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Water Quality Analysis of the San Pedro River and Proposal of a Water Treatment Design for its Use as a Water Source for a Communitarian Irrigation Project

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Water Quality Analysis of the San Pedro River and Proposal of a Water Treatment Design for its Use as a Water Source for a Communitarian Irrigation Project

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Resumen

Actualmente, la mayoría de países en desarrollo, especialmente las comunidades rurales, se enfrentan a la falta de recursos hídricos. Esto a su vez afecta a sus actividades de supervivencia, una de ellas la agricultura puesto que depende únicamente de la precipitación, resultando en una baja productividad de los cultivos y por ende la erosión del terreno. El objetivo de este estudio es analizar el río San Pedro como posible fuente de agua para irrigación comunitaria. En base al análisis de calidad de agua y estimación de la demanda de agua de riego se determinó que este no puede ser utilizado para un proyecto de irrigación sin realizar previamente un tratamiento. Esto se debe a que parámetros como potasio, coliformes fecales y sólidos suspendidos totales exceden los estándares nacionales para agua de riego, presentando concentraciones de 12 mg L^{-1}, 8000 UFC 100 mL^{-1} y 353 mg L^{-1} respectivamente. Por otro lado, el análisis biológico reveló puntajes del índice ABI entre 3 y 14, indicando que este río se encuentra altamente contaminado. Finalmente, para reducir la concentración de dichos parámetros entre 75 y 90% y cumplir con la normativa nacional se propone el uso de un humedal de flujo subsuperficial horizontal. El humedal propuesto presenta un tiempo de retención de 2.2 días y un área superficial de 9.5 km^2.

Palabras Clave: Río San Pedro, comuna de Lumbisí, análisis de calidad de agua, demanda de agua de riego, evapotranspiración del cultivo, tratamiento de humedal

Abstract

The majority of developing countries are currently facing a lack of renewable fresh water resources, especially in rural communities, threatening agricultural productivity. These communities' agriculture currently depends solely on precipitation, resulting in low crop productivity and erosion of the land. The objective of this study was to analyze the San Pedro River as a water source for a communitarian irrigation project, based on water quality analysis and water demand estimation for irrigation purposes. The analysis determined that the San Pedro River could not be used as irrigation water without prior treatment, since parameters such as potassium, fecal coliforms and total suspended solids exceeded the national standards for irrigation water, presenting concentrations of 12 mg L^{-1}, 8000 UFC 100 mL^{-1} and 353 mg L^{-1}, respectively. The biological analysis revealed ABI index values between 3 and 14, determining that the river is highly contaminated. In order to treat and reduce the concentration of these parameters between 75 and 90% a horizontal sub superficial flow wetland treatment was proposed. The irrigation water demand for the 226 ha of the agricultural land of the Lumbisí Community was estimated to be of 0.05 m^3 s^{-1} based on crop evapotranspiration and it was used as the design flow rate for the system. The proposed wetland design presents a retention time of 2.2 days and a superficial area of 9495 m^2. The estimation of effluent pollutant concentration shows that the proposed treatment would allow the San Pedro River´s water to meet national standards for irrigation water except for potassium.

Keywords: San Pedro river, Lumbisí community, water quality analysis, crop irrigation water demand, crop evapotranspiration, wetland treatment

Introduction

Human´s population exponential growth is stressing the planet´s resources, especially water, due to climate change and the increase on this resource´s demand and its depletion as a result of contamination. Because of this, there is a complicated relation between the hydrological environments, economic development and people´s livelihoods [1]. The increase on water demand comes mainly from five different sectors: agriculture, food, energy, industry and human settlements [2]. From these sectors, agriculture has the largest water print, which accounts for crop water consumption and evaporation losses from the soil, rice crops and irrigation canals and reservoirs [2]. According to the United Nations report on World Water Development of 2012, in a global scale agriculture consumes 7130 km^3 per year only for irrigation [2]. However, the majority of developing countries are currently facing a lack of renewable fresh water resources, limiting the availability of water for agriculture [3]. Rural communities are vulnerable, since their agriculture activities depend mainly on precipitation, which can be insufficient to satisfy the crop´s water demands. “Agriculture is both a cause and a victim of water scarcity” [1]. Thus, the exploration of water sources and the design of irrigation systems is of utter importance for these types of communities.

A specific case of a rural community affected by water shortage in Ecuador is the community of Lumbisí located in the parroquia Cumbayá, which belongs to Distrito Metropolitano de Quito (DMQ). This is an ancestral community with approximately 500 years of history, which is determined as an agricultural community by Ministerio de Agricultura y Ganadería del Ecuador [4]. Traditionally, the community works mainly on crops such as maize, wheat, barley and other cereals [5]. The community was founded in 1535 and recognized by the Ecuadorian state in 1937 [5]. Currently, Lumbisí´s territory is composed of 612.5 hectares, from which 226 hectares are destined for agricultural activities [6]. The agricultural area is called “El Tablón” and is located to the South East part of the community. This area is divided in plots of 100 m and each plot belongs to a member of the community. In this community land cannot be sold to outsiders and thus the land is mainly obtained by inheritance [4].

Even though this community possesses agricultural lands, according to its members this economic activity is extremely challenged due to the lack of water resources. Currently, the community depends solely on precipitation for crop irrigation, resulting in low productivity of the crops and erosion of the land [7]. Irrigated crops have a production yield of approximately 2.7 times the yield of rained crops [2]. Furthermore, due to climate change, precipitation patterns have become unstable, resulting in scarce rain and affecting the sowing and harvesting of the crops. In the Interandean region of Ecuador, the rainy season starts in October and ends in May, while the dry season starts in June and ends in September [8]. Because of this, people from the community normally sows the land during the first rains of the year in October and harvest the crops in May, giving the land a period of inactivity during the dry season [7].

The dependence on rainwater from the community is affecting their agricultural productivity and thus other water sources should be explored. A water source near the community´s land is the San Pedro River, which belongs to the Guayllabamba watershed and it originates at the Illinizas peaks [9]. This river is highly impacted by anthropocentric activities such as hydroelectric centrals, extraction for potable water and irrigation water, and wastewater discharges [10]. According to EPMAPS, Empresa Pública Metropolitana de Agua Potable y Saneamiento, Quito produces $152x10^6$ m^3 per year of domestic wastewater, which is currently discharged without treatment into the Machángara, Monjas, San Pedro and Guayllabamba rivers [11]. FONAG describes the

San Pedro River as highly contaminated, based on chemical and biological analysis [12]. On the other hand, the river´s flowrate upstream is affected by the water catchment of 1.11 $m^3 s^{-1}$ for potable water and by the extraction of 9.43 $m^3 s^{-1}$ for irrigation water near the area of Machachi [13]. Downstream of this water catchments is located the Hydroelectric Plant of Guangopolo which functions with a flowrate of 13.8 $m^3 s^{-1}$ obtained from the San Pedro and Pita rivers [10]. This hydroelectric plant is located approximately 2.2 km upstream from Lumbisí and during the maintenance of this hydroelectric plant the sludge that accumulates in the water reservoir is discharged in the San Pedro River twice a week [14].

Due to the high level of contamination reported on the San Pedro River, the water quality of the river near the Lumbisí Community does not meet the requirements for use as irrigation water. Therefore, it would be important to design a water treatment system to improve the water quality of the San Pedro River for irrigation purposes. There are several options for water treatment systems, among these the most suitable ones include constructed wetlands and conventional water treatment plants. A constructed wetland is a type of treatment which uses the natural depuration of wetlands and macrophyte plants to reduce the organic material, total suspended solids, nutrients and pathogenic organisms [15]. The advantages of this type of system are the low construction and operational costs, esthetic value and simple maintenance processes [15]. On the other hand, a conventional treatment plant is composed of primary, secondary and tertiary treatment which generally includes processes such as coagulation, flocculation, softening, sedimentation, filtration and disinfection. This type of water treatment can generate an effluent of excellent quality; however, the high capital and maintenance costs, the high energy demand and the need of specialized personnel are required for proper functioning. A third treatment option could be a mixture of the two previously mentioned ones which consist of installing a constructed wetland and complementing the treatment with some of the processes from the conventional treatment plants.

The type of treatment needed to allow the water quality of the San Pedro River to meet the national standards for irrigation water depends on the type of contaminants present and their concentration. Therefore, it is necessary to conduct a water characterization based on physical, chemical, biological and microbiological parameters and determine which parameters do not comply with the requirements for irrigation water. The water treatment system will be designed to address all the parameters identified to exceed the Maximum Contaminant Levels (MCLs) in the Ecuadorian standards for irrigation; while the bioindicators such as the ABI index will allow to identify the riverbed and water quality based on the type of macroinvertebrates found in the San Pedro River.

In terms of designing the water treatment system, it is important to take into account the flow rate to be treated, since one of the most important parameters is the hydrology of the system [15]. The amount of water treated equals the amount of water needed for irrigation, which is determined mainly by the evapotranspiration of the crops [10]. This evapotranspiration depends primarily on environmental conditions such as temperature, relative humidity and precipitation, and also on the characteristics of the crop and its growth stages [16].

The main objective of this research project was to evaluate the use of the San Pedro River as a water source for the Lumbisí community, based on physical, chemical, and biological water quality analysis, the estimation of irrigation water demand and the proposal of a water treatment system design for this river.

Materials and methods

Area of Study

The area of study was the San Pedro River at the altitude of the Lumbisí community. Water samples were taken from the river and from a water spring located near the river and "El Tablón". The distribution of the sampling points is shown on Figure 1. The sampling points from 1 to 4 are located at a distance of 200 m from each other, while point 5 is located 593 m downstream from point 4. Point 6 is a water spring used as a water source by the people from the community, and thus included in this study. From all this points, Point 3 is the nearest one to "El Tablón", therefore it has been chosen as a tentative water caption point for the irrigation system. Water samples were taken on January 29th, March 11th, and April 22nd of 2016.

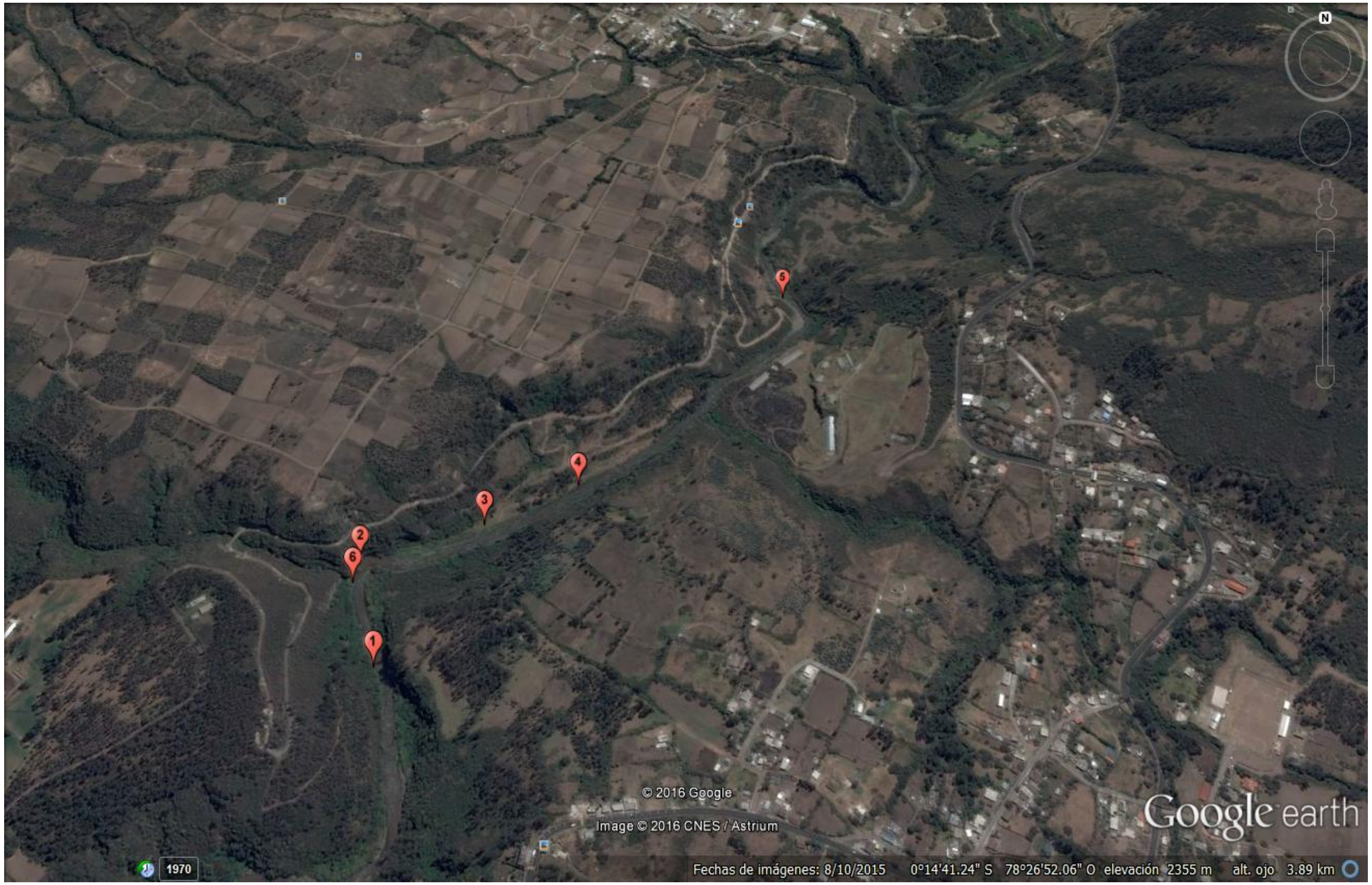

Figure 1. Map of the sampling points for the water quality analysis of the San Pedro River at the altitude of the Lumbisí community, Ecuador (Google Earth, 2016)

Physical-chemical and microbiological analysis

Samples were analyzed based on physical, chemical and microbiological parameters according to the protocols described in the Standard Methods of the American Water Works Association [17]. For the physical-chemical characterization, water samples were taken on amber bottles of 1 L and transported to the Environmental Engineering Laboratory at USFQ (LIA-USFQ) and refrigerated at 4^{o}C. Chloride (Cl^-), nitrate (NO_3^-), ammonium (NH_4^+) and fluorine (F^-) were analyzed with Orion ion selective electrodes. Sulphide (S^{2-}), phosphate (PO_4^{2-}), total chemical oxygen demand (COD) and soluble COD were analyzed through colorimetric methods, respectively, using a Spectronic 20D+ spectrophotometer (Thermo Fisher Scientific Inc. Waltham, MA, USA). Sulphate (SO_4^2), Total solids (TS), Total suspended solids (TSS), Volatile solids (VS) and Volatile suspended solids (VSS) were measured using a gravimetric method taken from AWWA. Biological oxygen demand after 5 days (BOD_5) was measured with Oxitop Box SN 110310 (WWT Inc., Weilheim, Germany). Dissolved oxygen (DO), pH, conductivity temperature and oxidation – reduction potential (ORP) were measured in situ with an Orion Star A329 portable multiparameter (Thermo Fisher Scientific Inc. Waltham, MA, USA). Turbidity was also measured in situ through an Orion AQ4500 portable turbidimeter (Thermo Fisher Scientific Inc. Waltham, MA, USA). Samples were also taken in nalgene bottles for metal analysis using a 210 VGP atomic absorption spectrophotometer (Buck Scientific Inc., Norwalk, CT, USA). The metals analyzed were potassium (K), magnesium (Mg), manganese (Mn), lead (Pb) and iron (Fe).

For the microbiological analysis, water samples were taken on sterilized plastic bottles. Total coliforms and *E. coli* were analyzed employing 3M Petrifilm Rapid Count Plates for *E. coli*. The plates were incubated at a temperature of 37 ºC and the counting of colonies was done 24 hours after inoculation.

Biological Analysis

A biological analysis was done on Sampling Point 5 during the second sampling. Three sediment samples were taken from the river. The protocol was described by Encalada et al [18]. First, the riverbed was moved to make the macroinvertebrates move to the superficial part of the sediments. Afterwards, a sediment sample was taken with a mesh, which was deposited on a tray with water from the river. All the elements in the sample were examined to separate the macroinvertebrates and they were deposited in a recipient with ethanol. With these samples, the abundance and generic richness from the macroinvertebrate community present in the river was determined through an identification of the taxonomic species and counting of specimens [19]. These samples were analyzed in the Laboratorio de Ecología Acuática USFQ, identifying the Order and Family of each specimen.

The ABI Index (Andean Biotic Index) evaluates both water and ecological quality of a river, based on the number of specimens and the species to which they belong [18]. Each family of macroinvertebrates has an ABI punctuation that goes from 1 to 10. The higher values are assigned to sensitive organisms while the lower values are applied to the most tolerant species towards contamination [18]. For each sampling point an ABI Index was calculated, through the addition of the ABI punctuation of all the species identified through the analysis. Finally the ABI Index obtained for each sampling point allowed to determine if the water quality of this segment of the San Pedro River is very good (>96), good (59 – 96), regular (35 – 58) or bad (<35).

Water Demand Estimation

The estimation of the irrigation water demand from the Lumbisí Community was conducted applying the Blaney Criddle Method, which is a standard method to determine a crop´s water needs used internationally by institutions like FAO (Food and Agriculture Organization), ASCE (American Society of Civil Engineering), EGU (European Geophysical Union) and nationally, this method is applied by the FONAG (Fondo para la Protección del Agua).

The method consists on the estimation of the evapotranspiration of a reference crop (ETo), taking into account the influence of the climate of the region on the crop´s water demand [16]. ETo represents the evapotranspiration rate of a large area covered by grass that is 8 to 15 cm tall and is normally expressed mm per unit of time. The evapotranspiration of the crop is calculated based on environmental parameters and the type of crop [20]

$$ETo = p(0.46T_{mean} + 8) \qquad (1)$$

Where p is the mean daily percentage of annual daytime hours and T_{mean} is the mean daily temperature. The mean daily percentage of annual daytime hours depend on the latitude and the month of the year, in the case of Ecuador this value is 0.27 all year long [16]. This reference evapotranspiration (ETo) allows to estimate the evapotranspiration for a determined crop based on Equation 2.

$$ETcrop = ETo * Kc \qquad (2)$$

Where Kc is the crop factor, which depends on the type and the growth stage of the crop. There are in total four growth stages for a crop: Initial, Crop Development, Mid-season and Late season [16]. As well, it is important to mention that Kc is affected by the relative humidity (RH%). In the case the RH% is higher than 80%, then Kc = Kc - 0.05, while if RH% is lower than 80% then Kc = Kc + 0.05.

The water demand estimation was calculated according to two scenarios, the first one is the current water demand calculated for the sole cultivation of corn (100%), while the second one takes into account the cultivation of corn (50%), barley/wheat (20%), tomatoes (15%) and potatoes (15%). The percentage of the land destined to each type of crop in the second case scenario was determined through a survey.

Based on these crops, the evapotranspiration was calculated for each crop taking into account the crop coefficient Kc [16]. The ETcrop was calculated assuming that crops are seeded in October and harvested in April and May. Since potatoes have a lower cultivation time, they are assumed to be harvested twice with a seeding on October and another one on Febraury. For the estimation, a spreadsheet was used, inputting data of mean temperature, relative humidity and precipitation obtained from Estación de Mediciones Atmosféricas (EMA-USFQ). This data was expressed as a daily average taking into account values from 6 am until 6 pm. To estimate the amount of irrigation water, the precipitation of the area was deducted from the evapotranspiration, this value was multiplied by the percentage of land area destined to the crop and the area of El Tablón to obtain a flow rate in $m^3 s^{-1}$. Irrigation water demand was determined for two periods: October 2014-May 2015 and October 2015-May 2016.

Survey

A survey about the crops cultivated in “El Tablón” was conducted to the members of the community. 25 surveys were made randomly, which represented the 5% of the registered population of the community (empadronados). The questions of the survey included the type of crop, the number of farming plots, the area of each farming plot, the months of seeding and harvesting.

Results

The main purpose of this research was to obtain baseline data on the San Pedro River water quality and to design a treatment process for irrigation water for the Lumbisí community. In order to accomplish this, the project was divided in three phases: water quality analysis, water demand estimation and water treatment system design.

Phase I: Water Quality Analysis

The flow rate measured on the San Pedro River during samplings 1, 2 and 3 were 0.59, 2.09 and 1.59 m3 s-1, respectively. Table 1 shows the mean values obtained for each parameter of the physical-chemical water quality analysis for the San Pedro River (P1, P2, P3, P4 and P5) and the water spring (P6) during the three samplings. These values were compared to the Maximum Contaminant Levels (MCLs) for irrigation water established in the Ecuadorian legislation [21].

Table 1. Physical-chemical parameters of the San Pedro River and the water Spring obtained during the first, second and third sampling at the altitude of the Lumbisí community

Point	Sampling	Conductivity	pH	ORP	Turbidity	S^{2-}	SO_4^{2-}	PO_4^{2-}	Cl^-	NO_3^--N	NH_4^+-N	F^-	Total COD	Soluble COD	BOD_5	TS	TSS	VS	VSS	K	Mg	Mn	Pb	Fe
Unit		uS cm^{-1}		mV	NTU	mgL^{-1}	meL^{-1}	meL^{-1}	meL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	meL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}
MCL*		700	6.5-8.4	-	-	-	20	0.2	4	10	10	1	-	-	-	-	50**	-	-	2	5	0.2	5	5
P1	1	690.5	8	299.7	2.1	0.04	2.7	1.1	1.6	1.20	2.85	0.52	223.7	155.8	10	543.3	20	223.3	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P2	1	713.1	8.2	338.3	2.9	0.04	2.7	0.1	1.9	1.27	3.47	0.8	266.5	218.3	5	553.3	30	240	-	12.1	1.9	<0.5	<0.1	<0.05
	2	346.8	7.2	369.8	125.5	-	0.8	0.3	0.6	1.2	1.1	<0.1	57.4	9.6	5	583.3	353.3	160	-	193.3	1.0	14	<0.5	<0.1
	3	606	8	318.5	3.9	<0.05	2.3	0.3	1.4	1.7	4.3	<1	68.8	42.2	-	633.3	16.7	230	-	-	0.9	1.8	<0.5	<0.1
P3	1	806.3	8.3	321.1	2.1	0.05	2.7	0.2	2.4	1.19	2.44	0.66	300.4	241.3	10	553.3	16.7	226.7	-	12.9	2.1	<0.5	<0.1	0.1
	2	414.1	7.4	369.3	93.1	-	0.8	0.5	0.7	1.3	1.5	<0.1	50.5	11.3	7	556.7	203.3	173.3	-	156.7	1.0	17.5	<0.5	<0.1
	3	609.6	8.1	325.9	3.3	<0.05	2.5	0.2	1.8	1.8	5	<1	62.2	20.1	-	533.3	13.3	203.3	-	-	0.9	1.8	<0.5	<0.1
P4	1	688.1	8.3	325.5	1.8	0.04	2.6	0.1	1.7	1.08	2.71	0.67	170	152.5	10	560	23.3	276.7	-	13.5	2.0	<0.5	<0.1	0.1
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	605.9	8	357.3	7.7	<0.05	2.4	0.3	1.7	1.9	6	<1	55.5	31.2	-	366.7	30	206.7	-	-	1.1	1.7	<0.5	<0.1
P5	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	423.8	7.7	366.6	96.7	-	1.3	0.2	0.6	1.2	1.1	<0.1	83.5	14.7	6	653.3	230	263.3	-	236.7	1.1	16.1	<0.5	<0.1
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P6	1	486.7	8.4	284.4	31.9	0.04	2.1	0.2	1	1.86	2.68	1.16	405.6	244.5	20	416.7	46.7	150	-	11.5	3.0	<0.5	<0.1	0.1
	2	481.9	7.7	371.1	87.7	-	1.7	0.6	0.9	1.9	5.5	<0.1	238	73.2	40	693.3	193.3	313.3	-	-	0.9	25	<0.5	<0.1
	3	491	8.1	292.6	31.9	<0.05	2.3	0.6	1.2	1.2	7.6	<1	192.9	82.1	-	766.7	70	633.3	-	-	1.3	2.6	<0.5	<0.1

***** Tables 4 and 5 Water Quality Criteria for use in Agriculture Irrigation, Anexo 1, VI book of the TULSMA reformed on the Acuerdo Ministerial 097 on July 30, 2015 [21].

** Water Quality for Agriculture, FAO, 1994 [23]

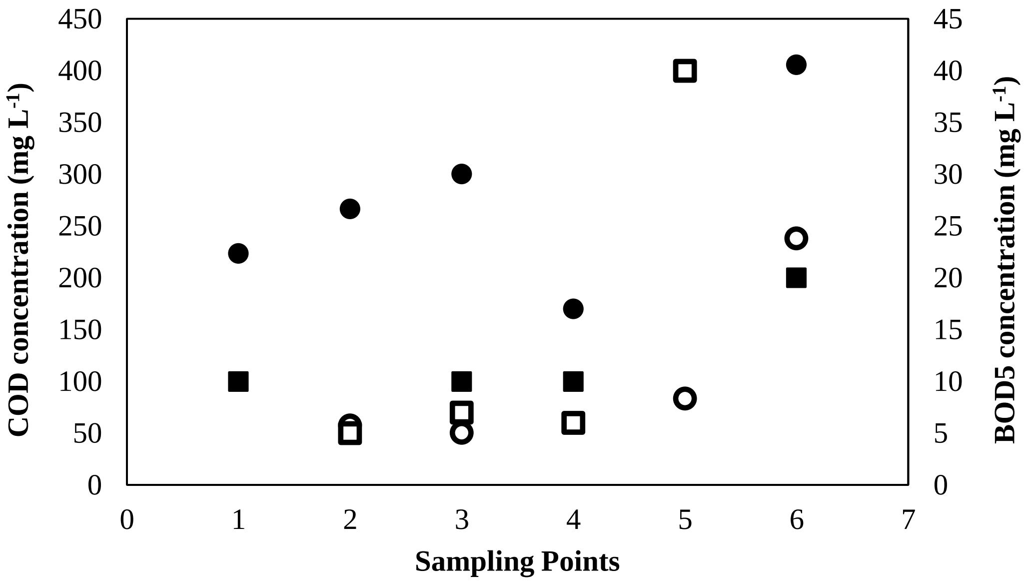

Figure 2 COD and BOD concentration on the different aampling points of the San Pedro River. Legend: (●) COD and (■) BOD5 at Q=0.59 m^3 s^{-1} and (○) COD and (□) BOD5 at Q=2.09 m^3 s^{-1}

Table 2 presents the values obtained for each of the microbiological parameters, fecal coliforms and total coliforms during the three samplings, for both the San Pedro River and the water spring.

Table 2. Microbiological parameters of the San Pedro River and the water Spring obtained during the first, second and third sampling at the altitude of the Lumbisí community

Point	Sampling	Fecal Coliforms (CFU $100mL^{-1}$)	Total Coliforms (CFU $100mL^{-1}$)
MCL*		1000	-
P1	1	6000	800000
	2	-	-
	3	-	-
P2	1	6300	-
	2	1300	5200
	3	27500	282500
P3	1	8000	-
	2	2900	7100
	3	15000	237500
P4	1	8000	-
	2	-	-
	3	22500	257500
P5	1	-	-
	2	2100	5200
	3	-	-
P6	1	70000	360000
	2	8200	14200
	3	330000	2760000

*World Health Organization, 2006 [23].

The variation of the Fecal Coliforms along the San Pedro River and the effect of flow rate on this parameter are shown on Figure 3.

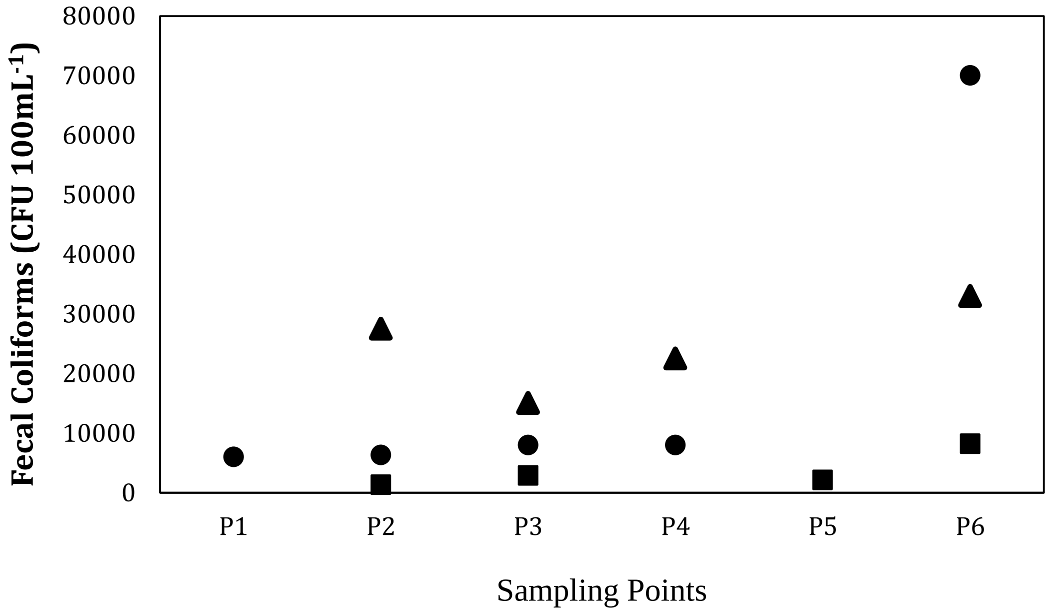

Figure 3. Fecal coliforms concentration on the sampling points of the San Pedro River. Legend: (●) Q=0.59 m^3 s^{-1}, (■) Q=2.09 m^3 s^{-1}, (▲) Q=1.59 m^3 s^{-1}

The results obtained for the biological analysis of the San Pedro River through the ABI Index are presented on Table 3.

Table 3. Biological analysis of macroinvertebrates found in the San Pedro River during the second sampling at the altitude of the Lumbisí community

	Sample 1		Sample 2		Sample 3	
Family	**No. Specimens**	**ABI**	**No. Specimens**	**ABI**	**No. Specimens**	**ABI**
Oligochaeta	12	1	3	1	4	1
Chironomidae	3	2	4	2	3	2
Baetidae	-	-	1	4	-	-
Hydrocarina	-	-	1	4	-	-
Hirudinea	-	-	1	3	-	-
Muscidae	1	2	-	-	-	-
Psychodidae	1	3	-	-	-	-
Hirudinea	4	3	1	-	-	-
Collembola	1	-	1	-	-	-
Pupa	2	-	1	-	2	-
Diptera	-	-	3	-	1	-
Diplopoda	-	-	-	-	1	-
TOTAL	24	11	15	14	11	3

Based on this data, the ABI Index for this portion of the San Pedro River is between 3 and 14, significantly below 35 meaning the river quality is bad and that the river is highly contaminated.

Phase II: Water Demand Estimation

The surveys revealed that there is a great variation on the size of the farming plots between the comuneros and the farmers mostly cultivate corn due to the lack of irrigation water. The most cultivated crops were identified as corn (50%), wheat (15%), barley (5%), potatoes (14%) and peas, morocho, beans and other grains (2%). Based on the results obtained from the survey, the water demand for El Tablón was estimated, which is shown on Table 4.

Table 4. Mean and maximum irrigation water demand for different scenarios of crop cultivation for the agricultural period 2014-2015 and 2015-2016.

Case		**Mean irrigation water demand (m^3 s^{-1})**	**Maximum irrigation water demand (m^3 s^{-1})**
2014-2015	Corn	0.04	0.09
	Various Crops	0.06	0.14
2015-2016	Corn	0.05	0.10
	Various Crops	0.08	0.14

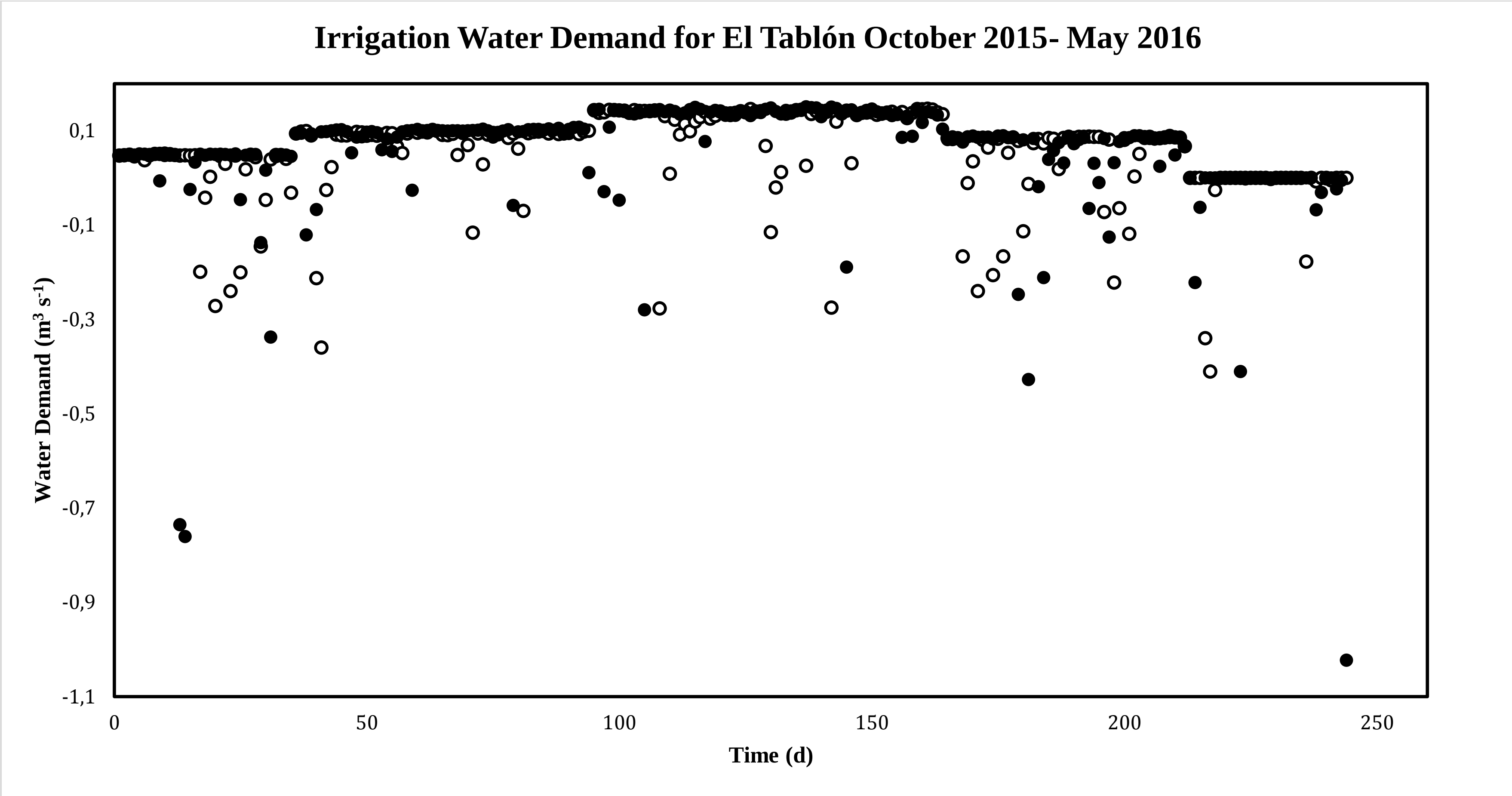

Figure 4. Daily irrigation water demand for El Tablón estimated through the various crops case scenario. Legend: (○) Period October 2014 – May 2015, (●) Period October 2015 – May 2016.

Phase III: Water treatment design

Based on the information obtained from the two previous phases, a water treatment system was designed to model the use of San Pedro River as irrigation water. The parameters that do not comply with the MCLs for irrigation water were potassium, fecal coliforms, conductivity and TSS. To reduce the concentrations of these parameters, two treatment options were considered: a conventional treatment plant and a wetland treatment system.

For a conventional treatment plant, the system will be composed of processes such as coagulation, flocculation, sedimentation, disinfection and ion exchange, which are physical-chemical treatments. However, these processes are highly energy demanding, operation and maintenance is expensive and needs specialized personnel [24]. Therefore, its application on the Lumbisí community is not plausible.

On the other hand, a wetland treatment system allows the reduction of organic material, total suspended solids, nutrients and pathogenic organisms, while being space and cost efficient [15]. Wetlands are the most biologically productive ecosystems, and thus this type of treatment allows the degradation and transformation of pollutants into harmless byproducts and nutrients [25].

A type of constructed wetland is the horizontal subsurface flow (HSSF), in which water passes through a gravel bed planted with wetland vegetation, removing pollutants as the water flows through the permeable material [15]. These wetlands are efficient on the removal of suspended solids, nitrogen and pathogens while having low maintenance and construction costs and a shorter development period, though they need higher land area [25]. HSSF systems are an attractive option to treat irrigation water for the Lumbisi community since the land is extensive and the economic resources and technical personnel required are lower in comparison to other water treatment processes.

The proposed HSSF wetland´s vegetation will be composed of reeds (*Phragmites australis*) and its main purpose will be the removal of fecal coliforms from an original concentration of 8000 to 1000 CFU 100 mL^{-1}. The wetland area was calculated using Equation 4 [26].

$$A_S = Q\,\frac{(\ln C_O - \ln C_e)}{K_T h n} \quad (4)$$

Where As is the superficial area of the wetland, Q is the flow rate ($m^3\,d^{-1}$), C_o is the inlet concentration of fecal coliforms, C_e is the effluent concentration, K_T is the rate coefficient dependent on temperature (d^{-1}), h is the depth of the wetland (m), which in this case will be 1 m, and n is the porosity. The media selected for the proposed wetland bed is coarse sand that possesses a porosity of 0.43 and a hydraulic conductivity of 1000 m d^{-1} [27]. The rate coefficient dependent on temperature is calculated through the following equation [26].

$$K_T = K_{20}(1.06)^{T-20} \quad (5)$$

Where T is the temperature in Celsius and K_{20} is the rate coefficient at 20ºC, 1.66 m d^{-1} for fecal coliforms [25]. Since the water will need to infiltrate the porous bed for the treatment, the Darcy Law is contemplated in the design through Equation 6.

$$A_c = \frac{Q}{K_s S} \quad (6)$$

Where A_c is the cross sectional area of the wetland, K_S is the hydraulic conductivity and S is the slope of the porous bed, which is assumed 1% [27]. Based on this cross sectional area, the length and width of the wetland can be determined through Equations 7 and 8 respectively [28].

$$L = \frac{A_c}{h} \quad (7)$$

$$W = \frac{A_S}{L} \quad (8)$$

Table 5 shows the design parameters for the proposed horizontal sub superficial flow wetland (HSSF) for a flow rate of 0.05 $m^3 s^{-1}$.

Table 5. Design parameters for the proposed HSSF wetland treatment system for a flow rate of 0.05 $m^3 s^{-1}$.

Parameter	Unit	Design value
Superficial Area	m^2	9495
Cross Sectional Area	m^2	432
Depth	m	1
Width	m	21.98
Length	m	432
Detention Time	d	2.2

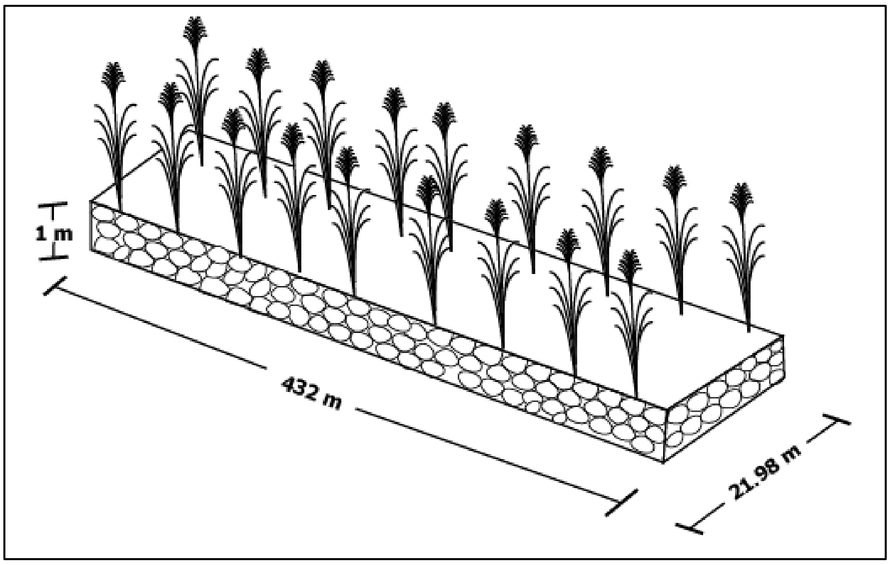

Figure 5. Representative diagram of the dimensions for the proposed HSSF wetland treatment system for irrigation at the Lumbisí community (Adobe Illustrator, 2016).

The removal efficiency was also evaluated for COD and BOD_5, applying Equation 4, with a K_{20} value of 1.104 and an inlet concentration of 300.4 and 10 mg L^{-1} for COD and BOD_5, respectively. For TSS removal, the effluent concentration was determined through Equation 9 [25]. For potassium removal, a 30% removal efficiency was used to determine the effluent concentration, which is a typical potassium removal efficiency for this type of wetlands according to Kadlec and Wallace [25].

$$C_e = C_o \left[0.1139 + 0.00213 \left(\frac{Q}{A}\right)\right] \quad (9)$$

Due to the high flow rate instability of the San Pedro River, a constant flow rate catchment is proposed, regulated through a valve, along with a storage tank for the treated water, which will be used for irrigation when the available precipitation is not enough to satisfy the crop needs. The storage tank was designed for a capacity of 21600 m^3, assuming the need to storage treated water through 5 days. . The depth was estimated to be 3 m and the superficial area needed will be 7200 m^2. Based on the dimensions and the retention time of this storage tank, oxidation processes can occur and further improve the removal efficiency of contaminants. Oxidation ponds present removal efficiencies of 90% for fecal coliforms, providing a general fecal coliform removal efficiency of 98.75% for the entire system [29]. To determine the effluent concentrations after the complete treatment system, typical removal efficiency values for the oxidation process were used [30].

Table 6. Estimated inlet and effluent concentrations from the proposed HSSF wetland and removal efficiency of this irrigation water treatment for potassium, fecal coliforms, COD, BOD_5 and TSS.

System	**Parameter**	**Potassium ($mg\ L^{-1}$)**	**Fecal coliforms ($CFU\ 100\ mL^{-1}$)**	**TSS ($mg\ L^{-1}$)**	**DQO ($mg\ L^{-1}$)**	**BOD_5 ($mg\ L^{-1}$)**
HSSF wetland	Inlet	12.9	8000	353	232	10
	Effluent	9	1000	40.55	56.94	2.96
	Removal Efficiency (%)	30	87	88	75	75
Storage Tank	Removal Efficiency (%)	0	90	87	70	82
Treatment system	Effluent	12.9	100	5.5	18.56	0.13
	Total Removal Efficciency (%)	30	98.75	98	92	95

The proposed system is shown in the following diagram.

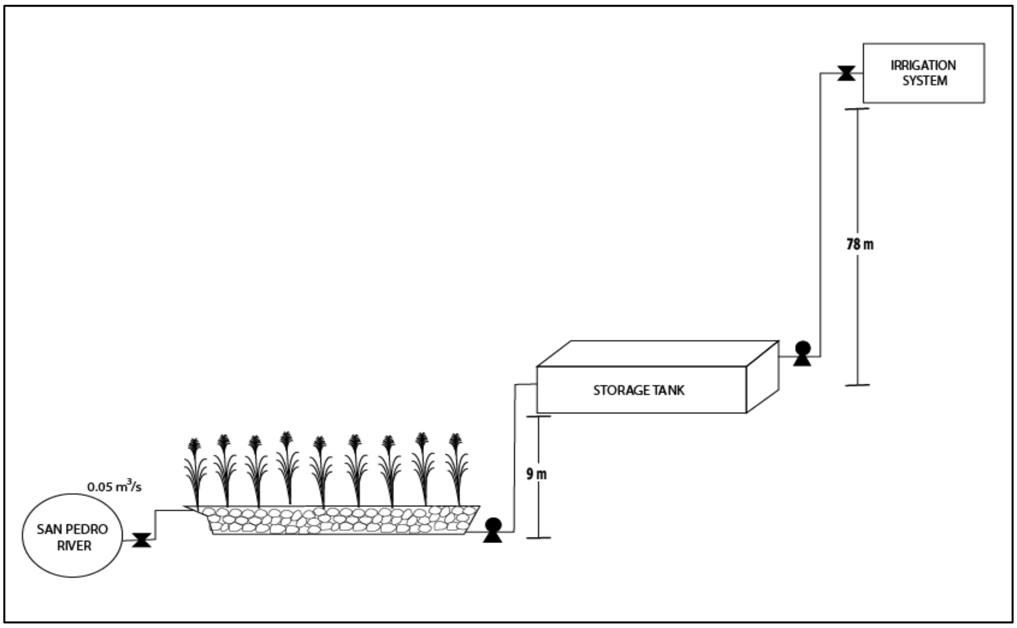

Figure 6. Diagram of the proposed water treatment system for irrigation of the Lumbisí community composed by a HSSF wetland and a storage tank (Adobe Illustrator, 2016).

Discussion

The results of the physical-chemical analysis of the water quality from the San Pedro River show that it is highly contaminated. The concentration of COD and NH_4^+ do not meet the criteria for the preservation of aquatic life on fresh water according to the Ecuadorian legislation. A study conducted by Voloshenko *et al* on the San Pedro River, present similar BOD and the COD values to the ones measured in this study, while the values of conductivity and dissolved oxygen are higher [9]. This variation is also natural, since the flow rate of the river is really unstable, depending on the wastewater discharge, precipitation and the sludge purge from the Hydroelectric Plant at Guangopolo. As seen on Figures 2 and 3, there is a relation between the flow rate and the concentration of the contaminants; with a lower flow rate the contamination sources have a higher impact on water quality since there is a lower dilution factor [29]. This occurs for the first and second samplings, coliforms, COD and BOD have a higher concentration when the flow rate is lower. However, the contaminants concentration found on the third sampling are similar to the values obtained during the first sampling, even though the flow rate was similar to the one found during the second sampling. In this case concentration is not correlated to the flow rate, and this variation can be attributed to the variability that occurs due to the impact of the hydroelectric plant on the river.

Other studies done on the San Pedro River by EPMAPS and FONAG show that the water quality of the river is degraded due to anthropogenic activities, which is in accordance to the results obtained in this study. The BOD/COD ratio is approximately 0.05, indicating that the water of the San Pedro River possesses a low concentration of biodegradable organic matter [31]. This is an indicator of the possible presence of chemical contamination; most likely coming from industries, since domestic wastewater normally has a high load of organic matter [31]. As well, the results from the ABI Index indicate that the river is highly contaminated due to the presence of pollution tolerant macroinvertebrates. Even this tolerant species presented low abundance on the San Pedro River, suggesting the presence of chemical contamination [32].

The microbiological analysis show there is a high concentration of fecal coliforms, too high for the use of this water directly on irrigation. This microbial contamination could be originated by raw domestic wastewater discharges and animal feces coming from the cattle in the area. The spring water presents a higher concentration of fecal coliforms than the San Pedro River, which is surprising because the quality of springs is usually better than surface water sources [29]. The most plausible explanation for this is that the spring water is probably getting in contact with animal feces, since there is no population settled near this area.

The agricultural development of the Lumbisí community is limited by the availability of irrigation water. Due to this, the community´s main crop is corn, since it is resistant towards drought [33]. If the community has access to irrigation water, different type of crops could be cultivated in the area, which is the reason that, the water demand estimation contemplated also a diversification of crops once irrigation water becomes available. Table 4 shows that the variation on the mean value of irrigation water needed is minimum if the two cases are compared (corn and various crops). However, when taking into account peak values, the various crop scenario requires a higher water demand than corn monoculture. The higher variability on the irrigation water demand in the period 2015-2016 compared to the period 2014-2015 observed in Figure 4 is only due to the changes on precipitation patterns, since 2015-2016 presented longer periods of drought and peaks of high precipitation. Therefore, the system is still dependent on environmental factors and climate change will still have an impact on agricultural productivity [34].

The mean value for irrigation water demand chosen for the design of the HSSF wetland was 0.05 $m^3 s^{-1}$. This amount of water was selected only based on the crop water needs, however the concept of environmental flow rate should also be considered in future studies to define the sustainability of this water source.

The fecal coliform concentration on sampling point 3 was 2900, 15000 and 8000 UFC $100mL^{-1}$ for the first, second and third sampling respectively. For the design of the HSSF wetland, the average fecal coliform concentration was chosen, assuming an inlet concentration of 8000 UFC mL^{-1}. Due to the high removal efficiency of fecal coliforms needed, the superficial area of the proposed HSSF wetland will be 9495 m^2, presenting a removal efficiency of 87.5%. In case the inlet concentration is 15000 UFC 100 mL-1 the wetland will not be able to reduce the fecal coliform concentration to meet the MCLs. However, the storage tank will work as an oxidation pond, allowing further removal of fecal coliforms and providing the system with a general removal efficiency of 98.75%.

The detention time of the designed wetland of 2.2 days is within the expected values for this type of system which is between 1 and 6 days, in accordance with the results of Kadlec and Wallace, 2009 [15] ; Miglio, 2013 [25]; Yocum, 2006 [35]; Zhang, 2012 [36] and Guerra and Peñafiel, 2012 [37]. Finally, the plug flow conditions necessary for the treatment and removal of contaminants through the proposed HSSF wetland are met since the length to width ratio of the wetland is higher than 10:1 [38]. The design water treatment system contemplates the removal of fecal coliforms, TSS, COD and BOD at removal efficiencies of 87.5%, 88.5%, 75.5% and 75.4% respectively. The only parameter that will not comply with irrigation water standards is potassium, presenting a concentration of 9 mg/L, approximately two times higher than the MCL, since its removal is low in this type of systems [25].

This proposed system can be further improved by adding other treatment processes such as sedimentation before the HSSF wetland treatment. A sedimentation basin will reduce the concentration of the TSS, thus reducing the clogging of the wetland and improving its operation [25]. As well, primary sedimentation presents a 44% removal efficiency of fecal coliforms, thus allowing to reduce the area occupied by the wetland system to a more feasible size [39]. Another option to improve the efficiency of the system is the recirculation of the treated water, presenting a higher flow rate that allows dilution of pollution and increasing the buffer capacity of the system [40].

Conclusions

The water quality of the San Pedro River was evaluated based on physical, chemical, microbiological and biological parameters, resulting in the identification of a deficient water quality for a fresh water source and not usable for its direct use on crop irrigation. A horizontal subsurface flow (HSSF) wetland treatment system was proposed for the removal of pollutants and the possible use of the San Pedro River as an irrigation source for the crops located at El Tablón in the Lumbisí community. The removal efficiencies of the complete treatment system for fecal coliforms, TSS, COD and BOD were estimated to be higher than 90%. This irrigation water treatment will allow the water of the San Pedro River to meet all the MCLs for irrigation water, except for potassium. The dimensioning of the system was based on the flow rate needed for irrigation water, which was calculated through the evapotranspiration of the crops. To obtain a better understanding of the varying river flow rate, more studies and samplings should be done to determine the daily variation of the pollutants concentrations in the river. As well, in order to determine a more exact estimation of the water demand, more historic data should be analyzed and further models should be applied to project environmental conditions for the future years, allowing to obtain more realistic information on crop evapotranspiration and irrigation water demand. Aspects such as the ecological flow rate and feasibility of the dimensioning and construction of the treatment system should be taken in to consideration before the implementation of the project. Finally, the proposed water treatment system can be further improved by the addition of other processes such as sedimentation, oxidation and recirculation to increase removal efficiency and to reach feasible dimensions for the system.

References

[1] FAO. 2012. Coping with Water Scarcity: An Action Framework for Agriculture and Food Security. FAO Water Reports. Rome, Italy.

[2] UN-Water. 2012. The United Nations World Water Development Report 4: Managing Water Under Uncertainty and Risk. World Water Assessment Programme (WWAP). Unesco, Paris, France.

[3] Khan, T. 2014. Water Scarcity and its Impact on Agriculture: Case Study of Layyah, Pakistan. Swedish University of Agricultural Sciences. Uppsala, Sweden.

[4] Williams, J. 2012. Cosmopolitan Comuneros: Celebrating Indigeneity Through the Appropriation of Urbanity in the Quito Basin. University of Illinois at Urbana Champaign.

[5] Paredes, B. 2011. El Patrimonio Inmaterial de Lumbisí: La Fiesta de San Bartolomé Apóstol. Patrimonium. <http://www.patrimonium.ec/index.php/2013-05-15-14-05-21/volumen-3/item/146-el-patrimonio-inmaterial-de-lumbis%C3%AD> August 21, 2016.

[6] Williams, J. 2006. Celebrando el pasado del future: la negociación de la identidad indígena en Lumbisí, Ecuador. Estudios Ecuatorianos en Aporte a la Discusión Tomo II. Ediciones Abya Yala, Quito, Ecuador.

[7] Lumbisi Community. 2016. Personal interview

[8] INAMHI. 2001. Detección del Cambio Climático en Ecuador. <http://www.serviciometeorologico.gob.ec/cambio-climatico/> August 22, 2016.

[9] Voloshanko-Rossin A, Gasser G, Cohen K, Gun J, Cumbal Flores L, Parra Morales W, Sarabia F, Ojeda F, Lev O. 2015. *Emerging pollutants in the Esmeraldas watershed in Ecuador: discharge and attenuation of emerging organic pollutants along the San Pedro-Guayllabamba-Esmeraldas Rivers*. Royal Society of Chemistry, Environmental Science: Processes and Impacts, January 2015, Vol 17, Number 1, 41 - 55.

[10] FONAG. 2009. Plan de Manejo Integrado de los Recursos Hídricos en la Cuenca Alta del Río Guayllabamba. <https://issuu.com/fonag/docs/plan_de_manejo ?backgroundColor=> August 20, 2016.

[11] EPMAPS. 2015. *Programa para la descontaminación de los ríos de Quito*. < http://www.aguaquito.gob.ec/descontaminacion-de-rios-del-dmq/programa-para-la-descontaminacion-de-los-rios-de-quito> September 8, 2015.

[12] FONAG. 2011. Información de la Cuenca del Río Guayllabamba. <http://visor.infoagua-guayllabamba.ec/visor/index.html> August 20, 2016.

[13] SENAGUA-FONAG. 2013. Sistema de Información y Monitoreo de Recursos Hídricos: Inventario Participativo. <http://infoagua-guayllabamba.ec/index.php/concesiones-de-agua/inventario-participativo> October 10, 2016

[14] Guerra, D., Villarroel, R. 2009. Diseño del Sistema de Gestión Ambiental y Aplicación de la Primera Etapa Bajo la Norma ISO 14001 en la Central de Generación Hidroeléctrica Guangopolo EEQ S.A. Escuela Politécnica Nacional.

[15] Zhang, Y. 2012. Design of a Constructed Wetland for Wastewater Treatment and Reuse in Mount Pleasant, Utah. Utah State University.

[16] Brouwer, C., Heibloem, M. 1986.Irrigation Water Management Training Manual. FAO. <http://www.fao.org/docrep/s2022e/s2022e00.htm#Contents> March 14, 2016

[17] *AWWA*, APHA, WEF. 2012. *Standard Methods* for examination of water and wastewater. *22nd ed*. American Public Health Association. Washington D.C.

[18] Encalada, E., Rieradevall, M., Rios T., Garcia, N., Prat, N. 2011. Protocolo Simplificado y Guia de Evaluacion de la Calidad Ecologica de Rios Andinos. Quito> Proyecto FUCARA.

[19] Maine DEP (Department of Environmental Protection). Macroinvertebrate

Sampling in Rivers and Streams.<http://www.maine.gov/dep/water/monitoring biomonitoring/sampling/bugs/riversandstreams.htmhttp://www.maine.gov/dep/water/monitoring/biomonitoring/sampling/bugs/riversandstreams.htm. 2016> September 27, 2016

[20] Moran, M., Clarke, T., Inoue, Y., Vidal, A. 1994. Estimating crop water déficit using the relation between surface-air temperatura and spectral vegetation index. < http://www.sciencedirect.com/science/article/pii/0034425794900205> October 20, 2016

[21] Acuerdo Ministerial 097. Anexo 1, Libro VI TULSMA.

[22] Ayers, R., Westcot, D. 1994. Water Quality for agriculture. FAO. California, USA.

[23] Jeong, H., Kim, H., Jang, T. 2016. Irrigation Water Quality Standards for Indirect Wastewater Reuse in Agriculture: A Contribution toward Sustainable Wastewater Reuse in South Korea. MDPI.

[24] Metcalf , Eddy. 2013. Wastewater Engineering: Treatment and Resource Recovery. New York: McGrawhill.

[25] Kadlec, R. Wallace, S. 2009. Treatment Wetlands. 2nd edition. Boca Raton: CRC Press

[26] Reed, S., Crites, R., Middlebrooks, E. 1995. Natural Systems for Waste Management and Treatment. Second Edition. New Yotk: McGraw-Hill.

[27] Espinoza, C. 2014. Factibilidad del Diseño de un Humedal de Flujo subsuperficial para el Tratamiento de Aguas Residuales Municipales de 30000 Habitantes. Escuela Colombiana de Ingeniería Julio Garavito. <http://repositorio.escuelaing.edu.co/bitstream/001/114/1/FACTIBILIDAD%20DEL%20DISENO%20DE%20UN%20HUMEDAL%20DE%20FLUJO%20SUBSUPERFICIAL%20PARA%2030000%20HABITANTES.pdf> August 22, 2016.

[28] Martins, M., Ferreira, M. 2003. Wastewater stabilization ponds fecal coliform removal efficiencies. University of Espirito Santo. Praia da Costa.

[29] *AWWA*, APHA, WEF. 2012. *Standard Methods* for examination of water and wastewater. *22nd ed*. American Public Health Association. Washington D.C.

[30] Alcocer, J., Lugo, A., López, A., Sánchez, R. 1993. Efficiency of a Waste Stabilization Pond System in a Subtropical Area of Mexico. UNAM. <http://www.revistascca.unam.mx/rica/index.php/rica/article/viewFile/29856/27760>

[31] Zaher, K., Hamman, G. 2014. Correlation between Biochemical Oxygen Demand

and Chemical Oxygen Demand for Various Wastewater Treatment Plants in Egypt to obtain the Biodegradability Indices. International Journal of Sciences> Basic and Applied Research (IJSBAR) Volume 13, No. 1, pp 42-48.

[32] Prat, N., Rios, B., Acosta, R., Rieradevall, M. 2012. Los Macro invertebrados como Indicadores de Calidad de Aguas. San Miguel de Tucumán.

[33] CGIAR (Consultative Group on International Agricultural Research). 2015. Drought Tolerant Crops for Drylands. < http://www.cgiar.org/web-archives/www-cgiar-org-impact-global-des_fact2-html/> October 20, 2016

[34] Pepper, I., Gerba, C., Brusseau, M. 2006. Environmental and Pollution Science. Elsevier. San Diego.

[35] Miglio, R. 2013. Humedales Artificiales para el Tratamiento de Aguas Residuales. <http://biorem.univie.ac.at/fileadmin/user_upload/p_biorem/education/lectures/UNASAM_2/Modulo_12.1_Humedales_subsuperficiales_para_el_tratamiento_de_aguas_residuales_domesticas.pdf> October 15, 2016

[36] Yocum, D. 2006. Manual de Diseño: Humedal construido para el Tratamiento de las Aguas Grises por Biofiltración. University of California: Bren School of Environmental Science and Management. <http://www2.bren.ucsb.edu/~keller/courses/GP_reports/Diseno_Humedal_AguasGrises.pdf> October 15, 2016

[37] Guerra, L., Penafiel, R.2012. Implementacion de un sistema de humedales artificiales

[38] US EPA. 2000. Wastewater Technology Fact Sheet Wetlands: Subsurface Flow. Washington D.C.

[39] Hinds, T., Brown, R., Burns, E. 2014. Reduction of fecal coliform levels in two c created wetlands at the Olentangy River Wetland Research Park. Ohio University.

[40] Morató, J., Codony, F., Sánchez, O., Pérez, L., García, J., Mas, J. 2013.Key design factors affecting microbial community composition and pathogenic organisms removal in horizontal subsurface flow constructed wetlands.