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Design and construction cost of two constructed wetlands treating municipal wastewater

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Abstract: The aim of the paper is to present design details and construction cost of wastewater treatment plants appropriate for small rural communities. These systems include hybrid natural systems such as constructed wetlands (CWs) and stabilization ponds. The advantages and disadvantages of these systems are summarized in comparison with conventional systems (i.e., biological wastewater treatment plants). The processes and the performance of these systems in the removal of various pollutants are described. Design guidelines from various EU countries for CW systems used in municipal wastewater treatment, recommended organic and hydraulic loading rates, and data on the operation of such systems are presented. Finally, the wastewater treatment facilities of two communities, Mesoropi and Moustheni, located in the Municipality of Paggaio, Northern Greece, are presented. For both treatment plants, a hybrid system was designed, consisting in series of a screen, a double chamber anaerobic tank, two stages of vertical flow (VF) CW beds, followed by one stage of horizontal subsurface flow (HSF) CW bed and a chlorination tank. The treatment plants have been designed considering 825 and 1,138 population equivalents for Mesoropi and Moustheni, respectively. The total active treatment areas of the two hybrid systems were 1,782 m^2 and 2,418 m^2 for Mesoropi and Moustheni plants, respectively. The total construction costs were 386,971 Euros and 603,244 Euros for Mesoropi and Moustheni systems, respectively.

Key words: Decentralized wastewater treatment systems; natural treatment systems; constructed wetlands; vertical flow; horizontal subsurface flow.

1. INTRODUCTION

Greece, with a population of approximately 10.8 million inhabitants (ELSTAT 2011), has to comply with the EU Urban Wastewater Treatment Directive (1991/271/EEC), according to which the connection of towns over 2000 inhabitants to wastewater treatment plants is imperative. In Greece, according to data from the Ministry of Environment and Energy (2022), 240 wastewater treatment plants (WWTP) are currently in operation. These units are located in urban areas and in settlements with more than 2000 inhabitants, and treat wastewater generated by households and certain industries of 10.7 million population equivalent (p.e.). In addition, 217 units are planned to be built in settlements with more than 2000 inhabitants to serve 1.1 million p.e. In settlements in rural areas with a population of less than 2000 inhabitants, the estimated wastewater needs correspond to approximately 2.5 million p.e. For treating wastewater, these small communities use domestic treatment plants and mainly septic tanks. For these cases, the construction of sewage networks is not an institutional requirement, but the implementation of "appropriate" wastewater management and treatment systems is recommended (2022). The operating cost of conventional wastewater treatment plants makes these energy-intensive and highly mechanized systems unsuitable for rural communities and settlements (Kadlec and Wallace 2009, Gkika et al. 2014). In these cases (i.e., small rural settlements), a very good alternative is to use natural treatment systems such as stabilization ponds and constructed wetlands (CWs) (Alemu et al. 2016, Angassa et al. 2019, Ioannidou and Pearson 2018, Kotti et al. 2016, Papadopoulos and Zalidis 2019).

CWs is a nature-based technology, which uses renewable energy sources such as the sunlight and the wind in the treatment process, and gravity in water movement. CWs are designed and built to use the physical, chemical and biological processes that occur in the natural environment when soil, water, vegetation, microorganisms and the atmosphere come into contact (Kadlec and Wallace 2009). For these reasons, it is recognized and characterized as green, sustainable and environmentally friendly technology (Kadlec and Wallace 2009, Waly et al. 2022, Kumar et al. 2019, Wu et al. 2015).

CWs, in addition to using mainly renewable energy sources compared to conventional wastewater treatment plants (WWTPs), they also have additional advantages, such as: they require low operation and maintenance cost as they have minor mechanical parts, and therefore, they do not need specialized operators; they have lower or comparable construction cost than conventional WWTPs; they produce low amounts of sewage sludge which can be treated inside the same facility. The main disadvantage of CWs vs conventional WWTPs is the larger area requirement (Kadlec and Wallace 2009, Tsihrintzis and Gikas 2010, Machado et al. 2017, Gikas and Tsihrintzis 2014). The above advantages of CWs make them an attractive treatment alternative for small rural settlements (up to 3000 p.e.) where there is usually land availability at low land price (Nas and Cop 2017, Wang et al. 2017, Abou-Elela 2013, Rizzo et al. 2018, Gikas and Tsihrintzis 2010).

Constructed wetlands may be classified according to vegetation type in emergent, submerged, floating leaved and free-floating (Stefanakis et al. 2014, Papadopoulos and Tsihrintzis 2011, Pavlineri et al. 2017, Pavlidis et al. 2022a, b). They can also be divided according to hydraulics in free water surface (FWS) CWs and subsurface flow (SSF) CWs, which can be further classified based on the flow direction to vertical flow (VF) CWs and horizontal subsurface flow (HSF) CWs (Zhang et al. 2009, Spieles 2022). Treatment of wastewater in CWs is achieved by its passing through gravel-filled beds planted with emergent macrophytes. The design of CWs involves two principal features: hydraulics and pollutant removal. There is extensive literature concerning the design of such systems. However, wetland performance is highly variable due to input flow and pollutant concentrations fluctuations, and changes in weather (Kumar and Dutta 2019). Thus, design and sizing has been based on laboratory studies (Akratos and Tsihrintzis 2007, Stefanakis and Tsihrintzis 2012, Stefanakis et al. 2014) and large-scale experiments (Gikas et al. 2007, 2011, Tsihrintzis et al. 2007, Gikas and Tsihrintzis 2012).

The use of HSF and VF CWs is more common in the treatment of municipal wastewater. The main differences between the two types are the area requirements, the feeding regime and ammonia oxidation. VF CWs compared with HSF CWs have lower area demand, i.e., 1-2 m^2/p.e. and 5 m^2/p.e., respectively. This fact makes VF CW systems more attractive, especially in regions (e.g., Europe) where there is limited land availability (Cooper and Green 1995). The feeding strategy in VF CWs usually consists of a wet period (e.g., 2 days of wastewater inflow) and a dry period (e.g., 4, 6 or 8 days). The feeding regime of VF CWs helps in the oxidation of organic matter and ammonia by aerobic bacteria during the dry period, which contributes to the introduction of oxygen in the substrate. On the other hand, continuous flow is used in HSF CWs which leads mainly to anaerobic environments. Aerobic conditions exist only in the area around the plant root system. Therefore, regarding the removal of nitrogen in VF and HSF CWs, nitrification and denitrification dominate, respectively (Gikas and Tsihrintzis 2014, Vymazal 2011).

A combination of HSF and VF systems, commonly referred to as “hybrid” systems, can also be used for wastewater treatment. Such systems optimize the removal of organic compounds and nitrogen due to the presence of aerobic, anaerobic and anoxic conditions (Gkika et al. 2014, Gikas and Tsihrintzis 2014, Vymazal 2005). In hybrid systems, efficient removal of nitrogen and other pollutants is achieved as the two types of subsurface flow CWs (i.e., HSF and VF) complement each other and the disadvantages of individual HSF and VF CWs are reduced. In hybrid systems, there are various configurations for placing individual HSF and VF CWs in series. Studies have shown that arranging a hybrid system in three stages in series, with VF CWs in the first two stages followed by one stage of HSF CWs gives better results (Cooper 1999, del Castillo et al. 2022). In such hybrid systems, high organic (i.e., BOD, COD) and total suspended solids (TSS) removal, and complete oxidation of ammonia to nitrate ions due to aerobic conditions is achieved in the first two VF CWs; the HSF CW that follows provides further removal of BOD and COD and denitrification due to anaerobic conditions and low carbon content (Waly e al. 2022, Almuktar et al. 2018). Hybrid CWs achieve greater pollutant removal because they combine aerobic and anaerobic processes. Effluents with average concentrations of total suspended solids (TSS) of less than 30 mg/L and biochemical oxygen demand (BOD) of less than 20 mg/L and 30–50% reduction in nitrogen are possible through proper design and construction of these systems (Wallace and Knight 2006, Kadlec 2009). Typical BOD, COD, TSS, total Kjeldahl nitrogen (TKN) and total phosphorus (TP) removal efficiencies in hybrid CW systems, in European countries are 98%, 92%, 96%, 91% and 43%, respectively (Paing and Voisin 2004). The mean removal efficiencies of hybrid systems in Gomati, Chalkidiki Prefecture North Greece (Gikas et al. 2007) and Nea Madytos, Thessaloniki Prefecture, North Greece (Gikas et al. 2011) for BOD, COD, TKN, NH_4-N, TSS, TP were 92.3%, 91.7%, 80.3%, 87.5%, 93.2%, 61.3%, respectively, and 90.8%, 89.0%, 83.9%, 83.8%, 12.3%, 38.8%, respectively.

Municipal wastewater treatment of small communities with use of CWs is already implemented on a worldwide scale (Kadlec and Wallace 2009, Wu et al. 2015). In Greece, such systems have been constructed and operate efficiently in Nea Madytos, Thessaloniki Prefecture (3,000 p.e.) (Gikas et al. 2011), in Gomati, Chalkidiki (1,000 p.e.) (Gikas et al. 2007), in Korestia, Kastoria Prefecture (600 p.e.) (Gikas and Tsihrintzis 2014), in Komara (800 p.e.) and Kyprinos (1,200 p.e.), Evros Prefecture, in Nymfaio (540 p.e.), Asprogia (560 p.e.) and Sklithro (900 p.e.), Florina Prefecture (Gkika et al. 2014). In addition, efforts are made in Greece for the promotion of the use of these systems in other areas of the country.

The purpose of this paper is to summarize CW use and present the design of the wastewater treatment plants of two adjacent communities, Mesoropi and Moustheni, located in the Municipality of Paggaio, North Greece, with a view of contributing to the expansion of constructed wetlands use as wastewater treatment systems in small communities. Furthermore, construction and other costs of these two systems are compared with those derived from empirical models.

2. WASTEWATER TREATMENT PLANTS OF MESOROPI AND MOUSTHENI SETTLEMENTS

2.1 Study area

Two hybrid CW wastewater treatment plants in two adjacent communities, Mesoropi (40°51'10"N, 24°05'05"E) and Moustheni (40°51'04"N, 24°06'53"E), located in the Municipality of Paggaio, Northern Greece were designed (Figure 1). Based on the census data for 1991, 2001 and 2011, the population of Mesoropi was 546, 523 and 456 residents, respectively, representing a 4.2% decrease during the first decade and a decrease of 12.8% during the second decade. The population of Moustheni was 788, 828 and 647 residents for 1991, 2001 and 2011 respectively, representing a 5% increase, initially, and a significant decrease of 22% thereafter. In 2016, when the project was designed, the populations of Mesoropi and Moustheni were 456 and 647 residents, respectively.

Up to date, the sewage of each community is discharged untreated into two adjacent streams, which eventually confluence to Marmara Stream. These streams have been selected as recipients of the CW treated discharge.

2.2 Design parameters

According to the latest data of Paggaio Municipal Enterprise for Water Supply and Sewerage, there is an increase of 80% in water consumption in the summer months, which can be attributed to the increase in population at that time. Thus, the wastewater treatment plants were designed considering current (2016) and future population (2036) equal to 825 and 1,138 p.e. for Mesoropi and Moustheni, respectively. The unit discharge of wastewater is considered to be 150 L/p.e./d; therefore, the total flow of wastewater for Mesoropi is 68 m^3/d during the winter and 124 m^3/d during the summer. The total flow of wastewater for Moustheni is 97 m^3/d during the winter and 171 m^3/d during the summer. The design parameters of Mesoropi and Moustheni facilities are presented in Table 1. The two WWTPs were designed to respect the effluent limits set by the EU Council Directive 1991/271/EEC concerning urban wastewater treatment (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31991L0271): effluent concentration for BOD_5, COD, TSS, TP and total nitrogen (TN) (i.e., TN=TKN + NO_3-N + NO_2-N) of 25 mg/L, 125 mg/L, 35 mg/L, 2 mg/L and 15 mg/L, respectively, or minimum percentages of reduction of 70-90%, 75%, 90%, 80% and 70-80%, respectively.

The climatic conditions of the area are suitable for natural systems, as the average monthly temperature throughout the year, with certain exceptions, is higher than 0^oC. The occasional drop in air temperature will not affect the operation of the system, as the temperature of the incoming wastewater is always above 0^oC and its flow will take place underground for the entire system.

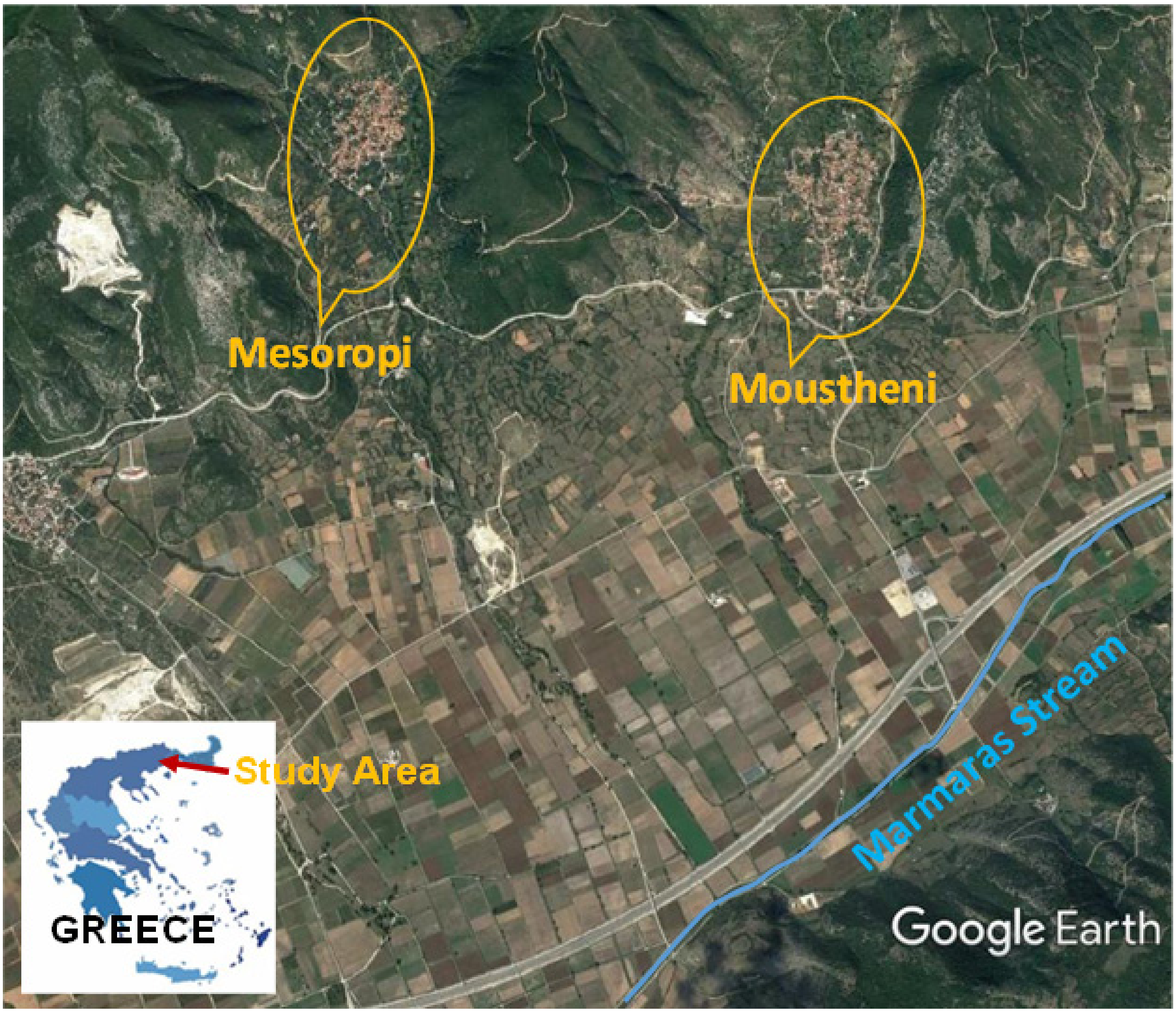

Figure 1. Study area.

Table 1. Design parameters of Mesoropi and Moustheni plants.

Parameters	Mesoropi	Moustheni
Total flow (m^3/d)	124	171
BOD_5 (g/p.e./d)	60	60
BOD_5 load (kg/d)	49.5	68.3
BOD_5 concentration (mg/L)	400	400
COD concentration (mg/L)	600	600
TSS (g/p.e./d)	60	60
TSS load (kg/d)	49.5	68.3
TSS concentration (mg/L)	399	399
TN (g/p.e./d)	10	10
TN load (kg/d)	8.3	11.4
TN concentration (mg/L)	67	67
TP (g/p.e./d)	1	1
TP load (kg/d)	0.83	1.14
TP concentration (mg/L)	6.7	6.7

2.3 Systems description

The two designed WWTPs (i.e., Mesoropi and Moustheni) in terms of layout of the treatment stages are similar to each other and differ only in the dimensions of the CW beds and the anaerobic tank. The layout of Mesoropi facility and the flow diagram along the facility are presented in Figures 2 and 3, respectively. Each system comprises in series: a screen, a Parshall flume for measurement of wastewater flow, an anaerobic stabilization tank consisting of two chambers, two siphons, two treatment stages of VF CW beds followed by one treatment stage of HSF CW bed, a chlorination tank for disinfection purposes and a sludge drying reed bed (SDRB) bed for receiving and mineralizing the sludge accumulated in the anaerobic tank. The suspended solids contained in the wastewater settle in the anaerobic tank and are pumped to the SDRB of the treatment plant.

The wastewater from the settlement reaches the treatment plant through PVC pipes and ends up in the anaerobic tank (AΔ1, AΔ2; Figure 2) after passing through a screen (manually cleaned with grid opening of 1.5 cm) used for the collection of coarse materials, and then through the Parshall flume. The anaerobic tank is made of reinforced concrete (RC) and consists of two equal compartments which operate in parallel (Table 2). The pre-treatment in the anaerobic tank increases the efficiency of the system as it removes various pollutants such as TSS, BOD, COD and organic nitrogen, and reduces the potential risk of clogging of CWs. The hydraulic residence time in the anaerobic tank is about 3 days in the summer and 5.4 days in the winter, and the BOD removal is estimated at about 30%. Sludge accumulated in the anaerobic tank is periodically removed and pumped to the SDRB (KI, Figure 2), which is a VF CW for sludge with a rectangular plan view, planted with *Phragmites australis* (Table 2). This is the only place where electrical energy is used to transport the sludge. Throughout the facility the wastewater is transported by gravity (Figure 2).

The effluent of the anaerobic tank enters the tank of the siphon Σ1 which is made of RC. The siphon operates by gravity and its role is to feed in batches (periodically) the first stage VF CW. The first stage consists of three parallel identical VF CW beds (A1, A2, A3; Figure 2), the second stage of two parallel identical VF CW beds (B1, B2; Figure 2), and the third stage of one HSF CW bed (Γ; Figure 2). The technical specifications of the CW beds of both systems, which are earthen basins, are presented in Table 2. One of the three CW beds of the first stage is fed with wastewater for a period of 2 days (wet period) followed by a resting period (dry period) of 4 days. The alternation of wet and dry periods plays an important role: (a) to maintain aerobic conditions in the beds; (b) to convert the organic residues retained on the surface of the porous media to inorganic substances; (c) to control the growth of biomass attached to the substrate (i.e., the porous media and the rhizome); (d) to ensure that there is sufficient wastewater volume for its good distribution over the entire surface of the bed with a minimum flooding depth of about 5 cm.

The effluent from the first-stage VF CWs is collected in the Σ2 siphon tank, which periodically feeds the second-stage VF CWs (B1, B2; Figure 2). The loading phase for each bed is 3 days. After the second treatment stage, the wastewater with a continuous flow enters the HSF CW which was added mainly for denitrification purposes. Chlorination is the final treatment stage for the disinfection of treated wastewater and is carried out in a RC tank. For the complete waterproofing of the beds, in order to avoid leaching of sewage to the groundwater, high density polyethylene (HDPE) geomembrane, 1 mm thick, is used. In order to avoid damage to the geomembrane (holes, tearings, etc.) that may be caused by direct contact with sharp-edge stones or gravel, special geotextile is placed on both sides. All CW beds are planted with Phragmites australis (6 plants/m^2).

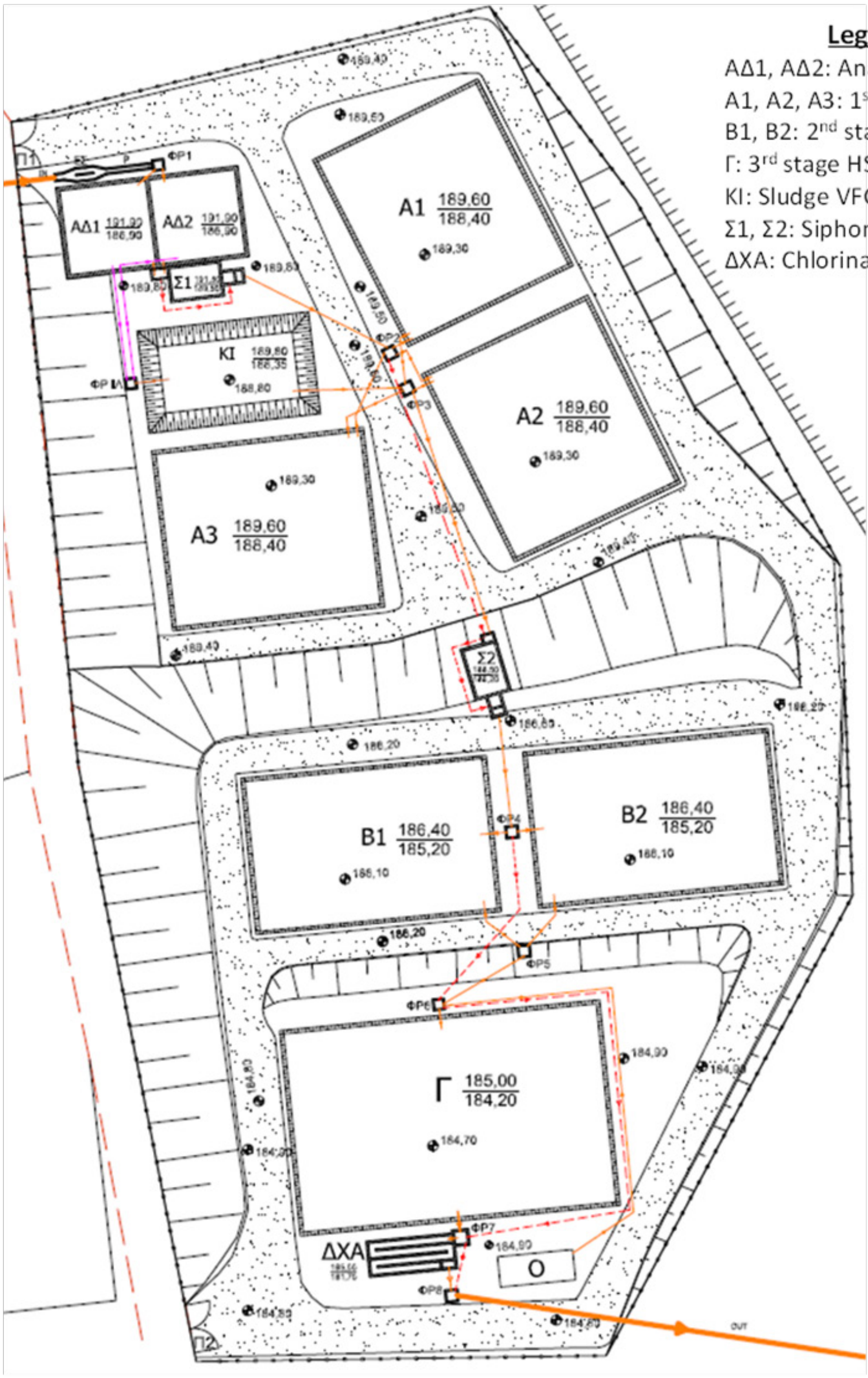

Figure 2. Plan view of Mesoropi WWTP.

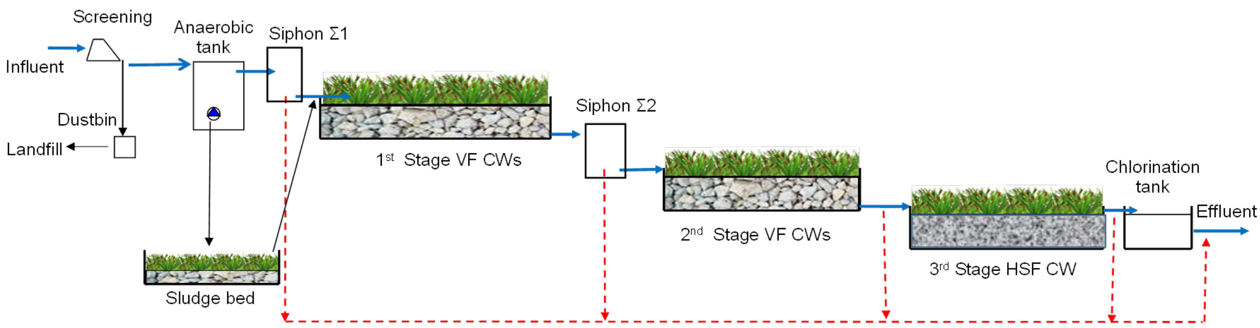

Figure 3. Flow diagram (not to scale) of Mesoropi WWTP.

Table 2. Technical characteristics of Mesoropi and Moustheni facilities.

Parameters	**Mesoropi**	**Moustheni**
Population equivalent (p.e.)	825	1138
Total land area (m^2)	5,759	8,804
Land area per p.e. (m^2/p.e.)	7.0	7.7
Active treatment area (m^2)	1,782	2,418
Active treatment area/p.e. (m^2/p.e.)	2.16	2.12
Inlet works – Screening	Yes	Yes
Anaerobic Tank	98 m^2, 431.2 m^3	112.5 m^2, 508.2 m^3
First and second stage treatment		
Surface area of 1st stage VF CWs (m^2)	3×240.5	3×331.1
Surface area of 2nd stage VF CWs (m^2)	2×240.5	2×331.1
Total thickness of porous media (cm)	90	90
Four porous media layers (from bottom to top):		
cobbles (diameter 30-60 mm)	20 cm	20 cm
coarse gravel (diameter 8-20 mm)	30 cm	30 cm
fine gravel (diameter 3-10 mm)	30 cm	30 cm
sand (diameter 0.2-3.0 mm)	10 cm	10 cm
freeboard height	30 cm	30 cm
Third stage treatment		
Surface area of HSF CW (m^2)	1×420.7	1×590.3
Total thickness of porous media (cm)	50	50
One layer of coarse gravel (diameter 18-30 mm)	50 cm	50 cm
Freeboard height	30 cm	30 cm
Sludge Treatment		
Surface area of VF CW (m^2)	1×119	1×119
Total thickness of porous media (cm)	45	45
Porous media layers (from bottom to top):		
cobbles (diameter 30-60 mm)	20 cm	20 cm
coarse gravel (diameter 8-20 mm)	10 cm	10 cm
fine gravel (diameter 3-10 mm)	10 cm	10 cm
sand (diameter 0.2-3.0 mm)	5 cm	5 cm
freeboard height	100 cm	100 cm
Chlorination Tank	Yes	Yes
MOW	Yes	Yes

MOW: Miscellaneous Other Works (fence, warehouse, internal access roads, landscape).

2.4 Construction and operation cost

For costing of the construction activities of WWTPs of Mesoropi and Moustheni settlements, the detailed cost tables of the General Secretariat of Public Works for the year 2016 were used (General Secretariat of Public Works 2022). The total construction costs are presented in Table 3. The cost of the land acquisition is not included since both facilities will be placed on public land. The total construction costs were estimated at 386,971 Euros and 603,244 Euros for Mesoropi and Moustheni systems, respectively. The construction cost of the two facilities is in accordance with the value reported by Rizzo et al. (2018) for a CW WWTP designed for 1000 p.e. at a cost of 394 €/p.e. However, that system did not include an anaerobic tank.

The operating costs of the facilities studied are small, because: (a) the flow of wastewater through the facility, as mentioned above, is by gravity; (b) pumps are not used except to transport the sludge from the anaerobic tanks to the SDRBs; (c) there is low electrical energy consumption mainly for the lighting of the facilities; (d) there are limited working hours for maintenance and supervision of the facility. It is estimated that the annual electrical consumption for the pumps and lighting is 7.5 MWh/year and 5.9 MWh/year for Mesoropi and Moustheni, respectively. The man-hours required to operate and maintain the system are on average 3 hours/day for Mesoropi and 4 hours/day for Moustheni facilities. Considering the cost of electricity equal to 0.127 €/kWh and man-hour cost 8 €, the operation costs are estimated at 6984 €/year and 9273 €/year for Mesoropi and Moustheni, respectively (Table 3).

Table 3. Construction and operation cost of the studied facilities.

Parameter	Mesoropi	Moustheni
Construction cost (€)	229,973	358,502
Construction cost/p.e. (€/p.e.)	279	315
Total construction cost[a] (€)	386,971	603,244
Total construction cost/p.e. [a] (€/p.e.)	469	530
Annual operation cost (€/year)	6984	9273
Operation cost/p.e./year (€/p.e./year)	8.5	8.2
Operation cost per m^3 wastewater (€/m^3)	0.15	0.15

[a] It includes professional engineers' and contractors' fees (18%), unforeseeable expenses (15%), and VAT (24%).

Various researchers have presented empirical equations of the form $y=a(p.e.)^b$ to express construction costs and area requirements as a function of design population (Kadlec 2009). Gkika et al. (2014) reported the following two Eqs. (1) and (2) for the estimation of total construction cost as function of design p.e. and the total active area required for wastewater treatment, respectively, and Eq. (3) for the estimation of total area required for the facility as function of design p.e.:

$$C=2827\times(p.e.)^{0.738};\ R^2=0.97 \quad (1)$$

$$C=1073\times A_a^{0.667};\ R^2=0.88 \quad (2)$$

$$A_t=4.9\times10^{-4}\times(p.e.)^{1.062};\ R^2=0.97 \quad (3)$$

where C is the total construction cost, A_a is the total active area (ha) which includes area of inlet works, anaerobic tank, CW beds, etc., and A_t is the total area (ha) of the facility. These equations are derived through regression analysis using data of nine hybrid systems designed in Greece (Gkika et al. 2014). These systems present some differences (e.g., for pre-treatment one system has an Imhoff tank, seven of them have anaerobic tank, and one has not an anaerobic tank; only five of them have SDRBs for sludge treatment etc.) (Gkika et al. 2014). Therefore, these differences are incorporated in the above equations.

Based on Eq. (1), the construction costs of the Mesoropi and Moustheni facilities are estimated at 401,488 and 509,048 Euro, respectively, which slightly differ from the actual cost (Table 3) by 3.7%, and -15.6%, respectively. Also, using Eq. (2), the construction costs of the Mesoropi and Moustheni facilities are estimated at 339,590 and 416,260 Euro respectively, which differ from the actual cost (Table 3) by -12.2% and -30.9%, respectively. Therefore, Eq. (1) estimate is closer to the current estimates than Eq. (2). The main reason for these differences is the fact that Eqs. (1) and (2) were derived for 2010 prices, while the cost of the Mesoropi and Moustheni units was calculated for 2016 prices.

Based on Eq. (3), the total area of the Mesoropi and Moustheni facilities are estimated at 8626 m^2 and 6130 m^2, respectively, which only slightly differ from the actual land area (Table 2) by

6.4% and -2.0%, respectively. These results show that Eq. (3) estimates very well the total area required for the installation of the two units.

3. CONCLUSIONS

Conventional wastewater treatment systems are difficult and expensive to operate and maintain in small municipalities. On the other hand, the constructed wetlands technology has proven to be a highly efficient alternative for wastewater treatment of small communities. In addition, in rural areas, where a small percentage of the population has access to a sewage network, these systems are particularly attractive. The two projects will contribute to the upgrading of the natural and man-made environment of the area by treating the wastewater of the communities, which are currently disposed of untreated in the adjacent stream. After the completion of the projects, the wastewater of both Moustheni and Mesoropi will end up treated in the adjacent streams, and finally, in the Marmara Stream. During the dry periods of the year, the wetlands will contribute to the indirect enrichment of the underground aquifer through the stream beds. Moreover, the construction and operation of the facilities will contribute to the economic development of the area. Overall, CWs seem to be the ideal choice for wastewater treatment in small communities in rural areas.

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