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RESEARCH ARTICLE

ASSESSMENT OF GROUNDWATER QUALITY FOR IRRIGATION AROUND THE URBAN GABORONE DISTRICT, KGATLENG AND SOUTHERN VILLAGE DISTRICTS OF BOTSWANA

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ABSTRACT

The groundwater quality assessment study occurred in Urban Gaborone District, Kgatleng and Southern Village Districts. Six boreholes were identified and six composite samples were analysed for water quality for irrigation. The chemical constituents were evaluated using water quality standards developed by the Republic of Botswana, South Africa, Ayers and West cot. Irrigation water quality indices SAR, SSP, RSBC, PI, MAR, KR and TH were calculated and used to determine the quality of the water samples. The study revealed that most of the chemical constituents were within the recommended limits. Generally, the indices were also within the recommended limits. All the groundwater samples were suitable for irrigation. However some samples required good management for them to become usable for irrigation

INTRODUCTION

Good quality water for irrigation is a scarce resource in arid and semi- arid regions. This scarcity is no longer associated with dry regions only, poor quality water has become a general concern as climate changes from humid to arid condition (Hoffman, 1997). Water quality concerns have been neglected because good quality water has been plentiful and readily available (Shamsad and Islam, 2005). This situation has changed with respect to water quality and quantity. The Republic of Botswana is not an exception to water quality problems. Botswana has only two sources of irrigation water namely surface water and groundwater. These sources are not reliable because rainfall is low, erratic and variable. The quality of water from some of these sources is low and occasionally of poor quality. Water quality may be defined by its physical, chemical and biological characteristics. These characteristics influence its suitability for a specific use (Tsado et al., 2014). The sources of the minerals and salts found in water for irrigation are from natural weathering, effluent from city sewage and industrial waste and drainage waters from irrigated fields. Characteristics of water vary with the source of water and also from region to region due to the geological setup, and climate parameters. Shirazi et al. (2011) indicated that environmental characteristics are the most important factors related to irrigation water quality. As a result, irrigation water may be of poor quality due contamination and natural causes. The chemical composition of irrigation water affect plant growth directly and indirectly.

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Poor water quality for irrigation may result in accumulation of salts in the root zone, and loss of soil permeability. The poor quality water decreases crop yields and degrades soil (Anikwe et al., 2002). Irrigation can also degrade the soil quality and cause crop yields to decline to the point of field abandonment when water quality is poor. Developed and developing countries require sustainable agriculture to enable them to feed the ever increasing population. The limitations of sustainable irrigation agriculture are shortages of suitable water supply and irrigable land. Determination of the water quality enables crop producers to better understand the relationship among the soil, crop and water and apply appropriate management practices. Information on the water quality of some groundwater sources of Botswana is lacking and therefore, the objective of this study was to identify groundwater that has a potential to meet the water quality for irrigation.

MATERIALS AND METHODS

The boreholes Rural Training Centre (RTC) S24^{0}34’45.3’’ E025^{0}5400.5”, Notwane Farm (NF) S24^{0}34’51.3’’, E025^{0}58’ 00.3’’, Boladu Farm (BF) S24^{0}35’56.3,’’E026^{0}24’49.3’’Valley View1(VV1) S25^{0}25’53.2’’ E025^{0}38 20.6’’, Valley View2 (VV2) S25^{0}25’ 53.2’’ E025^{0}38’21.8’’ E025^{0} 25’ 21.8’’ and Mohohlo Farm (MF) S25^{0}24’ 53.2’’ E025^{0} 38’ 20.6’’are located in the urban Gaborone district, Kgatleng and Southern village district respectively. The boreholes occur in the hard veld land system and the area has an annual rainfall that varies from 450 to 550 mm. The area is dominated by metamorphic rocks of Achaean age and has good soils that support irrigated and dry land farming. In order to clear water standing in the pipes, the water was allowed to run for twenty minutes before the samples were taken. Four replicates were taken from each borehole and a composite groundwater sample was made for each borehole resulting in a total of six samples. The samples were introduced into clean labelled containers and were immediately transported in a container of ice for analysis of physicochemical properties. The samples were stored at 4°C in order to avoid changes in the original properties. The physicochemical parameters of the samples were determined by the standard operating procedures for chemical and biological analysis of waters and effluents (SOPCBAWE, 1999). The indices that determine water quality for irrigation such as sodium adsorption ratio(SAR), sodium solution percentage(SSP), residual sodium bicarbonate(RSBC), Permeability Index(PI),Magnesium Absorption Ratio(MAR), Kelly's Ratio (KR) and Total hardness(TH) were calculated using the equations below. The units used for the ionic expressions for equations are in mill- equivalents per litter ($meql^{-1}$).

$$SSP = \frac{Na^{+}+K^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \text{ x } 100. \qquad \text{Equ. 1}$$

Definition of sodium solution (SSP) (D.K. Todd, 1980).

$$SAR = \frac{Na^{+}}{\sqrt{Ca^{2+}+Mg^{2+}/2}} \qquad \text{Equ.2}$$

Expression of Sodium Adsorption Ratio (SAR) (L.A. Richards, 1954).

$$RSB = HCO_3^- - Ca^{2+} \qquad \text{Equ.3}$$

Expression of residual sodium Bicarbonate (S.K. Gupta and I. C. Gupta, 1987).

$$PI = \frac{Na^{+}+\sqrt{HCO3-}}{Ca^{2+}+Mg^{2+}+Na^{+}} \text{ x } 100 \qquad \text{Equ.4}$$

Definition of permeability index (PI) (L. D. Doneen, 1962).

$$MAR = \frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} x\ 100 \qquad \text{Equ.5}$$

Calculation of magnesium absorption ratio (MAR) (H. N. Raghunath, 1987).

$$KR = \frac{Na^{2+}}{Ca^{2+}+Mg^{2+}} \qquad \text{Equ.6}$$

Description of Kelley's ratio (KR) (W. P. Kelley, 1963).

$$TH = 2.497\ Ca^{2+} + 4.115\ Mg^{2+} \qquad \text{Equ.7}$$

Calculation of total hardness (TH) (D. K. Todd, 1980).

The properties were evaluated using water quality standards developed by Ayers and Westcot, (1985); South African Water Quality Guidelines for Agricultural Use (SAWQGAU), 1993; Botswana Bureau of Standards (BBS463, 2011).

RESULTS AND DISCUSSION

The physiochemical properties of the samples are shown in Table 1. The International, Regional and National Recommended Guidelines for Irrigation Water Quality are also shown in Table 2. The anion – cation balance of the water samples analysed was low and it ranged from -2.31 to 2.71% (Table 1). A balance of less than 5% indicates that the chemical analysis was good (H. M. Rahman et al., 2012).The balance also indicates that the H^+ concentration was low and significant amounts of organic ions were low or absent. The most important properties of irrigation water are pH, Na^+, Cl^-, HCO^-_3, NO^-_3, total concentration of dissolved salts (TDS)and relative proportions of Na^+ to some cations like Ca^{2+} and Mg^{2+} (Tables 1). The availability of nutrients is highly influenced by soil pH. The desirable pH range for optimal plant growth varies with crops. However the ideal soil pH range for optimal availability is 6.5 to 7.5. Most nutrients are available within this range and the range is compatible with plant root growth. The pH of the water for irrigation may have a significant influence on the soil pH. Soils with a high buffer capacity have the ability to resist changes in pH while soil with a low buffer capacity can change rapidly if the difference between the soil and water pH is significant.

The pH of the groundwater water samples from the study area varied from 7.05 to 7.54 with an average of 7.32. The pH of all the samples was within the recommended limits of 6.5 to 8.4 pH range shown in Table 2 (Ayers and Westcot, 1985;4; SAWQGAU, 1993, BBS463, 2011). The most common salts in irrigation water are table salt (sodium chloride NaCl), gypsum (calcium sulphate $CaSO_4$), epsom salts (magnesium sulphate $MgSO_4$), baking soda (sodium bicarbonate ($NaHCO_3$). The salts dissociate in water and form ions. The most common ions in irrigation water are sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulphate (SO_4^{-2}), bicarbonate (HCO_3^-), potassium (K^+), carbonate (CO_3^{-2}) and nitrates (NO_3^-). Some irrigation waters especially groundwater contain boron in concentrations toxic to some crops. High sodium content induces soil dispersion, clay platelet and aggregate swelling and this results in reduced infiltration, hydraulic conductivity and surface crusting (K. E. Pearson, 2003). The Na^+ content of groundwater samples ranged from 0.55 to 20.71 $meql^{-1}$ with an average of 7.83 $meql^{-1}$ (Table 1).

The sodium values forfour groundwater samples of a total of six (6) samples were within the recommended limits (Table 2) for irrigation (CWQG, 1987; SAQGAU, 1993; BBS463, 2011).The Na^+ content of NF and RTC samples were beyond the recommended limits. However, the water can be used for irrigation provided farmers accept reduced yields, grow salt tolerant crops and apply gypsum to correct nutritional imbalances caused by excess sodium. The Cl content of the six (6) groundwater samples varied from 0.48 to 33.71 $meql^{-1}$ with an average of 7.40 $meql^{-1}$ (Table 1). A high value of Cl^- concentration occurred in NF while the rest of the values were within the recommended limits (Table 2) for irrigation (Ayers and West cot, 1985; SAWQGAU, 1993; BBS463, 2011).The groundwater sample containing 33.71 $meql^{-1}$ of Cl^- can be used by farmers who can increase the leaching fraction, accept a reduced crop yield, produce crops that are chloride tolerant (SAWQGAU, 1993). The concentration of the HCO^-_3 in the irrigation water samples varied from 5.15 to 7.46 $meql^{-1}$ with an average of 6.05 $meql^{-1}$ (Table 1). Table 2 indicates that all of the HCO_3^- values for the groundwater samples were within the recommended limits for irrigation (Ayers and West cot, 1985).

Table 1. Physiochemical properties of groundwater samples used in the study

		dSm^{-1}	mgl^{-1}	Cations ($meql^{-1}$)				Anions ($meql^{-1}$)					%
Location	pH	EC	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	NO_2^-	NO_3^-	SO_4^{2-}	IB
BF	7.35	1.35	8788	2.09	0.56	6.75	5.54	4.43	5.59	1.35	1.09	0.23	1.50
NF	7.19	5.02	3112	20.71	0.06	18.16	14.97	33.71	5.15	0.00	0.00	6.01	0.01
RTC	7.54	1.74	1064	20.71	0.06	18.16	14.97	5.27	7.46	0.00	4.14	0.75	2.71
VV1	7.47	0.78	416	0.72	0.02	3.88	2.44	0.47	6.49	0.00	0.00	0.40	2.27
VV2	7.34	0.61	400	0.55	0.03	4.63	1.55	0.47	5.79	0.00	0.26	0.09	- 0.95
MF	7.05	0.72	444	2.20	0.02	2.36	2.65	0.73	5.80	0.00	0.27	0.42	-2.31
Average	7.32	1.70	2371	7.83	0.13	8.99	7.02	7.51	6.05	0.23	0.96	1.81	
Max	7.54	5.02	8788	20.71	0.56	18.16	14.97	33.71	7.46	1.35	4.14	6.01	
Min	7.05	0.61	400	0.55	0.02	2.36	1.55	0.47	5.15	0.00	0.00	0.09	

Table 2. International, regional and national recommended guidelines for irrigation water quality

Parameters	*Ayres and Westcot 1985	[o]DWAR 1993	[a]BBS463 2011	Average Values in the Study area
Temperature(^oC)	7.49			
pH	6.5 – 8.5		6.5 – 8.4	7.52
EC(DSm^{-1})	0.7 – 3.0		3	1.70
TDS(mgl^{-1}	450 - 2000	500 - 2000	2000	2370.67
HCO_3-($meql^{-1}$)	1.5 – 8.5		1.5	7.62
Cl^-($meql^{-1}$)	4 - 10	0 - 10	9.86	7.4
NO_3^-($meql^{-1}$)	0.16 0 0.79	0.16 – 0.97	0.96	
Na^+($meql^{-1}$)		0 – 3.04	10	

*International, [o]Regional, [a]National, DWR= Department of Water affairs and forestry, BBS= Botswana Bureau of Standards

Table 3. Irrigation indicative properties used for water quality assessment

	Parameters						
Locations	SAR	SSP	RSBC($meql^{-1}$)	PI	TH(mgl^{-1})	MAR	KR
BF	0.68	17.3	-1.16	32.10	610.64	45.08	0.17
NF	4.10	39.0	-4.01	42.68	1646.13	45.19	0.62
RTC	4.10	39.0	-10.70	42.68	1646.13	45.19	0.62
VV1	0.40	10.5	2.61	46.45	314.25	38.61	0.11
VV2	0.31	8.4	1.61	43.98	307.76	25.08	0.09
MF	1.40	28.2	3.44	64.03	248.71	52.89	0.45
Average	2.06	25.0	-1.37	45.32	795.60	42.01	0.34
Max	4.10	39.00	3.44	64.03	1646.13	52.89	0.62
Min	0.31	8.40	-10.70	32.10	248.71	25.08	0.09

Table 4. Classification of water quality for irrigation

Category	EC_w	SAR	RSC	SSP	Suitability for Irrigation
i	<700	<10	<1.25	<20	Excellent
ii	700 – 3000	10 - 18	1.25- 2.5	20 – 40	Good
iii	>3000	18 – 26	>2.5	40 - 80	Fair
iV		<2.6		<80	Poor

Eaton (1950); Wicox (1955); Todd (1980); Westcot (1985)

The NO_3^- values for the irrigation water varied from 0.00(undetected) to 4.14 meq l^{-1} with an average of 0.96 $meql^{-1}$ (Table 1). According to Ayers and West cot (1985), the NO_3^- values for samples NF, VV1, VV2 and Mohohlo were within the recommended limits for irrigation (Table 2) and NO_3^- values for Boladu and RTC were above the limits recommended for irrigation. The presence of NO_3^- in irrigation water is beneficial because it is an essential element. However, high concentration of NO_3^- results in excessive vegetative growth, lodging, delayed crop maturity and poor quality. Salinity is the amount of salts dissolved in water. Irrigating with saline water results in soil salinity. Saline water is characterized by two common water quality assessments namely total dissolved solids (TDS) and specific conductance or electric conductivity (EC_w).

EC_w determines salinity hazard, one of the most influential water quality guideline for irrigation. The EC_w of groundwater samples varied from 0.61 to 5.02 dSm^{-1} with an average of 1.70 dSm^{-1} (Table 1). Table 2 indicates that five out of a total of six samples fell within the recommended range for irrigation (Ayers and West cot, 1985; BBS463, 2011). EC_w value for RTC was above the recommended limits and its use for irrigation may result in a salinity hazard. Salinization induces hydrological drought and reduces crop yields especially after the salinity threshold has been exceeded (SAWQGAU, 1993). In order to minimize salt damage, soils irrigated with the RTC groundwater will require the use of salt tolerant crops, good management that includes improved irrigation systems and proper irrigation schedule (Tsado et al., 2014).

Table 3 and 4 show indicative properties used for assessing water quality for irrigation and classification of water quality for irrigation respectively. The proportions of sodium ions to other ions in irrigation water and soils is determined by equations 1 to 7 above. The soluble sodium percentage (SSP) was calculated using equation 1 (Todd, 1980). It is used to characterize water for irrigation purposes. A high and low value of SSP indicates soft and hard water respectively (Wilcox, 1955). It also indicates sodium hazard but not as a good indicator like sodium adsorption ratio (SAR). High SSP in irrigation water may retard plant growth and reduce the permeability of the soil (Joshi et al., 2009). The SSP values of the groundwater samples ranged from 8.4 to 39% with an averages of 23.8% (Table 3). Groundwater samples for Boladu, VV1 and VV2 were less than 10% and were classified as excellent. SSP values for Mohohlo fell between 20 – 40% and were classified as good. Values for NF and RTC were classified as fair (Table 4). SAR determines the sodicity or alkali hazard of irrigation water to crops. The hazard is caused by that fraction of Na^+ adsorbed to the exchange complex (Islam and Shamsad, 2009). The sodicity hazard caused by irrigation water is determined by the absolute and relative proportions of sodium to calcium and magnesium (Richards, 1954). When sodium replaces calcium and magnesium from the exchange complex, the soil structure is destroyed and it becomes compact and impervious (Raju, 2006). The presence of calcium and magnesium in significant amounts counters the effects of sodium. The SAR values of analysed groundwater samples varied from 0.31 to 4.10 with an average of 1.83. All the groundwater samples SAR values were less than 10 and Table 4 indicates that water is classified as excellent. The SAR values indicated that the waters are safe for irrigation and their use cannot damage the soil structure.

The residual sodium carbonate (RSBC) determines the hazardous effects of CO_3^{2-} and HCO_3^- on the quality of water for irrigation (Vasudevan and Varghese, 2013). The amounts of Na_2CO_3 and $NaHCO_3$ forms residual alkalinity (RA). RA occurs in the soil when the CO_3^{2-} and HCO_3^- concentration is higher than the concentration of Ca^{2+} and Mg^{2+}. The values of RSBC for the samples varied from -10.70 – 3.44 $megl^{-1}$ with an average of -1.37 $meql^{-1}$(Table 3). When the RSBC values are positive, the contents of Ca^{2+} and Mg^{2+} dissolved is less than that of CO_3^{-2} and HCO_3^- (F. Raihan and J.B. Alam, 2008). The RSBC values for Boladu, ART and NF were less than 1.25 (Table 3), and they fell under category I and classified as excellent (Table 4). VV2 fell under category II and it was classified as good. The RSBC value for VV1 and Mohohlo were more than 2.5 $meql^{-1}$ and fell under category III and classified as fair for irrigation purposes. Magnesium absorption Ratio (MAR) is an expression of the magnesium hazard. Magnesium is considered the most important factor for determination of water quality for irrigation (Yinusa et al., 2013). Under normal circumstances, magnesium and calcium are in an equilibrium state in most waters. However, when magnesium content is significantly higher than calcium, crop yields are reduced and the soil becomes saline. The MAR values of the groundwater samples under study are shown in table 3. The values ranged from 25.08 to 52.89% with an average of 42.01%. Five samples out of a total of six (6) samples have MAR values within the 50% acceptable limit for irrigation (Ayers and West cot, 1985). The MAR value for Mohohlo is more than 50% and therefore the water is unsuitable for irrigation uses. Kelley's Ration (KR) is a measure of levels of Na against Ca and Mg. It was introduced by W. P.Kelly (1963) and it is used to evaluate water quality for irrigation. Irrigation water with KR <1 are considered suitable for irrigation. The KR values for the groundwater samples varied from 0.09 to 0.62 with an average of 0.34 (Table 3). The KR values of all the water samples were less than 1 indicating that the water is suitability for irrigation purposes. Total hardness (TH) indicates the content of $Ca^{2+}$and Mg^{2+} in irrigation water and it does not affect the safety of water. The TH values for the ground water samples ranged from 248.71 to 1646.13 mgl^- with an average of 795.60 mgl^{-1}. Out of a total of six groundwater samples, Mohohlo groundwater sample fell within the 150 – 300 mgl^{-1} range and was classified as hard (C.N., Sawyer and P.L. McCarty, 1967) and five samples were above 300 mgl^{-1} and classified as very hard. High level of these elements is tolerated by plants (Ourimbar, 2011) and the issue of toxicity is absent. However, deposits of $CaCO_3$ and $MgCO_3$ may be found on leaves and fruits if the sprinkler irrigation system is used. Permeability Index (PI) is influenced by a long term use of irrigation water (Yinusa et al., 2013). It is affected by sodium, magnesium, calcium and bicarbonates contents of the soil. The PI values of the groundwater samples ranged from 32.10 to 64.03% with an average of 42.35%. All the PI groundwater sample values fell within the recommended limits for irrigation (Doneen, 1964). As a result, all groundwater samples were classified as suitable for irrigation.

Conclusion

The pH values of the groundwater samples were within the recommended limits for irrigation. This shows that most of the plant nutrients will be available for absorption. The analysed chemical constituents were generally low in most of the samples and they were within the recommended limits for irrigation. However, Na^+ was beyond the limits in two samples, Cl^- in one sample and NO_3^- in two samples. All the groundwater quality indices were within the limits for irrigation except MAR where only one sample was beyond the limits.

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