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Review

The State of the Art of Clogging in Vertical Flow Wetlands

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Abstract: Clogging in vertical flow (VF) wetlands is an important process influencing water purification processes. The main contributing factors are the growth of microorganisms within the filter media, the accumulation of suspended solids on top of the wetland, as well as within the filter media. Both processes lead to a decrease of the available pore space, hence changing the soil's hydraulic properties. This will alter the water flow and cause malfunctioning of the system. This paper summarizes the state of the art of the prevailing physical, biological and chemical processes influencing clogging in VF wetlands. Different design and operational parameters are discussed to give a better understanding on their influence to prevent malfunctioning. Based on a literature review, a detailed overview on experimental as well as modelling studies carried out is presented. The main conclusions are that on the one hand, important insights on clogging processes in VF wetlands have been gained but, on the other hand, design parameters such as intermittent loading operation and the grain size of the filter media are not well represented in those studies. Clogging models use different conceptual approaches ranging from black box models to process based models.

Keywords: clogging; experimental; modelling; treatment wetland; vertical flow

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1. Introduction

Vertical flow (VF) wetlands are nowadays referred to as a mainstream technology for wastewater treatment. Due to their proven robustness as well as low costs for operation and maintenance, this technology is implement around the world to treat various polluted waters, e.g., domestic wastewater, combined sewer overflow, stormwater and all sorts of industrial wastewaters. [1–3]. VF wetlands evolved from the work of Seidel [4] and have been developed due to the legal requirements of ammonia reduction in the effluent. When nitrification is required, only a system providing a positive oxygen balance is appropriate. This led to the design of VF wetlands with intermittent feeding, where oxygen can enter the filter during the resting time [5–7]. Using the standard design, VF wetlands are suited for treating mechanically pre-treated wastewater. For the treatment of a raw wastewater, the so called French VF wetlands were developed. This system is capable of nitrification, but also stabilizes the accumulated sludge. For detailed descriptions, the reader is referred to the listed literature [1,8–10].

The main process leading to the malfunction of VF wetlands is clogging. Despite specific recommendations for design and operation by national guidelines and scientific literature [9,10], clogging is still listed as the number one problem. The main reasons for clogging of well-designed systems are failure or mismanagement of the pre-treatment and overloading of organic matter (OM) as well as suspended solids (SS). This has to be considered especially during the start-up time when plants and microorganisms are not yet fully developed. Two main processes leading to clogging can be identified, namely clogging due to SS and bioclogging. SS, which can be retained within the filter matrix due to sedimentation, filtration and attachment. Bioclogging occurs due to the growth of bacteria. What has to be kept in mind is that bacteria growth within the media is required to efficiently degrade wastewater pollutants, hence there needs to be a distinction between normal operation and dysfunctional clogging [11].

In order to get a perspective on the experimental and modelling research on clogging in VF wetlands, a literature search was conducted in the Scopus and Web of Science databases using the following search string: "vertical AND wetland AND clogging". The results (22 February 2019) provided 123 hits for Scopus and 108 for Web of sciences (18 results of the latter were not included in Scopus). Based on the abstracts, publications not having their main emphasis on clogging were eliminated. In the next step, conference papers and publications not available in English language were sorted. Based on the remaining 54 publications, the following sections are compiled, including the cited primary literature. Eleven publications were chosen to present the development of experimental studies on clogging within the last two decades. In the second part, eight publications were used to describe the different modelling approaches on clogging.

2. Clogging Processes in VF Wetlands

Clogging is defined as blockage and/or filling of the pore space which alters and hinders the movement of water and pollutants. Such behaviour is described by a decrease of the main soil's hydraulic properties of the filter media, namely the infiltration rate (k_i) at the surface, the hydraulic conductivity (k_f) within the filter body, as well as the local porosity. Due to the heterogeneity of the clogging development within the media, the effects can range from minor changes of the local flow velocities to the development of preferential flow paths and the exclusion of main parts of the filter. The built up of a clogging mat on the surface of VF wetlands leads to an uneven distribution of the wastewater, followed by exclusion of filter parts, surface ponding and overflow. Consequences thereof can be the risk of human contact with wastewater and the development of bad odour [12].

Clogging can be categorized by its spatial occurrence into inner and outer blockage, and is mainly influenced by the pre-treatment, the applied organic loading rate (OLR, g COD m^{-2} day^{-1}) and SS concentration (mg L^{-1}). Other influential parameters include the grain size distribution of the filter media, the feeding intervals and resting periods. Outer blockage occurs due to the accumulation of SS, namely particulate organic and inorganic matter, at the surface, while inner blockage happens within the filter media [13–15]. Two main types of clogging are identified, namely bioclogging and clogging due to SS. Bioclogging describes the blockage of the pore space due to surplus sludge production based on biofilm (BF) growth and microbial uptake. A BF is composed of extracellular polymeric substances (EPS) and cells which undergo replication producing biopolymers when sufficient nutrients are present [16]. Clogging due to SS describes the accumulation of SS on and its deposition within the filter. Caselles-Osorio et al. [17] differentiate two types of accumulated solids, namely interstitial solids entrapped in the empty space between the media and adhered solids which are tightly adsorbed by the media. Interstitial solids are easily released by washing and filtering while adhered solids need ultrasonic treatment to be released by the media.

The prevailing mechanisms for SS removal from the wastewater are transport, filtering and attachment [18]. Based on the particle size, different physio-chemical processes occur. Four main filtration mechanisms can be identified, namely (i) surface filtration, (ii) straining, (iii) bridging and (iv) physical-chemical filtration [19]. Surface filtration describes the accumulation of particles on the wetland surface which are larger than the pore size of the media. Straining defines a blockage within the media when the average particle size is smaller than the pore size but, depending on the local pore-size distribution, those particles are trapped within smaller pores. Bridging occurs when several particles smaller than the pore size arrive at the same time and together block the pore. This is mainly driven by high flow velocities [20].

Particles smaller than 10 µm are subjected to physical-chemical processes, namely electrostatic and London–Van der Waals forces. Those forces determine if particle–media or particle–particle associations are favourable. This depends on the charge of the media and the particle. If particles are already attached, the capacity of the media to attract more is limited, hence only small changes of the porosity are observed. Changes in water chemistry may destabilize particles which can form aggregates and attach via London–Van der Waals forces. These larger aggregates can have an impact on the local porosity. The actual attachment is controlled by hydrodynamic forces [19].

The aggregates of the filter media, as well as the BF, provide surface area for the attachment of decomposing biological matter. Microbial BF growth decreases the local porosity and the hydraulic conductivity, because cells and their EPS plug the pores between aggregates. Biological clogging will be enhanced if nutrient loadings are high [21].

3. Design and Operational Suggestions to Avoid Clogging

3.1. Design

In recent years, several national design guidelines for VF wetlands have been updated. The main suggestion is that by fulfilling these recommendations, the risk of clogging should be eliminated [1,9]. An overview on the main design parameters is given in Table 1. Detailed information including expected treatment efficiencies can be found elsewhere [1].

Table 1. Comparison of design parameters of VF wetland types to prevent clogging (adapted from [1]).

Type	Surface Area Per PE	Pre-Treatment	Media		OLR	Dosing
Single stage VF	4 m^2 4 m^2	Yes Yes	Sand Sand	0–2 mm 0–4 mm	20 20–27	>6 h >6 h
Two stage VF	2 m^2	Yes	Sand	1–4 mm/0–4 mm	80	>3 h
French VF	2–2.5 m^2	No	Fine gravel	2–8 mm/0–4 mm	100–350	3.5 day 7 day rest

Generally, three types of VF wetlands are implemented, namely the single stage system, the two-stage system and the French system. The single stage and the two-stage system are designed for the treatment of mechanically pre-treated wastewater. The single stage is designed with a surface area of 4 m^2 per person equivalent (PE) and is operated in unsaturated free flow conditions.

The two-stage VF wetland system [10,22] is designed by using 2 m^2 per PE. The first stage has a coarser filter media with a grain size of 1–4 mm and an impounded drainage layer (15 cm). In this faster flowing media, OM and nitrogen (after nitrification) is available in the impounded layer leading to denitrification. In the second stage (0–4 mm), the remaining COD and NH_4-N is treated.

The French VF wetland system [8] treats raw wastewater. Due to accumulation of sludge on the surface, this system is fed intermittently for 3.5 days followed by a resting period of 7 days, where the sludge is mineralized and the surface is opened up by wind induced plant stem movement. The recommended surface area is 2–2.5 m^2 per PE. One of the biggest VF wetlands implemented is a French system in Moldova treating the wastewater of up to 20,000 PE [23].

3.1.1. Filter Media

The grain size distribution of the media is crucial for the general operational strategy and pollutant removal performance of VF wetlands and can be related to the recommended OLR and hydraulic loading rate (HLR). Based on several studies, three different media sizes are identified, namely single stage systems using washed sand with a grain size of 0–2 mm and 0–4 mm respectively, two stage systems using a 1–4 mm sand in the first stage and 0–4 mm sand in the second stage and the French system, fed with raw wastewater having a 2–8 mm gravel in the first stage and a 0–4 mm sand in the second stage [9] (Table 1).

To prevent clogging, it is crucial to use washed sand. Parameters listed in the design guidelines to ensure the quality of the sand are the effective grain size d_{10} and the uniformity coefficient $U = d_{60}/d_{10}$. d_{10} and d_{60} describe the grain size under which 10% and 60% of the grains pass during sieve analysis (by weight), respectively. The German design guideline DWA-A262 [24] requests a grain size of 0–2 mm d_{10} = 0.2 to 0.4 mm and U < 5, for a size of 0–4 mm d_{10} = 0.25 to 0.4 mm and U < 5.

3.1.2. Loading

The OLR is one of the most crucial parameters. For single stage systems, the OLR can range from 20 to 27 g COD m^{-2} day^{-1} [9,13,25,26], 80 g COD m^{-2} day^{-1} for a two stage system [9,27] and 100–350 g COD m^{-2} day^{-1} for French VF wetlands [8,9]. It is important to note that the OLR is also a temperature dependent parameter, as the prevailing biological processes decrease with decreasing temperatures [28]. In order to avoid clogging, it is recommended to not only choose the appropriate OLR but also the related dosing strategy, which will be discussed in the next section.

3.1.3. Dosing Strategy

Intermittent feeding has proven to be a sufficient strategy to foster the preferred aerobic conditions in VF wetlands [25] and is compulsory based on several national design guidelines [1,9]. This operational strategy is also beneficial to hinder clogging as it supports an equilibrium in BF production [14].

During the resting period, three main processes prevail [29]. As no nutrients are available outside of the cells, microorganisms enter an endogenous respiration state which leads to a decrease in BF and EPS respectively. Oxygen can enter the filter by convection and diffusion. Convection is driven by the gradient of air pressure resulting in a vacuum produced by the effluent water. Diffusion can be related to the actual resting time. Platzer [6] gives a diffusion rate of 1 g O_2 m^{-1} h^{-1}. The availability of O_2 supports degradation processes during the resting period as accumulated SS are hydrolysed with its products adding another source of COD which has to be further degraded by bacteria [1,30].

3.2. Pre-Treatment

Pre- or primary treatment is an important step as it prepares the influent for biological treatment. Generally, it consists of a screen, grit removal and primary sedimentation. Grit includes well settleable inorganic and organic solids like sand, gravel, coffee grounds and seeds. The aim of the primary treatment is the reduction of the solid load on the wetland and should not exceed a SS concentration of 100 mg L^{-1} [13,31,32]. Regular maintenance of the pre-treatment facility is of the upmost importance to avoid solids carryover which will lead to clogging [1,33].

3.3. Effects of Macrophytes

In VF wetlands, macrophytes have mainly physical functions. Developed plant roots loosen the filter media, and plant stems break up the surface area due to wind-induced movement [34]. This effect is especially important for opening up the sludge deposition layer in the French system [35]. Decomposition of plant litter on the surface can lead to an increase in the COD and SS load [36], but a relation to clogging effects is not mentioned in the literature. Maintenance recommendations [1] when cutting is carried out in fall state that the plant material shall be left on the filter to provide insulation during winter.

4. Remediation Strategies

Available methods to remediate a fully clogged system can be characterized as destructive active or passive treatment methods. As shown in Table 2, destructive methods, either excavation and replacement or washing and reuse, are associated with high costs but have proven to be highly effective [25,37–39].

While passive treatment is carried out by applying a resting period for the clogged filter, active treatment offers various options. Several authors investigated the use of hydrogen peroxide (H_2O_2), an aggressive oxidation agent [40–42]. Based on their findings, good results are achieved within a short time period, but the method of application is crucial. The injection of 1600 L of H_2O_2

directly into the media of a 670 m^2 horizontal (HF) wetland was effective immediately. The use on the surface of a VF wetland (75 m^2, 100 L of 35% H_2O_2) was reported as insufficient, as the peroxide reacted with the clog matter on top of the filter but not within the subsurface media [42].

Table 2. Available remediation strategies for clogged wetlands.

Category	Method	Time Until Recovery
Destructive methods	Excavation and replacement using new media Excavation, washing and reuse of media	Within one day Several days
Active treatment	Application of oxidising agent Addition of solubilisation agent Enzyme treatment Addition of earthworms	Immediate up to several hours One week - Around 10 days
Passive treatment	Resting of the whole treatment wetland (TW)	10–20 days

Based on a laboratory study, three solubilisation agents, namely sodium hydroxide (NaOH), hydrochloric acid (HCl) and sodium hypochlorite (NaClO), were under investigation for the remediation of planted columns filled with gravel [43]. The clogging of the columns was accelerated by feeding with activated sludge. After a clogging state was reached (effective porosity was decreased from 27% to 5%), each agent was applied daily for one week. Results showed an increase of the effective porosity up to 15% (HCl), 18% (NaOH) and 25% (NaClO) respectively. Damage of plant roots was observed when using NaClO.

In a recent study [44], the use of hydrolytic enzymes, namely α-glucoamylase and β-glucan, to catalyse and hydrolyse large molecular polymers of the EPS was investigated to treat bioclogging. Results of column experiments show a positive effect by monitoring the hydraulic conductivity. For the remediation of a full scale treatment wetland (TW), large quantities are needed, resulting in high costs.

The application of earthworms accelerates the biodegradation of accumulated SS and can force translocation of clog matter from the pore space to the surface and thereby reduces the dry weight of clog matter on average by 56% [45]. Studies on VF wetlands [46,47] show an efficient remediation performance when using 0.5 kg m^{-2} of earthworms after 10 days, as well as their positive effect during ongoing operation.

Passive treatment is equal to applying an overall resting period on the clogged bed. During this time, bacteria enter an endogenous respiration state as no nutrient supply from outside the cell is occurring. These starvation conditions limit the microbial growth, hence decay of BF is the prevailing process [48,49]. Langergraber et al. [14] observed a recovery time of 14 days after clogging of an intermittent feeding system operating at an HLR of 250 mm day^{-1} and a TSS loading rate of 48 g TSS m^{-2} day^{-1}. Based on a VF column experiment using artificial wastewater without SS, the recovery time of the filter was achieved after one to three weeks [50,51], while others suggest 10 days in summer and 20 days in winter conditions [52].

5. Experimental Studies on Clogging

5.1. Methods to Evaluate Clogging Behavior

The quantification of accumulated SS within the pore matrix is mainly carried out by extracting a media sample, washing of the clog matter and determine its dry weight after drying at 105 °C. To determine the OM content, loss-on-ignition (heating to 550 °C) is used resulting in the measured mass of volatile SS (VSS) [53]. Based on this method, the conclusion was drawn that preferential accumulation of solids takes place in the upper layer of the VF wetland [54]. Two different types of SS accumulation are distinguished, namely interstitial solids which are trapped in the pore space and adhered solids which are tightly adsorbed on the media. While interstitial solids are the solids washed off, adhered solids are determined by ultrasonic treatment [17].

A direct correlation of accumulated solids and the decrease of hydraulic conductivity as well as the porosity is difficult to assess. The form, density and water retention characteristics of the solids effects the free volume available for water movement and therefore the local water content, hence the hydraulic conductivity [25,55]. To determine the hydraulic conductivity two in situ methods can be used, namely the falling head and the constant head method [56].

The change in porosity of different layers can be determined by the drainable porosity method. This method is mainly applicable for column experiments where the height of the water table can be more easily determined. Thereby the volume of water needed to fill the system from the bottom to a certain height is measured. A similar approach can be used to determine the hydraulic conductivity using Darcy's law by measuring the drainage volume over time [15].

In situ measurements of water content and matrix potential are done by using time domain reflectometry (TDR) probes and tensiometers. This provides detailed data describing the water flow for each feeding at different depths. Change in water content is a good indicator for the occurrence and extant of clogging [14].

The actual observation of the pore space by producing images is a promising method to directly investigate clogging processes. Kim and Forquet [57] used the "Thin Section Method" to produce 2D images of undisturbed samples. They analysed the images and estimated phase volume fractions and void size distribution. By using X-ray Computed Tomography in combination with image processing algorithms, actual 3D images of the pore space can be produced [58]. With this novel method, changes in pore morphology and retained solids' agglomeration by drying can be illustrated.

5.2. Experimental Studies

Based on the literature research, two main types of experiments are identified, namely experiments using continuous feeding and others using intermittent feeding operations. While the intermittent feeding operation is carried out in unsaturated conditions, continuous feeding experiments are carried out in unsaturated as well as saturated conditions.

Different types of wastewaters are used based on the objective of the study, namely real or synthetic wastewater. Table 3 presents the mixtures of synthetic wastewaters used in clogging investigations. Information on the different VF wetland experiments including filter media, loading rates and feeding schemas is given in Tables 4 and 5.

Table 3. Mixtures of synthetic wastewater used for investigation.

Study		Bioclogging	SS Clogging	Nutrients Added
Zhao et al.	[59]	Glucose	Starch	KNO_3, K_2HPO_4
Hua et al.	[60]	-	Lake sediment	-
Hua et al.	[61]	Glucose	-	$(NH_4)_2SO_4$, $CO(NH_2)_2$, K_2HPO_4,
Rajabzadeh et al.	[62]	Molasses, urea	-	$NH_4H_2PO_4$
Song et al.	[63]			not mentioned
Yang et al.	[31]	-	Zeolite powder	-
Zhou et al.	[64]	Glucose	Starch	NaCl, $(NH_4)_2SO_4$, $CO(NH_2)_2$, K_2HPO_4, $NaH_2PO_4{\cdot}12H_2O$, $MgSO_4{\cdot}7H_20$, $CaCl_2$

Langergraber et al. [14] investigated the effect of different HLRs on media clogging of pilot scale VF wetlands designed based on the Austrian guideline [65] and fed with real wastewater. Two different grain sizes of sand were used, namely 0–4 mm and 1–4 mm. Clogging occurred within the fine media for a HLR of 150 L m^{-2} day^{-1} after two months and in the coarse media at a HLR of 250 L m^{-2} day^{-1} after one month. Measured NH_4-N effluent concentrations were low also for high HLRs with removal rates of 99% for the fine and 90% for the coarse media. For early detection of clogging monitoring the water content within the substrate showed good results. For the 0–4 mm substrate, a linear increase in the residual water content before a dose was observed two weeks before clogging occurred. Based on soil physical and structural investigations, the main cause for clogging was found to be the SS load and not BM growth.

Hua et al. carried out several studies [60,66] using continuously fed column experiments to investigate clogging behaviour. In the first study [60], the accumulation of particulate inorganic matter, namely river sand, on top and within the filter was determined. The columns were loaded with a HLR of 500 L m^{-2} day^{-1} and an SS loading rate of 300 g SS m^{-2} day^{-1} and filled with different grain sizes of gravel, namely 3, 10 and 20 mm. Based on monitoring the infiltration rate and the effective porosity at different depths, the study concludes that firstly a blanket-like deposition layer is formed on top of the filter, followed by particles accumulating within the pore space in the first 0–4 cm. In a follow-up study, Hua et al. [66] investigate the time until clogging occurs, which was observed as 75, 120 and 240 days.

In the study by Sani et al. [15], column experiments using pea gravel of 10 and 20 mm grain size were fed with real wastewater. The feeding pattern used is described as continuously with a resting period, namely 72 or 36 h of feeding and 48h of rest. Two different OLRs were used, namely 11 and 22 g COD m^{-2} day^{-1}. The effluent quality, as well as the k_f and the SS distribution within the filter, were monitored. A change in porosity/k_f was measured but no clogging leading to malfunction of the columns occurred during the measurement campaign of one year.

Zhao et al. [59] investigated the effect of both bioclogging and clogging due to SS in column experiments using two synthetic wastewater receipts, one glucose based and one starch based. Each process was investigated by using five columns fed with different OLR. The effective porosity as well as the infiltration rate decreased with an increase in the OLR and was higher overall in the starch-fed system. The reduction of the effective porosity over the depth of the filter was as follows: for the glucose-fed system, an effect was measured over the total filter depth with a decreasing extant while the starch-fed systems were only affected within the first 25 cm. The influence of bioclogging on the infiltration rate was negligible. Therefore, the authors conclude that bioclogging is mainly accelerating already occurring clogging behaviour.

Hua et al. [50] investigated the effects of a resting period after clogging due to BF growth occurred. Therefore, glucose based synthetic wastewater was used to only trigger BF growth. The saturated columns were fed continuously for 90 days at a high HLR of 500 L m^{-2} day^{-1} and a BOD concentration of 600 mg L^{-1}. The influence a resting time was determined after 3, 7 and 10 days in different filter depths. Main BF accumulation was found in the top 20 cm of the filter. The recovery ratio for k_f was high after 7 and 10 days but started decreasing, while for the porosity it stayed constant. One explanation, therefore, was the remaining inert BF within the pore space. To evaluate the reduction of BF, polysaccharides and proteins were measured as a good correlation is stated. The anthrone–sulfuric acid method is used to measure polysaccharides and Coomassie Brilliant Blue G-250 colorimetry for the measurement of proteins. The quantity of EPS is calculated as the sum of both, and a significant decrease over the resting period is observed.

In a follow up study, Hua et al. [29] investigated the contribution of evapotranspiration (ET) as well as oxygen diffusion into the media to alleviate clogging. Oxygen transport was measured using an optical probe (Unisense, Aarhus, Denmark). Results show that oxygen enters the resting filter over time, supporting OM degradation. ET was calculated using an equation by Fujimaki and Inoue [67], which depends on the relative humidity (RH) within the media. RH was determined by measuring the water content. The results point out a contribution of ET but did not separate the evaporation and the transpiration by the plants.

Another experimental study investigated the effects of BF growth on the local porosity in a saturated VF column with a full water recirculation batch operation [62]. A constant oxygen influent concentration of 4–5 mg L^{-1} was supplied within the recirculation process. Every week, the column was drained and filled with new synthetic wastewater. Thereby the porosity was evaluated. BF development caused preferential flow and local porosity reduction in dead zones within the column after one year.

Song et al. [63] investigated the effect of different packing strategies on the nitrogen treatment performance and clogging behaviour in VF column experiments. Four layers with different grain sizes of sand where either in increasing or decreasing size stacked. A third column was packed universally with 5–6 mm sand. The operation followed a fill and drain pattern with an HRT of 10 h and a drainage time of 2 h. The OLR was alternated between high and low loads. BF accumulation was determined by the decrease in media water storage volume. COD and NH_4-N removal rates of 39%–46% and 28%–39% respectively for the high load regime. The coarse to fine layering (from top to bottom) showed the least reduction in the water storage volume.

The effect of aeration in a saturated VF wetland on clogging is that aeration influences the distribution over the depth of accumulated SS and promotes its mineralization as well as BF growth [68]. Compared to a non-aerated system, bioclogging becomes more of a factor.

Petitjean et al. [11] conducted a column experiment to investigate the interplay between clogging and oxygen concentration to identify parameters capable of determining clogging when it occurs. Their results show that the absence of oxygen within the filter was leading to clogging one day after. This also correlated with a decrease of measured NO_3-N while measured NH_4-N increased only nine days after clogging occurred. Measuring the oxygen concentration within the media using a portable gas analyser (Dräger X am 7000) is easy to do, but the as the oxygen content varies quickly, the time of observation is critical and therefore not practical. Observation of the NO_3-N effluent concentration combined with an observation of surface ponding can be a valid method to identify if clogging is occurring.

An investigation in the spatial and temporal distribution of accumulated insoluble inorganic particles was carried out by Yang et al. [31]. In total, 80%–90% of accumulated solids were distributed in within the first 6 cm [60] of the columns with a media height of 10 cm. In total, 15 columns were established. Every 15 days, one column was dismantled and separated into five 2 cm layers. Extracted media was washed and filtered using a microporous membrane of 0.45 µm. The dry weight represents the amount of interstitial solids. The media is than subjected to ultrasound treatment (Jiupin JP10-200) and filtered (0.45 µm) to quantify adhered solids. The particle size of accumulated solids is determined using a laser particle size analyser (Malvern MS-2000). The prevailing mechanism on particle accumulation was adsorption. Therefore, the pore space was reduced but not filled completely. At the end of the experiment, the number of large particles in the first 0–2 cm increased, leading to a significant reduction of the pore space. Based on these results, the importance of pre-treatment can be pointed out to reduce the SS influent load.

The interaction of EPS and SS is presented in a study by Zhou et al. [64]. Based on four saturated VF columns the impact of different synthetic wastewater mixtures on the clogging behaviour was under investigation. The four mixtures were glucose-based (Bioclogging), starch-based (Ip-clogging), starch with bacteriostatic (Op-clogging) and glucose with starch (C-clogging). Feeding was carried out until clogging, which occurred after 48, 24, 24 and 28 days respectively. In the following resting period, a reduced water level to 20 cm was established and porosity and k_f were monitored. The main conclusions were as follows: bioclogging is a main driver while SS accelerates clogging. Undegraded starch particles are compacted by EPS and reduce the porosity. Bioclogging, Op-clogging and C-clogging can be relieved by a resting period, especially when the water level is reduced.

Table 4. Operational description of experimental studies.

Authors		**Feeding**		**Wastewater**	*OLR* (*gCOD* m^{-2} *day*$^{-1}$)	*TSS* (*gTSS* m^{-2} *day*$^{-1}$)	*HLR* (*L* m^{-2} *day*$^{-1}$)	**COD** (**mg** L^{-1})	**TSS** (**mg** L^{-1})
Langergraber et al.	[14]	intermittent	every 6 h	real	5–100 * 5–120 *	8–29 8–48	40–150 40–250	100–700 * 100–700 *	50–300 * 50–300 *
Zhao et al.	[59]	continuously		synthetic	40–343	40	850	47–404	
Hua et al.	[60]	continuously		Lake sediments		300 300 300	500 500 500		
Sani et al.	[15]	continuously	72 h/36 h feeding 48 h rest	real real diluted	22 11	23 8	73	301 151	
Hua et al.	[50]	continuously		synthetic	300 (as BOD)		500		
Rajabzadeh et al.	[62]	continuously		synthetic				500	
Song et al.	[63]	fill and drain 10 h HRT 2 h draining		synthetic				112 236 113	
Ren et al.	[68]	continuously		real	66	28	800	82	35
Petijean et al.	[11]	intermittent	every 6 or 8 h	real	35	9	73	483	119
Yang et al.	[31]	continuously		synthetic		18.5	37		500
Zhou et al.	[64]	continuously		synthetic	163	137 68	815	200	168 84

* unpublished data.

Table 5. Description on the filter media used in the described experiments.

Authors		Media	$\frac{Size}{mm}$	Porosity	$\frac{kf}{cm\ s^{-1}}$	$\frac{d10}{mm}$	$\frac{d60}{mm}$	Cu
Langergraber et al.	[14]	Sand	0.063–4 1–4			0.13 1.1	1 3	7.69 2.73
Zhao et al.	[59]	Coarse sand		0.36	4.85×10^{-2}	1	4.4	4.4
Hua et al.	[60]	Gravel	3 10 20	0.34 0.44 0.47		2.5 6 15	5.8 11.4 25	2.32 1.9 1.67
Sani et al.	[15]	Pea gravel	10 20					
Hua et al.	[50]	Coarse sand				0.12	0.2784	2.32
Rajabzadeh et al.	[62]	Pea gravel	10					
Song et al.	[63]	Sand, 4 layers Sand, 4 layers Uniform	3–8 8–3 5–6					
Ren et al.	[68]	Sand						
Petitjean et al.	[11]	Sand	0–4			0.16	0.048	0.3
Yang et al.	[31]	Gravel	3–4	0.37	0.458			
Zhou et al.	[64]	Sand	1–2					

6. Model Concepts

In the field of treatment wetlands (TW), two main types of models can be identified, namely (i) models to design TW which is mainly done using so called black box models and (ii) the application of process-based models to describe the processes occurring within the wetland. The latter type of models are generally built up using several sub-models, usually including a water flow model, a transport model, a biokinetic model, a plant model and a clogging model [69]. Within the next section, several approaches on modelling clogging are described (including other sub-models when provided by the authors). Different approaches can be identified ranging from black box models to white box models. Black box models are data dependent and based on functions relating input to output without describing the occurring processes. White box models on the other hand describe the actual processes. Data in white box models are used for calibration and validation of the models only and are not needed for developing the model itself. In between, grey box models combine both approaches based on the existing knowledge [70].

The general approach for modelling clogging is described by determine the pore space reduction based on BF development and SS retention. This change alters the initial soil hydraulic parameters (SHP) of the initial or clean filter media, hence the water flow behaviour is changed.

The next subsections are divided based on the type of clogging modelled, namely clogging due to SS, bioclogging and both combined. The units of the described parameters are generalized using L as a length unit, M as a unit of mass and T as a unit of time. An overview on the discussed models is given in Table 6.

6.1. Clogging Due to SS

In the work of Hua et al. [66], a model to estimate the clogging time based on SS is described. The conceptual model considers the effluent concentration of SS as a function of the operation time which is influenced by the gradual reduction of the infiltration rate and the particle size distribution of SS. Clogging is described as pore volume reduction caused by the mass of SS accumulated as volume over time. A mass balance (Equation (1)) is used to determine the accumulated SS (M_{ss}, M) within the pore space based on the flow rate Q_{in} (L^3 T^{-1}) and the SS influent and effluent concentration (C_{in}, C_{out}, M L^{-3}). The SS mass in the outflow (M_{out}, M) is assumed to relate to a certain particle size (d_0), hence a fraction of the total mass (Equation (2)). The certain sized SS accumulated in the pores would be washed off when the flow rate is higher than that of the maximum tolerated impact speed. Therefore, $M_{\leq d0\%}$ is a function of the infiltration rate K (L T^{-1}) (Equation (3)). The calculation of K (Equation (4)) is based on the Hagen–Poiseuille equation in combination with Darcy's law and the porosity ε (-),

$$\frac{dM_{SS}}{dt} = Q_{in} \times \left(C_{in} - C_{out}\right) \tag{1}$$

$$M_{out} = M_{ss} \times M_{\leq d0\%} \tag{2}$$

$$M_{\leq d0\%} = f(K) \tag{3}$$

$$K = \varepsilon\left(\frac{\rho_w g}{u_w}\right)\left(\frac{d_0^2}{32}\right) \times \phi(t) \tag{4}$$

where g is acceleration of gravity (L T^{-2}), u_w is the viscosity of the fluid (M T^{-1} L^{-1}) and ρ_w is the fluid density (M L^{-3}). The authors further assume that K is a function of the operational time $\phi(t)$.

After n days of operation, the SS mass accumulated within the pore space ($M_{ss,n}$) is calculated as follows (Equation (5)): clogging is described as pore volume reduction, hence when a certain mass is reached the pore space is used up and a fully clogged state is reached. This threshold condition is described in Equation (6),

$$M_{ss,n} = M_{ss,n-1} + Q_{in,n} \times C_{in} \times \left\{1 - f\left[\varepsilon\left(\frac{\rho_w g}{u_w}\right)\left(\frac{d_0^2}{32}\right) \times \phi(t)\right]\right\} \tag{5}$$

$$\frac{M_{ss,n}}{\rho \times (1 - \omega)} \geq \varepsilon \times h_c \times A \tag{6}$$

where $\varepsilon \times h_c$ describes the total pore space per unit area (L), A (L^2) is the filter area, h_c is the height of the clogging layer (L) and ρ and ω are the density (M L^{-3}) and moisture content (%) of SS, respectively. Values for the last named parameters are not provided by the authors.

Sani et al. [15] present a model to describe the impact of SS on clogging. Three mechanisms are incorporated which affect particle transport in a filter, namely diffusion, sedimentation and particle adsorption. Settling and aggregation mechanisms are described in Equation (7),

$$\frac{\partial \varphi_i}{\partial t} = D\frac{\partial^2 \varphi_i}{\partial z^2} - (u - v_i)\frac{\partial \varphi_i}{\partial z} \pm \psi_i + \frac{q(z)}{A}\varphi_{i,in} \tag{7}$$

where φ_i is the SS concentration with particle sizes in the range of i (M L^{-1}), D is the dispersion coefficient (L^2 T^{-1}), z is the depth (L), u is the vertically flowing water velocity (L T^{-1}), v_i is the fall velocity or settling velocity of SS of particle size i (L T^{-1}), ψ_i is the source or sink term of the SS of particle size i (M L^{-3}) and is used to take account of the effect of the aggregation or break-up of particles, $q(z)$ is the lateral inflow to the wetland (L^3 T^{-1}), A is the wetland area (L^{-2}) and $\varphi_{i,in}$ is the concentration of the SS of size i in the lateral flow (M L^{-3}). For the described continuous flow system, Darcy's law (Equation (8)) is used to model the water flow where u is calculated as,

$$u = -K\frac{\partial H}{\partial z} \tag{8}$$

where K is the hydraulic conductivity (L T^{-1}), H is the water head (L) and z is the depth (L). Within Equation (7), lateral flow is neglected and effects of aggregation and breakup of SS are reflected by the dispersion coefficient and the settling velocity. A modified mass conservation model is given in Equation (9), where R is the source or sink term of SS,

$$\frac{\partial \varphi_i}{\partial t} = D\frac{\partial^2 \varphi_i}{\partial z^2} - (u - v_i)\frac{\partial \varphi_i}{\partial z} + R \tag{9}$$

Four sub-models (Equations (10)–(13)) provide the needed parameters for Equation (9). Two mechanisms can be described using dispersion, namely molecular diffusion and mechanical dispersion [71]. In this model, only mechanical dispersion is respected (Equation (10)),

$$D_{md} = \alpha \times u \tag{10}$$

where D_{md} is the mechanical dispersion ($L^2\ T^{-1}$), α is the dispersivity (L) and u is the velocity based on Equation (8). The settling velocity for SS is represented using Equations (11) and (12) [72].

$$v_i = w_0^i \times f_i \tag{11}$$

$$f_i = (1 - \varphi)^n \tag{12}$$

where w_0^i represents the terminal settling velocity of an isolated particle of size i, f_i is the hindered settling velocity, φ is the total particle concentration ($M\ L^{-3}$) and n is an empirical parameter given the value of 5.1 [72] as this represents the physical properties of the presented work [15]. The parameter w_0^i is an adjustable parameter representing the average effect of the sedimentation velocity of varied particle sizes. The last equation to solve Equation (9) is the description of the source or sink term R (Equation (13)). As attached BF supports SS accumulation, a form of the Monod equation [73] is used to describe particle adsorption.

$$R = -M_{bss} \times q_m \times \frac{\varphi}{\varphi_S + \varphi} \tag{13}$$

where M_{bss} is the adsorbed SS concentration on the substrate grains, q_m is the maximum growth rate (T^{-1}) and φ is the total SS concentration and φ_S represents the half-saturation-coefficient ($M\ L^{-3}$) of the Monod equation. The reduction of the hydraulic conductivity based on the decreasing pore space is taken into account using the Kozeny–Carman Equation (14) [74],

$$K = \frac{K_0}{\left[\left(1 + p\frac{D_{vtot}}{\varepsilon_0}\right)^x \left(1 - \frac{D_{vtot}}{\varepsilon_0}\right)^y\right]} \tag{14}$$

where D_{vtot} is the total volumetric specific deposit ($L^3\ L^{-3}$), K_0 is the hydraulic conductivity ($M\ T^{-1}$) and ε_0 the porosity (-) of the clean filter respectively and p, x and y describe empirical parameters (-).

6.2. Bioclogging

Mostafa and van Geel [75] present a microscopic conceptual model for bioclogging in unsaturated conditions. The voids in the unsaturated soil are simulated as capillary tubes with different diameters, where each diameter represents a volume of void space which can be filled at a certain capillary pressure. The capillary pressure–saturation relationship (Equation (15)) [76] and the permeability equation [77,78] are used to determine the relationship of the flow factors with and without BF. The relationship between capillary pressure and saturation is described by,

$$P_c = \frac{\left(S_e{}^{-\frac{1}{m}} - 1\right)^{\frac{1}{n}}}{\alpha} \tag{15}$$

where P_c is the capillary pressure (L) and α (L^{-1}), m and n are van Genuchten model parameters [76]. The radii of the capillary tube can be determined by (Equation (16)),

$$r_i = -\frac{2\sigma cos\beta}{P_{c,i}} \quad (16)$$

where r is the radii of the capillary tube (L), σ is the water surface tension (M T^{-2}) and β is the contact angle, which is generally set to 0. The bundle of capillary tubes representing the porous media is divided into a user specific number N. The thickness of the BF t_h (L) is calculated using Equation (17) where the microbial volume V_m (L^3) is an input parameter. Equation (18) defines the relationship between the clean filter media and the impact of the BF thickness on the media. In a last step, the hydraulic conductivity (L T^{-1}) is updated based on the BF thickness in Equation (19). Growth and decay of BF is described using the Monod [73] equation similar to Equation (20).

$$V_m = \sum_{i=1}^{N}\left[N_i\pi r_i^2 - N_i\pi(r_i - t_h)^2\right] \quad (17)$$

$$U = \frac{\sum_{i=1}^{N} N_i\pi(r_i - t_h)^4}{\sum_{i=1}^{N} N_i\pi {r_i}^4} \quad (18)$$

$$K(S_e) = K_{sat} \times \sqrt{S_e}\left[1 - \left(1 - {S_e}^{\frac{1}{m}}\right)\right]^2 \times U \quad (19)$$

Brovelli et al. [79] present a macro scale model describing the effect of BF growth on the hydraulic properties of saturated porous media. In their work, only BF in the immobile phase is considered. BF growth (Equation (20)) and decay (Equation (21)) are described using a Monod equation,

$$u = u_{max} \times \frac{C_{ea}}{K_{ea} + C_{ea}} \times \frac{C_S}{K_S + C_S} \quad (20)$$

$$d_r = k_d \times X \quad (21)$$

where u is the growth rate (T^{-1}), X is the BF concentration (M L^{-3}), u_{max} is the maximum growth rate (T^{-1}), C is the concentration of the substrate (M L^{-3}) and K is the half saturation constant (M L^{-3}). The subscripts *ea* and *s* stand for electron acceptor and substrate respectively. d_r represents the lysis rate with k_d as the first-order decay constant (T^{-1}). As within a porous media, the space for growth of BF is limited. Brovelli et al. [79] introduced a self-limiting function (Equation (22)) [80,81],

$$I_{bio} = \frac{X^{max} - (X_S + X_a)}{X^{max}} \quad (22)$$

where X^{max} is the maximum BF content of the porous media per mass of solids and X_S and X_a represent the current amount of mobile and immobile BF, respectively. I_{bio} is defined by an upper bound with a maximum near the porosity but generally should be smaller as with the increasing BF growth, nutrient transport becomes a diffusion-controlled process. To account for BF attachment and detachment, the authors [79] adopted the classical deep-bed filtration. Thereby, the attachment coefficient (T^{-1}) (Equation (23)) is described as [82,83],

$$k_{att} = \frac{3(1-n)v_P\eta}{2d_g} \quad (23)$$

where v_P is the pore velocity (L T^{-1}), d_g is the characteristic grain diameter (L) and η is the collector efficiency representing the frequency of collisions between mobile BF and grain surface (-). The collector efficiency is used by the authors as fitting parameter during model calibration as its general determination is difficult to assess [83]. Detachment due to shear forces is well discussed within the literature providing different approaches from dismissal [84] to simplified laws independent from the flow velocity. Here, a semi-empirical equation proposed by Rittmann [85] (Equation (24)) is used,

$$k_{det} = c_d \left(\frac{\gamma v_p (1-n)^3}{d_g^2 n^3 M} \right)^{0.58} \tag{24}$$

where k_{det} represents the detachment rate (T^{-1}), γ is the viscosity of water ($M\ L^{-1}\ T^{-1}$), M is the specific surface area (L^2) and c_d is an empirical parameter which is dependent on the experimental setup and calibrated for the work of Brovelli et al. [79]. Rittmann [85] proposes a value of 2.29×10^{-6}. When combining Equations (20) to (24) one gets the variation of BF over time,

$$\frac{\partial X_s}{\partial t} = u_s I_{bio} X_s - k_d X_s - k_{det} X_s - k_{att} X_a \tag{25}$$

$$\frac{\partial X_a}{\partial t} = u_a I_{bio} X_a - k_d X_a - k_{det} X_s - k_{att} X_a \tag{26}$$

where the subscripts s and a refer to the immobile and mobile BF, respectively. As BF consists of up to 95% water, their density is assumed equal to that of water. Furthermore, the fraction of soil grains and water phase remain constant over time, hence solid BF is expressed as pore-fluid concentration instead of concentration per unit of soil [79]. The porosity of the filter media and its reduction due to BF as calculated in Equations (27) and (28) are described as follows,

$$n = n_0 - n_{bio} \tag{27}$$

where n is the current porosity, n_0 is the porosity of the clean material and n_{bio} the porosity when occupied by BF. The latter represents the sum of different components of the BF, namely multiple bacteria strains, EPS and macromolecules. Therefore, n_{bio} is calculated as,

$$n_{bio} = \sum_{i=1}^{n} \frac{X_S^i \rho_b}{\rho_S^i} \tag{28}$$

where X_S^i represents the dry weight of the ith component of the immobile BF (M), ρ_b is the bulk density of the clean porous media ($M\ L^{-3}$) and ρ_S^i is the density of the ith component of the immobile BF ($M\ L^{-3}$). The change of the hydraulic conductivity based on the reduction of the pore space has been investigated based on experiments providing an exponential relationship (Equation (29)) [86,87],

$$\begin{gathered} K_{rel}(n_{rel}) = n_{rel}^p,\ p > 0 \\ K_{rel} = \frac{K}{K_0},\ n_{rel} = \frac{n}{n_0} \end{gathered} \tag{29}$$

where K_{rel} and n_{rel} are the relative hydraulic conductivity ($L\ T^{-1}$) and porosity (-), respectively, the subscript 0 represents the value of the clean media and, based on fitted data, $p = 19/6$. The model based on Equation (29) assumes that BF clogs bigger pores first [86]. Another model describing the reduction of the hydraulic conductivity is based on pore network simulations where the assumption is in contrast with the description above stating that BF growth occurs first in the smaller pores [88]. This so called colonies model (Equation (30)) is described as

$$K_{rel}(n_{rel}) = a \times \left(\frac{n_{rel} - n_{rel}^0}{1 - n_{rel}^0} \right) + (1-a) \times \left(\frac{n_{rel} - n_{rel}^0}{1 - n_{rel}^0} \right)^2 \tag{30}$$

where a and n_{rel}^0 are adjustable parameters and $1 - n_{rel}^0$ being interpreted as the relative volume of BF needed to get a maximum reduction of the hydraulic conductivity. This maximum reduction occurs when n_{rel} approaches n_{rel}^0. Good agreement on the model fitting is found in the literature [84] with values between 0.4–0.9 for n_{rel}^0 and −1 to −1.9 for a. A third model presented assumes a single, connected layer of BF covering the wall of each pore leading to a reduction of the pore radius [88]. Equation (31) presents the relationship of the hydraulic conductivity and the porosity as follows,

$$K_{rel}(n_{rel}) = \left[\left(\frac{n_{rel} - n^0_{rel}}{1 - n^0_{rel}}\right)^b + K_{min}\right] \times \frac{1}{1 + K_{min}} \tag{31}$$

where K_{min} is the lower limit of the hydraulic conductivity. A good fit of the model was reached using parameters n^0_{rel} in the range of 0.2–0.4 and 6×10^{-3}–6×10^{-2} for K_{min}. Within the model, the update of the hydraulic conductivity is carried out using the presented Equations (29)–(31) but no detail on which is actually used, nor a comparison of modelling results, is given.

Rajabzadeh et al. [62] implemented a computational fluid dynamics (CFD) model in COMSOL, accounting for spatial and temporal dynamics in VF wetlands. The model combines five sub-models, namely a fluid transport model, a solute transport model, a biokinetic model, a BF detachment model and a clogging model. The local porosity is estimated based on a BF model considering two mechanisms, namely growth of BF due to organic pollutants and the effect of fluid shear stress on local BF detachment. Darcy's equation provides a linear relationship between hydraulic gradient and the flow velocity in porous media, ignoring the viscosity as well as inertia effects of the fluid flow. For the coarse media used (pea gravel) (Table 5), the relationship between velocity and hydraulic gradient can be non-linear [89], hence the Brinkman model, which extends Darcy's law, is used (Equations (32) and (33), combining the continuity equation and momentum balance equation,

$$\frac{\partial}{\partial t}\left(\varepsilon_p \rho\right) + \nabla \times (\rho u) = Q_{br} \tag{32}$$

$$\frac{\rho}{\varepsilon_p}\left(\frac{\partial u}{\partial t} + (u \times \nabla)\frac{u}{\varepsilon_p}\right) = \nabla p + \nabla\left[\frac{1}{\varepsilon_p} u\left(\nabla u + (\nabla u)^T - \frac{2}{3} u(\nabla u)\right) I\right] - \left(\frac{u}{K} + Q_{br}\right) u + F \tag{33}$$

where μ is the dynamic viscosity (M L^{-1} T^{-1}), u is the velocity vector (L T^{-1}), ρ is the density of the fluid (M L^{-3}), p is the pressure (Pa), ε_p is the porosity (-), K is the permeability (L^2) and Q_{br} is defined a mass source/sink (M L^{-3} T^{-1}). The influence of volume forces such as gravity is respected by the force term F (M L^{-2} T^{-2}). As the column experiment was carried out in saturated conditions, a single phase flow model was used. The solute transport is described by a simple advection-diffusion Equation (34), incorporating the biokinetic model within the source/sink term R,

$$\frac{\partial c}{\partial t} = \nabla(D \nabla c) - (u \times \nabla c) + R \tag{34}$$

where c is the solute concentration (M L^{-3}), D is the molecular diffusivity (L^2 T^{-1}) and R is the reaction rate for the solute (M L^{-3} T^{-1}) derived from a biokinetic model. The biokinetic model used in cooperates the processes of mineralization, hydrolysis, growth and lysis of heterotrophic bacteria (XH), respectively and is based on the work of Langergraber and Simunek [90]. For OM, three fractions are respected, namely, readily, slowly and inter OM. Hydrolysis of slowly to readily available OM is described in Equation (35), while the growth and decay of XH on readily OM is described by Equation (18),

$$\frac{dS_S}{\partial t} = k_h \times \frac{\frac{C_S}{X_H}}{k_x + \frac{C_S}{X_H}} \times X_H \tag{35}$$

where k_h and k_x are rate constants for hydrolysis (T^{-1}) and saturation/inhibition of hydrolysis (M M^{-1}), S_S is the readily available OM concentration (M L^{-3}) and C_S is slowly available OM (M L^{-3}).

$$\frac{dX_H}{\partial t} = u_{max,H} \times \frac{S_S}{K_S + S_S} \times X_H - b_{ina,H} \times X_H \tag{36}$$

where $u_{max,H}$ ist the maximum aerobic growth rate (T^{-1}), $b_{ina,H}$ is the lysis rate (T^{-1}) and K_S is the half saturation coefficient ($M\ L^{-3}$). The removal of S_S is further described by Equation (37),

$$\frac{dS_S}{\partial t} = -\frac{1}{Y_H} u_{max,H} \times \frac{S_S}{K_S + S_S} \times X_H \tag{37}$$

where Y_H is the yield coefficient representing the stoichiometric link between BF growth and OM consumption and is defined as BF production by OM consumption ($M\ M^{-1}$). The next sub-model describes the BF detachment rate [85] implement in this model (Equation (38)). BF detachment is caused by fluid shear stress and is based on the flow rate, and therefore increases the local porosity.

$$b_{det,H} = 2.29 \times 10^{-6} \left(\frac{uu\left(1 - \varepsilon_p\right)^3}{dp^2 \varepsilon_p{}^3 M} \right)^{0.58} \tag{38}$$

where $b_{det,H}$ (T^{-1}) is the BF detachment rate, *dp* is the average spherical gravel diameter (L) and *M* is the specific surface area of the filter media (L^{-1}). The parameter M is determined by using a uniform gravel size with a spherical shape.

The fifth model, namely the clogging model, describes the hydrodynamic change caused by BF development within the pore space. Therefore, the local porosity at each time step is calculated based on the estimated BF concentration (Equation (39)),

$$\varepsilon(x, y, t) = \varepsilon_0 \left(1 - \frac{X_H(x, y, t)}{\rho_{Biofilm}} \right) \tag{39}$$

where $\varepsilon(x, y, t)$ is the calculated local porosity (-), ε_0 is the initial porosity (-) and $\rho_{Biofilm}$ is the BF density ($M\ L^{-3}$). With this information, the relative change in local porosity and its effect on the permeability is calculated using the Kozeney–Carman Equation (40) [91] and is used to update the velocity and pressure profile (Equations (32) and (33),

$$K(x, y, t) = K_{t=0} \left(\frac{\varepsilon(x, y, t)}{\varepsilon_0} \right)^3 \left(\frac{1 - \varepsilon(x, y, t)}{1 - \varepsilon_0} \right)^{-2} \tag{40}$$

A parameter efficient bioclogging model is presented Hua et al. [92]. Water flow is described by using the Darcy Equation (42) and the Kozeny–Carman Equation (49) [93] for the relationship between hydraulic conductivity and porosity. The change of BF accumulated within the pore space is described by an advection-reaction (41). Only BOD as substrate for BF growth is respected.

$$\frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial x} - r \tag{41}$$

where *C* is the substrate concentration ($M\ L^{-3}$) and u is the pore-water velocity ($L\ T^{-1}$) described as

$$u_{i,j} = K_{i,j} \times \frac{i_{i,j}}{n_{i,j}} \tag{42}$$

where *i* is the hydraulic gradient (-), *K* is the hydraulic conductivity ($L\ T^{-1}$) and *n* is the porosity (-). The subscripts *i* and *j* represent the time index and the space grid index, respectively. The reaction term *r* is represented by the following equation,

$$\frac{\partial C}{\partial t} = -k \times C \times BM \tag{43}$$

where *k* is the degradation rate constant (T^{-1}). The BF growth is described by

$$\frac{\partial BM}{\partial t} = -\frac{\partial C}{\partial t} - k_d \times BF \quad (44)$$

where k_d is the lysis rate of BF (T^{-1}). Here the authors claim using the Monod equation, but BF growth is only related to consumption of substrate as well as lysis. The substrate concentration within the micro region for the time step Δt is described as

$$C'_{i,j} = C'_{i-1,j} exp\left[\frac{-\lambda(x_i - x_{i-1})}{2} \times \left(\frac{1}{u_{i-1,j}}\right) + \frac{1}{u_{i,j}}\right] \quad (45)$$

where λ represents the deposition coefficient (T^{-1}) of BF and is determined empirically by Kretzschmar et al. [94] as,

$$\lambda = \frac{v}{L} ln\left(\frac{C_0}{C}\right) \quad (46)$$

where v is the flow velocity ($L.T^{-1}$), L is the column length (L) and C_0 and C represent the influent and effluent BOD concentration ($M.L^{-3}$), respectively. The total amount of BF deposition $\sigma_{i,j}$ ($M\ L^{-3}$) is calculated as

$$\sigma_{i,j} = \sum_{j=1}^{j} \lambda C'_{i,j} \Delta t \quad (47)$$

The change in porosity based on deposited BF and follows

$$n_{i,j+1} = n_0 - \frac{n_{i,j} \times \sigma_{i,j}}{\rho_s} \quad (48)$$

where ρ_s is the BF density ($M\ L^{-3}$) and n_0 is the initial porosity. The update of the hydraulic conductivity $K_{i,j+1}$ is finally carried out using the Kozeny–Carman equation

$$K_{i,j+1} = K_{i,j} \times \left(\frac{n_{i,j+1}}{n_{i,j}}\right)^3 \times \left(\frac{1 - n_{i,j+1}}{1 - n_{i,j}}\right)^2 \quad (49)$$

6.3. Bioclogging and SS Clogging

With FITOVERT [95], a model is presented to model unsaturated water flow, transport of dissolved as well as particulate components and a biodegradation model. To describe clogging, a model is formulated for the reduction of the porosity due to BM growth and accumulation of particulate matter. The one dimensional model formulation was developed using the Matlab®(Natick, MA, US) environment. Within the model domain, different layers can be implemented which are described by van Genuchten–Mualem SHP [76,78]. The variable saturated water flow is described by the Richards Equation (50) [96],

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} - 1\right)\right] \quad (50)$$

where θ is the volumetric water content ($L^3\ L^{-3}$), t is the time (T), z is the spatial coordinate (L), K is the unsaturated hydraulic conductivity ($L\ T^{-1}$) and h is the matrix potential (L). The relationship between the pressure head, hydraulic conductivity and water content are described by the van Genuchten–Mualem model (Equations (51)),

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha \times h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (51)$$

$$K(h) = K_S \times S_e^l \times \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2, \qquad m = 1 - \frac{1}{n} \tag{52}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{53}$$

where θ_r is the residual and θ_s the saturated water content (L^3 L^{-3}) as well as K_S are the saturated hydraulic conductivity (L T^{-1}). The empirical parameters α (L^{-1}) m and n influence the shape of the functions $\theta(h)$ and $K(h)$, and l is defined as the pore-connectivity parameter. Se equals the effective water content as shown in Equation (51a). Transport of dissolved components is described using Bresler's equation (Equations (54)) [97],

$$\theta \times \frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(d \times \frac{\partial C}{\partial z}\right) - q \times \frac{\partial C}{\partial z} + R \times \theta \tag{54}$$

where C is the concentration of a single soluble component in the liquid phase (M L^{-3}), d is the dispersion coefficient (L^2 T^{-1}), q is the specific flow rate (L T^{-1}) and R is the reaction term. The dispersion coefficient accounts for diffusion and mechanical dispersion, but the authors assume that in the liquid phase the effect of diffusion compared to dispersion can be neglected. Under saturated conditions and constant flow, the mechanical dispersion is considered to be proportional to the average flow velocity and dependent on the dispersivity λ (L),

$$d = \lambda \times \frac{q}{\theta} \tag{55}$$

The authors assume further that the same relationship is true for unsaturated conditions. The reaction term R is determined by the biokinetic model implement based on the Activated Sludge Model 1 (ASM1) [98] describing the degradation of 13 components, seven of which are dissolved and six are particulate. Detailed information is missing within the original publication. The transport and filtration of particulate components is described using the sand filtration process [99],

$$-q\frac{\partial T_m}{\partial z} = +\theta\frac{\partial T_m}{\partial t} + q \times f \times T_m \tag{56}$$

where T_m is the concentration of each single particulate component in water (M L^{-3}) and f is the filter coefficient (L^{-1}). The reduction of the porosity is related to the total volumetric specific deposit D_{vtot} (L^3 L^{-3}), which is continuously updated. How this parameter is determined is not further described. The effect of the change in porosity on the hydraulic conductivity is described using the Kozeny–Carman Equation (57) [100],

$$K = \frac{K_0}{\left[\left(1 + p\frac{D_{vtot}}{\varepsilon_0}\right)^x \left(1 - \frac{D_{vtot}}{\varepsilon_0}\right)^y\right]} \tag{57}$$

where K_0 is the hydraulic conductivity (L T^{-1}), ε_0 is the porosity (-) of the clean filter respectively and p, x and y describe empirical parameters (-).

Hua et al. [101] developed a clogging model describing the pore volume reduction based on BF growth, SS retention and plant detritus. The model calculates the mass of each substance contributing to clogging and converts it to the volume reduction within the pore space. The overall application is the calculation of the operational time until the porosity is near zero, hence full clogging is reached. Influent parameters are defined as inert SS and BOD, as well as plant roots. SS and BOD are considered within one sub-model and plant root detritus in another sub-model. The model is based on the mass balance of the named contributors,

$$\frac{dM}{dt} = F_{in} - F_{out} + S \tag{58}$$

where M is the total solid mass (M), F_{in}/F_{out} represent the influent and effluent mass (M T^{-1}) and S the source/sink term (M T^{-1}) representing reaction and conversation rates. This is used as analogues for the influent parameters SS (M_{IS}) and BF solids (M_{BS}), contributing to SS clogging and bioclogging, respectively. The accumulation of total solid mass is represented by Equation (59). Two source terms represent the contributing loads from either BF development based on BOD (S_{BS}, (Equations (60)) and from inert matter production (S_{IS}, (Equations (61)),

$$\frac{dM_{TS}}{dt} = \frac{dM_{IS}}{dt} + \frac{dM_{BS}}{dt} \tag{59}$$

$$S_{BS} = \frac{Q_{in} \times C_{BOD} \times Y_H}{1 + K_d \times \theta} \tag{60}$$

$$S_{IS} = f_p \times K_d \times \theta \times S_{BS} \tag{61}$$

where Q_{in} is the influent flow rate (L^3 T^{-1}), t is the time (T), C_{BOD} the BOD influent concentration (M L^{-3}), Y_H is the observed yield for heterotrophic BF (-),K_d is the heterotrophic microbial endogenous decay coefficient (T^{-1}), θ is the mean residence time of biosolids within the system (T) and f_p is the fraction of microbial BM converted to inert matter (-).

While $F_{in,BS}$ is represented by the BOD influent concentration, $F_{in,IS}$ is calculated using Equation (62). The effluent mass of each parameter, represented by F_{out} is assumed to be proportional to their respective influent mass (Equations (63)),

$$F_{in,IS} = Q_{in} \times C_{SS} \times (1 - f_v + f_v \times f_{nv}) \tag{62}$$

$$F_{out} = F_{in} \times \lambda \tag{63}$$

where C_{SS} is the SS influent concentration (M L^{-3}), f_v is the proportion of organic matter in SS (-), f_{nv} is the proportion of the inert matter in the organic SS (-) and λ is a proportional factor with a value between 0 and 1. The authors are aware of the simplification representing BF detachment and SS retention. In addition, Hua et al. [101] introduce a model predicting the effect of plant roots on clogging depending on two seasons, namely the growing season (Equations (64)) and the non-growing season (Equations (65)). During the growing season plant BM is increasing while during the non-growing season plant decay is prevailing,

$$\textit{Growth season}: \ \frac{dM_{plant,L}}{dt} = M_{plant,L} \times (f_{NH} + f_{NO} - b_P) \tag{64}$$

$$\textit{Non growth season}: \ \frac{dM_{plant,L}}{dt} = M_{plant,L} \times b_P \tag{65}$$

where $M_{plant,L}$ is the living plant BM (M), b_P (T^{-1}) is the plant decay coefficient for living plant material, f_{NH} is the plant growth rate depending on ammonia and f_{NO} is the plant growth rate depending on nitrate (T^{-1}). Those growth rates are calculated as follows,

$$f_{NH} = k_{pl} \times \left(\frac{C_{NH}}{K_{pNH} + C_{NH}} \right) \tag{66}$$

$$f_{NO} = k_{pl} \times \left(\frac{C_{NO}}{K_{pNO} + C_{NO}} \right) \times \left(\frac{K_{pNH}}{K_{pNH} + C_{NH}} \right) \tag{67}$$

where k_{pl} is the relative plant growth rate (T^{-1}), K_{pNH} and K_{pNO} (M L^{-3}) are the half saturation coefficients for ammonia and nitrogen respectively and C_{NH} and C_{NO} are the influent concentrations (g m^{-3}) for ammonia and nitrogen respectively. Due to plant decay, dead plant BM is produced. The change of this mass over time is calculated using Equation (68),

$$\frac{dM_{plant,D}}{dt} = M_{plant,L} \times b_p - M_{plant,D} \times k_{deg} \tag{68}$$

where $M_{plant,D}$ represents the dead plant BM (M) and k_{deg} is the first order decay rate (T^{-1}) representing the loss of BM due to physical degradation processes such as physical degradation and invertebrate consumption. The total plant BM for the growth season (Equations (69)) and non-growth season (Equations (70)) is calculated by combining Equations (64) and (65) with Equation (68).

$$Growth\ season: \ \frac{dM_{plant}}{dt} = M_{plant,L} \times (f_{NH} + f_{NO}) - M_{plant,D} \times k_{deg} \tag{69}$$

$$Non\ growth\ season: \ \frac{dM_{plant}}{dt} = -M_{plant,D} \times k_{deg} \tag{70}$$

The underground portion of the plant mass is then computed as follows,

$$M_{root} = M_{plant} \times \eta \tag{71}$$

where η is the root shoot ratio (-). In a final step, the models are coupled to predict the total volume occupied by the total solids M_{TS} (Equations (59)) and the root mass M_{root} (Equations (71)),

$$V_T = \frac{M_{TS}}{\rho_S \times (1 - \omega)} + \frac{M_{root}}{\rho_{root}} \tag{72}$$

where ρ_S and ω are the density (M L^{-3}) and the moisture content (-) of the total solids and ρ_{root} is the density of the plant roots (M L^{-3}). The time after full clogging is reached is determined over the operational time of the model run and the following criteria,

$$V_T \geq \varepsilon \times h_c \times A \tag{73}$$

where ε is the porosity (-), h_c (m) is the depth of the filtration layer and A is the surface area (L^2).

Table 6. Overview on the modelling studies investigated.

Reference		Description	Clogging	Model Type	SHP Update	Sub-Model
Hua et al.	[66]	Estimate clogging time based on SS influent and effluent data	SS	BB	Non	Based on mass balance
Sani et al.	[15]	Describe the impact of SS on clogging	SS	GB	Kozeny-Carman	Water flow Mechanical dispersion Settling Adsorption
Mostafa and van Geel	[75]	Conceptual model describing the impact of BF growth on the SHP	BC	WB	Change of porosity	Water flow Change of SHP based on reduction of pore space
Brovelli et al.	[79]	Simulate effect of biomass on SHP in saturated conditions	BC	WB	Change of porosity	Biokinetic model BF attachment and detachment
Rajabzadeh et al.	[62]	Effect of BF on permeability in saturated conditions, including BF detachment due to shear stress	BC	GB	Kozeny-Carman	Fluid transport Solute transport Biokinetic model BF detachment Clogging
Hua et al.	[92]	Parameter efficient model to describe bioclogging based on colloid transport models	BC	BB	Kozeny-Carman	Water flow Solute transport (advection) Linear growth of BF Clogging model
Giraldi et al.	[95]	Forecast behaviour and treatment properties due to clogging	SS, BC	GB	Kozeny-Carman	Water flow Solute transport Biokinetic model Transport and filtration of SS
Hua et al.	[101]	Clogging time based on influent of SS, BF, development on BOD and Plant detritus	SS, BC, P	BB	Non	BF, SS based on mass balance Plant clogging model

SS: suspended solids, BC: bioclogging, P: plant detritus; BB: Black Box, GB: Grey Box, WB: White Box; SHP: soil hydraulic parameters.

7. Summary and Conclusions

7.1. Experimental Studies

Throughout the literature, not many practical definitions on the extent of clogging are given. The authors mainly use the expression "clogged" to escribe a fully clogged system. Only one study evaluated different stages of clogging. Based on the observations of 21 VF wetlands, three categories of clogging were defined as the extent of permanent surface ponding between two loadings [13] (Table 7).

Table 7. Identification and classification of clogging (adapted from [13]).

Degree of Clogging	Description
Clogging	>80% of the surface is permanently ponded between two loadings
Partly clogged	30%–70% of the surface is ponded between two loadings
No clogging	<30% of the surface is ponded between two loadings

As presented, most studies are well documented, but usually some information is missing and full comparability is not given (Tables 4 and 5). Table 8 presents a recommendation on data necessary to fully describe an experimental setup of VF wetlands, not only for studies on clogging.

Table 8. Recommendations on information for describing VF wetland experimental setups.

Geometry of Plot/Column	Filter Media	Loading Rates	Quality Parameters
Diameter or length width	Material used	OLR	COD
Area	General grain size distribution	HLR	SS
Total height	d_{10}, d_{60}	SS LR	VSS
Height of main layer	Porosity	Loading interval	NH_4-N
Height of other layer	Hydraulic conductivity	Duration of a single dosing	NO_3-N

In most experimental studies, the system is overloaded on purpose to get a fully clogged system in a short period of time for investigation. From studies investigating both types of clogging it can be concluded that SS is the main contributing factor to clogging. Only the study by Zhou et al. [64] comes to a different conclusion. In this study, bioclogging occurred faster within the glucose fed column than in the column investigating clogging due to SS. This can be explained by the rather high OLR (163 g COD m^{-2} day^{-1}) used compared to other studies (Table 4). Generally, it can be concluded that

- A general definition of clogging in various states is missing.
- The majority of the experimental studies in the literature used continuous loading to fast track clogging of the system.
- Besides analyses of occurring processes, the impact of resting on the recovery is observed and its importance pointed out. This strongly supports the importance of the intermittent loading operation used in the design guidelines [9].
- For future studies on clogging processes, using real life operation is highly recommended to close the gap between experimental studies and implemented systems.

7.2. Modelling

As stated in Table 6 several models are set up as black box models, which provide good results but are only valid for the system under investigation. Fitted parameters cannot not be transferred to other systems, hence will need new fitting based on measured data. In order to get a deeper understanding of the underlying processes, grey box or white box models need to be developed further.

Existing water flow models follow two main approaches. Often, Darcy's law is used which is a simplification when describing water flow in unsaturated conditions as the hydraulic conductivity is depended on the water content. This is respected when using the Richards equation in combination with a soil hydraulic model such as the one by van Genuchten–Mualem [76,102]. Here it should be mentioned, that by using this particular model only uniform or matrix flow is respected. Preferential flow, when occurring, cannot be described [103–105].

For updating the SHP of the filter material the semi empirical Kozeny–Carman equation, providing a porosity-permeability relationship is used regularly [62,95]. This equation which is based on a power function of the effective saturation, gives a relationship between the permeability, the porosity and the grain size and assumes Darcian flow which describes laminar flow and low pore water velocity. For media used in VF wetlands, this assumption might not be true [93]. Another approach, introduced by Mostafa and van Geel [75], is based on the work of Mualem [78] describing and changing unsaturated flow parameters based on the soil water retention curve. By using the capillary model, an applicable concept for the representation of the pore space and its change due to BF development is available. Based on this conceptual model Soleimani et al. [106] set up a two-dimensional unsaturated flow and transport model. For describing the BF growth the Monod equation is used. Their results show that the time until a clogged state is reached depends on the SHP of the media described by the van Genuchten–Mualem model [76]. The most influential parameters are the saturated hydraulic conductivity, the residual water content and the parameter n. The work by Samso et al. [107,108] is mainly concerned with HF wetlands but also provides a model implementation for variable saturated porous media [109] based on the concept of Mostafa and van Geel [75] to describe the change of porosity and hydraulic conductivity. Water flow is described using the Richards equation and BM growth using the Monod equation. Results showed that the model calculates the same BF thickness in all pores, hence also within bigger pores where no water content is expected. Still, this can be also related to a residual water content in big pores [75] but should be further investigated. Generally, it can be concluded that

- A variety of modelling concepts are available to describe clogging processes in VF wetlands, ranging from simple black box models to deterministic process based models describing the actual processes.
- Thereby different contributing factors, alone or in combination, are included, namely clogging due to SS, bioclogging and plant detritus.
- Interactions between those contributors are, up to now, not implemented in existing models.
- The main sub-models used [69] follow the same concepts over all modelling studies despite different details in the implemented versions.
- Only a small fraction of the sub-models describe water flow in unsaturated conditions.
- Detailed information on model parameters is often missing.

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Abbreviations

BF	Biofilm	PE	Person equivalent
BM	Biomass	RH	Relative humidity
CFD	Computational fluid dynamics	SHP	Soil hydraulic parameters
COD	Chemical oxygen demand	SS	Suspended solids
EPS	Extracellular polymeric substances	TDR	Time domain reflectometry
ET	Evapotranspiration	TSS	Total suspended solids
HF	Horizontal flow	TW	Treatment wetland

HLR	Hydraulic loading rate	VF	Vertical flow
OLR	Organic loading rate	VSS	Volatile suspended solids
OM	Organic matter	XH	Heterotrophic bacteria

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