

CRANFIELD UNIVERSITY

OLHA KHOMENKO

ADAPTATION OF TWO-STAGE VERTICAL FLOW CONSTRUCTED
WETLANDS FOR TREATING UNSCREENED SEWAGE IN THE UK

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
CRANFIELD WATER SCIENCE INSTITUTE

MSc BY RESEARCH
Academic Year: 2018 - 2019

Supervisor: Dr. Yadira Bajón Fernández & Dr. Gabriela Dotro

March 2019

CRANFIELD UNIVERSITY

SCHOOL OF WATER ENERGY AND ENVIRONMENT
CRANFIELD WATER SCIENCE INSTITUTE

MSc BY RESEARCH

Academic Year 2018 - 2019

OLHA KHOMENKO

ADAPTATION OF TWO-STAGE VERTICAL FLOW CONSTRUCTED
WETLANDS FOR TREATING UNSCREENED SEWAGE IN THE UK

Supervisor: Dr. Yadira Bajón Fernández & Dr. Gabriela Dotro

April 2019

This thesis is submitted in partial fulfilment of the requirements for the
degree of MSc BY RESEARCH

© Cranfield University 2019. All rights reserved. No part of this publication
may be reproduced without the written permission of the copyright owner.

Executive summary

The UK water industry has made a priority of embracing low energy sewage treatment, making of two-stage vertical flow constructed wetlands (VFCWs) a plausible alternative to conventional systems. However, for successful implementation of the technology in the UK a further understanding of any required adaptations in its design and operation is required, in particular linked to the UK use of spot sampling regulation of treated effluents and differences in rain profile affecting hydraulic loads in combined sewers. There is also a paucity of information regarding required time for full maturation of the technology and of performance during early operation. In response, the first UK full-scale WWTP based on two-stage VFCWs was built in Derbyshire, UK, and closely monitored during the initial three years of operation, allowing investigation of the system performance and robustness. The efficacy of the system for removal of total suspended solids (TSS), BOD₅ and NH₄⁺-N has been evaluated by composite and spot samples analysis.

The technology was found to efficiently remove pollutants to the level of $6 \pm 3 \text{ mg}\cdot\text{L}^{-1}$, $5 \pm 2 \text{ mg}\cdot\text{L}^{-1}$ and $5.8 \pm 3.8 \text{ mg}\cdot\text{L}^{-1}$ for TSS, BOD₅ and NH₄⁺-N, for 24 hour composite samples. After one year of operation the system was retrofitted with forced aeration on the second stage, which enabled a higher ammonia removal with concentrations in final effluent of 95th percentile concentration of $5.3 \text{ mg}\cdot\text{L}^{-1}$ comparing to $9.6 \text{ mg}\cdot\text{L}^{-1}$ achieved in the system with passive aeration.

The first stage filters were observed to be hydraulically limited during the first year of operation, with a hydraulic conductivity (HC) of $<5.7 \times 10^{-6} \text{ m}\cdot\text{s}^{-1}$ which caused prolonged ponding occurrence. This in turn led to poor re-oxygenation of the first stage filter beds and low mineralization of the sludge layer deposited on its surface, which was characterized by TS and VS content of $11.5\% \pm 1.9\%$ and $64.5\% \pm 7.3\%$ respectively. A more mineralised sludge layer was present after three operational years, with $\text{HC} < 4.9 \times 10^{-4} \text{ m}\cdot\text{s}^{-1}$ and sludge

properties of $20.4\% \pm 3.5\%$ TS and $62.3\% \pm 3.5\%$ VS. These values are comparable to data reported for two-stage VFCWs operated in France and ponding was minimal after three years, suggesting this as the required length for system maturation. Close monitoring of the system during the first three years of operation evidenced the need to adapt rotating period lengths according to system age and sludge layer properties. Resting periods of up to 14 days were required for the young system to encourage sufficient hydraulic conductivity of the sludge layer, while the conventional 3.5 days feed/ 7 days rest cycle is appropriate after three years of operation.

The influence of sludge properties on permeability was assessed in laboratory experiments, as well as artificial modifications of the sludge surface that could sustain increased permeability and accelerate sludge layer mineralisation. A positive impact of increased VS on permeability was found, with an increase in VS from 60% to 75% improving permeability from $6.14 \times 10^{-17} \text{ m}\cdot\text{s}^{-1}$ to $2.00 \times 10^{-16} \text{ m}\cdot\text{s}^{-1}$ in samples with TS of 9% and from $2.06 \times 10^{-17} \text{ m}\cdot\text{s}^{-1}$ to $1.25 \times 10^{-16} \text{ m}\cdot\text{s}^{-1}$ in samples with TS 15%. A greater relative contribution to permeability of preferential flow pathways (PFPs) present in the sludge layer than of sludge properties (TS, VS) was observed. PFPs were scarce in the young full scale primary VFCWs, which was believed to be the reason for their poor hydraulic acceptance. A positive effect on PFP formation and sludge drying rate was observed when artificially modifying the sludge layer by application of secondary activated sludge or by making initial cuts on its surface. Artificial modifications of the sludge layer could be implemented in full-scale systems to improve hydraulic acceptance and re-oxygenation, to shorten maturation of primary filters and to maintain prolonged operational periods without desludging.

Keywords:

Nitrification, permeability, preferential flow pathways, sludge, vertical flow constructed wetlands, young filters.

Acknowledgments

First of all, I would like to express gratitude to my primary supervisor Yadira Bajón Fernández for mentoring, guidance, positive attitude, and for endless patience. I am thankful to my secondary supervisor Gabriela Dotro for sharing experience and ideas and making sure results of my work are delivered properly. Also, I would like to acknowledge Prof. Bruce Jefferson for assistance on all stages of my work – from experiments design to data analysis, and to Prof. Frederic Coulon for support.

I am grateful to industrial partner of the project Severn Trent Water, in particular Richard Smith, Ricky Shepherd, Dan Cunliffe, and Stuart Rosewarne for help with the site accessing and organising sampling and experimental works. To Martin Horsley and James Ballard for assistance with access to historical data

Also, I am immeasurably grateful to technician team in Cranfield university, Jane Hubble, Richard Andrews, Alan Nelson, and Paul Barton for assisting with laboratory set ups. To my Cranfield colleague Olivia for assisting me with samples collection and help with tests which were completely new for me on the very beginning of my journey.

Безкінечна любов і вдячність – моїй сім'ї. Моїм батькам за підтримку, розуміння, і за те, що завжди були для мене прикладом. Мій кожен крок вперед – це ваша заслуга, Моєму старшому брату, найкращому другу, май компаньєра - Олегу. To Monique, my sister by heart, for always being marvelous friend regardless distance and time zones. And to Kyle. Your endless patience, positive attitude, and understanding made it possible to get through the toughest time in my studies with no (almost!) panic.

Thank you.

Table of contents

Executive summary	i
Nitrification, permeability, preferential flow pathways, sludge, vertical flow constructed wetlands, young filters.	iii
Acknowledgments	iii
Table of contents	iv
List of figures	vi
List of tables	vii
List of notations	viii
List of abbreviations	ix
1 Introduction.....	10
1.1 Aim and objectives.....	11
1.2 Thesis plan	12
2 Adaptation of two stage vertical flow constructed wetlands for treatment of unscreened sewage in the UK.....	14
2.1 Abstract.....	14
2.2 Introduction	15
2.3 Materials and Methods.....	17
2.3.1 Full-scale wastewater treatment plant design and operation.....	17
2.3.2 Sampling procedure	19
2.3.3 Sludge layer hydraulic conductivity	21
2.3.4 Analytical methods	21
2.3.5 Full scale VFCW robustness	22
2.4 Results and discussion	22
2.4.1 Treatment in the full-scale VFCW	22
2.4.2 Evolution of the first stage filters	32
2.5 Conclusion	39
2.6 References	40
3 Influence of sludge layer properties on the hydraulic behaviour of gravel-based vertical flow constructed wetlands for primary treatment of sewage.....	47
3.1 Abstract.....	47
3.2 Introduction	48
3.3 Materials and Methods.....	50
3.3.1 Sample preparation	50
3.3.2 Sludge layer permeability	51
3.3.3 Preferential flow pathways formation.....	52
3.3.4 Analytical methods	55
3.4 Results and discussion	55
3.4.1 Influence of sludge properties on its permeability	55
3.4.2 Preferential flow pathways formation and sludge evolution during drying	60
3.4.3 Implications of the findings for operation of full-scale VFCWs.....	64
3.5 Conclusion	66
3.6 References	67

4 Overall discussion	74
4.1 Suggested adaptations	78
5 Conclusions.....	80
6 Future work	81
7 References	82
Appendices.....	84

List of figures

Figure 2-1 Flowsheet of the full-scale two stage VFCWs.	18
Figure 2-2 Evolution of $\text{NH}_4^+\text{-N}$ (a) and $\text{NO}_3^-\text{-N}$ concentration on spot samples in the effluent of the second stage of a two stage VFCWs system (adapted from (Gomez, 2016)).	26
Figure 2-3 HL distribution over three years of the system operation. Treatment performance evolution in relation to ammonia concentration in final effluent (b) and turbidity of the final effluent (c).	28
Figure 2-4 Robustness curve of the studied system over three years with RI calculated against consent range from 1 mg.L^{-1} to 20 mg.L^{-1} ammonia concentration in the final effluent.	31
Figure 2-5 Reed health on the first stage bed №1. Reeds development on the second year of operation (May 2017).	33
Figure 2-6 Beds development on the first stage bed №2: reed debris in the sludge layer (a), litter accumulation on the bed surface (b).	34
Figure 2-7 Evolution of TS (a) and VS content (b), HC (c), and sludge layer height (d) over the operational cycle of bed №2 for 3 rd year of operation.	38
Figure 3-1 Preferential flow pathways formation test layout. Red arrows show warm airflows.	54
Figure 3-2 Relationship between sludge composition and permeability.	57
Figure 3-3 Drying curves of modified and non-mofied sludge samples : PFP1 (Thickened primary sludge with no modification) (a), PFP2 (Thickened primary sludge with initial V-cut) (b), PFP3 (Thickened primary sludge with initial III-cut) (c), PFP4 (Thickened primary sludge modified with wooden cylinders of 1.5 mm diameter) (d), PFP5 (Thickened primary sludge with secondary waste activated sludge application) (e), PFP6 (Thickened aerated primary sludge with no surface modification) (f). The curves are plotted for single testing trays.	63
Figure 4-1 The visual comparison of not modified sludge surface (left) and sludge surface modified by SAS application during drying (right).	77

List of tables

Table 1-1 Connection between thesis chapters.....	13
Table 2-1 Sampling campaign schedule (third operational year).....	20
Table 2-2 Comparison of treatment performance of two stage VFCWs operated in the UK (1 st operational year, composite sampling) (Gomez 2016) and France (survey completed for 169 sites with HL under 0.6m·d ⁻¹). Data for systems operated in France are extracted from Paing et al. (2015)	24
Table 3-3 Visual evolution of the 1 st stage filter beds	35
Table 2-4 Comparison of sludge layer characteristics of the UK two-stage VFCW and French systems.	36
Table 2-1 Sludge modifications used in preferential flow pathways formation test...	53
Table 3-2 Characteristics of primary sludge with different aeration times.	59
Table 3-3 Sludge layer evolution during drying.	62
Table 4-1 Comparison of design of the studied two-stage VFCWs WWTP and standard design in France.	75
Table 4-2 Comparison of sludge layer properties during the first three years of operation for the monitored full scale WWTP.	76

List of notations

A – filtration area (m^2)

a – surface of falling water (m^2)

h_1 and h_2 - initial and final water column height in falling head test (m^2)

k - permeability (m^2)

K_{sat} – saturated hydraulic conductivity ($\text{m}\cdot\text{s}^{-1}$)

l - cake thickness (m)

L – length across which pressure drop is taking place (m)

l – thickness of the sludge layer (m)

P - applied pressure (Pa)

ΔP - pressure drop (Pa)

Q – total discharge over the test period ($\text{m}^3\cdot\text{s}^{-1}$)

t_1 and t_2 – the beginning and end test times respectively

μ - viscosity ($\text{Pa}\cdot\text{s}$).

List of abbreviations

BOD ₅	5 days Biological Oxygen Demand
COD	Chemical Oxygen Demand
CW	Constructed Wetland
DEFRA	Department of Environment, Food and Rural Affairs
DM	Dry Matter
DO	Dissolved oxygen
DWF	Dry Weather Flow
HFCW	Horizontal Flow Constructed Wetland
HL	Hydraulic Load
IR	Infiltration Rate
N	Nitrogen
NH ₄ ⁺ -N	Ammonium - Nitrogen
NO ₃ ⁻ -N	Nitrate - Nitrogen
OL	Organic Load
OM	Organic Matter
p.e.	Population equivalent
PFP	Preferential flow pathway
RI	Robustness Index
SDRB	Sludge Layer Reeds Bed
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UK	United Kingdom
VFCW	Vertical Flow Constructed Wetland
VS	Volatile Solids
WWTP	Waste Water Treatment Plant

1 Introduction

In the past decade two-stage vertical flow constructed wetlands (VFCWs) have been successfully implemented for municipal and domestic wastewater treatment, allowing effective near passive treatment of total suspended solids (TSS), organic matter (OM) and $\text{NH}_4^+\text{-N}$ on small to medium wastewater treatment plants. While most two-stage VFCWs sites are located in France, the interest for this technology has recently grown in countries like the UK, where water utilities are driven to achieve low energy and low maintenance sewage treatment. Successful implementation of the technology in the UK requires understanding of its performance when effluent quality is consented on spot samples and of any design and operation alternations needed because of differences in rain profile affecting hydraulic loads in combined sewers. Besides, there is a lack of information regarding performance of the technology during its early stages of operation, which requires addressing to guarantee sufficient performance until a new system achieves maturation.

Pollutants removal in two-stage VFCWs takes place by various mechanisms including particles precipitation, plants uptake and OM decomposition, which in two-stage VFCWs relies on aerobic conditions within the treatment beds. Maintaining aerobic conditions is achieved by feed/rest cycles and batch-feed operation, which highly depends on hydraulic acceptance of the filter beds and is believed to be limited by the sludge layer deposition on the beds surface. Sludge layer accumulation on the filter beds has been reported to have a positive impact since it increases the water retention time, promotes ammonium absorption and provides additional area for microbial community activity hence improving treatment performance. A positive impact of sludge layer deposition was previously reported for gravel VFCWs treating wastewater, stating an enhanced water retention time (up to 5 times lower HC for the beds with developed sludge layer)

with improved water distribution and microbial diversity for beds with a developed sludge layer (Chazarenc and Merlin 2005).

A poorly developed sludge layer can however restrict HC to an extent where ponding occurs and oxygenation of the filter body is compromised. Anaerobic conditions occurrence in VFCWs means not only reduced treatment performance, but it has also been reported as one of possible reasons for poor sludge layer structure due to breakage of the sludge flocs which leads to a highly impermeable so-called skin layer development, compromising overall hydraulic acceptance of the filter beds (Bruus et al.1992; Dominiak 2010). For successful implementation of the technology for wastewater treatment in the UK the role of the sludge layer in the system's hydraulic behaviour needs to be understood, as so does the sludge layer evolution throughout the system maturing.

1.1 Aim and objectives

The aim of the thesis is to investigate treatment efficiency and hydraulic performance during the start-up of two-stage VFCWs for unscreened sewage treatment under UK conditions.

To deliver against the research aim the following objectives were developed:

1. Monitor two-stage VFCWs performance in terms of TSS, BOD₅ and NH₄⁺-N removal and robustness during the system start-up in UK climate conditions.
2. Understand influence of sludge layer properties on VFCWs' hydraulic behaviour and ways to enhance those favouring greater infiltration rates.
3. Inform any design and operation modifications required for successfully implementing this technology in the UK.

1.2 Thesis plan

The thesis consists of chapters structured as journal papers. All chapters were written by the first author Olha Khomenko and edited by Dr. Yadira Bajón Fernández and Dr. Gabriela Dotro. Collection and analysis of the sludge layer (sludge layer height, Total Solids (TS) and Volatile Solids (VS) content and beds hydraulic conductivity (HC)) and wastewater samples (TSS, BOD₅, ammonia and Chemical Oxygen Demand (COD)) collected in 2015 and 2016 was undertaken by Leticia Pereira and Antonio Labella de Tomas and the data analysis was performed by Olha Khomenko. Sampling of sludge layer and sludge analysis from full scale VFCW was performed by Olha Khomenko in October 2018. Some samples and wetlands pictures of Chapter 2 were collected by Stuart Rosewarne (Severn Trent) in November 2018. All data analysis was completed by Olha Khomenko. Sampling, sample preparation and all experimental work described in Chapter 3 was done by Olha Khomenko.

Chapter 2 investigates maturing of the first full-scale UK WWTP plant based entirely in VFCWs. Treatment performance and hydraulic acceptance of the filters were investigated and the impact of system age (1 to 3 years) and forced vs passive aeration was examined.

Chapter 3 investigates the impact of wastewater sludge properties on its permeability and ways to enhance it. Results of the study were presented on poster competitions at two conferences: CWA annual conference (Portsmouth, UK, September 2018) and 6th Wastewater Network Conference (Cranfield University, November 2018). An abstract discussing performance of the full-scale site (Chapter 2) and one comprising the laboratory work (Chapter 3) have been accepted for oral presentation at the annual Constructed Wetlands Association conference (Birmingham, UK, July 2019).

The connection between thesis chapters is shown in Table 1.1.

Table 1-1 Connection between thesis chapters.

Chapter	Paper title	Scope
1		Introduces project scope and objectives.
2	Adaptation of the two-stage vertical flow constructed wetlands for treatment of unscreened sewage in the UK	Investigates differences in treatment performance of the first UK two-stage VFCWs site and similar systems operating in France. Highlights changing in treatment performance over three years and maturing of the first stage filters.
3	Influence of sludge layer properties on the hydraulic behaviour of gravel-based vertical flow constructed wetlands for primary treatment of sewage	Identifies the influence of sludge properties on its permeability and means to improve it by sludge surface modification.

2 Adaptation of two stage vertical flow constructed wetlands for treatment of unscreened sewage in the UK

Khomenko, O.¹, Pereira, L, Blanco, I.², Cook, A.², Cunliffe, D.², Dotro, G. ¹, Jefferson, B.¹, Coulon F. ¹, Jordan, T.², Shepherd, Tomás, A.¹, R.², Smith, R.², and Bajón Fernández, Y^{1*}.

¹ Cranfield University, Cranfield, UK

² Severn Trent Water, Coventry, UK

^{1*}corresponding author: y.bajonfernandez@cranfield.ac.uk

2.1 Abstract

The first UK wastewater treatment plant based entirely on two-stage vertical flow constructed wetlands (VFCWs) was built in 2015 and studied over the first three years of operation to investigate treatment performance and hydraulic behaviour of young filters. The site was monitored both with analysis of composite and spot samples, allowing comparison of treatment performance with data reported in the literature (composite) and assessment of suitability of the technology to meet UK legislation requirements (spot). Efficiency of pollutants removal confirmed the site performance based on composite samples was comparable to data reported for similar sites operated in France. Global efficacy for TSS and BOD₅ removal was 98.1% and 97.7% in the UK system compared to 96% and 98%, respectively, for French sites. This corresponded to concentrations in the final effluent of $6.0 \pm 3.0 \text{ mg} \cdot \text{L}^{-1}$, $5.0 \pm 2.0 \text{ mg} \cdot \text{L}^{-1}$ and $5.8 \pm 3.8 \text{ mg} \cdot \text{L}^{-1}$ for TSS, BOD₅ and NH₄⁺-N, respectively, in the UK system and $10.0 \pm 10.0 \text{ mg} \cdot \text{L}^{-1}$, $6.0 \pm 4.0 \text{ mg} \cdot \text{L}^{-1}$ and $5.0 \pm 6.0 \text{ mg} \cdot \text{L}^{-1}$ in French literature.

Differences in treatment performance of two-stage VFCWs with forced and passive aeration were investigated. Forced aeration was confirmed to be an effective strategy to meet tighter ammonia consents when the systems are oxygen limited, achieving a 95th percentile ammonia concentration of 5.3 mg·L⁻¹ compared to 9.3 mg·L⁻¹ for the passive aeration.

Sludge layer evolution in terms of total solids (TS), volatile solids (VS) content and hydraulic conductivity (HC) was studied over three years and informed recommendations for rotation period length. A cycle of 3.5 days feeding and 7 days resting is recommended for systems after 3 years of operation while prolonged resting times (up to 14 days) were required during system start up to avoid ponding events.

2.2 Introduction

Two stage vertical flow constructed wetlands (VFCWs) can successfully substitute conventional wastewater treatment plants (WWTPs) and have been widely implemented in France with over 3,000 full scale installations serving 20 to 6,000 population equivalent (p.e.) (Troesch & Esser 2014). The reduced energy consumption and maintenance requirements associated with this technology makes it attractive for further implementation in other countries, where embracing nearly passive and low energy technologies has become a priority for water utilities (Gomez 2016). The typical technology flowsheet comprises of two stages of constructed wetlands (CWs), with three wetlands on the first stage and two wetlands on the second stage. The first stage filters are typically operated with a rotational period of 3.5 days feed and 7 days rest and target removal of total solids (TS) and partial removal of organic matter (OM) (Paing et al. 2015). The second stage is typically comprised of two filter beds operated with rotational period of 7 days feed and 7 days rest and are

used for polishing and nitrification (Morvannou et al. 2015; Paing et al. 2015). Wastewater treatment in two stage VFCWs relies on aerobic processes taking place within the beds, thereby re-oxygenation of the filter beds is essential for effective pollutants removal (Daltro et al. 2017). Moreover oxygen promotion is needed for sludge layer mineralization on the first stage filter beds, which avoids prolonged ponding and allows operation without desludging for 10 to 15 years (Molle et al. 2006). Despite increasing interest in the technology, there is a lack of information available concerning its performance during the first years of operation, which limits understanding of commissioning times required before stable process performance is achieved.

The vast majority of information available in literature discusses performance after one year of operation and beyond (Molle et al. 2006), with limited or no information about changes in treatment performance and sludge layer during system maturation. Information about young systems' behavior and maturing is important to ensure efficient treatment of wastewater during commissioning and to avoid hydraulic limitations on filter beds. Another difficulty in evaluation of the technology's suitability for wastewater treatment in the UK, is the approach to final effluent permitting. In the UK it is based on spot samples while information available in literature typically reports treatment performance on composite samples analysis (Paing et al. 2015). However, composite sampling does not reflect dynamic changes in treatment performance when the load on the system varies, which complicates the understanding of how robust the system is operating under various flows.

To investigate the potential of two-stage VFCWs for treatment of unscreened municipal wastewater in the UK, a full-scale system was built in 2015 to treat

wastewater from a 941 population equivalent (p.e.) town. To minimize risks related with high hydraulic loads (HL) during storm events, which are typical of the region, some modifications were required, i.e. increased dry weather flow, alterations in rotation periods and implementation of forced aeration on the second stage. The full-scale site was closely monitored during its first three years of operation, allowing evaluation of its suitability to meet treatment goals as well as suggesting recommendations for design and operation in future sites. During the first year of operation efficiency was evaluated based both on spot and composite samples, which allowed performance comparison with previously available literature (composite) and reporting of system's performance under different hydraulic loads according to the UK regulatory requirements (spot sampling). Impact of the system age, hydraulic load, and passive vs forced aeration of the second stage filter beds on ammonia removal and effluent turbidity was studied over three years based on information recorded with online monitors. The first stage filter beds were also monitored to inform optimal length of feeding and resting periods which would benefit hydraulic acceptance of the filters and avoid ponding.

2.3 Materials and Methods

2.3.1 Full-scale wastewater treatment plant design and operation

The two-stage VFCW site was built in Derbyshire, UK in 2015 for treatment of unscreened wastewater from a catchment of 941 population equivalent. The system is comprised of two stages: three Phragmifiltre® CW with an active area of 1.2 m² p.e.⁻¹ on the first stage followed by two planted filter beds on the second stage with an active area of 0.8 m² p.e.⁻¹ (ARM technology) (Fig. 2-1). Unlike conventional French systems, the filters received unscreened wastewater. The average rainfall in the region

is 798 mm per year, similarly to sites operated in France characterised by an annual average rainfall of 750 – 850 mm (Paing et al. 2015). The average annual temperature in French regions where VFCWs are in operation is 17.5 °C being 4 °C higher than Derbyshire average annual temperature of 13.6 °C. To provide sufficient hydraulic acceptance of the system it was designed to operate with a load of 2.27 L·s⁻¹ under dry weather flow (DWF), which corresponds to a hydraulic loading rate of 0.52 m·d⁻¹ compared to typical values reported in literature for similar systems of 0.37 m·d⁻¹ (Paing et al. 2015). The design average flow, defined as 1.2xDWF, was 0.62 m·d⁻¹.

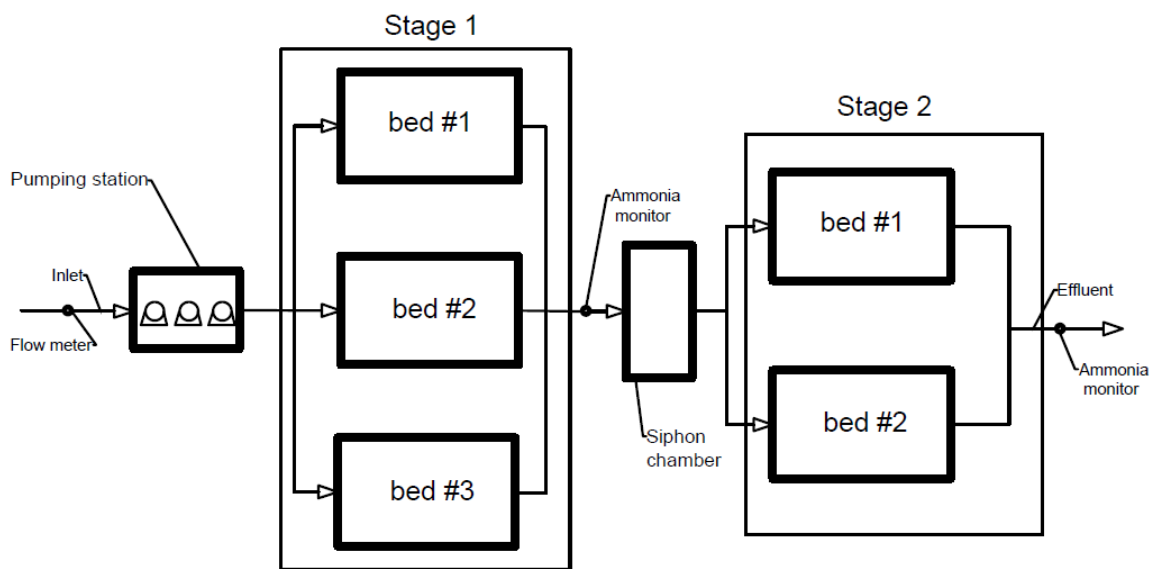


Figure 2-1 Flowsheet of the full-scale two stage VFCWs.

The beds are planted with *Phragmites australis* at a density of 4 m⁻² and are operated on a batch feed basis. The first stage beds are fed with dedicated pumps with a batch volume of 7.5 m³ and operate with a fountain type system with a feeding point density of 1 per 47 m². This resulted in a variable number of batches loaded per day depending on incoming flowrate from combined sewerage system. The second stage is fed by a syphon with water distribution through perforated pipes providing 1 feeding point per 1 m². The first stage beds target removal of SS and organic matter and the main target

of the second stage is polishing and nitrification. The first stage filter beds were initially operated with a feeding-resting pattern of 3.5 days feeding / 7 days resting. This pattern was altered to 5 days feeding/10 days resting and 7 days feeding / 14 days resting on the 2nd and 3rd years of operation, respectively, to allow a greater time for mineralisation of the sludge layer deposited on the beds surface. The 2nd stage filters were operated with a 7 days feeding and 7 days resting pattern. The second stage was retrofitted with forced aeration in December 2015 in order to improve oxygen promotion to the filter body and enhance nitrification. After implementation of forced aeration only one secondary bed is in operation.

2.3.2 Sampling procedure

Treatment performance during the first year of operation was evaluated by collection of spot and composite samples, which were analysed for total suspended solids (TSS), ammonia nitrogen ($\text{NH}_4^+\text{-N}$), nitrates ($\text{NO}_3\text{-N}$), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP). Time-proportional 24 hours composite samples were collected up to 3 times a week using an auto-sampler (Aquacell P2-compact CL-1010, Aquamatic, UK) taking one sample every 1 hour during 24 hours. Spot samples were collected up to 3 times a week during the first 5 months of the system operation covering the period between July and December 2015. The sampling points were at the inlet, effluent of the first stage and effluent of the second stage. Treatment performance of the system over the first three years of operation was evaluated by recording ammonia concentration and turbidity levels with online monitors installed on the final effluent pipe.

Three sludge layer sampling campaigns were completed for the first stage beds, covering a full operational cycle (feed & rest) for each operational year. The first

campaign covered between the 5th and the 6th operational months (December 2015 – January 2016), the second campaign covered May 2016 to June 2016 and the third year sampling took place in October and November 2018 (Table 3-1). To ensure the sludge layer samples were representative, samples were collected at least 1 meter away from the feeding points and bed boundaries (Molle 2014). The height of the collected samples was recorded. Undisturbed sludge columns from the 1st stage reed beds were collected for determination of TS and VS content. Columns were collected using a sediment sampling kit consisting of a steel tube with a fitted one-way valve and an inner plastic core (liner) (AMS inc., USA). The sampling kit allowed for samples to be extracted from the steel tube and enclosed within the plastic core, so that they could be transported with minimal disruption of the sludge layer structure.

Table 2-1 Sampling campaign schedule (third operational year).

	October 2018																													
	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30									
Bed №1	R	R	R				R	R	R	R				R	F	F	F													F
Bed №2	F	F	F				F	R	R	R				R	R	R	R													R
Bed №3	R	R	R				R	F	F	F				F	R	R	R													R
	Limited access to site.																													
F	Feed																													
R	Rest																													
	Sampling																													

2.3.3 Sludge layer hydraulic conductivity

On-site saturated hydraulic conductivity of the sludge layer was determined by falling head test using a single-ring infiltrometer: a plastic tube of 0.35 m height and 100 mm diameter opened at both ends which was carefully inserted into the primary beds sludge layer. The test tube was filled with 1000 ml of water and the water allowed draining before starting the HC measurement tests in order to ensure saturation of the tested medium. The tube was then refilled with 1000 ml of water and the changing water level over time was recorded. This method has been previously used in literature to measure hydraulic conductivity of porous medium (Angulo-Jaramillo et al. 2000).

Saturated hydraulic conductivity was calculated using Equation (2-1)

$$K_{sat} = \left[\frac{a \cdot l}{A(t_2 - t_1)} \right] \ln \left(\frac{h_1}{h_2} \right) \quad \text{Equation 2-1}$$

where K_{sat} is saturated hydraulic conductivity (m/s), a is surface of falling water (m²), l is thickness of the sludge layer (m), A is the sludge surface (m²), t_1 and t_2 are the beginning and end test times respectively, h_1 and h_2 are initial and final water column height.

2.3.4 Analytical methods

Homogenized sludge samples cleared from gravel and plant debris were analysed for TS and VS content and wastewater samples were tested for TSS, NH₄⁺-N, NO₃-N, BOD₅, COD, TN and TP using analysis methods in accordance with British standards (Standing Committee of Analysts (SCA, 2011)). Samples were analysed in triplicates. Differences between samples were considered to be statistically significant when the p-value was < 0.05 as determined by ANOVA test. The robustness index (RI) of the

system was calculated using data collected from online ammonia monitors and the curve-fitting modelling approach previously used by Hartshorn et al. (2015).

2.3.5 Full scale VFCW robustness

Robustness of the full-scale VFCW was accessed using curve-fit approach (Hartshorn et al., 2015). Curve fitting approach was based on the time series data analysis collected from online ammonia monitors installed on site and calculated using equation 2-2:

$$RI = \left[\left(1 - \frac{G\%}{100} \right) \times \frac{T_{90}}{T_{50}} \right] + \left[\frac{T_{90}}{T_{goal}} \times \frac{G\%}{100} \right] \quad \text{Equation 2-2}$$

where RI is system robustness index in relation to ammonia concentration in a final effluent, G% is treatment goal, T₅₀, T₉₀, T_{goal} are percentage time below the treatment goal (G%).

2.4 Results and discussion

2.4.1 Treatment in the full-scale VFCW

2.4.1.1 Full-scale system performance during the early stages of operation

Mean concentration of pollutants in the influent was $315 \pm 146 \text{ mg} \cdot \text{L}^{-1}$, $260 \pm 97 \text{ mg} \cdot \text{L}^{-1}$ and $43.1 \pm 12.8 \text{ mg} \cdot \text{L}^{-1}$ for TSS, BOD₅ and NH₄⁺-N, respectively (Table 2-2). Pollutant concentrations in the final effluent were $6.2 \pm 3.4 \text{ mg} \cdot \text{L}^{-1}$, $5.6 \pm 2.6 \text{ mg} \cdot \text{L}^{-1}$ and $5.8 \pm 3.8 \text{ mg} \cdot \text{L}^{-1}$ for TSS, BOD₅ and NH₄⁺-N, respectively. Treatment efficiency for TSS, BOD₅ and NH₄⁺-N was 79.2%, 79.9% and 30.4% for first stage and 98.1%, 97.7% and 86.8% on the second stage. The performance of the young UK system was comparable to that reported by Paing et al. (2015) for 169 sites operated in France. The global removal efficiencies for TSS and BOD₅ of 98.1% and 97.7% observed

during the studied period corresponds with values reported in literature for French systems of 96% and 98% TSS and BOD₅ removal, respectively. The ammonia level of $5.8 \pm 3.8 \text{ mg}\cdot\text{L}^{-1}$ translates in an overall ammonia removal efficiency of 86.8%, compared to 5 mg/L ammonia (92% removal efficiency) in French systems (Table 2-2).

Table 2-2 Comparison of treatment performance of two stage VFCWs operated in the UK (1st operational year, composite sampling) (Gomez 2016) and France (survey completed for 169 sites with HL under 0.6 m·d⁻¹). Data for systems operated in France are extracted from Paing et al., (2015).

	(mg·L ⁻¹)	TSS	BOD ₅	COD	NH ₄ ⁺ -N	NO ₃ ⁻ -N	TP	TSS	BOD ₅	COD	TKN	NH ₄ ⁺ -N	NO ₃ ⁻ -N	TP
		UK system						French system						
Inlet	Mean	315.5	260.4	665.9	43.1	0.81	8.7	353	360	841	94	70		12
	SD	146.4	97.1	236.6	12.8	0.47	3.3	207	159	340	27	22		4
1ststage effluent	Mean	55.8	45.8	169.1	28.1	1.6	4.5	43	46	153	35	32	31	9
	SD	20.8	17.9	59.3	7.4	2	3.3	38	43	91	18	17	36	3
	Efficiency	79.2%	79.9%	73%	30.4%		44.4%	85%	86%	80%	62%	54%		30%
2ndstage effluent	Mean	5.62	5.1	38.7	5.8	19.2	0.33	10	6	51	7	5	56	8
	SD	2.5	1.7	11.3	3.8	8	0.27	10	4	21	7	6	25	3
	Efficiency	88.4%	87.7%	74.7%	77.9%		90.8%	53%	79%	59%	78%	84%		-12%
Global efficiency	Mean	98.1%	97.7%	93.5%	86.8%		94.8%	96%	98%	93%	93%	92%		30%

A closer study of the ammonia removal efficiency based on spot sample analysis allowed evaluation of dynamic operational changes and revealed events of higher concentration of ammonia in the final effluent (Fig. 2-2) during the first year of operation. For each operational cycle, fluctuations of ammonia concentration in the final effluent were observed, with an increase of the ammonia concentration as the feeding cycle progressed and lower ammonia values on commencement of a new cycle, which matched a release of nitrates. To illustrate, an increased trend of ammonia concentration can be observed after day 43 when the concentration increased from 11.5 mg.L⁻¹ to 13.4 mg.L⁻¹ on day 45 and dropped to 0.6 mg.L⁻¹ on day 47 on start of a new cycle when a nitrate release of 23.6 mg.L⁻¹ was recorded. A similar pattern could be observed up to day 108. After this point the surface of the second stage wetlands was scrapped to resolve ponding episodes on the second stage, which were believed to be attributed to the beds blinding as a result of solids deposition on their surface. The maximum ammonia concentration observed before scrapping was 18.9 mg.L⁻¹ on day 99 of operation. The pattern in ammonia concentration fluctuation with feed/rest cycle corresponds to pathways reported in the literature with adsorption of ammonia by the biofilm during feeding and nitrification during resting with further nitrates flushing from the treatment beds with the next feeding event (Boutin and Lienard 2010). A tertiary bio-filter was in place as a supporting unit to ensure safe ammonia concentrations in the final effluent during start-up period.

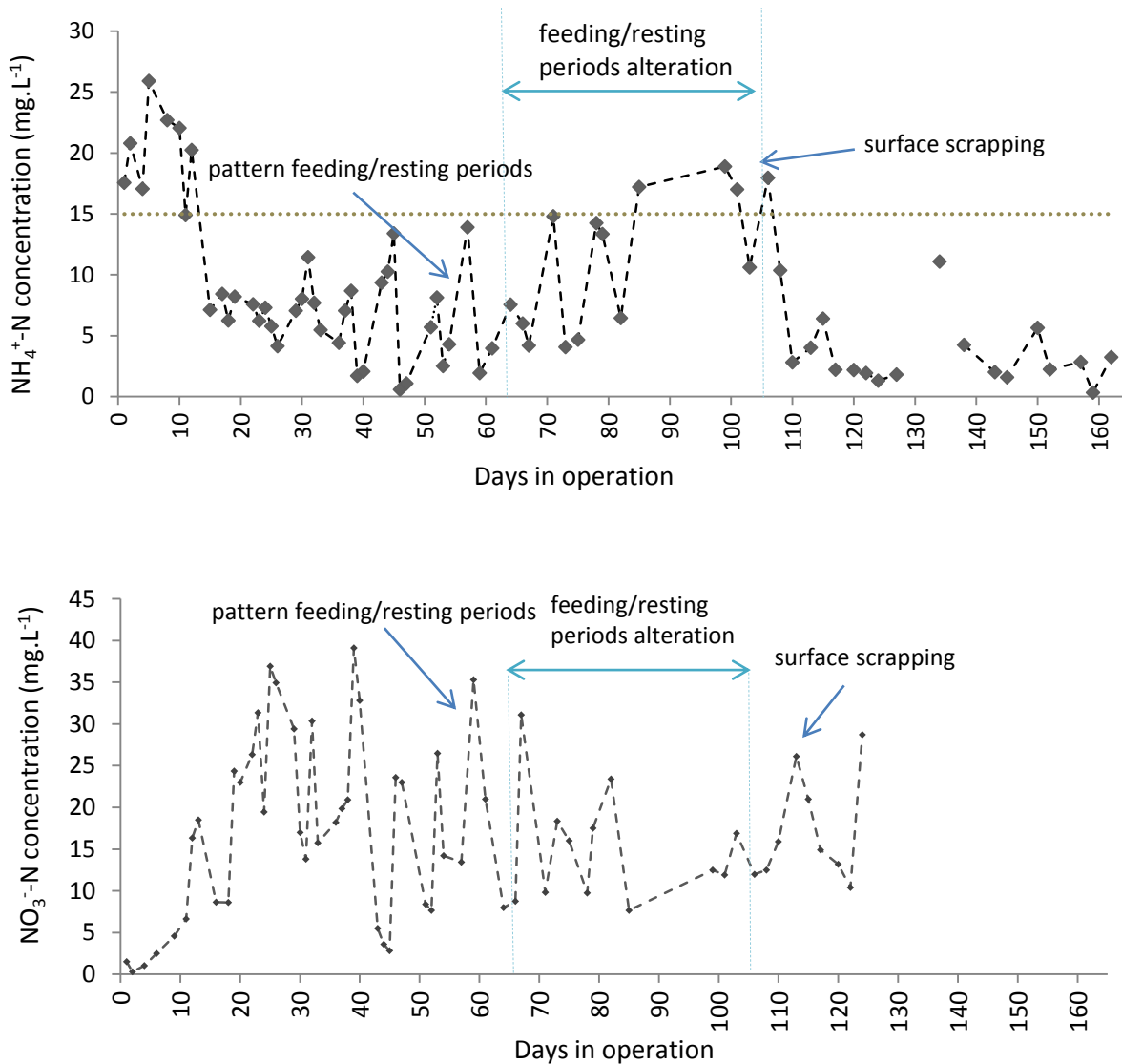


Figure 2-2 Evolution of $\text{NH}_4^+\text{-N}$ (a) and $\text{NO}_3^-\text{-N}$ concentration on spot samples in the effluent of the second stage of a two stage VFCWs system (adapted from (Gomez, 2016)).

Data collected from online monitors was grouped by age of the system and by HL allowing to evaluate treatment efficiency when the system operated under HL below designed value $<0.4 \text{ m}\cdot\text{d}^{-1}$, under HL close to designed value $0.4 < \text{HL} < 0.6 \text{ m}\cdot\text{d}^{-1}$, and operation under $\text{HL} > 0.6 \text{ m}\cdot\text{d}^{-1}$ which corresponds to storm events. The system was observed to operate with $\text{HL} < 0.4 \text{ m}\cdot\text{d}^{-1}$ for 85% of the operational time, and with overloading events ($\text{HL} > 0.6 \text{ m}\cdot\text{d}^{-1}$) accounting for less than 6% of the time (Fig 2-3 a).

In terms of the system ageing, treatment efficiency changed significantly ($p < 0.05$) after one year of operation and remained at the same level afterwards. Ammonia concentration in the final effluent within the group of $HL < 0.4 \text{ m}\cdot\text{d}^{-1}$ was $3.4 \pm 2.2 \text{ mg}\cdot\text{L}^{-1}$, $2.6 \pm 1.4 \text{ mg}\cdot\text{L}^{-1}$ and $1.9 \pm 1.7 \text{ mg}\cdot\text{L}^{-1}$ for the first, second and third operational years respectively. When the system treated wastewater under HL close to the design value, the ammonia concentration changed from $4.4 \pm 2.8 \text{ mg}\cdot\text{L}^{-1}$ to $1.7 \pm 1.9 \text{ mg}\cdot\text{L}^{-1}$ and $2.0 \pm 1.1 \text{ mg}\cdot\text{L}^{-1}$ over three operational years. Under high HL ($> 0.6 \text{ m}\cdot\text{d}^{-1}$) a mean ammonia concentration in the final effluent of $3.1 \pm 2.0 \text{ mg}\cdot\text{L}^{-1}$, $1.7 \pm 1.9 \text{ mg}\cdot\text{L}^{-1}$ and $1.9 \pm 2.6 \text{ mg}\cdot\text{L}^{-1}$ was observed during the first three years of operation. During the first and second operational years the system performance was significantly impacted by HL (with $p < 0.05$ ANOVA test) as opposite to the third operational year when no statistically significant impact of HL on ammonia concentration in final effluent was observed (Fig. 2-3 (b) and (c)) (with $p > 0.5$ ANOVA test). In relation to solids removal no statistically significant changes were observed on final effluent turbidity with site ageing except with low HL ($< 0.4 \text{ m}\cdot\text{d}^{-1}$) when turbidity of the final effluent was as high as $13.75 \pm 23.01 \text{ FTU}$ during the first operational year and dropped to $2.18 \pm 2.64 \text{ FTU}$ and $1.95 \pm 2.04 \text{ FTU}$, respectively, during 2nd and 3rd year (Fig. 2-3 c).

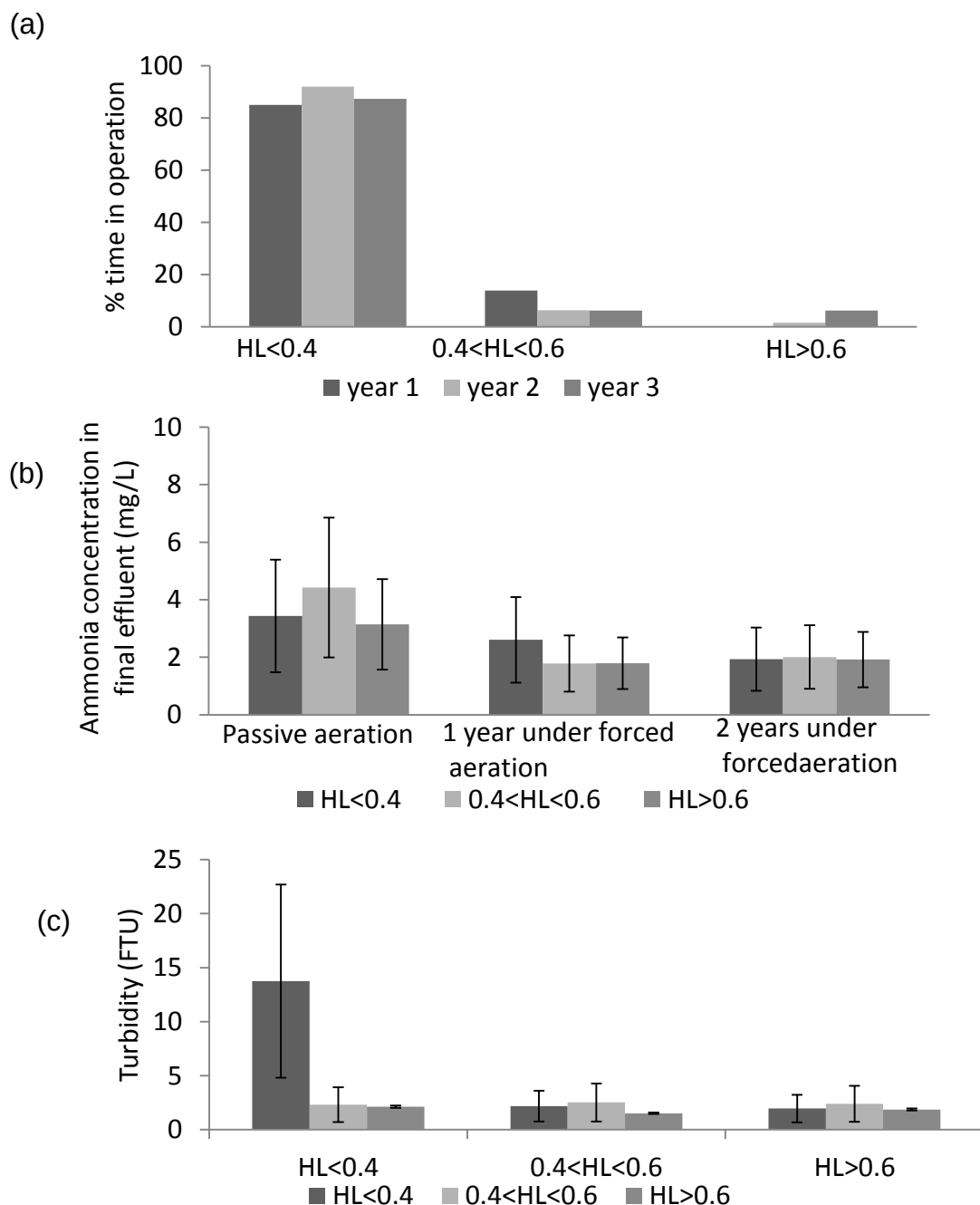


Figure 2-3 HL distribution over three years of the system operation. Treatment performance evolution in relation to ammonia concentration in final effluent (b) and turbidity of the final effluent (c).

The higher ammonium concentration in the final effluent recorded during the first operational year can be caused by several factors. Ponding occurred on the second stage filters until the sixth month of operation, hindering oxygen promotion, which in turns decreases nitrification efficiency and leads to increasing ammonia concentration.

Ponding on the first stage filters was also observed, with untreated wastewater bypassing the primary treatment and increasing organic and solids load onto the second stage. Another possible reason for the higher ammonia concentration during the early stages of the system operation is the lack of or poorly developed sludge layer, which when present increases water retention time and improves treatment performance (Molle 2014). A poor development of the sludge layer may also be linked to the higher turbidity levels on the primary treated wastewater during the first operational year (Table 2-2), since a developed sludge layer provides additional filtration on the first stage and decreases solids carry over to a second stage, hence avoiding blinding of the second stage filters and higher turbidity of the final effluent.

2.4.1.2 Impact of forced aeration on process performance

To mitigate against blinding which occurred on the first operational year on the second stage filters and to enhance ammonia removal when the system received high loads (untreated wastewater by-passing from the first stage) the second stage filter beds were retrofitted with forced aeration. To reflect the impact of forced aeration on the system performance the data was grouped as follows: 1st year of operation, which includes the start-up period with passive aeration of the second stage (December 2015 – December 2016); 2nd year operation with forced aeration of the second stage bed (December 2016 – December 2017), and 3rd year of operation with the second stage being forced aerated during two years (December 2017 - December 2018). Forced aeration implementation allowed to achieve higher ammonia removal. Thus 95 percentile ammonia concentration in the final effluent during the first year of operation (passive aeration by batch feeding) of 9.6 mg·L⁻¹ was observed. After the forced aeration started the system performance improved with 95th percentile ammonia

concentration in the final effluent dropped to $5.3 \text{ mg}\cdot\text{L}^{-1}$. Further study of the impact of forced aeration on the system performance was done with consideration of HL on the system. During the first year of operation, ammonia concentrations in the final effluent of $3.43 \pm 2.27 \text{ mg}\cdot\text{L}^{-1}$, $3.23 \pm 2.71 \text{ mg}\cdot\text{L}^{-1}$ and $3.14 \pm 2.01 \text{ mg}\cdot\text{L}^{-1}$ for $\text{HL} < 0.4 \text{ m}\cdot\text{d}^{-1}$, $0.4 < \text{HL} < 0.6 \text{ m}\cdot\text{d}^{-1}$, and $\text{HL} > 0.6 \text{ m}\cdot\text{d}^{-1}$, respectively, were recorded (Fig. 2-3 b). A significant (p value < 0.05) drop in ammonia concentration in the final effluent was achieved after installation of forced aeration with values of $1.93 \pm 1.79 \text{ mg}\cdot\text{L}^{-1}$, $0.52 \pm 1.09 \text{ mg}\cdot\text{L}^{-1}$ and $1.92 \pm 2.62 \text{ mg}\cdot\text{L}^{-1}$ for $\text{HL} < 0.4 \text{ m}\cdot\text{d}^{-1}$, $0.4 < \text{HL} < 0.6 \text{ m}\cdot\text{d}^{-1}$, and $\text{HL} > 0.6 \text{ m}\cdot\text{d}^{-1}$ respectively. These results confirmed the positive impact of forced aeration on treatment performance. Turbidity levels of $13.5 \pm 23.01 \text{ FTU}$ were observed for HL above $0.4 \text{ m}\cdot\text{d}^{-1}$ during the first year of operation, while values of 2.3 ± 2.64 and 2.12 ± 2.00 were recorded for $0.4 < \text{HL} < 0.6 \text{ m}\cdot\text{d}^{-1}$ and $\text{HL} > 0.6 \text{ m}\cdot\text{d}^{-1}$. A more consistent effluent quality based on turbidity levels was observed during the second and third year of operation when forced aeration started, with levels of $2.3 \pm 2.64 \text{ FTU}$ regardless of HL. Where passive re-oxygenation is insufficient for complete nitrification, forced aeration of CWs can provide enhanced organic matter removal and nitrification. Aeration tubes installation in pilot scale VFCWs treating $0.195 - 0.439 \text{ m}\cdot\text{d}^{-1}$ allowed reaching 67.9% and 69.7% removal for TKN and $\text{NH}_4^+\text{-N}$, respectively, compared to 44.7% and 43.5% for TKN and $\text{NH}_4^+\text{-N}$, respectively, for not aerated VFCWs (Stefanakis and Tsihrintzis, 2012). A positive impact of forced aeration was also reported for horizontal flow CWs used for tertiary treatment. Ammonia removal efficiency in non-aerated wetlands was reported as 13% whereas 99% mass removal was achieved on the same full-scale site operated under forced aeration. The positive impact of forced aeration was also observed in the final effluent TSS concentration of aerated CWs with $14 \pm 9 \text{ mg}\cdot\text{L}^{-1}$ comparing to $22 \pm 11 \text{ mg/L}$ in control tests, and BOD_5

of $4 \pm 3 \text{ mg O}_2\cdot\text{L}^{-1}$ for the aerated bed and $7 \pm 6 \text{ mg O}_2\cdot\text{L}^{-1}$ obtained in the control bed (Butterworth et al. 2013).

The full-scale site was subjected to variable loads and flows, which makes important understanding the technology's robustness under these operational conditions. Robustness index (RI) determined for each operational year proved the system to be robust ($\text{RI} < 1$) against the current ammonia treatment goal of $15 \text{ mg}\cdot\text{L}^{-1}$, with RI of 0.46, 0.36 and 0.3 for the 1st, 2nd and 3rd year of operation, respectively. For further evaluation of system stability operated under tighter consents a curve-fitting approach (Hartshorn et al. 2015) was implemented. The robustness curves showed that the system with passive aeration on the second stage was capable to remain robust meeting consent of $7.5 \text{ mg}\cdot\text{L}^{-1}$ ammonia. Implementation of forced aeration on the second stage improved system robustness and allowed to achieve tighter consent of $5.5 \text{ mg}\cdot\text{L}^{-1}$.

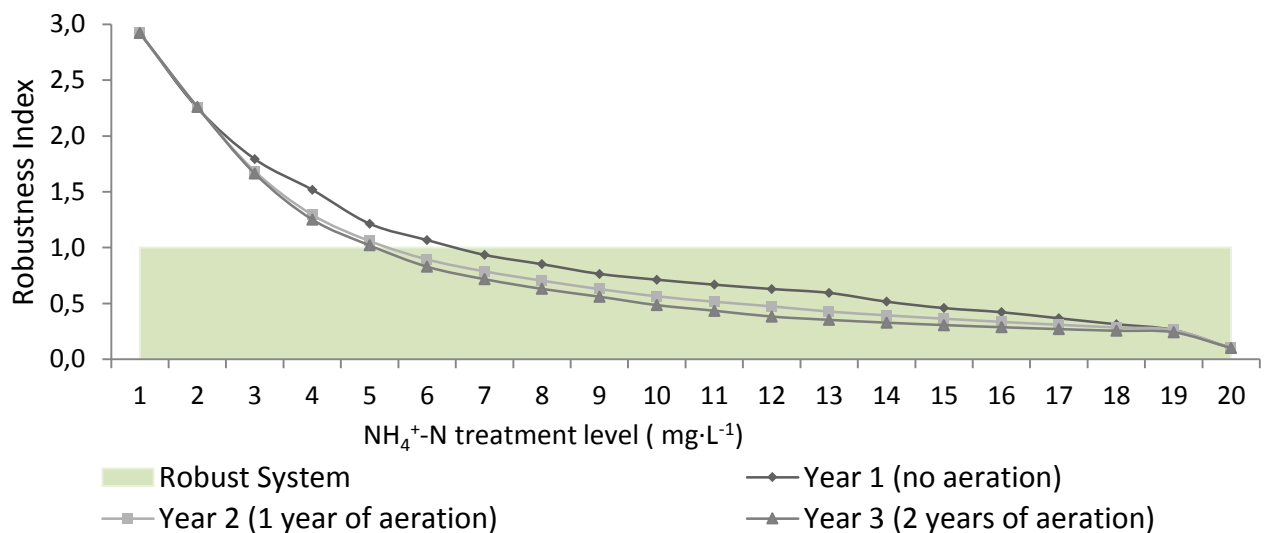


Figure 2-4 Robustness curve of the studied system over three years with RI calculated against consent range from $1 \text{ mg}\cdot\text{L}^{-1}$ to $20 \text{ mg}\cdot\text{L}^{-1}$ ammonia concentration in the final effluent.

2.4.2 Evolution of the first stage filters

Site treatment performance was heavily influenced by the hydraulic characteristics of the first stage filter beds. During the first year of operation the first stage filters were found to be hydraulically limited, with frequent prolonged ponding episodes compromising the recommended 8.5 hours (López 2013) to 12 hours (Molle et al. 2006) of water free surface. These ponding events in turn limited the system's re-oxygenation, negatively impacting treatment performance and sludge layer mineralization. Furthermore, the low infiltration rate (IR) observed on the first stage filters led to wastewater overflowing to the second stage beds, which increased load on the secondary treatment. Previous studies investigating sludge drying reed beds (SDRB) reported occurrence of ponding and anaerobic conditions to have a negative impact on sludge layer properties, causing formation of impermeable layers and decreasing overall hydraulic acceptance of the beds (Dominiak et al. 2011). Sludge layer on the first stage filter beds is known to be hydraulically limiting (Molle 2014), although its properties and their changes during VFCW maturing is not well studied to date. In the current study sludge characteristics such as TS, VS, height and HC of the full-scale primary wetlands were monitored during the first three years of operation, which were then evaluated within the context of treatment performance.

2.4.2.1 Visual observations of the first stage beds evolution

On the early stages of system operation (first two years) development of the *Phragmites australis* reeds was uneven and some areas with dead or poorly developed reeds were observed (Table 2-3, Fig. 2-5a), mainly around feeding points and close to the beds' edges. Positive changes were observed in October 2018 (3rd operational year) when the overall density of reeds was higher across the beds (Table

2-3) and they were observed to follow the natural reed cycle with predominantly dormant reeds (Table 2-3, Fig. 2-5b). No preferential flow pathways (PFP) were present on the first operational year and development of voids around the reed stems and cracks on the sludge layer were observed in the second operational year. Part of the PFPs observed in the sludge layer were made by plant debris (Fig. 2-6a). The amount of litter on the first stage beds was relatively low considering the treatment of unscreened wastewater, with some plastics and sanitary products found around feeding points (Fig. 2-6 b).

Occurrence of PFPs was in accordance with previous literature on wastewater treatment reed beds (López 2013; Molle 2014) and sludge drying reed beds (Brix 2017), which reported PFPs to have a positive impact on the beds permeability. Cracks formation in planted beds is typically linked to plant movements due to wind, although they can also be linked to tension occurrence (Marklund 1997; Singh et al. 2009), consolidation (Barua 2014) and wetting-drying cycles (Tang et al. 2011).

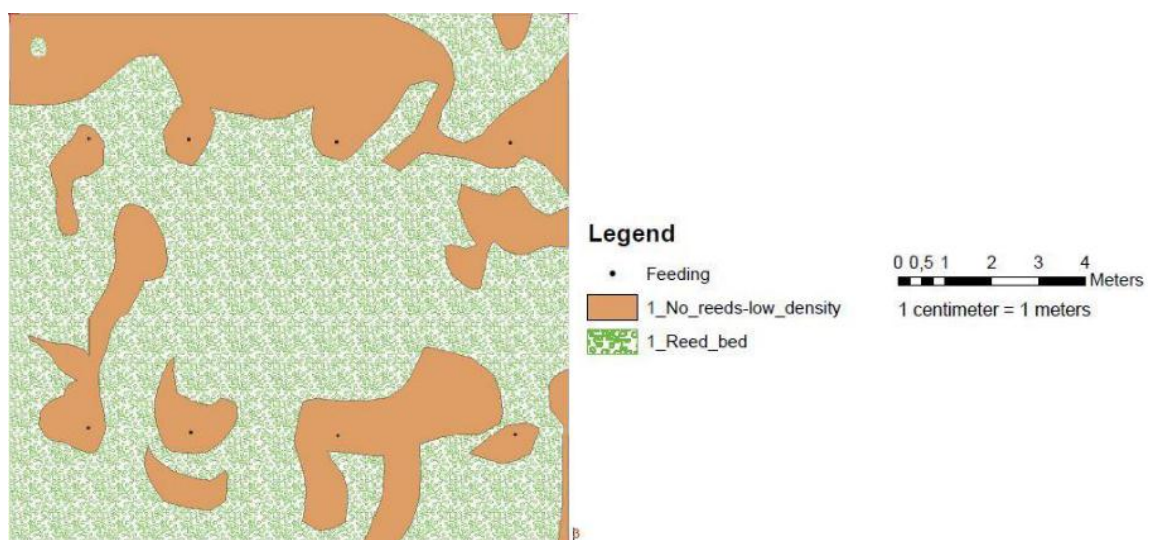


Figure 2-5 Reed health on the first stage bed №1. Reeds development on the second year of operation (May 2017).

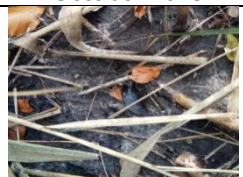
(a)

(b)



Figure 2-6 Beds development on the first stage bed №2: reed debris in the sludge layer (a), litter accumulation on the bed surface (b).

Table 2-3 Visual evolution of the 1st stage filter beds

		Overall bed health		Beginning		End	
		May 2017	October 2018	May 2017	October 2018	May 2017	October 2018
1 st stage bed №1	Feeding period						
1 st bed №2							
1 st bed №3							
		Beginning		Middle		End	
		May 2017	October 2018	May 2017	October 2018	May 2017	October 2018
1 st stage bed №1	Resting period						
1 st bed №2							
1 st bed №3		Not available		Not available			

2.4.2.2 Evolution of sludge layer properties during the operational cycle

TS content of the sludge layer almost doubled between the first and third operational years, from $11.5 \pm 2\%$ to $20.4\% \pm 3\%$ and VS content decreased from $64 \pm 7\%$ to $62 \pm 3\%$. The sludge layer accumulation rate was higher during the first operational year when the sludge layer height reached 5 cm after 6 months of operation and was expected to reach 15 cm after 3 years of operation. However only 5-6 cm thickness was recorded in the 3rd operational year. HC was found to be below $5.7 \times 10^{-6} \text{ m}\cdot\text{s}^{-1}$ and $1 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$ (Table 2-4) on the first and second operational years, respectively, when continuous ponding on the first stage filter beds was observed (Table 2-4), and improved to $4.9 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$ on the third year with no ponding observed even during storm events (October 2018).

Table 2-4 Comparison of sludge layer characteristics of the UK two-stage VFCW and French systems.

Time in operation	Sludge layer height (cm)	TS (%)	VS (%)	HC ($\text{m}\cdot\text{s}^{-1}$)
UK site				
6 months	3-5	11.5 ± 2	64.5 ± 7	$<5.7 \times 10^{-6*}$
2 years	4-13	12.3 ± 7	75.5 ± 7	$<1 \times 10^{-5*}$
3 years	5-6	$20.4\% \pm 3$	$62.3\% \pm 3$	$<4.9 \times 10^{-5*}$
French sites				
Site A (1 year) (López 2013)	n/a	n/a	n/a	$1\text{E-}5$
Site B (1 year) (Molle et al. 2006)	1	n/a	n/a	$>3.6\text{E-}4$

* HC reported for the last day of resting period reflecting the highest value achieved.

During the first year the first stage beds were operated with 3.5 days feeding and 7 days resting period lengths, equivalent to common values reported in literature (Morvannou et al. 2015; Paing et al. 2015). However, lower HC than reported for similar young systems operated in France were recorded with values $<5.7 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$ comparing to $1 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$ (López 2013) and $>3.6 \times 10^{-4} \text{ m}\cdot\text{s}^{-1}$ (Molle et al. 2006) for similar systems. The feeding/resting period length was changed to 5/10 days on the second operational year to allow greater time for mineralization of deposited organic matter and recovery of HC during the resting period. HC improved to $<1 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$ although ponding was still observed. A feed and rest cycle of 7 and 14 days, respectively, was adopted from the third year of operation which improved sludge layer mineralization and increased HC of the beds. The HC on the third year of operation was $<4.9 \times 10^{-4} \text{ m}\cdot\text{s}^{-1}$, which is close to previously reported data for a young system operated in France for 1 year ($>3.6 \times 10^{-4} \text{ m}\cdot\text{s}^{-1}$) (Molle et al. 2006).

Closer investigation of sludge layer characteristics over the operational cycle showed that sludge layer recovery slows down after the 7th day of the resting period (Fig. 3-7). TS of 24%, VS of 65% and HC of $5.3 \times 10^{-4} \text{ m}\cdot\text{s}^{-1}$ were recorded on the 7th day of resting period with further fluctuation of the values which may have been caused by weather conditions (TS), uneven distribution of the organic matter plant debris in the sludge layer (VS) and PFPs presence in the tested area (HC). The observation allows suggesting that the length of the resting and feeding period may be safely changed to the initial strategy recommended for VFCWs which is 3.5/7 days. The resting period of 7 days is enough for sludge layer to mineralize and the shortened feeding period allows a lower loading on the bed within a cycle.

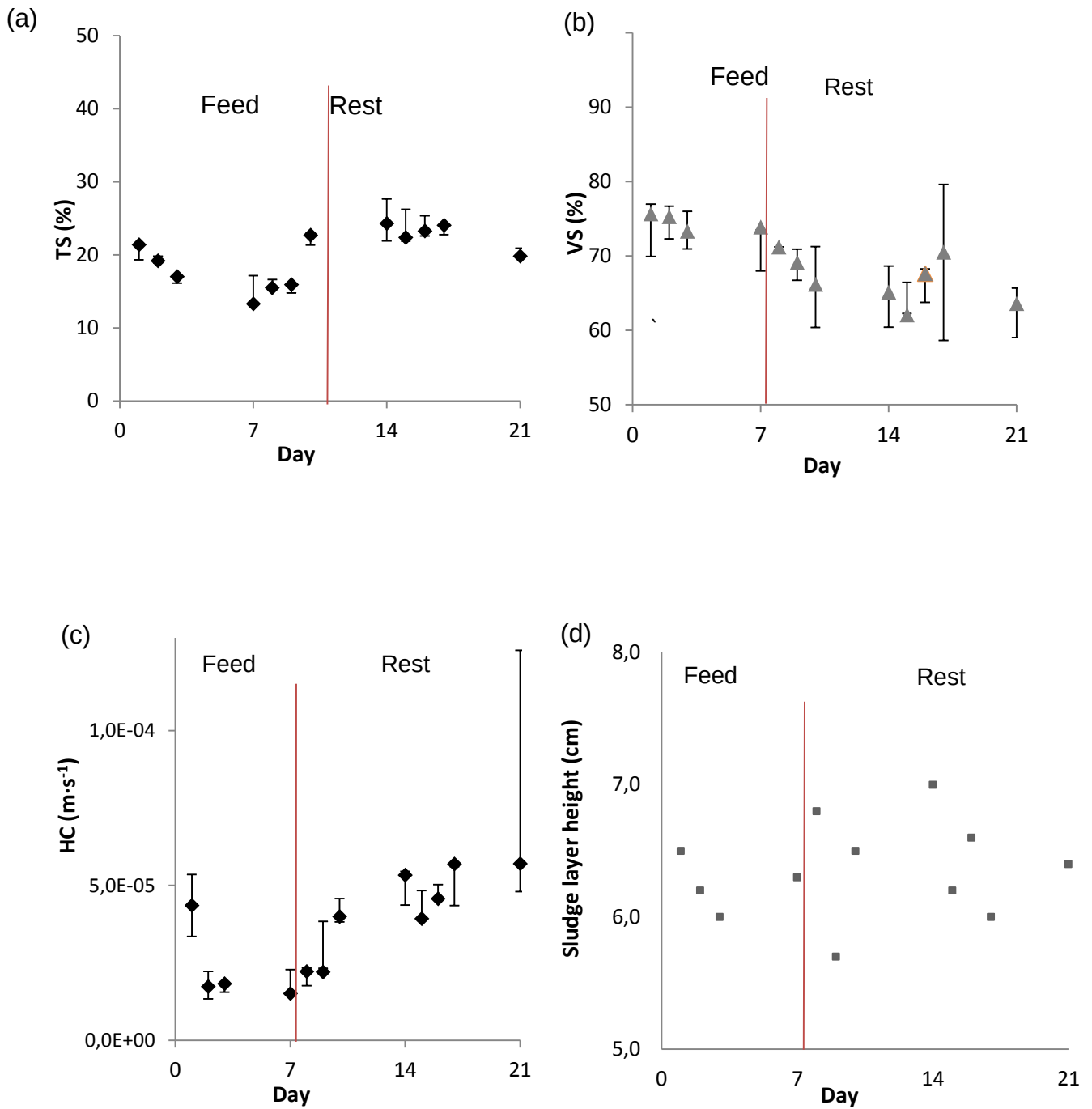


Figure 2-7 Evolution of TS (a) and VS content (b), HC (c), and sludge layer height (d) over the operational cycle of bed N°2 for 3rd year of operation.

The sludge accumulation rate of up to 7 cm/year observed during the first year of operation would mean that the critical sludge layer of 10-15 cm recommended for desludging (Molle et al. 2005) would be reached after 2-3 years of operation. However,

after 3 years of operation sludge accumulation rate dropped to 2 cm/year corresponding with values reported in literature for similar systems (Paing et al. 2015) and increasing the estimated operational time before desludging to 10 years. The lower sludge accumulation rate on the third operational year was attributed to an improved mineralization rate of the sludge layer when ponding on the first stage filter beds stopped and PFPs were formed, hence enhancing oxygen promotion to the sludge layer.

2.5 Conclusion

The first UK two-stage VFCW site achieved a treatment performance similar to that reported in literature for French sites. Global treatment efficiency of the UK site based on composite sample analysis was 98.1% and 97.7% for TSS and BOD₅ removal, respectively, comparing to 96% and 98% in French systems. Ammonia removal efficiency of the UK system operated under passive aeration (86.8%) was lower than for French sites (92%), although similar ammonia effluent concentrations of $5.8 \pm 3.8 \text{ mg}\cdot\text{L}^{-1}$ (comparing to $5 \pm 6 \text{ mg}\cdot\text{L}^{-1}$, in literature) were recorded. Implementation of forced aeration of the second stage filter beds improved treatment performance, allowing a 95th percentile ammonia concentration of $5.3 \text{ mg}\cdot\text{L}^{-1}$ compared to $9.6 \text{ mg}\cdot\text{L}^{-1}$ when passive aeration was used.

Modification of the rotational period's length is recommended to mitigate against hydraulic limitation on the first stage filter beds during the start-up period; and must be done with consideration of system age and sludge layer properties. Longer rotation periods with up to 14 days resting are required for young systems while resting periods beyond 7 days after three years of operation do not benefit sludge layer evolution. Sludge layer after three years of operation was characterised by TS, VS content and

HC of 14%, 65% and $5.3 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$, respectively. These sludge layer characteristics are close to values reported in the literature for mature systems with no hydraulic limitations of the first stage filter beds. Two-stage VFCWs have been proved to be a successful wastewater treatment solution in the UK, with up to three years required for maturation of the first stage beds.

Pollutant concentration in the final effluent was $6.2 \pm 3.4 \text{ mg}\cdot\text{L}^{-1}$, $5.6 \pm 2.6 \text{ mg}\cdot\text{L}^{-1}$ and $5.8 \pm 3.8 \text{ mg}\cdot\text{L}^{-1}$ for TSS, BOD₅ and NH₄⁺-N, respectively.

2.6 References

- Angulo-Jaramillo R., J. P. Vandervaere, S. Roulier, J. L. Thony, J. P. Gaudet, and M. Vauclin. 2000. "Field Measurement of Soil Surface Hydraulic Properties by Disc and Ring Infiltrimeters: A Review and Recent Developments." *Soil and Tillage Research* 55(1–2):1–29.
- Arias L., J. Luis. 2013. "Vertical-Flow Constructed Wetlands for the Treatment of Wastewater and Stormwater from Combined Sewer Systems Traitement Des Eaux Résiduelles de Temps Sec et Temps." PhD Thesis, L'Institut National des Sciences Appliquées de Lyon.
- Arias L., J. Luis, J. L. Bertrand-Krajewski, and P. Molle. 2014. "Simplified Hydraulic Model of French Vertical-Flow Constructed Wetlands." *Water Science and Technology* 70(5):909–16.
- Baroutian, S., N. Eshtiaghi, and D. J. Gapes. 2013. "Rheology of a Primary and Secondary Sewage Sludge Mixture: Dependency on Temperature and Solid Concentration." *Bioresource Technology* 140 (May) :227–33.
- Barua, A. 2014. "Experimental study of filter cracking." PhD Thesis, Imperial College of Science, Technology and Medicine.

- L. Bennamoun, P. Arlabosse, and Angélique Léonard. 2013. "Review on Fundamental Aspect of Application of Drying Process to Wastewater Sludge." *Renewable and Sustainable Energy Reviews* 28:29–43.
- Bourcier, D., J. P. Féraud, D. Colson, K. Mandrick, D. Ode, E. Brackx, and F. Puel. 2016. "Influence of Particle Size and Shape Properties on Cake Resistance and Compressibility during Pressure Filtration." *Chemical Engineering Science* 144:176–87.
- C. Boutin, A. Lienard. Constructed wetlands for wastewater treatment: the French experience. *1st international seminar on the use of aquatic macrophytes for wastewater treatment in constructed wetlands*, May 2003, Lisbonne, Portugal. p. 437 - p. 466.
- ffhal-00508191fBrix, Hans. 2017. "Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds." *Water (Switzerland)* 9(3).
- Butterworth, E., G. Dotro, M. Jones, A. Richards, P. Onunkwo, Y. Narroway, and B. Jefferson. 2013. "Effect of Artificial Aeration on Tertiary Nitrification in a Full-Scale Subsurface Horizontal Flow Constructed Wetland." *Ecological Engineering* 54:236–44.
- Christensen, M., K. Keiding, P. Nielsen, and M. Jørgensen. 2015. "Dewatering in Biological Wastewater Treatment: A Review." *Water Research* 82:14–24.
- Cleverson V. A., Marcos von Sperling and F. Fernandes (Editors). 2007. *Sludge Treatment and Disposal*. IWA Publishing
- Coombs P. , Wagner D. , Bateman K., Harrison H., Milodowski A. E., Noy D., West J. M. 2010. "The Role of Biofilms in Subsurface Transport Processes." *Quarterly Journal of Engineering Geology and Hydrogeology* 43(2):1–14.
- Dominiak, D., M. L. Christensen, K. Keiding, and P. Nielsen. 2011. "Sludge Quality Aspects of Full-Scale Reed Bed Drainage." *Water Research* 45(19):6453–60.

- Dominiak, D. M. (2010). Drainage properties of activated sludge. (1 ed.) Aalborg Universitet: Institut for Kemi, Miljø og Bioteknologi, Aalborg Universitet. Dotro, Gabriela, Günter Langergraber, Pascal Molle, Jaime Nivala, Jaume Puigagut, Otto Stein, Marcos Von, and Sperling Volume. 2017. *Treatment Wetlands*. Vol. 7. IWA Publishing.
- Easton, Z. M. and E. Bock. 2016. "Soil and Soil Water Relationships." *Virginia Cooperative Extension* 1–9.
- Eriksson, L. and B. Alm. 1991. "Study of Flocculation Mechanisms by Observing Effects of a Complexing Agent on Activated Sludge Properties." *Water Science and Technology* 24(7):21–28.
- Frølund, B., R. Palmgren, K. Keiding, and P. Nielsen. 1996. "Extraction of Extracellular Polymers from Activated Sludge Using a Cation Exchange Resin." *Water Research* 30(8):1749–58.
- Giuseppe G., D. Chiarani, D. P. Saroj, G. Andreottola. 2010. "Sludge Filterability And Dewaterability In A Membrane Bioreactor For Municipal Wastewater Treatment." : : *Desalination* 250:1–9.
- Gomez, L.. 2016. "Vertical Flow Constructed Wetland for Treating Unscreened Sewage in the UK." MSc By Research thesis, Cranfield university.
- Hartshorn, A. J., G. P., A. Upton, J. Macadam, B. Jefferson, and P. Jarvis. 2015. "Assessing Filter Robustness at Drinking Water Treatment Plants." *Water and Environment Journal* 29(1):16–26.
- H. Mikkelsen, K. Keiding. 1999. "Equilibrium Aspects of the Effects of Shear and Solids Content on Aggregate Deflocculation." *Advances in Colloid and Interface Science* 80(2):151–82.
- Hsu, Jyh-ping, Tao Tao, Ay Su, Arun S. Mujumdar, and Duu-jong Lee. 2010. "Model

- for Sludge Cake Drying Accounting for Developing Cracks Developing Cracks.”
Drying Technology, 28: 922–926, 2010.
- Hua, G. F., Z. W. Zhao, J. Kong, R. Guo, and Y. T. Zeng. 2014. “Effects of Plant Roots on the Hydraulic Performance during the Clogging Process in Mesocosm Vertical Flow Constructed Wetlands.” 13017–26.
- Jin, Bo, B. Marie Wilén, and P. Lant. 2004. “Impacts of Morphological, Physical and Chemical Properties of Sludge Flocs on Dewaterability of Activated Sludge.” *Chemical Engineering Journal* 98(1–2):115–26.
- Kahl, S., J. Nivala, Manfred van Afferden, R. A. Müller, and T. Reemtsma. 2017. “Effect of Design and Operational Conditions on the Performance of Subsurface Flow Treatment Wetlands: Emerging Organic Contaminants as Indicators.” *Water Research* 125:490–500.
- Kusnierz, M. and P. Wiercik. 2016. “Analysis of Particle Size and Fractal Dimensions of Suspensions Contained in Raw Sewage, Treated Sewage and Activated Sludge.” *Archives of Environmental Protection* 42(3):67–76.
- Li, Wenping, C. Kiser, Q. Richard 2005. “Paper Presented at the American Filtration & Separations Society 2005 International Topical Conferences & Exposition, September 19-22, Ann Arbor, Michigan.” Pp. 1–9 in *Development of A Filter Cake Permeability Test Methodology*.
- Liu, Hong and Herbert H. P. Fang. 2002. “Extraction of Extracellular Polymeric Substances (EPS) of Sludges.” *Journal of Biotechnology* 95(3):249–56.
- Markis, F, K. Hii, R. Parthasarathy, J. C. Baudez, Paul Slatter, and Nicky Eshtiaghi. 2013. “Rheological Characterisation of Blends of Primary and Secondary Sludge.” *Soft Matter* 500.
- Marklund, S. 1997. “Dewatering of Wastewater Sludge by Natural Air Drying.”

- Mikkelsen, L. and K. Keiding. 2002. "Physico-Chemical Characteristics of Full Scale Sewage Sludges with Implications to Dewatering." *Water Research* 36(10):2451–62.
- Molle, P., A. Liénard, A. Grasmick, and A. Iwema. 2006. "Effect of Reeds and Feeding Operations on Hydraulic Behaviour of Vertical Flow Constructed Wetlands under Hydraulic Overloads." *Water Research* 40(3):606–12.
- Molle, P. 2005. "French Vertical Flow Constructed Wetlands : Design for Storm Event Acceptance."
- Molle, P. 2014. "French Vertical Flow Constructed Wetlands: A Need of a Better Understanding of the Role of the Deposit Layer." *Water Science and Technology* 69(1):106–12.
- Molle, P, A. Liénard, C. Boutin, G. Merlin, and A. Iwema. 2005. "How to Treat Raw Sewage with Constructed Wetlands: An Overview of the French Systems." *Water Science and Technology* 51(9):11–21.
- Morvannou, A., N. Forquet, S. Michel, S. Troesch, P. Molle, A. Morvannou, N. Forquet, S. Michel, S. Troesch, and P. Molle Treatment. 2015. "Treatment Performances of French Constructed Wetlands : Results from a Database Collected over the Last 30 Years" *Water Sci Technol.* 2015;71(9):1333-9
- Morvannou, A., N. Forquet, M. Vanclooster, and P. Molle. 2013. "Characterizing Hydraulic Properties of Filter Material of a Vertical Flow Constructed Wetland." *Ecological Engineering* 60:325–35.
- Nivala, J., Manfred van Afferden, R. Hasselbach, G. Langergraber, P. Molle, H. Rustige, and J. Nowak. 2018. "The New German Standard on Constructed Wetland Systems for Treatment of Domestic and Municipal Wastewater." *Water Science and Technology* 2414–26.

- Olboter, L. and A. Vogelpohl. 1993. "Influence of Particle Size Distribution on the Dewatering of Organic Sludges." *Water Science and Technology* 28(1):149–57.
- Paing, J., A. Guilbert, V. Gagnon, and F. Chazarenc. 2015. "Effect of Climate, Wastewater Composition, Loading Rates, System Age and Design on Performances of French Vertical Flow Constructed Wetlands: A Survey Based on 169 Full Scale Systems." *Ecological Engineering* 80:46–52.
- Singh, K. B., Laxman R. Bhosale, and Mahesh S. Tirumkudulu. 2009. "Cracking in Drying Colloidal Films of Flocculated Dispersions." 25(9):4284–87.
- Standing Committee of Analysts (SCA). 2011. *Methods for the Examination of Waters and Associated Materials*. Environmental Policy and Law.
- Stefanakis, A. I. and Vassilios A. Tsihrintzis. 2012. "Effects of Loading, Resting Period, Temperature, Porous Media, Vegetation and Aeration on Performance of Pilot-Scale Vertical Flow Constructed Wetlands." *Chemical Engineering Journal* 181–182:416–30.
- Tang, Chao Sheng, Yu Jun Cui, Bin Shi, Anh Minh Tang, and Chun Liu. 2011. "Desiccation and Cracking Behaviour of Clay Layer from Slurry State under Wetting-Drying Cycles." *Geoderma* 166(1):111–18.
- Tao, T., X. F. Peng, and D. J. Lee. 2005. "Thermal Drying of Wastewater Sludge: Change in Drying Area Owing to Volume Shrinkage and Crack Development." *Drying Technology* 23(3):669–82.
- Troesch, S., F. Salma, and D. Esser. 2014. "Constructed Wetlands for the Treatment of Raw Wastewater: The French Experience." *Water Practice & Technology* 9(3):430.
- Uggetti, E., I. Ferrer, E. Llorens, and J. García. 2010a. "Sludge Treatment Wetlands: A Review on the State of the Art." *Bioresource Technology* 101(9):2905–12.

- U., Enrica, I. Ferrer, E. Llorens, and J. García. 2010b. "Sludge Treatment Wetlands: A Review on the State of the Art." *Bioresource Technology* 101(9):2905–12.
- Vladisavljevic, G.T. and Schubert, H. 2003. "Preparation of Emulsions with a Narrow Particle Size Distribution Using Microporous α -Alumina Membranes."

3 Influence of sludge layer properties on the hydraulic behaviour of gravel-based vertical flow constructed wetlands for primary treatment of sewage.

Khomenko, O.¹, Dotro, G. ¹, Jefferson, B.¹, Coulon F.¹, and Bajón Fernández, Y.^{1*}

¹ Cranfield University, School of Water, Energy and Environment, Cranfield, MK430AL, UK

*corresponding author: y.bajonfernandez@cranfield.ac.uk

3.1 Abstract

Sludge accumulation on the first stage of French design vertical flow constructed wetlands has been reported to improve treatment performance by favouring even sewage distribution on the beds' surface and increasing water retention time. However, due to its relatively low permeability, sludge layer can restrict the hydraulic capacity of the wetlands, requiring careful consideration of the feeding and resting strategy in order to avoid system ponding. This study aimed to elucidate the impact that sludge layer properties have on its permeability and investigate artificial modifications that could enhance it.

A positive impact of increased organic matter content on sludge permeability was observed, with a 3-times permeability increase for a 15 percentage points higher volatile solids content. The opposite effect was observed for total solids, where an increase of 19 percentage points led to a drop of $1.6 \times 10^{-16} \text{ m}^2$ on permeability. The impact of different surface modifications on drying kinetics and sludge layer properties was studied as a means to accelerate sludge layer mineralisation. Artificial modifications that modify surface tension of the sludge layer have been proved to achieve greater permeability and

faster mineralisation of the sludge, with potential to achieve higher hydraulic acceptance and reduced operational costs (lower sludge accumulation) if implemented in full scale vertical flow constructed wetlands.

Keywords: mineralization, organic matter, preferential flow pathways, solids, sludge permeability, vertical flow constructed wetlands

3.2 Introduction

Two stage vertical flow constructed wetlands (VFCWs) (commonly known as French design) are subsurface flow constructed wetlands (CWs) used for raw sewage treatment which are typically comprised of three CWs on the first stage and two on the second stage and are operated with cyclical flow regimes (batch feed). The first stage filter beds target the removal of total solids (TS) and partial removal of organic matter (OM) while polishing and nitrification occurs on the second stage. Since solids are removed by filtration and particles precipitation, formation of a sludge layer on the first stage filter beds takes place.

Wastewater treatment in CWs involves both physical and biological mechanisms for pollutants removal. Since OM removal and further nitrification relies on aerobic processes, effective aeration and re-oxygenation of the filter body has to be achieved for effective wastewater treatment. In VFCWs filter beds oxygenation can be achieved by operating a batch feeding strategy, where intermittent surface loading allows beds to saturate with air (Dotro et al. 2017). The minimum surface water free time recommended to ensure sufficient filter beds re-oxygenation is 6 hours per day (Nivala et al. 2018) with data reported for full-scale sites between 8.5 hours (Arias López 2013) and 12 hours (Molle et al. 2006). Extended resting periods allow further beds re-oxygenation and mineralisation of the sludge layer, with typical operating sequences of 3.5 days feed/7 days rest for the first stage beds, and 7 days feed /7 days rest for the second stage beds

(Morvannou et al. 2013; Paing et al. 2015). Mineralization of the sludge layer deposited on the surface reduces sludge layer height and allows long-term operation of the wetlands with desludging frequencies of 10 — 15 years and typical sludge deposition rates of 1-2 cm/year (Molle et al. 2006). Sludge layer mineralization is also linked to hydraulic acceptance of the filters and mineralised sludge layers with higher dry matter content have been reported to favour the hydraulic capacity of VFCWs, while very wet sludge layers with high OM content can have low permeability, which can in turn limit water percolation through the bed (Molle et al, 2005; Lópe 2013). Hydraulic limitations of the sludge layer have previously been reported to occur in young filters with improvement of hydraulic acceptance after 2-3 years of operation. This is believed to be linked to sludge layer development and evolution, which involves organic matter degradation and formation of voids and cracks which act as preferential flow pathways (PFP) and improve permeability.

Sustained periods of operation under hydraulic overloading and ponding occurrence during start up period can compromise sludge layer mineralisation because of a lack of aerobic degradation, leading to poor permeability and hydraulic conductivity within first stage filters (López 2013; Molle 2014). The vast majority of existing literature investigating the hydraulic behaviour of CWs and soils discusses reduced percolation due to (1) pores blinding by smaller particles, (2) reduced effective porosity because of permanent attachment of biofilm to the filter medium (Coombs et al. 2010), (3) reduced effective porosity because of reed roots development inside the medium pores or (4) sludge deposition on the surface bed. Available information is typically focused on the impact of clogging and reduced porosity on the VFCWs hydraulic acceptance, with very little information about the impact of the sludge layer properties (e.g. TS, OM) on the hydraulic

behaviour of the system. Samples origin and composition also vary greatly within previously available studies, making difficult to evaluate impact of single sludge layer properties.

This study aimed to shed light on the influence of the sludge layer properties on its hydraulic behaviour and the rate of PFPs formation. Artificial means to accelerate PFP formation by sludge surface modification were also investigated to evaluate the potential for reduced start-up periods and higher hydraulic acceptance of young filters. The impact of the sludge layer's TS, volatile solids (VS) and particle size distribution (PSD) on its permeability was investigated in constant head pressure filtration experiments. The rates of preferential flow pathways (PFP) formation and impact of sludge surface modifications were investigated in temperature controlled drying tests.

3.3 Materials and Methods

For determination of the sludge layer permeability constant pressure filtration test under controlled conditions was conducted on sludge samples. To study the impact of sludge layer composition in terms of VS and TS content sludge samples were modified using aeration to decrease VS content; and hence mimic sludge mineralised samples; and centrifugation for TS adjusting.

Investigation of means to enhance PFP formation was conducted by artificially modifying sludge layer surface and assessing impact on PFP formation and on sludge layer evolution. The preferential formation was studied in drying tests under controlled conditions where sludge surface changes over the time weight of the tested samples and size of the formed PFPs were recorded.

3.3.1 Sample preparation

Primary and secondary sludge were collected from a wastewater treatment plant located in the Midlands region serving a population equivalent of 2.5 million. Primary sludge was

used to replicate wetland sludge in permeability and preferential flow pathways formation tests due to similarities in their composition. Similarly to wetland sludge, primary wastewater sludge accumulates as a result of primary precipitation of biosolids and inorganic particles with typical VS content of 75% (Cleverson et al. 2007) comparing to 64 – 75% reported for young full-scale VFCWs (Gomez 2016).

The impact of VS and TS on sludge permeability was investigated using modified primary sludge to assess a range of both parameters. Aerobic degradation was employed to obtain a range of VS, for which samples were aerated by means of a diaphragm air pump (air flow 60 L/h) and two fine bubble diffusers for 5, 10, 15, and 20 days. A range of TS content was achieved by centrifugation (Sorvall Legend RT, Kendro Laboratory Products, Asheville, US) at 17206 *g* during 60 minutes and further dilution of the samples. A concentrated sample was generated and supernatant from the centrifugation step was used for dilution to avoid chemical changes in the samples.

Primary sludge with a VS content of 75% was used in the drying tests. Secondary waste activated sludge (78.3 % VS, 5% TS) distributed on the surface of the primary sludge was used as one of the artificial modifications for crack and PFP formation. Previous studies of rheological characteristics of the secondary and primary sludge and their blends showed differences in viscosity and stress yield (Baroutian et al. 2013; Markis et al. 2013) which were hypothesised to impact behaviour of the surface layer during drying.

3.3.2 Sludge layer permeability

The permeability of sludge samples was determined using a method based on Darcy's law for the flow of liquid through an already formed filter (sludge) cake (Li et al. 2005). A constant pressure filtration rig with a tube diameter of 35 mm was used for the test

(Advantec KST 47, Japan). The rig was connected to a compressed air source, which provided constant pressure of 0.4 bar in the tube (Guglielmi et al. 2010). The pressure value was recorded using a mechanical manometer (18-013-989, IMI Norgren, Birmingham, UK). A scale (Practum 3102-1S, Sartorius, Göttingen, Germany) placed under the constant pressure filtration rig allowed for the filtrate amount to be continuously recorded. The tube was loaded with a sludge layer of 5-7 mm height and filled with 0.01M KCL solution (1413 $\mu\text{S}/\text{cm}$). A KCl solution as opposed to water was used to avoid any impact of the water ionic composition and conductivity on the sludge flocs properties. Each test was run in triplicates; with the sludge sample in the infiltration rig being replaced for each replicate.

The sludge layer permeability was calculated using the equation (Li et al. 2005):

$$k = \frac{\mu \cdot Q \cdot l}{p \cdot A} \quad \text{Equation 3-1}$$

where A is filtration area, (m^2); k - permeability, (m^2); l - cake thickness, (m); P - applied pressure, (Pa); Q – total discharge over the test period, (m^3/sec); μ - viscosity, ($\text{Pa}\cdot\text{s}$).

3.3.3 Preferential flow pathways formation

In the current study formation of PFP was investigated by performing temperature controlled convective drying experiments. Thickened primary sludge (TS content of 12-14%) with and without surface modifications was used. The initial TS content of the sludge samples was adjusted to a TS content close to that reported in literature for wetland sludge, which depending on the system age varies between 8% for a system operated for < 1 year (Gomez 2016) to 26.4% for mature sites operated for > 10 years (Molle et al.

2006). A TS value closer to young VFCW was selected as the study aimed to understand mineralisation and investigate means to accelerate it. Several sludge layer modifications targeting modification of the sludge layer surface tension were applied (Table 2-1). Surface tension distribution was modified by forming initial cuts (PFP2 – PFP3) (Tao et al. 2005) on the sludge layer surface and by placing wooden cylinders of 2 mm diameter (PFP4) to mimic tension distribution in planted beds. PFP5 and PFP6 samples were modified by changing sludge rheology which defers for primary and secondary waste activated sludge (SAS) (Baroutian et al. 2013) and was hypothesised to impact surface tension hence changing sludge behaviour during drying.

The sludge samples were placed into testing trays (Fig. 3-1 a), with an initial sludge layer height of 4 cm. For each condition tested three test trays were used for observation of changes in the sludge layer during drying, and one control tray was used for VS content changes monitoring throughout the test.

Table 3-1 Sludge modifications used in preferential flow pathways formation test

Sample name	Sludge used	Applied modification
PFP1	Thickened primary sludge	No surface modification. Reference test.
PFP2	Thickened primary sludge	Initial V-cut
PFP3	Thickened primary sludge	Initial III-cut
PFP4	Thickened primary sludge	Wooden cylinders of 1.5 mm diameter
PFP5	Thickened primary sludge	Application of SAS layer of 2 mm on top
PFP6	Thickened aerated primary sludge	No surface modification

Two dry warm air flows ($T\ 60^{\circ}\text{C}$, relative humidity 10%) from two identical sources were directed to the testing area avoiding direct contact of the air flow with the samples (Fig. 3-1a). The warm air flow was provided by two heat guns (AK06-GREEN, Aikou, China). The warm airflows were used to maintain conditions accelerating sludge layer drying and to prevent mould growth on the sample surface. Visual characterisation of the samples was performed during the test, with pictures of the samples surface taken at 30 minutes intervals and trays weight recorded for gravimetical determination of sludge drying rate (Tao et al. 2005) until PFP is fully developed (when the crack reached the testing tray bottom). Moisture content in the sludge layer surface was measured in 3 zones of the testing tray: near wall (zone 1), at a distance of 1-2 cm from the wall (zone 2), and in the central part (zone 3) (Fig. 3-1 b) by using a pin moisture meter (MO55, Extech Instruments, Massachusetts, US).

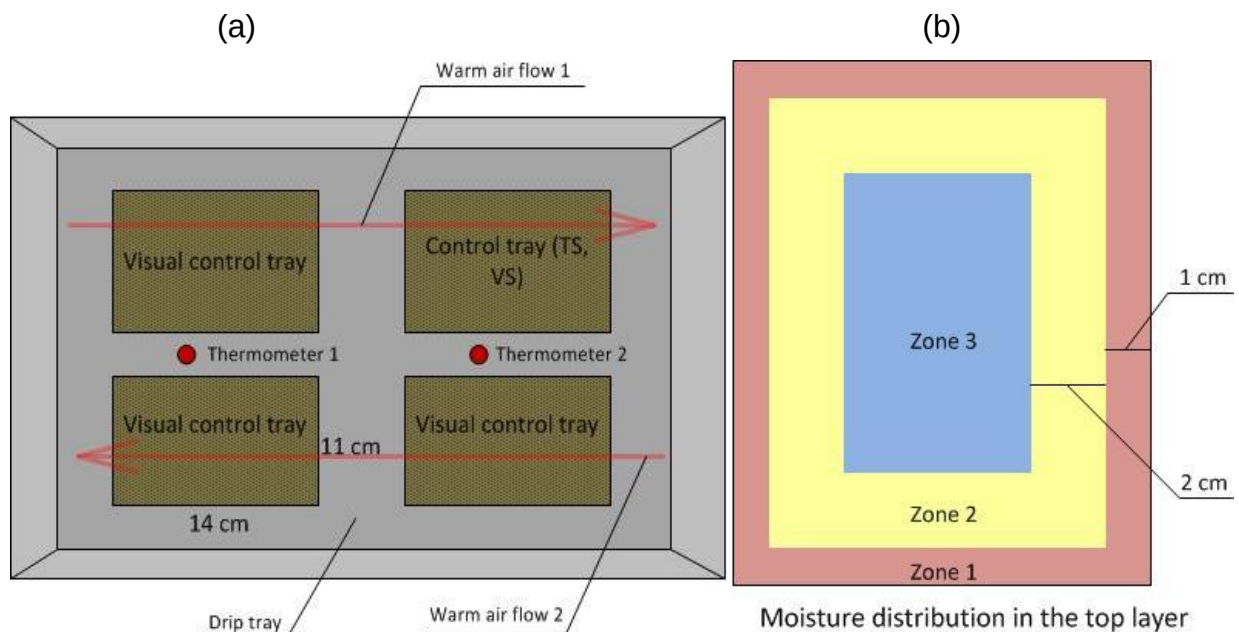


Figure 3-1 Preferential flow pathways formation test layout. Red arrows show warm airflows.

Sludge shrinkage with formation of a matte skin layer and formation of cracks were previously reported as typical changes in wastewater sludge during convective drying (Bennamoun et al. 2013) and were considered as critical points to be recorded in the current test. Two critical periods were determined for each drying test: initial period (t_1), which comprises from the beginning of the test until appearance of the first crack, and crack development period (t_2) – which is the period between occurrence of the first crack and full PFP development (when the crack reached the tray bottom). Size of the formed PFP was measured with a portable microscope with a 25× magnification (CrackScope CS-100, Germann Instruments, Denmark).

3.3.4 Analytical methods

Sludge samples were analysed for TS and VS content prior to permeability determination. TS and VS were determined in homogenised samples as per the standard methods (Standing Committee of Analysts (SCA) 2011) and expressed as a ratio of sludge weight before and after drying at 105 °C when a steady mass was achieved. VS was expressed as % of TS and measured by weight ratio of dried (for TS test) sludge samples before and after ignition at 550 °C until a steady mass was obtained. Particle size distribution (PSD) was characterised by laser diffraction spectroscopy. Tests were performed on a Malvern Mastersizer 3000 particle size analyser (Malvern Instruments Ltd, Malvern, UK) with a 30 rpm pump speed and 150 rpm stirrer speed. The tests were run in triplicates for each sample.

3.4 Results and discussion

3.4.1 Influence of sludge properties on its permeability

Both TS and VS were found to influence sludge permeability. A decrease in sludge permeability with increasing TS content was observed across all sample sets (Fig. 3-2 a).

Permeability of non-aerated primary sludge (75% VS content) decreased from $2.01 \times 10^{-16} \text{ m}^2$ to $7.47 \times 10^{-17} \text{ m}^2$ in samples with TS content of 9% and 24%, respectively. The correlation remains true for all sample sets with the lowest permeability values observed for samples aerated for 20 days (60% VS) with permeability decreasing from $7.75 \times 10^{-17} \text{ m}^2$ to $4.56 \times 10^{-18} \text{ m}^2$ with a TS range between 9 and 21%.

Increased TS levels in sludge have previously been found to lead to floc disintegration, which in turn increases degree of dispersion and impacts sludge permeability. Breakage of the sludge flocs with increasing TS can potentially deteriorate sludge cake structure and filterability by increasing small particles fraction. Break-up tests conducted on 30 types of activated sludge showed a correlation between solids concentration and sludge degree of dispersion, with an increasing sludge turbidity from 22.5 FTU for the sample with solids concentration of 0.74 g SS l^{-1} to 754.7 FTU for a sample with the same origin and solids concentration of 12.3 g SS l^{-1} (Mikkelsen et al., 1999). Later studies have also shown an increased sludge specific resistant to filtration with higher degree of dispersion (Mikkelsen et al., 1999). Thus, increasing TS content in wastewater sludge can have a negative impact on sludge filterability.

Unlike for TS, a decrease in VS content was found to decrease sludge permeability for the VS range tested of 60-75% (Fig. 3-2 b). Sludge permeability in sludge samples with 9% TS increased from $2.01 \times 10^{-16} \text{ m}^2$ to $6.14 \times 10^{-17} \text{ m}^2$ when increasing VS from 60% to 75%, respectively, and from $1.25 \times 10^{-16} \text{ m}^2$ to $2.06 \times 10^{-17} \text{ m}^2$ in samples with TS content of 15% for the same VS range.

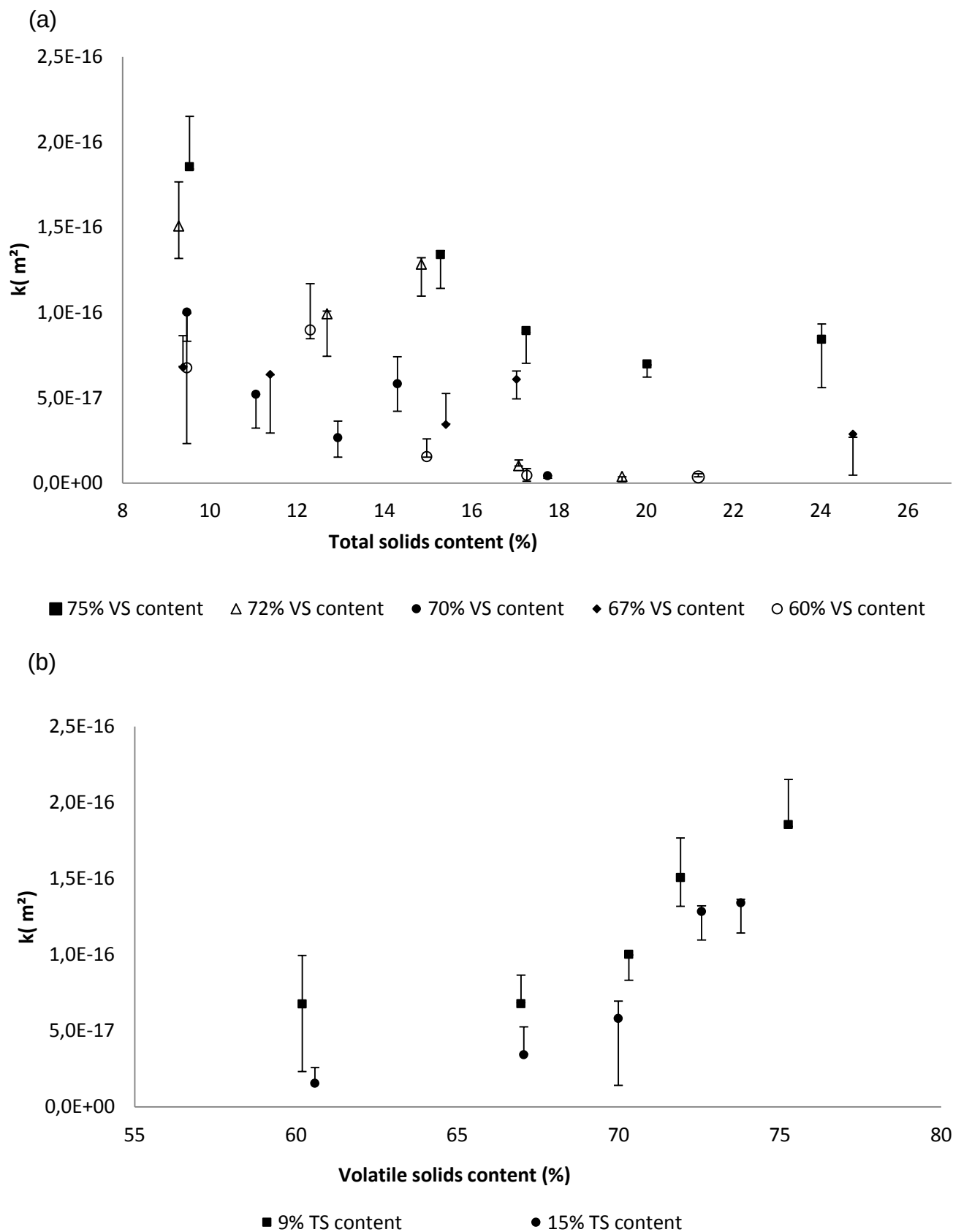


Figure 3-2 Relationship between sludge composition and permeability.

It was hypothesized that OM content influenced sludge structure by binding with positively charged inorganic particles, hence leading to formation of larger particles which favour sludge permeability. OM in sludge layers is present in various forms, with the largest fraction being extracellular polymeric substances (EPS) which make up to 95% of OM (Dominiak, 2010). For this reason influence of EPS on sludge properties has been previously studied, with a focus on the impact of proteins, carbohydrates and humic acids (Liu and Fang 2002). According to these studies a high protein concentration influences surface charge (SC), which has an indirect effect on floc stability (Frølund et al., 1996). A decrease of capillary suction time has been reported in sewage sludge with greater EPS content (in samples with EPS concentration range between $40 \text{ mg}\cdot\text{g}^{-1}$ and $130 \text{ mg}\cdot\text{g}^{-1}$) and proteins concentration (between $25 \text{ mg}\cdot\text{g}^{-1}$ and $60 \text{ mg}\cdot\text{g}^{-1}$), indicating an improved filterability of the sludge (Frølund et al. 1996; Liu & Fang 2002). The findings of these previous studies support the proposed hypothesis that the increased permeability in samples with greater VS content (Fig. 3-2b) was due to formation of larger particles. Since sludge layer composition changes during the feeding and resting periods in full scale VFCWs, further investigation of the evolution of OM composition (proteins, carbohydrates and humic acids) and its links with permeability is recommended.

Relative span was used to describe PSD in the tested samples, which allows to evaluate the ratio of coarse and fine particles within each sample (Vladisavljevic & Schubert, 2003). Particle size of aerobically treated sludge varied with aeration time and hence with VS content (Table 3-2). For the most mineralized sludge after 20 days of aeration PSD was characterised by d_{10} 13 nm and d_{90} 512 nm with a relative span value of 7.8, which indicated a greater presence of coarse particles when compared with raw (not aerated) primary sludge, which was characterized by d_{10} 17 nm, d_{90} 42 nm and relative span of

0.9. Sludge permeability decreased with aeration time and larger relative span (Fig. 3-2b and Table 3-2).

Table 3-2 Characteristics of primary sludge with different aeration times.

Aeration period length (d)	VS (%)	Relative span	Particle size distribution (nm)			Relative standard deviation (%)			k, m ²	Fractal dimension, D
			d ₁₀	d ₅₀	d ₉₀	d ₁₀	d ₅₀	d ₉₀		
0	75	0.9	17	28	42	1.1	1.2	2.8	1.34×10^{-16}	2.81
5	72	4.5	17	82	385	2.7	0.9	0.2	1.28×10^{-16}	2.82
10	70	4.3	21	99	447	2.6	1.1	1.4	5.82×10^{-17}	2.84
15	67	4.8	19	89	448	0.4	0.5	0.7	3.43×10^{-17}	2.85
20	60	7.8	13	64	512	3.1	0.7	1.1	1.55×10^{-17}	2.85

Fractal dimension of the samples was determined based on PSD data and cumulative volume distribution. Fractal dimension determined by this method lays in a range between 1 and 3 with results for the tested sludge being between 2.81 to 2.85 (Table 3-2). High values of fractal dimension indicates complex structure of sludge flocs meaning expansion of flocs surface and appearance of spatial structure (Jin et al 2004; Kusnierz and Wiercik 2016). Flocs of such structure are known to cause increased sludge bulkiness and amount of bound water in sludge, which negatively impacts sludge permeability (Kusnierz and Wiercik 2016). The lowest fractal dimension value of 2.81 was observed in primary sludge before aeration and increased to 2.85 in samples aerated for 15 and 20 days, with an associated drop in permeability from 1.34×10^{-16} m² to 1.55×10^{-17} m², respectively. Thus, sludge mineralization (VS reduction) simultaneously

increased particle size (d_{90}) and complexity of the sludge flocs (higher fractal dimension), which were expected to enhance and hinder permeability, respectively. Permeability was reduced with reduced VS content (Fig. 2-2b), suggesting that floc complexity had a greater relative contribution than particle size within the ranges tested. Alteration of sludge flocs shape has previously been shown to greatly impact filterability, with specific filtrate flow of 100 and 38 for sludge samples with large compact round flocs and large regular flocs, respectively (Christensen et al. 2015). Floc morphology was not further investigated with imagery analysis and is recommended for future work.

3.4.2 Preferential flow pathways formation and sludge evolution during drying

During the sludge drying experiments similarities in visual evolution of the primary sludge with and without modifications were observed, which can be divided into 3 stages as follows: (1) sludge cake shrinkage and skin layer formation, (2) occurrence of the initial fissures and cracks, and (3) further development of cracks and sludge cake volume reduction. Formation of the skin layer occurs as water evaporates from the sample surface and moisture content in the surface layer decreases. A decrease in moisture content and formation of a matte skin layer occurred from the walls towards the tray centre. Moisture content decreased to 20-26% in zone 1 (Fig. 3-2 b) during the first 30 minutes of the test and reached a value of 14-17% in zones 2 and 3 when the skin layer fully formed. While all samples seem to follow the 3 stages described above, PFP5 and PFP6 samples modified by SAS application and aeration for 20 days respectively showed slightly different patterns. In these samples formation of multiple cracks was observed in the shape of a cracked rind during the first 30 minutes of the test (Table 3-3), indicating a shortened first stage (cake shrinkage and skin formation) or its absence. However, not

all cracks formed during the initial period evolved into fully formed PFP. Drying rates for PFP5 and PFP6 samples fluctuated during the remaining two stages, which may be explained by the formation of a large number of cracks throughout the test in the aerated primary sludge and in the samples modified by application of SAS on top of the primary sludge samples. The visual changes in sludge surface during these periods are shown in Table 3-2 and the drying kinetics changing over the time are shown on the drying curves (Fig.3-4).

Table 3-3 Sludge layer evolution during drying.

Sample	t_2/t_1^*	TS (%) at the end of the crack development period	Beginning of the initial period	Beginning of the crack development period	End of the crack development period
PFP1	1	26.5			
PFP2	0.5	32			
PFP3	0.3	31.5			
PFP4	1.2	38			
PFP5	0.8	39			
PFP6	0.6	32			

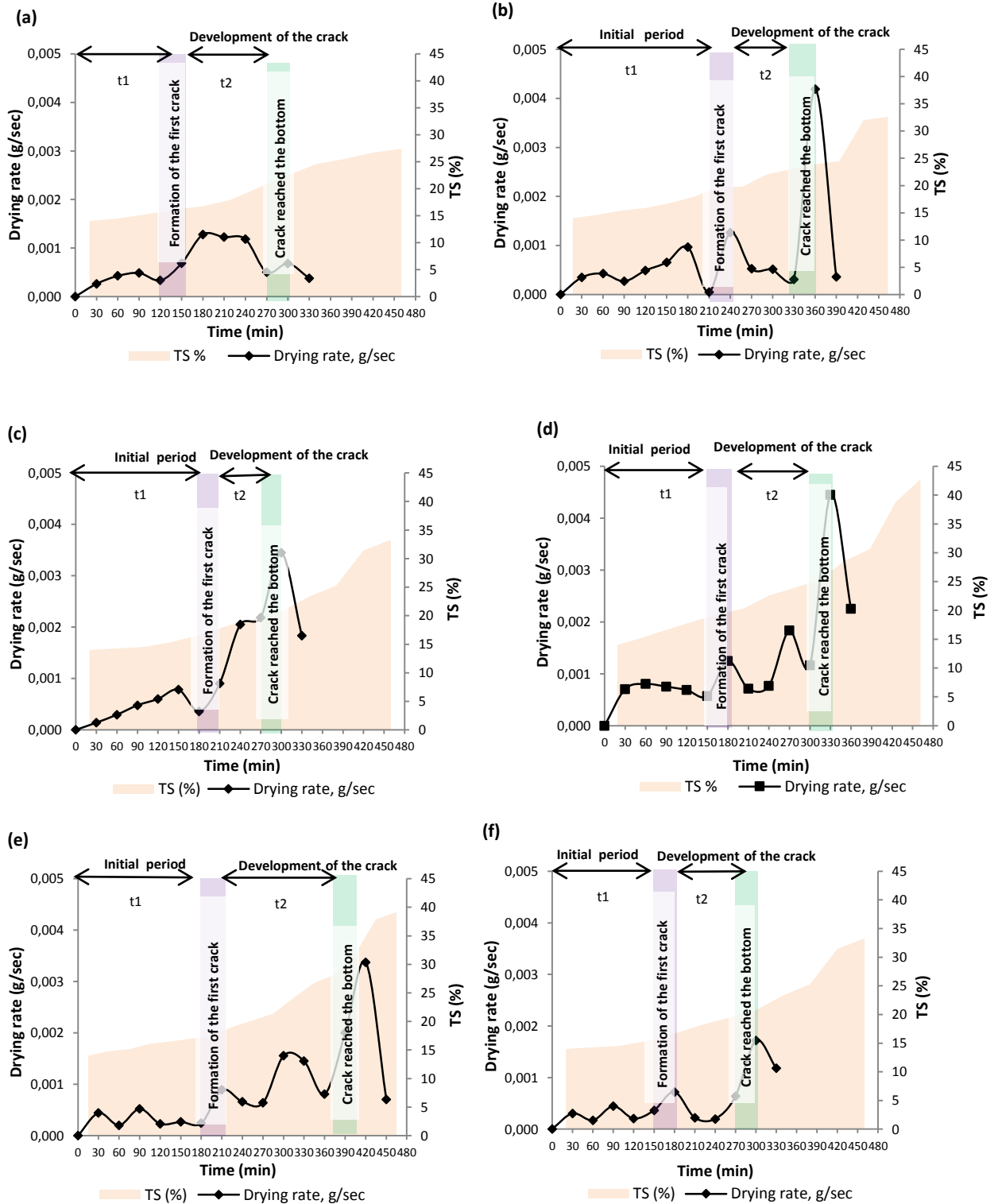


Figure 3-3 Drying curves of modified and non-modified sludge samples : PFP1 (Thickened primary sludge with no modification) (a), PFP2 (Thickened primary sludge with initial V-cut) (b), PFP3 (Thickened primary sludge with initial III-cut) (c), PFP4

(Thickened primary sludge modified with wooden cylinders of 1.5 mm diameter) (d), PFP5 (Thickened primary sludge with secondary waste activated sludge application) (e), PFP6 (Thickened aerated primary sludge with no surface modification) (f). The curves are plotted for single testing trays.

Higher concentration of TS at the end of the experiment, considered when a fully developed PFP was formed, was observed for all sludge samples where physical modifications were tested. The greater impact of the modification on sludge TS content was observed for samples with application of secondary waste activated sludge layer on top (PFP5), where TS content at the end of the test was as high as 39%, followed by samples modified with wooden cylinders of 1.5 mm diameter (PFP4) with 38% TS in final cake and aerated primary sludge (PFP6) with TS of 36%. For unmodified primary sludge (PFP1) a value of 27% TS was recorded at the end of the test. The impact of the artificial modifications on the kinetics of PFP formation was evaluated by comparing the PFP formation coefficient, expressed as a ratio of crack development period length (t_2) to initial period length (t_1). A lower PFP formation coefficient would indicate positive impact of the sludge modification on evolution of the cracks to a fully developed PFP. The PFP formation coefficient was higher for samples PFP5 and PFP4 with a value of 0.8 and 1.2, respectively, compared to 0.3 and 0.5 for PFP3 and PFP2.

3.4.3 Implications of the findings for operation of full-scale VFCWs

The correlations between sludge characteristics and permeability observed in the current study contradicts data previously reported in literature for full-scale VFCWs, where higher mineralization and dry matter content have been reported to favour IR of the sludge layer (Arias et al. 2014; Gómez 2016). The differences in hydraulic behaviour of the sludge observed during this study and those reported for full-scale systems is

believed to be associated with the formation of PFPs, which are an inherent component of the system and naturally form as a result of biotic (Brix 2017) or abiotic (Hsu et al. 2010) processes . These PFPs are characteristic of full scale systems and were not present in sludge cakes tested in the permeability lab-scale experiments, which indicates a higher relative contribution of sludge layer structure (e.g. PFPs) than of its composition (e.g. TS, VS) to permeability.

The sludge layer properties observed to have a positive impact on sludge permeability (high VS and low TS) would restrict filter beds reoxygenation and increase the sludge accumulation rate. It is hence concluded that sludge layers characterised by a high degree of mineralisation (low VS, high TS) and with high abundance of PFPs are desired in full scale systems, so that low sludge accumulation rates and high permeability can be simultaneously attained. Artificial means to accelerate PFPs formation have potential to avoid operational issues associated with low hydraulic acceptance of the first stage filters and increase operational time between desludging.

With a view to determine possible ways to stimulate formation of PFPs the impact of several artificial sludge layer modifications on sludge layer evolution during drying was investigated. The tests evidenced a positive impact of all the sludge surface modifications tested on the drying rates, which in full-scale systems could be implemented to improve TS evolution between feeding periods and hydraulic acceptance of the beds after the sludge layer is formed. Artificial formation of the initial cracks, addition of a SAS layer on the sludge surface and aeration of the sludge decreased PFP formation coefficient and moisture content in the sludge cake at the end of the experiment. Application of the activated sludge and aeration of the sludge caused positive changes in the sludge surface from the early stages of the experiments, with

formation of multiple cracks which promote additional aeration of the sludge layer and generate a greater surface area, hence improving drying rates and mineralisation kinetics. No positive impact of physical imitation of the reed stems (without considering the roots) on the crack formation time was observed, although this modification had a positive effect on the TS evolution and formation of voids around the sticks, which in the full-scale system may also act like preferential flow pathways. Artificial sludge layer modifications could be valuable for both SDRBs and VFCWs, with potential to ultimately allow a consistently higher hydraulic acceptance and reduced operational costs linked to the longer periods between desludging events associated with greater sludge mineralisation rates (Brix 2017).

A better understanding of the mechanisms by which sludge layer modifications change sludge structure and lead to formation of PFPs is still needed. In case of SAS application on top of the sludge layer, which showed promising results, the relative contribution of rheology modifications and biotic processes to PFP formation require further investigation, as well as the impacts of biological modification of the surface on system performance.

3.5 Conclusion

The impact of sludge properties such as TS, VS content and PSD on its permeability were investigated, as well as the impact of sludge surface modifications on PFPs formation. A positive impact of increased VS on permeability was found in 5 sample sets, with VS ranging between 60 and 75% with permeability improving from $6.14 \times 10^{-17} \text{ m}^2$ to $2.00 \times 10^{-16} \text{ m} \cdot \text{s}^{-1}$ in samples with TS of 9% and from $2.06 \times 10^{-17} \text{ m} \cdot \text{s}^{-1}$ to $1.25 \text{ m} \cdot \text{s}^{-1}$ in samples with TS 15%.

A positive effect of artificially modifying the sludge layers on PFP formation and sludge drying rate was observed, which could be implemented in full-scale systems to improve hydraulic acceptance and re-oxygenation and shorten maturation of primary filters. Higher TS contents were achieved for the modified sludge samples, which could translate in prolonged operational periods without desludging (reduced maintenance costs) in full-scale VFCWs and SDRB.

3.6 References

- Angulo-Jaramillo R., J. P. Vandervaere, S. Roulier, J. L. Thony, J. P. Gaudet, M. Vauclin. 2000. "Field Measurement of Soil Surface Hydraulic Properties by Disc and Ring Infiltrimeters: A Review and Recent Developments." *Soil and Tillage Research* 55(1–2):1–29.
- Arias L. , J. Luis. 2013. "Vertical-Flow Constructed Wetlands for the Treatment of Wastewater and Stormwater from Combined Sewer Systems Traitement Des Eaux Résiduares de Temps Sec et Temps."
- Arias L., J. Luis, J. L. Bertrand-Krajewski, and P. Molle. 2014. "Simplified Hydraulic Model of French Vertical-Flow Constructed Wetlands." *Water Science and Technology* 70(5):909–16.
- Baroutian S., N. Eshtiaghi, and D. J. Gapes. 2013. "Rheology of a Primary and Secondary Sewage Sludge Mixture: Dependency on Temperature and Solid Concentration." *Bioresource Technology* 140(May):227–33.
- Barua A. 2014. "Experimantal studying of filter cracking." PhD Thesis, Imperial College of Science, Technology and Medicine.
- Bennamoun L., P. Arlabosse, and A. Léonard. 2013. "Review on Fundamental Aspect

- of Application of Drying Process to Wastewater Sludge.” *Renewable and Sustainable Energy Reviews* 28:29–43.
- Bourcier D., J. P. Féraud, D. Colson, K. Mandrick, D. Ode, E. Brackx, and F. Puel. 2016. “Influence of Particle Size and Shape Properties on Cake Resistance and Compressibility during Pressure Filtration.” *Chemical Engineering Science* 144:176–87.
- Boutin C., A. Lienard. Constructed wetlands for wastewater treatment: the French experience. *1st international seminar on the use of aquatic macrophytes for wastewater treatment in constructed wetlands*, May 2003, Lisbonne, Portugal. p. 437 - p. 466. fahal-00508191fBrix, Hans. 2017. “Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds.” *Water (Switzerland)* 9(3).
- Brix H., 2017. “Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds.” *Water (Switzerland)* 9(3).
- Butterworth E., G. Dotro, M. Jones, A. Richards, P. Onunkwo, Y. Narroway, and B. Jefferson. 2013. “Effect of Artificial Aeration on Tertiary Nitrification in a Full-Scale Subsurface Horizontal Flow Constructed Wetland.” *Ecological Engineering* 54:236–44.
- Christensen M., K. Keiding, P. Nielsen, and M. Jørgensen. 2015. “Dewatering in Biological Wastewater Treatment: A Review.” *Water Research* 82:14–24.
- Cleverson V. A., Marcos von Sperling and F. Fernandes (Editors). 2007. *Sludge Treatment and Disposal*.
- Coombs P. , Wagner D. , Bateman K., Harrison H., Milodowski A. E., Noy D., West J. M. 2010. “The Role of Biofilms in Subsurface Transport Processes.” *Quarterly*

- Dominiak, D. M., M. L. Christensen, K. Keiding, and P. Nielsen. 2011. "Sludge Quality Aspects of Full-Scale Reed Bed Drainage." *Water Research* 45(19):6453–60.
- Dominiak, D. M. 2010. Drainage properties of activated sludge. (1 ed.) Aalborg Universitet: Institut for Kemi, Miljø og Bioteknologi, Aalborg Universitet.
- Dotro, Gabriela, Günter Langergraber, Pascal Molle, Jaime Nivala, Jaume Puigagut, Otto Stein, Marcos Von, and Sperling Volume. 2017. *Treatment Wetlands*. Vol. 7. IWA Publishing.
- Dotro, G., G. Langergraber, P. Molle, J. Nivala, J. Puigagut, O. Stein, M. Von, and Sperling Volume. 2017. *Treatment Wetlands*. Vol. 7. IWA Publishing.
- Easton, Z. M. and E. Bock. 2016. "Soil and Soil Water Relationships." *Virginia Cooperative Extension* 1–9.
- Eriksson, L. and B. Alm. 1991. "Study of Flocculation Mechanisms by Observing Effects of a Complexing Agent on Activated Sludge Properties." *Water Science and Technology* 24(7):21–28.
- Frølund, Bo, R. Palmgren, K. Keiding, and P. Nielsen. 1996. "Extraction of Extracellular Polymers from Activated Sludge Using a Cation Exchange Resin." *Water Research* 30(8):1749–58.
- Guglielmi G., D. Chiarani, D. Prakash Saroj, G. Andreottola. 2010. "Sludge Filterability And Dewaterability In A Membrane Bioreactor For Municipal Wastewater Treatment." : : *Desalination* 250:1–9.
- Gomez, L. P. 2016. "Vertical Flow Constructed Wetl and for Treating Unscreened Sewage in the UK." MSc By Research thesis, Cranfield university.

- Hartshorn, A. J., G. Prpich, A. Upton, J. Macadam, B. Jefferson, and P. Jarvis. 2015. "Assessing Filter Robustness at Drinking Water Treatment Plants." *Water and Environment Journal* 29(1):16–26.
- H. Mikkelsen, K. Keiding. 1999. "Equilibrium Aspects of the Effects of Shear and Solids Content on Aggregate Deflocculation." *Advances in Colloid and Interface Science* 80(2):151–82.
- J. P. Hsu, Tao Tao, Ay Su, Arun S. Mujumdar & Duu-Jong Lee (2010) Model for Sludge Cake Drying Accounting for Developing Cracks, *Drying Technology*, 28:7, 922-926, DOI: 10.1080/07373937.2010.490775.
- Hua, G. F., Z. W. Zhao, J. Kong, R. Guo, and Y. T. Zeng. 2014. "Effects of Plant Roots on the Hydraulic Performance during the Clogging Process in Mesocosm Vertical Flow Constructed Wetlands." *Environ. Sci. Pollut. Res.*, 21, pp. 13017-13026.
- Jin, Bo, B. M. Wilén, and P. Lant. 2004. "Impacts of Morphological, Physical and Chemical Properties of Sludge Flocs on Dewaterability of Activated Sludge." *Chemical Engineering Journal* 98(1–2):115–26.
- Kahl, S., J. Nivala, Manfred van Afferden, R. A. Müller, and T. Reemtsma. 2017. "Effect of Design and Operational Conditions on the Performance of Subsurface Flow Treatment Wetlands: Emerging Organic Contaminants as Indicators." *Water Research* 125:490–500.
- Kusnierz, M. and P. Wiercik. 2016. "Analysis of Particle Size and Fractal Dimensions of Suspensions Contained in Raw Sewage, Treated Sewage and Activated Sludge." *Archives of Environmental Protection* 42(3):67–76.

- Li, Wenping, C. Kiser, Q. Richard “Paper Presented at the American Filtration & Separations Society 2005 International Topical Conferences & Exposition, September 19-22, Ann Arbor, Michigan.” Pp. 1–9 in *Development of A Filter Cake Permeability Test Methodology*.
- Liu, Hong and Herbert H. P. Fang. 2002. “Extraction of Extracellular Polymeric Substances (EPS) of Sludges.” *Journal of Biotechnology* 95(3):249–56.
- Markis, F., K. Hii, R. Parthasarathy, J. Christophe Baudez, Paul Slatter, and Nicky Eshtiaghi. 2013. “Rheological Characterisation of Blends of Primary and Secondary Sludge.” *Soft Matter* 500.
- Marklund, S. 1997. “Dewatering of Wastewater Sludge by Natural Air Drying.” Div. Sanitary Engineering, Luleå University of Technology, Licentiate thesis, 1997:10, ISSN 1402-1757.
- Mikkelsen, L. Haugaard and K. Keiding. 2002. “Physico-Chemical Characteristics of Full Scale Sewage Sludges with Implications to Dewatering.” *Water Research* 36(10):2451–62.
- Molle, P., A. Liénard, A. Grasmick, and A. Iwema. 2006. “Effect of Reeds and Feeding Operations on Hydraulic Behaviour of Vertical Flow Constructed Wetlands under Hydraulic Overloads.” *Water Research* 40(3):606–12.
- Molle, P. 2005. “French Vertical Flow Constructed Wetlands: Design for Storm Event Acceptance.”
- Molle, P. 2014. “French Vertical Flow Constructed Wetlands: A Need of a Better Understanding of the Role of the Deposit Layer.” *Water Science and Technology*

69(1):106–12.

Molle, P, A. Liénard, C. Boutin, G. Merlin, and A. Iwema. 2005. “How to Treat Raw Sewage with Constructed Wetlands: An Overview of the French Systems.” *Water Science and Technology* 51(9):11–21.

Morvannou A., N. Forquet, S. Michel, S. Troesch, P. Molle. Treatment performances of French constructed wetlands: Results from a database collected over the last 30 years. *Water Science and Technology*, IWA Publishing, 2015, 71 (9), pp.1333-1339.

Morvannou, A., N. Forquet, M. Vanclooster, and P. Molle. 2013. “Characterizing Hydraulic Properties of Filter Material of a Vertical Flow Constructed Wetland.” *Ecological Engineering* 60:325–35.

Nivala, j., Manfred van Afferden, R. Hasselbach, G. Langergraber, P. Molle, H. Rustige, and J. Nowak. 2018. “The New German Standard on Constructed Wetland Systems for Treatment of Domestic and Municipal Wastewater.” *Water Science and Technology* 2414–26.

Olboter, L. and A. Vogelpohl. 1993. “Influence of Particle Size Distribution on the Dewatering of Organic Sludges.” *Water Science and Technology* 28(1):149–57.

Paing, J., A. Guilbert, V.Gagnon, and F. Chazarenc. 2015. “Effect of Climate, Wastewater Composition, Loading Rates, System Age and Design on Performances of French Vertical Flow Constructed Wetlands: A Survey Based on 169 Full Scale Systems.” *Ecological Engineering* 80:46–52.

Singh, K. B., Laxman R. Bhosale, and Mahesh S. Tirumkudulu. 2009. “Cracking in

- Drying Colloidal Films of Flocculated Dispersions.” *Langmuir* 2009 25 (8), 4284-4287.
- Standing Committee of Analysts (SCA). 2011. *Methods for the Examination of Waters and Associated Materials*. Environmental Policy and Law.
- Stefanakis, A. I. and Vassilios A. Tsihrintzis. 2012. “Effects of Loading, Resting Period, Temperature, Porous Media, Vegetation and Aeration on Performance of Pilot-Scale Vertical Flow Constructed Wetlands.” *Chemical Engineering Journal* 181–182:416–30.
- Tang, Chao Sheng, Yu Jun Cui, Bin Shi, Anh Minh Tang, and Chun Liu. 2011. “Desiccation and Cracking Behaviour of Clay Layer from Slurry State under Wetting-Drying Cycles.” *Geoderma* 166(1):111–18.
- Tao, T., X. F. Peng, and D. J. Lee. 2005. “Thermal Drying of Wastewater Sludge: Change in Drying Area Owing to Volume Shrinkage and Crack Development.” *Drying Technology* 23(3):669–82.
- Troesch, S., F. Salma, and D. Esser. 2014. “Constructed Wetlands for the Treatment of Raw Wastewater: The French Experience.” *Water Practice & Technology* 9(3):430.
- Uggetti, E., I. Ferrer, E. Llorens, and J. García. 2010a. “Sludge Treatment Wetlands: A Review on the State of the Art.” *Bioresource Technology* 101(9):2905–12.
- Uggetti, E., I. Ferrer, E. Llorens, and Joan García. 2010b. “Sludge Treatment Wetlands: A Review on the State of the Art.” *Bioresource Technology* 101(9):2905–12.
- Vladisavljevic, G.T. and Schubert, H. 2003. “Preparation of Emulsions with a Narrow Particle Size Distribution Using Microporous α -Alumina Membranes.”

4 Overall discussion

The evaluation of the technology success for unscreened sewage treatment under UK conditions was done based on data gathered during the first three years of operation of the full-scale site. The design of the first UK two-stage VFCWs is similar to the standard French design, with the exceptions of a higher DWF HL in the UK design to accommodate for frequent storm events, and to the lack of sewage screening (Table 4-1). The close monitoring of the full-scale site allowed a comparison of treatment efficacy of the UK system and systems operated in France, and suggestion of adaptations needed for successful implementation of the technology in the UK.

Overall treatment performance of the UK system was found to be on the same level as similar systems reported in the literature. However, several differences in treatment performance and hydraulic behaviour were observed highlighting young filters evolution and the impact of the system design and site management on performance. The observations are as follows:

- Treatment performance of the site is impacted by choice of aeration strategy. Forced aeration allowed to achieve higher ammonia removal and improvement of the system robustness;
- Young first stage filters have lower hydraulic acceptance and alterations of the length of the feeding/resting periods are required to avoid ponding occurrence and compromising re-oxygenation;
- PFP development is one of the factors impacting hydraulic acceptance of the filter beds having a higher relative contribution than sludge layer properties such as TS and VS content;

- PFP formation can be accelerated by sludge surface modification, contributing to higher hydraulic acceptance and beds re-oxygenation.

Table 4-1 Comparison of design of the studied two-stage VFCWs WWTP and standard design in France.

	UK design	French design
Pollutants load per 1 p.e.	160L with 60g SS, 115g COD, 60g BOD ₅ , 10g TN, 2g TP	150L with 60g SS, 120g COD, 1-12g TKN (Molle 2005)
HL (DWF)	2.27 L·s ⁻¹ (0.52 m·d ⁻¹)	0.37 m·d ⁻¹ (Arias López 2013)
Pre-treatment	None	Screening
Total area	2 (m ² ·p.e. ⁻¹)	
Media (1 st stage)	40 cm gravel 2/6mm 20-40 cm gravel 10/63 mm	40–50 cm gravel 2/8 mm 15–20 cm gravel 10/20 mm 20 cm gravel 20/40 mm (Paing et al. 2015)
Media (2 nd stage)	40 cm sand 0/4 mm 40 cm gravel 2/6mm 20cm gravel 20/40mm 0-30cm gravel 10/63mm	40 cm sand 0/4 mm 15–20 cm gravel 4/10 or 4/20mm 20 cm gravel 10/20 or 20/40 mm (Paing et al. 2015)
Operational cycle (1 st stage)	1 st year: 3.5/7 days; 2 nd year: 5/10 days; 3 rd year: 7/14 days	3.5 days/7 days (Morvannou et al. 2015)
Operational cycle (2 nd stage)	7 days/ 7 days before the forced aeration implementation. One filter bed has been in continuous use since the forced aeration started in 2015.	7 days/7 days (Paing et al. 2015)
Feed batch volume (1 st stage)	2 cm over the bed surface (7.5 m ³ batch volume)	3-4 cm over bed surface (Paing et al. 2015)
Batch volume (2 nd stage)		4 cm over bed surface (Paing et al. 2005)
2 nd stage aeration	Passive until December 2015. Forced from December 2015.	Passive

Treatment performance of the system improved after the second stage was retrofitted with forced aeration. Implementation of forced aeration also halved the footprint required for secondary treatment as it allowed for continuous operation of a single bed with no resting period. 95th percentile ammonia concentration in the final effluent during the first year of operation was 9.6 mg·L⁻¹, compared with a value of 5.3 mg·L⁻¹ after forced aeration started. The first stage filters were found to be hydraulically limited during the first year of operation when working with a 3.5 days feeding and 7 days resting operational cycle, which is generally implemented for the technology in France. To reduce ponding time, bring the technology closer to the recommended 6 hours of water-free surface (Nivala et. al, 2018) and improve sludge layer mineralisation, alterations to the operational cycle were implemented (Table 4-2) with a longer resting time of 14 days. This allowed achieving IR, TS and VS values close to those reported in literature (Table 4-2).

Table 4-2 Comparison of sludge layer properties during the first three years of operation for the monitored full scale WWTP.

Time in operation	Sludge layer height (cm)	TS (%)	VS (%)	HC (m·s ⁻¹)	Feed/rest (days)
1 st year	3-5	11.5±1.9	64.5±7.3	<5.7 × 10 ⁻⁶	3.5/7
2 nd year	4-13	12.3±7.3	75.5±7.3	<1 × 10 ⁻⁵	5/10
3 years	5-6	20.4%±3.5	62.3%±3.3	<4.9 × 10 ⁻⁴	7/14

Investigation of the sludge layer properties throughout a single operational cycle on the third year of operation showed that at this point of the filters development resting periods

of 14 days do not benefit sludge layer evolution. TS, VS and IR of the sludge layer remained constant after 7 days of resting, suggesting that an operational cycle with 3.5 days feeding / 7 days resting is suitable and will indeed reduce stress on the beds because of a shorter feeding time.

The low hydraulic capacity of the system on the early stages of the system operation is believed to be caused by poor structural properties of the deposited sludge layer when PFP are not well developed. Acceleration of PFPs formation was not previously discussed in the literature in the context of VFCWs' IR. According to results of the lab scale experiments conducted during the current study sludge surface modifications can potentially reduce the time needed for sludge layer to develop PFPs. Thus, application of SAS on the sludge surface in the laboratory scale tests allowed achieving faster development of the PFPs (relative PFP formation time 0.8 comparing to 1 for not modified surface). Also, this modification allowed developing larger amount of small cracks, which increases surface area improving by this water evaporation rates and providing additional oxygen promotion (Fig. 4-1).



Figure 4-1 The visual comparison of not modified sludge surface (left) and sludge surface modified by SAS application during drying (right).

Physical modification of the sludge surface by applying initial cuts showed a positive impact on PFP formation, with relative PFP formation time of 0.3 and 0.5 for samples with initial surface cuts comparing to 1 in not modified samples. Faster drying kinetics were also observed in modified samples with 5% to 6% higher TS content in sludge layer at the end of the experiment. Modifying the deposited sludge surface on the early stages of VFCWs operation has a potential to accelerate PFP network development and achieve higher HC during system start up. However, further investigation is required for this to become an implementable full-scale solution. SAS application onto the sludge surface needs further research to elucidate possible biological effects on the filter beds when implemented as a long-term strategy. Raking the sludge layer surface or seeding with worms appear a simple way to generate initial cracks that can then deliver the benefits observed in the laboratory scale experiments, although the lowest water content which would allow for cuts to develop into PFP must be determined.

4.1 Suggested adaptations

To increase efficiency of two-stages VFCWs operation in UK conditions the next adaptations are suggested:

(1) First stage rotation

Implementation of the classical rotation periods of 3.5 days feeding / 7 days resting (López 2013) does not allow achieving suitable levels of sludge layer mineralization and to avoid prolonged ponding occurrence. The adaptation needed for ponding avoiding must be done with consideration of the system age and HL on the system. In literature the maximum daily HL which allowed effective first stage filters operation is 1.81 m per day which corresponds to 100 batches. However, the studied UK system showed that

HL over 24 batches leads to prolonged ponding occurrence of up to 24 hours comparing to maximum recommended 18 hours discussed in literature (Nivala, 2018). The observation was made during the first operational year when IR was $5 \times 10^{-6} \text{ m} \cdot \text{s}^{-1}$. The rotation period was experimentally adjusted to a feeding/resting period length of 7/14 leading to an increased IR and avoiding of ponding. After three years of operation a resting period length beyond 7 days does not benefit IR and the rotational period can be reduced to 3,5/7 days feed/rest.

(2) Sludge layer structure development acceleration

Modification of the deposited sludge layer has potential to improve hydraulic acceptance of the young first stage filters. Over the first operational year deposited sludge layer height was as high as 5-6 cm and TS content in sludge layer was $11.5 \pm 1.9\%$. The sludge texture of this TS content was liquid-like, which would have restricted filter bodies re-oxygenation. To achieve faster development of the sludge layer structure, which has been found can take up to three years, artificial modifications of the sludge layer can be applied, which will allow forming PFPs and increase sludge layer surface due to formation of multiply cracks on top. This would improve hydraulic acceptance of first stage filters, avoiding ponding occurrence, and lead to higher TS contents, which can ensure long periods without desludging.

(3) Forced aeration of the second stage

Since nitrification on the second stage relies on aerobic conditions, the aeration approach on the second stage filter greatly influences treatment efficacy of the system. The monitored full-scale two-stage VFCWs were retrofitted with forced aeration of the second stage. This decreased the second stage footprint with only one bed being in continues operation. Forced aeration of the second stage decreased ammonia

concentration in the final effluent from $9.6 \text{ mg}\cdot\text{L}^{-1}$ for passive aeration, to $5.3 \text{ mg}\cdot\text{L}^{-1}$. after the forced aeration implementation,

5 Conclusions

The three-year investigation of the first UK two-stage VFCWs showed that the technology can be effectively implemented for raw sewage treatment in the UK. Comparison of the UK system with analogous systems operated in France showed the UK system achieved similar performance. Several differences in hydraulic behaviour and first stage filters development were observed.

The first stage filter beds were found to be hydraulically limited on the early stages of the system operation, which led to prolonged ponding occurrence and hindered filter body and sludge layer re-oxygenation. Poor re-oxygenation of the system leads in turn to decreased treatment performance and poor mineralisation of the sludge layer. Several strategies were suggested for improving hydraulic acceptance and sludge layer mineralization. The first choice to reduce ponding on the first stage filter beds was to adjust rotation period length. This approach reduced ponding and achieved HC values similar to those reported in literature. Rotational period on the first stage needs to be chosen taking into account system age and sludge layer properties. During the first years resting period can be extended for up to 14 days to provide sufficient time for filter beds re-oxygenation, sludge layer mineralization, and achieve higher TS content and HC at the end of resting period. After three years of operation, when the sludge layer is developed, hydraulic acceptance of the system improves and longer resting periods (above 7 days) do not benefit sludge layer evolution and HC. Another strategy to

improve sludge layer HC and accelerate sludge layer development is its artificial modification to achieve faster development of PFPs. Laboratory experiments showed the application of initial cuts and SAS on top of the sludge layer to be effective to stimulate development of PFPs and to increase TS content in sludge layer.

The second stage VFCWs were retrofitted with forced aeration after one year of operation. The modification improved ammonia removal and robustness of the system. 95th percentile ammonia concentration in the final effluent of 9.6 mg·L⁻¹ was observed with passive aeration. Forced aeration allowed to achieve 95th percentile ammonia concentration as low as 5.3 mg·L⁻¹ and improved system robustness under variable HL.

6 Future work

In order to advance knowledge of two-stage VFCWs, to adapt the technology for operation in the UK and to address the limitations determined in the current study, the following areas are recommended for further investigation:

- Evaluation of VS in permeability at a VS range representative of mineralized sludge layers as opposed to of young filters.
- Investigation of OM composition (e.g. proteins, carbohydrates and humic acids), its changing throughout an operational cycle and during prolonged system operation, and its links with sludge permeability is recommended.
- Influence of PFPs size and amount on sludge layer permeability and filter beds re-oxygenation is recommended for better understanding of relative contribution of PFP to system hydraulic behaviour and sludge mineralization. Mechanisms of PFP formation on the first stage filter beds

in planted and unplanted systems and ways to accelerate formation of PFPs.

- Pilot scale experiments in controlled conditions to translate scientific findings of this thesis into practical solutions implementable at full-scale VFCWs. In particular for determination of impact of rotation period length and artificial modifications of sludge layer on sludge layer properties evolution and on HC of first stage filter beds.

7 References

- Arias López, José Luis. 2013. "Vertical-Flow Constructed Wetlands for the Treatment of Wastewater and Stormwater from Combined Sewer Systems Traitement Des Eaux Résiduelles de Temps Sec et Temps." PhD Thesis, L'Institut National des Sciences Appliquées de Lyon.
- Dotro, G., G. Langergraber, P. Molle, J. Nivala, Jaume Puigagut, Otto Stein, Marcos Von, and Sperling Volume. 2017. *Treatment Wetlands*. Vol. 7. IWA Publishing.
- GOMEZ, L. P. 2016. "Vertical Flow Constructed Wetland for Treating Unscreened Sewage in the UK."
- Molle, P., A. Liénard, A. Grasmick, and A. Iwema. 2006. "Effect of Reeds and Feeding Operations on Hydraulic Behaviour of Vertical Flow Constructed Wetlands under Hydraulic Overloads." *Water Research* 40(3):606–12.
- Molle, P. 2005. *French Vertical Flow Constructed Wetlands : Design for Storm Event Acceptance*.
- Morvannou, A., N. Forquet, S. Michel, S. Troesch, P. Molle, A. Morvannou, N. Forquet, S. Michel, S. Troesch, and P. Molle Treatment. 2015. "Treatment Performances of French Constructed Wetlands : Results from a Database Collected over the Last 30 Years" *Water Sci Technol*. 2015;71(9):1333-9

- Morvannou, A., N. Forquet, M. Vanclooster, and P. Molle. 2013. "Characterizing Hydraulic Properties of Filter Material of a Vertical Flow Constructed Wetland." *Ecological Engineering* 60:325–35.
- Nivala, J., Manfred van Afferden, R. Hasselbach, G. Langergraber, P. Molle, H. Rustige, and J. Nowak. 2018. "The New German Standard on Constructed Wetland Systems for Treatment of Domestic and Municipal Wastewater." *Water Science and Technology* 2414–26.
- Paing, J., A. Guilbert, V. Gagnon, and F. Chazarenc. 2015. "Effect of Climate, Wastewater Composition, Loading Rates, System Age and Design on Performances of French Vertical Flow Constructed Wetlands: A Survey Based on 169 Full Scale Systems." *Ecological Engineering* 80:46–52.

Appendices

(a)

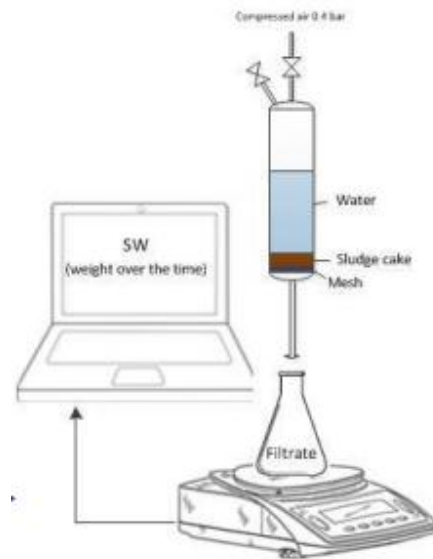


(b)



Figure 1: Change in reed coverage over the time in unharvested reed beds. First stage filter bed №1 after 5 months of operation, December 2015 (Gomez; 2015) (a) and after 3 years of operation, October 2018 (b).

(a)



(b)



Figure 2: Filtration test. Filtration experiment design (a), filtration rig (b).