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Model of Suspended Solids Removal in the Primary Sedimentation Tanks for the Treatment of Urban Wastewater

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Abstract: Primary settling tanks are used to remove solids at wastewater treatment plants and are considered a fundamental part in their joint operation with the biological and sludge treatment processes. The aim of this study was to obtain a greater understanding of the influence of operational parameters, such as surface overflow rate, hydraulic retention time, and temperature, on the removal efficiency of suspended solids and organic matter by the measurement of chemical oxygen demand and biochemical oxygen demand in the primary sedimentation process. The research was carried out in a semi-technical primary settling tank which was fed with real wastewater from a wastewater treatment plant. The physical process was strictly controlled and without the intervention of chemical additives. Three cycles of operation were tested in relation to the surface overflow rate, in order to check their influence on the different final concentrations. The results obtained show that the elimination efficiency can be increased by 11% for SS and 9% for chemical oxygen demand and biochemical oxygen demand, for variations in the surface overflow rate of around ± 0.6 $m^3/m^2{\cdot}h$ and variations in hydraulic retention time of around ± 2 h. The results also show that current design criteria are quite conservative. An empirical mathematical model was developed in this paper relating SS removal efficiency to q, influent SS concentration, and sewage temperature.

Keywords: primary settling tank; surface overflow rate; hydraulic retention time; removal rate; wastewater treatment

1. Introduction

Physical settling operations are widely used in the treatment of wastewater. Primary settling tanks have been extensively used for the removal of suspended solids (SS) by gravitational settling that are not removed by preliminary treatment [1], and are also used as an integral part of the biological wastewater and sludge treatment process [2]. The removal of SS also results in a significant decrease of organic load, usually expressed in terms of biochemical oxygen demand (BOD) or chemical oxygen demand (COD). PSTs are one of the controlling factors for the total construction costs of wastewater treatment plants and are, nowadays, essential for wastewater treatment and also for the production renewable energy in the form of biogas and electrical energy production in the wastewater treatment plant (WWTP). The function and operation of PSTs has become more complex, especially since biological nutrient removal is required and given that optimal performance is critical [3].

The physical phenomenon associated with the gravitational precipitation of solid particles in a liquid has been a subject of research since Stokes, in 1851, formulated the equation describing the velocity of sedimentation of spherical discrete particles under quiescent laminar flow conditions [4]. Kynch, in 1952, proposed a kinetic theory of sedimentation based on concentration changes valid for ideal suspensions, but not an appropriate model for flocculent suspensions forming compressible sediments. In the 1970s a mathematical theory was developed which attempted to unify studies on sedimentation of dispersed and flocculating suspensions [5]. The theory applied continuum mechanics to particulate systems and the phenomenological framework has led to a variety of similar mathematical models of spatially one-dimensional solid-liquid separation processes of flocculent suspensions [6].

When considering the process of sedimentation as applied to PSTs, discrete settling conditions could be assumed for relatively low inlet concentrations. Work by Hazen, in 1904, saw the first analysis of factors affecting the settling of solid particles form dilute suspensions and introduced the surface loading concept [5]. However, sewage contains a considerable proportion of flocculent particles that do not have constant settling characteristics and there is a number of published studies [7–9] developing a variety of mathematical models of spatially one-dimensional soli-liquid separation processes of flocculated suspensions. Flow conditions are also subject to a variety of disturbances due to hydraulic conditions, density currents and wind action. A certain amount of work has been undertaken to study the dynamic behavior [10–16] and hydraulic characteristics of reservoirs and PSTs. In recent years, in order to consider the fluid dynamics of the tank, models based on computational fluid dynamics (CFD) [6,17–24] have been used to predict flow patterns and suspended solid distributions within sedimentation tanks.

For the design and calculation of the dimensions of PSTs, exhaustive experimental measurements are required for the construction of solid-removal percentage curves. Several experiments are necessary to obtain solid-removal contour plots at different heights and times, which are also required for construct charts that describe the total solid-removal percentage in the tank at given time. This procedure is laborious because it is necessary to have a large amount of experimental data to obtain plots with an acceptable accuracy [6] and can be applied to laboratory studies, but is not practically affordable for the design and operation of PSTs.

The design procedures of PSTs currently used are still based on the Sierp and Greely diagrams considering surface overflow rate or surface hydraulic load (q = Q/A, where Q is the flowrate (m^3/s) and A is the surface area (m^2) of the sedimentation basin) and hydraulic retention time (HRT) [25–27]. PSTs are regarded as a black box and their geometry, operation, and other important features are poorly addressed. Design and operation is still based on empirical relationships, whereas homogeneous turbulence, flow pattern, and the direct way of describing the movement of SS and their interaction mechanism with settling and removal are rarely considered [3].

Traditionally, the performance of full-scale WWTPs is measured based on influent and/or effluent, waste sludge flows, and concentrations. WWTPs remain notorious for poor data quality. Sensor reliability problems due to the hostile environment, missing data, and various other problems [28], means that data typically have a high variance and often contain measurement errors. Comparative full-scale evaluations seldom result in meaningful and/or distinguishable results [29], and there is a considerable difference between the expected removal efficiency rates (50–70%) for SS and (25–40%) for BDO_5 when using the currently used values for the design, such as q and HRT, more frequently the removal rate of different PSTs shows an increasingly strong fluctuating pattern even for the same range of the HRTs [2]. Some research [30] shows the difference between real plant removal rates with the recommendations of the ATV guideline and analyzing the design criteria applied to small systems of wastewater treatment, the official HRT design criteria may be too conservative Q < 0.21 m^3/h, as well as inadequate for Q > 0.83 m^3/h [31].

In order to optimize the design and assessment of PSTs, it is necessary to determine their pollutant removal efficiency as a function of the geometric and operating characteristics of the settling tank and the solids concentration of the fed suspension. Some surveys [1,3,6,18,32–35] showed the effects of SS concentration in raw wastewater, temperature, and some operating characteristics, such as HRT or q, on the performance of PSTs. These studies provided simplified the empirical mathematical models to describe the average removal of wastewater pollutants that are helpful in the design of sedimentation tanks or to predict the behavior of sedimentation tanks under certain operating conditions. Subsequent details of tank design are usually based on empirical experiences [24]. For the design of PSTs, the use of CFD-based models has not been common due to the inherent complexity of the corrected Navier-Stokes equations for turbulent flow and the costs associated with the specialized hardware and software required [6].

Primary sedimentation accounts for an important part of the capital cost of a conventional plant, comprising both primary and secondary stages. Designing of the PST needs the setting operational parameter q, which will involve variations on the HRT and efficiency removal. An increase in retention time will mean a greater volume of PST and also a higher performance; this variation of performance will, in turn, condition the design and volume of the secondary treatment.

Previous works have related removal efficiencies to surface overflow rates [1–3,6,24,31,33,34]; some of them [2,3,24,33] focused their research in a high value of surface overflow rate, in the range of 4 $m^3/m^2{\cdot}h$ to 13 $m^3/m^2{\cdot}h$, which are considerably higher than those recommended in the design guidelines. Other works [1,32] researched the range of q between 0.25 $m^3/m^2{\cdot}h$ and 6.25 $m^3/m^2{\cdot}h$, closer to those recommended in the design guidelines. The range of HRTs obtained, included values of 0.33 h to 13 h [1–3,6,24,31,33,34]. According to Metcalf and Eddy [27], in cold climates, the viscosity increases of water, slow the sedimentation rate, establishing a relation between the temperature and the increase of the hydraulic retention time. Previous research [1] explicitly included water temperature in their work, with variations between 18 °C and 26 °C.

After a previous investigation to know the average value of surface overflow rate in the real PSTs of the WWTP, which allowed to fix it in 1 $m^3/m^2{\cdot}h$; the aim of the present investigation of PSTs, comprising in situ q measurements between 0.8 $m^3/m^2{\cdot}h$ and 1.4 $m^3/m^2{\cdot}h$ in conjunction with the removal efficiency analysis, is to contribute to a better understanding of the connection between flow and removal processes in PSTs and to develop and approximate a feasible empirical mathematical model that allows for the prediction of performance removal rate based on surface overflow rate and temperature which would, in turn, optimize the design of the treatment plant.

2. Materials and Methods

2.1. Semi-Technical PST

For the development of the research, a semi-technical PST was used, located at the pre-treatment stage of the WWTP Rincón de León in Alicante, Spain. The selected WWTP is a conventional activated sludge plant with anaerobic digestion for sludge treatment. The semi-technical PST was located parallel to the full-scale primary sedimentation tanks and prior to the existing biological reactors in the treatment plant, as indicated in the process diagram of Figure 1.

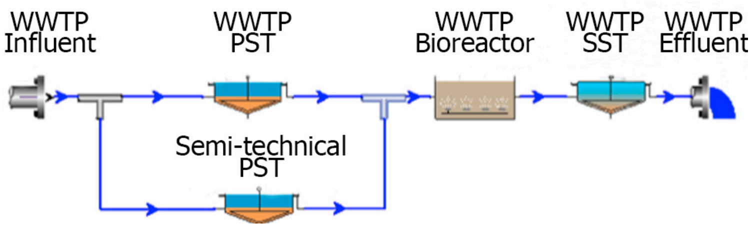
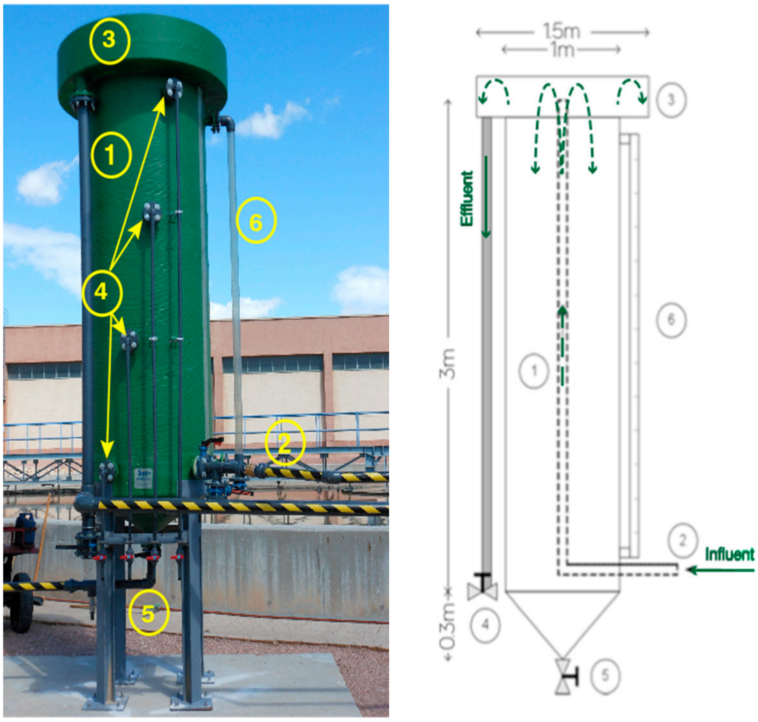


Figure 1. Semi-technical PST: schematic diagram of the process.

As shown in Figure 2a,b, the semi-technical PST system consists of the following elements: (1) GRP circular vessel 3 m deep (the same as full-scale PST of WWTP), 1 m in diameter, with an operating volume of 2.3562 m^3 and an area of 0.7854 m^2; (2) wastewater supply pipe from feed pumping, with cylindrical inlet baffle to dissipate the kinetic energy of the jet; (3) outlet weir 1.5 m in exterior diameter; (4) control valves at different heights for water samplings of decanted water; (5) bottom slurry purge; and (6) communicating graduated vessel for balancing out the levels.



(**a**) (**b**)

Figure 2. Semi-technical PST: (**a**) picture; (**b**) schematic diagram.

2.2. Experimental Procedure

A data evaluation of full scale PST from the WWTP on the basis of annual continuous measurements, allowed us to know the average value of q at which the tanks worked, reaching a value of around 1 $m^3/m^2 \cdot h$. The value of q has been calculated based on the flow rate and the surface of the PST during the measurement period. Over four months, the pilot plant was operated at three different cycles, corresponding to three decreasing surface hydraulic loads (q) of 1.4, 1.0, 0.8 $m^3/m^2 \cdot h$, these low values were chosen to obtain relatively high removal efficiencies according to typical operating values for primary settling systems [26,27]. Samples of raw water of 0.5 L from the feed and of decanted water form the effluent of the pilot plant were taken three days/week in triplicate, to determine the values of temperature, SS, COD, BOD_5, pH, and conductivity. Sludge purge was performed daily to avoid affecting the operation of the decanter, even on days when no water samples were taken from the decanter.

2.3. Analytical Method

2.3.1. Physical and Chemical Determination

COD and BOD_5 were determined according to the American Public Health Association, the American Water Works Association and the Water Environment Federation (APHA-AWWA-WEF) methods. The suspended solids (SS) were determined by gravimetric methods [36]. The pH was determined using a pH meter (Crison pH CM 35®, Hach Lange Spain S.L.U, BI, Spain) and conductivity was determined using a conductivity meter (Crison CM 35®).

2.3.2. Statistical Analysis

The data obtained throughout this study were analyzed using a computer-assisted statistics program, SPSS 20 for Windows. A least significant difference test (LSD test) was used to measure the differences between the different operational conditions studied (SHL and HRT). Normality tests of the data were performed using the Shapiro-Wilk test, since the dataset was lower than 2000 elements. An analysis of variance (ANOVA) was used to assess the homogeneity of variance, with a significance level of 5% ($p < 0.05$).

Moreover, a multivariable statistical analysis using the software Canoco for Windows, version 4.5, was used to quantify the influence of the variables on the parameters of the behavior of the sedimentation tank and to obtain variables with the greatest influence on the working of the membrane. A detrended correspondence analysis (DCA), the most appropriate ordination statistical analysis, was carried out in order to obtain gradient lengths. DCA revealed that the longest ordination axis was lower than three, which meant that the distribution of the model was linear. Redundancy analysis (RDA) was used due to the fact that the distribution of the model was linear, as described by the statistical method recommended by Lepš and Šmilauer [37]. Statistical significance was tested using a Monte Carlo test with 499 permutations and a selected significance level of 0.05.

2.4. Mathematical Model

Considering the basic theory of sedimentation, removal efficiency is related to initial SS concentrations and hydraulic factors such as surface overflow rate or hydraulic retention time and existing performance relationships include these variables [6,34]. Flocculation and settling are influenced by other factors such as the velocity field, particle size, and density and the density and viscosity of the fluid; Flocculation is also affected by chemical characteristics of the particles and fluid. Inlet conditions or environmental factors (wind action and heat flux) cause changes to the density and velocity field [1].

The proposed model, based on the expected behavior of the system, is an exponential model depending on surface overflow rate:

$$E_{SS} = A \cdot e^{-B \cdot q} \tag{1}$$

where E is the removal efficiency; q is the surface overflow rate $m^3/m^2{\cdot}h$; and A and B are unknown coefficients:

$$E = \frac{(S_i - S_e)}{S_i} \tag{2}$$

and where S_i and S_e are influent and effluent concentrations.

3. Results

3.1. Influent Characteristics

The average values of the influent characteristics for the three cycles of q and HRT, are shown in Table 1.

Table 1. Influent characteristics: SSi, CODi, BOD_5i, pH, and conductivity.

Influent Characteristics	Stage 1	Stage 2	Stage 3
q ($m^3/m^2{\cdot}h$)	1.4	1.0	0.8
HRT (h)	2	3	4
t^a (°C)	23.64 ± 2.00	23.10 ± 2.22	21.70 ± 2.00
SSi (mg/L)	382.14 ± 54.66	415.43 ± 40.99	418.57 ± 67.01
CODi (mg/L)	835.07 ± 102.91	862.29 ± 84.67	836.86 ± 91.01
BOD_5i (mg/L)	396.64 ± 42.46	428.16 ± 42.12	405.23 ± 40.11
pH	8.30 ± 0.24	8.13 ± 0.21	8.20 ± 0.17
Conductiv. (µS/cm)	2517.14 ± 465.48	2530.71 ± 260.87	2771.07 ± 246.69

There are no statistically significant differences in the values of the influent. Therefore, the data obtained in each cycle are perfectly comparable.

All samples were taken on dry weather days. The raw water temperature varied between 20.5 °C and 25.0 °C during stage 1, 18.9 °C and 28.0 °C during stage 2, and 17.9 °C and 26.0 °C during stage 3, as a consequence of fluctuations throughout the year when operating under real conditions. The small differences in the values in temperature are due to the fact that the raw water samples came from the pre-treatment entry channel, located inside the pre-treatment building. The SS, COD, and BOD_5 loading showed little variation in the three cycles. The measured influent concentrations of SS are on the average of the observed by Tebbutt [32] in a wider range of 200–800 mg/L, but higher than those reported by Christoulas [1], the observed variations could be due to differences in population habits.

3.2. Removal Efficiency

The mean data obtained for the decanted water effluent for the three cycles of q and HRT, are shown in Table 2.

Table 2. Effluent characteristics: SSe, CODe, BOD_5e, pH, and conductivity.

Effluent Characteristics	Stage 1	Stage 2	Stage 3
q ($m^3/m^2 \cdot h$)	1.4	1.0	0.8
HRT (h)	2	3	4
t^a (°C)	25.00 ± 3.50	23.00 ± 3.60	20.60 ± 3.30
SSe (mg/L)	165.00 ± 26.53 ^{a}	155.00 ± 28.76 ^{a,b}	138.57 ± 20.33 ^{b}
CODe (mg/L)	521.57 ± 75.32 ^{a}	493.93 ± 45.19 ^{a,b}	449.07 ± 62.57 ^{b}
BOD_5e (mg/L)	283.92 ± 31.19 ^{a,b}	288.08 ± 24.51 ^{a}	256.80 ± 34.22 ^{b}
pH	7.93 ± 0.24	7.83 ± 0.32	7.83 ± 0.14
Conductiv. (µS/cm)	2424.21 ± 274.7	2747.14 ± 235.84	2650.79 ± 330.9

Note: ^{a,b} Statistically significant differences.

The study was completed by variance analysis to significance of an assigned confidence level. If the values shown have the same superscript in the table, they do not present differences, only statistically significant differences are shown for those cycles that do not share any superscript. Statistically significant differences between the different cycles are observed; since they have not been shown in the characteristics of the influent, they have to be as a consequence of the variation of the process variables. The data of each cycle presents with the rest of the cycles, statistically significant differences.

The decanted water temperature varied between 18.9 °C and 31.0 °C during stage 1, 15, and 26.5 °C during stage 2, and 16.0 °C and 25.5 °C during stage 3, as a consequence of the fluctuations throughout the year when operating under real conditions. The greatest dispersion in the measured water temperature values is due to the outdoor location of the decanter. The values of SS obtained are similar to those reached by Patziger [2].

As a first step in analyzing the performance data it was decided to obtain an efficiency-overflow rate relationship. The removal efficiency (E) of SS, COD and BOD_5, obtained in the process at different surface overflow rates, is indicated in Figure 3.

Higher hydraulic flow rates generates higher turbulent kinetic energies affecting sedimentation and lower efficiency removals [3]. Comparing with current values from the design guidelines the data obtained is slightly higher. The increased removal in the pilot-plant tank is probably caused by the combination of longer settling time and, almost certainly, to a degree of flocculation that does not exist in the laboratory test [33]. Since the pilot plant was close to full-scale depth and operated with real sewage, it is believed that the results are comparable to those that would be obtained in an actual plant. The calculated results of E_{SS} are also higher than the results obtained by other researchers with $E_{SS} < 50\%$ [18] or $E_{SS} < 57\%$ [24].

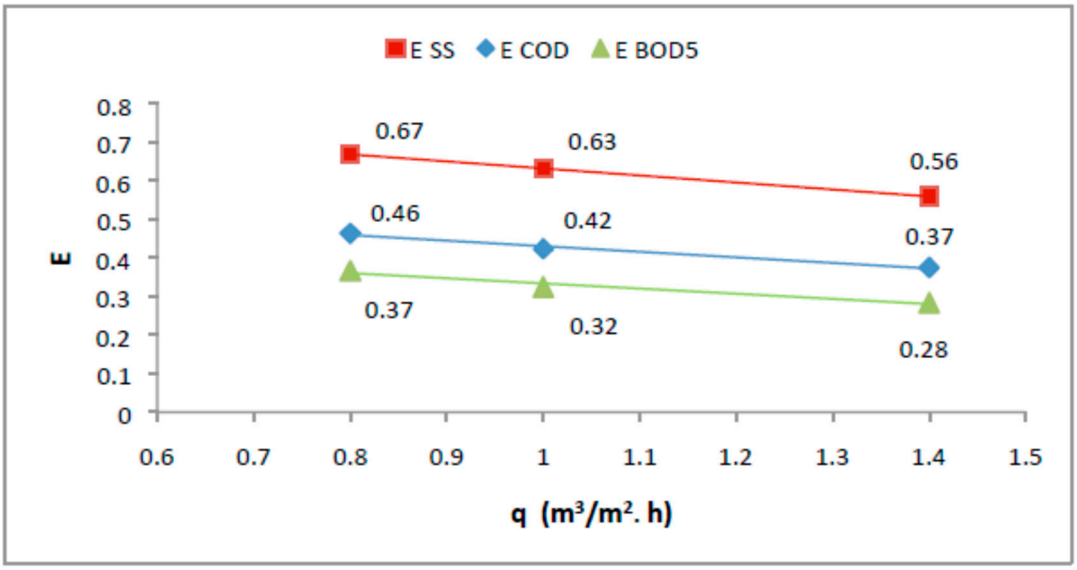


Figure 3. Effect of q on SS, COD and BOD_5 Efficiency.

The second analysis, as shown in Figure 4, was performed on the original data grouped into SS influent (SSi) ranges (300–400 mg/L and 400–500 mg/L). It is believed that the SS range of 200–600 mg/L is likely to be more representative of normal sewage [32]. It can also be observed that the SS concentration influent (SSi) had an effect on the removal efficiency, since flocculation is more significant at higher SS levels, different authors have described the same influence [1,18,32,33,38].

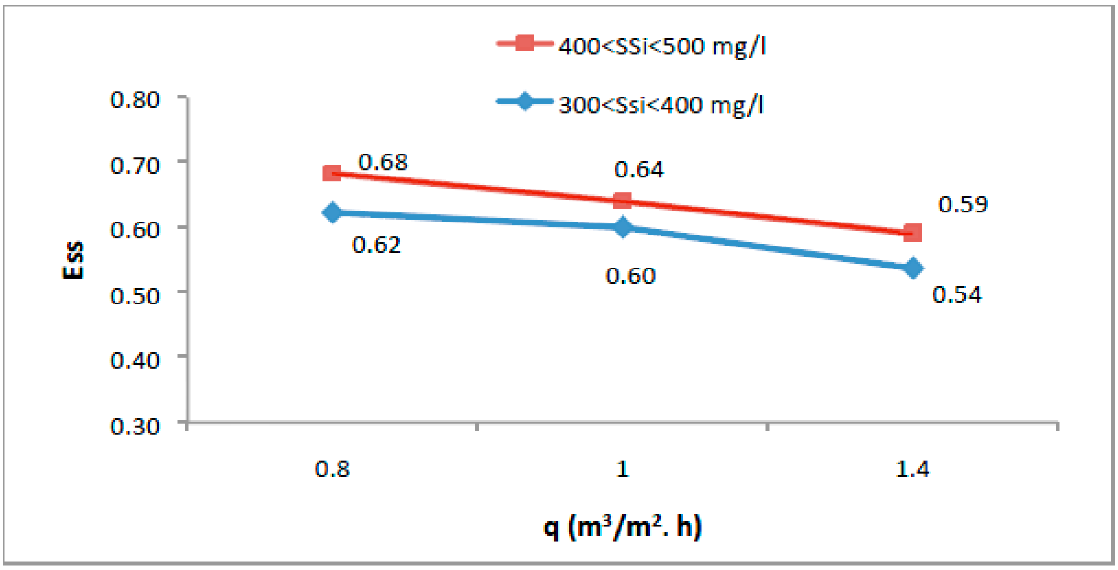


Figure 4. Efficiency at Different SSi Ranges.

The effect of hydraulic retention time (HRT) on removal efficiency E_{SS} and E_{BOD5} obtained from experimentation and its comparison with other previous plots [25,39], are shown in Figures 5 and 6.

Any settleable solids are removed quite rapidly and settlement times in excess of 2 h bring little increase in the removal rate and an increase in the volume in the PST.

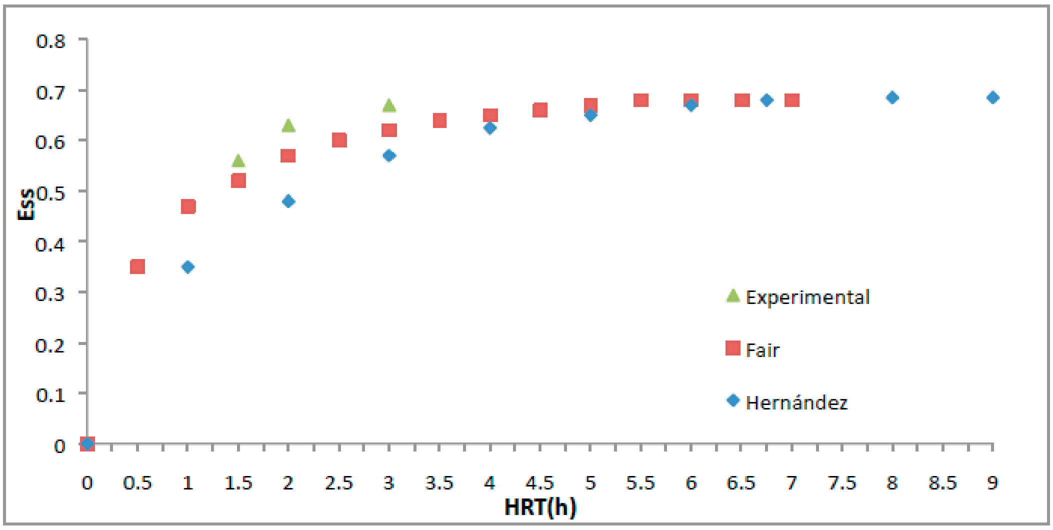


Figure 5. Effect of HRT on SS Efficiency.

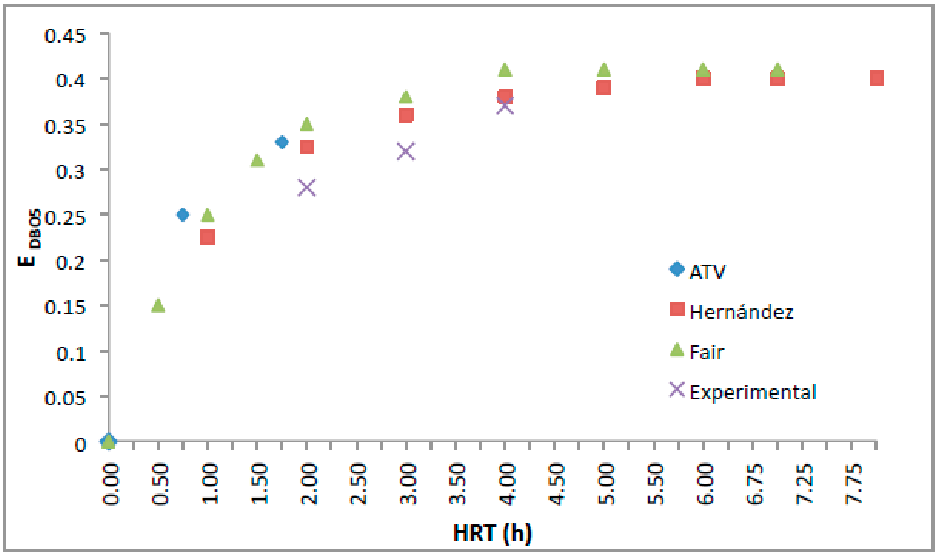


Figure 6. Effect of HRT on BOD_5 Efficiency.

3.3. Combined Multivariate Analysis

As a consequence of the temporary development of the experiment, the evolution of the temperature was closely linked to the surface overflow rate. In the different phases the temperature decreased as the surface overflow rate decreased. As a consequence of this, in order not to de-virtualize the multivariate analysis, the temperature variable was eliminated, and it was analyzed later in each one of the cycles of constant q.

In all statistical analyses, it was observed that efficiency removal in organic matter (COD and BOD_5) and suspended solids was put in order in the same quadrant; thus, the effect of the variables was the same in all them.

The analysis of all the data (Figure 7) revealed that, the most influential variable in the relation of variance between the results and the variables of the process was the concentration of SS, which presented a strong positive correlation with the efficiency of the process—the higher the SS concentration in suspension, the greater the removal. This may be due to flocculation being more significant at high levels of SS concentration.

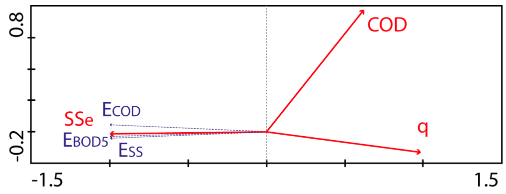


Figure 7. Efficiency combined multivariate analysis.

The next variable with the greatest influence on the variability of the system was the surface hydraulic load, which, as many authors have studied [1–3,6,24,31,33,34] had a strong negative correlation, i.e., the lower the HRT in the tank (higher hydraulic loads), the more the process performance is greatly reduced. The organic matter concentration, on the other hand, hardly showed any correlation in the variability of the system (angle of the vector near 90°).

Regarding the analyses performed at each of the cycles of constant q, as can be seen in the Figure 8 ($q = 1.4\ m^3/m^2{\cdot}h$), Figure 9 ($q = 1.0\ m^3/m^2{\cdot}h$) and Figure 10 ($q = 0.8\ m^3/m^2{\cdot}h$), the cycle most affected by temperature was the first one. This could be due to the fact that at higher sewage temperatures, particle-settling velocities increase, and consequently the effect of flocculation and SSi on SS removal becoming less significant [1].

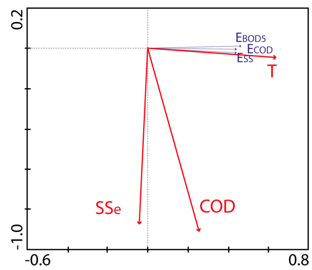


Figure 8. Combined multivariate analysis $q = 1.4\ m^3/m^2{\cdot}h$.

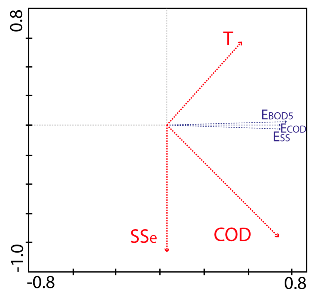


Figure 9. Combined multivariate analysis $q = 1.0\ m^3/m^2{\cdot}h$.

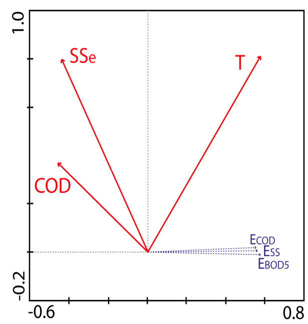


Figure 10. Combined multivariate analysis $q = 0.8\ m^3/m^2{\cdot}h$.

Temperature was positively strongly correlated with the removal rates (Figure 8), i.e., the higher the temperature, the higher the removal rates that were obtained. In the other cycles (Figures 9 and 10), no variables were correlated with the removal rates, so the most influential variable in the process is the HRT, being that the temperature is an especially influential variable when the HRT is high. The effects of density differences and temperature variation can give significantly different flow-through times for the same hydraulic loading conditions [32].

3.4. Empirical Model

The general equation was selected as a simple mathematical model for a complex process:

$$E_{SS} = A \cdot e^{-B \cdot q} \tag{3}$$

The mode of this form is similar to that used by Tebbutt [33] and implies a linear relationship between q and log E, with B in a range of 0.0020 and 0.123 d/m, with no dependence of B on the temperature upon comparison. Considering low differences between low q values, due to the exponential dependence of Ess on $(-q)$, the effect of influent SS concentration was considered on coefficient A as an increasing linear function or SSi. To include the influence of temperature (T), an exponential dependence, similar to that proposed by Christoulas [1], was considered.

The general relationship satisfactorily fits ($R^2 = 0.7837$) the obtained data with:

$$A = 0.0004 \cdot SS + 0.6779 \tag{4}$$

$$B = 0.2287 \cdot e^{(0.006 \cdot T)} \tag{5}$$

Therefore, the performance data from the pilot plant are suitable for studying the influence of SS and temperature on sedimentation. Figure 11 shows the experimental values and the expected with the proposed model.

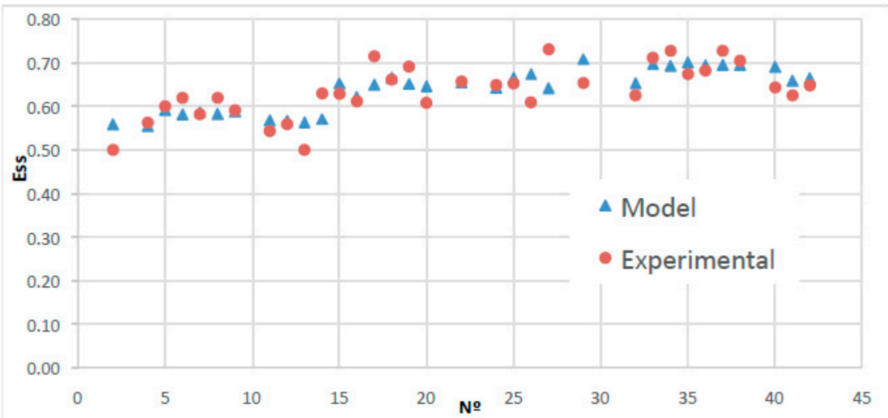


Figure 11. Experimental Data and Model Values.

With the aim of examining the validity in previously existing relationships, the experimental data were applied to other correlations or models proposed in the literature [33], but with a poor fit. Differences in parameter temperature could partially explain the different results given by different models [1].

4. Conclusions

In this research, the evaluation of surface overflow rate, hydraulic retention time, influent SS and temperature and their influence on the removal efficiency of SS, COD, and BOD5, through comprehensive in situ measurement procedures were presented. Studies carried out at one semi-technical PST with the same depth as full-scale PST from WWTP, and fed with real sewage water.

The variable that most affects the elimination of SS and organic matter, is the influent SS load; the second most important variable was the surface overflow rate.

The results provide an effective approach for full-scale plant evaluation that can never be as well planned or controlled, e.g., lab or pilot studies, and a useful account of how the surface overflow loading affects efficiency removal, which may increase by 11% for SS and 9% for COD and BOD_5, for low q variations of $\pm 0.6\ m^3/m^2 \cdot h$ and HRT of ± 2 h.

The proposed empirical model describes the average removal of SS in terms of surface overflow rate, influent suspended solids, and temperature and, therefore, the results can be deemed as helpful in the design and operation assessment of PSTs with in similar environmental conditions, and wastewater characteristics.

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Conflicts of Interest: The authors declare no conflict of interest.

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