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Sludge accumulation in stabilisation ponds in the Soudano–Sahelian climate of Burkina Faso

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ABSTRACT

Sludge accumulation in waste stabilisation ponds based on local conditions is of great interest for successful sludge management, and accurate accumulation data are essential for WSP design based on reasonable data for model development in relation to the effect of climate variability. For this purpose, a series of three ponds treating domestic wastewater in the Soudano–Sahelian climate of Burkina Faso were monitored for sludge accumulation. After five and a half years of operation, the rates of sludge accumulation in the ponds were evaluated at 0.019, 0.009 and 0.007 m^3 per capita per year, respectively, for the anaerobic (AP), facultative (FP) and maturation pond (MP). The corresponding rates of accumulation in dry weight (dw) per person per year were calculated to 1.3, 0.43 and 0.26 kg dw per capita per year, respectively, in AP, FP and MP. A coefficient of high biodegradability of sludge was found in the AP. In contrast to the seasonal evolution of sludge accumulation reported in Mediterranean climatic conditions characterised by a succession of winter and summer, in Sahelian climate regions, a continuous digestion of sludge during its accumulation was observed, due to the warmer Sahelian conditions prevailing most of the year.

Keywords: Wastewater treatment; Sludge accumulation rate; Biosolids; Waste stabilisation pond; Burkina Faso

1. Introduction

Developing countries, particularly those of Sub-Saharan Africa such as Burkina Faso, have been characterised by low indices of wastewater treatment. The main reason of this situation was linked in the past to the early failure of energy intensive electro-mechanical wastewater treatment technologies imported from industrialised countries in the generally mistaken belief that they were the most appropriate technologies to implement. This belief was mistaken due to the expensive cost of the intensive technologies, and the difficulty to operate and maintain them in developing countries as the case of Burkina Faso. Nevertheless, the hot climatic conditions in this country are ideal for a biological treatment process, especially a natural-based and non-mechanised one. Among processes considered to be suitable for these hot parts of the world, wastewater stabilisation ponds

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(WSPs) seem to constitute an appropriate and sustainable solution. WSPs are highly recommended for warm climate areas in developing countries due to (1) sufficient land availability in a large number of locations, (2) favourable climate (high temperature and sunlight), (3) simple operation and (4) little or no equipment requirement [1]. Indeed, the low operation and maintenance costs of WSP coupled with the effective pathogen removal reported in the literature [2–5] have made them a popular choice for wastewater treatment particularly in developing countries.

With the scarcity of water resources and the increase of irrigation demand, the need for wastewater reuse has encouraged the government of the Burkina Faso to accelerate the construction of wastewater stabilisation ponds in the major cities of the country; WSPs are ideal for reuse projects due to their capability to remove pathogenic micro-organisms. A future increase in the number of WSPs is expected since the construction of WSPs in Sub-Saharan African countries is relevant as it illustrates a sustainable way of management of municipal wastewater. As a consequence, the amount of sludge produced and the need for its management are also expected to increase. Indeed, as in all forms of biological processes for wastewater treatment, there is also production of sludge in WSP. This sludge results from the solids fractions through the settlement and subsequent stabilisation of solids from raw wastewater, and micro-organism biomass developed in the biological treatment itself [1,6]. Unlike conventional treatment plants (i.e. activated sludge process), WSPs do not demand continuous removal of sludge. The sludge accumulated at bottom of the pond is stabilised anaerobically, being converted into water and gases; hence the accumulated volume is less than the settled volume [7]. However, the long-term accumulation of settled material in the ponds can affect pond performance by reducing its volume and, consequently, shortening the hydraulic residence time [6,8] and by changing the shape of the bottom surface [9]. In most cases, it is widely known that in a series of stabilisation ponds, the accumulation sludge is more significant in primary ponds [10]. Therefore, an appropriate management method is required, including periodic sludge removal, processing and final disposal.

The accumulation rate of sludge must be known so that the frequency of sludge removal can be determined and integrated into the pond design, maintenance schedule and budget [10]. Different values of sludge accumulation rates were reported in the literature. In anaerobic ponds (APs), the sludge accumulation rate, expressed as m^3 per capita per year, is in the order of 0.03–0.05 m^3 per capita per year [11] and 0.03–0.10 m^3 per capita per year [12], the lower range is more usual in warm climate areas. In primary facultative ponds (FPs), the sludge accumulation rates are in the range of 0.05–0.15 m^3 per capita per year in France [7] and 0.15–0.20 m^3 per capita per year in Nicaragua [13]. The value of 0.04 m^3 per capita per year often recommended for designing AP with average temperatures above 20°C [4,11,14] has not been widely validated [10] and sludge accumulation rates are believed to depend on temperature and others factors including pond inlet and outlet configuration, pond depth and geometry, hydraulic and organic loading rates may also be contributors. In hot climate, steady state equilibrium can establish when the rates of accumulation and degradation balance [15,16]. However, in cold and temperate climates, the degradation rates seem to be lower and it is observed that the effect of digestion is significant only during the summer [14,17,18]. All these considerations explain the need of establishment of more regional data to support designers.

Up to now, little research has been conducted in Soudano–Sahelian climate conditions to study sludge accumulation in WSPs. The goal of this research is to contribute to our understanding of sludge accumulation rates in different type of ponds, and to produce a useful database for sludge accumulation that can be used for successful pond operation and maintenance based on local data.

2. Methodology

2.1. Characteristics of field sites

This work was carried out at the wastewater stabilisation pond system (12°22′ N, 1°30′ W) of the International Institute for Water and Environmental Engineering (2iE) in Ouagadougou, Burkina Faso (a Western African Country). The site was characterised by the Soudano–Sahelian climate conditions with a long dry season (October–May) and short rainy season (June–September) with rainfall varying between 600 and 900 mm/year. More details on the climatic conditions of the site are described in a previous study [19].

The wastewater treatment system consists of three ponds connected in series: one AP with 2.6 m depth; one FP with 1.4 m depth; and one MP with 0.9 m depth. The plant treats the wastewater from the 2iE campus that is a residential facility. The wastewater passes through a bar screen for pre-treatment before it enters the primary AP. This pond has a vertical geometric form of a truncated cone (with a useful volume of 107 m^3) while the FP (433 m^3 of useful volume) and

MP (236 m^3 of useful volume) are of trapezoidal form. The three ponds had been in continuous operation for 5.5 years (from October 2004 to April 2010).

2.2. Ponds sludge survey methods

Different authors have developed wide methods for sludge thickness measurement in ponds. The manual common method used is the white towel technique [14,20]. The method consists of wrapping a white towel around the bottom of the long wooden pole attached with a tape measure. The depth of the sludge is measured from a boat by lowering the pole vertically into the pond until it reaches the bottom; it is then slowly withdrawn. The depth of sludge is clearly visible through sludge particles trapped on the towelling material. Another methodology for the measurement of sludge depth in AP consists in the use of a pH electrode fixed on a graduated pole [21]. The pH at the liquid sludge interface dropped suddenly as the electrode entered the sludge. The total pond depth was measured by the graduated pole, without the pH probe, and the sludge depth was obtained from the difference. Others apparatus less accessible in developing countries were developed: such as the sludge measuring optical gauge system [10] and the DGPS system more sophisticated [22].

In our study, the two first methods (white towel technique and pH probe technique) were used. Sludge thicknesses were measured during monthly bathymetric surveys of the distribution of sludge in the three ponds from March 2009 to April 2010. The ponds were divided into bathymetric sections spaced by 1 m for the AP and by 2 m for the FP and the MP. The bathymetric surveys were accomplished by the placement of longitudinal and transverse string lines placed on the surface of each pond. Pond depth and sludge thickness were measured at a total of 84 locations over the AP, 95 over the FP and 105 over the MP. At each coordinate, the thickness of the sludge layer was measured using the white towel technique and 10 measurements by pond were realised using the pH probe method for comparison. At each pond, sludge samples were collected using a tube in transparent *Plexiglass* [19]. Basic physical and chemical properties of the sludge samples were measured: total solids (TS), fixed solids (FS) and volatile solids (VS) according to standard methods [23]. Fig. 1 shows the geometric form of ponds with a pre-prepared grid. Three-dimensional surface profiles of the sludge distribution for each pond were created using a surface mapping program (Surfer Version 7.00). This software allows interpolation by Kriging. Water volume and total sludge volume for each ponds were determined

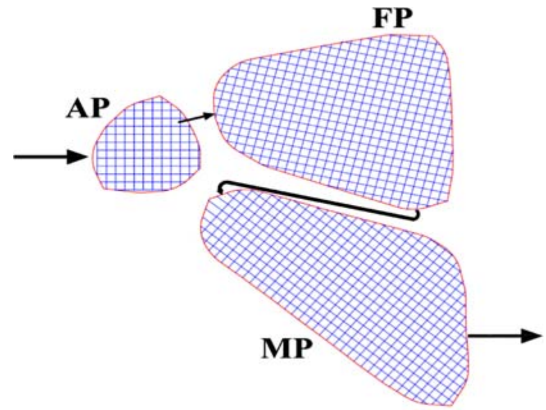

Fig. 1. Schematic representation of ponds and pre-prepared grid established for sludge distribution study. AP = Anaerobic Pond; FP = Facultative Pond; MP = Maturation Pond.

by this software using Simpson's 3/8 rule and integrating. Sludge accumulation rates, expressed as cm/year for the FP and MP, were calculated by dividing the total sludge volume by the pond's bottom area and the number of years of operation. This method was not used for the AP because of its geometric form of a truncated cone that cannot give a realistic accumulation rate in term of height/year. Sludge accumulation rates were also expressed as volume of wet sludge per capita year and as dry weight of sludge per capita year for the three types of ponds.

The quality (chemical oxygen demand, biochemical oxygen demand [BOD], suspended solids and volatile suspended solids [VSS]) of the raw wastewater (based on composite samples) was analyzed at weekly intervals during the entire 5.5 year period. Population equivalents (PE) were calculated on the basis of annual means of the mass of organic matter entering the pond per day (g BOD/d) and the BOD contribution per person per day (60 g BOD/person day).

3. Results and discussion

3.1. Wastewater flow and organic load

During the first four years, the AP received average flow rate of 55 $m^3\,d^{-1}$ and an equivalent organic load of 448 PE. During the last 1.5 years, a transfer of staff members and students to another campus had an impact on the flow of wastewater and the load of organic matter in the ponds: we observed a decrease in flow to 42.16 $m^3\,d^{-1}$, hence a decrease in load to 232 PE. The global equivalent organic load of 389 PE during the 5.5 years operation was determined by weighting the PE values of each operating period by the length of time. The AP operated with an average volumetric BOD loading of 218 g BOD_5 m^{-3} d^{-1}.

3.2. Comparison of two methods for sludge depth measurement: white towel test and pH probe method

Typical pH profile in water and sludge of the AP obtained by pH probe method is shown in Fig. 2, which clearly shows a sudden drop of the pH at the liquid sludge interface. The pH probe method was found to overestimate the heights of sludge compared to the white towel method. In AP, the values of sludge height measured by the pH probe method were found to overestimate the values measured with the white test method from a minimum of 4.5% to a maximum of 6% with an average of 5%. In FP, the values measured with the pH probe method were found to be 39% (minimum 21% and maximum 54%) higher than those obtained with the white towel method. Likewise, in MP, the pH probe method gave values 47% higher (minimum 39% and maximum 79%) than those obtained with the white towel method. Thus, the heights measured in these ponds with the pH method do not express exactly the heights of sludge. This could be due to photosynthesis activities inducing a vertical variation of pH during the day (sunshine hours). Indeed, algal activity in FP and MP increased after sunrise to reach a maximum between 13:00 and 15:00 GMT. This change of algal activity induced high values of pH occurring in the upper water layers in FP and MP and peaks ($\geq$9) concomitant with peaks of photosynthesis. Consequently, different gradients of pH were observed. During the morning (8:00–9h:00 GMT) gradients of 0.6 pH unit/m in FP and 0.7 pH unit/m in MP were observed. After sunrise (13:00–15:00 GMT), the pH gradients doubled and reached 1.3 pH unit/m in FP and 1.9 pH unit/m in MP. Due to these variations of pH induced by photosynthesis activities, the measurements of sludge height by the pH probe method were less accurate. The white towel method is more recommended in the Sahelian climate context: it is economical, reliable and sensitive to the small heights of sludge [24] and the results are directly interpretable. Moreover, the use of the white towel permitted the observation of two distinguishing layers of sludge: the first layer with a distinguishable dark black color at the bottom layer and a dark grey color at the top layer. The same observations were reported in an AP in Mediterranean climatic conditions [18]. The characteristics of these two sludge layers are discussed below.

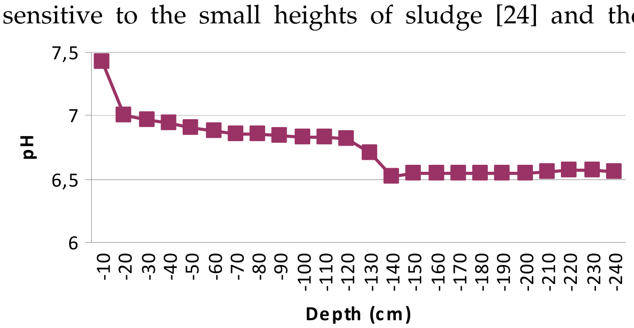

Fig. 2. pH profile in AP.

3.3. Sludge distribution and rate of accumulation

Our previous study [19] detailed the accumulation pattern in AP after four years of continuous operation. The trend was the same after 5.5 years. Fig. 3 shows sludge accumulation pattern viewed in reverse: from bottom up. The unique geometric form (truncated cone) of the AP in this study did not affect the pattern of sludge distribution as compared to the sludge distribution in other geometric forms of ponds reported in the literature. Figs. 4 and 5 show the distributions of sludge, respectively, in FP and MP. In these cases, the distribution of sludge was found uneven. The maximum sludge thickness occurred near the inlets; higher accumulations also occurred in some of the corners and near the outlets of ponds. Similar observations have been reported by different authors [7,10,24–26]. The accumulation in the corners in our case seems to be more linked to the wind direction; the trapezoidal form of ponds can also favour the accumulation at the sides of ponds. This confirms that the distribution of sludge in ponds is primary a function of the pond configuration [12]. Also, the high thickness of sludge around the inlets of the ponds is thought to originate from the residual suspended solids in effluent of preceding pond, whilst that around the outlet originates from biological detritus generated in the pond [27].

After 5.5 years of continuous operation, sludge accumulation represented as a reduction of useful volume of 38.7, 4.5 and 6.5%, respectively, for the AP, FP and MP. This demonstrates that, a majority of sludge accumulation occurred in the primary AP. It is advised to desludge ponds when they are around

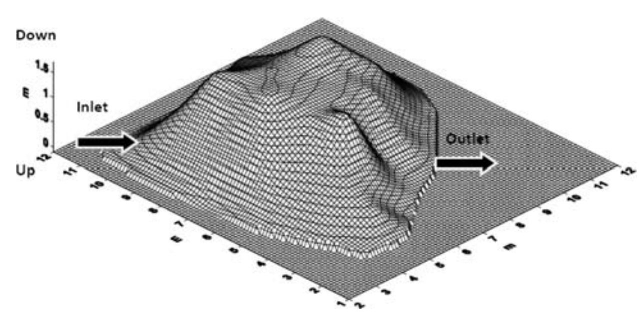

Fig. 3. Sludge distribution in the AP.

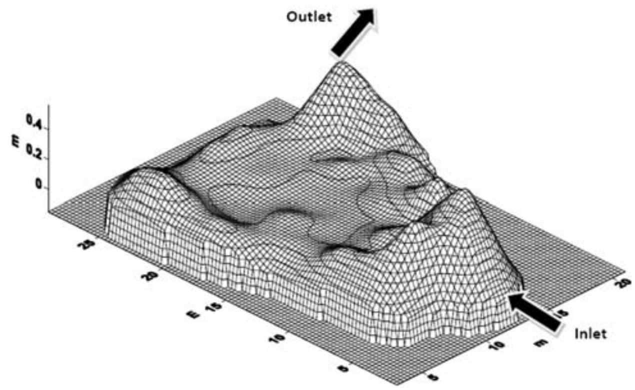

Fig. 4. Sludge distribution in the FP.

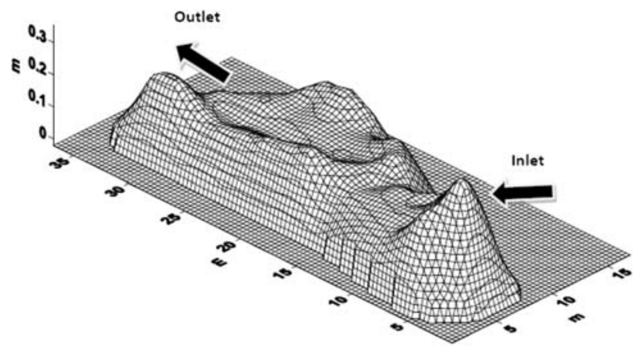

Fig. 5. Sludge distribution in the MP.

one-third full of sludge (by volume) [4]. In this respect, the desludging interval of the AP was calculated to be 4.75 years. In the same way, the desludging intervals of FP and MP were calculated to be, respectively, 40 and 28 years.

The sludge accumulation rates were determined based on the types of ponds: (1) the average annual net increase in sludge thickness for the FP and MP and (2) the per capita accumulation rates on a volumetric and dry weight for all the ponds. Table 1 summarises sludge accumulation rates for the three ponds.

These rates are compared to literature values reported in others climatic conditions (Table 2). For the AP, the accumulation rate of 0.019 m^3 per capita per year is close to the 0.02 m^3 per capita per year measured in Portugal [28] and the value of 0.022 m^3 per capita per year reported in Mexico [10] on AP with relatively similar operating period, depth and hydraulic retention time. This rate is much lower than the design value of 0.04 m^3 per capita per year recommended by several authors in warm climates [4,11,14], the rates of 0.04 and 0.05 m^3 per capita per year found in Colombia [9] and the value of 0.056 m^3 per capita year reported in Brazil [29]. The low accumulation rate of sludge in anaerobic under Sahelian climate could be more related to hot climatic condition that

Table 1
Sludge accumulation rates

Pond	Age	Sludge volume	Accumulation rate		
	year	m^3	cm/yr	m^3/capita yr	kg dw/capita yr
AP	5.5	41.3	–	0.019	1.30
FP	5.5	19.6	1.59	0.009	0.43
MP	5.5	15.5	1.3	0.007	0.26

prevails favoring the sludge anaerobic digestion. However, with an operating period of 15 years (three time older than our AP), it was found a rate of 0.011 m^3 per capita per year on an AP in Spain [30]. The difference could be related to the important transformation processes of compression and anaerobic degradation that take place in sludge layer over time.

The sludge accumulation rates on APs are less than the values observed on primary FPs [7,10]. For the secondary FP and MP, sludge accumulation rates values in our research were, respectively, 0.009 and 0.007 m^3 per capita per year. These accumulation rates are lower than the values of 0.03 m^3 per capita per year reported on a secondary FP in Ecuador [31], and the value of 0.015 m^3 per capita per year reported on a secondary MP in France [25].

The characteristics of sludge for each pond are given in Table 3. The AP sludge had less water content and a higher specific gravity and higher TS content compared to those found in FP and MP. For the specific case of the AP, the two distinguishing layers of sludge (mentioned above) exhibited the following characteristics: the first layer (older stabilised sludge) with a dark black color is characterised by less water content, averaged at 91.6% and a specific gravity of 1.14, while the dark grey sludge (viscous) presented an average of 94.9% for water content and a specific gravity of 1.11. Moreover, regarding the solid composition of the two sludge layers, the following values were found: the VS expressed as percentage of TS were 48.9% in the dark black color sludge layer with 90 g/l of TS and 65.6% in the dark grey sludge layer with 57 g/l of TS. The dark grey sludge layer can be considered as the "volatile sludge layer" (the most biologically active zone where much of the anaerobic degradation occurs in ponds), and the dark black sludge layer as "high- density sludge" composed by more inorganic materials [18].

The monthly accumulations of sludge in AP are presented in Fig. 6. As it can be seen, the accumulation did not show great variation on a monthly basis. This conclusion differs totally to the seasonal fluctuation (an annual sinusoidal pattern)

Table 2
Sludge accumulation rates in the ponds from this research compared to the literature values from other countries

Location	Pond type	Population	Loading rate		Depth	HRT	OP	Accumulation rate			Sludge (%)	References
		PE	gBOD/m^3 d	kgBOD/ha d	m	day	yr	mm/yr	m^3/per yr	kgdw/per yr		
Burkina Faso	AP	389	215		2.6	2	5.5	NA	0.019	1.30	38.7	This study
Portugal	AP	NA	300		3	1.2	1.5	NA	0.020	NA	NA	Gomes de Souza (1987) [28]
Mexico	AP	3,754*	NA		2.72	2.5	5	119	0.022	NA	25.3	Nelson et al. (2004) [10]
Brazil	AP	6.840	NA		NA	NA	21	NA	0.026	NA	NA	Reami et al. (2009) [29]
Colombia	AP	NA	120		4	2	5	NA	0.04	NA	NA	Pena et al. (2000) [9]
Brazil	AP	5.600	NA		NA	NA	5	NA	0.054	NA	NA	Reami et al. (2009) [29]
Colombia	AP	NA	120		3.5	2	2.6	NA	0.055	NA	NA	Pena et al. (2000)[9]
France	AP	6.925	83		3.1	4.6	1.6	120	0.017	1.39	NA	Picot et al. (2003) [17]
Spain	AP	250	NA		3	2.1	15	NA	0.011	NA	55.8	Bouza-Deano and Salas-Rodriguez (2013) [30]
Burkina Faso	SFP	389		277	1.4	8.4	5.5	15.9	0.009	0.43	4.5	This study
Ecuador	SFP	174,561*		NA	1.7	2.32	5.7	40	0.03	NA	13.4	Alvarado et al. (2012) [31]
Mexico	PFP	312*		NA	1.64	24	6	21	0.036	NA	8.2	Nelson et al. (2004) [10]
Mexico	PFP	NA		NA	1.56	10.6	10	21	NA	NA	14.4	Nelson et al. (2004) [10]
Mexico	PFP	501*		NA	2.39	47	15	19	0.02	NA	13.2	Nelson et al. (2004) [10]
France	PFP	150–10,000		[80–240]	[0.9–1.5]	NA	[10–24]	19 [10–27]	0.084 [0.05–0.15]	8 [4.3–14.9]	15−39	Picot et al. (2005) [7]**
France	PFP	8.000		120	1.6	35	8	44	0.21	NA	18	Hammou et al. (1992) [25]
Tunisia	PFP	8.148		260	1.3	9.3	14	10.7	0.025	NA	NA	Jupsin et al. (2009) [22]
Burkina Faso	MP	389			0.9	4.6	5.5	13	0.007	0.26	6.5	This study
France	MP	8.000			1.5	17	8	19	0.046	NA	9	Hammou et al. (1992) [25]
France	MP	8.000			1.3	14	8	6	0.015	NA	4	Hammou et al. (1992) [25]

*Data calculated from sludge volume and sludge accumulation rate given in papers by authors.

**Data were mean, [minimum–maximum values] from 19 primary FPs.

AP = Anaerobic pond; PFP = primary facutative pond; SFP = secondary facultative pond; MP = maturation pond.

PE = Person equivalent; HRT = hydraulic retention time; OP = operation period; NA = not available.

Table 3
Physical characteristics of sludge, mean, [minimum–maximum], in AP, FP and MP at 2iE WSP system

Parameters	AP	FP	MP
Specific gravity	1.1 [1.01–1.13]	1.01 [1.01–1.03]	1.01 [1.01–1.10]
Water content (%)	93.9 [86.9–99.7]	95.3 [92.9–99.8]	96.4 [89.1–99.7]
TS (g/L)	61.3 [3.4–133]	46.5 [16–126]	35.5 [2.2–111]
FS (% TS)	50.6 [28.3–80.5]	58.2 [37.4–83.5]	67.1 [35–82]
VS (% TS)	49.4 [19.5–71.7]	41.7 [16.5–62.6]	32.9 [18–65]

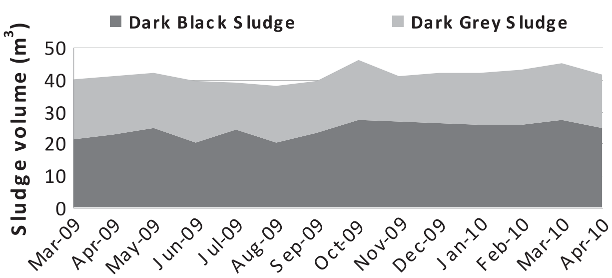

Fig. 6. Evolution of sludge volume on the basis of monthly measures.

reported in APs under Mediterranean climatic conditions [17,18]. These authors observed high values of sludge accumulation during winter and low ones during the summer due to the increased digestion rates at this period. High temperatures are characteristic of the Sahel regions that could explain the continuous digestion of sludge as it accumulates [32].

3.4. Prediction model calibration

From data on the AP in Alsamra, Jordan, a model has been developed to predict the volume of sludge accumulated in AP [33]. The volume of sludge accumulated (V_{AS}), in $m^3\,yr^{-1}$, was expressed in terms of the mass input rates of volatile suspended solids (F_{XVSS}) at the pond inlet, in $kg\,yr^{-1}$, fixed suspended solids (F_{XFSS}) at the pond inlet, in $kg\,yr^{-1}$, total BOD_5 (F_{BOD_5}) at the pond inlet, in $kg\,yr^{-1}$, and the accumulated sludge coefficient (K_{AS}) with following equation:

$$V_{AS} = K_{AS}(1.7F_{XVSS} + 4.5F_{XFSS} + F_{BOD_5})/1,000 \quad (1)$$

K_{AS} represented the biodegradability rate of the settled sludge, the lower the value, the higher biodegradability of settled sludge. This equation is based on the principle that the volume of sludge accumulating in AP is controlled by the non-biodegradable portion of the settled solids that either enter the pond or produced as a result of bacterial activity.

In this study, the mass input rates of F_{XVSS}, F_{XFSS} and F_{BOD5} were determined during the 5.5 years of operation using the time-weighted averages values for each parameter. The annual accumulation of sludge in AP was evaluated to be $7.5\,m^3yr^{-1}$. Thus the accumulated sludge coefficient (biodegradability rate of the settled sludge) of the AP was calculated to be: $K_{AS} = 0.38$. This value was lower than those reported by different authors $K_{AS} = 0.6$ [33] and $K_{AS} = 1.4$ [18,21]. The high temperature in Soudano–Sahelian climate of Ouagadougou induces a high biodegradation of settled sludge by methanogenesis.

On the same basis, a simplified equation can be used but less accurate to estimate the volume of accumulated sludge [33]:

$$V_{AS} = 2.1[(F_{XSS,0})/1,000)] \quad (2)$$

where: V_{AS} = the predicted volume of accumulated sludge in m^3.

$F_{XSS,0}$ = flow rate of the suspended solids at the pond inlet in $kg\,d^{-1}$.

On the same approach, Eq. (3) has been establish in our context for the estimation of the volume of sludge accumulated when only limited information is available.

$$V_{AS} = 1.436[(F_{XSS,0})/1,000)] \quad (3)$$

4. Conclusions

- This study has provided useful data on sludge accumulation in three types of ponds (anaerobic, facultative and maturation) in Soudano–Sahelian climate conditions. The sludge accumulation rate of 0.019 m^3 per capita per year evaluated for the anaerobic was found to be lower than a wide range of sludge accumulation rates reported in the literature under different climatic conditions. Likewise, sludge accumulation rates on secondary FP and tertiary MP (0.009 and 0.007 m^3 per capita per year, respectively) were found to be lower in comparison to the literature values. These data can be used for local design of pond.
- While higher rates of sludge digestion were observed in summer than in winter in temperate climate, a continuous digestion of sludge as it accu-

mulates were observed in this study under Sahelian climatic conditions.

- From the calibration of the prediction model of Saqqar and Pescod [33], the biodegradability of sludge was found to be very high compared to the findings of other authors. This constitutes an advantage of AP use in the Sahelian climatic regions.

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