GROUNDWATER HYDROCHEMISTRY EVALUATION IN RURAL BOTSWANA: A CONTRIBUTION TO INTEGRATED WATER RESOURCES MANAGEMENT

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Abstract

Groundwater is one of the major sources of exploitation in arid and semi -arid regions. To protect this scarce resource information on its quality status over time is important. This paper examines the quality of groundwater from domestic water supply boreholes across rural Botswana. Ionic concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, SO_4^{2-}, HCO_3^-, Fe^{3+}, Mn^-, and N. Parameters such as pH, total dissolved solids (TDS), and electrical conductance (EC) were correlated and their levels compared to international standards. Levels of various physico-chemical parameters were also analyzed for temporal trends for in the various districts across the country and those with significant trends were then contoured to determine areas at risk of groundwater contamination. Groundwater in rural Botswana is generally suitable for human consumption despite high levels of cations. Nevertheless, levels of Na^+, Ca^{2+}, EC and TDS are showing increasing trends in some parts of the country highlighting the need for periodic monitoring of groundwater quality to isolate and possibly advise on discontinuation of polluted boreholes.

Key words: *Groundwater, Rural, Physico-chemical, Water Resources, Botswana*

Introduction

Extreme climate conditions in the form of higher maximum temperatures and frequent droughts are expected in the twenty-first century due to climate change. In particular, Africa and Asia are expected to become more vulnerable to droughts (Sukhija, 2008). This situation is expected to affect arid regions most as humanity's sustenance hinges on groundwater in these places (Sukhija, 2008). Khodapanah *et al*. (2009) noted that groundwater is the only reliable water resource for human consumption in semi-arid regions. While (JMP, 2008, MacDonald *et al*., 2009) observed that one of the key uncertainties surrounding the impacts of a changing climate in Africa is its effect on the sustainability of rural water supplies. Furthermore, the rapid depletion of groundwater supplies as a consequence of continued population growth and pollution threatens the quality of many aquifers in these regions (Khodapanah *et al*., 2009).Once the groundwater is contaminated, its quality cannot be restored by stopping the pollutants from the sources. It therefore becomes imperative to regularly monitor the quality of groundwater and to device ways and means to protect it (Lateef, 2011).

In many areas, particularly arid and semi-arid zones such as Botswana, groundwater quality limits the supply of potable fresh water. To utilize and protect valuable water resources effectively and predict the change in groundwater environments, it is necessary to understand the hydrochemical characteristics of the groundwater and its evolution under natural water circulation processes (Lawrence *et al*., 2000; Edmunds *et al*., 2002, 2006; Guendouz *et al*., 2003; Wen *et al*., 2005; Ma *et al*., 2005; Ma and Edmunds 2006; Jianhua *et al*., 2009).

Thus, knowing the quality of groundwater is a crucial component of integrated water resources management. As such improved knowledge can contribute to effective management and utilization of this vital resource. In this regard, monitoring the quality of groundwater is as important as assessing its quantity (Khodapanah *et al*., 2009).Botswana is part of the drought prone region of Southern Africa, therefore, conservation and careful management of water resources is a matter of necessity and great importance. Hence the focus on water resources management in the country and in particular, an integrated approach that links both ground and surface sources has become critical over the past decade (Ganesan, 2001).

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Consequently, the goal of this paper is to add to overall knowledge on groundwater status and subsequently water resources management in Botswana. It reaches this goal through three analyses. The first analysis evaluates various water quality parameters through basic statistics in an attempt to compare their levels with acceptable international standards. The second analysis determines trend in levels of various parameters over time to identifying areas at risk of water pollution. Thirdly, significant trends of physico-chemicalparameter levels were displayed spatially explicitly.

Materials and Methods

Study Area

Botswana is a land-locked country straddling the tropic of Capricorn in the center of the southern African plateau. The mean altitude above sea level is approximately 1000 m, with total land area of 582,000 km^2 and population of 2 million. The country shares borders with Zimbabwe, South Africa, Namibia, and Zambia (Figure 1). Much of the country is flat, with gentle undulating, occasionally rocky, outcrops. About two thirds of the land comprises the kgalagadi desert, which supports scrubs and grasses, despite almost lacks surface water sources.

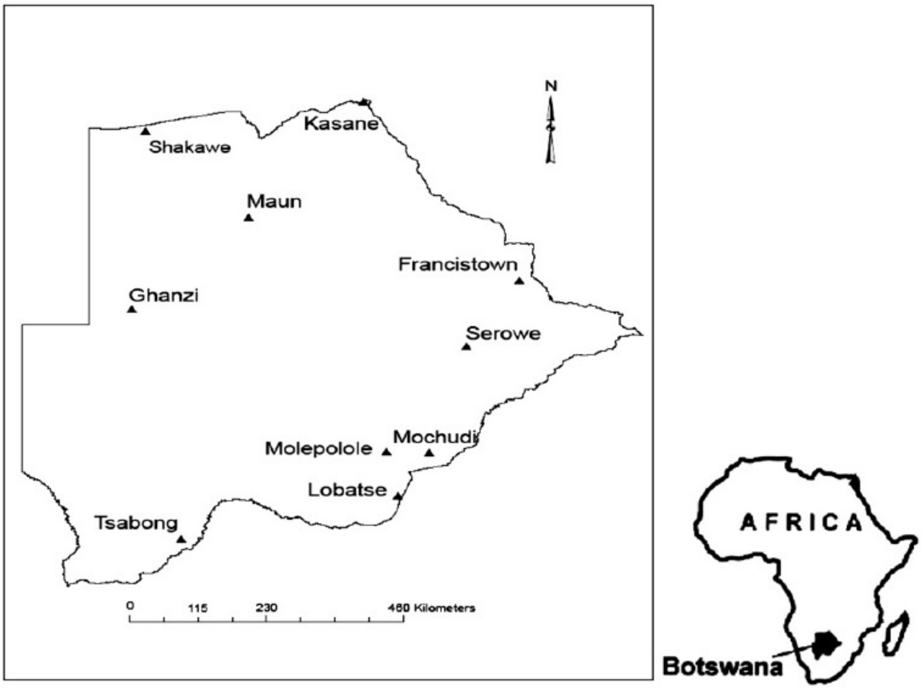


Figure 1 Map of Study Area

Botswana is situated close to the subtropical high pressure belt of the southern hemisphere. As a result, the country is largely arid or semiarid. Mean annual rainfall ranges from 650 mm in the extreme northeast to less than 250 mm in the extreme southwest. Almost all the rainfall occurs during the summer months, from October to April, while May to September is normally dry. Most of the rainfall occurs in localized showers and thunderstorms, and its incidence is highly variable both in time and in space. Average daily maximum and minimum temperatures range from 22^{0}C in July to 33^{0}C in January (max.) and 5^{0}C in July to 19^{0}C in January (min.). Evaporation rates are high, ranging from 1.8 to 2.2 m annually for surface water. Clear skies and low relative humidity lead to maximum insolation during the day and rapid energy loss at night, resulting in relatively hot days and cool nights and a large diurnal of temperature range. Drought is a recurring event in the country resulting in poor crop production and reduction in livestock population (Khupe, 1996).

Groundwater Resources in Botswana

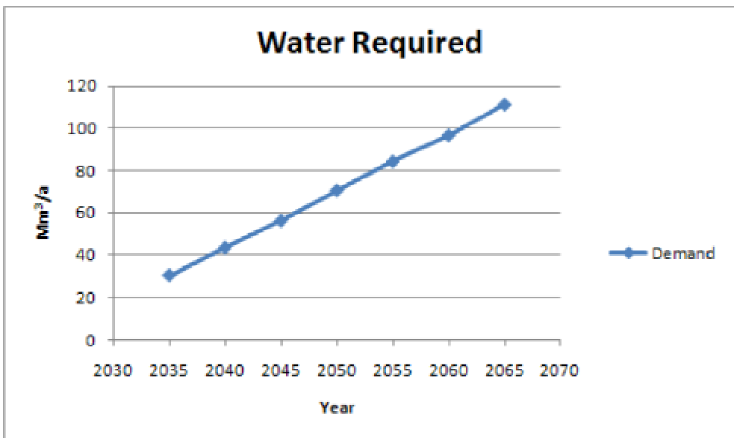
Groundwater is the main source of portable water supply in Botswana. Much of the country (about 66 percent) depends entirely on groundwater (Table 1). Although groundwater recharge is very limited, thus making the resource finite and non-renewable, it is an indispensable water resource in the country. With the envisaged increase in water demand in the country, (Figure 2), its importance is set to increase. Besides pollution, over abstraction is likely to be a threat in to groundwater sustainability in the future (Table 2).

Table 1. Availability of groundwater in Botswana (2008)

Wellfield	Developed available resource (m^3/d)	Cumulative Resources developed (m^3/d)	Sustainable Resource (Mm^3/yr)
Dukwi	5700	5700	0.039
Palla Road	7500	13200	1.46
Ghanzi	1850	15050	0.68
Kanye	3950	19000	1.44
Letlhakane	1500	20500	0.06
Gaotlhobogwe	7500	28000	5.84
Palapye	4000	32000	1.64
Ramotswa	5000	37000	1.83
Serowe	6200	43200	1.28
Tsabong	2000	45200	0.73
Kang-Phuduhudu	7860	53060	3.27
Boteti	8950	62010	1.96
Maitengwe	9400	71410	3.43
Matsheng	9600	81010	3.52
Pitsanyane	1000	82010	0.37
Maun	8000	90010	10.07
Masama*	20480	110490	-
Botlhapatlou*	14000	124490	-
Bobonong*	3800	128290	-
Mabule Dolomite Cluster*	3000	131290	-

(Department of Water Affairs, 2008)

NB: m^3/d refers to cubic metres per day, Mm^3/yr refers to million cubic metres per year
*expected yield per day



Time	2035	2040	2045	2050	2055	2060	2065
Demand	30.5	43.4	56.2	70.65	84.47	96.88	111.5

Figure 2. Botswana water demand projection per annum (GoB, 2010).

Table 2. Sustainable Groundwater Resources in Botswana (2008)

Wellfield	Available Developed resource	Sustainable Resource (m^3/d	Current Abstraction (m^3/d)	Annual Abstraction (Mm^3/y)
Dukwi	5700	600	6600	2.44
Mahalapye	7500	4000	4000	1.48
Ghanzi	1850	1850	1850	0.69
Kanye	3950	3950	6900	2.56
Letlhakane	1500	950	1500	0.56
Palapye	4000	2700	3200	1.19
Ramotswa	5000	5000	4000	1.48
Serowe	6200	3500	4500	1.67
Tsabong	2000	300	1600	0.59

(Department of Water Affairs, 2008)

Data

Ionic concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, $SO4^{2-}$, $HCO3^-$, Fe^{3+},Mn^-, and NO^-_3; along with pH, total dissolved solids (TDS), and electrical conductance (EC) of groundwater (boreholes) for domestic use across the country for the period of 1985-2006 at district level were obtained from the Department of Water Affairs, Botswana Government.

Analysis

Basic descriptive statistics such as correlation matrix and range were calculated to evaluate water quality standard. While level trends of various parameters over time were determined through Mann-Kendall test (MK) (Mann, 1945, Kendall, 1975; Turkes *et al.*, 2002). In MK, the standardized statistical test (Z) is used, with positive Z values indicating increasing trends and negative Z values indicates decreasing trends. When testing either increasing or decreasing monotonic trends at a *p* significance level, the null hypothesis is rejected for absolute values of Z greater than $Z_{1-p/2}$, obtained from the standard normal cumulative distribution tables. In this paper, standard significance levels of p = 0.05 and 0.10 were applied. Parameters showing significant trends were then contoured using the spline interpolation technique in ArcGIS 9.2 to determine areas at risk of ground water contamination.

Results and Discussion

Correlation matrix between the different chemical parameters was computed in order to deduce geochemical processes determining the quality of groundwater (Table 1). Statistics of groundwater show poor correlation ions. Nevertheless a few such as EC with TDS, EC with Ca^{+2} and Mg^{+2}, Mg^{+2} with Cl^-, Ca^{+2} with Mg^{+2}, Ca^{+2} with $So4^{2-}$, and Na^- with $HCO3^-$ show moderate to high correlation. High correlation and also level indicate chemical weathering and leaching of secondary salts contribution followed by multiple source inputs like industrial and agricultural effluents, which exhibit poor correlation in groundwater (Udayalaxmi *et al.*, 2010). Other anthropogenic sources such as sewage effluent (McCarthy *et al.*, 1994) also play a major role in controlling shallow groundwater chemistry.

A high positive correlation is observed between TDS and EC because conductivity increases as the concentration of all dissolved constituents/ions increases. Likewise, a strong correlation is also observed between Mg^{2+} and Ca^{+2} indicating most of the ions are involved in various physiochemical reactions, such as oxidation-reduction and ion exchange in the groundwater aquifer system (Udayalaxmi *et al.*, 2010). A marginal negative correlation is seen between the pH and all other parameters, except potassium (Table 3).

Table 3. Correlation matrix for groundwater quality

	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO4^{2-}$	$HCO3^-$	NO^-_3	pH	TDS	Fe^{3+}	F	Mn	EC
Na^+	1													
K^+	0.19	1												
Ca^{2+}	0.73*		1											
Mg^{2+}	-0.05		0.84	1										
Cl^-	0.13	0.17	0.45	0.83	1									
$SO4^{2-}$	0.83		0.79	0.13	0.53	1								
$HCO3^-$	0.84		0.01	0.13	0.01	0.21	1							
N								1						
pH	-0.19	0.43	-0.24	-0.27	-0.04	-0.22	-0.53		1					
TDS	0.55	0.20	0.43	0.51	0.93	0.61	0.14	-0.21	-0.19	1				
Fe^{3+}			0.36	-0.40							1			
F										-0.18		1		
Mn^-			0.12	-0.02					0.54				1	
EC	0.68	0.08	0.86	0.77	0.64	0.49	0.13		-0.37	0.87				1

Groundwater Chemistry

Among major cations, Na^+ was generally dominant with concentration ranging from 38.4 to 450 mgl^{-1}. Calcium ion was second highest with maximum concentration of 98 mgl^{-1}. Potassium and magnesium ions were of secondary importance, with maximums of 29 and 58 mgl^{-1} respectively. While maximum concentrations of chloride, sulfate and bicarbonate ions were 532, 220, and 287 mgl^{-1} respectively. The electrical conductivity (EC) varies from 300 to 18200μmhos cm^{-1} indicating that there are fresh water (<500 μmhos cm^{-1}), marginal water (500-1500 μmhos cm^{-1}) and brackish water types (>1500μmhos cm^{-1}) in domestic groundwater boreholes in the country. Total dissolved solids ranges from 245 to 583 mgl^{-1}. The pH value is high (8.5 to 10.3) indicating the alkaline nature of rural groundwater in the country (Table 4).

Table 4. Physico-chemical characteristics of groundwater in rural Botswana

Parameter	**Range** (mgl^{-1})	**WHO limit (2004)**
Na^+	38.4-450	200
K^+	2-29	30
Ca^{2+}	26-98	200
Mg^{2+}	14-58	150
Cl^-	110-532	250
$SO4^{2-}$	34-220	400
$HCO3^-$	72-287	-
NO^-_3	0.32-9.2	10
pH	8.5-10.3	6.5-8.5
TDS	245-583	1000
F	0.10-1.20	1.50
EC	0.30-18.20 (mS/m)	-

Spatio-Temporal Physico-Chemical Trends

Of the various chemical parameters evaluated, only Ca^{2+}, EC,pH, and TDS showed significant temporal trends at different boreholes across the country, which were then interpolated to get country coverage. Calcium levels depict increasing trend in the extreme north of the country while decreasing in the southern part. Electrical conductivity shows increasing trend in the dry south west and also in the north east but decreasing in the north and southern parts. Trends in pH across the country display increase in the southwest, and decrease in the north and northeast.TDS show a decreasing trend for most parts of the country except the northeast (Table 5, Figure 3).

Table 5. Groundwaterphysico-chemical temporal trends across the country

District	**EC trend**	**p value**	**pH**	**p value**	**TDS**	**p value**	**Ca**	**p value**
Central (central)	1.69	0.009***	-1.41	0.16	0.48	0.63	-0.59	0.55
Chobe (north)	-1.38	0.01***	0.90	0.37	-1.72	0.09***	0.81	0.02**
Kgatleng (southern)	-3.67	0.000*	2.20	0.003 **	-3.19	0.000*	-1.04	0.03**
Kgalagadi (south western)	0.68	0.005***	-1.58	0.11	0.73	0.46	-0.28	0.04*
South-East	-0.82	0.004**	-2.85	0.000*	-0.10	0.34	-0.03	0.006***

*Significant at p<0.001,**significant at p<0.005, *** significant at p< 0.1

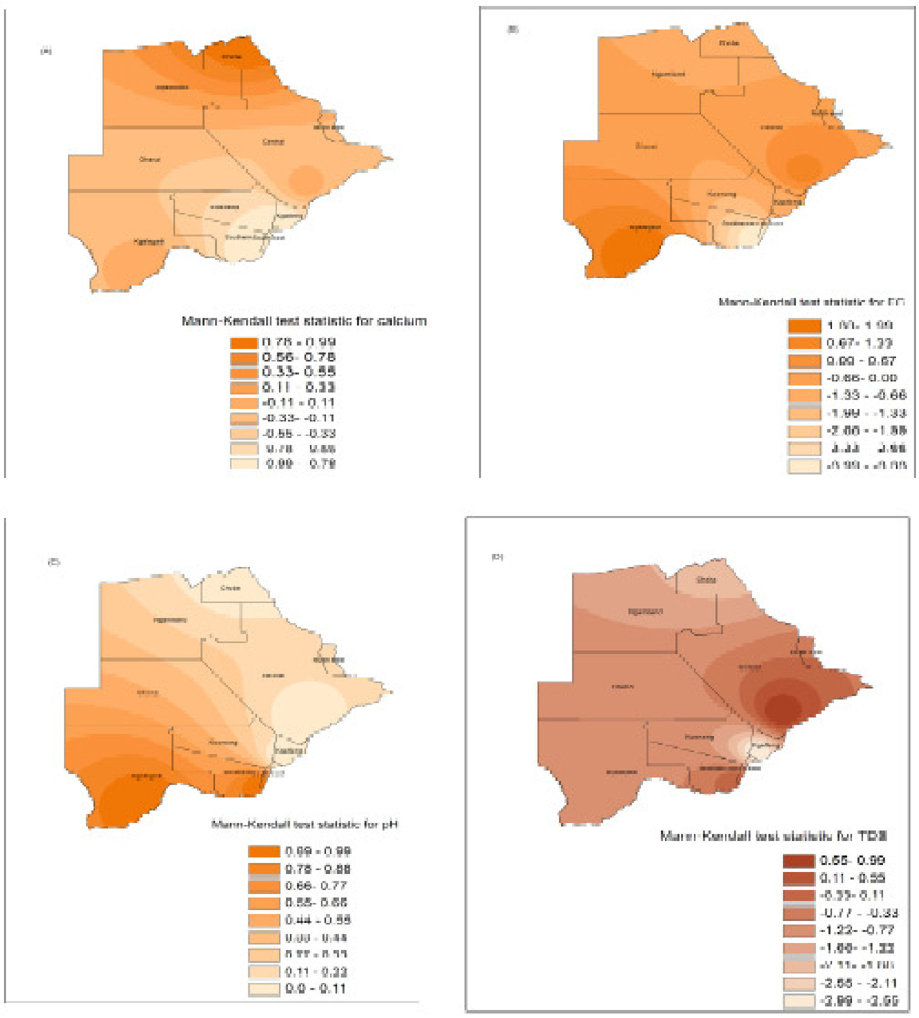


Figure 3. Trends in physico-chemical levels

Water Quality Assessment

The goal of hydrogeochemical assessment is to determine groundwater suitability to different uses based on different chemical indices. An assessment of rural borehole water suitability for domestic consumption was evaluated by comparing the aggregated hydrochemical parameters of the water with prescribed specification of World Health Organization (WHO, 2004) (Table 4). Although the desirable pH range for drinking water is 6.5 to 9.2, the range for rural groundwater in Botswana is 8.5 to 10.3, indicating the alkaline nature of the water and values outside WHO standards. Furthermore, the upper range of EC is also more than the maximum permissible limit of 1500 μmhos cm^{-1}.In the same vain, the upper range of sodium is also outside the prescribed limit of 200 mgl^{-1}

Conclusion

This paper evaluated the quality status of groundwater in Botswana; a vital component of integrated water resources management. In general, groundwater in the country is suitable for human consumption except for some high levels of cations. The Physico-chemical levels are constant across the country except for Ca, EC, pH, and TDS, which depict either increasing or decreasing trends in different parts of the country. Therefore, periodic monitoring of groundwater quality to isolate and possibly advise on discontinuation of boreholes with high levels of physico-chemicals need to be carried out. Such groundwater quality monitoring could, provide invaluable information for water management strategies.

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