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Sludge distribution and annual accumulation rate in wastewater stabilization ponds in Northern Greece regions

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ABSTRACT

The designers and the managers of wastewater stabilization pond (WSP) systems need to know the accumulation rate of sludge in WSPs so that the frequency of WSPs sludge removal can be determined. A better understanding of the sludge distribution in WSPs could lead to design improvements to achieve optimal distribution of the sludge for improved efficiency. Therefore, this knowledge needs to be integrated into the pond design, maintenance and management. The first objective of this study was to determine the distribution and accumulation rate of sludge accumulation in full-scale WSP systems consisting of facultative pond and maturation ponds in series, situated in Northern Greece, treating municipal wastewater of rural settlements. The measurements were taken after some years of system operation, without any maintenance. The accumulation rates and distribution of sludge were determined by measuring the thickness of the sludge layer at several locations throughout each pond. The second objective is to assess the relationship between the annual sludge accumulations with organic load treated by the system. Mathematical relationships were derived, correlating the annual sludge accumulation with the mean annual TSS and BOD_5 concentration. These equations can be used to calculate the mean annual sludge accumulation at systems of similar climate.

Keywords: Wastewater; Stabilization pond; Sludge; Accumulation rate; Organic load

1. Introduction

In the last 50 years, wastewater stabilization ponds (WSPs) have been widely used for primary, secondary and tertiary treatment as they are a simple low-cost and low-maintenance process for treating urban wastewater effluents. Wastewater treatment in WSPs exploits the physical and biochemical interactions that occur naturally in aquatic systems to remove pathogens, organics, nutrients, suspended solids and other pollutants. The treatment of wastewater in WSPs occurs due to the removal of several components via sedimentation or transformation of various components by biological and chemical processes. Thereby, at the bottom of the WSPs, a sludge layer is being formed due to the sedimentation of the influent's suspended solids and due to the precipitation of algae and bacteria that grows in the ponds. The amount of the sludge layer can influence the system's performance, as the effective volume and the shape of ponds bottom are impairing. Therefore, periodic sludge removal is required and the long-term sustainability of WSP systems depends on the safe and effective management of their sludge [1]. For the development of WSPs sludge management, the knowledge of accumulation rates of sludge and its characteristics is required. Moreover, the sludge removal frequency from the lakes must be determined and incorporated into the pond design along with the maintenance schedule and the

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operation budget of the WSPs system [2,3]. The most common method to estimate sludge accumulation is the empirically determination of accumulation rate, both as volumetric per capita (m^3 $year^{-1}$) and as the average annual net increase in sludge thickness (mm $year^{-1}$) [4–9]. The accumulation rate, the amount and the distribution of sediments, depend on the temperature, the wind velocity and direction, the age, and the geometry of the pond, as well as on the qualitative characteristics of treated wastewater, such as TSS and BOD_5.

Some of these parameters, such as the wind velocity and direction, and the geometry of the pond affect the sludge distribution [8]. Furthermore, the temperature and the wind velocity have a significant impact on the systems flow dynamic [10] and they affect the treatment efficiency directly and indirectly. Alvarado et al. referred that sludge accumulation patterns in WSPs are strongly influenced by pond hydrodynamics [9]. Some authors demonstrate that greater accumulation can occur in the corners [11–13]. They explained that when the sludge becomes anaerobic and is buoyed up by the gaseous products of anaerobic decomposition, these floating masses are then blown into the corners by the wind [12]. The accumulation in the corners seems also to be more linked to the wind direction [13]. In most of the cases, the deposit thickness is greater nearest to the inlet of the pond, where the majority of the heavy solids, particularly inorganic matter such as sand and grit, settle first and become shallower towards the outlet of the pond [4,11].The volume and the characteristics of the sludge change by time due to many parameters; some of them are the age of the sludge, the compression, the anaerobic degradation and the pathogen inactivation [4]. According to several authors, the accumulation rate is not constant and decreases with time due to anaerobic degradation and sludge consolidation [11]. So, the sediment accumulation rate is depending on the number of operation years. According to several researchers [11] sludge accumulation is generally in proportion to the flow rate and, hence, the loading rate imposed on the treatment plant. Thus, more regional data is needed to determine values for sludge accumulation rate. There have been a number of researchers having worked with this issue and have given variable information about sludge accumulation in several climate conditions, from the cold climate of Alaska [7], to the Mediterranean climate [14,15], from the semi-arid conditions [16] up to warm tropical and sahelian climate [13], from the warm Indonesia climate [17] to the highland conditions of central Mexico regions (2,500 m above the sea level) [4] etc. Most researchers referred to the anaerobic ponds sludge accumulation rate [5,13,14,18–20] and little information has been published about the sludge characteristics changes along with the time processes and the sludge layers [4,11,13].

Only a few WSP systems exist in Greece, representing just 8% of all urban wastewater treatment plants in the country even though WSPs are a simple, low-cost and low-maintenance process for treating wastewater. It is worth mentioning that 90% of those systems are situated in Northern Greece, serving populations ranging from 500 up to 4,000 equivalent populations (e.q.) in rural regions [21]. The 76% of them are located in the Region of Serres, where the research reported herein was held. Three full–scale WSP systems treating municipal wastewater were monitored for approximately 3 years. The first objective of this study was to determine the distribution and accumulation rate of sludge. The second objective was to assess the relationship between the annual sludge accumulations with organic load BOD_5 and TSS treated by the system in order to estimate the average annual sludge accumulation in systems of similar climate. The researchers need to know the accumulation rate of sludge so that the frequency of sludge removal can be determined. Furthermore, it integrates into the pond design, maintenance and management. Moreover, a better understanding of the sludge distribution in ponds could lead to design improvements to achieve optimal distribution of the sludge for improved efficiency [22].

2. Materials and methods

All the three systems are situated in a lowland area in the mainland of northern Greece in latitude ϕ: 41° up to 41°15′ N, longitude λ: 23°21΄ up to 23°36΄ E and altitude from 14 m to 52 m. They consist of a facultative pond and one (N. Skopos system) or two (Vamvakofito and Charopo systems) maturation ponds in series and a limestone rock filter before the final discharge for algae filtration. Every system has a different total hydraulic retention time (HRT) and other design elements (see Table 1).

To determinate the qualitative characteristics, like BOD_5 and TSS concentration for each system, instantaneous samples were taken from the inflow of the 1st pond and the outflow of the last pond, during the years 2006, 2007 and 2012, twice a month, at least while meteorological data was recorded [23,24]. The samples were collected approximately at the same period each morning, but different day of the

Table 1
Variations between manufacturing and current situation on the three WSP systems

WSPs system	Vamvakofito (V)		N. Skopos (N.S.)		Charopo (Ch)	
	Construction	Current situation	Construction	Current situation	Construction	Current situation
Inflow (m^3 d^{-1})	121	121	152	152	137	137
HRT (d)	84.8	68.7	22.9	18.6	85.6	72.4
Area (m^2)	6,016	6,016	2,112	2,112	7,415	7,415
Volume (m^3)[a]	10,262	8,311	3,476	2,827	11,733	9,921
m^3/e.p.	11.0	8.9	3.0	2.4	11.1	9.4
m^2/e.p.	6.5	6.5	1.8	1.8	7.0	7.0

[a]The volume reduction in the current situation is due to the silting of lakes due to the precipitation and non-removal of the sludge throughout the duration of systems operation.

week, according to the suggestion of D. Mara and H. Pearson [25]. The samples were placed into 1000 mL polyethylene bottles, and were transferred immediately to the wastewater laboratory of Serres City. To enhance the range and accuracy of data, each of the samples were analyzed separately twice, with methods proposed by Simplified Laboratory Procedures for Wastewater Examination [26] and the averages were considered. The inflow and the outflow rates were measured with handheld electromagnetic flow meter, with the assumption that the wastewater supply was constant during the day. The climate is classified as dry to semi-humid with excess of water in winter. The average annual temperature is 15.2°C and the average annual rainfall is 448.5 mm. The winds in the area are very weak and their velocity does not exceed the 4 km h^{-1}; so the impact to the ponds accumulation is rather insignificant. The outflow data have been corrected by the mass balance method to eliminate errors from atmospheric precipitation and evapotranspiration by using the Thornthwaite method [27–29], since many researchers believe that the mass balance is the most authoritative method to approach mechanisms and parameters that determine the performance of natural systems and the changes occurring in these [30–32]. Characteristics of the lagoons are given in Table 2.

The ponds of Vamvakofito (V) system are oriented so that their length is aligned on an east–west axis. N. Skopos (N.S.) system is oriented so that the length of the facultative pond is aligned on a south-north axis and the maturation pond is in an opposite orientation. In Charopo (Ch) WSPs system, the orientation of facultative pond is on a north-south axis and maturation ponds are aligned in a south–north axis (Fig. 1).

Operation of Vamvakofito WSPs system began in 1989, of N. Skopos in 1980 and of Charopo in 1994. The influents entered the ponds continuously through single pipes located, in most cases, in the corner of the pond and the entrance and the exit of the wastewater are diagonal. Effluents exit from the upper 0.40 m of the last pond by gravity in a free flow. Sludge had not been removed all these years, nor had the ponds been agitated during the study period. So, the measurements were made after some years of systems operation, without any maintenance. The accumulation rates and distribution of sludge were determined by measuring the thickness of the sludge layer at several locations throughout each pond during the last year of the study in 2012 after 23, 32, 18 years of operation for Vamvakofito, N. Skopos and Charopo WSP system respectively.

The sludge thickness in each pond was measured by using the white towel test as described by Malan [33,34]. The white towel test was chosen because it was economical, reliable and quite sensitive to the small heights of frequently encountered sludge (around 1–2 cm), and the results were quick and easy to interpret. To identify the measurement locations, the lagoons were divided into roughly equal sections by transect lines running the width and the length of the lagoon. The intervals were about 3 m, marked around the edges of the ponds with colored iron sticks. Horizontal measurements were made with a surveying wheel. A rope was floated along each transect line. The measurements of sludge-bottom were made along the transect lines from a boat connected to the marked rope. Attention was given to the days of sampling, in order to avoid both the rainy days and the days with high velocity wind, that could lead to false measurements due to the resuspension of sludge.

Average sludge and bottom elevations were determined using the selected data. For each pond a spot soundings was created with the EXCEL aid with a grid size of 1 × 1 m. Based on these new bottom elevations, the volumes of present ponds situation were estimated. The difference of the two volumes is the sludge accumulation. Dividing the result by the total years of system's operation the average annual sludge accumulation is obtained, since according to Picot et al. [12] the annual accumulation rate is the same after 17.5 years of operation.

3. Results and discussion

The TSS and BOD_5 concentrations of the three WSP systems are quite different from each other, since the same system has significant differences. This is because the supply of the system is with real wastewater of different inflow quantity (Table 1) and quality characteristics (Table 3, Table 4). Thus, significant divergences between their concentrations were recorded. In Tables 3 and 4 the statistic elements of TSS and BOD_5 inflow and outflow concentrations are presented. The thickness accumulation is strongly affected by the pond-loading rate and the treatment efficiency [4,11].

Table 2
WSP systems: locations, dimensions and organic matter loading rates

WSPs system	Vamvakofito	N. Skopos	Charopo
Volumetric loading	3.1 gr BOD_5 m^{-3} d^{-1}	5.6 gr BOD_5 m^{-3} d^{-1}	2.1 gr BOD_5 m^{-3} d^{-1}
Side slope	45°	45°	45°
Maximum constructed depth	F: 2.40 m	F: 2.40 m	F: 2.40 m
	M: 1.50 m	M: 1.50 m	M: 1.50 m
Current depths	F: 1.00–2.40 m	F: 0.75–2.40 m	F: 0.80–2.40 m
	M: 0.75–1.50 m	M: 0.70–1.50 m	M: 0.70–1.50 m
Saturation facultative pond	Width : 39.5 m	Width: 16.0 m	Width: 25.0 m
	Length: 62.0 m	Length: 66.0 m	Length: 75.0 m
1st MPond	Width: 29.0 m	Width: 16.0 m	Width: 65.0–20.0 m
	Length: 61.5 m	Length: 66.0 m	Length: 90.0 m
2nd maturation pond	Width: 29.0 m	–	Width: 25.0 m
	Length: 61.5 m		Length: 75.0 m

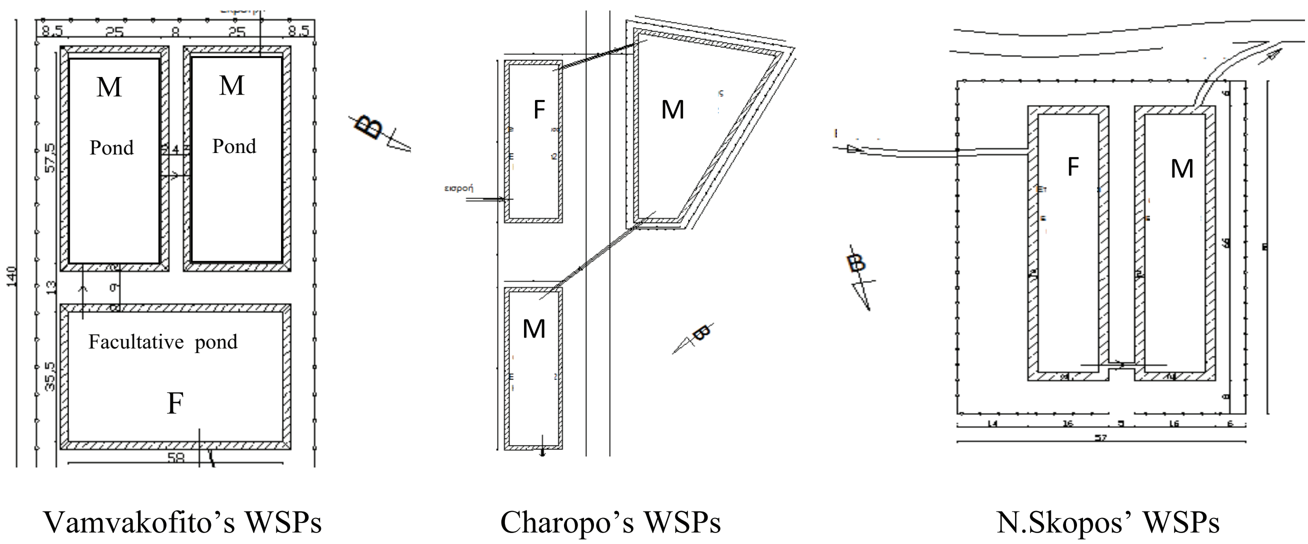

Fig. 1. Ground Plan of WSP systems.

Table 3
The TSS annual inflow and outflow concentrations in three WSP systems (mg L^{-1})

WSPs	Max		Min		Median		Mean		STDEV	
	In	Out	In	Out	In	Out	In	Out	In	Out
V	115.70	45.00	5.30	0.80	58.30	25.93	62.61	26.68	24.06	8.60
N.S.	20.80	15.30	10.60	3.20	15.40	9.35	15.44	5.00	2.39	2.69
Ch	79.70	61.80	12.90	10.10	53.55	41.85	49.22	42.33	7.18	21.42

Table 4
The BOD_5 annual inflow and outflow concentrations in three WSP systems (mg L^{-1})

WSPs	Max		Min		Median		Mean		STDEV	
	In	Out	In	Out	In	Out	In	Out	In	Out
V	217.00	101.19	110.00	39.99	158.00	66.52	160.68	67.23	28.88	24.38
N.S.	204.00	153.41	56.00	15.12	89.50	29.96	105. 03	47.99	44.25	40.60
Ch	201.30	91.72	102.00	49.78	166.45	65.90	155.20	68.26	30.64	12.24

In Fig. 2, the scheme of the bathymetry simulation of Vamvakofito ans N.Skopos WSP systems is presented and in Fig. 3 the Chpropo's one.

Based on the changes of ponds volumes, it was calculated both the sludge volume and the amount of sludge accumulation during the years of operation, as well as the percentage of ponds filled with sludge (r) (Table 5). Moreover, in the same Table (i) the volume of accumulation per ponds area per year ($m^3\,m^{-2}\,yr^{-1}$), (ii) the volume of sludge accumulation per year per m^3 of wastewater inflow rate (S) ($m^3\,m^{-3}\,yr^{-1}$), (iii) the sludge accumulation per year per equivalent capita ($m^3\,yr^{-1}\,p^{-1}$) rate (s), are presented.

The maximum thickness that was measured was 1.40 m and the minimum was 0.10 m, both in N. Skopos system. In all three facultative ponds the distribution of sludge was uneven (Fig. 4). In the maturation ponds, especially in the last one, the sludge distribution was even more layering (Fig. 5) than in the facultative ponds. The maximum thickness that was measured was 0.75 m and the minimum was 0.10 m, both in Vamvakofito system. The maximum sludge thickness occurred near the pond inlet and outlet; higher accumulation also occurred in some of the corners. The same conclusions were reported by other researches [4,11–13].

The different wind direction, the shape and the geometry of the pond affect the sludge distribution. Sludge in the three WSP systems has a different age and density, since the operation of the systems is varied from 18 years (Charopo) to 32 years (N.Skopos) without any sludge removing or other maintenance. This affects the mean sludge thickness; the mean accumulation volume per wastewater annual inflow rate or the mean sludge accumulation per year per equivalent capita (Table 5). It is obvious that the measured mean sludge volume accumulation per year is inversely with the year of operation, presumably due to the density of the sludge.

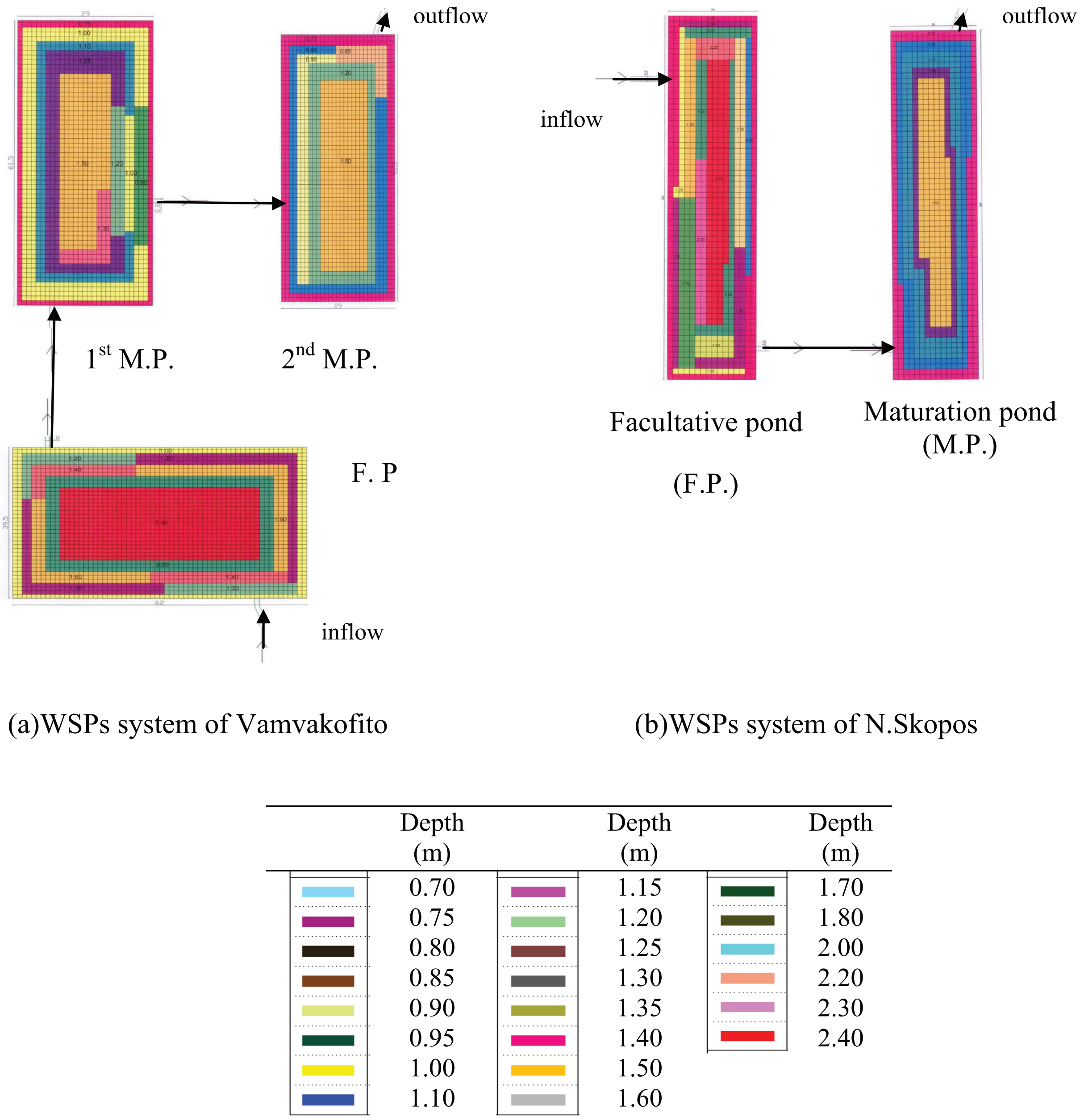

Fig. 2. Bathymetry of Vamvakofito and N.Skopos WSP systems (in 2012).

The correlation between the years of operation and the mean sludge volume accumulation per year per equivalent capita or per wastewater annual inflow rate in present case is strong (Fig. 6) with $R^2 > 0.90$.

The hydraulic residence time (HRT) has a significant contribution to sludge accumulation. As the (HRT) is much less, the overflow rate in the pond was much higher and solids were carried further into the pond before settling to the bottom. The relationship, for these systems, can be expressed by the following formulas:

$$h_a = 0.0081 + 8 \times 10^{-5}\ (\text{HRT})$$
$$R^2 = 0.9736 \qquad (1)$$

where h_a is the mean annual sludge thickness in m and HRT is the HRT in days.

$$s = 0.0013\ \text{HRT} - 0.0038$$
$$R^2 = 0.9767 \qquad (2)$$

where s is the mean volume of sludge accumulation per year per equivalent capita.

Given the mean annual concentration of organic solids TSS (Table 3) and the volume of annual sludge accumulation per m^3 of wastewater inflow in the three WSP systems, a simple relationship is generated (Eq. (3)) by linear regression. According to the Eq. (3) the volume (m^3) of annual sludge

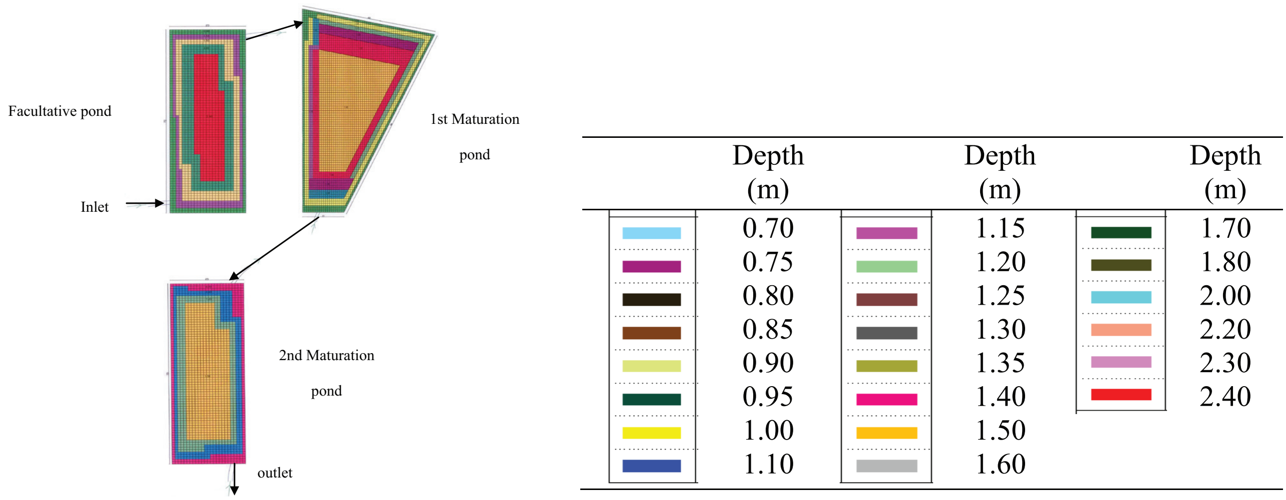

Fig. 3. Bathymetry of Charopo WSP systems (in 2012).

Table 5
Accumulation volume, percentage (r) of ponds sludge filling, sludge thickness, accumulation volume per wastewater annual inflow rate (S), sludge accumulation per year per equivalent capita (s)

WSPs	Total accumulation volume (m³) (T.A.V.)	r (%)	Total sludge thickness (m) ($m^3\,m^{-2}$)	h_a sludge thickness per year (m $year^{-1}$)	S A.V per Q per year ($m^3\,m^{-3}\,year^{-1}$)	s ($m^3\,year^{-1}\,p^{-1}$)
Vamvakofito	1,951.05	19.01	0.324	0.0141	0.001921	0.080
N. Skopos	649.57	18.69	0.308	0.0096	0.000366	0.021
Charopo	1,811.47	15.44	0.244	0.0136	0.002013	0.097

accumulation per m³ of flowrate S can be estimated knowing the mean TSS inflow concentration C_{TSS} (mg L^{-1}).

$$s = 0.0012\,\mathrm{Ln}(C_{TSS}) - 0.0029$$
$$R^2 = 0.9561 \text{ and } 5\text{ mg/L} \leq C_{TSS} \leq 116\text{ mg/L} \tag{3}$$

with $R^2 = 0.9561$ and 5 mg $L^{-1} \leq C_{TSS} \leq 116$ mg L^{-1}.

To assess the relationship between the annual sludge accumulations A_y with organic mean annual load BOD_5 (Table 4) and TSS (Table 3), treated by the system, the multiple regression method is used. The following formula (Eq. (4)) is proposed.

$$Ay = 0.022\,C_{BOD} - 0.902\,C_{TSS} + 138.318 \tag{4}$$

where C_{BOD} is the mean annual BOD_5 concentration (mg L^{-1}). With the following regression statistic characteristic: multiple R = 0.93, R^2 = 0.86, adjusted R^2 = 0.82, standard error 8.48. ANOVA regression: regression df = 2, SS = 3005.69, MS = 1502.28, F-test = 20.87, significance F = 0.001, total df = 9, Regression coefficients: standard error for Intercept = 7.19, for TSS = 0.16 and for BOD_5 = 0.05, t-test are respectively 19.24, –5.53, 0.45, P-value are respectively 2.55×10^{-7}, 8.80×10^{-4}, 0.66, confidence interval 121.32 < 95% < 155.31 for intercept, –1.29 < 95% < –0.52 for TSS and for BOD_5 –0.09 < 95% < 0.13.

In this research, 15% to 19% of the ponds' volumes were occupied by solids (Table 5), resulting in proportional decreases in the design HRT (Table 1). The effective HRTs in the facultative and maturation ponds maybe were even further reduced by the potential formation of preferential flow paths and dead zones according to the research of Nelson et al. [4]. This effect has resulted in lower system performance.

The average, per capita accumulation rates ranged from 0.021 to 0.097 (m³ capita⁻¹.year) (Table 5), whereas in three facultative Mexican ponds, in operation for 6 to 15 years, these rates were from 0.021 to 0.036 (m^3 $capita^{-1}$.year) [4]. In three ponds in Tunisia, the mean rate was 0.029 (m^3 $capita^{-1}$.year) [8]. In France measures of twelve facultative ponds, 3 to 10 years of operation, gave a value of 0.17 m^3 $capita^{-1}$.year [6] other researcher gives the following results: for 19 primary facultative ponds, in operation for 12–24 years, the net average sludge accumulation rate was 19 mm $year^{-1}$. The average per capita accumulation rates ranged from 0.04 to 0.148 m^3 $capita^{-1}$.year (mean of 0.08 m^3 $capita^{-1}$.year). In primary facultative ponds the volume of sludge represented 15–39% of the total volume of the basin [12]. In southern Spain the rate of sludge accumulation of a system operating during 20 years 0.027 m^3 $capita^{-1}$.year in the facultative pond, and 0.015 and 0.09 m^3 $capita^{-1}$.year, respectively, in the maturation ponds [15]. The average accumulation of sludge in Canadian and Alaskan ponds, as reported by Schneiter et al. [7], was from 0.073 to 0.146 m^3 $capita^{-1}$.year, while in United Kingdom over the 4 years of operation, the mean accumulation rate was 0.13 m^3 $capita^{-1}$.year; after the first year, the range was among 0.08–0.16 m^3 $capita^{-1}$.year [34]. It is obvious that the rate of accumulation of sludge is thought

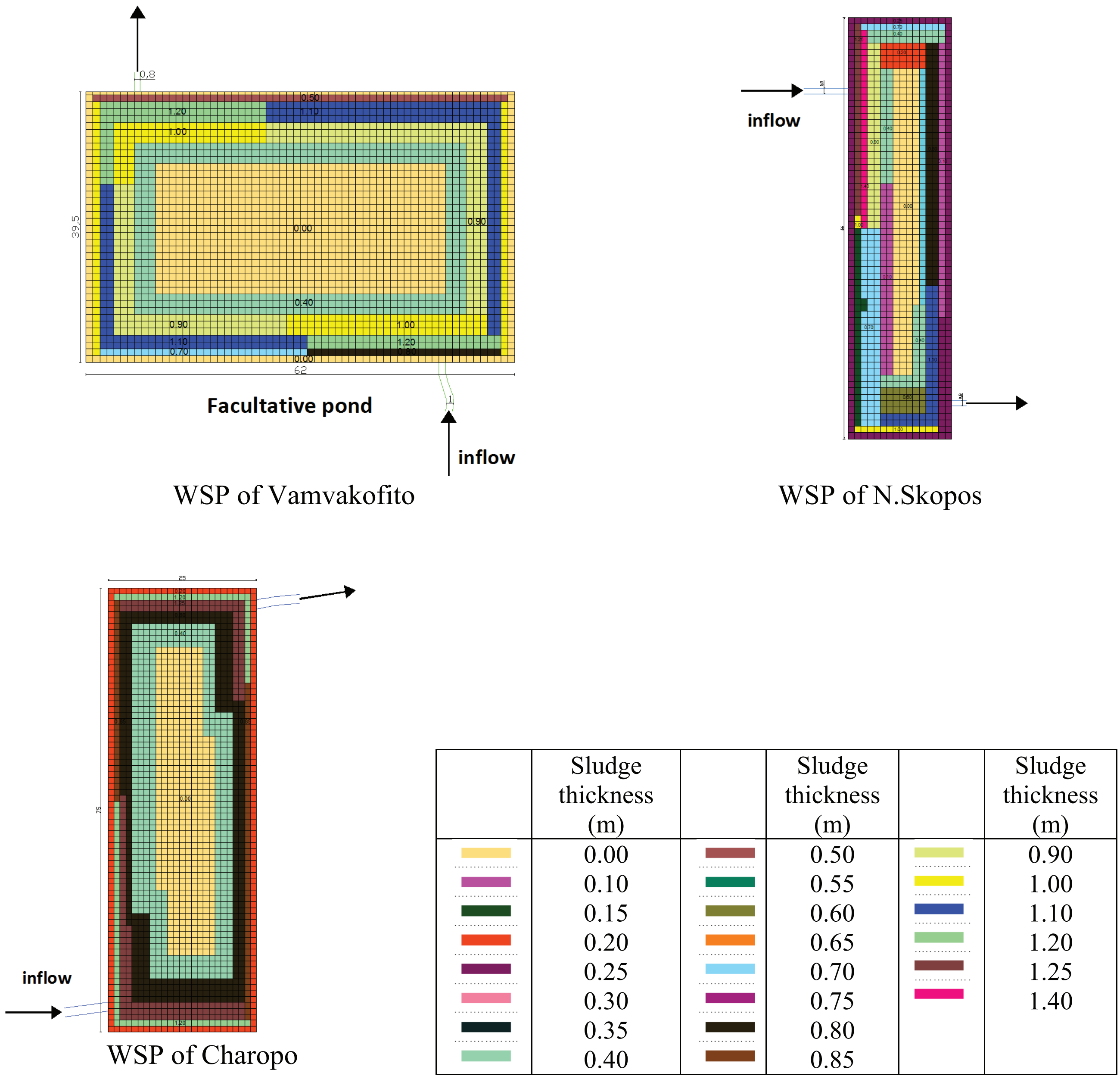

Fig. 4. Sludge thickness distribution in facultative ponds of three systems.

to depend on wastewater characteristics, ambient environment (especially temperature), operational variables and the rate of anaerobic degradation and compression as has been reported in previous researches [4,11,35].

From the results of this research, it can be concluded that 0.09 (m^3 capita^{-1}.year) is a reasonable estimate of the average rate of sludge accumulation in both facultative and (two) maturation ponds systems in the Northern part of Greece regions. In the case of one maturation pond (N.Skopos WSPs system), the rate was much lower that is, 0.021 m^3 capita^{-1}.year; the different accumulation rates may be due to the excessive low TSS load and greater sludge age of this WSP system. The different accumulation rates between the ponds of several countries and geographical regions may be partly due to different temperatures, the inputs wastewater quality, the stormwaters, the infiltration, and other parameters. The volume of sludge accumulation per wastewater inflow rate per year is the same in the two WSP systems and equal to 0.002 (m^3 m^{-3} y^{-1}) (Table 5). The sludge thickness ranged from 9.6 to 14.1 (mm.year^{-1}) and is within the values reported in the literature [11]. These variations were predictable, since the thickness of the accumulation is affected by the amount of solids precipitated in the ponds and the sludge density. This amount depends on the pond loading rate and their treatment efficiency, which are specific for each WSP system. Furthermore, the sludge density depends on the years

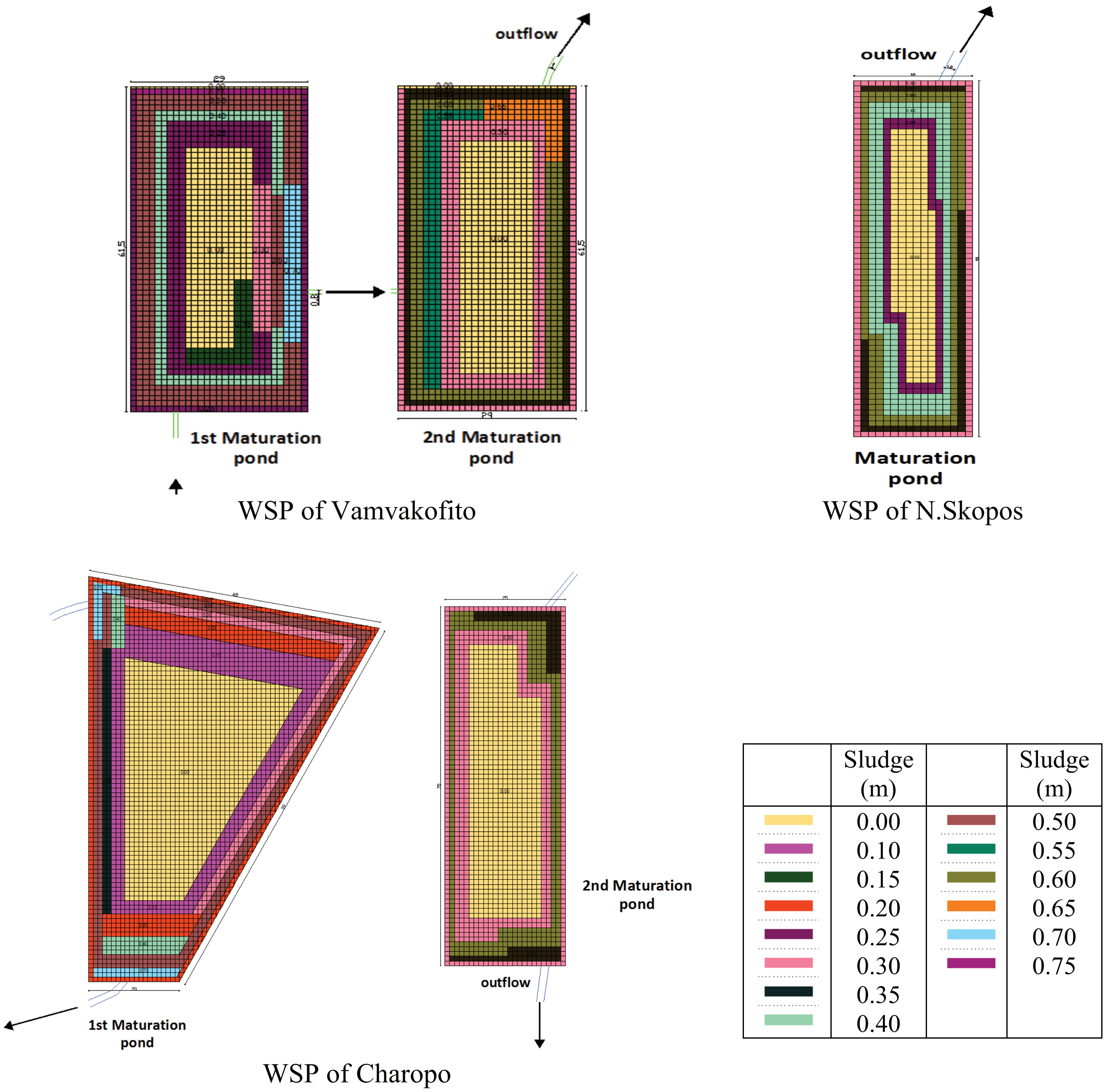

Fig. 5. Sludge thickness distribution in maturation ponds of three systems.

of system operation, which are also different for each WSP system. From the results of this research it is concluded that 13.3 (mm.year^{-1}) is a reasonable estimate of the average rate of sludge accumulation in WSP system, consisting of facultative and maturation ponds in series, in Northern Greece regions.

4. Conclusion

In this research, the average rate of sludge accumulation in both facultative and maturation ponds, in three WSP systems in the Northern region of Greece, is determined. The values of all the three systems were similar. It can be concluded from the results of the research that 0.09 (m^3 person^{-1}.year) is a good proposed value for WSPs in similar climate, wastewater quality and treatment conditions. The volume of sludge accumulation per wastewater inflow rate per year is about the same in the two WSP systems with similar design (a facultative and two maturation ponds in series) and a good proposed value is 0.002 m^3 per m^3 flow rate per y (m^3 m^{-3} y^{-1}). The sludge thickness ranged from 9.6 to 14.1 (mm year^{-1}). As a result of this research, the proposed mean annual sludge thickness is equal to 13.3 mm per m^2 pond area (mm m^{-2}.year). In all three systems, the distribution of sludge was uneven. The maximum sludge thickness occurred near the pond inlet and outlet; higher

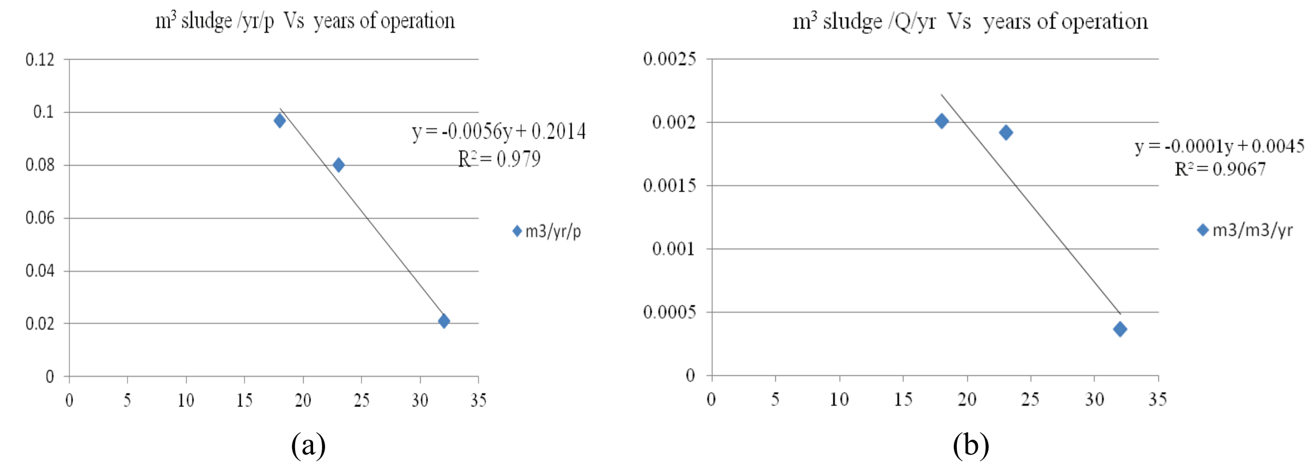

Fig. 6. Relationship between the years of operation and the mean volume of sludge accumulation per year per equivalent capita (a) or per wastewater annual inflow rate Q (b).

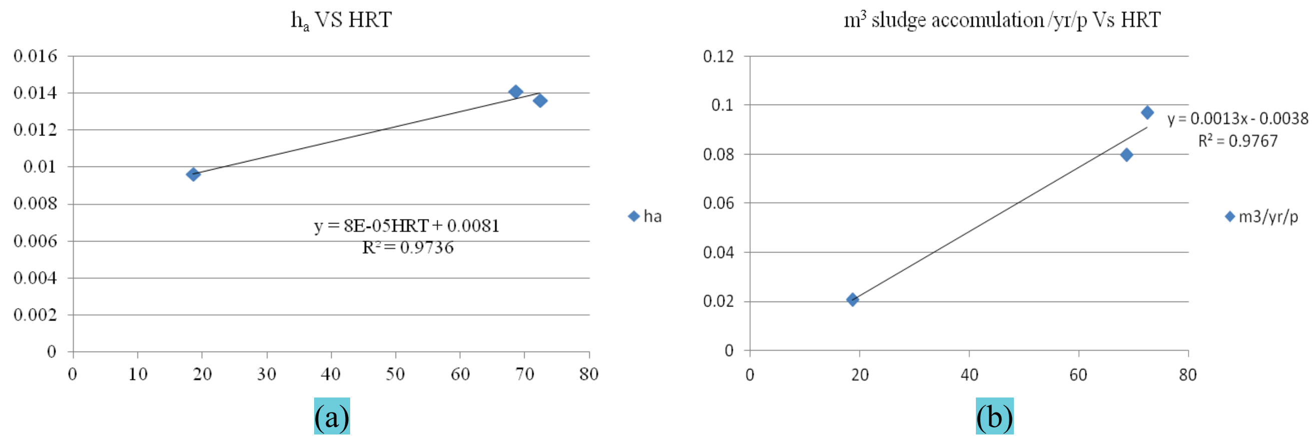

Fig. 7. The relationship between the hydraulic residence time (HRT) and the mean annual sludge thickness h_a or the mean volume of sludge accumulation per year per equivalent capita (b).

accumulation also occurred in some of the corners. The HRT is a significant factor in sludge accumulation. As the HRT is much less, the overflow rate in the pond was much higher and solids were carried further into the pond before settling to the bottom. The relationship, for these systems, can be expressed by the formula: mean annual sludge thickness in m is equal to 0.0081 plus 8×10^{-5} the HRT, in days, with coefficient of determination R^2 equal to 0.9736 or the mean volume of sludge accumulation per year per equivalent capita m^3 $capita^{-1}$.year is equal to 0.0013 the HRT (in days) minus 0.0038, with R^2 equal to 0.9767. Given the mean annual concentration of TSS (mg L^{-1}), the annual accumulation volume of sludge per m^3 of inflows can be estimated with a simple logarithmic equation with coefficient of determination R^2 equal to 0.9561. Given the mean annual concentration both of TSS and BOD_5 (mg L^{-1}), the annual accumulation volume of sludge (m^3 $year^{-1}$) can be also estimated with a simple linear equation, with a coefficient of determination R^2 equal to 0.86. These equations can be used to calculate the mean annual sludge accumulation at systems with similar climate and treatment conditions.

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