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Towards an efficient and functional design of constructed wetlands systems for wastewater and sludge treatment in high altitude tropical regions

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Resumen

El tratamiento de aguas y lodos residuales mediante sistemas descentralizados naturales, como el Sistema Francés, representa una estrategia sostenible y eficaz de tratamiento. Este sistema emplea dos etapas de humedales de flujo vertical (VFCWs) para tratar aguas residuales crudas, eliminando la generación de lodos. A pesar de su uso extensivo en Francia, su aplicación en Latinoamérica, especialmente en zonas andinas de altura, ha sido limitada. El principal objetivo de esta tesis fue investigar la viabilidad de aplicar el Sistema Francés para el tratamiento de aguas residuales domésticas y lodos sépticos bajo las condiciones climáticas de la Región Andina, a 2500 m.s.n.m. mediante un estudio piloto en Cuenca, Ecuador. Los resultados mostraron que los FVFCWs pueden manejar continuamente cargas hidráulicas extremas de agua residual diluida, teniendo presente un adecuado tiempo de alimentación y descanso, lo que reduce el área de tratamiento necesaria y minimiza la acumulación de lodos. Se determinó también que el uso de fosas sépticas sigue siendo común en zonas urbanas y rurales, por lo que el tratamiento de lodos fecales es necesario. Al utilizar los FVFCWs para este tipo de lodos, se observó que el uso de múltiples lechos permite un tratamiento adecuado y que la retención del percolado durante 7 días, mejora significativamente la remoción de DQO y ST, sin aumentar el área requerida. El Sistema Francés tiene un alto potencial para ser utilizado en zonas con climatología similar a la zona andina para el tratamiento de aguas residuales domésticas y lodos de fosas sépticas.

Palabras clave del autor: Sistema Francés, carga hidráulica, zona andina, lodos de fosas sépticas

Abstract

The treatment of wastewater and sludge through decentralised natural systems, such as the French System, represents a sustainable and effective strategy. This system uses two stages of vertical flow constructed wetlands (VFCWs) to treat raw wastewater, eliminating sludge generation. Despite its extensive use in France, its application in Latin America, particularly in high-altitude Andean regions, has been limited. The main objective of this thesis was to investigate the feasibility of applying the French System for the treatment of domestic wastewater and septic sludge under the climatic conditions of the Andean Region, at 2500 meters above sea level, through a pilot study in Cuenca, Ecuador. Results showed that VFCWs can continuously handle extreme hydraulic loads of diluted wastewater, with proper feeding and resting periods, reducing the required treatment area and minimizing sludge accumulation. It was also determined that septic tanks remain common in both urban and rural areas, making the treatment of fecal sludge necessary. By using VFCWs for this type of sludge, it was observed that the use of multiple beds allows for adequate treatment, and that retaining the percolate for seven days significantly improves the removal of COD and TS without increasing the treatment area. The French System shows great potential for use in areas with climates similar to the Andean region for the treatment of domestic wastewater and septic sludge.

Author Keywords: French system, hydraulic loading rate, highlands, septage

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Towards an efficient and functional design of constructed wetlands systems for wastewater and sludge treatment in high altitude tropical regions

Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Water Resources

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Hacia un diseño eficiente y funcional de sistemas de humedales artificiales para el tratamiento de aguas residuales y lodos en regiones tropicales de altura

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A mi hermosa familia: Pablo, Benja y Mati

“El Señor terminará en mí lo comenzado, porque es eterno su amor”

Salmo 138

Chapter 1

1. Introduction and Thesis Outline

1.1. Introduction

Wastewater and sludge treatment are critical components of modern environmental management. They are essential for protecting public health, safeguarding ecosystems, and ensuring the sustainable use of water resources. The treatment of wastewater, which includes domestic sewage, industrial effluents, and agricultural runoffs, prevents the contamination of natural water bodies with harmful substances and pathogens. Similarly, the treatment of sludge, which includes both the byproduct of wastewater treatment and faecal sludge, is crucial for safe disposal and for harnessing its potential as a resource.

According to the United Nations (2023), it was estimated that globally, 44% of domestic wastewater was not safely treated before being released into the environment in 2020. This issue is even more pronounced in Ecuador, where 69% of domestic wastewater is not safely treated (UNICEF/WHO, 2021). The management of faecal sludge is also a significant concern, with two-thirds not being securely handled (UNICEF/WHO, 2022). Additionally, around 32% of the Ecuadorian population lacks sewer connections and relies on Onsite Sanitation Systems (OSSs) such as septic tanks (UNICEF/WHO, 2022). These challenges are especially severe in rural areas, where the high costs of constructing and maintaining wastewater and faecal sludge treatment plants hinder efforts to increase sanitation coverage in developing countries.

To address these challenges, nature-based solutions such as constructed wetlands have emerged as a sustainable alternative to conventional treatment methods (Rahi et al., 2020). Constructed wetlands are artificial systems designed to treat various types of wastewater and sludge, including domestic and industrial effluents as well as septage (faecal sludge from septic tanks) (Jain et al., 2022; Vymazal, 2009). They mimic the physical, chemical, and biological processes of natural ecosystems (Rai et al., 2013). The low energy demand, simple operation, low cost, and production of high-quality effluent free of harmful chemical by-products make this technology particularly attractive, especially for rural and developing regions (Ghermandi et al., 2007).

Constructed wetlands can be categorized into surface flow and subsurface flow systems. Subsurface flow constructed wetlands are further classified into Horizontal Flow (HFCWs) and Vertical Flow (VFCWs) wetlands, based on the direction of water flow. HFCWs and VFCWs are generally used for secondary treatment of wastewater to prevent clogging of the porous filter material. However, VFCWs have also been successfully used to treat screened raw wastewater. This system, known as the French system or French VFCWs (FVFCWs), offers integrated sludge and wastewater treatment in a single system. Therefore, the system eliminates the need for primary treatment, thereby reducing construction costs (Dotro et al., 2017).

The classical French system consists of two stages. The first stage (FS-FVFCW) is designed to treat raw wastewater and comprises three parallel alternating unsaturated beds filled with various sizes of gravel. The second stage consists of two beds that also operate alternately. These beds are sequentially batch-fed through pulse loading (Molle et al., 2005). Another application of this system is the treatment of septage (Paing & Voisin, 2005). Septage is applied onto the surface of the first stage bed, where evapotranspiration and water infiltration occur, leaving behind a concentrated sludge on the surface (Uggetti et al., 2009). The system´s permeability and oxygenation are maintained by the canals formed during the growth of the plant root system (Bassan et al., 2014).

The efficiency of processes within VFCWs for wastewater treatment, sludge dewatering, organic stabilization, and mineralization depends on various factors. These include design and operational parameters, local and regional weather conditions, and the characteristics, quantities and variability of inflowing wastewater and septage (Ávila et al., 2016; Bassan et al., 2014; Nguyen et al., 2018). Key design parameters include hydraulic, organic and solids loading rates (HLR, OLR, SLR, respectively), and loading frequency. Local conditions, particularly temperature and its variability, are crucial as they determine the minimum area required for the wetland to meet discharge standards. Studies worldwide have investigated different levels of OLRs and HLRs, and various configuration systems, yielding a wide range of optimal values (Dubois & Molle, 2018; Kumar et al., 2018; Trein et al., 2019). This variability underscores the absence of a generic value for VFCWs design parameters.

Mathematical modelling in VFCWs is of great importance for optimizing their design and performance, and for understanding the complex biochemical process occurring. They can help to identify the design and operational parameters suitable for a wide range of conditions (Khan et al., 2022). Experience has shown that to accurately simulate effluent concentrations, the hydraulic behaviour of the system must first be well understood and described (Langergraber, 2017). For FVFCW, research has focused on developing of a simplified hydraulic model using an empirical infiltration coefficient (Arias et al., 2014), comparing various existing models simulating preferential flows in these wetlands (Morvannou et al., 2012), and using FVFCWs for managing urban runoff (Fournel et al., 2013). Additional studies have explored nitrogen removal modelling in classic systems (Morvannou et al., 2014) and compact systems that incorporate a zeolite layer (Pucher et al., 2017). There is no evidence of applications of simplified modelling for hydraulic behaviour and COD removal in FVFCWs, while exploring commonly used modeling platforms.

The successful application of the French system configuration has been demonstrated not only in France and other European countries but also in tropical regions. Research has shown a reduction in the area required for the first stage, especially in lowland (760 m.a.s.l) tropical regions (García Zumalacarregui & Von Sperling, 2018). However, uncertainty persists regarding the suitability of this system for wastewater and septage treatment in developing regions situated at high altitude in the tropics, which are distinguished by intense consistent year-round solar radiation, significant daily temperature fluctuations, strong winds (Ho et al., 2018) and less stringent regulations for treated wastewater discharges.

Given this context, there are opportunities to enhance operational strategies and design considerations in regions with stable climatic conditions throughout the year and broad discharge regulations. Moreover, among the numerous studies conducted worldwide, only two have been carried out in Latin America, specifically in Brazil and French Guiana, both of which have warm climates (Rodriguez-Dominguez et al., 2020). Notably, there is a lack of performance data for these systems at high altitudes, particularly in the Northern Tropical Andes. This study was conducted in Cuenca, Ecuador, due to its climatic characteristics typical of the Andean region. The primary focus of the research was on the removal of organic matter because the main source of contaminants come from households and the agriculture in this area is not intensive. The historic total nitrogen concentrations in the influent to the centralized wastewater treatment plant in Cuenca, over the past ten years have been below regulatory limits (NH_4^+ < 30 mgL^{-1} and TKN < 50 mgL^{-1}). However, once the major purpose is managed, attention can then shift to other important parameters, such as nutrient removal.

1.2. Objectives

The main objective of this PhD project is to investigate the feasibility of the FVFCWs as a viable solution for domestic wastewater and septage treatment under the climatic conditions of the Andean Region at an altitude around 2500 m.a.s.l. To achieve this, data was collected from pilot-scale FVFCWs and septic tank desludging operations in Cuenca, Ecuador, to assess septage management practices. The specific objectives of this research are summarised as follows:

1. To stablish optimal working conditions for FVFCWs to achieve efficient removal of organic matter and total suspended solids. This includes determining appropriate HLRs and OLRs, as well as effective feeding-resting and starting up strategies for treating raw wastewater.
2. To investigate the temporal and spatial distribution of septic tank usage in Cuenca Ecuador, to gain insight into current faecal sludge management practices. This will help to identify the operational strategies and SLR that maximize the performance of FVFCWs to septage treatment.
3. To test and examine a simplified mathematical model for the hydraulic behaviour and biokinetic performance in FVFCWs.

1.3. Outline of the PhD thesis

Figure 1.1 provides a graphical overview of the organization of this PhD thesis, detailing the chapters and illustrating their interrelationships. The thesis is structured into two main sections: wastewater treatment and sludge treatment, each containing the respective experimental chapters. Additionally, the thesis includes chapters outside of these sections: the introduction, literature review, and conclusions.

Chapter 2 presents a literature review of the French system, covering its classical configuration, evolution, modifications and the models that have been applied for this type of wetlands. Additionally, it addresses current challenges and knowledge gaps, highlighting future research directions for the French system.

Chapter 3 details the performance of two FVFCW pilots over 18 months, operated at HLRs of 0.94 and 0.56 m d^{-1} in two different operation schemes of feeding and resting durations. This chapter explores the feasibility of implementing the system in highland regions and examines how the system responds to high HLRs while maintaining satisfactory efficiencies.

In Chapter 4, the calibration of a hydraulic – biokinetic model to simulate the hydraulic behaviour and the effluent concentrations of DO and COD in a FVFCW is detailed.

Chapter 5 initiates the faecal sludge management section by exploring the temporal and spatial distribution of septic tank use in both urban and rural areas of Cuenca, Ecuador. It concludes by evaluating the current faecal sludge management practices, highlighting the need for a decentralised approach. This chapter presents an estimation of the required area of the FVFCWs as an effective solution for faecal sludge treatment, capable of handling the observed fluctuations in septage.

Chapter 6 addresses the faecal sludge management problem by evaluating the performance of a FVFCW treating septage. It analyses the pilot´s performance throughout its entire cycle, from start-up to closure.

Finally, Chapter 7 gathers the main conclusions of the entire study, with lessons learned during its execution, and outlines the future research directions for French style constructed wetlands in the treatment of wastewater and septage.

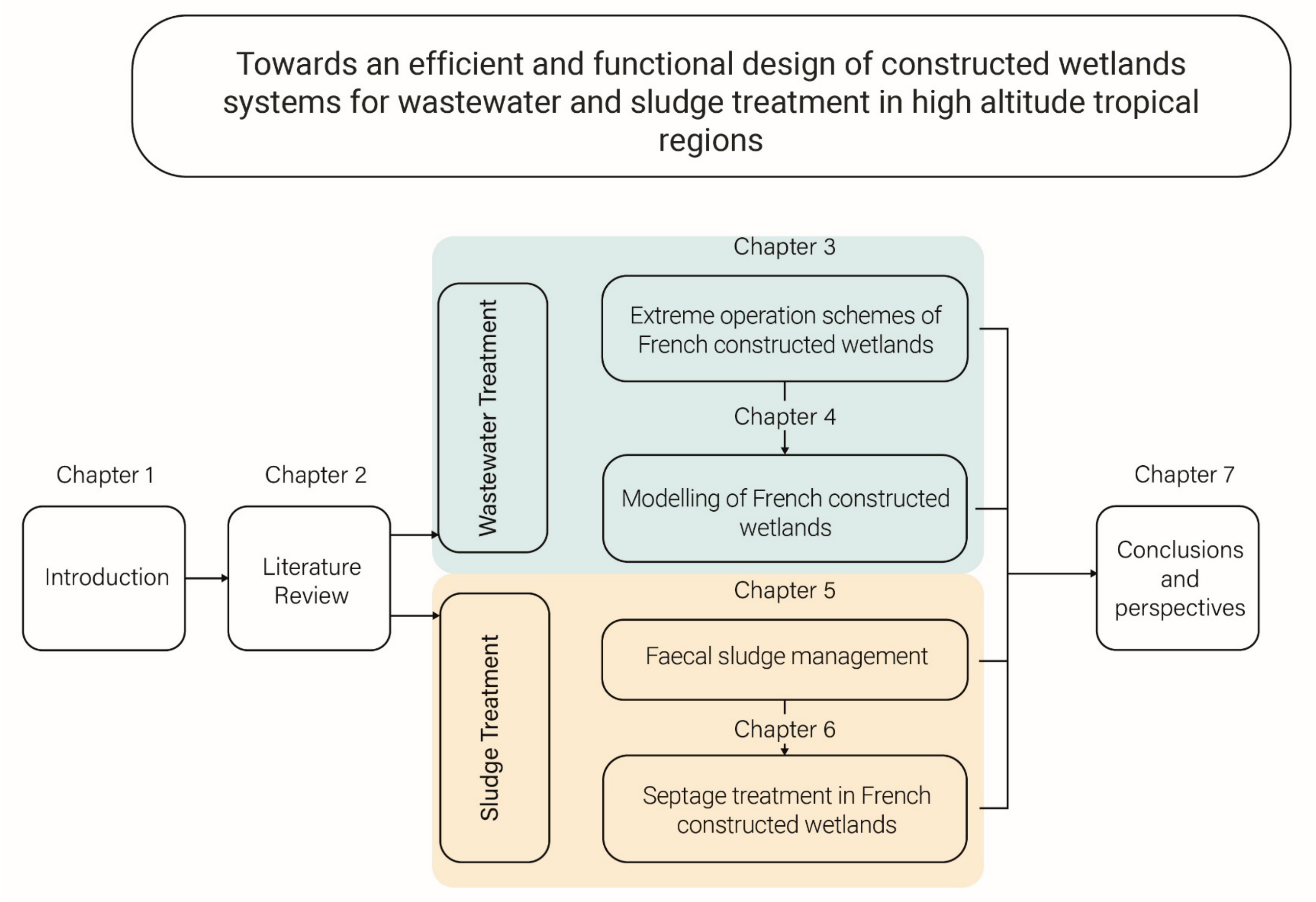

Figure 1.1 Outline of the doctoral thesis structure

Chapter 2

2. Literature Review

2.1. Introduction

A big challenge in wastewater treatment lies in managing both the wastewater and the sludge generated during the treatment process effectively and sustainably. This challenge has prompted that researches explore sustainable strategies and innovations that integrate both aspects. Water, being central to social, environmental, and economic activities, requires focused attention on technologies for wastewater treatment and sludge management, particularly in regions with inadequate infrastructure, such as many developing countries.

French vertical flow constructed wetlands (FVFCWs), a variant of the well-known vertical flow constructed wetlands (VFCWs), have emerged as a promising technology for wastewater treatment, particularly due to their unique ability to treat raw wastewater without the need for primary treatment and the associated sludge management challenges. In this type of system, both the sludge and the wastewater undergo treatment in the initial stage of the system. Besides, FVFCWs is a cost-effective and environmentally friendly treatment system and have garnered in recent years significant interest and research focus.

This review aims to gather literature on topics related to the application of constructed wetlands, specifically the French System, in order to distinguish the evolution of the system from its early stages to the present trends, through scientometric and bibliometric validation and analysis. Further, to clarify the different configurations of the French System, their associated removal mechanisms, and overview the optimal performances of the system. Finally, to incorporate pertinent affiliations and publications related to the French System, aiming to facilitate potential collaborations and support the advancement of this technology, exploring management strategies across various countries and regions.

2.2. Classical French System

2.2.1 Evolution

A comprehensive overview of the evolution of the classical French system is provided in this section, and depicted in Figure 2.1.

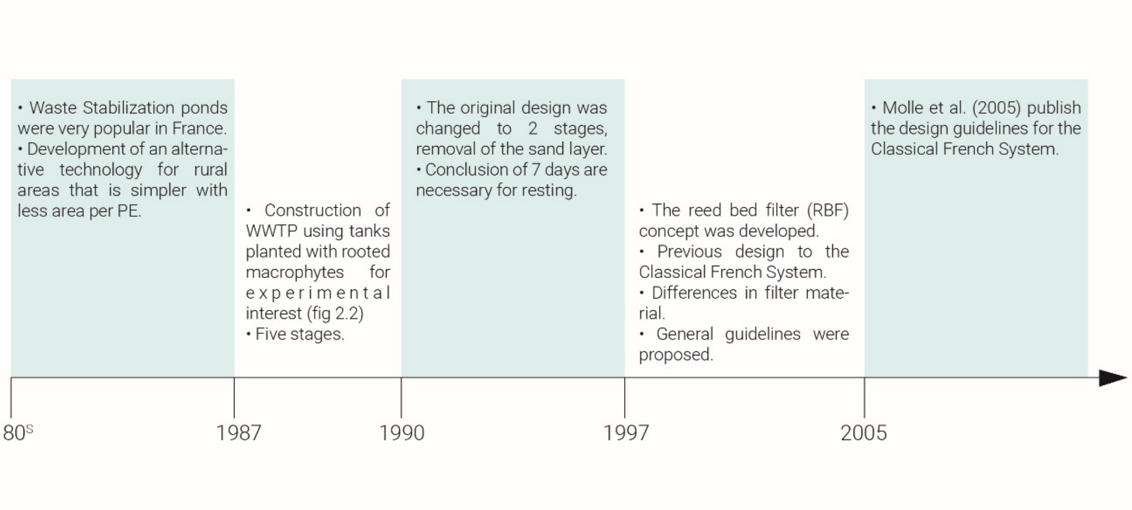

Figure 2.1 Chronological evolution of French System. Related references can be found in this section

The “Classical French System” was first developed by CEMAGREF (French Center for Agricultural Mechanization, Rural Engineering, Water and Afforestation), in the 80´s. This emerged as a response to the limitations of waste stabilization ponds that were very popular in France, but demanded extensive land use, approximately 10 m^2 per Person Equivalent (PE). Thus, a more efficient wastewater treatment technology was needed for rural areas, simpler and reducing the land requirement per PE (Liénard et al., 1990).

Based on the patented process developed by Dr. K. Seidel (Brix, 1994), two small wastewater treatment plants (WWTP) using tanks planted with rooted macrophytes were built in France. One of these WWTP, Saint Bohaire, was of experimental interest due to its heavy organic load. Boutin (1987) carried out studies in Saint Bohaire which revealed promising results that promoted future investigations and improvements to this system.

The system in Saint Bohaire consisted of five stages. The first stage had four parallel percolation (vertical filtration) beds, followed by the second stage with two parallel percolation beds. The 3 further stages were horizontal-flow, each one consisting of one bed. The percolation beds were filled with a 45 cm high layer of gravel with increasing granulometry from top to bottom. The horizontal-flow beds comprised a 30 cm high layer of gravel with only two different granulometries (Figure 2.2) (Boutin, 1987).

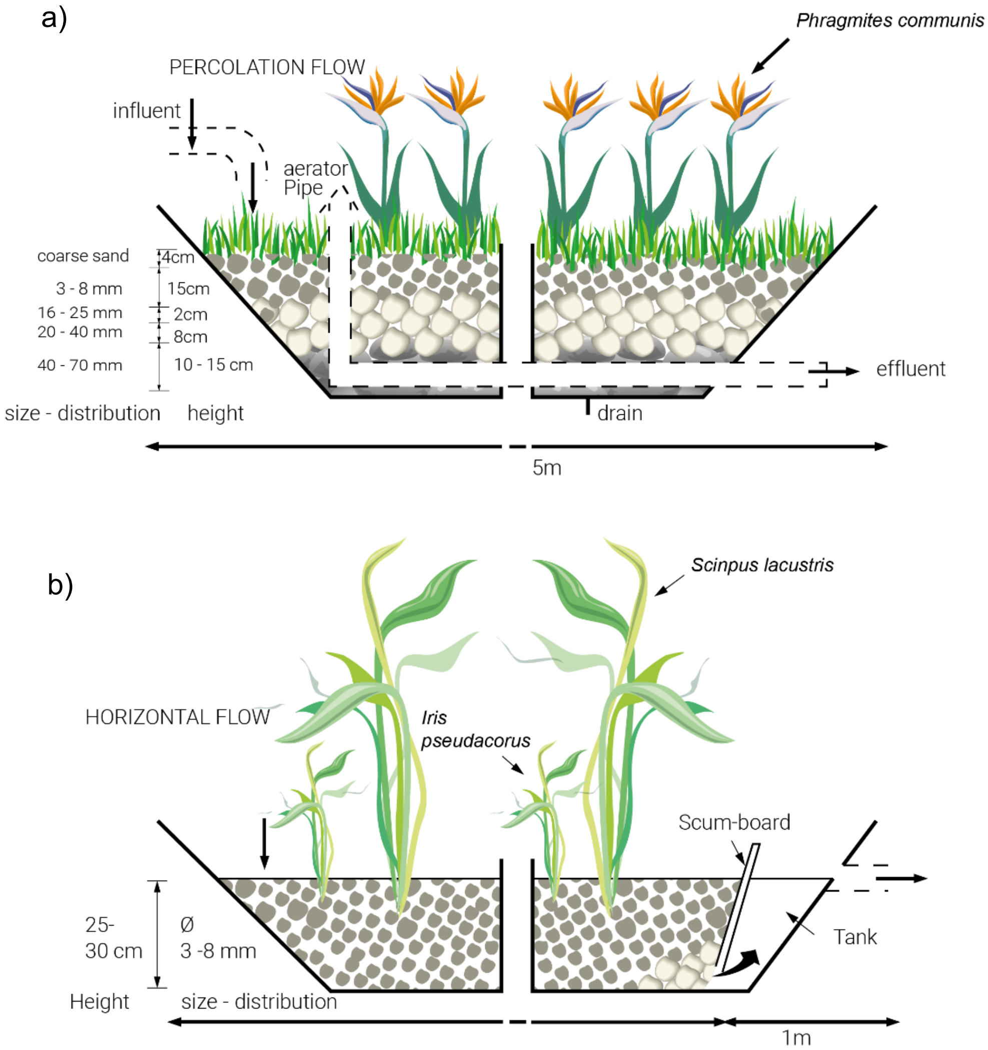

Figure 2.2 Description of Saint Bohaire system a) vertical filtration beds, b) horizontal flow beds (Adapted from Boutin, 1987)

After conducting measurements of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5) and Total Suspended Solids (TSS), Boutin (1987) observed the essential role of the first two stages in the removal of organic matter. These two levels alone achieved removal efficiencies of 75%, 80% and 85% for COD, BOD_5 and TSS respectively. Additionally, it was observed that for a better drying and mineralization of the filtered primary sludge in the percolation beds, a coarser upper layer would be necessary, consequently, the sand layer of the first stage was removed (Lienard, 1987). Further analysis of the WWTP performance, concluded that 7 days was required for the mineralization of the primary sludge layer. And that, by improving the batch feeding, the treatment efficiency can increase (Liénard et al., 1990).

An analysis of the initial design of the wastewater treatment plant, reveals two facts that differ from the current layout of the French System. Firstly, a significant reduction in the number of treatment stages, with the stages three to five disappeared in the present French design. This is primarily because it economizes the investment costs, while maintaining high removal efficiencies, which are mainly obtained in the first two stages: 75%, 80% and 85% for COD, BOD_5 and TSS respectively, as previously mentioned. Secondly, the upper layer in the percolation bed was made up of coarse sand, which is not used anymore in the first stage. All these changes and improvements come from the results obtained in studies carried out in the Saint Bohaire plant.

Based on the results from prior research, a reed bed filter (RBF) concept was developed (Boutin et al., 1997). This RBF plant is the previous design to the Classical French System that we know nowadays. It comprised a bar screen for retaining large-size particles (> 2 cm), followed by two types of filters. The primary stage filter consisted of two layers: a top layer of gravel (15 to 30 cm) and a bottom drainage layer of infill or pebbles. The filter for the secondary stage was formed of three layers, increasing in granulometry from top to bottom. The top layer was made of sand, the intermediate layer of gravel and the drainage layer of infill or pebbles. This configuration still presents some small differences from the French System, as detailed in 2.3. But, the operational strategy of the RBF configuration, with resting periods twice as long as feeding periods, is the accepted Classical French System operational strategy (Molle et al., 2005). This approach was fundamental to control the growth of the attached biomass, to maintain aerobic conditions and to mineralize the sludge.

2.2.2 Bibliometric analysis

To conduct the bibliometric analysis, a literature review was executed on the SCOPUS platform. The search terms were "constructed wetland" or "constructed wetlands" or "artificial wetland" or "artificial wetlands" or "treatment wetland" or "treatment wetlands" or "engineered wetland" or "engineered wetlands" or "reed bed" or "reed beds" or "man-made wetland" or "man-made wetlands" and "French". This bibliometric analysis aimed to collect data on metrics such as the annual publication count and the countries in which studies have been published. Additionally, temporal bibliometric analysis was carried out using the Web of Science (Thomson Reuters) database. Using information obtained from the database, bibliometric mapping was performed on VOSviewer software. This software generated maps based on citation frequency and connections between terms, organizing items into clusters according to their relationships.

The network view map is presented in Figure 2.3. In the network view, each extracted item is represented by a label, which may sometimes be hidden to prevent overlap within a circle. The size of each circle corresponds to the frequency of the item´s occurrence. The color signifies the cluster the item belongs to, while lines depict connections between items. The proximity of items reflects the strength of their relationship, meaning that items closer together have a stronger connection than those farther apart.

As illustrated in Figure 2.3, the most frequently occurring items, represented by the largest circles, included terms such as constructed wetland, wastewater treatment, France, nitrogen, biochemical oxygen demand and sewage. The software, through bibliometric mapping, divided and categorized these terms into four distinct clusters. The red cluster, the largest group, consisted on terms centered on nitrogen and biochemical oxygen demand removal processes. This included terms such as pollutant removal, suspended particulate matter, total kjeldahl nitrogen, vertical flow constructed wetlands, effluent and removal efficiency. In contrast, the green cluster grouped terms related to constructed wetlands for wastewater treatment. Examples from this group included vertical flow constructed wetlands, filter, treatment performance, nitrification, evaluation study. Then, the blue cluster, grouped terms focused on France as well as sludge treatment and sewage treatment, such as organic matter, mineralization, phosphorous, filtration. Finally, the yellow cluster was also focused on constructed wetlands and sewage but with terms related to plants such as *Phragmites australis* and reed bed. It should be noted that might be some terms, such as “nitrification” that appear in a different cluster than expected. For instance, “nitrification” might be found in a cluster separate from “nitrogen”. This discrepancy likely arises because the software categorizes publications based on their keywords. As a result, a publication related to nitrogen removal might not include “nitrification” as a keyword, whereas a publication on wastewater treatment might.

Figure 2.3 demonstrates that constructed wetlands are primarily associated with sewage treatment, emphasizing biochemical oxygen demand and nitrogen removal. However, the French system (represented by the blue cluster for France and constructed wetlands) is also linked to sludge treatment. The other terms directly related to France include organic matter, filtration and phosphorous. These terms might be noteworthy because the first stage of FVFCWs excels at removing organic matter and TSS, the latter benefiting from the system´s filtration capacity. Additionally, modifications to the French system have been considered for phosphorus reduction. Regarding plant species, the only species specifically mentioned is *Phragmites australis*, and reeds appear under the term “reedbed” which is a common term for wetlands used in sludge treatment.

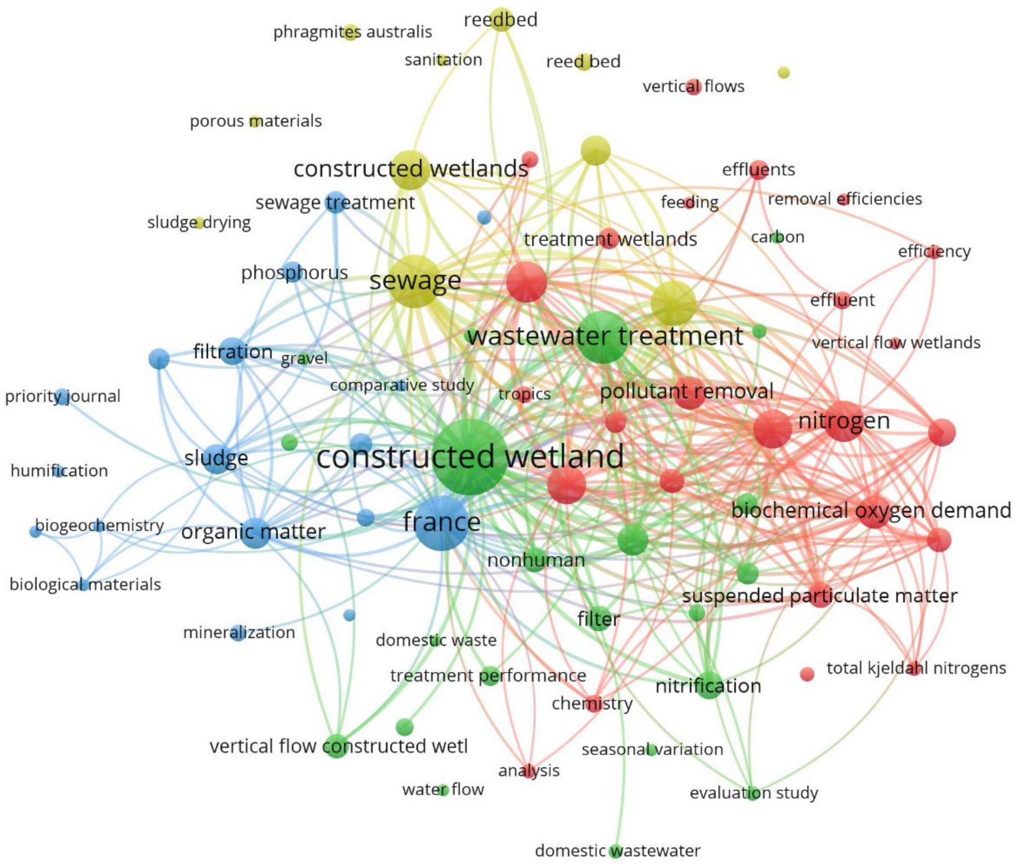

Figure 2.3 Network view map for French Constructed Wetlands

2.3. Design, operation and performance

2.3.1 Configuration

Over the years, the sizing of the Classical French System has been through empirical methods, based on the knowledge gained on the studies described in the evolution. The classical system is comprised by two stages and each stage is designed based on an acceptable organic load expressed as a filter surface unity per PE. For the first stage of the Classical French System, an area of 1.2 – 1.5 m^2 per PE is recommended (Molle et al., 2005), divided into three units. For the second stage, the area per P.E is suggested at 0.8 m^2 and is divided over two beds (Figure 2.4).

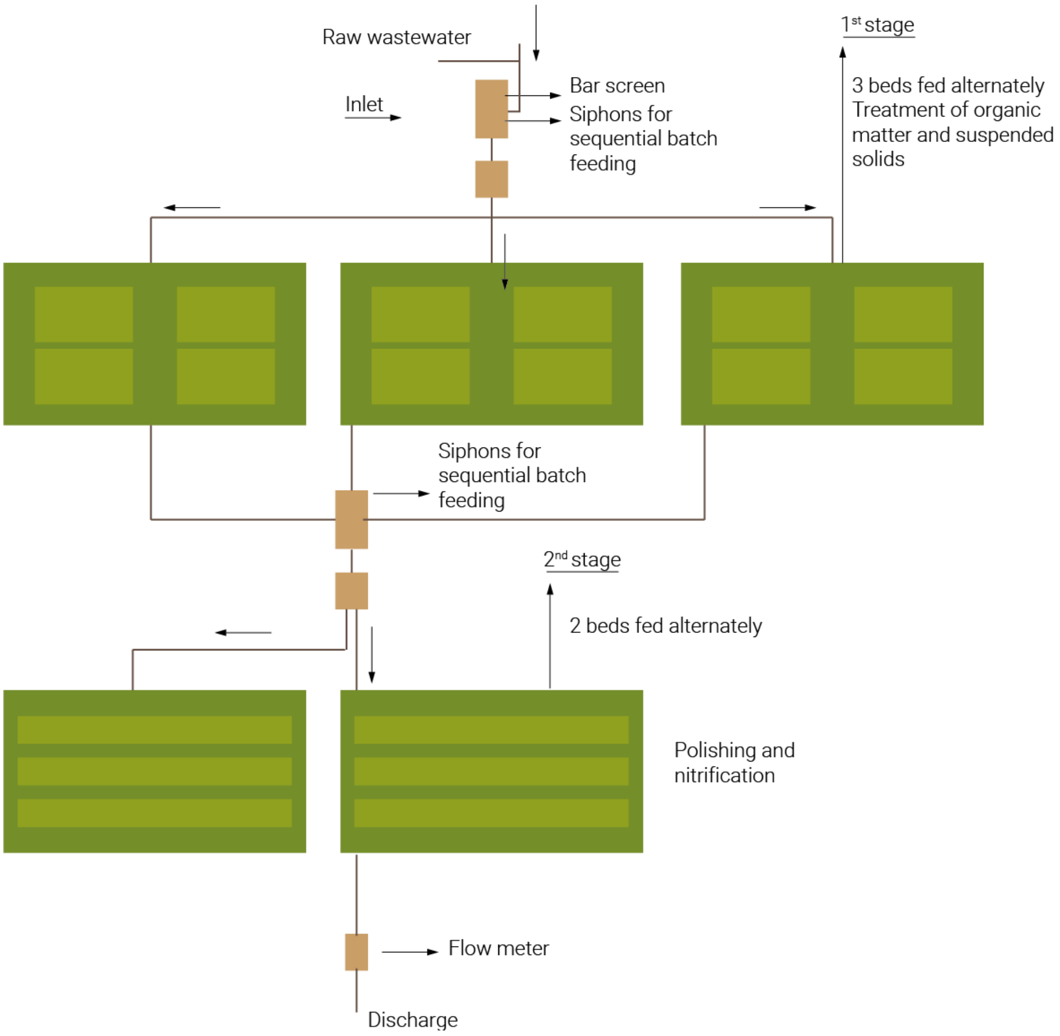

Figure 2.4 Configuration of the Classical French system: First and second stages

In the first stage, the unity area corresponds to an organic load of 300 g COD $m^{-2}d^{-1}$ and a mean hydraulic loading rate of 0.37 $m^3m^{-2}d^{-1}$ on the filter in operation. The beds in this stage are formed by three layers of filter media: drainage layer (bottom) is 10 to 20 cm of 20-40 mm gravel diameter; transition layer (medium) is 10 to 20 cm of adapted particle size (5 mm); and an upper layer higher than 30 cm with fine gravel (2-8 mm). In the second stage, each bed is composed by three layers of different granulometry: drainage layer is 10 to 20 cm of 20-40 mm particle size; the transition layer is 10 to 20 cm of adapted particle size (3-10 mm); and the upper layer is made of sand (0.25 mm) with a thickness greater than 30 cm (Molle et al., 2005) (Figure 2.5).

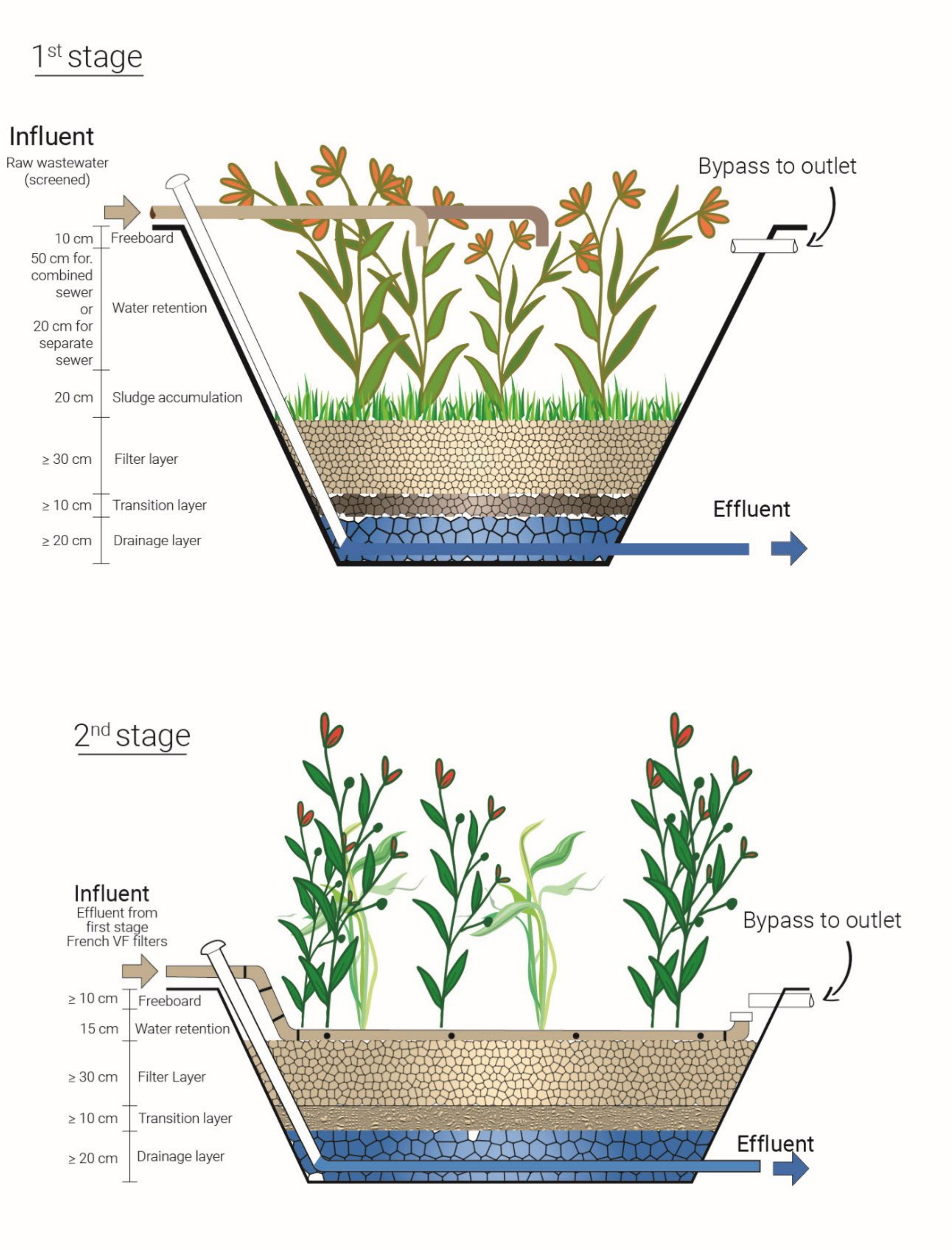

Figure 2.5 Detailed of the First and Second stages of the Classical French system (Adapted from Dotro et al., 2017)

The classical French system considers the resting period to be twice the feeding period. Molle et al. (2006) describe full-scale plants operated with 3-4 days feeding followed by resting for twice this amount of time. Paing & Voisin (2005) describe other full-scale systems with feeding periods of one week followed by resting periods of one or two weeks, achieving good performance. However, for warm climate regions, the classical feeding and resting periods can change. Because of the higher temperatures, the resting period can be reduced to equal the feeding period (Manjate et al., 2015).

With small variations around the described configuration, the overall efficiency expected of the French system is about 90% for COD, 94% for SS and 90% for TKN, but less than 20% removal of TN. This is because the system nitrifies but does not denitrify (Molle et al., 2005; Paing & Voisin, 2005; Troesch et al., 2014). To this point, only the treatment performance was taken into account without the consideration of the local climatic conditions and the effects of organic and hydraulic loading rates.

Taking into account the climate, Prost-Boucle et al. (2015) found that the French system located in mountainous regions maintains consistent treatment performance during winter. The cold temperatures do not affect the removal of COD, BOD_5 and TSS. However, nitrogen treatment, particularly the process of nitrification, is more sensitive to temperature. VFCWs demonstrated robust performance for TKN treatment in winter conditions. Key factors contributing to the sustained efficacy of the VFCWs in cold climates include the delivery of warm effluent, the insulating properties of snow and the accumulated deposit layer, as well as designed modifications such as alternating the filter twice a week rather than once a week. On the other hand, VFCWs perform exceptionally well in tropical climates with warmer temperatures, leading to high removal efficiencies for various pollutants, with average values of 80% for BOD, 85% for TSS and 60% for TKN (Trein et al., 2019).

A specific challenge in the French system´s design is the potential for the first stage to clog due to the feeding of raw wastewater. The design aims to build up a solids layer (surface sludge deposit layer), meaning these VFCWs are intentionally designed to "clog". Nevertheless, they are managed with the correct design parameters to ensure the surface layer enhances treatment performance without negatively impacting hydraulic performance. Understanding wastewater characteristics such as flow rates, solids content and pollutant types is crucial for understanding the clogging process (Knowles et al., 2011). The French system wetlands will function reliably as long as they are not subjected to consistent hydraulic overloading (Molle et al., 2006).

The feeding method can play a key role in ensuring treatment performance under hydraulic overload and minimizing the risk of filter clogging. For the same HL, the feeding operation can involve either frequent small batches or fewer batches of larger volumes (Molle et al., 2006). The design organic load applied on the French system is higher than in other systems (Stefanakis et al., 2014), yet it has been reported that the system can operate without clogging (Chazarenc & Merlin, 2005). Thus, the combination of adequate feeding strategy, HLR and SLR allows for adequate mineralization of organic solids, preventing clogging in most cases (Knowles et al., 2011), supporting the statement of Molle et al. (2005) that the FVFCWs operate clog-free.

2.3.2 Surface sludge deposit layer

Besides the potential clogging issue from the formation of the surface sludge deposit layer, this layer also offers several benefits for treatment performance. These benefits include enhanced filtration efficiency (solids removal), increased water retention time within the system, reduced filter permeability, improved water distribution, ammonia adsorption onto organic matter, and the promotion of biological activity (Molle, 2014). For this layer to function effectively over time, operating conditions must be carefully managed to promote the mineralization of the layer.

While primary treatment is imperative in different types of constructed wetlands to prevent clogging, the French system requires the absence of primary treatment to facilitate the formation of the sludge deposit layer. VFCWs that start functioning have lower efficiency in the removal of contaminants (Fu et al., 2015) because the sludge layer is not well-formed. Thus, the first stage of the French system demonstrates that a potential disadvantage can be transformed into an advantage for the treatment when its well operated.

To maximize the functions of the sludge deposit layer for filtration, adsorption and biological activity while reducing the negative clogging phenomena, it is required to study and understand the mechanisms of evolution of the sludge deposit layer and the proper operating conditions of the VFCWs. The accumulation rate of the sludge layer varies around 1.5 cm to 3.0 cm per year (Molle et al., 2005; Dotro et al., 2017). However, Trein et al. (2019) reported an accumulation rate of less than 1 cm per year in tropical conditions. To restore optimal hydraulic conditions, it may be necessary to remove the surface sludge layer after 10 to 20 years of operation.

Regarding the characterization of the organic deposit layer, Trein et al. (2020) found that the sludge deposit contained organic matter (OM) ranging from 51.3% to 52.7% in a deposit with nearly 10 years of accumulation. In a deposit with less than three years of accumulation, they reported an OM content of 61.2%, indicating the rapid mineralization of the sludge layer in a tropical climate. These findings are consistent with those of Kania et al. (2019), who observed that the sludge was primarily organic, averaging 62% particulate OM in a plant that had been operational for three years. Kim et al. (2013) also reported an OM content of 59% in a plant that had been running for nine years in a temperate climate.

Concerning the quantitative parameters of the sludge layer, Kim & Forquet (2016) observed the deposit distribution within filter media and quantified its pore size distribution, finding that the porosity is reduced by 35%. According to Kania et al. (2018), the sludge deposits presented common characteristics in the particle size distribution analysis, which might classify them within a special typology of sludge materials. Their fine porous structure improves water retention capacity over the years of operation of the VFCW. This agrees with Khomenko et al. (2019), who suggest that the distribution of particle sizes influences the ability to drain water through the sludge layer.

2.3.3 Plants

Plants are especially essential in the French system. They help to prevent the clogging of deposited organic matter formed from raw influent wastewater by facilitating water flow around the stems through the tubular spaces created by their wind-induced oscillation (Molle et al., 2006). The type of plants commonly used in the French system depends mainly on the climate. The plants need to resist periods when the wetlands are in rest, meaning there is no wastewater feeding the system. They must adapt to local climatic conditions.

A variety of species have been used around France and other places in the world. The most common is *Phragmites australis* (Millot et al., 2016; Molle et al., 2008; Morvannou et al., 2013; Paing & Voisin, 2005; Prigent, Belbeze, et al., 2013; Silveira et al., 2015) which has been regularly used in horizontal subsurface flow constructed wetlands, and now for VFCWs, specially in France and northern latitudes. The use of *Phragmites australis* in VFCWs has not been extensively studied for its nutrient uptake efficiency, but is considered a good alternative for plants that cope with the operating scheme of this wetlands. According to Lombard Latune & Molle (2017), *Phragmites australis* has invasive behavior and is not native for tropical climates, making its use in these regions less recommended.

Most studies conducted in tropical countries aim to identify the best suitable plant species for that climate. In Brazil, Lana et al. (2013) evaluated a VFCWs designed according to the first stage of the French system but planted with Tifton 85 (*Cynodon spp*). They compared a planted and unplanted VFCW, and found that the planted filter performed better for the removal of TSS and nitrogen compounds but only for phase 1 of the two operational phases tested (phase 1: 0.45 $m^3m^{-2}d^{-1}$ with batch frequency every 2 hours; phase 2: 0.38 $m^3m^{-2}d^{-1}$ with batch frequency every 1 hour). However, there was no difference between the planted and unplanted bed for the removal of BOD and COD. They concluded that *Tifton 85* had a secondary role in the removal of total N and P, because the plant uptake fraction was only a small one.

In India, Yadav et al. (2018) conducted an experiment comparing *Typha angustata* and *Canna indica*. There was not much difference in the treatment efficiency of the wetland when using one or other plant species. Lombard Latune & Molle (2017) conducted an extensive study on plant choice for the FVFCWs in tropical climates. They reviewed literature to identity a large list of potential plants and concluded that *Zingiberales, heliconiaceæ* and *cannaceæ* were suitable for the conditions needed for VFCWs in tropical climates.

2.4. Modified configurations of the French System

Since the classical called French System, different modified configurations have emerged to adapt the system to other climates, reduce the footprint and costs, and treat different types of effluents. Intensified systems aim to reduce the footprint and treat raw domestic wastewater using only one stage of the classical French System. Long-term monitoring of FVFCWs across multiple locations has shown that a specific design incorporating 80 cm of material and intermediate aeration can achieve high nitrification efficiency within a single treatment stage (Molle et al., 2015). Furthermore, in Brazil (tropical climate), the reduction of the total area of the first stage by one-third did not significantly impact removal efficiencies (Trein et al., 2019). This indicates that, under these climatic conditions, the system with a reduced area and extended feeding cycle of 7 days performs effectively.

Compact, recirculating, saturated/ unsaturated and aerated systems are the intensified configurations described here for wastewater treatment. Sludge drying reed beds, on the other hand, are the modified configuration for sludge treatment. A summary of publications demonstrating the performance of the classic French system and its modifications is presented in Table 2.1. The performances are evaluated based on various design and operational factors, as well as specific modifications.

Table 2.1 Classic French system and its modification data

Country	Treatment application	Scale	Type	Climate	Pre-treatment	Plant age	Feeding/resting	HLR (m d^{-1})	OLR or SLR	Species	Filter material	Efficiencies	Reference
France	RDW[a]	Full scale	Two stage	Temperate	Screening	2 – 6 years	3.5d/ 7d	< 0.75	223[b]		classic[c]	COD: 91% TSS: 95 % TKN: 85%	(Molle et al., 2005)
France	Septage	Full scale	Two stage	Temperate	Screening + mixing tank	4 years	7d/ 5w	0.19 per feeding	46[d]	*Phragmites*	classic	COD:99.5 % TSS: 99.8% TKN:98.5%	(Paing & Voisin, 2005)
France	RDW	Full scale	Two stage	Temperate	Screening	8 years	3.5d/ 7d	Up to 4		*Phragmites*	classic	COD: 81% TSS: 95 % TKN: 85%	(Molle et al., 2006)
Israel	Oil-rich farm wastewater	Full scale	One stage with two beds	Temperate	Anaerobic treatment	New	3d/ 7d	0.06	200[b]	*Canna indica and Salvia arizonica*	First layer: 30 cm of d10 0.4 mm; d60 3 mm Two layers:15 cm of d1 and d3 cm	COD: 75% TSS: 60 % TN: 67%	(Travis et al., 2012)
France	RDW	Full scale	One stage Compact	Temperate	Screening	5 years	3.5d/ R1:7d; R2:14d		90[b]	*Phragmites*	Ecophyltr using mayennite	COD: 89% TSS: 94 % TKN: 87%	(Prigent, Paing, et al., 2013)
France	RDW	Pilot	One stage [e] U/S [f] R:100%	Temperate	Screening	2 years	3d / 6d	0.48	251[b]	*Phragmites*	Mayennite and limestone	TN > 50%	(Prigent, Paing, et al., 2013)

France	RDW	Full scale	Two stage	Temperate	Screening	< 6 years	3.5d/ 7d	< 0.9	300 [b]	*Phragmites*	classic	COD: 92% TSS: 95 % TKN: 85%	(Troesch et al., 2014)
French outermost regions	RDW	Full scale	One stage	Tropical	Screening	9 years	F = R	0.43		*Thysanolaena maxima, Typha angustifolia*	First layer: 80 cm of 4/6-mm	COD: 91% TSS: 91 % TKN: 90 %	(Molle et al., 2015)
French outermost regions	RDW	Full scale	One stage [f] R< 125%	Tropical	Screening	9 years		0.49		*Thysanolaena maxima, Typha angustifolia*	First layer: 80 cm of 4/6-mm	COD: 93% TSS: 93 % TKN: 93 %	(Molle et al., 2015)
France	RDW	Pilot	One stage	Temperate	Screening	5 months	3.5d/ 7d	0.36	234 [b]	*Phragmites*	classic	COD: 82% TSS: 92 % NH_4: 63%	(Millot et al., 2016)
Brazil	Septage	Pilot	Two stage	Tropical	-		1d / 7d	0.27 per feeding	73 [d]	*Cynodon spp*	classic	COD: 81% TS: 42 % TKN: 25%	(Manjate, 2016)
France	RDW	Full scale	One stage [e] U/S	Temperate	Screening	6 years	3.5d/ 7d	0.2	156 [b]		Biho-Filter	COD: 89% TSS: 90 % TKN: 55%	(Morvannou et al., 2017)
France	RDW	Full scale	One stage [e] U/S [f] R:200%	Temperate	Screening	6 years	3.5d/ 7d	0.3	70 [b]		Biho-Filter	COD: 91% TSS: 97 % TKN: 65%	(Morvannou et al., 2017)

Brazil	RDW	Pilot	One stage	Tropical	Screening +grit removal	9 years	7d /7d	0.45	222 [b]	*Cynodon spp*	classic	COD: 79% TSS: 81 % TKN: 71%	(García Zumalacarregui & Von Sperling, 2018)
India	RDW	Pilot Single household	Two-stage	Tropical	-	7 months	1d /2d	0.15		*Typha angustata*	classic	COD: 90% TKN: 58%	(Yadav et al., 2018)
France	RDW	Pilot	One stage	Temperate	Screening	New	3.5d /7d		300 [b]	*Phragmites*	40 cm of pea gravel	COD: 85% TSS: 90 % TKN: 62%	(Ruiz-Ocampo et al., 2021)
France	RDW	Pilot	One stage	Temperate	Screening	New	3.5d /7d		300 [b]	*Phragmites*	10 cm zeolite 20 cm mayennite	COD: 90% TSS: 85%	(Ruiz-Ocampo et al., 2022)
France	RDW	Pilot	Aerated one stage (Rhizosph´air)	Temperate	-	1 month	3.5d /3.5d	0.15; 0.25; 0.35		*Phragmites australis*	Filtration 20 cm (2-6mm); Transition 15 cm (10-20mm) Saturated 1m (20-40mm)	COD > 85% TSS > 90 % TN > 60%	(Miyazaki et al., 2023)

[a] RDW: Raw Domestic Wastewater
[b] mean OLR (gCODm^{-2}d^{-1})
[c] Classic refers to the classical configuration of filter media described in the “Design and Operation” section
[d] SLR (kgSSm^{-2} yr^{-1})
[e] U/S: unsaturated/saturated
[f] R (%): recirculation ratio (%)

2.4.1 Compact French system

The compact French system represents an intensification technique to optimize the classical French system. In this compact VFCWs system, the 3 filters of the classical two-stage French system's first stage are operated in parallel. By using only the first stage, the total area required for the system is reduced by approximately 0.8 – 1 m^2 PE^{-1}. The challenge is to maintain good removal efficiencies with outlet concentrations below the allowed limits, applying only the first stage (compact).

The main issue when operating only the first stage of the French system, is the nitrification limitation. The second stage provides the adequate conditions for the complete nitrification. However, the single stage is known to have good removal efficiencies for organic matter and solids. Thus, when outlet requirements are not too stringent, the use of the compact French system would be preferred.

Modifications in the filter media type, depth, and operational parameters of the classical first stage of the French system have been studied to assess the removal performance of the single stage without increasing energy consumption. Millot et al. (2016) found that the depth of the filter media doesn't affect the removal efficiency of TSS and COD, meaning that the 60 cm depth specified in the French guidelines (Molle et al. 2005) is sufficient to achieve around 90% and 60% removal for TSS and COD respectively. However, the ammonium removal efficiency is improved with a deeper layer of filter media. Higher hydraulic and organic loads than the classical design (0.64 m d^{-1} and 536 g COD $m^{-2}d^{-1}$) do not affect the removal of TSS, but they do significantly reduce the removal of COD and ammonia. Wetlands operating under 0.37 m d^{-1} and 300 g COD m^{-2} d^{-1} (the classic hydraulic and organic loading rates for the first stage of the French system) perform better than those with higher loads (Millot et al., 2016).

Regarding the filter media type in the compact design, Paing et al. (2015) assessed the performances of 18 wastewater treatment plants WWTP with the compact VFCWs system composed by five layers: the first 30 cm of Mayennite (expanded schist media) of 2 - 4 mm, followed by 20 cm of 4 - 10 mm gravel, 20 cm of 0.5 – 4 mm Mayennite, 10 cm of 4 – 10 mm gravel and finally, 20 cm of 10 – 20 mm gravel. These wetlands showed good performance under normal operating conditions and maintenance, with hydraulic loading rates < 60 cmd^{-1}. They achieved mean removal rates of 91%, 94%, 86% and 81 % for SS, BOD_5, COD, and TKN respectively. Additionally, Ruiz-Ocampo et al. (2021) and Ruiz-Ocampo et al. (2022) investigated the use of pea gravel and zeolite and Leca® (light expanded clay aggregate) in addition to a Mayennite layer, respectively. They found reductions of over 87% for SS and 83% for COD in the filters with different heights of pea gravel, and removal efficiencies of over 90% for SS and 85% for COD when using zeolite and Leca®. The use of zeolite resulted in an average increase of 9% in NH4 removal efficiency compared to using Leca®.

2.4.2 Recirculating single stage

Recirculating single stage is used to improve the effluent quality when only the first stage of the French System is applied. This configuration reduces the footprint and investment costs, but it introduces the use of recirculation pumps, leading to energy consumption, different from the compact single stage. One of the main features of constructed wetlands is the sustainability of the system. The recirculating single stage diminishes this sustainable character of the constructed wetland process.

The use of recirculation in a VFCW primarily aims to increase nitrification and enhance de-nitrification. Recirculation dilutes the raw wastewater that enters the wetland and enhances nitrification in a single stage (Prigent, Paing, et al., 2013).

According to Prost-Boucle & Molle (2012), there is no impact of recirculation on the removal of COD in a single stage filter. However, the removal of ammonium depends on the design and recirculation rates. They found that complete nitrification cannot occur in a recirculating single vertical flow filter designed according to the classical French system. The 1.0 – 1.2 m^2PE^{-1} surface area is insufficient, Therefore, the recommendation was to use a total surface area of about 1.5 m^2PE^{-1} with a recirculation flow ratio of 100%.

2.4.3 Unsaturated and saturated zones in one stage

Another modification of the single stage French system for improving nitrogen removal is a recirculating/non-recirculating vertical flow system with an unsaturated layer at the top and a saturated layer at the bottom. The saturated layer is intended to promote denitrification and consequently, a better TN removal. A HRT of 0.8 d in the saturated layer of a VFCW filled with gravel allows for approximately 53% of TN removal (Langergraber, Leroch, et al., 2009).

In the study by Prigent, Paing, et al. (2013), the height of saturated layer used in the VFCWs affected the TN removal. They tested different heights of the saturated zone and noticed that when the saturated layer was double in height, there was an increase in removal by 5 – 10%. They concluded that with 1.8 m^2 PE^{-1}, a recirculation rate of 100% and with 40 cm of the saturated layer, outlet concentrations of less than 20 mgL^{-1} and 50 mgL^{-1} of TKN and TN respectively could be expected. Similarly, Silveira et al. (2015) demonstrated that the saturation level in the VFCWs impacted the denitrification, higher the saturated layer, higher the denitrification. Additionally, they found that the decrease of the saturation level in the vertical wetland, negatively affected the removal of TSS and dissolved COD (dCOD). Thus, even though the saturated layer was primarily intended to improve TN removal, this layer also enhances the performance of the bed in terms of TSS and dCOD removal.

Based on the good performances observed when a saturated layer was implemented in the VFCW, a Biho-Filter was developed in France by Epur Nature. This Biho-Filter consists of a vertical flow system with an unsaturated layer at the top and a saturated layer at the bottom. The unsaturated upper part follows the configuration of the classical first-stage French system. It contains aeration pipes at the interface of the unsaturated and saturated layers (Morvannou et al., 2017). The Biho-Filter showed much better removal performance than the classical first stage, with removal rates of 93%, 98% and 82% for COD, TSS and TKN respectively. It is stressed that the depth of the unsaturated layer of the wetland should be well designed because this layer improves nitrification but also induces carbon limitation for denitrification in the saturated layer. There is also an increase in TN removal in the Biho-Filter compared to the classical two-stage French system.

All the studies mentioned before were carried out in temperate climates. However, it is known that in tropical areas, the efficiency of the wetlands can improve. Tropical warm temperatures enhance the nitrification and denitrification kinetics. Lombard-Latune et al. (2018) proved that TN removal efficiencies were higher in unsaturated/saturated systems in tropical climates compared with similar systems in temperate climates. With this consideration, the area required for the first stage French system with unsaturated/saturated zones applied in tropical areas would be less than 1 m^2PE^{-1}.

2.4.4 Aerated single stage

The aerated modification of the French wetlands is the Rhizosph´air® system patented by Troesch et al. (2016). This is an aerated hybrid system that processes raw wastewater using a single-stage design that integrates an unsaturated vertical flow cell above a saturated horizontal flow cell. Specifically, it comprises a shallow unsaturated layer on top, followed by a saturated zone with mixed vertical and horizontal flow, and a third saturated zone with horizontal flow. Each saturated zone can be aerated differently, increasing the oxygen transfer by a factor of three compared to passive saturated treatment wetlands. This configuration reduces the required footprint of the classical design (2 m^2PE^{-1}) to 0.8 -1.2 m^2PE^{-1} depending on the conditions (Miyazaki et al., 2024).

In general, the Rhizosph´air® system demonstrated high removal of carbon and suspended solids with diverse influent concentrations, aeration duration, HLRs and addition of ammonium to the influent (Miyazaki et al., 2023). However, the most significant improvement compared to the classical French system, was observed in Total Nitrogen (TN) removal, achieving an approximate removal rate of 70% (Miyazaki et al., 2023).

2.4.5 Sludge treatment wetlands (STW)

The first stage of the classical French system is designed to treat wastewater and sludge simultaneously, because it doesn´t require a primary treatment. This important characteristic of the system, makes this type of wetlands an attractive solution for the management of the sludge, which is a non-desired by-product of wastewater treatment.

Drying sludge with reeds was first attempted at the end of the 1960´s in Germany, and then their use was spread to other sites in the world. These reed beds were used for treating different types of sludge: non-stabilized sludge, aerobically and anaerobically stabilized sludge, and they showed good results. The reeds in the beds allowed sludge to remain on the beds for several years without the occurrence of clogging, and they improved the dewatering and mineralization of the sludge (Lienard et al., 1990).

One useful application of the STW is for septage treatment. Paing & Voisin (2005) studied septage treatment in a vertical reed bed filter system designed as the first stage of the French system. This system consisted of, from top to bottom: 50 cm layer of small gravel (ϕ 2 – 8 mm), 20 cm intermediate layer of medium gravel (ϕ 10 – 20 mm), and 20 cm layer of large gravel (ϕ 20 – 40 mm). The study showed high removal performances:

99% for SS, 98.5% for BOD_5, 98.5% for COD, 94% for TKN and 94% for TP. They observed that long rest periods were needed to achieve those removal efficiencies, with a feeding-to-resting relation of 1 to 5. The vertical reed bed filter can effectively treat both the solid and liquid fraction of septage.

Manjate (2016) studied the retention of the percolate in a French STW and found that a fourteen-day retention period was the most effective strategy for removing OM, TS, TKN and *E. coli*. The system also demonstrated resilience to variations in sludge type and loading rates, with no bed surface clogging and successful sludge dewatering, resulting in 55% dry solids. However, according to Koottatep et al. (2005), STW perform best with an optimal solids loading rate of 250 kg Total Solids (TS) $m^{-2}yr^{-1}$, and a 6-day percolate impoundment, enabling high removal efficiencies of multiple pollutants. With this SLR, over a span of seven years, the accumulated biosolids in the STW were not removed, and the bed permeability remained stable.

2.5. Modelling

The processes in constructed wetlands are intricate, involving a wide range of simultaneous physical, chemical, and biological activities that interact with each other. Over the past few decades, interest in modelling pollutant removal in constructed wetlands has steadily grown.

Models are typically categorized into two types: data-driven models and process-based models. Data-driven models use measurement data to develop model equations, while process-based models are created based on the natural process occurring in wetlands. These models vary in complexity and are generally grounded in balance equations (e.g., for energy, mass). Experimental data are not needed to create the model equations, but they are essential for calibrating and validating the model (Langergraber, 2017).

In the context of VFCWs design guidelines predominantly rely on empirical rules-of-thumb such as specific surface area, maximum loading rate or kinetic approaches (Kadlec & Wallace, 2009; Meyer et al., 2015; Molle et al., 2005). However, a range of mathematical models have been proposed in the literature. Process-based models that account for transient variable saturated flow using the Richard´s equation (Langergraber & Šimůnek, 2018; Ma et al., 2021; Morvannou et al., 2014) and are based on the mathematical formulation of the Activated Sludge Models (ASMs) (Henze et al., 2000). More recently, researchers have introduced data-driven models using machine learning techniques such as Multiple Linear Regression (MLR), Support Vector Regression (SVR) or Artificial Neural Network (ANN) (Nguyen et al., 2022; Soti et al., 2023).

However, most of these models have primarily been tested on the general configuration of VFCWs. Their validation may be less reliable in the FVFCWs with a gravel first layer for treating raw wastewater directly, as the accumulation of sludge on the surface impacts performance. There is limited research on models specifically addressing FVFCWs. One study examines a modification to the FVFCW for managing urban runoff, while another focuses on the hydraulic behavior of the first stage, accounting for both rain events and dry weather flow. Other studies explore nitrogen removal modeling in classic systems and compact systems that incorporate a zeolite layer.

Focusing primarily on the system´s hydraulics, Fournel et al. (2013) discussed the successful application of a modification of VFCWs in reducing the ecological impact of urban runoff. They emphasized the importance of modeling the restricted outflow and the feasibility of using HYDRUS-1D for simulation. The study also highlighted the need for empirical models in urban runoff management and the challenges associated with calibration and validation in modeling. Arias et al. (2014) developed a simplified hydraulic model using an empirical infiltration coefficient inspired by Darcy´s law, using the “R” statistical software in one-dimensional approach. This enabled the identification of time-course shifts in ponding time and outlet flows. Since prolonged ponding impedes oxygen renewal, affecting nitrification and organic matter degradation, the study concluded that establishing ponding time limits is crucial for designing effective systems that can handle both dry and rain events.

In the context of modelling nitrogen removal, Morvannou et al. (2014) developed a model successfully predicting nitrogen concentrations in the effluent of a classical FVFCW. Pucher et al. (2017) used simulation to assess the treatment efficiency of a compact FVFCW with a zeolite layer to enhance ammonium nitrogen removal. Both studies used the biokinetic model CW2D from the HYDRUS Wetland Module.

Morvannou et al. (2014) found that during the feeding period, the amount of nitrogen adsorbed was on par with the amount nitrified. During the rest period, the adsorbed nitrogen was progressively nitrified, leading to increased nitrate levels during the initial two batches of the subsequent feeding period. The study also demonstrated that adjusting the model parameters significantly decreased discrepancies between predicted and measured effluent concentrations. This underscores the critical role of precise parameter determination in optimizing nitrogen removal in VFCWs.

Pucher et al. (2017) found that the calibrated model could predict how varying depths of the zeolite layer impacted nitrogen removal. They concluded that increasing the zeolite layer depth significantly reduced the simulated ammonium effluent concentration.

While the evolution of models for constructed wetlands has been extensive, their application to FVFCWs remains limited. Most existing models address only particular aspects of French system, such as hydraulic behavior, nitrogen removal and adaptation for urban runoff. This specificity provides valuable insights into the unique challenges and opportunities presented by the FVFCW configuration. However, it also indicates a need for more comprehensive modeling approaches. The existing models have demonstrated potential in improving system efficiency and treatment outcomes. Nevertheless, further research and model development are needed to encompass a wider range of variables and conditions specific to FVFCWs.

2.6. Current challenges/knowledge gaps and future research directions of the French system

The French system presents a promising approach for efficient and sustainable wastewater treatment, particularly in developing regions facing septage management challenges. This system eliminates the need for septic tanks, providing a solution to the associated environmental and health risks posed by septage. Despite the significant potential of FVFCWs, still current challenges and knowledge gaps hinder their broader application. These include the need for comprehensive system applications in regions with different climatic and socio-economic conditions than those already tested, the performance of the system with various types of wastewaters and sludge, and the system modelling.

Future research should prioritize integrated system modeling, innovative system upgrades, and the adaptation of French system to different environmental contexts. By exploring these areas, FVFCWs can evolve into a more versatile and sustainable solution for wastewater treatment across diverse regions.

2.6.1 Application in regions with different climatic conditions

While the French system has been successfully applied in Europe and other European countries, as well as in tropical regions particularly in lowland tropical areas, with promising results, its performance in high-altitude tropical regions remains uncertain due to their unique climatic conditions. Investigating the system´s efficiency, adaptability, and long-term sustainability in these distinct environments will provide valuable insights and potentially expand the applicability of the French system to a wider range of geographical and climatic contexts.

2.6.2 Implementation in Developing Countries

The application of FVFCW systems in developing countries presents a potential solution to septage management challenges. However, more research is needed on system design and operational adjustments tailored to the specific environmental and economic contexts of these regions. Research should explore the adaptation of FVFCW systems to address the specific needs of developing countries, such as low-cost design options and strategies for effective septage management.

2.6.3 Different types of wastewaters and sludge

Future research should explore the performance and optimization of the French system for various types of wastewaters and sludge, considering a constant dilution of wastewater and the real-world variability of septage. Given the diversity of wastewater sources—from domestic (combined and separate sewer) and industrial to agricultural—each type presents distinct challenges in treatment due to variations in composition and contaminant load. Additionally, septage characteristics can vary significantly based on factors such as local sanitation practices and seasonal changes. Understanding how these variables impact the system's efficiency and effectiveness will be crucial for developing robust treatment solutions. Experimental studies and pilot projects in different settings can provide insights into how the French system can be adapted or modified to handle these diverse conditions, ensuring reliable and sustainable wastewater and septage management across a broad spectrum of real-world scenarios.

2.6.4 System modelling

While existing models have provided insights into specific aspects of the French system, there is a lack of simple models that can first represent the hydraulics and then the biokinetics of the system. Simplifying these models will be crucial to making them accessible and understandable to a wider audience, including engineers, policymakers, and local stakeholders. By creating user-friendly models, more people can effectively apply and adapt the French system to diverse environmental settings, enhancing its performance and resilience. This broader accessibility will facilitate better decision-making, improved system optimization, and greater overall sustainability in wastewater and septage.

2.7. Conclusions

FVFCWs have been refined since the 1980´s and have extended their use beyond France. Given the ongoing and future challenges related to water scarcity and pollution, the value of this nature-based solution is significant, especially in the developing world where cost remains a major barrier to wastewater treatment infrastructure.

The integration of FVFCWs with cutting-edge technologies and advanced modeling techniques can improve system management and control. This can transform these wetlands from a simple low-cost solution to a more sophisticated method of wastewater treatment. By leveraging advance online monitoring and control systems, the quality of effluent discharge can be enhanced, facilitating its reuse.

Moreover, climate change introduces new challenges and opportunities for FVFCWs applications. In the face of extreme weather conditions, wastewater facilities must enhance their resilience, and FVFCWs have demonstrated this adaptability. These advantages, along with the eco-friendly aspects of FVFCWs, make this treatment technology a strong contender against other methods.

Chapter 3

3. Modified First Stage of French Vertical Flow Constructed Wetlands performance during extreme operation conditions

Based on: Arévalo-Durazno, M.B.; García Zumalacarregui, J.A.; Ho, L., Narváez, A., Alvarado, A. (2023). Modified First Stage of French Vertical Flow Constructed Wetlands performance during extreme operation conditions. *Water Science and Technology, 88*(1), 220–232. https://doi.org/10.2166/wst.2023.201

Abstract

Operation conditions considerably affect the removal efficiency of wastewater treatment systems, and yet we still lack data on how these systems function under extreme dilution rates and climatic conditions at high altitude. Here, we applied two Modified First Stage French Vertical Flow Constructed Wetlands (FS-FVFCW) for sewage treatment in Northern Tropical Andes. Specifically, within 18 months, we conducted a pilot-scale experiment at two hydraulic loading rates (HLRs) of 0.94 and 0.56 m d^{-1}, representing 2.5 and 1.5 times the recommended design values, with two different feeding/resting periods to investigate the impact of HLRs and operational strategy on system performance. We found that COD and TSS removal was satisfactory, with average values of 53% ± 18% and 69% ± 16%, respectively. Moreover, reducing HLRs resulted in higher removal efficiency for COD, from 46% ± 15% to 64% ± 15%, but had no impact on TSS removal, with 3 days feeding and 6 days resting. For an equal time of feeding and resting, COD and TSS removals were not affected by the modified HLR. These findings suggest that high HLRs can be applied to FS-FVFCW without compromising the system operation and obtaining satisfactory results, leading to opportunities to reduce areas, and costs.

Chapter 4

4. Modelling FVFCWs using the Rauch biofilm model implemented in the WEST software platform

4.1. Introduction

Modelling is a useful tool that has been developed to simulate the performance of natural treatment processes and pollutant removal. Models are typically categorized into two groups: black-box models and process-based models (Langergraber, 2017). Process-based models aim at elucidating the intricate and interrelated physical, chemical, and biological processes occurring in these environments, potentially leading to improved design and operation (Rahi et al., 2020). These models require several sub-models for different wetland processes: the water flow model, the transport model, the biokinetic model, the plant model and the clogging model (Langergraber, 2017).

The most advanced process-based model developed for Vertical Flow constructed wetlands (VFCWs) is the HYDRUS Wetland Module (Langergraber & Šimůnek, 2012). The model uses the biokinetic models: Constructed Wetland 2D (CW2D) (Langergraber & Šimůnek, 2005) and Constructed Wetland Model #1 (CWM1) (Langergraber, Rousseau, et al., 2009). These models are derived from the Activated Sludge Models (ASMs) outlined by Henze et al. (2000), incorporating multiple processes to capture the intricate dynamics of wetland interactions. Regarding the other submodels, HYDRUS employs the Richard equation to model variably saturated flow, and for the transport model, it integrates advection, dispersion, and adsorption processes. It also accounts for the influence of plants through evapotranspiration and the uptake and release of substances, although the clogging model is omitted (Langergraber & Šimůnek, 2012). Implementing these models effectively demands significant computational resources.

The choice between a detailed description and user-friendly implementation is heavily contingent on the modeling objectives, as noted by Arias et al. (2014). If the goal is to achieve a broad overview or global design, opting for simplified models can be a pragmatic choice. These models offer a streamlined approach that prioritizes ease of use and accessibility, making them well-suited for capturing essential aspects of the system without excessive complexity.

Rauch et al. (1999) developed a simplified mixed-culture biofilm model for substrate removal simulation in a biofilm reactor. This model decouples the calculations of the two major processes in the biofilm: substrate diffusion (transport) and biokinetic reactions. By separately assessing substrate diffusion, it becomes possible to establish a connection between the depth of substrate penetration and the proportion of biomass engaged in conversion. Consequently, the conversion process is calculated based solely on the active fraction of the biomass, significantly simplifying the conversion process and reducing computational demand.

French Vertical Flow constructed wetlands (FVFCWs) have gained widespread popularity not only in France but also worldwide. Their primary characteristic is their capability to treat raw wastewater without the need for primary treatment processes (Molle et al., 2005). FVFCWs offer an attractive alternative for wastewater treatment due to this distinctive feature. Within these wetlands, numerous processes unfold to effectively treat raw wastewater. Much of the research conducted on simulating VFCWs has focused on conventional VFCWs, which treat primary effluent (Fournel et al., 2013; Giraldi et al., 2010; Martí et al., 2018; Yang et al., 2017). The validation status might be limited for FVFCWs with gravel treating raw wastewater directly, primarily due to sludge accumulation on the surface. However, Morvannou et al. (2014) calibrated the CW2D for nitrogen removal in a FVFCW treating domestic wastewater directly. Additionally, Arias et al. (2014), developed a simplified hydraulic model for FVFCW using an empirical infiltration coefficient – infiltration capacity parameter (ICP).

This chapter aims to calibrate a simplified hydraulic model (equalization tank of variable volume) for the FVFCWs, and then simulate Dissolved Oxygen (DO) and Chemical Oxygen Demand (COD) concentrations in the effluent using the Rauch model, which is already integrated into the WEST software from MIKE by DHI (Denmark). The primary objective is to employ a simplified model that is easier to comprehend and requires fewer parameters. This approach can be implemented using existing software.

4.2. Materials and Methods

4.2.1 Site location and operation scheme

The location, description and feeding/resting operation schemes of the pilot system are comprehensively detailed in Chapter 3, particularly in section 3.2.1. Furthermore, the outlet flowrates for the modelling were determined using the volumetric method. Volumes of 3.8 liters were measured, and the time taken to fill this volume was recorded during the hour (approximately) when there was flow at the outlet, just before the next batch.

4.2.2 Wastewater data

Grab samples were collected from the influent and effluent during the 8 am batch on the second day of each feeding period. Then, the samples were analysed for COD following the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012). Additionally, *in situ* DO was measured using a WTW Multi3420 probe.

To calibrate the model using the collected data, all data points were adjusted to a single cycle consisting of three days of feeding followed by six days of resting. This assumption was made under the premise that it would not significantly alter the overall behavior of the FVFCW. Furthermore, because the model is also used for simulating nitrogen, a Total Kjeldahl Nitrogen (TKN) value of 50 mgL^{-1} was adopted. This value was deliberately set sufficiently high to avoid affecting COD removal.

For the fractionation of COD, an additional wastewater sampling campaign was conducted in combination with the regular samplings at the WWTP from April to August 2023. The sampling location for the raw wastewater was identified at the inlet channel of Ucubamba WWTP, while the soluble COD was sampled at the outlet of the maturation ponds, using an ISCO 4700 automatic composite sampler. Seventeen composite samples were taken and brought to the laboratory for the analysis of Ultimate BOD (BODu), COD and Soluble COD (CODs). The respirometric method was employed to obtain the BOD, determining continuous oxygen consumption over a 20 days period. Specifically, the manometric respirometric method was used with the BD 600 Lovibond equipment, which relates oxygen consumption to pressure variation in a constant volume, following Method 5210 D (APHA, 2017). Further, COD and CODs were analysed according to Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

4.2.3 Modelling

The software WEST+2023 from MIKE by DHI was used to simulate the concentrations of COD and DO in the effluent of the pilot system. WEST is a powerful simulation tool designed to evaluate the performance of a treatment plant under various boundary conditions. The software has different models implemented which can be customized to meet specific needs. It uses the ASM models as a base.

To simulate the performance of the pilot FVFCW, different models from the WEST environment were used, and a steady state simulation was run before the dynamic simulation. The biofilter model in WEST was modified for this purpose. Then, different submodels were chosen and modified for each of the processes. These included a model for the fractionation of organic matter, a water flow model, a transportation model and finally a biokinetic model.

Fractionation model

A modified version of the WEST.ASM1.MO.Input.Layout model (Figure 4.1) was used for the fractionation of the organic matter. Where:

- S_I: Soluble inert organic matter
- S_S: Readily biodegradable substrate
- X_S: Slowly biodegradable substrate
- X_BH: Active heterotrophic biomass
- X_I: Particulate inert organic matter
- X_BA: Active autotrophic biomass
- X_P: Particulate products arising from biomass decay
- S_NH: NH_4^+ + NH_3 nitrogen
- S_N: Soluble biodegradable organic nitrogen

- X_ND: Particulate biodegradable organic nitrogen
- S_AL: Alkalinity
- S_O: Oxygen
- S_NO: Nitrate and nitrite

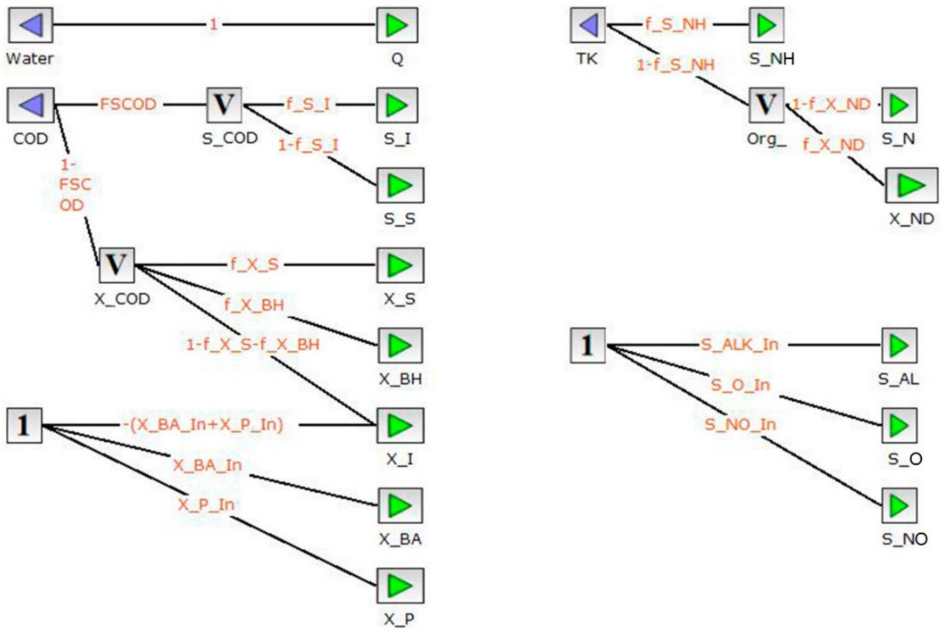

Figure 4.1 Layout of the organic matter fractionation based on the ASM1

The STOWA protocol was applied for the fractionation. This methodology directly determines the non-biodegradable soluble fraction (Si) as the soluble COD of the effluent treated in the maturation pond (Ekama et al., 1986). The sample for this determination was taken on subsequent days to ensure consistency with the original influent sample. Due to factors like sludge accumulation and lack of current data, an average total hydraulic retention time of 7 days was assumed for the stabilization ponds, despite previous studies suggesting a range of 9.8 to 10.5 days (Ho et al., 2018).

The modified model removed the conversion factor TSS/COD (Total Suspended Solids/COD), instead, it calculated the particulate COD solely using results from the STOWA protocol. The parameters and their description are shown in Table 4.1.

Table 4.1 Description of the parameters used in the fractionation model

Parameter	Description
f_S_I	Si fraction of soluble COD
f_S_NH	S_NH fraction of TKN

f_X_BH	X_BH fraction of particulate COD
f_X_ND	X_ND fraction of biodegradable organic nitrogen
f_X_S	Xs fraction of particulate COD
FSCOD	Fraction of soluble COD (modification)
S_ALK_In	Alkalinity
S_NO_In	Nitrate
S_O_In	Oxygen
X_BA_In	Autotrophic biomass
X_P_In	Decay

The readily biodegradable fraction Ss (assumed to be soluble), was obtained by subtracting Si from the total COD. Considering the biodegradable fraction (CODb) as the sum of soluble (Ss) and particulate (Xs) fractions, Xs was determined accordingly. Finally, the inert suspended fraction (Xi) was calculated by subtracting the sum of the three fractions from the total COD (Melcer, 2003) .

For CODb, the relation given by Roeleveld & van Loosdrecht (2002), was taken according to equation (4.1)

$$\frac{1}{1\text{-}f_{BOD}} * BOD_u \qquad (4.1)$$

Where f_{BOD} was assumed to be 0.15 (Roeleveld & van Loosdrecht, 2002).

Water flow model

Research has shown that simulated effluent concentrations match measured data effectively only when the system's hydraulic behavior is accurately defined (Langergraber, 2017). Understanding the hydraulic dynamics of the FVFCW during the feeding phase is crucial. Challenges arise due to the discharge of wastewater in pulses onto the filter and the unsaturated state of the porous medium through which the liquid percolates. These factors complicate the hydraulic characterization of the unit, the accurate estimation of retention time, and the resulting temporal profile of effluent flow.

Hence, the initial step involved calibrating the hydraulic behavior of the pilot. The biofilter model in WEST was intended for use—a system akin to an ideally mixed reactor with a constant volume—where the outflow flow rate equals the inlet flow rate without retardation. However, we adjusted this to an ideally mixed reactor with a variable volume. An equalization tank with variable volume is designed to regulate the flow and characteristics of influent wastewater. Unlike a standard equalization tank with a fixed volume, a tank with variable volume can adjust its capacity based on the incoming flow rate or other parameters.

In this model, the effluent flow rate is a function of the type, number and design of the weirs:

$$Q_{out} = N * \alpha * \left(\frac{V - V_c}{A}\right)^{\beta} \quad (4.2)$$

Where:

- α and β are empirical factors (-), function of the type or width and of the design of the weirs respectively.
- N is the number of weirs (-)
- V_c is the volume (m^3) of the tank under the weirs
- V and A denote the volume (m^3) and the surface area (m^2) of the tank, respectively

Here, the parameters α, β and N were manually calibrated in order to match the peak flow observed in the outflow.

The transport and biokinetic model

For the simulation of COD removal in the biological system, the simplified mixed-culture biofilm model (Rauch et al., 1999) was used. The biokinetic processes in the biofilm model take into account aerobic and anoxic growth of heterotrophs, the aerobic growth of autotrophs, hydrolysis, and decay. The description of the biokinetic processes in the biofilm follow the concepts of the ASM1 (Henze et al., 2000). However, there are some adjustments in the simplified mixed-culture biofilm model in comparison to the ASM1 due to the active fraction concept. Firstly, bacterial growth diverges from a Monod-type reaction as seen in ASM1. Instead, it is represented as a first-order process solely concerning the active fraction of the bacterial mass. This adjustment is necessary for zero-order substrate kinetics and diffusion limitations. In ASM1, limitations on reactions regarding oxygen and ammonia are expressed through Monod-type switching functions. These functions are conveniently omitted in the simplified mixed-culture biofilm model because all limitations are encompassed within the active fraction concept. Hydrolysis operates as a first-order process concerning the concentration of slowly biodegradable organic matter. According to the model's assumptions, the readily biodegradable organic matter from hydrolysis is depicted as rapidly transitions into the bulk liquid (Rauch et al., 1999).

The initial conditions used for Rauch model are presented in table 4.2

Table 4.2 Initial conditions for the Rauch model

Parameter	Value
Biofilm thickness (m)	1 e-06
Fraction of autotrophs	0.05
Fraction of heterotrophs	0.4
Fraction of inert material	0.04
Fraction of decay products from X_BA	0.04
Fraction of decay products from X_BH	0.32
Fraction of hydrolisable material	0.15

Parameter determination

The Nash-Sutcliffe efficiency coefficient (Nash & Sutcliffe, 1970) was employed to assess the agreement between simulated outflow and measured values. The parameters N, α, and β were calibrated to accurately replicate the observed data. The mean absolute error (MAE) was computed to assess the predictive accuracy of DO and COD. Parameter calibration was conducted using a trial-and-error approach, using primarily the kinetic and stoichiometric parameters presented by Langergraber & Šimůnek (2005) for CW2D. For biofilm parameters, specifically the detachment coefficient, the value provided by Rauch et al. (1999) in the simplified mixed-culture biofilm model was used. Additionally, the diffusion coefficients were sourced from WEST for the Rauch model. The parameter kLa, which represents the volumetric mass transfer coefficient for oxygen, was adjusted to minimize the disparity between simulated and measured effluent concentrations.

4.3. Results and discussion

4.3.1 Influent characteristics and COD fractionation

The general characteristics of COD from influent sampling in the pilots are detailed in Table 4.3. Throughout the entire operational period, COD exhibited extreme values, reflecting the dynamic nature of the sewage system. This variability stemmed from seasonal fluctuations and significant infiltration. Consequently, wastewater values ranged from very low to high, particularly during discharges from the industrial park, as discussed in Chapter 3.

Table 4.3 COD concentrations (mean and standard deviation) in the influent to the pilots

	COD (mgL^{-1})
Mean	188.47

Standard Deviation	132.43
Max	812.8
Min	30.4
Number of values	89

The results obtained from the fractionation of COD applying the STOWA methodology are presented in Table 4.4. These results are derived from the samples taken specifically for fractionation purposes, as detailed in Materials and Methods section.

Table 4.4 Mean, median and standard deviation values of COD fractions using the STOWA methodology

	Soluble COD (mgL^{-1})	Particulate COD (mgL^{-1})	CODb (mgL^{-1})	Si (%)	Ss (%)	Xs (%)	Xi (%)
Median	51	223	197	14	5	64	19
Mean	56	240	207	14	6	64	16
Standard Deviation	15	72	56	3	4	12	10

All the calculated fractions fall within the typical ranges reported by Melcer (2003) and Pasztor et al. (2009). The dominance of the Xs fraction indicates the wastewater´s domestic origin, which typically ranges from 40% to 80%. Notably, the Si fraction, comprising 70% of solubles (14% of total COD), falls at the upper range of expected values, which typically range from 2% to 15% (Pasztor et al., 2009). This higher value may be attributed to the direct measurement of the Si fraction at the outlet of Ucubamba WWTP's maturation ponds.

Currently, the WWTP operates at full capacity, with a substantial sludge volume in the ponds. This reduces the contaminant removal and hydraulic retention time. Consequently, the ponds struggle to effectively remove the readily biodegradable Ss fraction of COD, implying that soluble COD at the pond outlet may comprise both Si and a portion of the Ss fractions.

Considering these factors, and including a maximum value of 10% for Si from around 50% solubles reported in Roeleveld & Van Loosdrecht (2002), and a previous study done with the same wastewater which reported a Si fraction of 10% and SS fraction of 10% (Larriva et al., 2018), the value of f_S_I was adjusted to 0.5. Table 4.5 presents the COD fractionation values utilized in the model.

Table 4.5 Parameter values used in the fractionation model in WEST software

Parameter	Value	Unit	Observation
f_S_I	0.5	-	Obtained in this study
f_S_NH	0.65	-	Default WEST value
f_X_BH	0.1	-	Default WEST value
f_X_ND	0.6	-	Default WEST value
f_X_S	0.8	-	Obtained in this study
FSCOD	0.2	-	Obtained in this study
S_ALK_In	30	gm^3	Default WEST value
S_NO_In	0.01	gm^3	Default WEST value
S_O_In	0.01	gm^3	Default WEST value
X_BA_In	0.01	gm^3	Default WEST value
X_P_In	0.01	gm^3	Default WEST value

4.3.2 Calibration of water flow model

To accurately model the system's behavior, it's essential to consider both hydraulic and biokinetic aspects. In this instance, the hydraulic model was simplified to the greatest extent possible, treating the wetland as an equalization tank with variable volume. This approach involved assuming virtual weirs that mimic the relaxation and retardation of influent flow rates, aiming to closely match the outflow observed in the field.

The adoption of the equalization tank with variable volume concept was based on the behavior of the storage volume within the FVFCW. According to De Andrade Moraes et al. (2019), the liquid volume stored within the system initially rises upon discharge. The maximum storage volume during the pulse phase is reached when liquid feeding halts, followed by a decrease to minimum storage as the pulse recommences with discharge from the storage tank.

The pulse feeding regime of the FVFCW during the first two hours of a feeding cycle is plotted in Figure 4.2 as a function of time. The requirement of the input flow was to relax the peak value to around 65.6 m^3d^{-1} (average outlet peak flow rate) and prolong the flow to around 0.3 h, according to the characterised outflow measured, also presented in Figure 4.2. Notice that during the operational period, two different volumes at distinct times were applied, but both resulted in the same inflow value (217.14 m^3d^{-1}).

In this study, the peak outflow was attained in approximately 2 minutes, a shorter duration compared to the 7 minutes reported by De Andrade Moraes et al. (2019). The primary distinction between this study and the aforementioned one is that, in the latter, the feeding duration was also approximately 5.5 minutes, whereas in this study, it was around 2.4 minutes. Consequently, in this case, the peak flow occurs before the feeding is halted, whereas in the other study, it happens after the feeding pulse concludes. These differences may arise from the higher instantaneous HLR in this study (0.93 m^2h^{-1}) compared to the other one (0.2 m^2h^{-1}). It is noteworthy that in this study, the instantaneous HLR was set higher than the recommended value of 0.5 m^2h^{-1}(Dotro et al., 2017). By increasing the instantaneous HLR, the hydraulic gradient and volume recovery also increase (Molle et al., 2006). However, this higher instantaneous HLR results in reduced contact time between the wastewater and the biofilm, which could potentially impact the pilot's performance. Another comparable factor is the ratio between the peak outflow and the inflow, which in this case is approximately 0.3. In the study by De Andrade Moraes et al. (2019) this ratio was approximately 0.35. This insight provides valuable information about the expected relationship between inflow and peak outflow in such systems.

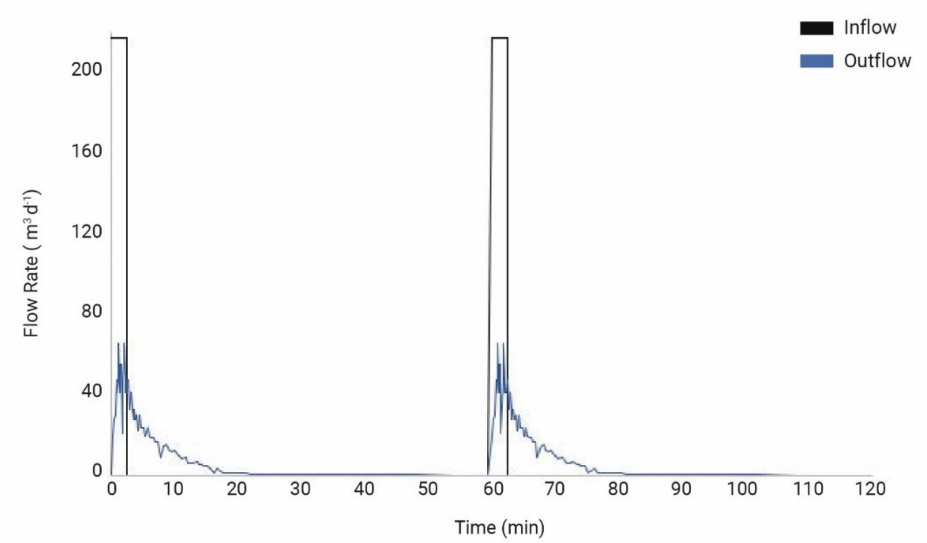

Figure 4.2 Observed flow rates during two pulses for the inlet and outlet of the pilot

The factor *β* was taken at a value of 1.5, as for rectangular weirs. The values of *N* and *α* were adopted as 10 and 1100, respectively, because they showed the best fitting. With these values, the outflow rate profile from a typical pulse was simulated, as seen in Figure 4.3. The rapid flow dynamics inherent in these systems are easily observable. The simulated outflow profile, matches the average peak flow measured in the pilots, capturing the essential characteristics of the outflow profile and ensuring reliability in simulating the hydraulic dynamics of the system. The shape, with a sudden peak flow with a brief duration followed by a gradual decline, is comparable to those measured in another system in Belo Horizonte, Brazil, as shown by De Andrade Moraes et al. (2019), and as described by Kadlec & Wallace (2009). Arias et al. (2014) conducted a comparative study between a simplified hydraulic model for FVFCW and the Hydrus model. Their findings indicated a strong agreement between both models, affirming the simplified model's ability to accurately replicate the hydraulic dynamics of a VFCW.

Comparing the outputs of those models with the output of the equalization tank with variable volume utilized in this study reveals similar behaviors.

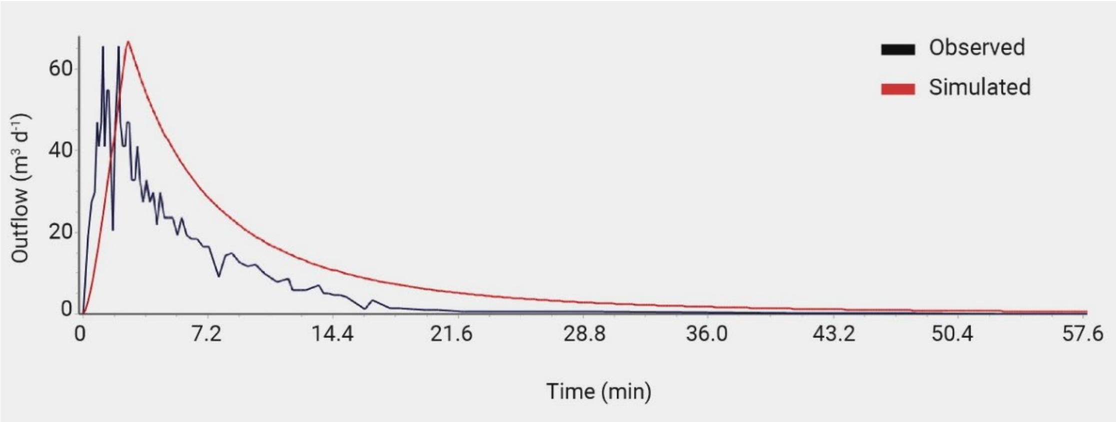

Figure 4.3 Outflow measured and simulated by WEST using the equalization tank with variable volume concept during one pulse period

When comparing the observed outflow to the simulated outflow (Figure 4.3), the model hydrograph is slightly shifted to the right, with a difference of 1.4 minutes compared to the observed values. This disparity is demonstrated in the obtained low value of the Nash-Sutcliffe efficiency coefficient of 0.24. Nevertheless, the peak flow value closely matches the observed one, and the overall shape corresponds similarly.

4.3.3 Adjusted parameters in the transport and biokinetic model

The parameters listed in Table 4.5 remained unchanged. With these values, we adjusted the Oxygen transfer coefficient kLa to match the DO and COD concentrations in the effluent.

Various values of the oxygen transfer coefficient kLa have been documented, depending on the wetland type and the HLR applied. Morvannou et al. (2014) reported a calibrated value of 576 d^{-1} when developing a model for nitrogen removal in a French vertical Flow constructed wetland operating at an HLR of 0.46 md^{-1}. Decezaro et al. (2019) observed kLa values of 52.56 d^{-1}, 41.04 d^{-1} and 36 d^{-1} at 20°C for HLRs of 60, 90 and 120 mmd^{-1} respectively, within a VFCW employing primary treatment. In García Zumalacarregui (2018) study, kLa values of 92.54 d^{-1} and 96 d^{-1} were identified at 20°C, corresponding to an HLR of 0.45 md^{-1}. These values were observed in units with and without the development of a sludge deposit layer on the surface of the wetlands, respectively. Here, we obtained a calibrated value of 5 d^{-1}, much lower than those reported; however, it provided the best fit for the dissolved oxygen (DO) effluent concentrations. This discrepancy in values could be attributed to the altitude, which influences atmospheric pressure . None of the reported values were obtained from locations at the altitude of the pilot testing site, which was 2500 meters above sea level (m.a.s.l.). There is a reference value of kLa = 43.9 d^{-1} measured for activated sludge in drinking water at the same altitude (2500 m.a.s.l). This technology includes equipment that increases oxygen transfer. In VFCWs, without such equipment, lower mass transfer coefficients are expected in comparison (Kadlec & Wallace, 2009). Additionally, the range of the values mentioned in the literature is very wide, with the lowest value at 36 d^{-1} and the highest at

576 d^{-1}, indicating that the conditions for measurement or calibration significantly impact the values. Given these variables, it is crucial that kLa be measured directly.

Table 4.6 Values of kinetic and stoichiometric parameters, and diffusion coefficients used in the simulation model

Parameter	Value	Unit	Description	Source
KINETICS				
b_A	0.15	d^{-1}	Decay coefficient for autotrophic biomass	Langergraber & Šimůnek (2005)
b_H	0.4	d^{-1}	Decay coefficient for heterotrophic biomass	Langergraber & Šimůnek (2005)
k_a	0.08	$m^3gCOD^{-1}d^{-1}$	Maximum specific ammonification rate	Default WEST value
k_h	3	gCOD. $gCOD^{-1}d^{-1}$	Maximum specific hydrolysis rate	Langergraber & Šimůnek (2005)
k_mu	1	-	Temperature correction factor for growth	Default WEST value
kdt	0.1	-	Detachment coefficient	Rauch et al. (1999)
mu_a	0.9	d^{-1}	Growth rate of autotrophs	Langergraber & Šimůnek (2005)
mu_h	6	d^{-1}	Growth rate of heterotrophs	Langergraber & Šimůnek (2005)
mu_hh	4.8	d^{-1}	Growth rate of heterotrophs (anoxic)	Langergraber & Šimůnek (2005)
STOICHIOMETRY				
Y_A	0.24	$gCOD.gN^{-1}$	Yield for autotrophic biomass	Langergraber & Šimůnek (2005)
Y_H	0.63	$gCOD.gCOD^{-1}$	Yield for heterotrophic biomass	Langergraber & Šimůnek (2005)
f_P	0.1	-	Fraction of biomass converted to inert matter	Langergraber & Šimůnek (2005)
DIFUSSIVITY				
DiSnh	1.8 e-4	m^2d^{-1}	Diffusion coefficient for S_NH	Default WEST value

DiSno	1.0e-4	m^2d^{-1}	Diffusion coefficient for S_No	Default WEST value
DiSo	2.1e-4	m^2d^{-1}	Diffusion coefficient for S_O	Default WEST value
DiSs	0.58e-4	m^2d^{-1}	Diffusion coefficient for S_S	Default WEST value

Figure 4.4 presents the measured and simulated concentrations of DO in the effluent. The mean absolute error (MAE) of 0.54 mgL^{-1} was calculated for DO. The simulated DO concentrations fall within the range of the observed values, suggesting a reasonably satisfactory fit. This alignment indicates that the model captures the general trend of DO concentrations adequately, although there may still be room for improvement to achieve a more precise fit. When experimenting with higher values of kLa, the effluent DO exceeded the saturation level at the altitude of the testing site (approximately 7.47 mgL^{-1}). This finding underscores the influence of altitude on the oxygen transfer coefficient, indicating that the pilot's performance differs at this altitude compared to other locations.

Another notable factor (Figure 4.4) is the decline in DO concentrations after each batch. This aligns with the findings of De Andrade Moraes et al. (2020), who observed that the minimum DO concentration coincided with increased outflow at the beginning of a new batch in the first stage of the French System. However, when examining DO concentrations during feeding days, the model simulated similar values of DO on the second and third days, with only the initial hours of the first day showing higher DO concentrations. De Andrade Moraes et al. (2020), in the same study, reported a progressive decrease in DO during feeding days, suggesting a decline in aeration capacity. Here, neither the observed nor the simulated DO concentrations exhibit this behavior, potentially due to the presence of an aeration pipe connected to the drainage pipe extending to the surface. With a diameter of 110 mm, significantly larger than the dimensions of the pilots, this setup enables aeration of the pilot even during subsequent feeding days.

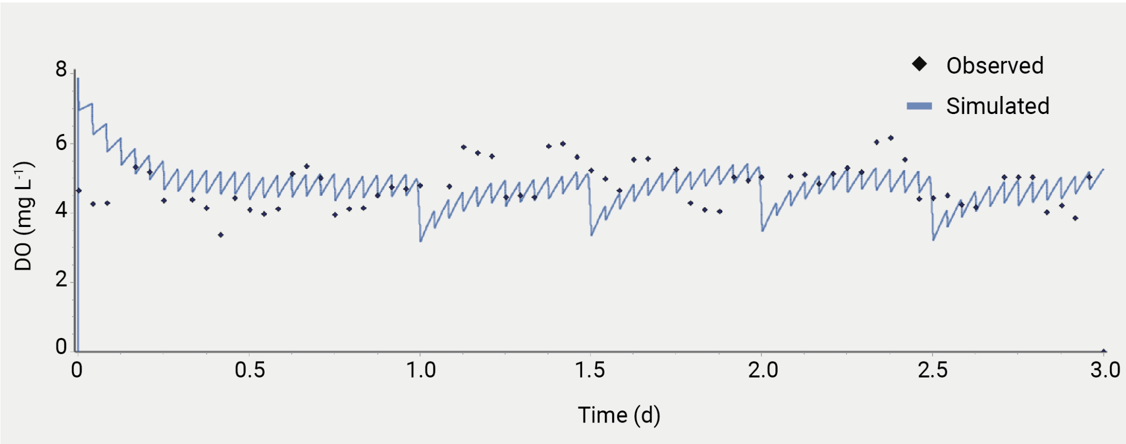

Figure 4.4 Observed and simulated concentrations of DO during the feeding period

Similarly, Figure 4.5 shows the measured and simulated effluent concentrations of COD, distinguishing between effluent concentrations from influent COD levels above and below 180 mgL^{-1}. Further explanation of this distinction will be provided in the next paragraphs. The simulated concentrations did not entirely match the observed values (MAE = 88.02 mgL^{-1}). The model failed to reproduce the lowest observed concentrations, suggesting that it underestimated the pilot's performance. The high simulated effluent values could be attributed to the size of the treatment unit, particularly the small volume of the pilot compared to a full-scale WWTP. The volume of the pilot influenced the model's predictive capabilities, potentially leading to an overestimation of effluent concentrations. This distortion highlights the importance of considering scale effects when extrapolating results from pilot-scale studies to full-scale applications. Adjustments or corrections may be necessary to account for these differences in scale and ensure the accuracy of model predictions.

In turn, the model may acknowledge the high instantaneous HLR applied in this study. As previously mentioned, the short time available to promote attachment to the biofilm and organic matter degradation (Molle et al., 2008) could have influenced the performance of the pilot.

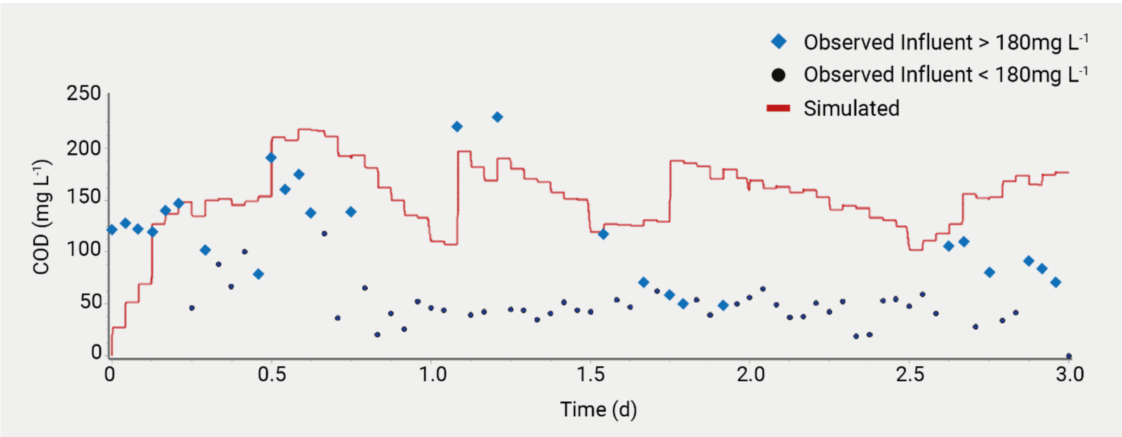

Figure 4.5 Observed and simulated concentrations of COD during the feeding period (Observed influent > 180 mgL^{-1} corresponds to effluent COD concentrations associated with COD influent concentrations greater than 180 mgL^{-1}; Observed influent < 180 mgL^{-1} corresponds to effluent COD concentrations associated with COD influent concentrations below that level)

Finally, Figure 4.6 shows the influent COD concentrations alongside the simulated effluent COD concentrations. The model's performance is particularly effective at higher influent concentrations. However, for influent concentrations below 180 mgL^{-1}, the model predicts higher concentrations than those observed at the inlet. This could be due to the model interpreting that such low concentrations would washout the biomass due to limited microbial growth. Additionally, this discrepancy may arise from the assumption of zero-order reaction rates in the Rauch model. Zero-order kinetics generally provide a good representation of biofilm behavior when substrate concentrations are adequately high (Rauch et al., 1999).

In this study, a majority of the inlet COD concentrations (63 %) were below 180 mgL^{-1}, indicating that the raw wastewater falls within the category of low-strength wastewater, as defined by Tchobanoglous *et al* (2014). However, upon analyzing the mean values of observed and simulated COD when influent COD exceeded 180 mgL^{-1} the disparity between them is smaller (Figure 4.5) The observed mean effluent COD concentration was 107 mgL^{-1} (SD: 54 mgL^{-1}), while the simulated mean effluent COD concentration was 140 mgL^{-1} (SD: 47 mgL^{-1}). This suggests that the model performs better in simulating effluent COD concentrations when the influent COD is higher.

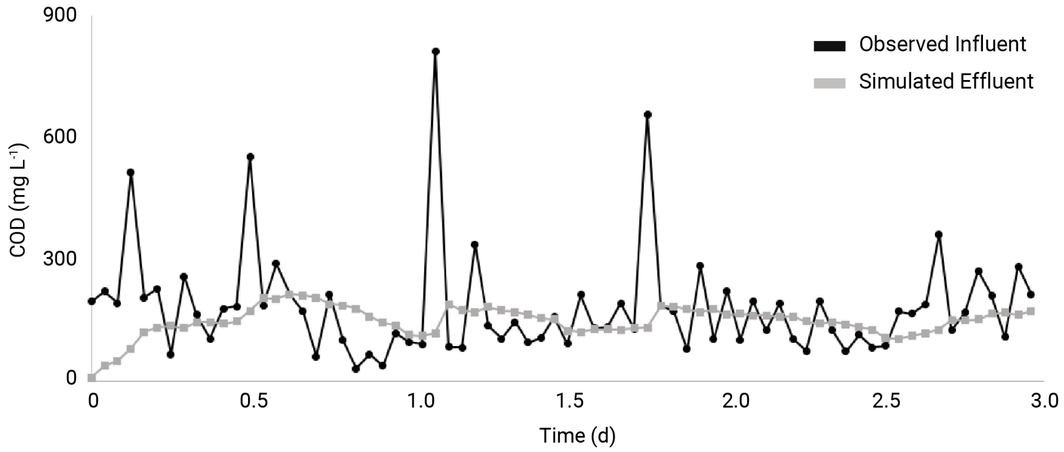

Figure 4.6 Observed influent COD concentrations and their simulated COD effluent concentrations

The simulated outlet concentrations are conservative. This means that if the model predicts outlet values that meet discharge standards, the actual concentrations in real life will likely be even lower.

4.3.4 Challenges and future directions of the proposed model

The primary objective of the proposed model was to obtain a simplified hydraulic representation of the FVFCWs. This model considered the short hydraulic retention time due to the high permeability of the gravel used in the French System (Morvannou et al., 2014). As for the biokinetic model, it is important to note that the conditions simulated do not include limitations on Nitrogen or DO (both in excess). Parameters calibration under these idealized conditions would not be realistic. The values taken for the biokinetic parameters were those mentioned in the literature (Langergraber & Šimůnek, 2005; Rauch et al., 1999) which have demonstrated good results in VFCWs.

The modelling exercise highlighted the limitations of modelling low-strength wastewater, which is characteristic of a combined sewer system, thus pointing out areas for further refinement. Additionally, the model could serve as an educational tool, helping to understand the influence of various parameters on system performance.

Future perspectives include developing an integrated model that uses the hydraulically calibrated model of the equalization tank with variable volume and measures field parameters for the biokinetic model. Additional calibration, sensitivity analysis, and scale-specific adjustments will enhance the model´s reliability and applicability, making it a more robust tool for both practical applications and educational purposes.

4.4. Conclusions

The Rauch biofilm model with variable volume was employed to simulate DO and COD effluent concentrations in a FVFCW treating raw domestic wastewater. The hydraulic model, simulated as an equalization tank with variable volume, demonstrated good agreement with the observed hydraulic behavior of the pilot system. Despite obtaining a significantly lower kLa value compared to previous reports, it effectively reproduced DO concentrations within the measured range. This discrepancy in kLa values is possibly attributed to the unique conditions of this study, conducted at an altitude of 2500 meters above sea level.

The model struggled to accurately predict COD effluent concentrations, showing a reasonable performance only when influent COD concentrations were sufficiently high. Future research should focus on identifying optimal parameters for simulating COD effluent concentrations more accurately, particularly when wastewater influent is highly diluted.

Chapter 5

5. Septic tank usage and its faecal sludge management in Cuenca-Ecuador

Based on: Arévalo-Durazno, M. B., Ballari, D., & Alvarado, A. (2024). Septic tank usage and its faecal sludge management in Cuenca, Ecuador. *Journal of Water, Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2024.223

Abstract

On-site sanitation systems such as septic tanks are widely used for treating domestic wastewater in urban and rural areas which lack sewage systems. However, a large portion of these systems do not properly treat human excreta. A main challenge to improve this, is the absence of comprehensive data regarding the usage, emptying and maintenance. In this study, records of septic tank desludging frequency during 2009–2022 and the sewerage coverage updated to 2022 were used to investigate their spatial and temporal utilization, and the persistence of septic tank usage in areas with sewer networks and uncover the current state of Faecal Sludge Management in Cuenca, Ecuador. The spatial behaviour revealed that OSSs are still in use besides the presence of sewer network. In 2022, there were 109 active septic tanks (units with at least one desludging in 2022) in urban areas with 14.7% in sectors with sewerage service. In rural areas, 469 active septic tanks were recorded with a 7.8% situated in areas with sewer network. Although there is no specialised infrastructure in place for the treatment and disposal of faecal sludge, the city has effectively managed it with the existing sanitation facilities. This assessment contributes to the formulation of a secure framework for a safely managed sanitation.

Chapter 6

6. Septage treatment using the First Stage of French Vertical Flow Constructed Wetlands: From the beginning to the closure of the system

Based on: Arévalo-Durazno, M.B.; García Zumalacarregui, J.A.; Ho, L., Narváez, A., Alvarado, A. (2024). Septage treatment using the First Stage of French Vertical Flow Constructed Wetlands: From the beginning to the closure of the system. *Ecological Engineering,* 206(April). https://doi.org/10.1016/j.ecoleng.2024.107329

Abstract

The First Stage of French Vertical Flow Constructed Wetlands (FS-FVFCW) offers a sustainable solution for treating septage. The system operates through distinct phases: start-up, full operation and final rest. During full operation, factors such as feeding duration, rest periods and percolate impounding significantly affect performance. This study assessed the performance of a pilot-scale Modified FS-FVFCW in Northern Tropical Andes, from start-up to closure stages under three operational scenarios. These scenarios varied in planted/unplanted conditions and percolate drainage/impounding. A four-month start-up phase proved adequate for vegetation growth and adaptation, achieving over 50% COD removal efficiency. Percolate retention (impounding) during operation notably improved COD and TS removal, increasing efficiencies from 49% to approximately 90% for COD and from 39% to around 70% for TS. Plant presence contributed to mosquito control and odour reduction but had minimal impact on removal efficiencies. The pilot demonstrated significant dewatering potential, with sludge deposit samples showing water content below 76% across all scenarios after 24 hours; and a 10% reduction in VS/TS ratio during the operational resting period. After a 5-month closure, the sludge deposit layer exhibited organic matter content similar to long-rested sludge, albeit with persistent faecal contamination.

Chapter 7

7. Conclusions and perspectives

This thesis has successfully demonstrated the feasibility of French Vertical Flow Constructed Wetlands as an effective solution for domestic wastewater and septage treatment in the Andean Region. The research encompassed field experiments, data collection, and modeling efforts, providing comprehensive insights into the operational viability and scalability of FVFCW under the climatic conditions of high altitudes.

The results obtained demonstrated that both wastewater and septage can be effectively treated in the same facility using FVFCWs, e.g three units for wastewater treatment and additional units for septage treatment. This approach highlights a sustainable and practical treatment cycle suitable for decentralized wastewater treatment plants. By integrating the treatment of wastewater and septage, this method offers a comprehensive solution for the management and treatment of these waste streams. This innovation is particularly relevant for Ecuador and other regions with similar characteristics.

7.1 General conclusions

7.1.1 Wastewater treatment

This research established optimal operating conditions for FVFCWs to achieve efficient removal of organic matter and suspended solids in raw wastewater. Specific HLRs and OLRs were identified, along with effective feeding-resting and start-up strategies.

An important aspect of this research was that it began from zero, starting with the design and construction of the pilot systems. This process involved addressing various challenges during the implementation and calibration of the experimental plant. This initial phase, though not strictly scientific research, provided valuable lessons in overcoming practical obstacles to ensure proper operation of the pilots. One key insight gained was the importance of effective start-up strategies for the wetlands. The start-up phase was crucial for establishing a stable microbial community, ensuring efficient system operation from the outset. Besides, the chosen vegetation (*Lolium Perenne*), was selected for its common use in the region. This allowed for an evaluation of plants development and respond under the specific operational conditions of this type of wetlands. The vegetation demonstrated successful establishment and growth during the start-up, contributing significantly to the system's overall performance.

The study determined that specific HLRs and OLRs are critical for maintaining high treatment efficiency. Optimal HLRs ensure that the system can handle varying volumes of wastewater without compromising the removal efficiency, while optimal OLRs maintain the balance of organic matter within the treatment process, preventing overloading and system failure. In this research, we proved that FVFCWs are capable of treating diluted wastewater, handling continuous HLRs up to 0.94 md^{-1} when maintaining the resting time to be twice the feeding time, and HLRs in the range of 0.56 md^{-1} when the resting period is reduced. The implications of these high HLRs include a potential reduction in the required treatment area and a subsequent change in the design of wastewater treatment plants with similar conditions of the studied site. In developing countries with combined sewers, it is very common during the rainy season to divert a large percentage of the flow directly to the receiving body, as the treatment plant is not designed for these flows. With the results obtained here, it is possible to accept higher flows of diluted wastewater in the treatment plant, ensuring greater volumes of wastewater treated before being discharged.

Additionally, this study demonstrated that sludge accumulation on top of the VFCWs is minimal. This reduces the need for frequent maintenance and sludge removal, lowering operational costs and complexity, therefore ensuring long-term sustainability, factors that are decisive in wastewater treatment plants in rural areas of developing countries.

An important advantage of using FVFCWs is that they eliminate the need for primary treatment and its associated sludge management concerns. This is particularly beneficial in developing regions where sludge management is still in its early stages. With this type of treatment, the volume of sludge requiring management is significantly reduced. This makes FVFCWs a practical and cost-effective solution for wastewater treatment in such areas.

Finally, finding a simplified model to simulate the hydraulic and biokinetic processes within FVFCWs using existing wastewater treatment software posed challenges. However, the modified Rauch model provided valuable insights and demonstrated its applicability for treating concentrated wastewater, such as septage, while maintaining the same operational strategies of FVFCWs.

7.1.2 Septage treatment

The analysis conducted on the usage of septic tanks in Cuenca-Ecuador, revealed a prevalent utilization of these systems, extending even into urban areas. Of the 578 septic tanks recorded as active in 2022, 109 were located in urban areas and 469 in rural areas. Among these, 14.6% of the urban septic tanks were situated in zones with sewer coverage, while 7.8% of the rural septic tanks were in zones with sewer coverage. This highlights the urgent need for efficient decentralized septage treatment systems. In this context, FVFCWs emerged as a promising solution, demonstrating their remarkable ability to effectively manage diverse septage characteristics. These wetlands showed resilience and adaptability in handling highly concentrated and even potentially hazardous substances commonly found in septage.

The comprehensive study of FVFCWs for septage treatment, spanning from start-up to closure, provided valuable insights into the best practices necessary for the effective application of these systems. One key observation was the importance of replicating real-world conditions throughout the operational life of the wetland. This approach revealed that the FVFCWs successfully managed diverse feeding-resting times, yielding satisfactory results. Furthermore, the study highlighted the necessity of utilizing multiple beds for proper septage treatment. This ensures that each unit has sufficient resting periods to reestablish optimal conditions and prevent clogging. Remarkably, even when subjected to high concentrations of septage loads, the wetlands did not require sludge removal throughout their operational lifespan of 18 months. This represents a significant advantage compared to other sludge drying systems.

Regarding operational strategy, the study showcased that percolate impounding significantly enhances the system's overall performance in terms of COD and TS. This approach is particularly advantageous as it does not increase the required area. Nevertheless, it's crucial to recognize that while FVFCWs effectively treated septage, additional treatment is necessary, particularly to target pathogens. This aspect poses a challenge that requires attention to guarantee the thorough and safe treatment of septage before its discharge into the environment.

The sludge dewaterability potential of this technology was excellent, showing a reduction of around 30 % in water content in the sludge deposit layer. However, a disadvantage of is the low organic reduction rate, as indicated by a mean VS/TS ratio of 10 % from day 1 to day 7.

Upon the closure of the system, it was notable that sludge removal was not necessary. Instead, the sludge could remain on top of the bed, allowing it to dry and stabilize completely over time. However, it is important to acknowledge that the sludge may not be immediately safe for use. Despite this, the wetland’s infrastructure can remain unaltered, preserving its aesthetic value in the landscape. Additionally, it could be restored if necessary for wastewater or sludge treatment.

7.1.3 Perspectives

Future research should prioritize integrated system modelling, innovative system upgrades that address greenhouse gas emissions, align the system with circular economy goals and the removal of emerging contaminants. Comprehensive modelling approaches are needed to optimize system performance and adaptability. Specifically, a detailed hydraulic model for French vertical wetlands should be investigated, considering intermittent feeding and resting periods where organic matter stabilizes. Additionally, a biokinetic model should be developed to account for highly diluted organic loads that the Rauch model could not adequately represent.

FVFCW systems require ongoing upgrades to address emerging challenges such as greenhouse gas emissions, emerging contaminants and integration into the circular economy. These upgrades may include using advanced or region-specific materials for better treatment or fine-tuning system design to maximize performance based on the specific conditions of each region. Additionally, future studies should focus on exploring system modifications for improved efficacy and water reuse. Material recovery can also be addressed by include plants that can be harvested. This biomass can be composted or converted into bioenergy or other products, providing additional value and creating a closed-loop system.

While there is a growing concern regarding the impact of constructed wetlands on greenhouse gas emissions, FVFCWs can serve as a source of carbon sequestration. The plants in these wetlands absorb carbon dioxide from the atmosphere during photosynthesis, storing carbon in their biomass as they grow. Additionally, these wetlands offer improved aeration and oxygenation compared to other types of wetlands, which can help reduce methane production. Nonetheless, further research is needed to quantify and mitigate emissions from French systems to ensure their sustainability and environmental compatibility. Investigating methods to optimize aeration and plant selection can contribute to the long-term sustainability of these systems.

Significant knowledge gaps persist in understanding the mechanisms behind greenhouse gas emissions, carbon sequestration, and the removal of emerging contaminants. These challenges are of critical importance today, yet there is limited research on these topics specific to FVFCW technology. Additionally, more comprehensive studies on microplastics are needed, especially as plastics are very common in developing countries where this technology has great potential.

Supportive policies and regulations are crucial for promoting the adoption of FVFCWs. Governments and regulatory bodies can play a key role in incentivizing the implementation of these systems, providing funding support, and establishing standards for their design, operation and maintenance.

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PUBLICATIONS

Arévalo-Durazno, M. B., Ballari, D., & Alvarado, A. (2024). Septic tank usage and its faecal sludge management in Cuenca, Ecuador. *Journal of Water, Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2024.223

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PRESENTATIONS

Arévalo-Durazno, M. B., García Zumalacarregui, J. A., Ho, L., Narváez, A., & Alvarado, A. (2022, November). Performance of modified first-stage French Vertical Flow Constructed Wetlands during extreme operational conditions. In 17th International Conference on Wetland Systems for Water Pollution Control.

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DOCTORAL COURSES

- Tools for Doctoral Research
- Numerical Modeling
- Scientific Writing
- Advanced Topics in Water Resources
- Integrated Management of Drinking Water