hydrological dynamics and off-takes as well as state of the shallow brine of the Makgadikgadi need to be quantified if one aims determine future patterns of change.

Figure 27: Downwind Bicarbonate Footprint at Makgadikgadi. Background sampled upwind (east of pan)



Source: Wood *et al.* (2010)

Figure 28*:* Downwind Uranium Footprint at Makgadikgadi. Background sampled upwind (east of pan)



Source: Wood *et al.* (2010)

Box 8: Summary of Pan surface morphology

What we know so far:

- Current pan surface conditions are governed by shallow groundwater dynamics
- Surface salt crusts coverage is sporadic.
- The capillary fringe is often shallow
- A clay rich environment quickly initiates lacustrine conditions

What we do not know:

- How will pan surface respond to brine extraction or other forms of extraction?
- Need a systematic survey of pans surface morphology
- Need systematic monitoring of pan surface and shallow groundwater relationship
- Freshwater seepage points above the pan floor need to be mapped as an important water resource
- How will dust flux change with the utilisation of pan resources

3.8 Pan chemistry

In the absence of a systematic and ongoing water sampling and monitoring program it has been difficult to get to grips with the hydrological water/mass balance of the entire system. However with the strategic sampling of water and its associated analyses for chemistry it has been possible to make some headway with the chemistry and evolution of its water which does hint at some of the prevailing hydrological conditions. This section will review a recent publication by Eckardt *et al.* (2008) on the hydrogeochemistry of the Makgadikgadi which examined the relationship between the chemistry of soil leachates, fresh stream water, salty lake water, surface salts and subsurface brines at the Makgadikgadi.

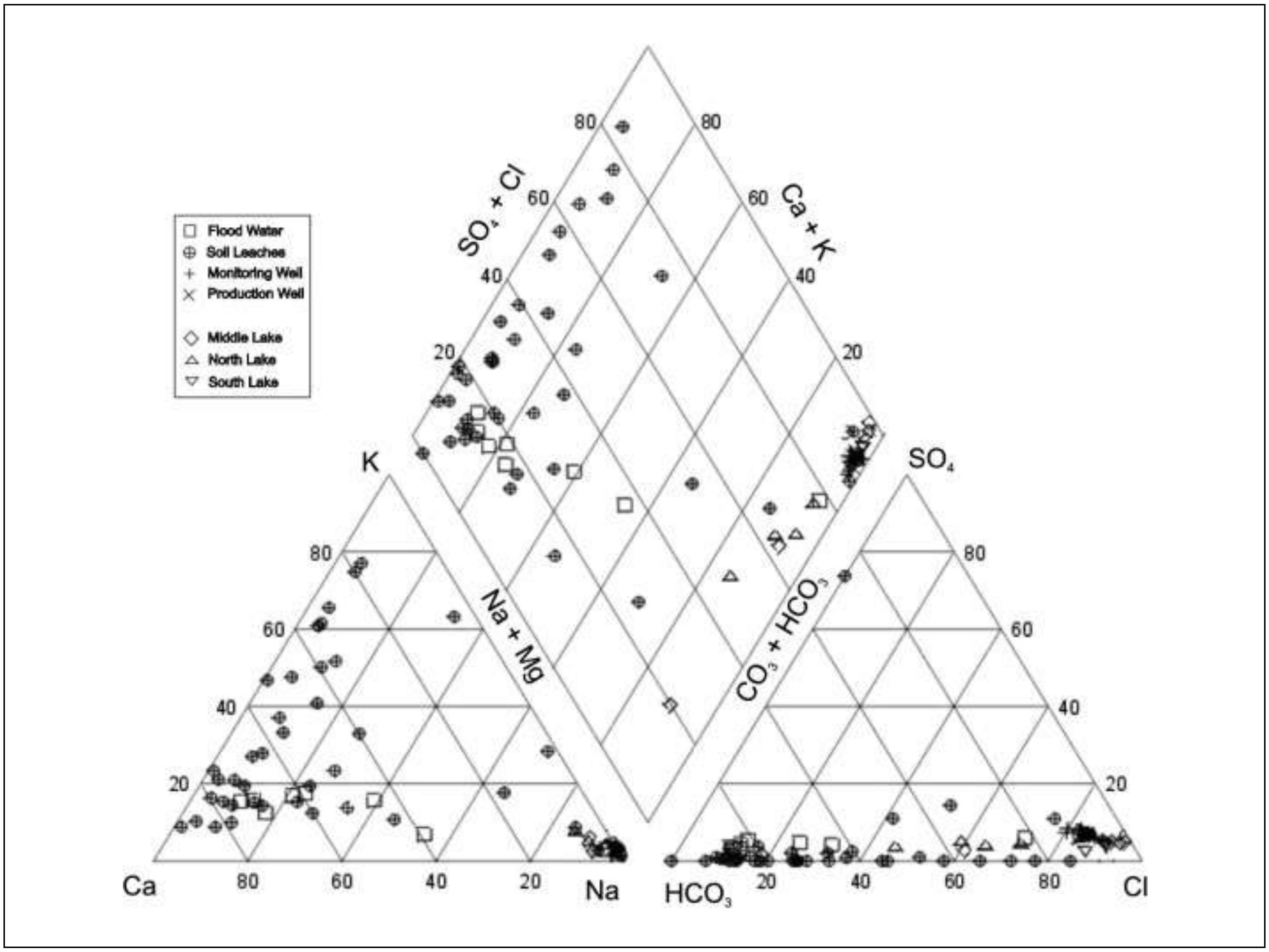
In summary it can be said that river water is generally high in $Ca\text{-}HCO_3$. This underlines the role and importance of the calcareous paleomargins as being important recharge zones. Na-Cl is added with the leaching of salty river sediments close to the pan margin and on the pan floor itself. Catchment soils add much of the Ca, bicarbonate, Mg and K (Figure 29). Once lacustrine conditions are generated, both calcium and magnesium go out of solution, which promotes the formation of calcite and dolomite in the pan environment (Figure 30), followed by sodium and nitrate evaporates which produces salt. This is a very simple “textbook evaporation sequence”. It has to be noted that stream water starts of as salty due to the evaporation of shallow groundwater in the dry stream beds during winter. These salts are quickly flushed out and replaced by the expected calcium and bicarbonate dominant in stream water.

The bulk chemistry of the surface lake and deep brine appears comparable at first glance, with the degrees of concentration being the only difference. However both strontium and sulphur isotopes suggest that the subsurface brine pumped at a depth of 38 m by BotAsh, has been in prolonged contact with some of the underlying geology. Therefore further suggesting little contemporary recharge from the surface lake or possibly even the shallow groundwater (Eckardt *et al.,* 2008). The brine therefore appears decoupled from the surface, the lacustrine water and even the shallow groundwater. Due to the location of the pan in the African rift and with the support of isotope chemistry Molwalefhe (2004) also considered geothermal contributions to the deepest brine in the basin.

The overall surface chemistry of the pan appears relatively homogenous without distinct evaporitic zonation being evident. In the absence of any major topography both surface wind and movement of water appears to mix materials sufficiently. This is quite different when compared with "basin and range" pans in both North and South America that show strong chemical surface and subsurface gradients.

Figure 29 *is a* Piper plot depicting water chemistry for fresh river flood water and surface leaches, saline lake water for Sua pan (north, middle and south pan) as well as subsurface brine. It is important to note transformation from calcium and bicarbonate rich water to sodium and chloride domination. BotAsh production wells are tightly grouped in the Na and Cl sectors. Shift in composition is in the first instance caused by dissolution and secondly by evaporation.

Figure 29: Piper plot depicting water chemistry for fresh river flood water and surface leaches, saline lake water for Sua pan and subsurface brine

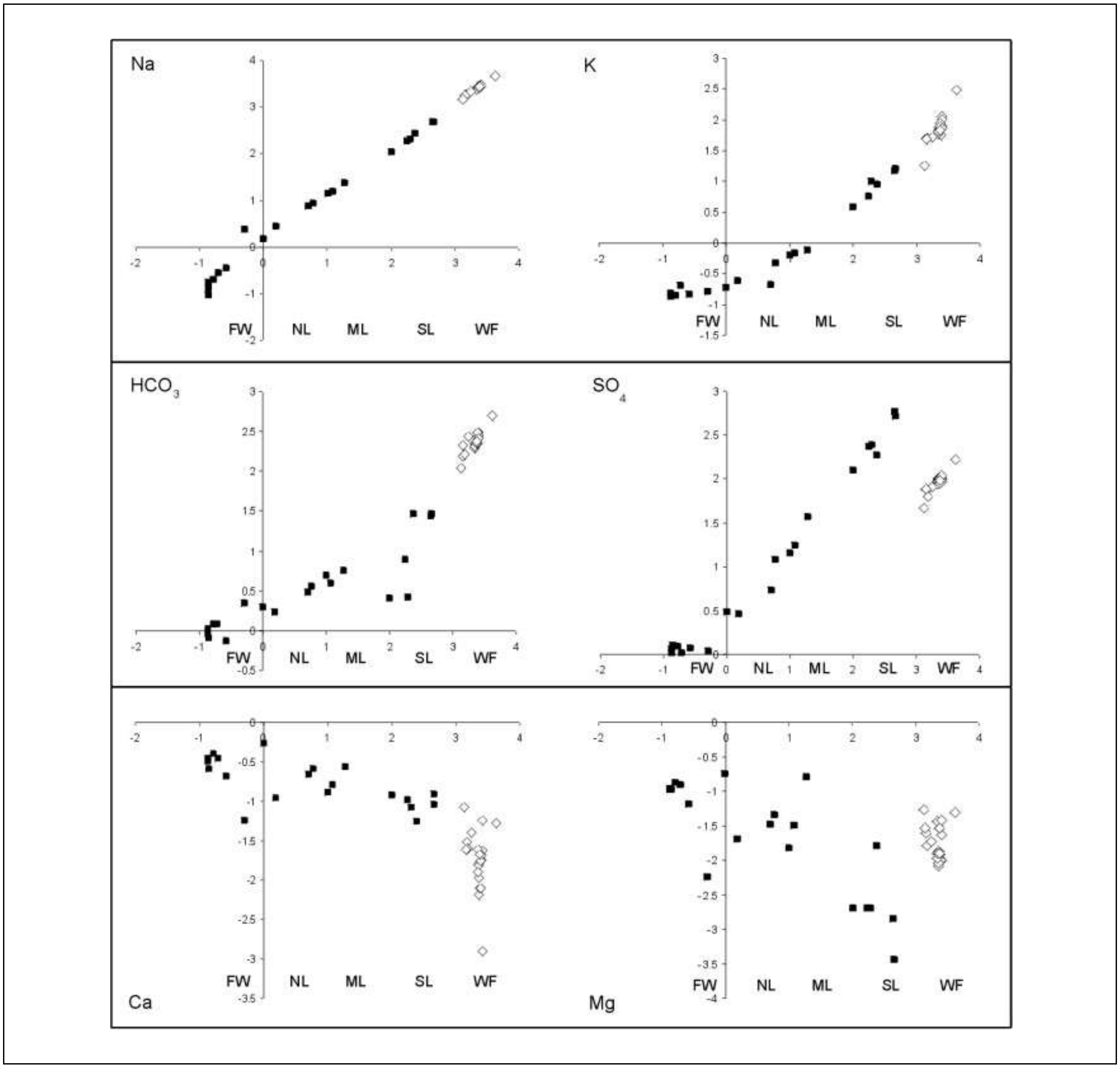


Source: Eckardt *et al.* (2008)

Figure 30 shows the Ion log concentration (mmol/L) plotted against Cl. Average Flood Water (FW), North Lake (NL), Middle Lake (ML), South Lake (SL) and Wellfield (WF) are demarcated. As concentration increases Ca and Mg are lost from solution by evaporation and the production of calcrete and dolomite.

It was not possible to sample most saline end products which depict Na Cl losses from the water. Sulphur response could be in part due to H_2S reducing conditions (Figure 30).

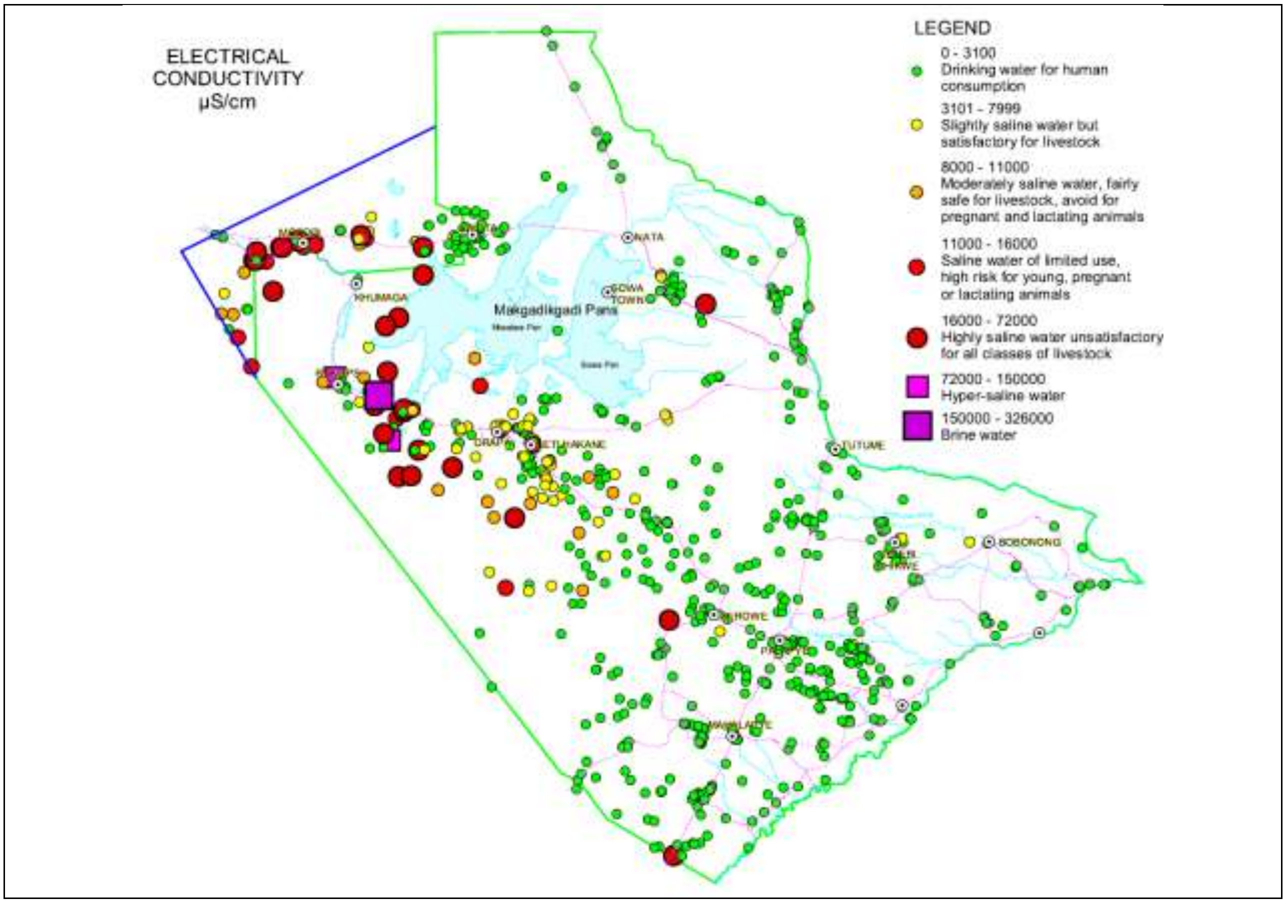
Figure 30: Ion log concentration (mmol/L) plotted against Cl



Source: Eckardt *et al.* (2008)

The groundwater quality in Makgadikgadi catchment is variable (Vogel, 2004), see Figure 31. In general the most saline water occurs around Rakops and Letlhakane as well as other sections of the Boteti. It is assumed that such shallow groundwater is subject to prolonged evaporation; hence the high salinity levels observed. Water at Gweta and Dukwi are pumped from some of the karstic terrain which is fresher in nature and more suitable for human consumption.

Figure 31: Water quality in Makgadikgadi basin



Source: Vogel (2004)

Box 9: Summary of the Pan chemistry

What we know so far:

- We have a general handle on the surface water and brine chemistry of the pan system.
- We have a good handle regarding the groundwater in the wider catchment

What we do not know:

- We have no detailed data on the chemistry of the pan surface and subsurface sediments
- We also have not detailed chemical data on the various MODIS derived wetspots
- Other water and soil chemistry indicators ought to be considered when assessing quality of various wetlands.

3.9 Groundwater

This section will first look at groundwater in the pan proper and second focus on groundwater in the wider catchment of the Makgadikgadi.

The Pan itself hosts 2 types of groundwater. The shallow near surface water, as well as the deeper saline brine (Refer to Figure 2). Due to the economic importance of the brine, more is known about the deeper saline water. The shallow groundwater of the pan on the other hand does not to appear to have been well documented.

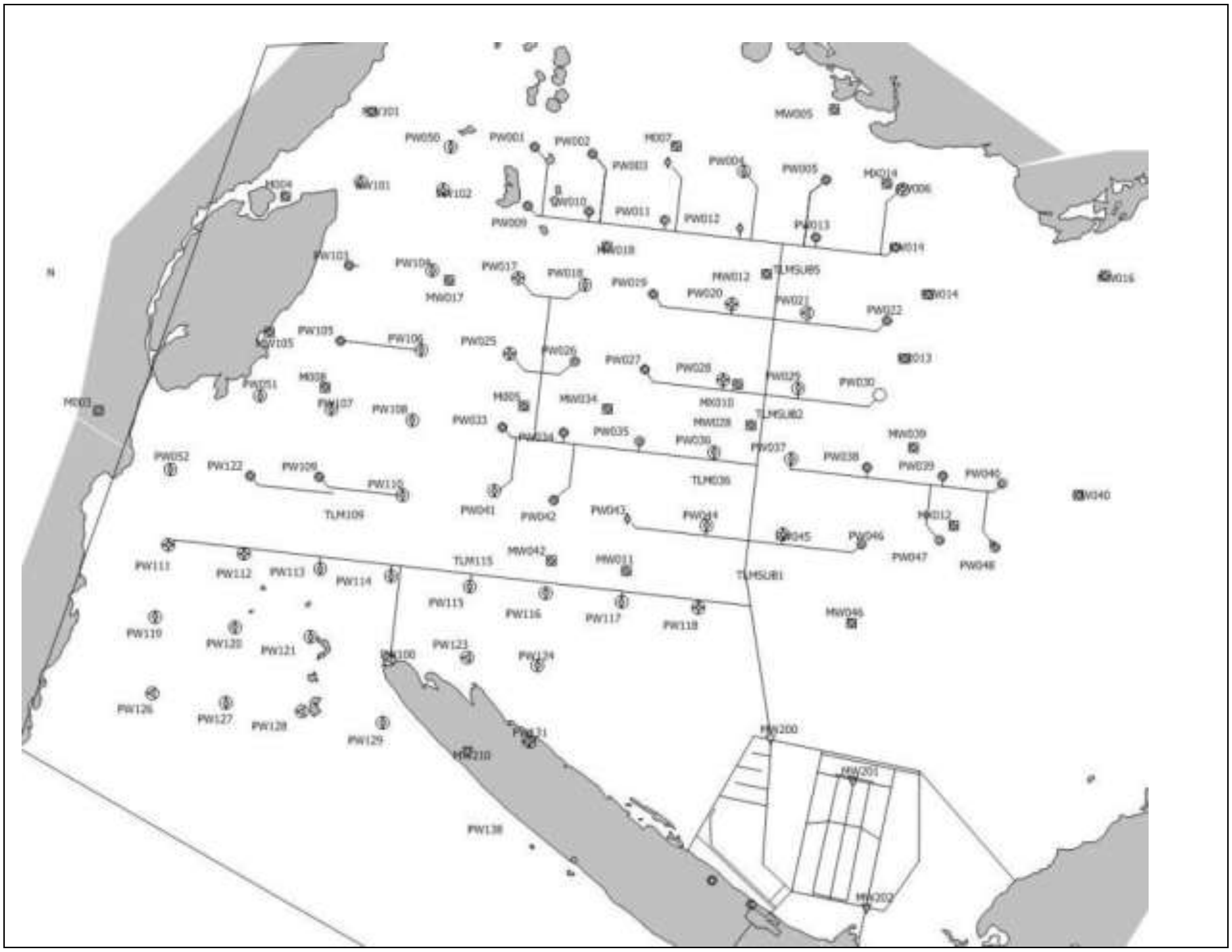
Gould (1986) stated that the pan holds 8 013 MCM (Million Cubic Meters) of brine containing 1026 million tons of NaCl and 233 million tons of Na_2CO_3. It was concluded that current river water had little to do with the development of the brine and that recharge from the surface was unlikely. The brine was considered a by-product of the pans past and that it was relatively homogenous. This was in part supported by Eckardt *et al.* (2008) which highlighted the importance of prolonged bedrock contributions made to the deeper saline water hence supporting its age and lack of modern day recharge.

Today Sua Pan and the BotAsh wellfield is home to more than 100 operational surface pumps which are mostly to the north and west of the spit and extract the deeper saline brine to produce various evaporation products but in particular Soda Ash. The wellfield is currently expanding southwards resulting in close to 150 production wellpoints (WP) over the next few decades. There are also number monitoring wells (MW) dotted around the perimeter of the field which are largely placed within the same hydrological context. In general pumping occurs below the surface clays from a sandy substrate at an average depth of approximately 38 m (Figure 32).

It has been shown that salinity yields (total dissolved solids: TDS) at individual production wells was inversely proportional to the pump rate (m^3) suggesting little brine recharge (Eckardt *et al.,* 2008) (Figure 33) but potential for freshwater recharge. A decoupling of surface and subsurface water in particular deep brine seems most likely. In essence this would support the fossil nature of the brine. In light of the current extraction and evaporation by BotAsh the pan brine is subject to a negative mass balance.
Pumping has been taking place since 1990 and the surface lacustrine environment does not appear to have been adversely affected by this activity. Quite the opposite, the proximity of the Nata River Delta

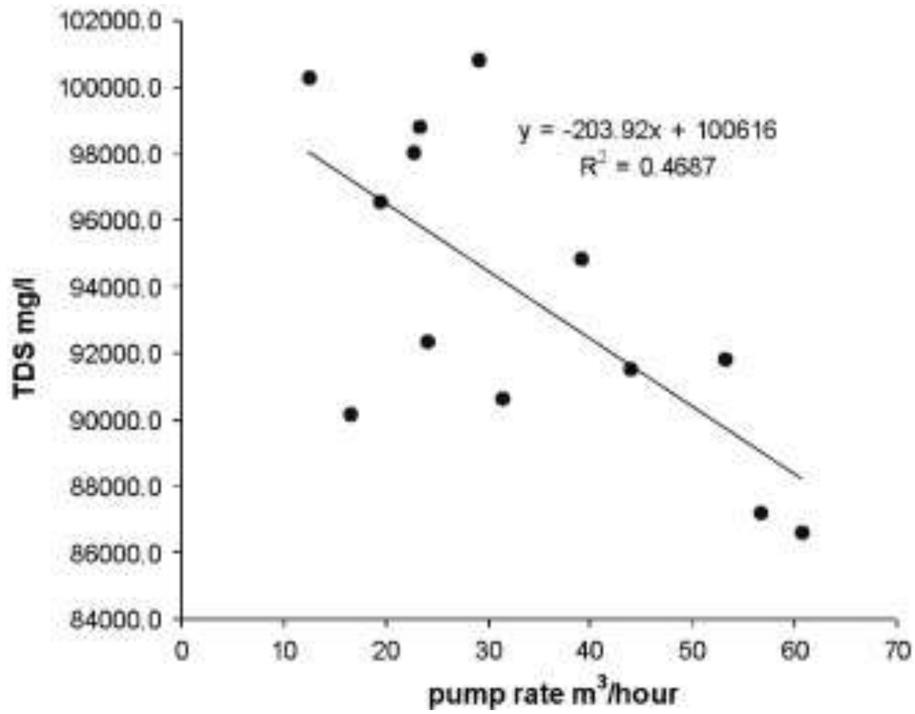
and its floodwaters makes both pumping and evaporation formidable engineering challenge. Nkala (pers. comm.) reported that pump rates increase during lacustrine emplacement but that this is not a function of recharge but loading of flood water on top of the wellfield. End of pipe salinity yields (one of the parameters measured at BotAsh) from the brine appear to be stable as pump rates have gradually increased to 2400 m^3/h. Up but 3500 m^3/h is considered feasible in light of future well field expansions (WMC 2008).

Figure 32: Northern Sua. Production Wells and Monitoring Wells



Source: BotAsh

Figure 33: Diminishing brine yields with increasing pump rates



Source: Eckardt *et al.* (2008)

WMC was commissioned with modelling the current state of the wellfield chemically as well as hydrologically using current and future extraction scenarios. The report notes that brines adjust laterally and vertically due to pumping. With an increase in brine extraction a drop in the brine water level it is expected. This is to be accompanied by a drawdown of the shallow groundwater and diminishing evapo-transpiration at the surface of the Pan. This trend has indeed been manifested in all monitoring wells with modelled and observed drawdown currently centered to the north west of the spit at (lat -20.38° lon +25.99°). The consultants postulate that the draw down will gradually shift southward as production also shifts in that direction. WMC (2008) states that:

"Over time the contribution of brine from storage decreases and abstraction is almost fully supported by infiltration. To compensate for the additional downwards flow there is a reduction in evapo-transpiration as brine levels start to drop below the extinction depth as a result of increased drawdown in the areas which were previously supported by the simulated river inflows ".

It goes on and justifiably states that:

" The current understanding of the boundary conditions, e.g. the amount of downwards flow from the surface into the brine aquifer and the volumes of lateral inflow, is uncertain, meaning that the results of the brine resource evaluation modelling should also be viewed as uncertain".

This is crucial. Despite the pumping we have no handle on how the system and in particular the lacustrine environment will respond to drawdown. At a first glance it must be noted that drawdown occurs largely to the west of Sua while “Nata lake” is more confined to the east of the pan. Still our understanding of the system is limited to the actual well points as we lack the vertical and wider hydrological context in particular the lateral flow of shallow groundwater.

The pumping by BotAsh has the potential to effect the lacustrine surface environment. Drawdown has been modelled and observed. This is currently the most utilized section of the entire Makgadikgadi and in close proximity to one of the most significant wetspots of the entire system. It is timely that after 20 years of brine extraction WMC (2008) flagged the need for wider scale and dedicated monitoring of the wellfield. There is a real need to understand the hydrological controls at northern Sua with additional fourteen experimental observation wells to be placed beyond the perimeter of the active wellfield. The consultants also recommend continuous brine level monitoring devices (pressure transducers and data loggers) in selected monitoring boreholes within the wellfield which sample at a 1 hour temporal resolution.

Groundwater is also pumped well beyond the pan margin in particular at the Dukwi, Letlhakane, Orapa and Gweta wellfields. How much of this extraction constitutes a loss from the Makgadikgadi or effects the status of groundwater in the pan or impacts on the presence of lacustrine surface environments cannot be quantified. The movement of underground water does not occur through a homogenous medium but is subject to highly variable geology consisting of relatively permeable sandstone, swarms of dolerite dykes, faults and structural controls including an extensional arm of the African rift as well as clays and sands of the pan basin. Geothermal contributions have also been proposed (Molwalefhe, 2004).

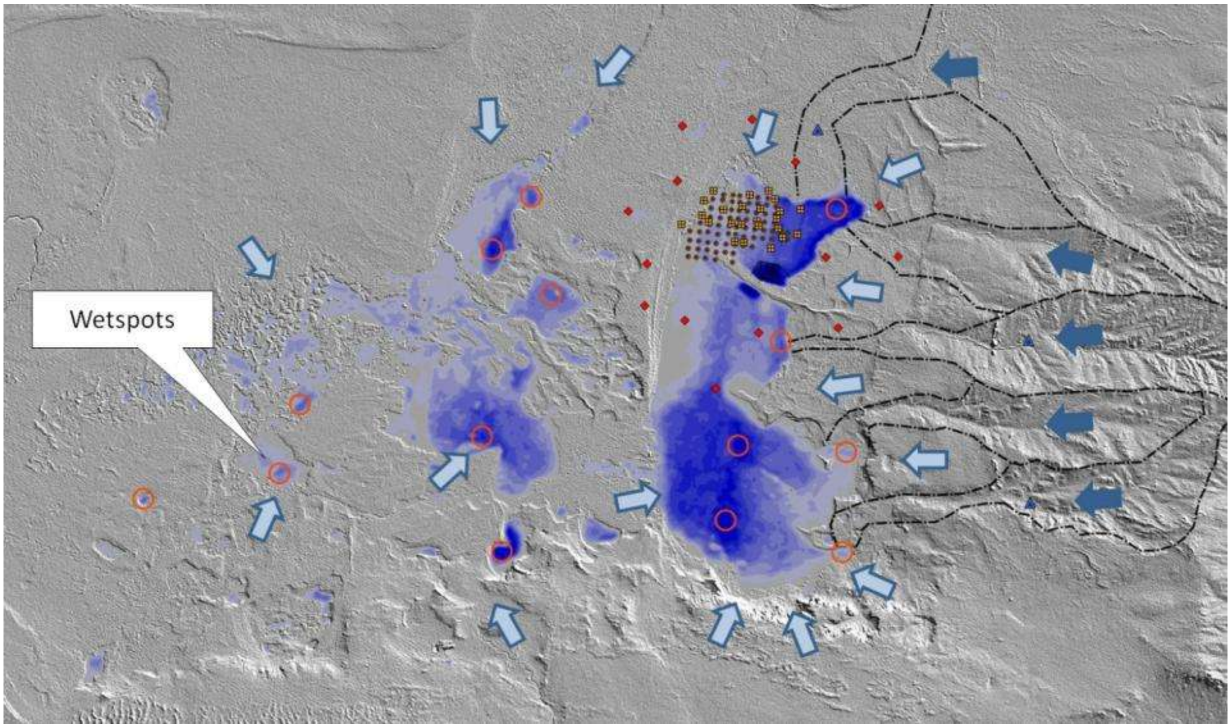
Groundwater flow rates and flow directions around the pans are not known. One can expect that most, if not all drainage lines provide an influx of groundwater into the Makgadikgadi. Significant pan recharge occurs around the pan margin above the 900 m contour and some of the smaller sunken proto-pans along the southern approach of the Makgadikgadi. Such groundwater may discharge from the pan floor but it also creates seepage points around the pan margin as manifested in Landsat imagery (Figure 17). Some notable fresh water springs and seepage points have been identified in imagery and the field. Local recharge sustains a small fresh water lake (Figure 34 bottom) (lat -21.1761° lon 25.9842°) below the Mosu escarpment. This wetland appears to be less saline then most other pan environments. At Mopipi salty ground water area discharges (Figure 34 top) and has formed a significant spring mount with permanent saline water seepage. It currently acts as the local scrap yard. (Lat -21.1874°, Lon 24.8606°).

We have a good handle on some of the yields from deep brines and boreholes from other wellfields etc. but in general shallow groundwater flow, which sustains surface wetlands is not captured. Such water will have too little of a yield and is most possibly of low quality and hence generally avoided and not extracted at all. As a result we simply have no handle on the shallow groundwater level and its dynamics which is the single most important factor determining the character and behaviour of the Pan and its surface. This is one of the biggest knowledge gaps in the functioning of Makgadikgadi and its wetlands (Figure 35).

Figure 34: Unusual discharge features. Top: At Mopipi salty ground water discharges at spring mount. Bottom: Local recharge sustains a small fresh water lake below the Mosu escarpment.

Figure 35 also depicts MODIS derived wetspots (orange circles) and MODIS derived relative surface wetness (section 3.6) as well as BotAsh wellfield (yellow) and proposed monitoring sites (red), see Figure 36.

Figure 35: Potential groundwater flow and surface water flow (solid arrows) in the Makgadikgadi



Source: Eckardt and Bryant (unpublished)

Box 10: Summary of Groundwater

What we know so far:

- We have a good record on brine yields and concentration
- We have a good handle on deep brine level and dynamics
- We have yields and water quality for boreholes in the basin

What we do not know:

- We have no record on deep groundwater movement in the pan basin
- We have no record on shallow groundwater dynamics in the basin or pan
- We have no record of pan surface recharge and discharge
- We have no record on the dynamics of the pans capillary fringe

3.10 Mass Balance Estimation

Average rainfall in the area is around 500 mm. This would add approximately a total of 3 600 MCM directly to the main pan surface each year, assuming the pan surface area measures approximately 7 200 km^2 of which Sua occupies a smaller portion (3 200 km^2) than Ntwetwe (4 000 km^2).

One should add stream input to this. The Nata River alone may receive a total of 10081 MCM of rain per annum (assuming 500 mm rainfall per annum and catchment size of 20161 km^2). Lesser contributions can be expected from the Semowane (483 MCM/966 km^2), Mosetse (775 MCM /1 549 km^2), Lepashe (518 MCM/ 1035 km^2), and Mosupe (584 MCM/ 1168 km^2). The eastern catchment in total would receive approximately 12000 MCM and assuming that this occupy roughly a third of the wider pan basin, the total rainfall directly received on the pan (3 600 MCM) and the wider basin may be as much as 40 000 MCM (total area of 80 000 km^2).

This is in stark contrast to the amount of water detected from remote sensing which estimates that on average 94 km^2 of the pan surface is witness to lacustrine conditions. The total amount of water may cover close to 1000 km^2 (14% of the pan floor). Since the bathymetry of wetspots is unknown, we have no handle on the volume of water present at the surface, but it is unlikely to be more than a few hundred MCM at most. This is not a lot compared to the overall inputs described above.

The lake at Nata may cover an area of up to 300 km^2 and assuming an average depth of 50 cm, may hold as much as 150 MCM. The Makgadikgadi surface as a whole probably never holds more than 200 MCM of surface water at the most.

There is clearly a stark discrepancy between the annual amount of water inferred from remote sensing on the pan surface (200 MCM at most) and the amount of water received by the pan surface (3600 MCM) and the wider catchment (40 000 MCM).

This can partly be attributed to potential evaporation rates (2 500 mm per annum) which are obviously high. From the pan floor alone (7 200 km^2) those may be in the order of 18 000 MCM per annum. However water does not spend much time at the surface, since the Kalahari arenosols and the pan surface have a high infiltration potential. Much of rainwater received, will recharge shallow and deep groundwater. This is certainly evident when looking at the stream gauge data. For example the Nata River may receive up to 10 000 MCM of direct rain input per annum, however mean annual flow rate at Nata is only 136 MCM with a maximum of 622 MCM. It is likely that a significant portion of the 10 000 MCM of rain is turned into groundwater. This may indeed be typical for most of the eastern catchments, karst areas, recharge areas and proto pans. Rain water is recharging the shallow and deeper groundwater of the wider basin. Some of this groundwater will follow the gentle topographic gradient and terminate in the Makgadikgadi pan.

At this point it is important to remember that pans are groundwater features and that surface water is only a temporary by-product. If groundwater is shallow it will evaporate and promote the production of surface salts and crusts. Shallow groundwater may even experience surface seepage and form pools of water driven by local discharge. If the groundwater is deeper, on the other hand, any surface water will contribute swiftly to groundwater recharge.

Pan surfaces are in general an indicator of the prevailing pan state. A salty crust would suggest shallow groundwater and dry sediments would suggest preferential recharge. The presence of surface clasts, such as silcrete, would suggest that the pan floor has dropped to accompany the falling groundwater level which exposed duricusts nodules, once formed at depth under the pan floor. In short the pan floor will through time, follow the net groundwater table. A moist surface will produce crusts and retain sediments and a lake may even accumulate sediments, whereas a dry pan is prone to sediment deflation and surface loss.

Hence the important distinction is made between recharge pans and discharge pans. A pan the size of the Makgadikgadi is both, recharging and discharging with pronounced variation in both space and time. It might in fact be recharging in some areas and discharging in others. The shallow groundwater level in the pan is likely to be dynamic. It determines the amount of crust that can form at the surface and the amount of infiltration that can take place. It represents the “pulse” of the pan and a driving parameter which is currently not measured at all. This represents one of the biggest knowledge gaps regarding the pan system and is by no means trivial.

Shallow groundwater may for example determine where and when wetspots form on the pan floor. Wetspots are not merely areas of pounded rainwater but areas where rainwater and surface runoff is prevented from rapid infiltration. Such low lying areas may act as topographic sumps but are also closer to the groundwater table, hence areas of potential discharge. The existence of wetspots may even be prolonged by active discharge.

Furthermore, shallow groundwater is able to sustain some of the wetspots. For example, some of the Nata groundwater will feed the northern Sua Pan. Water may even reach a point of surface discharge and small wetspots may form as a result of this. However it takes floods from the river itself which produce the most extensive wetspot in the Makgadikgadi. The Nata wetspot may hold as much as 150 MCM assuming a depth of 50 cm and area coverage of 300 km^2. This number compares favourably with the average annual flow volume for the Nata River which is 136 MCM at Nata, not far from the pan margin.

Any water present at the surface will infiltrate and evaporate at the same time. Potential evaporation rates (2 500 mm per annum) from the pan floor (7200 km^2) are in the order of 18000 MCM per annum. Evaporation rates are largely subject to known diurnal and seasonal dynamics and are relatively uniform over much of the basin.

The reason why wetspots are able to persist is partly because of the low infiltration capacity of crusts and sediments which in turn depends on the pore spaces of the sediment matrix and the amount of shallow moisture and water present. Along with the dynamic shallow groundwater level, we have to assume that the infiltration capacity of the surface is equally varied and dynamic but also equally unknown.

While evaporation can be considered as a loss from the system, infiltration will feed the pan sump and promote shallow and deep groundwater recharge. Such recharge is able to sustain surface water on the pan. Groundwater recharge is not only fed by drainage systems, but also numerous proto-pans and recharge windows such as the karstic terrain along the eastern margin. Actual rates and amount of infiltration and evaporation at the pan surface are undetermined; hence the fate of direct rainfall, groundwater discharge and runoff is not quantifiable but bound to be variable in both space and time. The vertical movement of water near the surface is one of the key controls governing the lacustrine environment and as yet not properly quantified.

This is in contrast to the deep brine resources which are assumed to be less dynamic. The northern Sua Pan hosts an estimated 8013 MCM of deep saline brine and 5 502 MCM for the shallow less saline brine (Gould, 1996). The current pump rate of 26.28 MCM/annum (3 000 m^3/hour) at BotAsh wellfield, translates into a low and gradual net loss from the deep brine. As the deeper brine is lost, the shallow brine adjusts; hence drawdown has been noted in monitoring wells which might cause changes to the pan surface.

This drawdown has resulted in lowering of saline yields for some of the wells with highest pump rates, suggesting that shallow brines are compensating for a loss from the deep brines (Eckardt *et al.,* 2008). This compensation is largely of a vertical nature but with time and deepening of the drawdown could also result in a lateral adjustment. The center of the drawdown and the western most margin of the Nata wetspot are separated by more than 10 km, hence contributions to the area of drawdown and losses from the wetspot are possibly minimal at this moment in time. Still this interface deserves to be monitored more closely. Baseline data needs to be collected in order to identify future trends. The pumping of deep brines may change pan surface properties, including recharge potential, surface composition and topography which also needs to be monitored along with accelerated losses of surface water.

A dam is being considered for the Mosetse catchment, which is upstream of central Sua and its wetspots. One has to draw particular attention to the presence of a major wetspot centered on the Mosetse River mouth which will be directly influenced by any upstream development. The dam, once in place, will be able to store 50 MCM, which is a third of the annual discharge measured for all the eastern catchments and is twice the mean annual surface flow of the Mosetse (23 MCM). Stream gauges at the Mosetse and Mosope (7 MCM/ average per annum) are positioned only halfway down the streams, which is not a good measure of how much runoff is contributed to the pan surface. However, significant infiltration losses can be expected in the karstic margin of the pan slope, below most of the stream gauges. In any case, a dam will most certainly prevent significant surface and groundwater from reaching the pan. Surface water which sustains the riparian and delivers water to the pan surface and groundwater which recharges the aquifer and pan subsurface will be reduced.

Our current lack of understanding of wetspot hydrology prevents us from truly quantifying the potential impact. The absence of any baseline data collected in and around wetspots such as the Mosetse mouth, underlines the need to specifically monitor such sites in the near future.

To conclude, the proportion of surface water on the pan is small (average 94 km^2, assuming 0.5 m depth, 47 MCM/annum) and a tiny fraction of rain contributed to the pan (5%) and the wider catchment (less than 1%). It is also not surprising that it is subject to such temporal and spatial variation. Estimation of surface water from remote sensing is in need of improvement and validation. Water depth, pan bathymetry and lateral movement rates of surface water are totally absent. The water body is so shallow and bathymetry so subtle that the lacustrine extent can even be subject to movement by wind (Nkala pers. comm.). The actual volume of surface water is one of the most important parameters to quantify wetland quality but is bound to be small and highly variable but is still a very rough estimate at best.

The pan surface represents a complex interface between the pan sediments, groundwater dynamics (recharge and discharge) and the atmosphere (runoff, evaporation and rainfall losses and contributions). The net state of the surface is a result of these variables which are not well constrained at this moment in time.

Overall, current records and observations are fragmented, with variable resolution, overlap and quality and were not gathered for the purpose of wetland characterization. Observations on climate, catchment and pan surface dynamics can only be tentatively linked, which hampers efforts to model the system or characterize its current state, trend and thresholds. Existing records focus on the distant flood volume and rainfall, which determine the state of the pan surface but only represent muffled linkages which are subject to lagging and unknown groundwater dynamics. Even less indicative is “end of pipe” volume and chemistry from the BotAsh wellfield. Deep monitoring wells need to be augmented with shallow groundwater and surface measurement equipment in the wellfield, pan margin and grassland perimeter and in particular around selected “wetspots” of the Makgadikgadi. Groundwater level, movement rate and direction can be considered, but due to the size of the entire basin it is suggested that an observational emphasis on the pan wetlands and their immediate surroundings be implemented.

It is unrealistic to accurately model the pan as whole and it is instead encouraged to monitor selected pan sub-systems or wetlands (wetspots) which are considered ecologically important. Such site specific monitoring will reveal natural on-site controls and dynamics essential for future management of this system.

3.11 Water Take-Off

Direct water take-off is currently taking place at BotAsh wellfield on north western Sua. The actual extraction of water and solutes is quantified, monitored and modelled. Its impact on the wider pan system and knowledge regarding exact brine origin and recharge is hampered by lack of data beyond the wellfield. This is likely the most significant hydrological change currently taking place within the Makgadikgadi system and its detailed understanding should be given a priority. Due to the depth of the extraction, surface manifestation may not be immediately apparent.

Significant groundwater is extracted from the wider pan catchment at Dukwi, Letlhakane, Orapa and Gweta, between 25 and 50 km from the pan margin. Records made available for this report state original borehole yields and make reference to water depth as well as chemistry. It is recommended that historic wellfield records are consulted with focus on sustainable and actual extraction rates and net water level response to pumping rates and recharge. How the extraction affects the pan surface environment or shallow and deep groundwater contributions to the pan is currently not known and will not be easy to ascertain even with existing data due to the distance between the individual wellfields and pan environment. Rate and direction of groundwater movement between wellfield and pan also need to be determined. Dukwi is likely to represent a take-off from Sua Pan while the Letlhakane, Orapa and Gweta wellfields have the potential to impact upon Ntwetwe Pan.

Dams and even surface water micro dams are currently not common in the Makgadikgadi catchment. Mosetse Dam has been proposed some 45 km from the eastern margin of Sua. It is to store around 50 MCM which will affect flow rates and groundwater recharge rates towards the pan margin in the central section of Sua.

In the past Boteti floodwater was diverted and pumped into Mopipi Dam. This activity has been discontinued and channels dug to support part of this diversion scheme have been filled in.

These water take-offs are only partially quantified and the knock on effect on the pan system are far from understood. Nevertheless, the following section will examine potential conflict in light of the significant pan wetspots identified from remote sensing in particular MODIS imagery (Section 3.6).

3.12 Water Conflict

Conflict areas can be identified by juxtaposing pan surface wetlands (“wetspots”) with various take-off scenarios as stated above. One has to take into account that there are uncertainties concerning both wetland detection and take-off scenarios. Impacts from take-offs are not always direct and remote sensing of surface water is still subject to some degree of validation. Still it is possible to identify and rank areas where conflict has the potential to arise.

There is no doubt that northern Sua and to some extent central Sua are the areas which deserve most of our attention. Extraction from the BotAsh wellfield, alongside significant surface water inputs by the Nata River play out north of Sua spit (Figure 36). In addition this area has the potential for surface dam construction in the Mosetse catchment and is subject to ongoing groundwater extraction in the Dukwi wellfield within the Semowane catchment. It is also the most visited area by tourists due to the proximity to the tar road the Nata Camp and Nata Bird Sanctuary. Brine extraction is set to continue and expand until 2050, providing scope for environmental change.

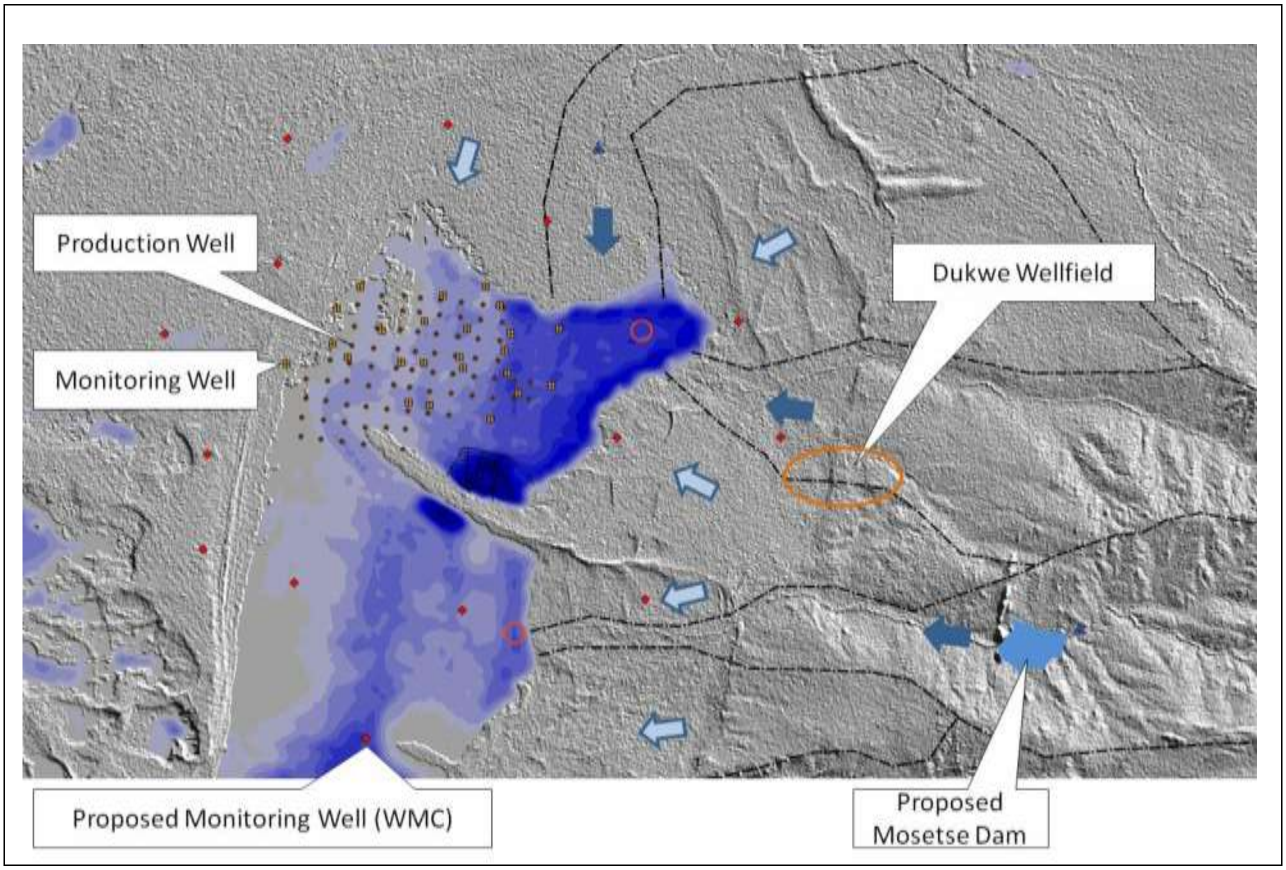
The retention of surface water with Mosetse Dam development would be the most significant surface water alteration this region has seen since Mopipi Dam was constructed. The proximity of the proposed dam to both the pan and known wetspots at Sua requires the fullest understanding of systems behaviour and potential impact. Base line observation on hydrological and limnological parameters need to be collected downstream of the proposed dam including the Mosetse delta and wetspot.

Southern Sua wetspots might cover larger areas but are more likely the result of direct rain and groundwater discharge. In a sense, this area is most similar to much of Ntwetwe. It is not clear how important it is ecologically but it is likely to be a shallow muddy puddle largely controlled by groundwater discharge. There are no known take-off issues here and hence conflict is not really much of a concern.

It is too early to recommend intervention, controlling or zoning measures without a better quantified handle on all the processes. Several large knowledge gaps need to be filled.

Figure 36 depicts the Northern and central Sua conflict area. Current Production and Monitoring Wells at BotAsh, as well as proposed expansion of monitoring wells put forward by WMC (red). Also note location of proposed Mosetse Dam and location of Dukwi wellfield on Semowane/Karst watershed (dashed line).

Figure 36: Northern and central Sua conflict area



Source: WMC, Bryant and author (unpublished)

3.13 Proposed monitoring program

The Makgadikgadi is vast, complex, dynamic and subtle. Rather than trying to determine inputs into the pan as whole it is recommended that monitoring should be focused on selected areas in particular with emphasis on the dynamic and persistent wetspots as identified from MODIS.

These sites need to be evaluated on the basis of their ecological merit upon which a shortlist should be subjected to on-site observations which fully capture the pan processes including atmospheric, pan surface and subsurface conditions. It should be the aim to fully quantify site specific water and solute dynamics as set out for Sabkhas in the Emirates (Yechieli and Wood, 2002). These observation points need to produce climatic data which includes rainfall, temperature, evaporation, windspeed and direction as well a surface state of the pan, water depth and conductivity, movement of water and sediment as well as groundwater dynamics and conductivity. Data needs to be collected at least at an hourly resolution.

This should not be considered a short term research endeavour but a systematic long term monitoring program which produces baseline data and captures environmental change and dynamics.

An integrated network of several such stations which measure synchronously in and around the wellfield as well as pan margin at northern Sua for example and would place the subsurface brine as well as the record from the hinterland (rain and stream gauges) into the appropriately nested context and allow for satellite data validation.

Such monitoring efforts should in the first instance be focused on northern Sua as well as the Nata, Semowane and Mosetse Rivers. The range of natural variability and the oscillations in lake cover against the backdrop of significant brine extraction renders this area worthy of such attention. It also features a host of infrastructure, such as existing wellpoints, power grid, telemetry networks and monitoring wells and is part of the mining concession given to BotAsh which would make the operation and supervision of such infrastructure feasible.

The exact locations for such stations requires consideration and refinement and this decision process should be executed in conjunction with the BotAsh mine, the wellfield consultants as well as the MMP and other stake holders such as the Nata bird sanctuary.

3.14 Summary of Makgadikgadi wetspots

This section represents a systematic breakdown of the Makgadikgadi into its subcomponents with emphasis on wetspots, taking into consideration the range of settings and controls including hydrological dynamics and potential for change. Some of these might turn out to be considered significant wetlands in need of future monitoring and protection.

Western Ntwetwe is home to shallow groundwater seepage along much of its north western edge. This has lead to numerous small spring seepage points amongst the islands in the Makgadikgadi Park within the home to range zebra and wildebeest. A number of related and nearby features stand out. A small pan 25 km northwest of Mopipi shows has a persistent wet appearance without any major indication of surface or subsurface water input. Its proximity to the Boteti proper and Boteti palaeo channel may give rise to the noted wetness of this small 7 km^2 feature.

Two additional wetspots are of note. One is nested in the extension of a pronounced Boteti riparian wetland and the result of groundwater seepage on the nearby Ntwetwe Pan. Surface water appears abundant and persistent along with the riparian. While surface runoff has not been observed east of Rakops since 1991 the meanders and state of the riparian would suggest that shallow groundwater seepage persists in the area. This process may also have lead to some of the most saline well water in the Makgadikgadi, outside the main pan. The second area 15 km to the north of this wetspot also hosts water seepage without a clear source. These two spots are similar in size, persistent throughout the 2000-2009 period but much less evident in the imagery from the 1970's and 1990's when strangely enough, rains where good and the Boteti was more active. They still deserve further examination as Ntwetwe in general is dryer than Sua and the entire SW corner has gone through significant change over the last 2 decades since the Boteti stopped reaching this area some twenty years ago. The return of the water in 2010 beyond Rakops and Lake Xau is an interesting development which will get much more attention if it persists and progresses towards the pans.

The southern and to some extent central Ntwetwe pan surface (50 km north of Orapa) is the most unusual of the entire Makgadikgadi. It is an extension of the Boteti River Mouth but overall not known as a wetland and extends as far as the Thabatshukudu area. It appears remarkably dark in satellite imagery suggesting some type of moisture including wet mud and salt. The area is about 300 km^2 in size but actual surface water is less evident. These local sediments appear unusual and should be collected for spectral analysis to account for its dark appearance in remotely sensed imagery. Massive salt crusts are not very common in the pans but this area might well host such surface crusts which might be sustained by shallow groundwater seepage from the Boteti into the pans. It could also be subject to additional water influx from the Letlhakane River. It is a clear extension of the Boteti Delta and could have seen a massive change over the last 20 years; one that might have gone unnoticed or undocumented. It currently is possibly the least understood area of the pans.

Northern Ntwetwe Panhandle hosts two wetspots which may on occasion link up. These seem to be contained by the eastern pan/fault margin and possible fed by channelled ground water along the rifted north of the pan which includes the Lememba catchment. Certainly no surface water inputs are evident but the northern sloping extension of Ntwetwe might also act as a good rain catchment.

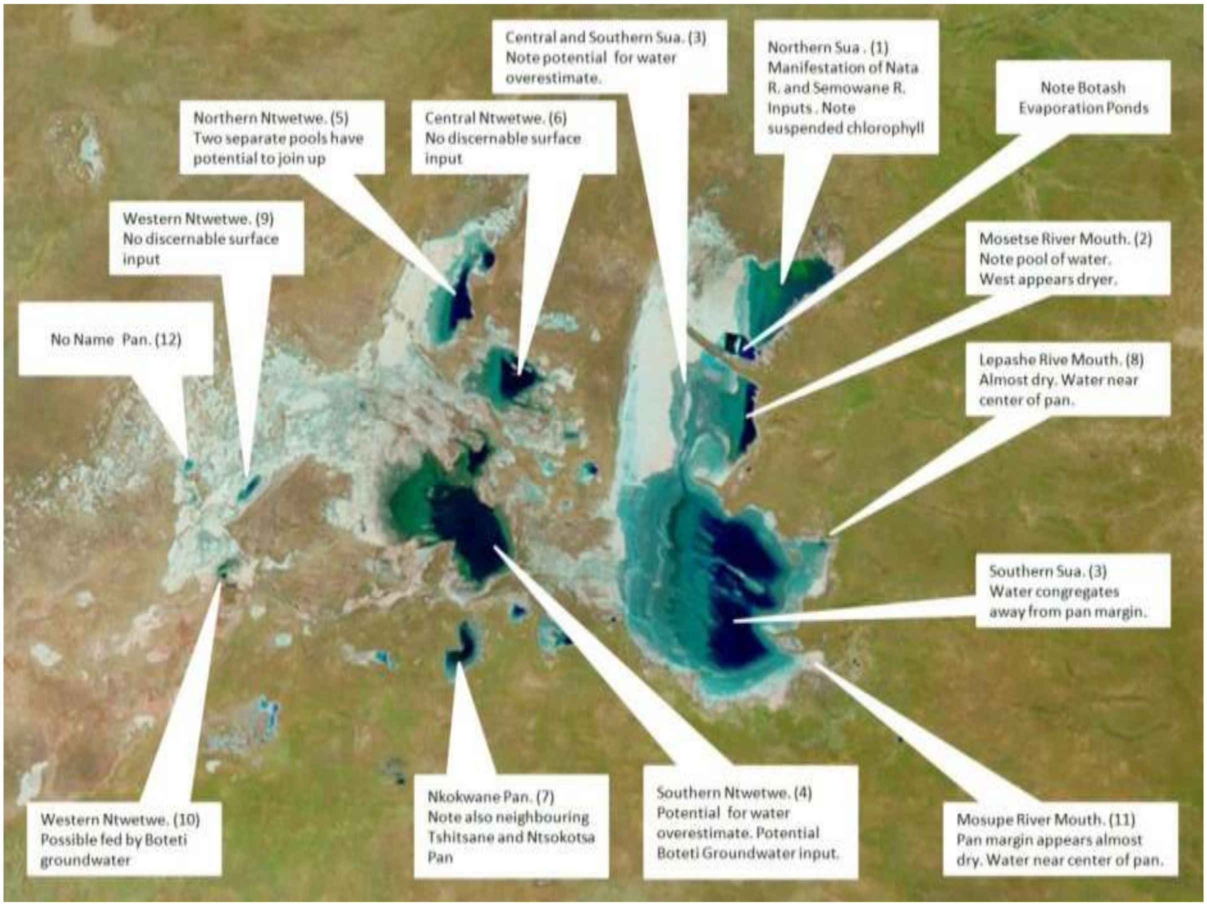
There are numerous pans beyond the southern boundary of both Sua and Ntwetwe which include Lake Xau and Rysana Pan. These are independent pan systems with their own dynamics and characteristics. Even though they are smaller, their setting in the karst margin and relative elevated height towards the main pan may cause the pans to act as recharge catchments for both Sua and Ntwetwe. Nkokwane Pan in the south, 30 km north from Orapa stands out and appears the wettest and most certainly receives groundwater from the Letlhakane River which in turn may flow onwards into the Makgadikgadi Basin. This Pan is one of the most persistently wet sites in the MODIS time series. Yet we have no handle on its surface characteristics or its potential as a wetland. Therefore, this site definitely needs further field validation. However both water outtake at Orapa and Letlhakane could have an impact at Nkokwane and Ntwetwe Pans.

Sua is quite different. Its western edge is consistently dry, due to the fact that Ntwetwe captures much of the shallow water seepage from the northwest and west of the basin. Further, most of the input comes in from the east as part of surface drainage input. Surface water has long been considered the main contributing source but its sole role may in fact be a little overestimated. Just as for Ntwetwe Pan, shallow groundwater is important and in fact without it, surface runoff could not persist on the surface for any length of time. The north and the south of Sua are really quite different. The **southern Sua Pan** west of Kukonje Island host water and wet sediments mostly in its central section covering an area of almost 1 000 km^2. Much of the margin features drainage input, riparian systems and deltas as well as seepage points but seems to remain largely dry including the Lepashe and Mosope deltas and mouths. This would suggest that surface runoff in the river and its mouth, largely infiltrates and may seep through the pan floor towards the middle of the pan at some 30 km distance. The pan margin on the south also has a gravely lag cover which would suggest that a drop in groundwater level there may not support much surface water. In general the gentle topographic gradient may affect surface characteristics which are expected to change from the pan margin towards the central depression on the pan floor. Overall the river mouths might be ecologically less important than the riparian systems upstream. Despite the size of this Sua pan sub system, actual water volumes are as unknown as water depth.

Central Sua is similar to the southern section; however Mosope water does have some presence on the eastern margin as well as central section of the pan. The entire eastern margin has drainage features but more importantly the karstified old lake floor may promote groundwater contributions to the pan.

Northern Sua home to the Nata Bird Sanctuary and contained by the grassland spit is by far the wettest place of the Makgadikgadi and water may attain depth of up to 2 m (McCulloch pers. comm.). The water body is largely confined by the spit and with increasing volume expands westward towards the BotAsh wellfield. The Nata River is largely responsible for this amount of surface water and distinct and well studied wetland and ecological system. The Semowane probably helps to maintain groundwater which in turn sustains the surface lake but its runoff is a small fraction of that of the Nata, whose catchment appears to have remained largely unaltered over the last 30 years. Pumping at the BotAsh wellfield further west is causing shallow groundwater drawdown where changes to the pan surface have been noted. These include primarily the formation of nebkha dunes and the establishment of salt bushes. This is most likely a recent a modern phenomena. The impact of the Dukwi wellfield and the Mosetse dam are as yet not identified or quantified.

Figure 37: Major wetspots summary in an August 2009 MODIS image



Note: Also refer to Table 7.

4. Major Findings for the MFMP

It has to be said that the pan environment has been through substantial tectonic and climatic changes over longer time periods and has been adjusting to rainfall variability over the last couple of decades but currently appears to be functional, dynamic and intact. Natural systems in general tend to change gradually and linearly. However many do have buried thresholds which once crossed result in rapid and often very surprising responses. Many reports and investigations are launched after systems have collapsed beyond the point of reversible change. Owens (dry) lake and the Aral Sea are just a few of such examples. This is certainly not the case with the Makgadikgadi. It is however worrisome that the demise of the Boteti as well the desiccation of the Lake Xau has gone relatively unexamined. It should also be of some concern that saline brines have been extracted at astounding rates without fully understanding their origin or appreciating the impact this may have upon the pan surface and its wetlands. The MFMP provides the opportunity to fully inform us of the current state of the system, highlight knowledge gaps and determine its future direction.

The main objective was to determine the current hydrological status of the Makgadikgadi with special consideration towards its aquatic ecosystems, lakes and wetlands. The system can be split into two subsets. The Ntwetwe and Sua Pans.

There are no other surface water inputs into Ntwetwe. Still its pan surface has dynamic "wetspots" which appear seasonal and persistent. These must all be fed by groundwater with its origin in the calcareous recharge zone and associated proto-pans as well as the ponding of direct rainwater additions to the pan floor. Ntwetwe is slightly higher and gently slopes towards Sua which could lend some benefit to the water status of eastern Ntwetwe as well as Sua itself. In general even brief rain makes the pan impassable suggesting shallow groundwater to be present. Short lived and ephemeral water discharge is evident in among the grass islands of the Makgadikgadi Park. This is possibly driven by groundwater recharge further upslope. In general the origin, recharge, discharge status as well as evaporation rate of groundwater here has not been determined.

The return of the Boteti to Rakops and beyond is a recent and exciting development. The water reached Lake Xau and the end of September 2010 and the removal of the Mopipi Dam water scheme might ensure a flood progression towards the Makgadikgadi.

Fossil rivers such as the Okwa and Passarge to the west, Letlhakane to the south, and Nunga and Lememba to the north are bound to make undetermined hydrological contribution to the Ntwetwe pan. Rates and direction of groundwater flow are not known.

Sua Pan by comparison appears to be the more dynamic of the two. It hosts numerous well defined and actively monitored catchments with persistent and substantial deltas and riparian wetlands leading up to the pan margin and with most of its headwaters in one of Botswana wettest places. The eastern catchments and flanks of the pan appear relatively intact and are characterized by Mopane bushveld, limited arable land cover and only few small dams and micro-dams are present which is in contrast compared to the other side of the watershed towards Shashe and Francistown. Many of the changes and responses that are currently apparent at Sua are most likely natural. The Pans in general strive to attain an input/output equilibrium against significant inter-annual rain fall oscillations which occur at a decadal as well as a 2-3 year time scale. Both Pans appear to respond rapidly to changes such as seasonality which would suggest that they are in some kind of equilibrium.

Sua's northern section receives significant runoff in particular from the Nata River. Lacustrine environments persist and may extend into the subsequent wet season with Sua spit acting as a retention barrier. South of the spit, surface water is also common but tends to be located more towards the middle of the pan without the direct input of runoff being as evident. Small surface water bodies persist on the eastern pan edge, close to the mouths and deltas of the Mosetse, Lepashe, and Mosope Rivers. However surface water congregates more towards the middle of the Pan because it is most likely the lowest point and has the most shallow groundwater table. Water in this part of the Pan could be maintained by a combination of direct rainfall or groundwater discharge.

For a pan such as the Makgadikgadi, the generation of surface lakes could come about through two distinct scenarios.

1) The clay-rich pan surface does not infiltrate and water from floods and rain simply is subject to ponding.

2) Shallow groundwater discharges directly from the lake floor and establishes a lacustrine environment.

The first scenario appears to hold well near the Nata Delta but might be less applicable elsewhere; in fact both of these are viable and most likely do take place simultaneously. We have however not enough information for the Pan as a whole or even selected sites to make this kind of distinction. As a matter of fact we have no data on the most crucial parameter regarding the depths and dynamics of the shallow groundwater at or near the Pan floor. Such boreholes would not be of direct economic benefit due to low yields and chemistry i.e. not enough salt to be considered brine and not fresh enough to be palatable. Chemically the inflow and precipitation products in the Pan are relatively straight forward. Still various surface waters might have slightly different evolutionary paths depending on preferential runoff or groundwater additions and could have different chemistry. Such site specific observations are yet to be made.

Due to the presence of the substantial BotAsh wellfield west of Sowa Town we have been able to make a series of observations which are worthy of some consideration. The deep subsurface brine appears to be fossil in nature. In addition pumping does not appear to be followed by recharge hence it is assumed that it is decoupled from contemporary surface waters (Eckardt *et al.,* 2008). Monitoring wells around the wellfield are reporting a drawdown which is also modelled as gradually moving southward along the western edge of the pan as the newer sections of the wellfield become active. The actual lateral and vertical rate of movement will depend on future extraction rates but this shift could take several decades. In a sense, subsurface brine on the western edge and surface waters to the east are separated by the current topography of the pan, which is reported to slope from west to east. They are furthermore vertically decoupled by thick layers of clay. One can only speculate, but it appears that this separation will not lead to immediate surface losses due to enhanced infiltration as a response to drawdown.

It is however remarkable that after 20 years of brine extraction at Sua Pan, still little is known about the origin of the brine or if it is indeed entirely decoupled from surface but more important lateral subsurface processes. It is also unclear what surface manifestation this pumping activity has. Encroachment of grasses has often been stated but has not been documented. Nebkha dunes and salt bushes on the pan floor could be early indicators of environmental change to the capillary fringe. What the implications of a drawdown in the wellfield are remains a simple but important question.

Groundwater management consultants have stressed that their predictive capabilities are limited by lack of an observation record beyond the monitoring wells. This statement really applies to much of the hydrological dynamics at the Makgadikgadi. Linkages are circumstantial and plausible but we are not in a position to produce conclusive results, involving a systems approach with stated inputs, outputs and associated pathways as well as a total mass balance. The existing observational record is not robust enough and was never collected with such an objective in mind. Scientific publications have stretched the utility of this record to its limit. To make any further headway requires dedicated monitoring efforts.

Additionally, there are a number of shortcomings with existing data records.

Rainfall records that are released remain at a monthly resolution. This is not sufficient if one were to examine the response of pan catchments to future climate. The daily records would need to be made available as individual rain events of the past need to be linked to short-lived synoptic scenarios of the atmosphere. Only then can regional or global climate models be downscaled to individual weather stations and predictions regarding change and extreme events that can take place. Existing analyses by Bryant *et al.* (2007) suggest that landfall of tropical cyclones is one factor responsible in extreme flooding. Weather such events are on the increase remains to be seen. In addition, rainfall and climate records from the Pan margin and Pan surface are absent. The only station which had any proximity to the pan was close to the BotAsh mine, but is now being relocated to Sowa Town.

Stream gauge records are daily but data post 1999 became less consistent. We also do not know how the recorded runoff is being modified beyond this point in the catchment. What are runoff contributions to groundwater? How much of it reaches the pan? What are the losses from the surface as it enters pan deltas? With the Nata River it appears that the connection between stream gauges and pan surface water are relatively strong. Other streams experience much less flow. This suggests a range of possible hydrological scenarios across the pans which are yet to be confirmed.

Validation of MODIS satellite images is required and unfortunately we do not have a good historic reference for the 2000-2009 period. The post 1999 stream gauge data is surprisingly fragmented and cannot be used alongside the latest MODIS "wetspot" record. One also has to be aware that MODIS is 5 years beyond is 5 years designed lifespan and that there is currently no replacement in the immediate wings. Therefore a gap in satellite data might be imminent.

It is also a sizable jump to go from surface area water cover to volume estimates for pan water. Hence there is a need for a water depth record as well a better handle on the actual pan topography and an identification of sub-basins in which water can accumulate. We do not know the micro bathymetry of the pan floor. Existing raster elevation data is not good enough and Icesat laser altimetry not extensive enough to capture pan topography. An evaluation of elevation data generated by the Botswana government could prove useful. On site GPS surveys can also be considered.

In general much more could be learned about the brine and the surface water by considering a dedicated monitoring network. Such equipment would represent the most important commitment towards understanding the pans but would also offer some of the biggest insight into its current response to climate variability, catchment alteration and water take-off.

5. Follow up work

1) Rainfall

Monthly rainfall data is available for the wider catchment of the Makgadikgadi Pans. While such data can give you a sense of seasonality, variability and trends it does not allow for climate change prediction. Climate change scenarios are played out using various shifts in southern Africa's synoptic states. Such analysis requires daily rainfall data against which synoptic information can be attached. In the absence of daily rainfall data, covering several decades, no reliable change analyses can be conducted. Such work could be carried out by attaching a Motswana student to the Climate Systems Analyses Group (CSAG) at UCT.

Furthermore rain records for the pan surface are nonexistent. The weather station near BotAsh mine, which was the only station in proximity to the pan, has just been moved to Sowa Town. Long term monitoring should consider rainfall observations dedicated to the pan environment in particular its wetspots.

2) Wetlands

Pan surface wetness maps have identified areas of persistent moisture, termed wetspots. Identification of wetspots is based on the 10 year observation record from the MODIS sensor, which provides daily, as well as 16 and 8 day averaged products. Future follow up instruments are to be deployed on the Joint Polar Satellite System (JPSS). As detection techniques develop, confidence in surface area estimation is improving. Satellite data validation should include on site observations on parameters such as water edge determination, pan spectra analyses and sediment and algae content of water bodies. The Makgadikgadi wetspot map is subject to ongoing improvement.

Precise determination of water volumes is hampered by lack of data regarding pan topography and wetland bathymetry. Future wetland monitoring should also include a measure on water depth. In addition maps on pan surface topography should be generated. Clearly global elevation data (SRTM and ASTER GDEM) are not of sufficient quality. Icesat data has an adequate vertical accuracy but only provides spot heights. Digital contour and elevation data generated by the Botswana Government (Department of Survey and Mapping) has as yet not been evaluated for this project. This should be considered a priority.

In the absence of any sufficient height data, deploying differential (precision) GPS on the pan surface should be considered. A UCT PhD student will be tasked with this objective as part of a wider pan surface characterization required to improve global dust modelling. Initial focus in 2011 will be on the area to the north of Sua spit and include the Nata Lake and BotAsh wellfield. However a wider survey of the entire Makgadikgadi Pan with focus on the wetspots would be desirable.

Wetspots identified in the MODIS 10-year time series, should be subject to a dedicated limnological and ecological characterisation. This would help determine the most important wetlands on the pan surface.

3) Shallow Groundwater

Pan surface water is being maintained by the presence of shallow groundwater. Such water is of a low quality and yield and has as such not been explored, extracted or monitored. It is however crucial in sustaining wetspots in the pan environment. Such shallow groundwater is partly derived by direct rain input, regional groundwater contributions and surface flood waters. Instead of monitoring all of these, it is recommended that piezometers are deployed at selected wetspots. Particular emphasis should be placed on the BotAsh wellfield – Nata Delta interface as this area arguably hosts the most important wetland and the largest off-take from the system. A piezometer transect could ascertain if there are linkages between brine extraction, drawdown, and surface recharge in the form of shallow groundwater movement.

A second shallow groundwater monitoring site should be considered at the outlet of the Mosetse River to determine the role of surface and groundwater inputs towards maintaining one of Sua Pans wetspots. Such baseline data would ascertain the impact of any future dam development.

4) Pan surface

The pan surface is the product of surface and subsurface processes including water, drying and wind. In particular the state of the crust and its relationship to groundwater is of interest. Efforts are currently underway to characterize the pan surface and shallow subsurface as well as vegetation cover such as grass invasion, in support NERC funded project to study dust transport at the Makgadikgadi. Current focus is on the area around Sua spit. A wider survey of the system would be desirable and is feasible in 2011. An attempt will be made to widen the scope of satellite data used to study the pan surface. Current focus has been on Landsat data but Spot and ASTER data is now also being considered. Recent high resolution georeferenced orthophotos, generated by the Botswana Government have not been made available to this project. Their acquisition and evaluation should be made a priority.

5) Deep Brine

The BotAsh wellfield is subject to significant brine extraction as well as drawdown. While chemical and physical parameters are generated by BotAsh and its consultants, focus so far has been on brine production. Monitoring efforts should give additional consideration towards pan surface alterations and relationship with surface waters and wetlands at north eastern Sua.

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