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Efficiency and design parameters of waste stabilization ponds in north-east Greece

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ABSTRACT

This paper examines three waste stabilization ponds (WSP) systems located in Vamvakofito, N. Skopos and Charopo, in the Prefecture of Serres. The systems were monitored for approximately four years and design assumptions were compared to real time data. After a series of chemical, biological and microbiological analyses, their efficiency at removing SS, BOD_5, COD, TN, N-NH_4^+, N-NO_3^-, TP, FC, TC, inorganic elements and heavy metals from wastewater was also estimated. Temperature and weather conditions were recorded and the suitability of the effluents for irrigation purposes was examined. Equations were derived, correlating the outflow with the inflow and the complete mix first-order reaction rate constant k_{20} was calculated for BOD and NOD. The assessment of the ponds' behaviour and performance not only provides information about those specific systems, but also offers guidelines for a future design and construction of WSPs systems at regions with similar geographic characteristics.

Keywords: Waste stabilization ponds; Efficiency; Reaction rate constant k_{20}; Performance equations

1. Introduction

Waste stabilization ponds (WSPs) are a simple, reliable, economical and low maintenance process that can be used as an appropriate alternative for wastewater treatment [1–3]. They are very effective in BOD removal [4–7] and they are widely used internationally for the treatment of both urban and industrial wastewater [8–10]. However, in Greece their use is limited, representing just 8% of all urban wastewater treatment plants in the country. It is worth mentioning that 90% of those systems are situated in North Greece, while 76% of them are located at the Prefecture of Serres [11].

This paper presents the qualitative characteristics of three WSPs systems located in Vamvakofito, N. Skopos and Charopo, at the Prefecture of Serres (Greece). The main objectives of the present work were to evaluate the performance and the effluent quality of the WSPs and to estimate the BOD and NOD reaction rate constants k_{20}. The assessment of the ponds' behaviour and performance not only provides information about those specific systems, but

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also offers guidelines for a future design and construction of WSPs systems at regions with similar geographic characteristics. Depending on the results obtained, we can also consider the effluents' suitability for irrigation.

2. Materials and methods

2.1. Site specifications, design and construction references

The latitude of the ponds' location is about 41˚N, the longitude is around 23˚E and the ponds' altitude ranges from 15 to 53 m above sea level. All the aforementioned systems consist of facultative and maturation ponds and a rock filter; they receive only domestic wastewater and are not expected to treat industrial effluent in the future. They were all designed based on the same assumptions: daily flow rate 120 L/p/d, influent organic load BOD_5 45 g/p/d, influent suspended solids (SS) 60 g/p/d, influent *total* coliforms 5×10^6/100 mL, detention time in the first pond 15–30 d for 30% BOD_5 removal, solids concentration at the bottom 6% and removal of the sludge every 5 years. For the maturation ponds' design, the detention time was chosen as 8 d with the effluent's required characteristics as follows: BOD_5 30 mg/L and *total* coliforms 5,000/100 mL. The studies proposed the construction of a facultative pond with a depth of 2.40–2.50 m and three maturation ponds with a depth of 1.50 m, as well as the placement of a rock filter before the final discharge for algae filtration [12]. The rock filter should have a depth of 1.50 m and be filled with gravel of 15 and 75 mm diameter. During the construction, some modifications occurred, mainly to the number and the dimensions of the ponds (Table 1), resulting in smaller retention times than predicted. The ponds were not lined with geomembrane and a compressed layer of clay was applied instead. There is no recirculation in the systems, neither systematic removal of the sludge every 5 years, as predicted. Wastewater is collected through the existing combined (multi-flow) sewer systems and through the main pipes connected to the ponds. The outflow takes place almost superficially. Generally, the construction and maintenance of the ponds, as well as the safety rules, are considered inadequate [13–15].

Information about the three WSPs systems, such as year of first operation, capacity, population and distance from the settlement, are given in Table 2.

The minimum wastewater temperature that was recorded at the ponds was 5˚C, with a mean value during winter 10˚C, while the design was made for a minimum wastewater temperature of 12˚C.

2.2. Sampling and analyzed parameters

In order to investigate the systems' efficiency, instantaneous samples were taken from the inflow of the first pond and the outflow of the last pond, during the years 2005, 2006, 2007 and 2012. Samples were collected approximately at the same morning period, while temperature and other meteorological data, like rainfall, overcast and sunlight, were recorded. The sampling was carried out throughout the year. Sampling frequency was fortnight. On January and July, months with the lowest and highest temperature, sampling frequency was week.

The parameters and the chemical elements that were measured are: SS, BOD_5, COD, pH, TN, N-NH_4^+, N-NO_3^-, TP, FC, TC, DO and 72 more chemical elements like Ag, Al, As, Au, B, Ba, Be, Bi, Br, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Hg, Ho, In, Ir, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, Os, P, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, S, Sb, Sc, Se, Si, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn and Zr.

The samples were placed into 1,000 mL polyethylene bottles, were directly fixed and were transferred immediately to the laboratories for physicochemical analysis by the methods described in the standard methods for the examination of water and wastewater [16]. For the heavy metals' and the other microelements' analysis, a quantity of 200 mL of every sample was filtered through a membrane with 0.45 μm pore diameter and was acidified with nitric acid, so as to

Table 1
Modifications between designs—construction in the studied systems

	Vamvakofito		N. Skopos		Charopo	
System	Design	Construction	Design	Construction	Design	Construction
Ponds[a]	F.M.M.M.RF	F.M.M.RF	F.M.M.M.RF	F.M.RF	F.M.M.M.RF	F.M.M.RF
Pond area (m^2)	6,900	6,016	3,600	2,112	7,950	7,415
Daily flow (m^3/d)	240	121	120	152	276	137

[a]A: anaerobic; F: facultative; M: maturation; RF: rock filter.

Table 2
Systems' year of operation, population and distance from the settlement

System	Year of operation	Capacity (equivalent people)	Population (2011)	Distance from the settlement (m)
Vamvakofito	1989	2,000	1,061	1,200
N. Skopos	1980	1,000	967	600
Charopo	1994	2,300	1,042	1,000

have a final concentration of HNO_3 1%. Afterwards, the samples were placed into bottles of polyethylene of 100 mL and were kept, until their analysis, in fridge (0–4˚C). The aforementioned elements were analyzed only for the years 2006 and 2007, to the ACME Analytical Laboratories Ltd of Canada, with inductively coupled plasma emission spectroscopy.

3. Results and discussion

Table 3 presents the mean, maximum and minimum concentrations of SS, BOD_5, COD, DO, TN, N-NH_4^+, N-NO_3^-, TP, FC and TC, at the inflow and the outflow of the systems under study, as well as the standard deviations and pH values.

The systems' efficiency at SS, BOD_5, COD, TN, N-NH_4^+, N-NO_3^-, TP, FC and TC removal presented significant variations and slightly improved during summer period. The relatively small efficiency and the significant variation of SS removal is possibly due to the fact that the sludge was not removed systematically throughout the operating period of the systems, although according to the study, the sludge should be removed every 5 years. The efficiency of similar systems at Arad (Israel) [17] and Kokkinohoma (Kavala) [11] at SS removal was 94 and 91%, respectively, while the average removals recorded at France, Spain and Cyprus were 76.6, 61.5 and 81.8%, respectively [18]. SS outflow concentrations are considered satisfactory, with a mean value for the three systems 23.47 mg/L, but not suitable for irrigation, as according to the current Greek legislation, the limit is 10 mg/L. Y. Racault reports that the equivalent mean concentration for WSPs at Bretagne was 50 mg/L [19], while the mean value of 178 similar systems studied at France was 60 mg/L [20]. Systems' efficiency at BOD_5 removal is not considered satisfactory. This is mainly due to the insufficient implementation of the project study. The ponds that were constructed were fewer (Table 1) and the minimum temperature was lower than the one predicted by the project study (5˚C instead of 12˚C), thus resulting in a much smaller area than the one required. The efficiency of a similar system studied at Kokkinohoma (Kavala) [11] was 99.5%, with BOD_5 concentration at the outflow 25 mg/L, and another similar system's efficiency at Arad (Israel) was 98% [17]. The average BOD_5 removals recorded at France, Spain, Cyprus and Portugal were 91.7, 70.1, 92.5 and 80%, respectively [18]. COD removal is considered satisfactory, with a mean outflow concentration for the three systems 75.5 mg/L. The maximum value of the unfiltered COD at the outflow was 121 mg/L, with a permissible limit 125 mg/L. The mean equivalent concentration of 178 similar systems at France was 99 mg/L [20], while the average COD removals at France and Cyprus were 84.9 and 89.5%, respectively [18]. The improvement of dissolved oxygen in the effluents was about 80%. TN and N-NH_4^+ removals are noticeably good, achieving even 88 and 90%, respectively. TN mean value for the three systems was 9.68 mg/L, while the limit for most cultivation is 30 mg/L. N-NH_4^+ average removals that were recorded at France and Cyprus were 70.8 and 84.5%, respectively [18]. On the other hand, N-NO_3^- removal can be considered insufficient, ranging among 15 and 19%. TP removal is quite satisfactory. The mean removal for the three systems was 30.2%, whereas the maximum value (75%) was observed during August at Vamvakofito. Bibliographically, it is reported that TP removal was 30–45%, while at Mediterranean regions the annual phosphorus removal can achieve 50% and during summer even 63% [21]. More specifically, the average TP removals that were recorded at France, Spain and Cyprus were 59.5, 52 and 45.1%, respectively [18]. Systems' efficiency for FC and TC removal is not considered satisfactory. This can be attributed to the insufficient design and construction of the ponds, as well as to the inexistence of maintenance. The emissions were much higher than the limits for irrigation according to the current Greek legislation, which imposes TC < 2cu/100 mL for 90% of the samples. As it clear from Table 3, in almost all of the cases, Vamvakofito has the best efficiencies among the three systems that were studied. This can be possibly attributed to the greater area of Vamvakofito's facultative pond per equivalent people, where the major part of the treatment takes place, for almost all the parameters. pH values were always lower than 8, while they never varied outside the recommended ranges 6–9, rendering the outflows suitable for irrigation.

Table 3
Mean, maximum, minimum concentrations, standard deviations of SS, BOD_5, COD, DO, TN, N-NH_4^+, N-NO_3^-, TP, FC and TC and pH values

Concentrations (mg/L)	Mean		STD		Max		Min		Efficiency (%)
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	
Vamvakofito (N = 49)									
SS	62.61	23.04	24.06	8.60	115.70	45.00	5.30	0.80	62.01
BOD_5	212.51	68.08	88.37	12.84	420.00	95.00	110.00	38.00	64.95
COD	299.57	78.57	139.32	12.02	621.00	99.00	132.00	48.00	69.89
DO	0.30	2.20	0.65	0.91	2.50	6.00	0.30	2.20	
TN	24.65	2.95	6.20	1.02	38.33	4.70	12.62	1.12	88.13
N-NH_4^+	19.45	1.96	4.96	0.74	29.97	3.26	9.72	0.56	90.02
N-NO_3^-	0.47	0.40	0.22	0.20	1.02	0.90	0.10	0.09	15.51
TP	6.50	3.51	2.42	1.38	14.60	8.10	2.80	1.30	44.83
FC10^3 cfu/100 mL	55.22	2.60	45.87	1.31	254.00	7.45	2.10	0.15	93.70
TC10^3 cfu/100 mL	106.22	29.02	72.98	19.87	412.50	98.75	18.30	4.10	71.83
pH	7.47	7.63	0.32	0.30	8.09	8.22	6.86	7.09	
N. Skopos (N = 34)									
SS	15.07	9.35	2.39	2.69	20.80	15.30	10.60	3.20	38.83
BOD_5	105.03	53.15	44.25	11.77	204.00	79.00	56.00	33.00	43.47
COD	112.00	59.83	46.52	12.19	216.00	83.00	58.00	35.60	40.81
DO	0.74	3.65	0.36	0.75	2.10	5.50	0.40	2.80	
TN	24.47	15.56	5.73	3.01	35.90	22.50	12.80	10.85	35.25
N-NH_4^+	19.28	12.23	4.50	2.48	28.70	17.60	10.00	8.10	35.57
N-NO_3^-	0.41	0.36	0.20	0.18	0.98	0.86	0.11	0.09	14.29
TP	3.55	2.67	0.78	0.48	5.10	3.70	2.10	1.67	23.55
FC10^3 cfu/100 mL	31.26	4.02	20.83	3.11	106.40	16.80	2.10	0.15	87.55
TC10^3 cfu/100 mL	67.18	17.27	27.10	6.08	129.50	29.65	18.30	6.55	72.98
pH	7.03	7.08	0.40	0.32	8.17	7.95	6.67	6.78	
Charopo (N = 34)									
SS	49.71	38.02	19.86	14.98	79.70	61.80	12.90	10.10	23.18
BOD_5	155.20	77.80	30.64	15.08	201.30	105.40	102.00	49.00	49.66
COD	177.83	88.11	42.21	18.58	245.00	121.00	108.00	52.80	49.99
DO	0.81	3.72	0.22	0.77	1.30	5,50	0.50	2.90	
TN	23.17	10.53	2.73	0.81	29.15	12.55	16.40	8.96	54.21
N-NH_4^+	18.44	8.18	2.39	0.69	23.30	9.90	12.00	6.65	55.27
N-NO_3^-	0.42	0.34	0.19	0.17	1.09	0.95	0.14	0.10	19.45
TP	4.51	3.49	1.32	1.00	6.20	4.90	2.10	1.60	22.32
FC10^3 cfu/100 mL	19.14	6.49	7.92	2.78	37.40	13.40	0.55	0.15	66.11
TC10^3 cfu/100 mL	37.43	12.97	11.14	4.21	77.30	29.75	18.25	5.35	65.45
pH	7.29	7.39	0.24	0.24	7.92	8.08	6.90	7.04	

The concentrations of Ag, Au, Be, Bi, Cd, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Lu, Nb, Nd, Os, Pd, Pr, Pt, Re, Rh, Ru, Sm, Ta, Tb, Te, Th, Ti, Tl, Tm and Yb, were below the laboratory detection limits and therefore they were not valued. The concentrations of the heavy metals and the rest microelements which were analyzed were much lower than the limits set by the Greek and International specifications for wastewater, even for discharge to sensitive receivers, or for irrigation water [17–23]. The concentrations of most elements remained stable over time, with the exception of Al, Cu, Mn and Zn, which presented a significant increase in their concentrations during spring and summer months (inflow samples) [14]. Temperature's increase seemed to have a positive effect to their efficiency, catching up 93, 86 and 57%, respectively. Systems' efficiency at Zn removal did not show stability, neither any connection to the temperature, while Pb and U presented a considerable reduction with increasing temperature [14]. Ca, Mg, K, Na, S, P, Si and Cl displayed the higher concentrations, reflecting their high content in natural waters (Ca, Mg, K, Si), as well as in domestic wastewater (Na, Cl, P, S), due to the use of detergents and liquids of personal care, domestic cleanliness, etc. In general, these WSPs systems did not show good performance in heavy metals' removal [14]. The lack of high pH did not help in the purification process, as it is known that pH causes sedimentation of metal ions when greater than 8 [24]. The instability in the process of heavy metals' removal might be due to the metals' complexation by hydrous oxides [25] and the hydrated humic-type substances [26]. Another important factor of this instability is the percentages of Chelex metal substances [27]. Contrary to the results of this study, other researchers report high rates of heavy metals' removal in WSPs' effluents [27–33].

Working out the measurements taken at the three systems during all those years, we can derive equations correlating the outflow with the inflow. These equations are presented at Table 4 and can provide useful information for regions with similar climate and WSPs systems with similar design. Rank correlation coefficient R^2 and the truth set (limitations) are also presented. The value of R^2 equal to 1 indicates that the model represents absolutely successfully the values of field measurements. Equations with $R^2 > 0.8$ considered a satisfactory approach.

Some other researchers' empirical equations for SS, BOD_5, TN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and TP removal are presented at Table 5 for constructed wetlands. It is true that each system has different design and different number and kind of ponds, thus a comparison is unlikely to be absolute.

Table 4
Relationships between influent (x) and effluent (y) SS, BOD_5, COD, TN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, TP, FC and TC concentrations ($N = 117$)

	Performance equations	R^2	x (mg/L)	y (mg/L)
SS	$y = 0.88x^{0.854}$	0.715	$5.30 < x < 115.70$	$0.80 < y < 61.80$
BOD_5	$y = 9.809x^{0.376}$	0.434	$56.00 < x < 420.00$	$33.00 < y < 105.40$
COD	$y = 15.26x^{0.303}$	0.437	$58.00 < x < 621.00$	$35.60 < y < 121.00$
TN	$y = -0.022x^2 + 1.355x - 9.976$	0.059	$12.62 < x < 38.33$	$1.12 < y < 22.50$
$N\text{-}NH_4^+$	$y = -0.031x^2 + 1.438x - 8.865$	0.062	$9.72 < x < 29.97$	$0.56 < y < 17.60$
$N\text{-}NO_3^-$	$y = 0.080x^2 + 0.793x + 0.002$	0.986	$0.10 < x < 1.09$	$0.09 < y < 0.95$
TP	$y = 0.416x + 1.153$	0.636	$2.10 < x < 14.60$	$1.30 < y < 8.10$
FC	$y = 0.372x^{0.643}$	0.419	$0.55 < x < 254$ (10^3 cfu/100 mL)	$0.15 < y < 16.80$ (10^3 cfu/100 mL)
TC	$y = 0.249x + 2.276$	0.892	$18.25 < x < 412.50$ (10^3 cfu/100 mL)	$4.10 < y < 98.75$ (10^3 cfu/100 mL)

Table 5
Empirical equations for SS, BOD_5, TN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and TP removal

	Performance equations	R^2	N	x (mg/L)	y (mg/L)	References
SS	$y = 1.125x^{0.58}$	0.38	460	$1 < x < 800$	$0.5 < y < 200$	[34]
	$y = 1.047x^{0.818}$	0.78	28	$84 < x < 545$	$23 < y < 191$	[35]
	$y = 0.76x^{0.706}$	0.55	78	$8 < x < 595$	$2 < y < 58$	[36]
	$y = 0.9x + 47$	0.67	77	$0 < x < 330$	$0 < y < 60$	[37]
BOD_5	$y = 0.33x + 1.4$	0.48	100	$1 < x < 57$	$1 < y < 36$	[34]
	$y = 0.11x + 1.87$	0.74	73	$1 < x < 330$	$1 < y < 50$	[37]
TN	$y = 0.52x + 3.1$	0.63	58	$4 < x < 142$	$5 < y < 69$	[37]
	$y = 0.36x + 7.54$	0.59	25	$11.1 < x < 100$	$0.5 < y < 49$	[38]
$N\text{-}NH_4^+$	$y = 0.46x + 3.3$	0.63	92	$0.1 < x < 44$	$0.1 < y < 27$	[34]
	$y = 0.36x + 7.54$	0.54	31	$2.5 < x < 53$	$0.1 < y < 28$	[38]
$N\text{-}NO_3^-$	$y = 0.62x$	0.80	95	$0.1 < x < 27$	$0.1 < y < 21$	[34]
	$y = 0.55x + 3.10$	0.41	16	$0.79 < x < 22$	$0.7 < y < 16$	[38]
TP	$y = 0.65x + 0.71$	0.75	61	$0.5 < x < 19$	$0.1 < y < 14$	[37]
	$y = 0.29x + 1.12$	0.27	27	$1 < x < 13.5$	$0.4 < y < 8.4$	[38]

Table 6
Values of k_{20} for BOD and NOD

WSP	BOD k_{20}, (d^{-1})	NOD k_{20}, (d^{-1})
Vamvakofito	0.307	0.297
N. Skopos	0.528	0.241
Charopo	0.447	0.204
Average	0.427	0.247

Table 7
Values of BOD k_{20} for various countries [22,36,37]

Region	k_{20} (d^{-1})
South Africa	0.230
North Africa	0.300
Israel	0.800
Nigeria	0.920
Malaysia	0.273

According to the equations of Tables 4 and 5, only $N\text{-}NO_3^-$ and TC showed to have a reliable expression, based on the coefficient correlation R^2.

The complete mix first-order reaction rate constant k_{20} was calculated for BOD and NOD with the least squares method for base *e*, based on the measurements and ranged from 0.307 to 0.528 d^{-1} and from 0.204 to 0.297 d^{-1} , respectively. As it can be seen from Table 6, the mean value for the three systems is 0.427 d^{-1} for BOD and 0.247 d^{-1} for NOD (base *e*). For polluted water and wastewater, k_{20} value for BOD ranges from 0.115 to 0.69 d^{-1} for base *e* and from 0.05 to 0.3 d^{-1} for base 10. A typical value of k_{20} is 0.23 d^{-1} for base *e* and 0.10 d^{-1} for base 10 [39]. The value of k_{20} for BOD (base *e*) is high for the raw sewage, ranging from 0.35 to 0.7 d^{-1} and low for the treated sewage, ranging from 0.12 to 0.23 d^{-1} [40].

At Table 7, k_{20} values for BOD (base *e*) are presented for various countries, as they are reported from Bradley [41] and Mara [42].

The system's efficiency for the reduction of BOD, FC and TC can be improved with a combination of activities, such as: redesign of the systems with the proper wastewater temperature and expansion of the units, total repair and replacement of the entrance and exit works, recirculation of part of the flow and design of a deep anaerobic pond before the other ponds [43]. The placement of two or four cross baffles at 1/3 and 1/5 L, respectively, is also a very efficient way to improve the overall water quality [44].

4. Conclusions

The estimation of WSPs' operation is a time-consuming and expensive procedure and requires specialized staff, which is able to interpret the information received. However, it is the only way to improve the ponds' design according to the local conditions.

The results of the chemical analysis and the concentrations of TN, $N\text{-}NH_4^+$, TP and COD, show that the ponds' waters are suitable for irrigation. However, the concentrations of SS, BOD_5, FC and TC do not fulfil the prescriptions for irrigation. Heavy metals and the rest microelements that were measured had concentrations, throughout the year, much lower than the limits prescribed by the Greek and International wastewater's specifications for sensitive receivers, as well as for irrigation water.

BOD and NOD reaction rate constants k_{20} (base *e*) range from 0.307 to 0.528 d^{-1} and from 0.204 to 0.297 d^{-1}, respectively. The mean value of k_{20} for the three systems is 0.427 d^{-1} for BOD and 0.247 d^{-1} for NOD.

The SS, BOD_5, TN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, TP, FC and TC derived empirical equations, correlating the outflow with the inflow; do provide useful information for regions with similar climate.

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