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Constructed and riverine wetlands design considerations for domestic and agricultural diffuse pollution treatment—a case study from Turkey

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ABSTRACT

In this study, a riverine constructed wetland system (RCWS) was monitored with the aim to investigate its functionality and cost-effectiveness in treating domestic wastewater. Turkey's second biggest freshwater lake, Eğirdir lake, is becoming polluted directly and indirectly with both domestic and diffuse pollution sources. In this paper we: (1) describe a water quality monitoring campaign on an existing long drainage channel where the majority of pollution originates from untreated urban sewage (2) discuss the design parameters and some considerations for a new RCWS to diminish and eliminate domestic and diffuse pollution loads originating from Gelendost and Yaka. In our design considerations, (1) we projected population increase over a 30-year period, which resulted in total 12,000 population equivalent, including the drainage network run-off originating from agriculture; (2) we aim to achieve 90% reduction in chemical oxygen demand, 70% of nitrogen (N) and 40% of total phosphorus. To achieve design objectives, we propose that the new RCWS consists of six horizontal flow CW and seven FWS systems, laid out within the drainage channel bed itself. This project would represent one of the few systems specifically designed to provide diffuse pollution treatment, and would be the first system of this kind in Turkey.

Keywords: Riverine constructed wetland; On-stream wetland; In-stream wetland; Agricultural return wastewater; Point and nonpoint pollution source; Drinking water resources

1. Introduction

Over the last two decades, water eutrophication caused by nutrients enrichment from point and nonpoint pollution sources (NPS) has become one of the most pressing water quality concerns worldwide [1,2]. NPS originating from urban and agricultural activities have been recognized as the primary contributor of phosphorus and nitrogen loading in the US and across the world [1,3,4]. Recent coastal surveys

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have revealed that 78 percent of the assessed continental US coastal area and approximately 65 percent of Europe's Atlantic coast exhibited symptoms of eutrophication [5]. The situation is equally alarming in the Mediterranean Sea, where coastal eutrophication has been attributed to human activities including habitation, industry, agriculture, fisheries, military facilities and tourist resorts [6,7].

Point source pollution is definable and thus controllable, therefore development of treatment technologies and regulatory framework for attenuation of this type of contamination has been much more advanced when compared to diffuse, NPS [1,8]. Moreover, as diffuse pollution originates from a variety of run-off sources, including agriculture, urban development, forestry and industry, controlling this type of contamination requires integration of technological, socio-economical and educational factors [8,9].

Constructed wetlands are used worldwide to treat wastewater from a wide array of sources by removing a variety of water contaminants (e.g. organic matter, nutrients) [10,11]. Wetlands have been utilized for centuries for the treatment of wastewater produced by residential settlements. In most cases, however, they were considered merely as storage basins before discharge to final receiving waters, not as real depuration plants [12]. Since the first investigations of wetlands as treatment plants in Germany 60 years ago [12] constructed wetland systems (CWS) have become globally recognized as a new generation of a low cost, energy efficient treatment technology for treatment of a variety of domestic, municipal, industrial and agricultural effluents originating from point pollution sources [13–15]. Along with the worldwide expansion of CWS, a number of researchers investigated sediment control abilities and nutrient retention of riverine (in-stream) wetlands [16–19].

Riverine wetland is defined as the area that is adjacent to a stream or a river with perennial flow, typically occurring in the floodplains major rivers, but can also occur along smaller rivers, streams and channels. They consist of interacting biological and physical components that substantially alter biogeochemical fluxes and, as such, have potential to play a significant role in nutrient retention [20]. In addition, riverine wetland vegetation can keep stream channels intact by slowing run-off and by evenly distributing the energy in run-off. Wetland vegetation also regulates stream temperature by providing streamside shading [20].

Over the past several years, there has been an increasing interest in investigation of riverine wetlands as an effective tool to control diffuse pollution originating from the agricultural and urban run-off. In addition to having the potential to provide treatment of wastewaters and stormwater run-off of different origins in the same medium, the construction of riverine wetlands is simpler and more economic when compared to other engineered wetland systems [18].

Extensive research has been conducted for water pollution control in in-stream wetlands. Abdel Naby [21] and Shehata [22] proved that water quality might have significantly improved the in-stream wetland system. Salva [23] investigated the potentiality of the in-stream wetland treatment system that can be used on existing drains in Egypt, and showed that system might improve water quality.

There are no application-oriented studies related to wastewater pollution control in stream wetlands in Turkey. In this regard, it is of utmost importance to make efforts to practice on those wetlands. In this regard, studies on wastewater pollution control in stream wetlands are of great importance.

Lake Egirdir is one of the most significant drinking water sources of Turkey, and domestic and agricultural return wastewater and run-off originating from the Gelendost and its immediate vicinity are among the most important pollution sources threatening this lake. Domestic wastewater originating from the settlement of Gelendost is discharged into a drainage channel previously created for agricultural return wastewater; and domestic wastewater from the settlement of Yaka will also be discharged to this channel in the near future. Therefore, it is the main objective of this effort to provide design for a riverine wetland system in order to achieve the treatment of mixed domestic and agricultural diffuse run-off pollution and improve the water quality of Lake Egirdir.

2. Methods

2.1. Description of the studied area

Lake Egirdir, located in the Mediterranean region, is the second largest freshwater lake in Turkey and is a tectonic lake that lies in northern–south direction in the north of Egirdir district (Fig. 1). The lake narrows in its middle, in the east–west direction. This narrow region is 2-km wide. The reservoir part that is located to the north is called the Hoyran part, while the one located to the south is called the Egirdir part. It is 50 km long in the north–south direction [24].

The location for this project was selected based on domestic wastewater discharges originated from both settlement units (Gelendost and Yaka) having the current population of 5,500 and 2,399 p.e., respectively. The primary wastewater discharge point is approximately 2.5 km outside Gelendost and Yaka settlements and also has the most intensive agricultural activities

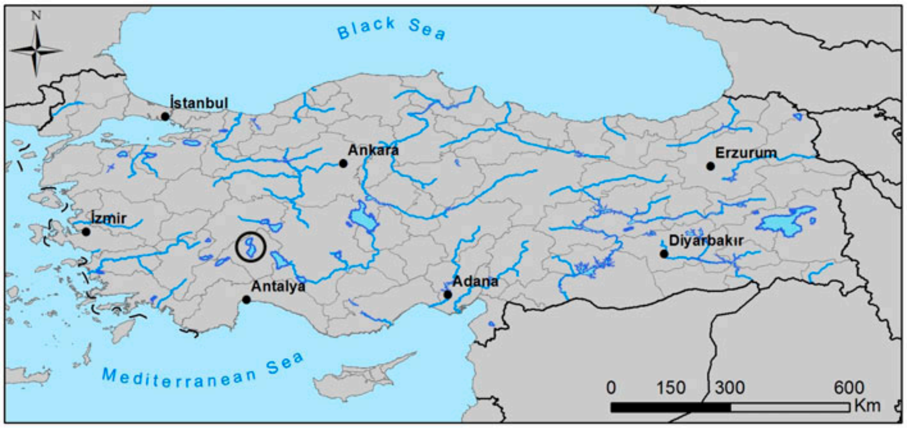

Fig. 1. Location of the study area (Source: TUBITAK MRC Environment and Cleaner Production Institute Geographic Information System Group).

particularly for apple production. Among the two settlement units, Gelendost settlement has sewer infrastructure implemented for about 40% population. On the other hand, Yaka settlement does not still have a sewage system infrastructure and thus domestic wastewater treatment relies on individual cesspools. Along with the commissioning of a designed treatment system, Yaka settlement unit will be able to convey its wastewater to the treatment system using the sewer system to be constructed. Additionally, Gelendost settlement unit will also complete its own sewer infrastructure. Wastewater flow to sewer systems has changed from 63 L/person to 100 L/person based on similar studies conducted in the area of Eğirdir Lake Basin [25,26]. Therefore, wastewater flow reaching to sewer systems is estimated as 100 L/person.

2.2. Drainage canal analyses for RCWC design and potential treatment

Wastewater of elendost and Yaka settlements were analysed and wastewaters were collected from the study area according to the “Water pollution and Control Regulation of Turkey” and transported immediately to laboratories by their preservation procedures. For the onsite measurements, a WTW Level 1 Multi Parameter brand instrument was used to measure temperature, pH, EC and dissolved oxygen. All other analyses were carried out in TUBITAK MRC accredited laboratories in accordance with standard methods [27]. Water quality parameters measured included suspended solids (SS) (SM-2540 D), biochemical oxygen demand (BOD_5) (SM-5210 B 5-Day), chemical oxygen demand (COD) (SM-5220 B Open Reflux Method), total nitrogen (TN) (SM-4500 Norg. B), total phosphorus (TP) (SM-4500 PD Stannous Chloride Method), As (SM-3114 AAS -Hydride), Hg (TS 2537 EN 1483 1999–04), Pb (SM-3111 AAS -Flame), Cd (SM-3111 AAS -Flame) and Ni (SM-3111 AAS Flame).

Riverine wetlands are generally built on existing creeks, channels or river systems. In fact, their design differs from other CWs. This is because the RW system is designed in accordance with the structure of an existing channel or creek. The plant species to be used for treatment typically consist of species that are currently found in the channel or creek. In this study, the six horizontal flow (HF) CW and seven FWS were used due to narrowness of the drainage channel being used for treatment. This number would decrease in case of a wider drainage channel.

3. Results

3.1. Wastewater characteristics

Typical characteristics of wastewater sampled in the main discharge point of Gelendost settlement unit are presented in Table 1.

Typical COD/BOD_5 ratios for municipal raw wastewater range 1.25–2.5, while it is generally 10 or more for industrial wastewater [28]. Results in this study revealed a COD/BOD_5 ratio higher than four, indicating that, apart from domestic wastewater, there were other sources of wastewater in a discharge point due to lower biologically oxidized organic portion. Despite some small-scale industrial activities in the area, wastewater analyses at the discharge point revealed that heavy metals and minerals concentrations were within permissible levels by EU standards [29]. However, upon the implementation of a riverine constructed wetland system (RCWS), continuous monitoring of heavy metals will be performed along with other water quality parameters.

Table 1
Wastewater characteristics of Gelendost settlement unit's main discharge point

Parameters	Units	Concentrations
Dissolved oxygen	mg/L	0.3
pH	–	7.2
EC	μS/cm	1,019
BOD_5	mg/L	95
COD	mg/L	412
Total-N	mg/L	57
Total-P	mg/L	13.19
Total suspended solids	mg/L	147
Temperature	˚C	22.6
As	ppm	<0.005
Hg	ppm	<0.0005
Pb	ppm	<0.0045
Cd	ppm	<0.001
Ni	ppm	<0.005

3.2. Treatment potential of drainage channel

Almost the entire drainage channel, which design and hydraulic conditions is quite similar to the wetland system, is fully vegetated. Variations in concentrations of TSS and BOD along the channel in terms of temperature and dissolve oxygen are shown in Fig. 2 while, and Fig. 3 displays TN and the TP in terms of temperature and dissolved oxygen. As shown in Figs. 2 and 3, organic matter and N and P nutrients decreased along the channel. While the levels of dissolved oxygen were similar up to a distance of 1,500 m away from the main discharge point, an increase was observed from this point until the end of the channel. This relevance shows that the majority of the oxygen required for oxygen consumer substances like organic matters and ammonia can be provided through natural sources, i.e. gas exchange with the atmosphere, contribution by plants roots in the bottom

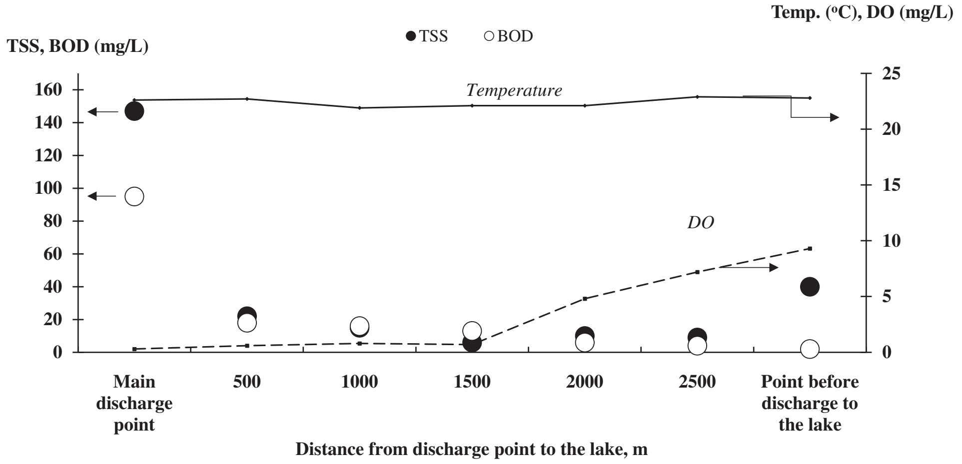

Fig. 2. Change of the TSS and the BOD concentrations along channel, depending on temperature and the DO.

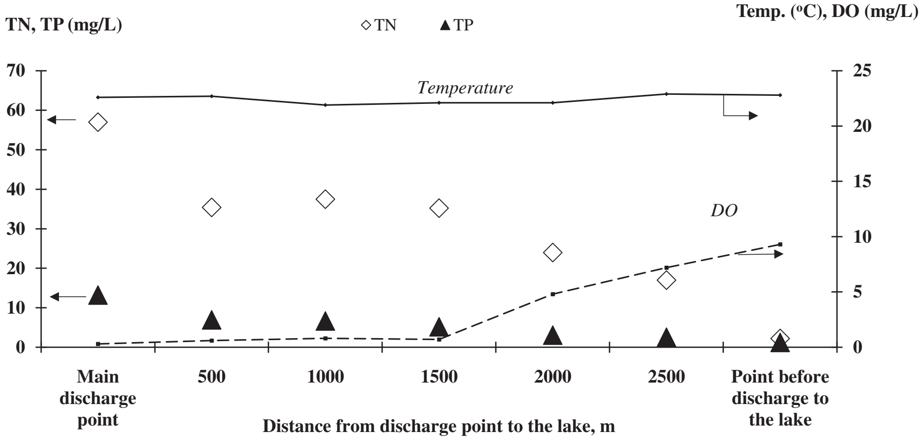

Fig. 3. Change of TN and the TP concentrations along the channel, depending on temperature and the DO.

part of the channel and so on, in the first 1,500 m of channel.

While the mean COD removal was 89% in the first 1,500 m of the channel, this ratio was 72% between the first 1,500 m and the end of the channel. However, while the mean TN removal was 38% in the first 1,500 m of the channel, this value was 72% thereafter to the end of the channel.

The increase in dissolved oxygen up to approximately 10 mg/L toward the end of the channel demonstrates the good self-treatment capacity of the channel as an appropriate recovery of the consumed oxygen without any other effective discharging point located downstream of the main one. While TSS decreased from 150 to about 40 mg/L, the BOD decreased from 95 to about 2 mg/L.

Both TSS and BOD decreased by approximately 74 and 98% along the channel, respectively. However, the TN concentration was approximately 2.2 mg/L at the end of the channel, with a successful removal of 96%. Denitrification was supposed to be more important than other processes (such as plant uptake, nitrification and adsorption) in gradually lowering TN concentrations together with the increase of oxygen after 1,500 m. A review of other studies indicates that biological denitrification mechanism is the most relevant pathway for the removal of nitrogen through the channel in [30]. Although this study did not measure the residence times of pollutants in the channel, we must take into account the effect of long residence times on those high treatment efficiencies.

Mitsch [31] reported in-stream wetlands reduced phosphorus by 63–96% and sediment by 88–98%. In this study, TP concentrations exhibited a continuous decline throughout the riverine wetlands. While the TP concentration was 13.2 mg/L at the beginning of the channel, this value was reduced to 1.2 mg/L at the end of the channel. The average TP removal efficiency of 91% can be regarded a good self-purification capacity of the stream. However, the change of the TP concentration through the channel must be monitored over the years so as to determine when to reach the maximum phosphorus removal capacity. The properties of filling materials of the channel and dimensions of the channel length have important implications in phosphorus removal.

A major part of the phosphorus can be removed from the water column by sorption on the substrate and organic matter, or by plant uptake in riverine wetlands [32]. While the temperature did not vary much along the channel, the EC value was reduced from 7,669 μS/cm to about 1,019 μS/cm, similar to the TSS removal observed. In addition, because EC is also an indicator of the salinity of water, the channel treatment provides a better quality effluent as it enters the lake.

Average treatment performance of the HF constructed wetlands is shown in Table 2 [33]. As is shown in Table 2, the treatment performance of the drainage channel operating in the style of a HF CW system is higher than the values recorded in the literature for the HF CWs. This result shows us the planted and well-designed drainage channels that can be transformed to a wastewater treatment system such as HF CWs.

3.3. Treatment system components

In order to accommodate both the projected population of 12,000 p.e., with a domestic wastewater flow of 120 m^3/d, and the potential agricultural run-off, the RCWS will consist of several treatment systems, covering a total area of 18,500 m^2 (Fig. 4).

Similar to traditionally constructed wetlands, the first treatment unit will be a screen system with a 5 mm pore diameter, followed by, a sedimentation pond (surface area 395 m^2, approximate depth 1.4 m) for further settlement of organic and suspended materials. The sedimentation pond will be deepest at the influent point (max. 2.5 m) decreasing gradually to 0.3 m depth at the effluent end (Figs. 5–7).

Table 2
Average treatment performance of HF CWs treating municipal and domestic wastewater [33]

	Concentration (mg/L)			
	In	Out	Removal efficiency (%)	n[a]
BOD_5	178	32	80.7	746 (261)
TSS	113	22.3	68.1	975 (319)
TN	53.0	29.8	39.4	419 (182)
TP	8.7	4.4	40.9	643 (247)

[a] The number denotes the number of annual means with number of systems in parentheses.

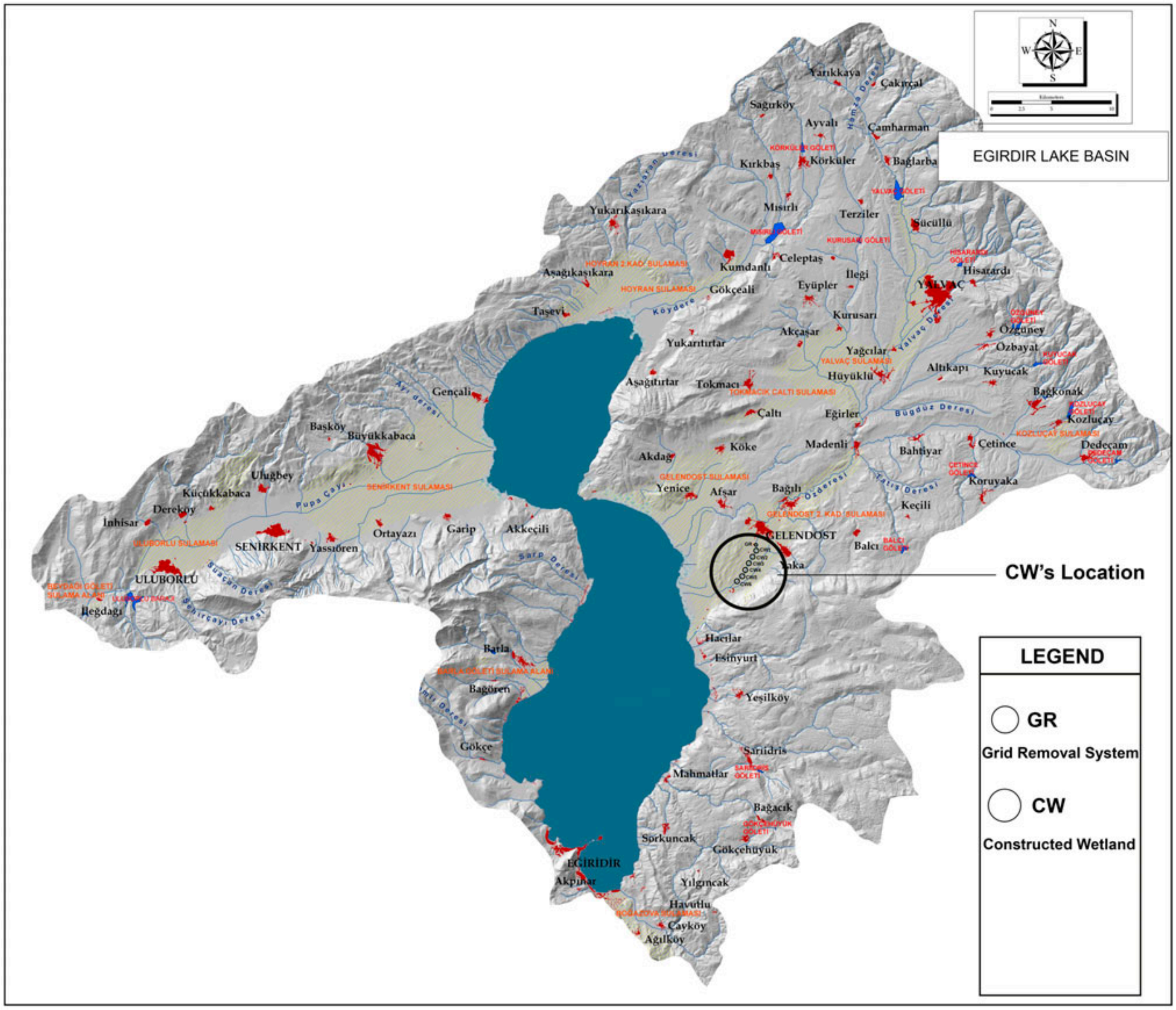

Fig. 4. Location of the riverine wetland systems (Source: TUBITAK MRC Environment and Cleaner Production Institute Geographic Information System Group).

SS and accumulated sludge will be emptied via submersible pump (with blade mounted type) and placed in the next treatment unit, a sludge drying bed. Sludge drying beds are the most common sludge dewatering process for small- to moderate-sized wastewater treatment facilities (WWTF) in the US, Mediterranean region and other parts of the world [34]. However, they often have insufficient performances in terms of dry matter content and mineralization [35]. Therefore, sludge drying reed beds for WWTF sludge dewatering and mineralization have been used in France since the early 1990s. Today there are approximately 300 systems built in France, with a treatment capacity between 200 and 12,000 people equivalent [35]. The sludge treatment bed to be constructed will have surface area of 2,200 m^2, depth 1.5 m (0.5 m filled with gravel and 1 m of free board) and will be planted with *Phragmites australis*.

3.4. Constructed wetland treatment system

The constructed Wetland Treatment System will consist of six subsurface HF cells, covering 1,000 m^2 each and seven free surface flow cells constructed

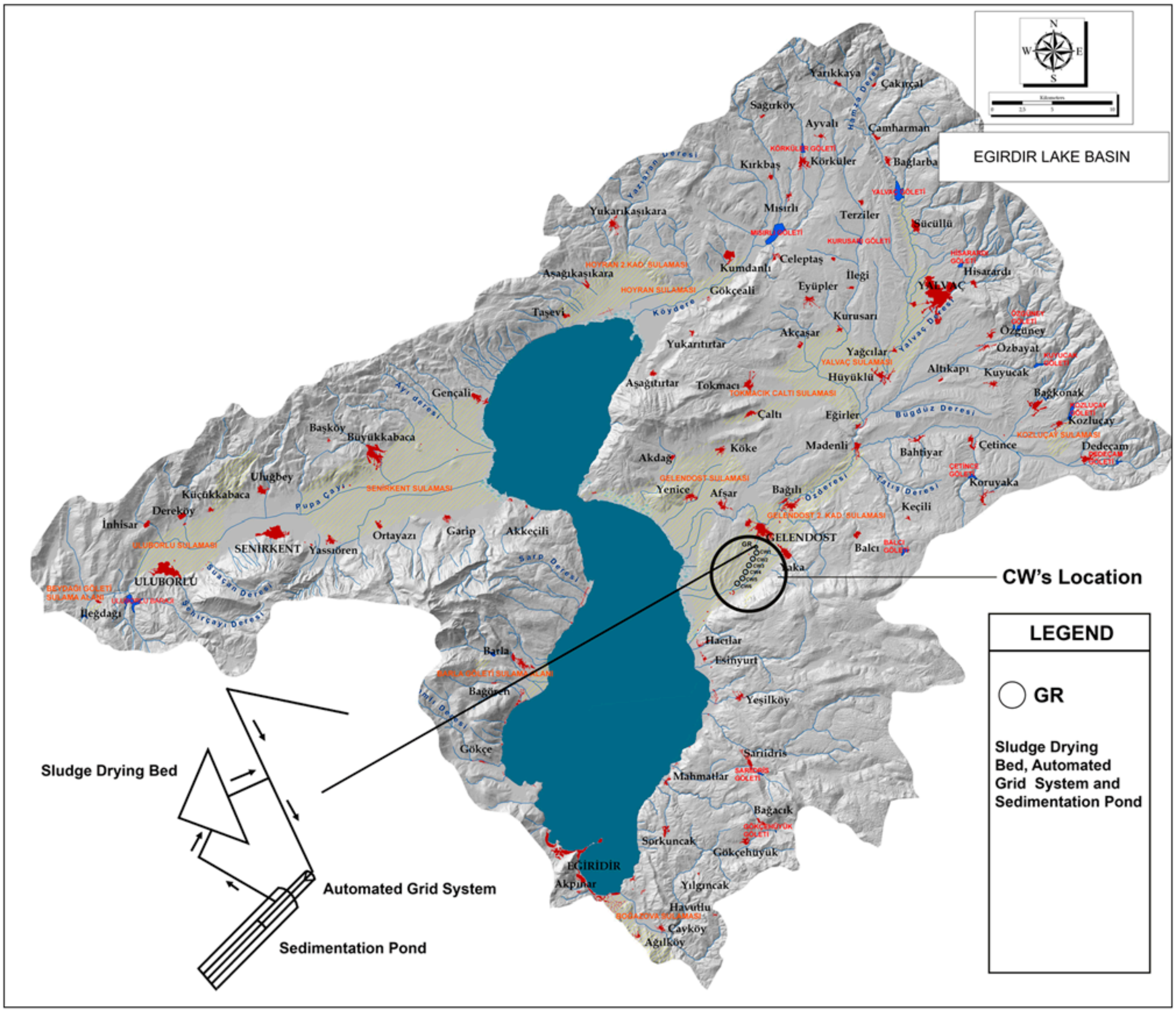

Fig. 5. View of sludge drying bed, automated grid system and sedimentation pond (Source: TUBITAK MRC Environment and Cleaner Production Institute Geographic Information System Group).

consecutively (e.g. a HF followed by FWS), Table 3 shows all design considerations of the treatment units.

HF wetland cells will be planted with *Typha* spp., which is one of the most common aquatic plants found in river channels in Turkey (Fig. 8).

3.5. Free water flow system (FWS)

There are currently seven units of FWS constructed wetland in place in Gelendost natural treatment system (Fig. 9). This system has a shallow treatment bed, it does not use any inert material as filling material (such as gravel, sand and stones) and has submerged, emergent and floating water plants, parts of the this system which are near the water surface are aerobic, while its bottom sections such as soil and turf, which provide the plants a rooting surface are generally anaerobic [36]. Free surface flow systems with a shallow depth within a canal and regulation of low flow speed with stems and plant remnants provide piston flow conditions, especially in narrow and long canals [37].

3.6. Treatment potential and design of existing drainage canal and it's comparison with the system being done

Wastewater measurements have been done at certain intervals starting from the discharge point in the canal, which currently serves as an agricultural

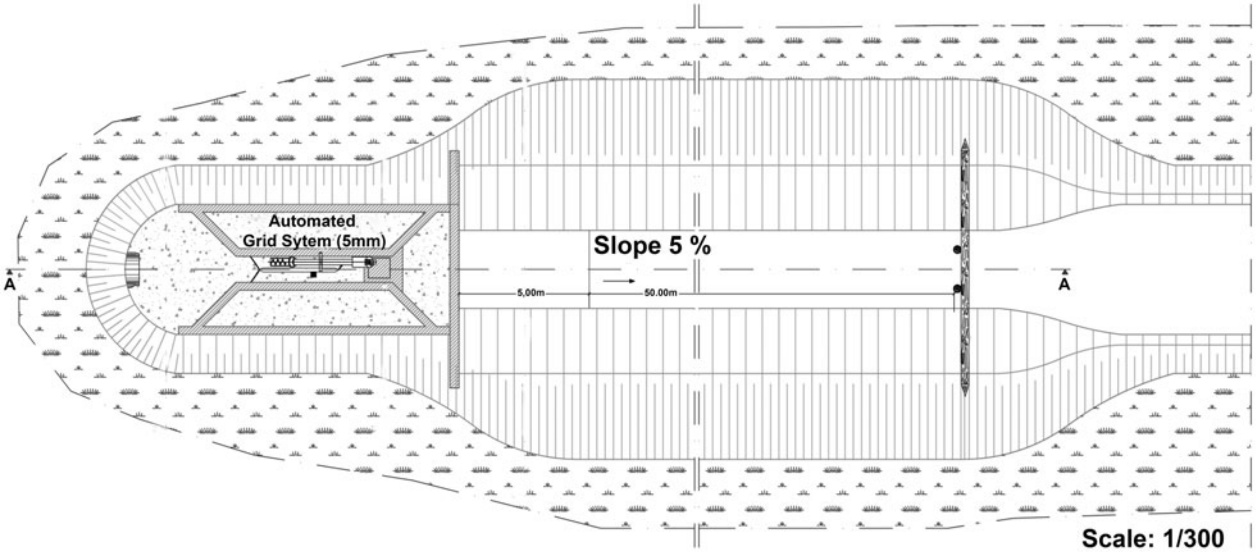

Fig. 6. Plan view of sedimentation pond system.

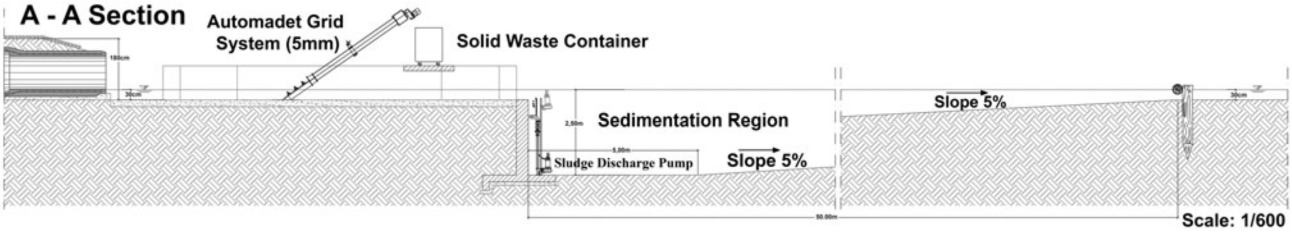

Fig. 7. A-A Section of sedimentation pond system.

drainage canal and also receives 40% of domestic wastewaters of Gelendost settlement unit. The drainage canal has 9 km length to Egirdir Lake and canal width gradually narrows until it reaches the lake. As given in Figs. 2 and 3 on the basis of TSS, BOD,TN and TP concentrations measured along the channel, the treatment potential of the current system is not satisfactory but the system could be more aesthetically pleasing and it could have increased nutrient removal. However, when considered from point of both aesthetics and potential treatment. Therefore, both an economic and environmental-friendly treatment system was gained when a natural discharge channel or creek including constructed wetland plants was restored in accordance with treatment purposes.

3.7. System cost

The current channel is 2 m wide and it carries agricultural and domestic wastewater to Lake Egirdir. In this study, only the channel width is increased from 2 to 5 m, using an existing treatment system effectively instead of making a new treatment system can enable cost reduction. However, the depth of gravel used in the system is lower compared to the other horizontal subsurface flow (HF) systems which also significantly reduce the costs. The total cost of the system was approximately €74.000 according to year of 2007. In addition, the total cost of sludge drying bed, automatic grid, and pumping costs was €148.000. Thus, the total cost of the project was €222.000 (about 19€/pe) except cost of the land, because, the channel was already used as drainage channel by the local authority. However, the cost of sewer system construction for approximately 60% of the population in Gelendost and all of Yaka settlement is not included in the above-stated costs. The major part of the capital expenses required the installation of a CWS is lined up as follows according to their importance: land, excavation, stuffing material, piping structure, vegetation and other

Table 3
Design parameters of Gelendost and Yaka settlements riverine constructed wetland

Design parameters	
Population (person)	12,000
Minimum daily flow (m^3/d)	1,200
Maximum hourly flow (peak coefficient = 3.38) (m^3/hour)	169
Maximum daily flow = 3 × (minimum hourly flow) (m^3/d)	3,600
Daily flow per person (L/person d)	100
Daily organic load per capita (grBOD_5/capita-d)	40
Minimum water temperature (℃)	6
Water height inside the treatment bed (HF) (m)	0.40
Hydraulic slope inside the treatment bed (S)	0.010
Treatment bed slope (%)	1
Porosity of treatment media (n) (Note: Gravel diameter 32 mm)	0.40
Theoretical hydraulic conductivity (ks) (m^3/m^2 d)	50,000
Inlet organic load (after pre-treatment) as BOD_5 (mgO_2/L)	400
BOD_5 removal at 6℃ (%)	90
BOD_5 removal at 14℃ (%)	92
BOD_5 removal at 24℃ (%)	99
Total treatment area (m^2)	18, 500
Configuration of the systems	6 HF beds + 7 FWS beds
Plant species inside the treatment beds	*Thpha* spp.
Geometry of the HF treatment beds	
Single HF treatment bed area (m^2)	1,000
Length (m)	200
Number of the beds	5

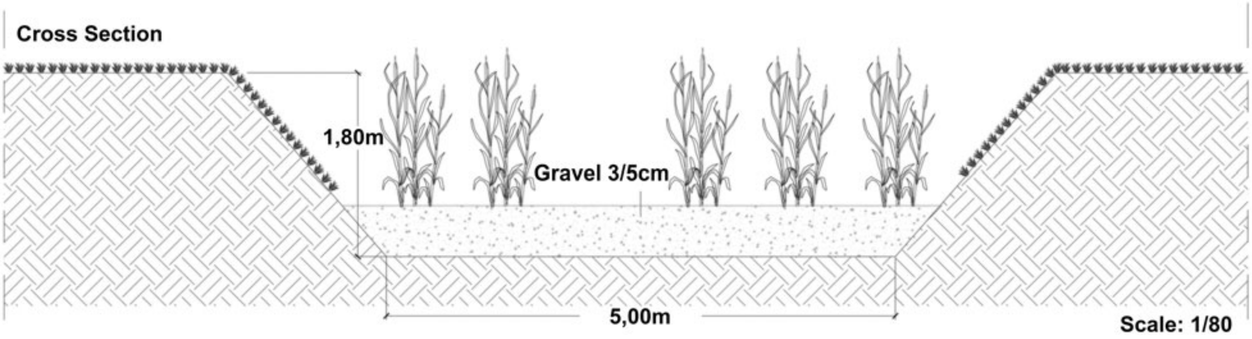

Fig. 8. Cross section of HF CWS.

activities. The first investment expenses required for the horizontal free surface flow wetlands (Horizontal-FWS) are shown in Table 4 [38].

As is seen in Table 4, these expenses show great differences from one country to another. Silva and Braga [45] correlated the investment expenses for H-SSF systems according to the number of the population to be served and for a population up to approximately 1,000 persons. Expense (€/person) $= -297\ln(\text{person}) + 2{,}103$ ($r^2 = 0.58$). That treatment system had a lower cost compared to other treatment options for a number of reasons (1) gravel and plant material were obtained from a close vicinity to the site location, (2) relatively low labour costs in Turkey and (3) that the new system represented a conversion of an existing treatment system.

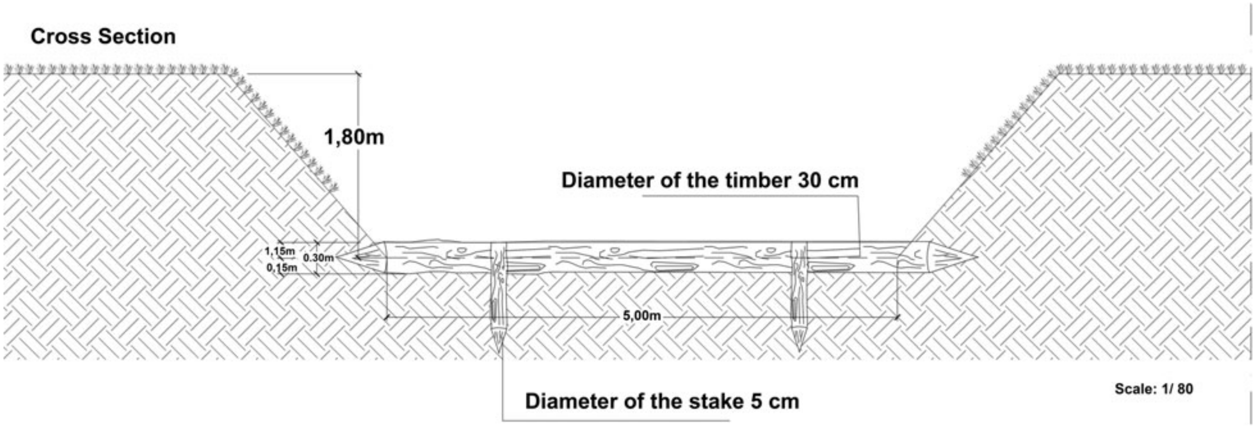

Fig. 9. Cross section of free water surface flow CWS.

Table 4
Capital (investment) cost for HF constructed wetland treating mostly municipal or domestic wastewater [38]

Reference	Country	Cost per m^2	Cost per PE	No. of systems
[39]	Poland	€31 (10–83)	€121 (25–411)	19
[40]	Belgium	€257 (237–277)	€1,258	2
[41]	Italy	€125 (38–247)	€441(80–1,240)	33
[42]	Italy	€115 (101–129)	€377 (362–392)	2
[43]	Central America	$ 61 (22–229)	$ 79 (34–103)	10
[2,44]	Turkey		€19 (10–160)	

4. Conclusions

Results show that riverine wetlands can provide significant water quality benefits in terms of organic matter and N and P nutrient removal. In the event of implementing the project improved the water quality of the Egirdir Lake water supply and use will sustainably secure water for future generations. The new system would also improve the aesthetic appearance of the area. Finally, the construction of the system would allow the reuse of wastewater.

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