Agricultural Drainage Water Assessment for Possible Reuse: A Case Study from Pandamatenga Commercial Arable Farms in Botswana.

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Abstract

This study set out to assess the quality of water in the drainage channel located in the northern plain of the Pandamatenga Commercial Arable farms in Botswana for possible agricultural reuse. This was achieved by analysing the physical, microbiological and chemical parameters of sampled Agricultural Drainage Water along the drainage channel. The results obtained from the Agricultural Drainage Water quality analysis were used in an Irrigation Water Quality Index model to assess the possibility of reusing the water. The Irrigation Water Quality Index results from the study revealed that the values computed from the five parameters of Sodium Adsorption Ratio, Electrical Conductivity, Sodium, Chloride and Hydrogen carbonate, ninety five percent of the samples fell within the "severe restriction" category, five percent of the samples fell under the "moderate restriction" and no samples belonged to the "no restriction" category. The low levels of Electrical Conductivity and Sodium Adsorption Ratio detected in the water samples during the study period indicated a mineral imbalance, hence making the Agricultural Drainage Water unsuitable for direct reuse. Therefore, using this Agricultural Drainage Water will require mixing it in proper ratios with groundwater to improve its quality for reusability during irrigation. If the Drainage Water is reused, this will have potential to increase the water for irrigation in semi-arid Botswana.

Keywords: Pandamatenga, Reuse, Agricultural Drainage Water, Irrigation Water Quality Index, Botswana.

Introduction

Botswana is a semi-arid country which experiences year-on-year droughts with low rainfall and a lack of water resources, however, the country is also facing increasing pressure on freshwater supplies due to rapid urbanization and climate change, requiring various measures to remediate the situation (UNDP, 2012). Botswana has reached its full potential in terms of surface water development, that is, the construction of dams, owing to the flat topography of the country (UNDP, 2012). All of Botswana's perennial rivers are shared with neighbouring countries, and these rivers are Okavango, Zambezi, Orange-Senqu and Shashe-Limpopo (Botswana National Water Policy, 2012). With an economy in transition, Botswana needs water for economic growth in the areas of households, energy, agriculture, tourism, manufacturing and mining, therefore making wastewater reuse an alternative (Botswana National Water Policy, 2012).

With the country having dry spells for the biggest part of the year, most commercial farmers in Botswana rely on irrigation for growing their crops (UNDP, 2012). Fields get wet when it rains or when irrigated, forcing water to penetrate the soil and be stored in its pores. Sustained rain or irrigation can cause puddles on the ground (Brouwer et al., 1985). The prolonged presence of excess water in the plant root zone causes stunted growth in some crops and therefore calls for remedial measures of reclaiming the soil such as removing the excess water through pipes, conduits, canals or any other preferred means. The removal of this excess water either from the surface or from the root zone is referred to as drainage. Drained water in most cases is discharged as runoff to open grounds, channels or water bodies. The dire need of conserving depleting water resources has seen drainage water being reused for irrigation in many parts of the world (Pereira et al., 2014).

Pandamatenga plains are known to be flat with heavy textured vertisol soils and a relatively higher average rainfall of 600 mm per annum, more than any other part of the country, thus, convincing the Government of Botswana (GoB) to allocate the area to farmers, to boost cereal production (Patrick et al., 2008). To prevent surface water ponding and control runoff without causing erosion brought about by the heavy rains and irrigation practices, surface drainage was developed on the Pandamatenga farms after conducting a series of feasibility studies (Patrick et al., 2008). Excess water collected from the soil surface flows as Agricultural Drainage Water (ADW) over the naturally sloping ground toward shallow drainage channels along the roads before being conveyed into the nearby open waterways and open lands. The Pandamatenga farms have got interconnected sub-drainages that discharge into 10 main channels. The drainage channels in the Central and Southern plains of the farms discharge runoff into open lands located in the West and South of the farms respectively; these channels are exposed to high evaporation and low recharge which leads to low channel water residence time. The main drainage channel in the northern plain discharges into the open waterways of one of the tributaries of the Matetsi river which flows into Zimbabwe. The tributary is believed to add to the volume of water flowing within the channel, hence making the channel able to hold water for a much longer period throughout the year.

The availability of ADW within the drainage channel for a long period creates a potential water source for agricultural reuse. However, to reuse ADW, it is necessary to evaluate its quality. Also, the expected water quality may differ depending on the type of irrigation. Therefore, a thorough strategy is needed to do a spatial-temporal assessment of the water quality in drainage channels for potentially water-stressed countries (Bouwer & Idelovitch, 1987). This provides insight into the types of crops that can be irrigated and the long-term environmental impacts that could adversely affect agricultural productivity. According to the Food and Agriculture Organization (FAO), there are several different water quality guidelines related to irrigated agriculture (Ayers & Westcot, 1985). Each of these guidelines has been useful, though none has been entirely satisfactory because of the wide variability in environmental conditions. To assess the suitability of ADW reuse, the Irrigation Water Quality Index (IWQI) model developed by Meireles et al., (2010) in Brazil, was used in this study. This model was developed from a study carried out in the northern portion of the State of Ceará, North-eastern Brazil, which shares similar semiarid climatic conditions as Botswana. The parameters mainly required by the model to determine the IWQI are electrical conductivity (EC), Sodium Absorption Ratio (SAR), sodium (Na^+), chloride (Cl^-), and bicarbonate (HCO_3^-).

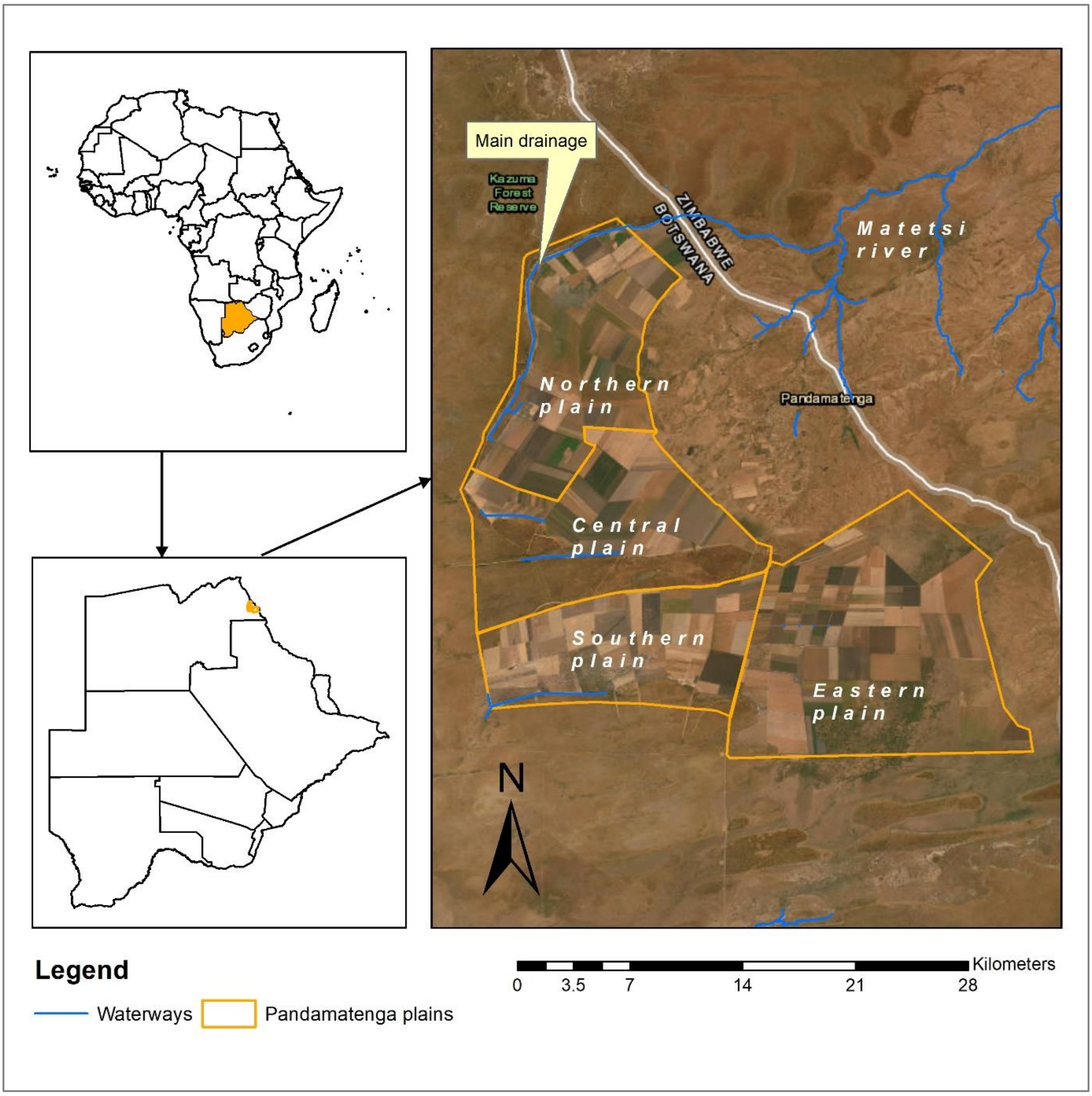
According to Botswana's National Master Plan for Wastewater and Sanitation of 2003 there is a goal to boost the reuse of wastewater through agricultural reuse and decreasing losses in the treatment systems from 96% to 20% of the outflow by the year 2030. This study, therefore, was set out to assess the quality of water in the drainage channel located in the northern plain of the Pandamatenga farms for possible reuse.

Material And Methods

Study Area

Pandamatenga is a village in the Chobe District, Botswana covering an area of approximately 280 380 ha. The Pandamatenga farms (Figure 1) cover over 25 074 ha of this total land area (Tapela et al., 2007). The area is located in the North-west region of the country bordering Zimbabwe to the East within geographical coordinates of latitude 18˚26′ to 18˚43′ and longitude 25˚27′ to 25˚37′. The study was conducted on the longest drainage channel (approximately 23 km) within the northern plain of the farms, which also drains into the Matetsi river (Figure 1). The farms comprise four lacustrine plains; the Northern, Central, Southern and newly established Eastern plains which have now been fully developed for agricultural production. These four plains have been demarcated into approximately 112 farms of an average size of 100 – 1 000 ha.

Figure 1: Pandamatenga Arable Farms Showing the Different Plains Including the Study Area.



The Pandamatenga region experiences a semiarid climate with hot, humid summers and dry, moderate winters. Rainfall in the area is highly variable, especially over short distances and it comes from conventional processes boosted by the Intertropical Convergent Zone (ITCZ) tail end that extends into the northern part of Botswana over summer. Practically all rain falls between October and April, with December, January, and February being the wettest months (Kapweke et al., 2021). Due to the significant amount of rain that falls during brief, intense storms, some farms experience considerable runoff and are immediately swamped. Data collected by Botswana Meteorological Services within the period of July 2021 to July 2022 from 8 weather stations located within Pandamatenga shows that the area received an average rainfall of 458 mm. Significant rainfall was received between November and March with January registering a peak amount of 250 mm.

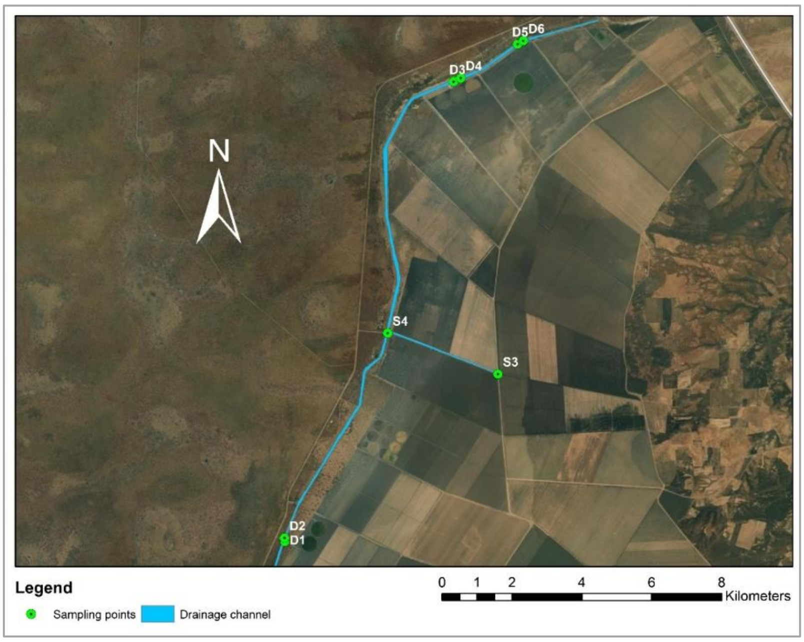
The rich "black cotton" vertisol soils, make Pandamatenga farms suited for rainfed arable cultivation or dryland farming. Sorghum, millet, wheat, maize, and a variety of beans are the principal crops farmed on the fields. Crops are planted between early November and late January. Sunflower is planted later in February since they can endure cold winter temperatures (Patrick et al., 2008). The area is generally flat, with a gentle slope and elevation ranging between 995 – 1 124 m above sea level.

The temperature of the Pandamatenga area is more amenable to farming as it has less extreme heat than the rest of the country as well, with mean maximum temperatures of 34°C in summer to 26°C in winter (Abdullahi & Bullen, 2008). From October to March, maximum temperatures in the range of 26 to 34^{o}C are common. The coldest months, from May to August, average minimum temperatures of 8 to 18^{o}C (Jain et al., 2006).

Study Design

The study covered one weather season of dry conditions since that is when irrigation is normally done to meet the crop water requirements. The water samples from the drainage channel were collected once every month in April, May, July, and August of 2022. During the study, both onsite and laboratory tests were conducted on water samples collected from selected sampling sites along the drainage channels situated at the north-down end of the farms (Figure 2). Two sampling points (S3 & S4) were chosen in the sub-drainage to represent the quality of runoff as it flows through the sub-drainage and is conveyed into the main drainage channel. Six sampling points were selected within the main drainage channel, the furthest upstream sampling points (D1 & D2) were used to assess the quality of water as it enters the canal, and the midstream sampling points (D3 & D4) were used to assess any changes in water quality from the time it entered the canal to those particular points, and the furthest downstream sampling points (D5 & D6) were used to assess the quality of water as it left the farm area to join the open waters of Matetsi river. Locations (longitude, latitude, and altitude) of the sampling points were recorded using a global positioning system (GPS). The acquired onsite and laboratory measurements for the selected sample points were used to generate spatial maps and an appropriate irrigation water quality index was used to transform the concentrations of water quality variables into a quality score.

Figure 2: Sampling Points Along the Sub-Drainage and Main Drainage



Sample Collection and Analysis

At the time of data collection, all the sub-drainages within the study area did not have water in them apart from one which is represented by S3 and S4 in Figure 2. During the entire sampling period, point S3 was sampled only twice in April and May, whereas point S4 was sampled only once in April before both points dried up. Similarly, points D1 and D2 of the main drainage did not hold water for the entire sampling season (i.e., both points were sampled once in April), whereas points D3, D4, D5 and D6 held water for the entire sampling period. This depicted a trend in the drying up of the drainage channel starting from points of high altitude to those with a low altitude (i.e., from west to east). The collected samples were placed in plastic sample bottles prewashed using distilled water and rinsed three times with the same water. For chemical, microbiological and ionic constituents, a purposive sampling technique was used to assess how the water quality varies upstream, midstream and downstream of the drainage channel. A total of 21 samples, each measuring one litre in volume were collected from the different sampling points along the channels. The samples were then transported under controlled temperature in a cooler box to minimise microbial-mediated transformation processes on the way to the laboratory. The analyses were carried out within the recommended sample holding times which vary from 1 – 28 days from the date of sample collection. The analyses of the water parameters were carried out based on WUC/CTM/004, WUC/CTM/005 and WUC/CTM/002 standards respectively using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). These standards were approved for use by the Southern African Development Community Accreditation Service (SADCAS). The standard solution for each tested element was prepared according to its concentration and used to calibrate the system before analysing each water sample. The results were recorded automatically on a computer connected to the ICP-OES system. In situ observations were recorded using an XS PC–5 Multi-meter Tester kit for the analysis of temperature, pH, electrical conductivity, salinity and TDS to assess the nature of the degree of contamination. The test kit was calibrated using standard buffer solutions before it was used in the field.

The water samples collected from both drainage channels were analysed independently to identify which one has got the highest level of contaminants in relation to the permissible standards. The mean values of the sub-drainage samples were calculated and compared with the samples at the downstream, midstream and upstream ends of the main drainage channel. This was used to identify the correlation between the ADW from the sub-drainage to that of the main drainage within the study area.

Irrigation Water Quality Index – IWQI

To assess the quality of drainage water for potential reuse, the Brazilian (IWQI) model formulated by Meireles et al., (2010) was employed in this study. The IWQI is a function of five water quality indicators i.e., electrical conductivity (EC), sodium adsorption ratio (SAR), sodium concentration (Na^+), chloride concentration (Cl^-), and bicarbonate concentration (HCO_3^-) (Abbasnia et al., 2018). As presented in Tables 1 & 2, the weight of water quality parameters including the water quality measurement parameter value (*qsi*), and the aggregation weights (w_i) were determined depending on each parameter value and finally considered in the criteria which were proposed byAyers & Westcot, (1985). In this model, the lower value represents the poor quality of water and vice versa. The value of (*qsi*) was calculated based on the following equation (1):

$$qsi = qsi_{max} - \left[\frac{(V_{ij} - V_{inf}) \times qsi_{ampl}}{V_{ampl}}\right] \quad (1)$$

Where; qsi_{max}, is the maximum value of (qsi) for the category in which the parameter is located; V_{ij}, is the measured value for the parameter; V_{inf}, is the value that represents the lower limit of the category to which the parameter is located; qsi_{ampl}, is category ampleness between the maximum and minimum qsi values; V_{ampl}, is category ampleness in which the parameter is located. It should be noted that the highest measured value is taken into consideration as the highest limit when finding (V_{ampl}) for the last category of each parameter.

Table 1: The Weights of IWQI Parameters (Meireles et al., 2010)

Parameters	w_i
EC	0.211
Na^{+}	0.204
HCO_3^{-}	0.202
Cl^{-}	0.194
SAR	0.189
Total	**1.000**

Table 2: Irrigation Water Quality Parameters and Their Proposed Limiting Values

qsi	**EC (µS/cm)**	**SAR $(meq/L)^{0.5}$**	**Na (meq/L)**	**Cl (meq/L)**	**HCO_3 (meq/L)**
85 – 100	200 – 750	3	2 – 3	<4	1 – 1.5
60 – 85	750 – 1500	3 – 6	3 – 6	4 – 7	1.5 – 4.5
35 – 60	1500 – 3000	6 – 12	6 – 9	7 – 10	4.5 – 8.5
0 – 35	<200 or >3000	12	<2 or >9	>10	<1 or >8.5

Each measurable factor listed above is given a weight based on how important it is in relation to other factors and how it affects the overall quality of irrigation water. The individual IWQI can then be calculated by applying the equation (2) below using the multiplying factors shown in Table 1 above:

$$IWQI = \sum_{i=1}^{n} (qsi \text{ x } wi) \quad (2)$$

Where; (IWQI) is a dimensionless number ranging from 0 to 100 divided into five categories as shown in Table (3). Each category of IWQI indicates the restrictions in the irrigation water use which are; the salinity problems risk, the soil water infiltration problems, and the plant's toxicity.

Table 3. Classifications of The Different Categories of IWQI (Meireles et al., 2010)

IWQI	Category; the restriction of water use	Advice	
		Soil	**Plant**
85 – 100	No restriction (NR)	It can be used when the soil is less likely to be affected by salinity and sodicity.	There is no risk of toxicity for most plants
70 – 85	Low restriction (LR)	It can be used for irrigated soils of fine texture or moderate permeability, being advised of the leaching of the salts. Salinisation of thicker textured soils may occur and it is recommended to avoid use in soils with high clay levels.	Avoid use in plants with salt sensitivity
55 – 70	Moderate restriction (MR)	It can be used on soils with high or medium permeability, which helps to wash out salts easily from the soil.	Plants with moderate salt tolerance still grow
40 – 55	High restriction (HR)	It can be used in un-compact soils (high permeability). A multi-irrigation program can be adopted, when the electrical conductivity is above 2000 µS/cm and SAR is above 7.	This water should be used for irrigation of plants with a high to medium tolerance of salts, with special management and practices to reduce the salinity effect, the water with low concentrations of HCO_3, Cl and Na is excluded.
0 – 40	Severe restriction (SR)	You should avoid using this water for irrigation under normal conditions. It can be used in special and specific cases. It is imperative to wash the soil frequently to prevent increasing its saltwater content and also to avoid the accumulation of salts.	This water is used for irrigation of plants with high tolerance to salinity only, and the water with low levels of Na, Cl and HCO_3 is excepted.

Statistical Analyses

The analysed results were subjected to descriptive statistics to calculate basic summary statistics (i.e., mean, standard deviation, coefficient of variation, max value, quantiles and minimum values) for the water quality parameters, irrespective of sampling points and sampling period. Due to the non-parametric nature of the raw and computed water quality data collected, a Mann-Kendall trend test and Wilcoxon Signed Rank Test were used to determine if there is an 'increasing', 'likely increasing', 'decreasing', 'likely decreasing', 'stable', 'no trend' or ‘significant relationship’ for each parameter at every sampling location. A correlation matrix between all tested water quality parameters and sampling stations was done and the results were plotted into a single correlation matrix plot. All analyses were performed using AquaChem (version 10.0), a software package developed specifically for managing, analysing, and plotting water quality data together with R (version 4.1.3) used for statistical computing and graphics.

Spatial Analysis

The spatial analyses for the study were done using ArcMap (version 10.7) for selected parameters (i.e., EC, Na^+, HCO_3^-, Cl^-, and SAR). For the analyses, all the sampling points within the research area were considered using the inverse distance weighted (IDW) interpolation technique. This method assumes that the sampling points closer to the unsampled points are more similar than those further away in their values, and it uses a linear combination of values at sampled points weighted by an inverse function of the distance from the point of interest to the sampled points to estimate the values of an attribute at unsampled points. Using nearby data points that are located within a user-specified search radius, the IDW approach determines a value for each grid node (Burrough & McDonnell, 1998).

Results and Discussion

Agricultural Drainage Water Quality Assessment for Irrigation

Since this study aimed at assessing the possible reusability of ADW for irrigation on the Pandamatenga farms, it was critical to determine the quality of the water for the specific purpose of irrigation and how this water would affect the soil and crops. Besides affecting crop yield and soil physical conditions, assessing irrigation water quality can help in determining fertility needs, irrigation system performance and longevity, and how the water can be applied. This study primarily focused on using the Irrigation Water Quality Index (IWQI) developed by Meireles et al., (2010) to determine the quality and suitability of ADW as irrigation water. Other water quality indices which influence water quality and its suitability for irrigation include Sodium Absorption Ratio (SAR), Soluble Sodium Percentage (SSP), Permeability Index (PI), and Soluble Magnesium Percentage (%Mg).

Calculated Irrigation Water Quality Index

The Irrigation Water Quality Index (IWQI) was calculated according to Equation 2. The water suitability for irrigation was based on the five physicochemical parameters of EC, SAR, Na^+, Cl^-, and HCO_3^-. The concentration units of the selected parameters were converted from (mg/L) to (meq/L) before starting data analysis, according to the conversion factors given by Lesch & Suarez (2009).

The computed IWQI values during the four months ranged from 22.7 to 57.1, with a mean value of 28.6 (Table 4). Accordingly, 95% of the samples that were analyzed fell within the "severe restriction" category, which restricts the usage of the ADW to irrigating only plants with a high tolerance to salt, while foregoing irrigation under normal circumstances. However, there is an exception for waters with extremely low values of Na^+, Cl^- and HCO_3^-, just like the ADW considered in this study. Only 5% of the samples under investigation fell under the "moderate restriction" category that limits the use of ADW for moderate salt-tolerance plants and calls for moderate to high permeable soil, considering moderate soil leaching processes. No samples were identified to fall within the "no restriction" category.

Table 4: Calculated Irrigation Water Quality Index (IWQI)

Site_no	Sampling date	SAR_{adj}	Na^+	Cl^-	EC	HCO_3^-	IWQI	Type of restriction
Site D1	21/04/2022	0.468	29.829	34.152	21.225	26.360	27.9	Severe restriction

Site D2	21/04/2022	0.176	32.419	34.322	20.996	25.120	28.9	Severe restriction
Site D3	21/04/2022	0.353	31.182	34.341	24.014	24.264	28.6	Severe restriction
Site D4	21/04/2022	0.346	31.735	34.484	24.929	26.360	29.4	Severe restriction
Site D5	21/04/2022	0.173	32.789	34.096	22.265	26.360	29.4	Severe restriction
Site D6	21/04/2022	0.425	30.290	34.218	22.422	25.419	28.1	Severe restriction
Site S3	21/04/2022	0.321	31.432	33.634	23.956	24.264	28.6	Severe restriction
Site S4	21/04/2022	0.292	31.068	33.634	20.588	24.264	27.9	Severe restriction
Site D3	23/05/2022	0.474	30.188	34.784	23.140	28.468	28.7	Severe restriction
Site D4	23/05/2022	0.460	30.159	34.862	23.498	28.468	57.1	Moderate restriction
Site D5	23/05/2022	0.511	27.959	34.058	19.434	24.264	26.6	Severe restriction
Site D6	23/05/2022	0.504	27.886	34.105	19.358	24.264	26.6	Severe restriction
Site S3	23/05/2022	0.432	27.818	32.252	16.949	23.991	25.8	Severe restriction
Site D3	13/07/2022	0.310	30.972	34.668	20.772	26.360	28.5	Severe restriction
Site D4	13/07/2022	0.408	30.064	34.629	19.199	25.120	27.5	Severe restriction
Site D5	13/07/2022	0.555	24.690	34.002	11.254	17.575	22.7	Severe restriction
Site D6	13/07/2022	0.554	25.087	33.928	11.094	22.612	23.8	Severe restriction
Site D3	31/08/2022	0.740	24.491	34.446	20.784	23.084	25.6	Severe restriction
Site D4	31/08/2022	0.363	31.242	34.745	20.710	25.120	28.2	Severe restriction
Site D5	31/08/2022	0.332	30.013	33.937	15.086	26.198	26.9	Severe restriction
Site D6	31/08/2022	0.600	24.005	33.753	15.021	21.228	24.0	Severe restriction

The low levels of EC and SAR detected during the study period showed that there was a mineral imbalance, thus making the ADW unsuitable for reuse. This is according to studies developed by Pearson et al., (2006), Nys et al., (2002), and Rhoades et al., (1992) that considered the concentration of salts in irrigation water, showing the importance of the balance of salts and excessive leaching of the stability of soil aggregates that might cause problems of reduced infiltration, reduced hydraulic conductivity and/or presence of surface crust.

Adjusted Sodium Adsorption Ratio (SAR_{adj})

Adjusted SAR was computed using equation 3 depending on the ion concentrations of sodium, calcium, and magnesium (all ionic concentrations are represented in milli-equivalent per litre).

$$SAR_{adj} = \frac{Na^{+}}{\sqrt{\frac{(Ca_{eq}{}^{2+} + Mg_{eq}{}^{2+})}{2}}} \quad (3)$$

The SAR_{adj} values as shown in Table 4 were in the range of 0.17 to 0.74 with a mean value of 0.42. All of the ADW samples fall under the excellent category of the classification system developed by Richards, (1954) based on values in Table 5. The life of vegetation is typically not threatened by SAR levels below 3.0 but is seriously threatened by SAR levels above 12.0, which reduce soil permeability and cause an increase in soil swelling or dispersion. SAR can indicate the degree to which irrigation water tends to enter cation exchange reactions in the soil. The replacement of calcium and magnesium with sodium is hazardous because it causes damage to the soil structure by making the soil compact and impervious (Rosu et al., 2014).

Table 5: Water Classification Based on SAR Values (Richards, 1954)

Sodium Adsorption Ratio (SAR)	Classification
< 10	Excellent
10 – 18	Good
18 – 26	Doubtful
> 26	Unsuitable

Soluble Sodium Percentage (SSP)

The SSP is an important parameter that can be used to evaluate the ADW quality and its appropriateness for irrigation purposes. The SSP was calculated, based on sodium, calcium and magnesium concentrations in the collected samples, using equation 7 where all ionic concentrations are expressed in milliequivalents per litre. The SSP ranged between 8.23 and 24.93 (Table 5). Based on the Wilcox, (1955) classification of irrigation water as shown in Table 5, 48% of the tested samples belonged to the excellent category whereas 52% belonged to the good category. The low level of sodium implies that the ADW does not pose threat to vegetation as well as the soil and can be cautiously used for agricultural purposes as irrigation water.

Permeability Index (PI)

A permeability index-based criterion was developed by WHO, (1989) to determine whether water is suitable for irrigation. Accordingly, the PI is classified under Class I (>75 %), Class II (25–75 %), and Class III (>25 %) orders. The PI in this study ranged between 21.98% and 90.07% with an average of 53.97%. Based on the results shown in Table 10, 19% of the tested samples fell under Class I and 81% of the samples were categorised under Class II. Class I and Class II waters are categorized as good for irrigation with 75% or more of maximum permeability.

Soluble Magnesium Percentage (%Mg)

A magnesium percentage of irrigation water of more than 50% is considered to be harmful and unsuitable for irrigation use. This would adversely affect the crop yield, as soils become more alkaline. The magnesium ratio values of the study area ranged from 10.96 to 43.27. All the ADW samples tested (Table 6) have a magnesium percentage below 50 which implies that the ADW can be cautiously used for irrigation.

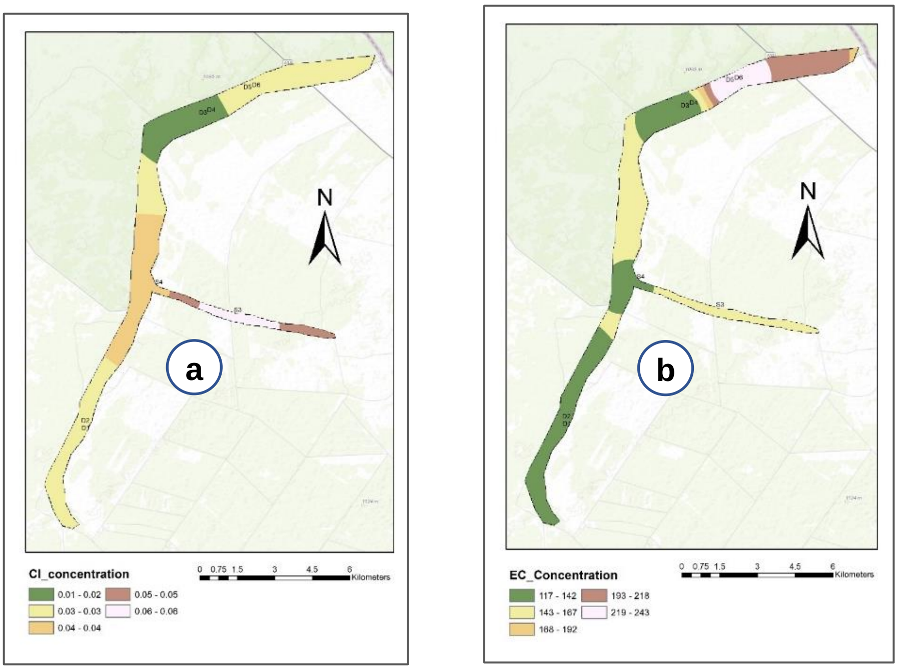
Table 6: Other Calculated Indices Including SSP, PI and Mg%

Site no.	Calcium (meq/L)	Magnesium (meq/L)	Sodium (meq/L)	Chloride (meq/L)	HCO_3 (meq/L)	SSP	PI	Mg%
D1	0.83	0.32	0.35	0.02	0.33	23.05	61.11	28.00
D2	1.40	0.38	0.16	0.02	0.39	8.23	40.66	21.28
D3	0.57	0.24	0.24	0.02	0.44	23.23	86.35	29.69
D4	0.46	0.20	0.21	0.01	0.33	23.81	90.07	30.49
D5	1.05	0.31	0.13	0.03	0.33	9.01	47.27	22.66
D6	0.74	0.29	0.31	0.02	0.38	23.21	69.03	27.74
S3	0.51	0.33	0.23	0.04	0.44	21.30	83.70	39.33
S4	1.00	0.43	0.25	0.04	0.44	15.00	54.43	30.06
D3	0.82	0.30	0.32	0.01	0.23	22.16	55.44	27.17
D4	0.94	0.31	0.32	0.00	0.23	20.44	50.93	24.69
D5	1.40	0.57	0.50	0.03	0.44	20.34	47.20	29.11
D6	1.50	0.60	0.51	0.03	0.44	19.48	44.89	28.64
S3	1.85	1.13	0.52	0.09	0.46	14.75	34.11	37.92
D3	1.21	0.40	0.26	0.01	0.33	13.91	44.53	25.10
D4	0.77	0.46	0.33	0.01	0.39	21.05	61.25	37.61
D5	1.95	1.49	0.84	0.03	0.99	19.51	42.77	43.27
D6	2.73	1.49	0.79	0.03	0.55	15.79	30.57	35.29
D3	1.58	1.01	0.86	0.02	0.52	24.93	45.80	38.90
D4	0.62	0.17	0.24	0.01	0.39	23.35	84.23	21.26
D5	2.49	0.31	0.33	0.03	0.34	10.63	29.18	10.96
D6	3.90	0.95	0.92	0.04	0.65	15.89	29.85	19.62

Spatial Distribution of IWQI

The computed IWQI values were further subjected to IDW interpolation to generate spatial maps that show the distribution trend of the selected parameters within the drainage channel. The mean of the data collected for each of the five parameters (i.e., EC, SAR, Na^+, Cl^-, HCO_3^-) from the sampled points was used in the calculation of each interpolated cell while the drainage channel was used for the mask. From the spatial maps (Figure 4) it can be deduced that the concentrations of the tested parameters steadily increased from the southern to the northern direction. This trend follows the direction of water flow and the fact that the water in the drainage channel was drying up from the south to the north. It can also be deduced that as the water flows within the drainage channel, it carries along with it all sorts of contaminants it picks up on its way and this leads to a build-up in concentrations of the various parameters downstream of the channel. Figure 4 further indicates that the ADW from the biggest part of the study area falls under the "severe restriction" category and therefore its use for irrigation should be avoided under normal conditions. The same figure shows that a small section within the study area has got ADW which falls under the high restriction category, suitable to be used on plants with moderate to high tolerance to salts with special salinity control practices. It is noteworthy that after the rainy season, steady water flow within the drainage channel ceases and this leads to the formation of water pools within the channel. The pool that holds ADW for the longest time is located at the sampling points D3 and D4. This explains why the ADW at this location is not as bad as the rest of the locations since it has been deduced that the volume of water within the channel has got a trickledown effect on the ion concentrations pertained in the water. Figure 4 further depicts the regional distribution of the IWQI within the drainage channel and might be viewed as a general map of suitability for supplying irrigation water from the drainage channel. It is now much simpler for a farmer to evaluate the quality of ADW for irrigation purposes and further locate the best suitable place for drawing the water since the map provides the spatial distribution of ADW quality in plain as index values.

Figure 4: Spatial Distribution of Cl^- (a), EC (b), HCO_3^- (c), Na^+ (d), SAR (e) and IWQI (f) for ADW Within the Main Drainage Channel in the Study Area

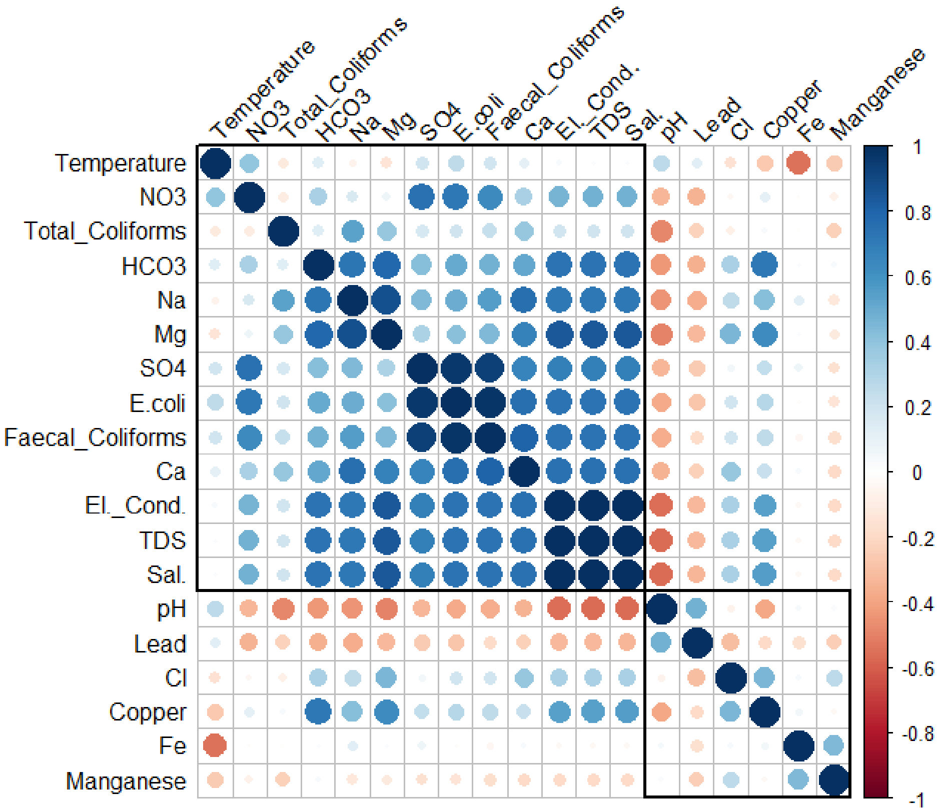



c
HCO3_Concentration
0.33 - 0.37
0.38 - 0.41
0.42 - 0.45
0.46 - 0.49
0.5 - 0.52
0 0.75 1.5 3 4.5 6 Kilometers
N
d
Na_Concentration
0.16 - 0.25
0.26 - 0.35
0.36 - 0.44
0.45 - 0.54
0.55 - 0.63
e
SAR_concentration
0.18 - 0.25
0.26 - 0.31
0.32 - 0.38
0.39 - 0.45
0.46 - 0.52
f
IWQI
Sampling points
Severe restriction
High restriction
S4
S3
D3D4
D5D6
D2
D1

Correlation of Water Quality Parameters

In this study, the correlation coefficients (r) among various water quality parameters were calculated using the Mann-Kendall Test and the numeral-graphical values of correlation coefficients (r) are represented in Figure 5. According to the results, EC and TDS; EC and Mg^{2+}; EC and salinity; Mg^{2+} and TDS; salinity and TDS; Na^{+} and Mg^{2+}; Mg^{2+} and salinity; Ca^{2+} and Faecal coliform; $SO_4{}^{2-}$ and E. coli; Faecal coliform and $SO_4{}^{2-}$; E. coli and Faecal coliform indicate high correlations (above 0.8). Out of the 190 correlation coefficients, 11 correlation coefficients (r) are found to be with highly significant levels (0.8< r < 1.0), and 29 values of r belong to the moderate significant coefficient levels (0.6< r < 0.8), 10 correlation coefficients fit within the significant coefficient levels (0.5< r < 0.6) of r values. Out of all the correlation coefficients, 130 cases were calculated as positive correlations making a percentage of 68.4% while 60 cases were calculated as negative correlations to make a percentage of 31.6%. In summary, high correlation coefficient between water quality parameters illustrates that EC, TDS, Mg^{2+}, Salinity and Faecal coliforms had significant interaction with other parameters. Therefore, these five parameters had high concentrations as a result of either natural occurrences or anthropogenic activities. Figure 5 below further classifies the analysed parameters with respect to the correlation strength. The blue colour signifies a positive correlation while the burgundy colour signifies a negative correlation. The stronger the colour the stronger the correlation and vice versa.

Figure 5: Correlation Matrix Between all the Parameters Analysed.



Conclusions

The analysis of ADW samples collected in April, May, July and August 2022, from different locations along the drainage channels within the northern plain of Pandamatenga Commercial Arable Farms in the Chobe district of Botswana revealed that almost all water quality parameters (pH, electrical conductivity, TDS, salinity, temperature, calcium, magnesium, sodium, chloride, nitrate, sulphate, and bicarbonate) are below the permissible limit as per BOS 463: 2011 and BOS 93: 2012 standards. The heavy metals which were analysed (copper, iron, lead and manganese) were non-detectable in most of the samples with some only having insignificant values way below the BOS standards. In comparison to all other parameters, there is an acute problem of extremely high levels of Total coliforms, E. coli and Faecal coliforms. Only 28.6% of ADW samples have no trace of E. coli content and the remaining 71.4% of samples are having very high E. coli concentrations. Similarly, 38.1% and 80.9% of the analysed parameters had low levels of Faecal coliform and Total coliforms respectively, while the rest of the percentages exceeded the permissible limits. Such high values are attributed to the wild and domestic animals that drink from the drainage channel and end up leaving their droppings in the water. The IWQI values computed from the five parameters of SAR, EC, sodium, chloride and bicarbonate during the four months of sampling ranged from 22.7 to 57.1, with a mean value of 28.6. Accordingly, 95% of the samples that were analysed fell within the “severe restriction” range, 5% of the samples under investigation fell under the “moderate restriction” and no ADW samples belonged to the “no restriction” category. Although 84% of the analysed ADW passes the quality mark of the wastewater and irrigation standards, the low levels of EC and SAR detected during the study period imply that there is a mineral imbalance, thus making the ADW unsuitable for direct reuse. Additionally, the high levels of microbiological parameters indicate that irrigating “ready-to-eat” crops with such ADW increases the risk of foodborne illness. Therefore, using this ADW will require mixing it in proper ratios with pure water to improve its quality for reusability during irrigation or using the ADW with trickle or drip irrigation systems since they present a lower risk for potential contamination of crops as compared to an overhead spray system.

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Author Contributions

Simon Peter Kakooza conceptualised the study, conducted the fieldwork and data analysis, Khumoetsile Bratah Mmolawa supervised the study, reviewed all the drafts, Gilbert Kabelo Gaboutloloe and Anne Clift-Hill reviewed the drafts.

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