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Management of Water Resources in the Peri-Urban Area of Niamey for Vegetable Production: Case Study of Three Ponds (Yaboni, Bangou Bi and Bangou Kirey)

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Abstract

Mobilizing water resources in the Sahel region presents significant challenges. Both surface water and groundwater are subjected to various pressures that hamper their effective management. In the peri-urban area of Niamey, these water resources are primarily used for agricultural production, especially for market gardening during the dry season. Beside river Niger and aquifers, ponds in the valleys around Niamey are used as water sources. This study aims to assess the dynamics of three specific ponds, examining their current exploitation and their potentialities for agricultural production. Different measurements have been carried out around the three selected ponds during two rainy seasons and one dry season (from May 2019 to October 2020). The measurements include rainfall, piezometry, and water volumes. A bathymetry survey was also performed on each pond. The results revealed a significant increase in water volumes during the rainy season, followed by a persistent depletion during the dry season. The increase in water level in the ponds varies from 1.44 m to 3.6 m depending on the rainfall amount during the rainy season. The annual hydrological balance of the ponds showed that a considerable portion of the inflow in the ponds is lost through evaporation and infiltration. However, the amount of water used for gardening around the ponds produces an important quantity of vegetables during the dry season. This production of vegetables offers a considerable economic potential to farmers due to the close proximity to Niamey. The market gardening production system contributes to strengthening the resilience of farmers against the harmful effects of climate change like food insecurity and income reduction.

Keywords

Water Resources, Peri-Urban Gardening, Vegetable Production, Irrigation, Sahel

1. Introduction

Since the 1970s, the Sahelian region of West Africa has been affected by changing climatic conditions [1] [2]. Severe droughts have characterized the period from 1968 to 1990, with a decrease of more than 23% in annual rainfall [3]-[5]. This region recorded the largest rainfall deficit, which was also materialized by a southward migration of the isohyets over 100 to 200 km [5] [6]. The decrease in the annual rainfall amount has led to a significant reduction in surface water and groundwater resources [7]. However, there has been a slight recovery of rainfall since the 1990s with an increase of about14% in the annual precipitation after the 1990s in comparison to the driest period of 1970-1990 [3]-[6]. The changes in the rainfall regime observed in the Sahel region have entailed manifold changes in the distribution of climatic and hydrological parameters [8]. The decrease in rainfall amount has highly affected the sector of agriculture in the region [9]-[12]. Niger, the driest country in the Sahel region, is facing a deficit in food production that has become increasingly acute since the 1970s [13]. Furthermore, the strong population growth (annual rate of 3.9%) has increased the demand for food and therefore, enhanced food insecurity [14] [15]. To overcome this situation, strategies have been developed by the government and various stakeholders [16]. In Niamey region, there has been a rise in the groundwater table since the 1990s, a phenomenon that is a priori contradictory to the decrease in rainfall (with regards to 1960s), but which is due to the increase in runoff in an endorheic context [17]. Thus, following the rise in the water table, perennial ponds have appeared and they constitute a market gardening production area close to Niamey. Market gardening around the water bodies is an alternative way to compensate for the economic deficits in rainfed crops in the region. The high demand for chili and pepper in sauces used in Niger's cuisine has accompanied the development of the market gardening. The inhabitants of Niamey consume slightly more vegetables than other urban dwellers in Niger, 31.5 kg/person/year compared to 29 kg/person/year [18]. The productions of the two crops are estimated at 515 tons for chili peppers and 669 tons for peppers [19]. The irrigation practice for market gardening consisted in the use of motor pumps, which jeopardizes the management of surface and groundwater resources. However, the agricultural activity in the region depends mainly on rainfall, which means that the plants' development and the size of the planted area, depends strongly on the climatic conditions and on the physiognomy of the rainy season. Under this condition, the management of water resources is one of the major challenges. In addition, climate change impacts are expected to increase variability in water availability with the rising evapotranspiration being the main output component of water systems in the region. It is therefore reliable to describe the main dynamic of water availability in water resources used for food production under the ongoing climate change condition. The objective of this study is to analyze the seasonal dynamics of three ponds and their contribution to food production in the peri-urban area of Niamey. Specifically, this research aims to evaluate the volumes of water available in the ponds and to determine the other components of the hydrological balance of the ponds (infiltration, evaporation and withdrawal).

2. Material and Methods

2.1. Study Area

The three ponds (Yabani, Bangou Bi, and Bangou Kirey) are located along kori Ouallam (large ravine), an ancient fossilized tributary of the Niger River (Figure 1). Along this Kori, some ponds have formed on a north-south axis. These ponds apparition has increased during the 1990s following the increase in the runoff and in the hydric erosion [20] [21]. As it is typical for the Sahelian region, the climate condition is characterized by a long dry season (October-May) and a short rainy season (June-September). The long-term average of annual rainfall amount in Niamey is amounting to 544 mm [22]. The Bangou Bi and Bangou Kirey ponds, 1 km apart, are situated more than 6 km downstream of Yaboni Pond. The banks of these ponds are increasingly occupied by market gardening crops, with most of the cultivated crop being: moringa, green pepper, pepper, chili, cabbage, tomato.

Figure 1. Location of the ponds of Yaboni, Bangou Kirey, and Bangou Bi ponds (Google Earth image from 4/5/2025).

2.2. Rainfall Measurements

Rainfall measurements were carried out daily during the rainy seasons (June-September) of 2019 and 2020. Rainfall was measured by using two direct-reading (observer) rain gauges installed at 1.5 m above the ground and near the ponds. The rainfall amount was recorded manually after each rain event by an observer.

2.3. Water Measurements

The water level measurements consist in a continuous monitoring of the variations in water levels in the three ponds (**Figure 2**). Three water level scales have been installed at Bangou Bi and Bangou Kirey, and four scales at Yaboni. The scales are graduated in centimeters and the difference in height between two consecutive scales is one meter (**Figure 2**). The water level measurements were carried out two times in a day: every morning (between 6 a.m. and 8 a.m.) before the pumping started and every evening (between 5 p.m. and 7 p.m.) after the pumping stopped. These measurements were carried out during 22 months (from January 2019 to October 2020).

Figure 2. Limnimetric scales in Bangou Kirey for water level measurement.

2.4. Piezometric Level Measurements

Figure 3. Piezometric measurement in a well with a piezometric probe.

The measurements of the piezometric level aim to monitor water table in the study area. The piezometric level was measured two times in a day with the piezometric probe (**Figure 3**): every morning (between 6 a.m. and 8 a.m.) and every evening (between 4 p.m. and 7 p.m.). The measurements were carried out around the market gardening wells in Yaboni (13˚32.318'N and 2˚13.398'E), Bangou bi (13˚30.230'N and 2˚13.150'E), and Bangou Kirey (13˚30.264'N and 2˚13.268'E). The measurements at these wells (**Figure 2**) enable to evaluate the changes in the groundwater table within the study area from May 2019 to October 2020 (18 months).

2.5. Bathymetry of the Ponds

The bathymetric measurements have been done in the three ponds (**Figure 4**). It was carried out in October 2019 on the Bangou Bi and Yaboni ponds by using the echo sounder and an Acoustic Doppler Current Profiler (ADCP). However, for the Bangou Kirey plant, the measurements were carried out in June 2019 with the same equipment. The geographical coordinates were noted in a notebook, coupled with the water depth indicated by an echo sounder. Also, the coordinates of the ponds contours were recorded using a GARMIN brand GPS (GPSmap 62 s). The method used to process this data was interpolation with the kriging method in ArcGIS. The analyses of the measured depth per location enabled to produce topographic maps of the bottom of each pond and to determine the different rating curves (height/volume and height/surface). The height/surface relationship is necessary for evaporation calculations, while the height/volume relationship is used to calculate water losses in the ponds.

Figure 4. Bathymetric measurement with an ADCP in Bangou bi.

2.6. Evaluation of Irrigation Withdrawals

The measurements of withdrawals for irrigation were made through the measurements of the flow rates of the motor pumps. These measurements consisted in determining the volume of water pumped during a given period. For that purpose a 25 L canister and a stopwatch were used. This method has been applied in several gardens around each of the ponds. Two measurement campaigns were carried out, one in May 2019 and second in December 2019. Thus, the data collected has helped to calculate the average pumping rate of the pumps. In all the gardens surveyed, the duration of watering per day was recorded as well as the surface area of the plot or of the garden. These measurements enabled to determine the total amount of water pumped from each garden during each campaign.

2.7. Determination of the Water Balance

The calculation of the hydrological balance consists in determining the water input, water output and the change in the storage. Major input components are rainfall and inflow, whereas evaporation, infiltration and water use (withdrawals for irrigation, livestock watering) constitute the output. The parameters for estimating evaporation were determined using field and climate data from the Niamey Airport synoptic station (2 to 3 km from the ponds) acquired from the National Meteorological Service. The total evaporation (Ep) in ponds is obtained by multiplying the coefficient (f) by evapotranspiration (ETP) [23]. For this purpose, the evaporation obtained makes it possible to determine the volume of the evaporation. This evaporated volume (Ve) is estimated by the formula:

$Ve = EpxSmx10^{-3}$ (Sm mean area of the water body) [24].

In previous studies in the region [25] [26], infiltration rate values range from 0.1 mm/day to 5 mm/day with an estimated average of 2.1 mm/day. Based on these studies, we consider the average infiltration rate of 2.1 mm/day in our study area. The infiltrated volume is obtained by multiplying the average infiltration rate by the average surface area of the ponds (Sm). Apart from these water losses, the ponds in our study area are used for watering the livestock. According to Desconnets [27], the volume of livestock watering in small ponds in the area around Niamey is between 4.8 and 11.6 m^3/day. Generally, the plateau ponds are very much used by livestock watering because of their location away from fields and villages. The ponds in the study area are in a very isolated area with little access to animals. This situation justifies to consider the lowest value of 4.8 m^3/day for each of the ponds: Yaboni, Bangou Bi, and Bongou Kirey.

3. Results

3.1. Rainfall Regime in the Study Area

The analysis of rainfall records revealed that the rainy season lasted 158 days in 2019 compared to 166 days in 2020. Annual rainfall amounts were 448.3 mm in 2019 compared to 611 mm in 2020 in Yaboni (**Table 1**). In Bangou Bi, the annual rainfall amounts are 564 mm and 663 mm in 2019 and 2020, respectively. The inter-annual variation in the rainfall amounts is very marked at all rainfall stations of the study. Thus, this amount of rainfall (564 mm) recorded in 2019 in Bangou Bi is at the same order of magnitude as the average rainfall amount recorded in

Niamey (560 mm) between 1950 and 2009 [6] [28]. As for Yaboni in 2019, there is a decrease (111.7 mm) in rainfall amount compared to this average. However, this difference in the annual amounts between the two stations could be explained by the high spatial variability in the rainfall which is typical for the convective precipitation system. Indeed, a difference of more than 100 mm has already been identified by [29], along a few kilometers: 150 mm over 6 km in 1990 in the square degree of Niamey (an area of 1˚ longitude by 1˚ latitude around Niamey); and 320 mm over 27 km in 1991.

The analysis of the parameters in **Table 1** reveals that the onset of the rainy season varies from year to year. Thus, the 2020 rainy season began on April 23 and was 23 days earlier than the rainy season in 2019. In Niamey region, the rainiest months are July and August. To this end, these months accounted for between 53% and 58% of the annual rainfall amounts recorded in 2019 and 2020. These results are in the same order of magnitude with the results presented by [30] where the two months (July and August) accounted for 54% of the annual amount in 2017. However, **Table 1** shows that July was wetter than August at the Yaboni station.

Table 1. Rainfall amounts in 2019 and in 2020.

Site	Year	April	May	June	July	August	September	October	Total
Rainfall in Yaboni (mm)	2019	0	19	62	144	111	66.3	46	448.3
	2020	5	35	67	181	177	124	22	611
Rainfall in Bangou Bi mm)	2019	0	19	55	176	172	77	65	564
	2020	10	54	99	167	188	123	22	663

3.2. Evolution of the Piezometric Level

Figures 5-7 illustrate the variations in the piezometric level and the daily rainfall between 22 May 2019 and 10 October 2020 respectively in Yaboni (**Figure 5**), Bangou Bi (**Figure 6**), and Bangou Kirey (**Figure 7**). The maximum rise in piezometric level is 1.83 m, 1.44 m, and 1.49 m, respectively, in the wells in Yaboni, Bangou Bi, and Bangou Kirey during the 2019 campaign. However, in 2020, this rise was 3.6 m, 2.7 m, and 2.85 m respectively in the same wells in Yaboni, Bangou Bi, and Bangou Kirey. This significant rise in Yaboni well is due to the fact that this well is very close to the pond. These increases are in the same order of magnitude as those observed in Banizoumbou, where the level of the water table increased by 0.5 to 2 m during the rainy seasons [31]. These results are also in the same range of magnitude as those determined between 1992 and 2000 in the southwestern terminal continental aquifer of Niger, where the increase was from 1 to 3 m [20]. From the end of the rainy season, there is a regular decrease in the piezometric level in all the wells. This decrease is about 1.62 cm/day, 1 cm/day, and 0.9 cm/day, respectively, at the Yaboni, Bangou Bi, and Bangou Kirey wells.

These results are lower than those observed in 2017 by [32] on another well near the Yaboni pond, with a steady decline of about 1.71 cm/day. This decrease is much higher than that observed in a well in Goudel (a village close to Niamey), where it is 0.44 cm/day [33]. This difference could be explained by the fact that these measurements were carried out at the level of the market gardening wells. The Yaboni well shows a very significant fluctuation, which reflects the impact of irrigation on the water table. This significant fluctuation is not observed in Bangou Bi and Bangou Kirey wells. This could be explained by the high recovery in the aquifers beneath Bangou Bi and Bangou Kirey just after the pumping. It appeared that the significant water table rise in these aquifers is the result of high infiltrations after intense rainfall events. A continuous decrease in piezometric levels is generally observed from November to July. The arrival of seepage water into the aquifer and the reduction in water withdrawal are marked by a rise in the piezometric level from August to October. The month of November marks the beginning of a decline in the piezometric level following the cessation of rainfall in September and pumping for irrigation (**Figures 5-7**).

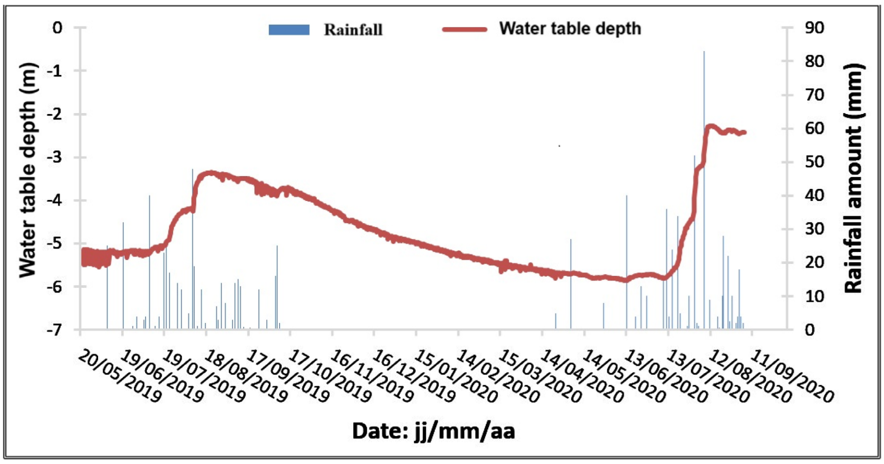

Figure 5. Evolution of the piezometric depth in Yaboni well.

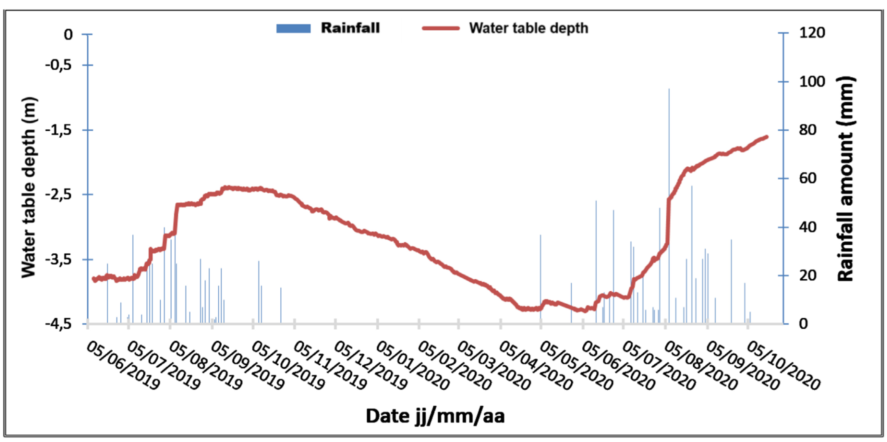

Figure 6. Evolution of the piezometric depth in Bangou Bi well.

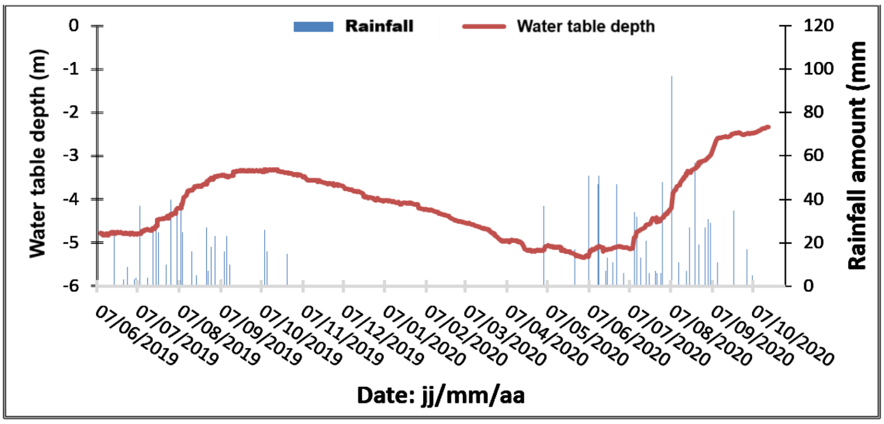

Figure 7. Evolution of the piezometric depth in Bangou Kirey well.

3.3. Assessment of Ponds Storage Capacities

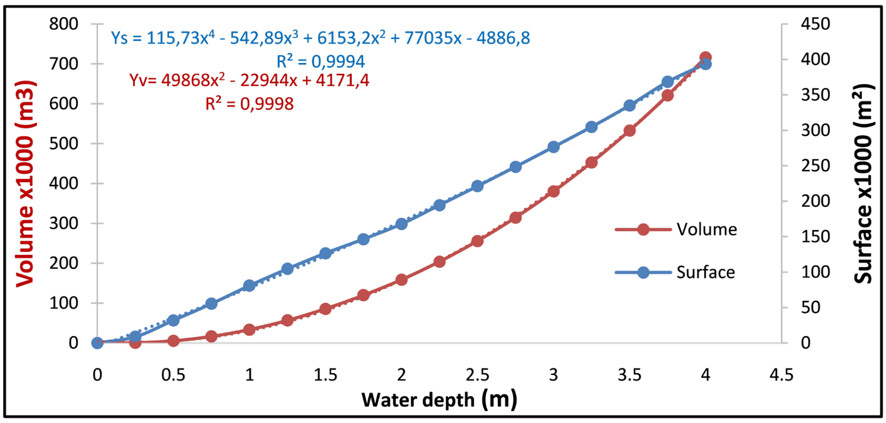

Figure 8. Rating curves of height/surface/volume curve of the Bangou Bi pond.

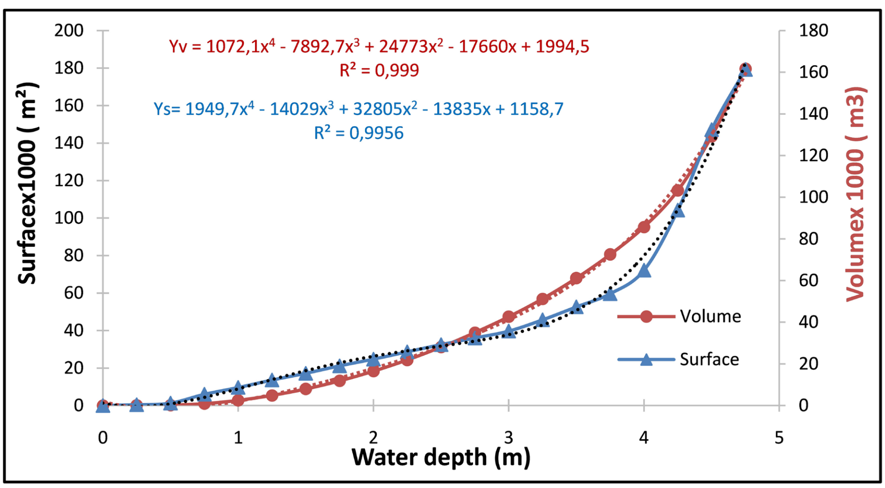

Figure 9. Rating curves of height/surface/volume of the Yaboni pond.

Some bathymetric measurements have been conducted in the three ponds in order to determine their storage capacities in terms of relationship between the volume of water and the water level (height-volume function). Furthermore, the relationship between the water level and the area of the water body has also been established. Two rating curves were established: the height-volume rating curve and the height-area curve for the three pond, Figure 8 for Yaboni, Figure 9 for Bangou Bi, and Figure 10 for Bangour Kirey. These curves on the relationship between two parameters (volume or surface area as functions of water level height) have helped to elaborate the mathematical functions (polynomial equations of order 4) from an adjustment model. The curves enable to determine the volume of water available and the water body area in the pond for a given water level. The water level is obtained from a direct reading on the water level scales (vertical gauge) installed in the ponds. The maximum level measured during the 2019 rainy season is 213 cm, 93 cm, and 165 cm respectively in Yaboni (Figure 8), in Bangou Bi (Figure 9), and in Bangou Kirey (Figure 10).

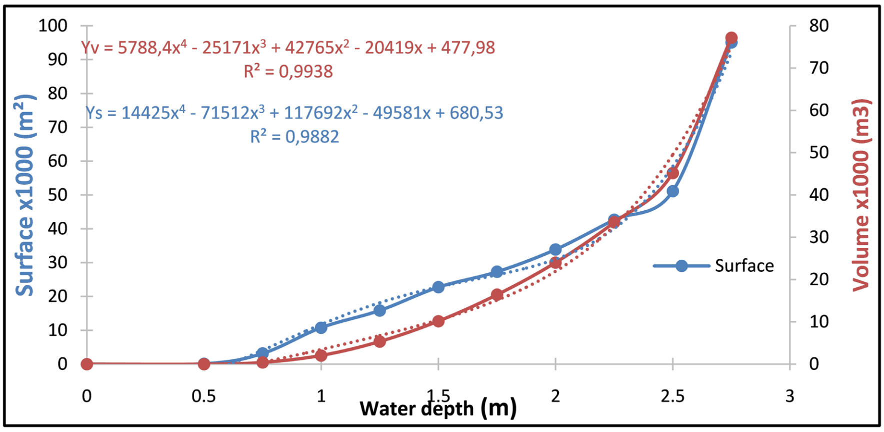

Figure 10. Rating curves of height/area/volume curve of the Bangou Kirey pond.

3.4. Evolution of the Volume of Water in the Ponds

The evolution of water volumes in the three ponds is characterized by a seasonal variation: Figure 11 for Yaboni, Figure 12 for Bangou Bi, and Figure 13 for Bangou Kirey. These variations consist in a strong increase in water volume during the rainy season, whereas the trend is steadily downward during the dry season (Figures 11-13). These fluctuations are linked to the inflow from runoff into the ponds. The increases in Yaboni (Figure 11) and Bangou Kirey (Figure 13) ponds are more sensitive than that in Bangou Bi pond (Figure 12), where the response time lasted 2 months (from May 15th to July 20th 2019). These results are in the same magnitude as those observed between 2008 and 2010 when the response time varied between 1 and 2.5 months in Bangou Bi. Amadou Abdou *et al.* [30] explain that the rapid onset of the flood at Yaboni is due to the high density of its drainage network. For Bangou Kirey, its catchment area is different from that of Bangou Bi, as it is fed by very large koris draining a catchment area of nearly 60 km^2 compared to 5 km^2 for the Bangou Bi pond [34]. It can therefore be expected that the functioning in these ponds will be different from that in the Bangou Bi pond since they receive significant surface runoff, particularly at the beginning of the rainy season. Indeed, during this period, Bangou Kirey and Yaboni behave like a temporary pond in the region featuring a water level increase from the first rain event with runoff. The flood/recession phase includes a phase of filling the pond that is generally short-lived, in a few hours, followed by a flood recession phase that lasts longer, from a few days to a few weeks or even a few months in the dry season [31].

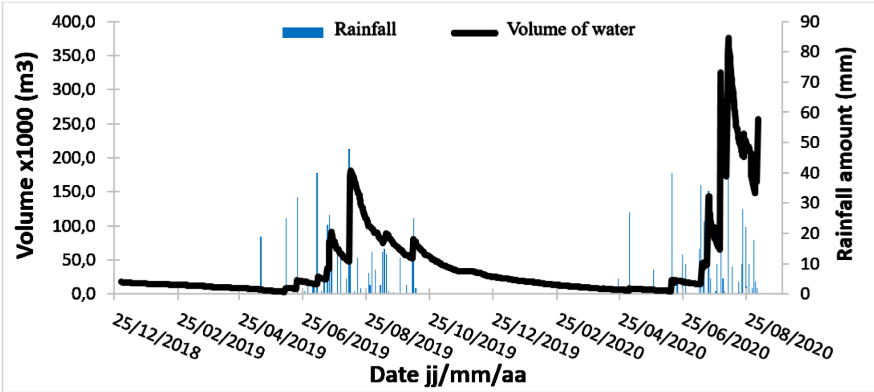

Figure 11. Evolution of volume of water in the pond of Yaboni.

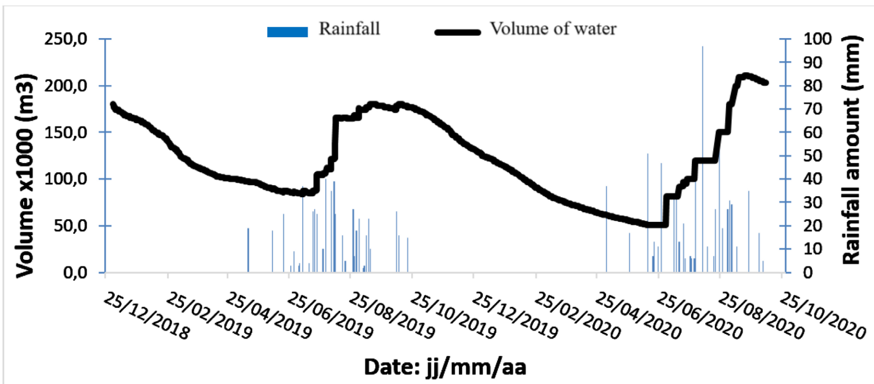

Figure 12. Evolution of volume of water in the Bangou Bi pond.

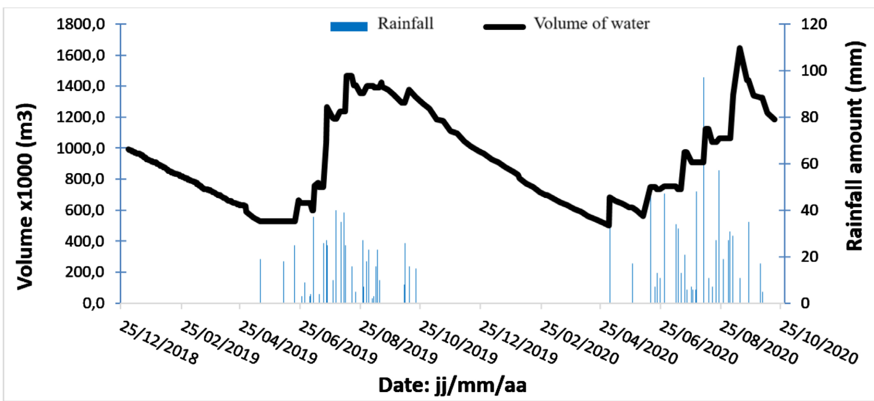

Figure 13. Evolution of volume of water in the Bangou Kirey pond.

Table 2 shows that all floods are observed between August and September. This period coincides with the period of high rainfall in the Sahel. However, the inflows in Yaboni and in Bangou Kirey ponds are systematic during heavy rainfall. Thus, these floods in 2020 caused flooding in Yaboni and Bangou Kirey. However, in Bangou Bi, no overflow was observed because of the shape of the basin, which is very confined and receives less runoff. The maximum volumes are higher in 2020 than in 2019 what can be explained by high rainfall recorded in 2020. Indeed, it is apparent from the analysis of this Table that the surface area and depth follow the evolution of water volumes. In addition, these ponds are the deepest of the endorheic systems existing in the vicinity of Niamey.

Table 2. Water body volume and extension in 2019 and 2020.

Site	Year	Flood date	Max volume (m^3)	Max water body (ha)	Water depth (m)
Yaboni	2019	10th August	180,694	25.95	3.3
	2020	8th August	375,986	61.4	3.82
Bangou Bi	2019	13th to 19th September	179,829	16.83	4.77
	2020	9th to 13th September	217,046	21.6	5
Bangou Kirey	2019	10th August	1,466,449	64.68	5.65
	2020	13th September	1,644,536	70.6	5.97

3.5. Water Losses and Water Withdrawals from the Ponds

The hydrological balance of a pond is based on the determination of water inputs and water outputs. Inputs and outputs are water fluxes and volumes which are exchanged between the pond and the outside environment. Major components at the output are losses through evaporation and infiltration, and the water withdrawals used for watering livestock.

➢ **Evaporation losses from the ponds**

The evapotranspiration values used in this study are monthly data in mm/month calculated with Penman-Monteith formula from the climate data collected at the synoptic station of Niamey airport. The calculated monthly PET ranges from 200 mm in August to 280 mm in May, with an average of 230 mm/month and an annual average sum of about of 2500 mm/year. The monthly evaporation from ponds ranges from 100 mm to 200 mm, with an average of 150 mm/month and an annual average sum of about of 1900 mm/year. This evaporation value is much lower than that observed on Lake Chad, where it is 2150 mm/year [23]. This strong difference can be explained by the change in hydroclimatic parameters. The volume of water lost through evaporation is minimal in all ponds in June (Table 3). This volume is high in August in Yaboni and in September on the ponds of Bangou Bi and Bangou Kirey. Generally, this volume lost through evaporation increases during the rainy season (the surface of the water body is larger) and decreases during the dry season. These variations can be explained by the evolution of the water body area in the ponds.

Table 3. Monthly volumes evaporated in ponds.

Months	Evaporated Volume in Yaboni (m^3)	Evaporated Volume in Bangou Bi (m^3)	Evaporated Volume in Bangou Kirey (m^3)
September	9498	16,408	60,644
October	6160	14,178	51,132
November	3290	10,235	37,874
Décember	2703	8854	34,668
January	2018	11,468	35,902
February	2034	10,283	35,545
March	2295	9231	39,935
April	2122	7720	37,720
May	1483	6349	32,025
June	983	2861	17,017
July	4609	5896	42,930
August	11,206	11,068	50,734
Total	48,401	114,546	476,124

- **Losses due to infiltration through the ponds**

Table 4. Monthly volumes infiltrated beneath the ponds.

Month	Infiltrated Volume in Yaboni (m^3)	Infiltrated Volume in Bangou Bi (m^3)	Infiltrated Volume in Bangou Kirey (m^3)
September	6001	10,364	38,316
October	4649	10,699	38,588
November	2992	9306	34,436
December	2286	9443	31,282
January	1755	9321	31,219
February	1507	7619	26,336
March	1559	6270	27,125
April	1358	4941	24,143
May	1059	4532	22,859
June	1373	3996	23,767
July	3423	4380	31,886
August	8826	8717	39,958
Total	36,787	89,588	369,912

The average infiltration rate of 2.1 mm/day found by other studies in the region [25] [26] is assumed to be constant for all months in our study area. Thus, the annual totals of water volumes infiltrated over the period of Sept-19/August-20 are estimated at about 36,787 m^3, 89,588 m^3 and 369,912 m^3 respectively in Yaboni, Bangou Bi and Bangou Kirey (**Table 4**). According to **Table 4**, the water infiltration at these ponds is maximum in August in Yaboni and Bangou Kirey and in October in Bangou Bi. Most of the infiltration is observed in August, September, and October, which coincides with the period of high water level and the largest water body area. It confirms the hypothesis that, as long as the water level in the pond is significantly higher than the clogged area, most of the infiltration takes place through the unclogged banks [35]. Hence, the strong infiltration in these ponds (Bangou Bi, Bangou Kirey, and Yaboni) confirms that the Sahelian ponds are key points in groundwater recharge [20] [21].

➢ **Animals watering**

The daily water consumption of livestock is very low; it is around 4.8 m^3/day in all the ponds [27]. The animals frequent the ponds during the period from November to May (09 months), *i.e.* 212 days. Indeed, the access is very limited during the rainy season for the animals. The animals are not allowed to cross the fields of crops during the rainy season. This maximum total pastoral consumption is estimated at an average of 1018 m^3 during the dry season at the level of each of the ponds.

➢ **Evolution of water availability in the ponds**

Table 5. Components of the water balance of Yaboni pond for the months of August and September in 2019 and 2020.

Components	Aug-19	Aug-20	Sep-19	Sept-20
Runoff (103 m^3)	132.8	263.2	16.4	113.4
Total volume lost (103 m^3)	20.03	51.2	15.5	36.37
Evaporated volume (103 m^3)	11.2	28.7	9.5	22.3
Infiltrated volume (103 m^3)	8.83	22.5	6	14.07

Table 6. Components of the hydrological balance of Bangou Bi pond for the months of August and September in 2019 and 2020.

Components	Aug-19	Aug-20	Sep-19	Sept-20
Runoff (103 m^3)	152.7	129.5	15.4	45.8
Total volume lost (103 m^3)	19.82	32.51	26.76	18.28
Evaporated volume (103 m^3)	11.1	18.2	16.4	11.2
Infiltrated volume (103 m^3)	8.72	14.31	10.36	7.08

Tables 5-7 show that water inputs in August and September 2020 are significantly higher than in 2019, except in Bangou Bi where the inputs in August 2019 exceed those in August 2020. Inflows are greater than the different losses during this monitoring period, which may mean low anthropogenic pressure on the ponds. Bangou, Kirey and Yaboni ponds contribute more to the groundwater re-

charge during the rainy season. These results show also that even over a short monitoring period, the ponds are characterized by a great variability in the different components of the water budget. This variability is mainly due to the irregularities in the inflows, which are controlled by rainfall and other features that influence runoff generation in the catchment areas.

Table 7. Components of the hydrological balance of Bangou Kirey pond for the months of August and September in 2019 and 2020.

Components	Aug-19	Aug-20	Sep-19	Sept-20
Runoff (103 m^3)	324.5	517.5	31.7	299.7
Total volume lost (103 m^3)	87.66	77.96	98.92	104
Evaporated volume (103 m^3)	50.7	43.7	60.6	63.8
Infiltrated volume (103 m^3)	36.96	34.26	38.32	40.20

➢ **Summary of the ponds water balances**

The assessment of Yaboni water balance indicates that 14% of the annual inflow evaporates and 10% of this inflow infiltrates, *i.e.* an annual loss of 24%. This assessment for Bangou Bi reveals that about 17% of the inflow evaporates and 12% of this volume infiltrates, *i.e.* an annual loss of 29%. For Bangou Kirey, 22% of the annual inflow evaporates against 15% that infiltrates. Indeed, the loss through evaporation is much greater in the annual stock in Bangou Kirey pond because of the extension of this pond. Overall, evaporation is the predominant factor in the decrease in the reservoir water stocks in the Sahel [26]. Indeed, this assessment shows that more than 35% of the volume of inputs is lost in Bangou Kirey pond through evaporation and infiltration. This volume could be more because the two components are not measured directly in the ponds [24]-[26].

The determination of the total volume of water in the ponds allows to calculate the amount of water available for irrigation. The volume of water available for irrigation is more than sufficient in Yaboni Pond and in Bangou Kirey pond (**Table 8**). The amount of water available in Bangou Bi pond does not cover the irrigation needs. Thus, to limit the damage caused by water shortages around this pond, an alternative solution is the use of groundwater as a source of water for irrigation.

Table 8. Volume of water available for irrigation in the different ponds.

Sites	Total volume of ponds (m^3)	Total losses (m^3)	Volume available for irrigation (m^3)
Yaboni	180,694	40,288	140,406
Bangou Bi	179,829	143,027	36,802
Bangou Kirey	1,466,449	544,114	922,335

The three ponds have a large quantity of water available for irrigation (**Table**

9), especially since the water requirement for the main crops (onion, tomatoes, cabbage) are much lower [36]: 9896.5 m^3/ha for onions, 9815.2 m^3/ha for tomatoes and 9591.3 m^3/ha for cabbages.

3.6. Water Withdrawals for the Market Gardening

Irrigation is carried out using watering cans with a capacity of 10 liters and motor pumps with flow rates varying between 1.3 and 1.5 l/s respectively in the cold period (November-January) and in the hot period (February-May). The frequency of irrigation is once every 2 days during the cold period for those who use the motor pumps and every day for those who use the watering cans. The determination of these flows enables to calculate the average amount of water withdrawn per day at each garden. The average daily quantity withdrawn is 9.36 m^3/day, 25 m^3/day and 28.08 m^3/day during the cold period in Yaboni, Bangou Bi, and Bangou Kirey respectively. For the hot period, the water withdrawn is 32.4 m^3/d, 86.4 m^3/d, and 97.2 m^3/d in Yaboni, Bangou Bi and Bangou Kirey, respectively. These water quantities were extrapolated to determine the amount of water withdrawn from each pond. Thus, the cumulative volumes taken for market gardening from the ponds during the 2019/2020 campaign are estimated at about 5525 m^3, 397,953 m^3 and 480,660 m^3 respectively in Yaboni, Bangou Bi, and Bangou Kirey. Bangou Kirey pond, unlike the other ponds, is the most used for irrigation. The information is collected during the survey and the mapping of the gardens around the ponds with Google Earth have been used to determine the average irrigated area per site. This area is 5 ha, 3 ha, and 10 ha, respectively, in Yaboni, Bangou Bi, and Bangou Kirey. The number of gardens that use well water for watering is 80%, 38.63%, and 59.7% respectively at Yaboni, Bangou Bi, and Bangou Kirey. This strong pressure on Yaboni and Bangou Kirey aquifers during the low water period causes the wells to dry out.

3.7. Vegetable Production

The total surface area of the gardens varies according to the site, they are respectively 5 ha, 3 ha, and 10 ha in Yaboni, Bangou Bi, and Bangou Kirey. Market gardening activity lasts nine (9) months along the year (from October to June). Thus, this duration is divided into two campaigns, the first campaign runs from October to January (cold season) and the second campaign from February to June (cold season). The survey noted that the largest area is exploited in the cold season. Vegetable crops (tomatoes, cabbage, lettuce, onion, chili pepper, pepper, eggplant, squash, moringa (Moringa oleifera), melon, watermelon, maize, sweet potato, cassava, potato, sorrel, green beans and okra) are grown during the dry season enabled by irrigation, mainly by pumping water from ponds, but also groundwater pumped from wells. The favorite and dominant crops in the study area are: chilli peppers, peppers, tomatoes and moringa. The most important factor that explains this enthusiasm of producers is the productivity and the marketing options of these crops at the nearby city of Niamey. This statement has also been noted by

MDAE [19], which announces that in Niamey, the use of stimulating plants (chilli peppers and peppers) in many sauces has a positive influence on the supply. The study found that peppers and green peppers are the two most profitable crops in all seasons. Also, tomatoes and cabbage are profitable during the cold season. Moringa, on the other hand, becomes more profitable during the rainy season. The evaluation of the crop production has faced the problem that the market gardeners are not measuring their productions in terms of kilograms. The production is estimated based on the local unit of measurement (bag, boxes, cup and basket). The survey shows that, despite the variations in harvests observed in several crops, the average production per season could be estimated referenced to the area (**Table 9**). Farmer-level production was estimated by plot and then reported to kg/m^2 and t/ha. The lowest production is obtained with moringa (leaves), and the highest is obtained with cabbage (**Table 9**).

Table 9. Crops production and yield.

Crops	Number of unit	Weight per unit (kg)	Plot area (m^2)	Production (Kg/m^2)	Production in t/ha
Green chilli	5 (bag)	80	400	1	10
Pepper	7 (bag)	60	400	1,05	10.5
Cabbage	30 (bag)	100	500	6	60
Tomato	5.5 (boxes)	20	500	2	20
Okra	8 (cup)	2	50	1,6	16
Moringa	5 (bag)	30	400	0,4	4
Lettuce	30 (basket)	25	500	1,5	15

4. Discussion

The Sahelian zone is facing strong and adverse effects of climate change on agricultural production [5] [37]. The droughts of the 1970s caused great interest in off-season crops, *i.e.* market gardening during the dry season. Gardens are created around water sources (ponds, boreholes, wells, etc.) to produce vegetables and crops during the dry season to compensate for the agricultural deficit or as a market gardening activity. A multitude of ponds are exploited around Niamey, which provide water supply to produce certain market gardening crops including tomatoes, cabbage, lettuce, onion, chili pepper, pepper, eggplant, squash, moringa (Moringa oleifera), melon, watermelon, corn, sweet potato, cassava, potato, sorrel, green beans, and okra.

Several studies [30] [31] [34] have been conducted in order to explore small scale gardening crop production around ponds. However, few studies have addressed the evaluation of the components of the water balance of these ponds. The main source of water to fill the ponds and aquifers in the area is rain. Annual rainfall varies from 450 mm in 2019 and 660 mm in 2020. The year 2019 was a deficit year featuring a much lower rainfall than the long-term annual average height of the Niamey area of 560 mm [22], and the year 2020 was in surplus. After each rainfall, a large quantity of water flows towards the ponds or infiltrates into the ground and contributes to recharge groundwater [3] [22]. Our measurements performed during the two rainy seasons (2019 and 2020) enabled to quantify the water inputs in the various ponds. The inputs evaluated from the variation of the water level in the ponds and the rating curves (height-volume) vary according to the size of the upstream catchment and the features of the basin influencing the processes generating surface runoff (e.g. slope, drainage density, soil). In 2019 inputs reached more than 177,125 m^3 (14,144 km^2) for Yaboni, more than 94,610 m^3 (3185 km^2) for Bangou Bi, and more than 938,202 m^3 (17,374 km^2) for Bangou Kirey. These ponds have a large stock of water despite the various losses (evaporation and infiltration). These losses represent more than 30% of annual inflows. The numbers achieved in our study are close to the values determined by Desconnets and Taupin [29] on ponds located in the valley (values between 35% and 43.6%). Despite these losses, the three ponds are permanent and present a considerable water availability. The minimum volume of water is about 3 570 m^3 in Yaboni, which is the smallest in term of capacity. Indeed, the quantity of water available in each of the ponds is sufficient to irrigate more area than the actual around each pond. The maximum water requirement in the area for the crops is given by onion with a total need of about 9896.5 m^3/ha/year [36]. Based on the quantities of water available for irrigation in each pond (**Table 9**), the areas that can be irrigated are respectively 14 ha for Yaboni, 4 ha for Bangou Bi, and 93 ha for Bangou Kirey. Therefore, they are some possibilities for extending the gardens around these ponds within the limit of the pedological and topographical constraints. Although the gardens around the ponds are rather small in size, their potentiality to improve farmers' living conditions is considerable and promising due to a high production level (4 to 60 t/ha). This levdel of production exceeds the agricultural production during the rainy season [38]-[40]. Furthermore, according to Rabo *et al.* [40], vegetable crops can provide up to 500,000 FCFA/ha/cycle (1000 $/ha/cycle).

5. Conclusion

The climatic condition in Niamey region is characterized by a single rainy season (from June to September). This rainfall is highly variable in time and space. The rainfall monitoring carried out in the region during the two years (2019 and 202), has shown that 2020 was rainier than 2019. Furthermore, the months of July and August are the wettest, with nearly 53% to 58% of the annual rainfall amounts. For the surface water resources, the study revealed that the ponds present a seasonal dynamic marked by an important amount of water in the rainy season and a significant depletion during the dry season. This study also shows that these ponds contribute to the recharge of the groundwater. Altogether, the availability of water resources in the peri-urban area of Niamey is governed by rainfall which is expected to become more variable under the climate change condition. Thus, it is urgently needed to establish an effective system for productive and sustainable management of the different ponds. Through the evaluation of the water balances of the three ponds and the water uses in the market gardening, this study has provided relevant information to support the elaboration of some water allocation strategies around the ponds towards the improvement of water productivity in the peri-urban area of Niamey and beyond.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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