AGENCE FRANÇAISE
POUR LA BIODIVERSITÉ
ÉTABLISSEMENT PUBLIC DE L'ÉTAT

Guides and protocols

Constructed wetlands for domestic wastewater treatment under tropical climate

Guideline to design tropicalized systems

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Acknowledgements

The authors warmly thank the following people for their invaluable contributions.

■ For monitoring and supervising various systems in the French overseas departments
Hugues DELANNAY (Water Authority—Guadeloupe), Nicolas FINA (COTRAM—Sanitation Division), Sarah GOBERT (Water Authority—Guadeloupe), Bruno GREZILLER (DEAL—Mayotte), Gérald LACOMBE (Étiage—French Guiana), Olivier LAPORTE-DAUBE (Étiage—French Guiana), Frédéric L'ETANG (SICSM—Espace Sud), Andinani M'GUEREZA (SIEAM), Lucas PELUS (Water Authority—Martinique), Christophe RIEGEL (SIEAM), Leslie VEREPLA (CANGT).

■ For feedback from the field on the construction-stage phases:
Antoine BAJEUX (Infrastructure design office—Mayotte), Nicolas FINA and Patrick LANES (COTRAM—Sanitation Division), Gérald LACOMBE (Étiage—French Guiana), Julien PHILIPPE (ETG 976).

■ For proofreading, technical review and editing the guide:
Véronique BARRE, Claire LEVAL and Béatrice GENTIL-SALASC (AFB—French Biodiversity Agency), Nicolas FINA (COTRAM—Sanitation Division), Laurence HAMONT (CANGT), Gérald LACOMBE (Étiage—French Guiana), Frédéric L'ETANG (SICSM—Espace Sud), Lucas PELUS (Water Authority—Martinique).

The authors also thank the French biodiversity agency for funding and support to get this guide published, and Béatrice SAUREL for creating the graphic design and artwork.

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Preface

The purpose of this guideline is to give a walk-through of constructed wetlands (CW) adapted to tropical-zone geographies. Design standards rules have been established and validated through performance monitoring on several full-scale treatment facilities specially equipped for scientific monitoring and located in four French overseas departments ['DOM']: French Guiana, Guadeloupe, Martinique and Mayotte. Nearly a hundred 24hr-composite performance assessments have been produced through research projects spanning a period of over decade, and have served to validate the technical design options presented here.

This guideline does not therefore cover all the various CW configurations but only those technologies that emerge as particularly appropriate for domestic wastewater treatment in the French overseas departments and the tropics as a whole. As the "tropicalization" of filter beds is a relatively recent development (around for no more than ten years), the requirements and recommendations set out here are liable to change as and when the future brings new technical advances, feedback, and research on these CW technologies in tropical regions.

This guideline is designed as a toolkit to support stakeholders and designers in the completion of CW projects in tropical and equatorial climate zones. Aspects tied to operability are covered in a succinct section of this guide and in a separate set of technical sketch-ups. The cost of CW projects is difficult to pin down, as costs are necessarily dictated by the specific contexts of each different overseas department, to the technical designs adopted, and to the pattern of development of these wetland technologies. We have thus elected not to address project costs in this document, but pointers can be made available on request and memos may be posted online by the Epnac—'Assessment of new sanitation processes for small and decentralized communities' taskforce on its dedicated website (www.epnac.irstea.fr/DOM/). Note that this guideline is in no way a code standard nailing down a wetland technology: each context has its own factors and features, and an appropriately optimized project requires expert design and construction.

CWr and CW

In mainland France, constructed wetlands are referred to as 'reed beds' [CWr here], as the wetland plant used is the common reed (*Phragmites australis*).

In tropical zones, *Phragmites australis* is considered an invasive species, so other plants are used (section 4, p.46), and the technology is simply dubbed 'constructed wetlands' [CW here].

This guide features five chapters.

Section 1, titled "**CW—How they work**", gives a primer on the filters, detailing the contaminant-removing processes at work in CW and the role played by plants and sludge management in this type of facility. It sets out the different process variants collapsed under the umbrella term 'CW', before going on to give a roll-up of the performances of the different technologies found in tropical-zone geographies.

Section 2 sets out the procedure for "**CW—Design for a sanitation system**". It gives a recap of the current regulatory provisions defining the effluent levels to be achieved, which will dictate which of the wetland technologies in our roll-up table should be selected as the most appropriate. Given unanimous consensus across the French overseas departments that treatment works are oversized, we wrap up with some pointers on properly assessing the loads to be treated.

Section 3 sets out the "**CW—Structural-code sizing standards**" that shape the definition of the build characteristics, as well as focusing on leak proofing standards and the composition of the filter beds.

Section 4 provides answers to the question "**CW—Which plants for tropical-zone geographies?**" and outlines the method employed and results produced by a study specifically addressing the topic.

Section 5 rounds up by addressing "**CW—Service, operation, management**". On top of the feedback from the field, collected from CW project builders, this final section also details the different phases in the life of a filter. Pointers on managing wetland facilities to deal with the specific constraints posed by tropical-climate zones can be found in supplementary material to the Epnac taskforce's Guide to operating constructed wetlands published in 2015. We wrap up with key pointers on self-monitoring for regulatory compliance.

This guideline will talk to different readers with different depths of knowledge—there are green-background boxes that define or detail key concepts, but also paragraphs that demand deeper subject-matter knowledge framed in brown-font boxes headed "To dig deeper".

To go straight to the big messages, the key figures and key takeaways are highlighted in bold, and there is a ready-reference glossary at the end of the guide—terms featuring in the glossary are flagged with an asterisk (*) the first time they are used.

Abstract and keywords

The French overseas departments have acute sanitation issues to deal with. One of the major bottlenecks has been under-adequate technologies under-adapted to the specific context of the French overseas departments.

To improve the sanitation provided to small and decentralized communities in the French overseas departments ('DOM'), the Onema - now the French Biodiversity Agency (AFB) - sponsored research on adapting reliable tropics-appropriate treatment technologies. This guideline to sizing constructed wetlands (CW) for tropical-zone geographies reviews a decade of research in the five DOM to adapt a technology that has already been tried, tested and proven in temperate-climate zones.

CWs encompass a whole family of relatively diverse processes spanning different types of flow, different levels of saturation, and so on, many of which can be combined together or with conventional treatment processes, thus creating an array of potential treatment train configurations. The objective of this research was to adapt a number of wetland systems, designed to cover different treatment-level objectives, aiming for packages that are more compact yet still deliver the same reliable and robust treatment performance.

The development effort focused on deploying vertical-flow filters fed with raw wastewater to facilitate sewage sludge management. Vertical-flow CW are graded-gravel beds on a ground-tight liner that are permeated with network of aeration and drainage pipes and topped with planted vegetation. They are wastewater treatment systems that host a complex interplay of several processes (filtration, biological activity, fluid flows, gas transfers, plant activity, and more) and where sustainable operability hinges on finding and maintaining a fine balance between all the process conditions, which requires both careful sizing and thoughtful ongoing management.

One of the features of tropics-adapted CW design is that they can work on a smaller footprint of the filters, as the regular high temperatures found in tropical climates make it possible to implement rest phases that are just as long as feed phases yet still deliver good sludge mineralization. This means that just two filters are set up in parallel, which makes for a smaller facility footprint than found in practice in mainland France.

Likewise, research was channelled into developing innovative systems capable of working on a single treatment stage according to effluent levels. CW sizing is scaled based on loadings (organic, hydraulic) that the in-feed-mode filter can accept, but it can also translate as filter surface area per population equivalent (PE) to deploy. Depending on the effluent levels required, the filters use from 0.8 m^2/PE to 1.6 m^2/PE. Even the most basic configuration delivers performances that go further than the regulatory-required minimum (removal rates of 75% for COD, 80% for BOD5, 80% for TSS and 60% for TKN with effluent concentrations below 125 mg COD/L). CW can be adapted, according

to needs and constraints, to effectively deliver over 95% carbon treatment, full nitrification, or 70% total nitrogen treatment. These sizings work to maintain strong resilience to wet-weather hydraulic overloads without compromising the dependability of the infrastructure.

The plants, via their mechanical action, are integral to the CW process. Phragmites australis is used in both mainland France and abroad, but is not naturally found in the tropics, where it carries strong invasiveness risk. A study specifically addressing which plant species to use in tropical-zone wetlands assessed a hundred-odd species via a three-step approach: desktop review, pilot trials, and full-scale real-world behaviour. Heliconia psittacorum, or bird-of-paradise, is one of the most attractive option, although other solutions are also proposed to help designers adapt to the constraints of each project site.

One of the keys to the success of CW in mainland France is that once built, operation is simple.

With little electromechanical hardware - or even none at all and therefore no electricity to manage if site topography is right -, there are no complex operation and maintenance tasks and little risk of operational trouble. Routine maintenance of the vegetation is more of a constraint in tropical-climate regions, where it represents the owner-manager's main task

The compact footprint of the tropical-zone wetland process not only enables it to compete with conventional processes in space-squeezed settings but also makes it competitive at above the economic capacity threshold in mainland France (5,000 PE). CW thus span a very broad capacity range, from semi-decentralized projects for isolated housing developments and rural communities up to medium-sized urban communities.

The design rules featured in this guideline, which has been put together through research led in the French overseas regions, can be used in all tropical-zone geographies.

The guideline starts with a primer on the processes at work in these wetland infrastructures and the performances of the different processes studied, before going on to set out the key considerations when planning an on-site sanitation project. It thus spells out:

- the characteristics of wastewater from small communities in the French overseas departments and the relationship between population and population equivalent;
- a recap of the rules for determining effluent level;
- the technology options dictated by local constraints and any phased staging to complete;
- precise design code and sizing standards for construction;
- the different plants species suitable for use;
- details of the routine operation and maintenance and monitoring tasks needed for optimum facility management.

Keywords: wastewater treatment, small communities, sewage sludge treatment, tropical zone, constructed wetlands

Contents

Introduction

The French reedbed constructed wetland system (CWr) has been developed by the French national institute of science and technology research for the environment and agriculture (Irstea[1]) since the 1980s. It stands out in the wider constructed wetlands landscape in that the filters are fed with raw water in a way that combines primary and secondary wastewater and sewage sludge treatment all in one package. The French system is currently the go-to treatment system for small communities in France: an estimated 80% of facilities built each year to serve communities of less than 2,000 population equivalents (PE) are CWr systems.

Irstea's wetland research in tropical-area started in 2005, in partnership with the 'Intercommunal water and sanitation authority - Mayotte' (SIEAM). The first two tropical-site CW were commissioned to service in Mayotte in 2006 (Hachenoua: 110 PE, and Totorossa: 145 PE).

In 2010, the French national agency for water and aquatic environments (Onema - which became the French Biodiversity Agency (AFB) in 2017) asked Irstea to lead research and development for on-site wastewater treatment schemes appropriately adapted to small communities in the French overseas. A situation audit in each of the French overseas departments showed that the technology best geared to addressing the French-overseas geocontext was the CWr (Eme, 2012).

Working in unison with local technicians, Irstea helped several facilities to emerge, in French Guiana (Bois d'Opale 1 [300 PE] in 2010 then Bois d'Opale 2 [480 PE] in 2012), Martinique (Mansarde Rancée [1000 PE] in 2013 and Taupinière [900 PE] in 2014), Guadeloupe (Les Mangles [120 PE] in 2015), Mayotte (Champ d'Ylang 2 [180 PE] in 2015) and Réunion (Salazie [90 PE] in 2017).

In October 2014, the 'Attentive' project (acronymed for 'tropics-adapted wastewater treatment through constructed wetlands systems), focused on the French West Indies won the national ecological engineering prize in the category "Alternative wastewater and rainwater management", awarded by French Ministry for Ecology, Sustainable Development and Energy.

This national recognition for CW in tropical area should facilitate adoption of the technology by local decision makers. Figure 1A shows that it took nearly 15 years for the number of constructed wetlands to really take off. Proportionally speaking, the picture is much the same in Mayotte, where after 8–10 years, the wetland system has finally gained credence with project owners (Figure 1B). The 2015 sanitation delivery roadmap for Mayotte makes CW the leading treatment scheme in terms of number of treatment plants in the archipelago's future infrastructure.

In French Guiana, six CW have emerged since 2010, and in 2017 the local Centre-Littoral cross-commune cooperation council tendered a public works contract for a 3,000-PE filter in 2017 - a choice that, given the treatment capacity involved, demonstrates just how much positive value the council has registered from feedback on the schemes deployed over the past decade.

Population equivalent (PE)

PE is the unit of measure used to assess the capacity of a wastewater treatment plant. It is based on the amount of pollutants released by a person in a day. The EU wastewater treatment directive of 21 May 1991 defines one PE as the "organic biodegradable load having a five-day biological oxygen demand (BOD5) of 60 g of oxygen per day".
The actual pollution load released per capita varies with context (subsection 2.3.1, p.32).

[1]*The then-named Cemagref—French national centre for agricultural mechanization, rural engineering, freshwater and forestry—became Irstea in 2011.*

A B

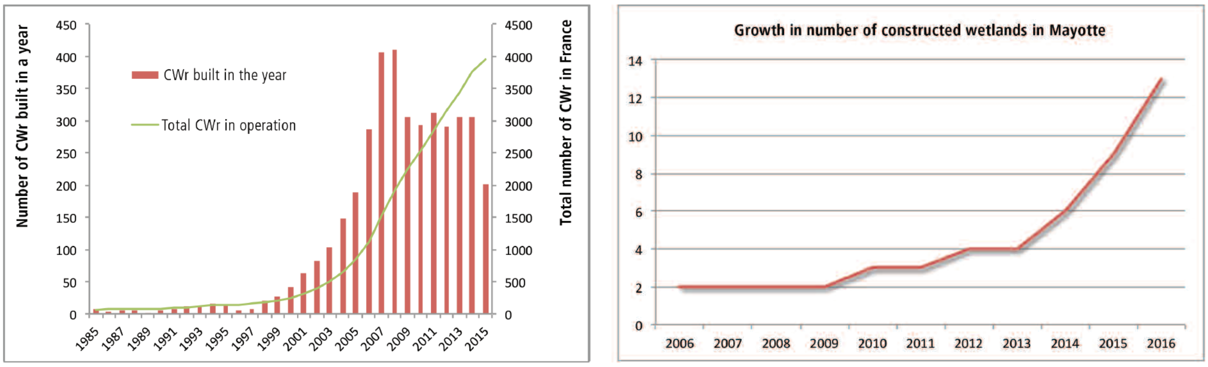

Figure 1. *Growth in number of constructed wetlands (CW) in mainland France (A) and in Mayotte (B) (ERU database, SIEAM).*

CWs offer a number of advantages for tropical areas and number of guarantees for owners:

- **robustness,** i.e. the ability to continue to maintain a high level of treatment (section 1.5, p.19) despite wildly fluctuating organic and hydraulic loads;
- **simple operability**, since routine maintenance of this type of facility does not need special expertise and does not take up much time (around 300 hours of work a year for a 1,000 PE capacity plant; section 5.3, p.57);
- **convenient utilization of locally-sourced materials** for construction, as the support used for biomass development is gravel and there is no need for (exogenous) electromechanical hardware compared to other technologies;
- **facilitated sewage sludge management**, as the filters are dosed with raw wastewater so there is also sludge treatment at the filter surface (section 1.3, p.17). In mainland France, the sewage sludge has to be emptying every 10-15 years but can be directly reclaimed for use in agriculture;
- **input-frugal system**, which does not use chemicals and can even run without electricity if the site topography is right (gravity flow; section 3.3, p.39);
- **can take on wet-weather rainfall flushing** to buffer a combined sewer system. The filters have already handled shock flush loadings of over 5 m, i.e. 15 times the nominal load! (Arias Lopez, 2013);
- **relatively compact footprint** (0.8 - 1 m^2/PE) compared to other extensive systems (ponds at 5–6 m^2/PE in tropical-climate) and even compared to the conventional system practiced in mainland France (2 - 2.5 m^2/PE);
- **phased project staging periods** (subsection 2.3.3, p.33; Figure 17, p.34). The filters are split into beds that can be constructed or rotated into service as and when change is needed, which is a particularly strong advantage in the French overseas regions where demographic growth is high and where investments are long-term packages.

CW - How they work

1

This section gives a primer on the tropics-adapted CW treatment system and the various CW scheme variants. It describes the water treatment processes involved in each step of the treatment train, illustrates the water performances of each process via a roll-up of the scientific monitoring campaigns conducted, and finishes by discussing sewage sludge management issues.

Systems like this have been dubbed "planted filters" on the grounds that they employ plants, but the wastewater-purifying role played by plant biomass (Epnac, 2014) is actually negligible compared to the wastewater-purifying action of bacterial biomass, so treatment wetlands is the more appropriate term.

1.1. Non-saturated vertical-flow filter

CWs mimic the natural biological contaminant-removing capacities of wetland ecosystems. Research into these extensive treatment processes employing attached-growth biomass began in Germany in the 1960s–1980s and took hold in North America and northern Europe (Denmark and the UK) over the 1970s. In the 1980s, Irstea (formerly Cemagref) launched pilot experiments to establish the design standards for what was to become the French design system. The standout feature of the French wetland system is that it provides integrated waste water and sludge treatment all in the same vertical-flow aerobic system, producing a stable organic sludge that can be reclaimed for use in agriculture.

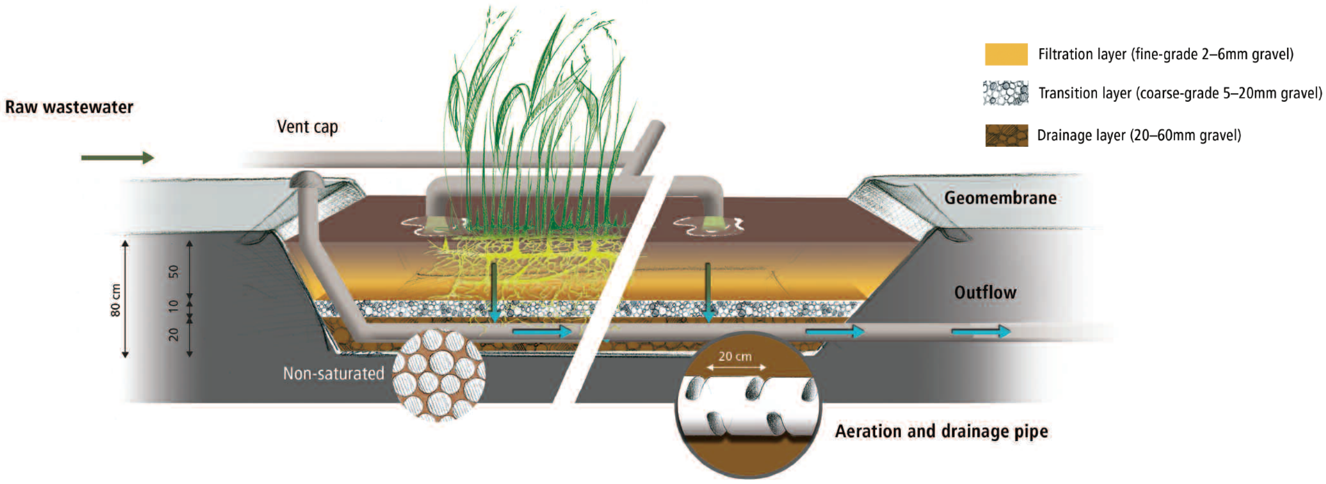

Figure 2. *Sectional schematic of a vertical-flow constructed wetland (artwork by Saurel for AFB).*

A vertical-flow CW is a graded-gravel bed on a water-tight liner that is permeated with a network of aeration and drainage pipes and topped with planted vegetation (Figure 2). Raw wastewater is fed onto the filter surface in intermittent doses* (each dose is a large volume of water corresponding to a 2.5cm flush distributed to cover the entire filter surface). Each dose will percolate through the filter bed matrix before being collected by the drainage system.

Total suspended solids (TSS) carried in the effluent get filtered out by the finest-grained gravel layer and retained at the surface of the filter, where they accumulate to form a sludge layer that progressively increases the physical filtration capacity of the filter. This biologically hyperactive biomass layer mineralizes quickly.


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Figure 3. *Illustration of the mechanical role of reedbed vegetation on sludge drying beds.*

The dissolved organic matter used by the bacterial biomass growing on the filter-media gravel and in the organic slime. To promote the growth of aerobic bacteria, the system is designed and engineered to ensure that the media bed is well oxygenated. The mechanical action of the plants on the filter surface aids the oxygenation process. Wind swaying the plants will move the stems, thus forming channels in the sludge layer accumulated on the filter surface (Figure 3). The channels help stop surface clogging by facilitating wastewater infiltration and air transfer.

The bacterial biomass will use the oxygen from the air in the bed matrix and the dissolved organic matter for its metabolism. To make sure the facility continues to perform efficiently for years, filter management has to keep this bacterial growth under control, otherwise it will tend to naturally colonize all the void space in the gravel, and ultimately foul, clog and plug the system. If the system clogs and plugs, then wastewater will no longer infiltrate and there will be no more air–gas exchange, which is why feeding is rotated between the vertical-flow filters. The tropical-format treatment chain features two filters, each of which gets dose-flushed in turn for 3.5 days (Figure 4), thus creating two separate filter phases: a feed-phase and a rest-mode phase. During the rest-phase, as there is no wastewater introduced, the bacterial population is able to self-regulate, thereby controlling the biomass produced.

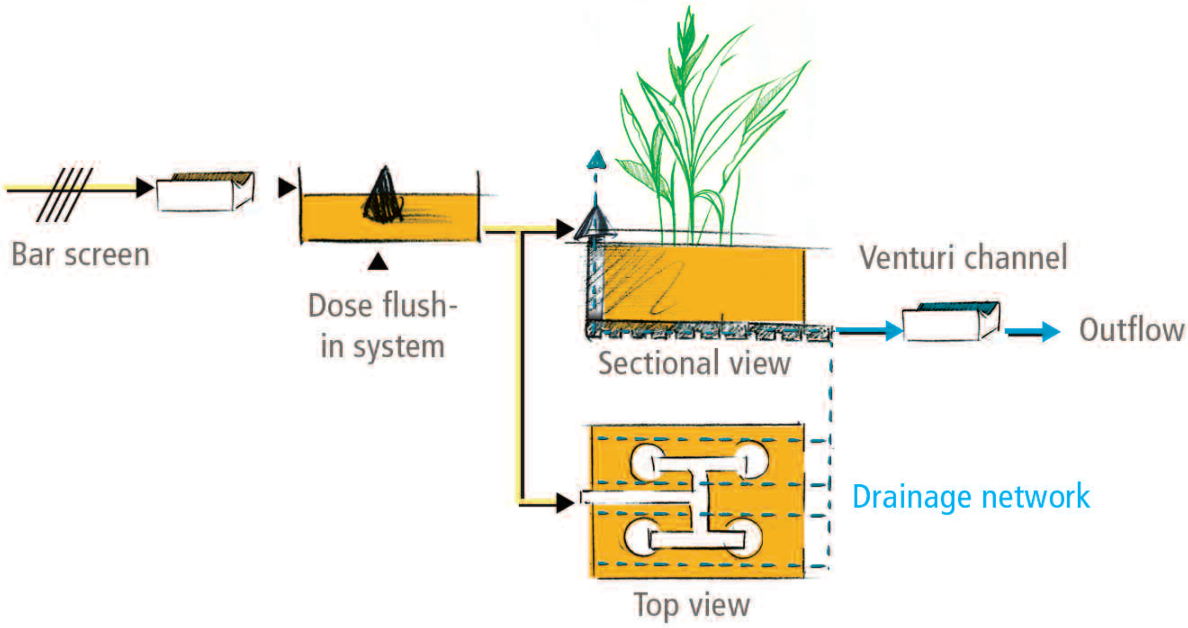

Figure 4. *Schematic illustration of the tropical-zone process technology.*

In contrast to the classical French-mainland wetland design (Figure 5), the basic tropical-zone wetland process has just one treatment stage with two dose-rotated filters. The higher mean temperatures in tropical climate zones favour microbial activity, to such a point that it is very often possible (depending on the target effluent quality levels) to dispense with the need for a second stage. This is a huge asset in terms of footprint, and also eliminates the filter media materials needed, as the second stage includes a layer of sand, which is in short supply in the French overseas departments.

The standard mainland-France technology

In mainland France, bacterial activity is slower due to the cold winter-season temperatures, and so the biomass needs longer rest-phase periods to re-establish the right balance. Consequently, the mainland system is built with three filters working side by side, so as to have the rest-phase period two times longer than feed-phase period.

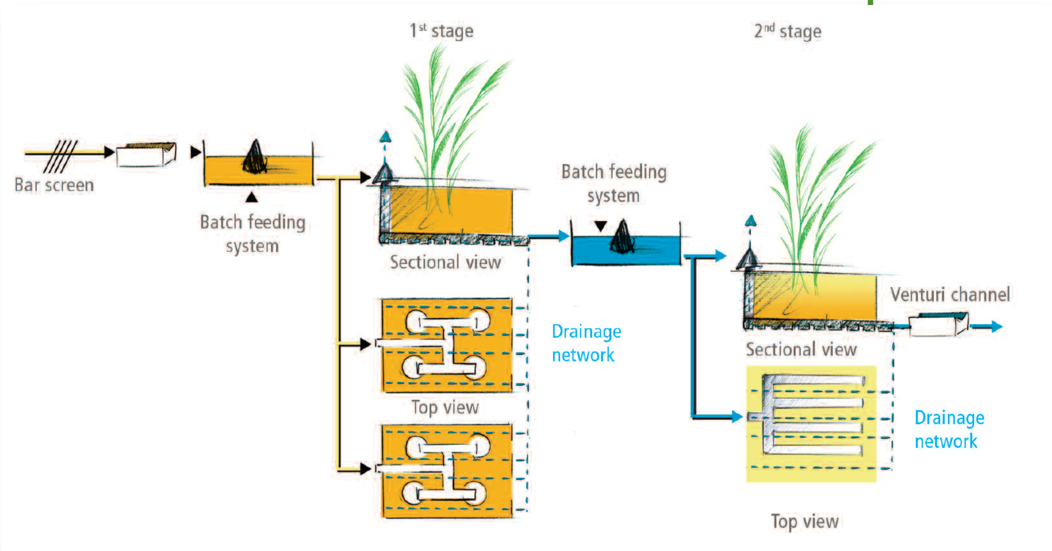

Figure 5. *Schematic illustration of the standard mainland-France process technology.*

1.2. Tropicalized wetland design—different configurations

Depending on the effluent quality levels required, the wetland design can be modified to improve performances on certain parameters, by adding:
- a recirculation loop;
- a saturated bottom layer;
- a second treatment stage or a disinfection module.

See section 2.2 p.29 for in-depth guidance on choosing the right variant configuration according to treatment-levels targeted.

1.2.1 Recirculation

A recirculation loop can be built to equip a single-stage treatment. It will require a recirculation inspection port and possibly a lift pump that recycles a fraction of the effluent back to the filter influent.

Calculating recirculation rate

Recirculation rate (%) = (recirculation flow/effluent flow) × 100

A recirculation rate of 100% means there is as much water being recirculated as outflowing, which effectively means double the hydraulic load received by the in-feed-mode filter.

The recirculation system serves to:
- **dilute the raw water** and thereby decrease H_2S production at the lift pump, which where objectionable odours may be released in the French overseas departments;
- **increase wastewater residence time** in the system and thereby improve of treatment performance of some parameters (COD, BOD_5);
- ensure the plants do not get water-stressed when the facility is left under-loaded, i.e. typically in the dry season.

The flipside is that recirculation adds to the daily flush applied on the filter and amplifies the hydraulic overload episodes that are commonplace in the rainy season. Prost-Boucle & Molle (2012) showed that recirculation rate is effectively capped at 100% as going any higher can negatively impact the nitrification process in mainland-France climate conditions (hydraulic load at under 75 cm/d on filter in operation).

However, this limit has not yet been confirmed in tropical-climate conditions. Either way, recirculation leaves the facility less equipped to handle wet-season loads than a non-recirculation system. Recirculation also means the facility requires on-plant electrical energy to operate a lift pump, either on the inflow line for batch-feeding (where recirculation is by gravity flow) or on the outflow to control recirculation. When recirculation works gravitationally, it is managed using a v-notch weir plate that is workable from inside the recirculation port (Figure 6). When recirculation is driven by a lift pump, it is strongly advised to design a gravity driven effluent flow in order to preclude any risk of filters getting recharged if there is a technical problem or a power outage.

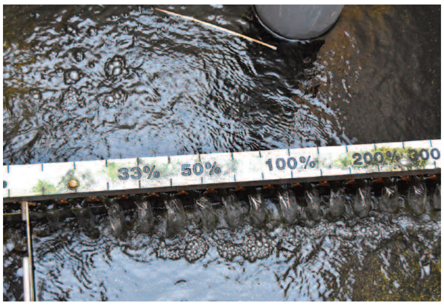

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Figure 6. *V-notch weir plate for manual recirculation.*

In terms of facility performance monitoring, having a recirculation loop installed means that there are now two sets of performance calculations to be performed:
- removal efficiencies of the facility between raw influent and treated effluent;
- removal efficiencies of the filter between the fed water loads (raw water influent + recirculated effluent) and the treated effluent.

1.2.2 Non-saturated/saturated vertical-flow filter

Conventional vertical-flow CW are all-aerobic systems, which means they cannot host anoxic decomposition processes (including denitrification). Engineering a saturated zone at the bottom of the filter makes it possible to establish anoxic conditions that will host a more advanced treatment of certain components (Figure 7). This basically equates to laying a non-saturated vertical-flow filter over the top of a horizontal-flow filter.

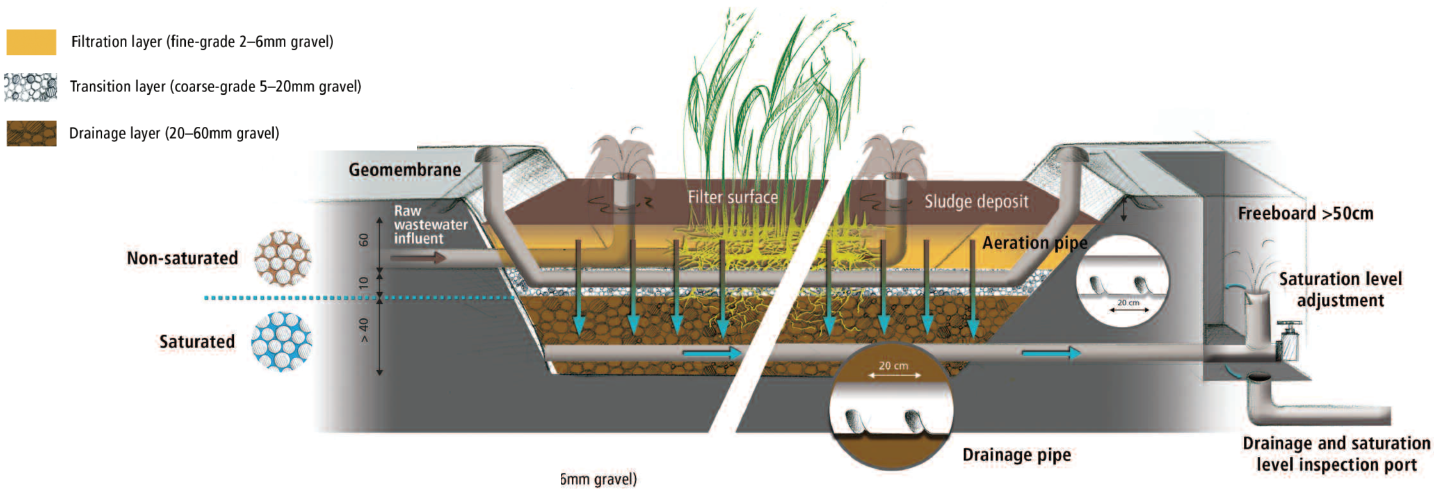

Figure 7. *Schematic illustration of a non-saturated/saturated vertical filter (artwork by Saurel for AFB).*

Other than introducing a deeper filter bed, installing a saturated bottom layer requires:
- an intermediate aeration network 5–10 cm over the upper level of the saturated part to maintain aerobic conditions in the upper media filter;
- a saturation level inspection port serving to check the depth of the saturated zone.

The depth of the saturated zone influences redox conditions, effluent residence time in the system, and flowrate in the porous media filter space. Note too that the saturated zone needs to be partly flushed every year to avoid clogging. The recycled effluent is then recirculated back to the filter influent so that the sludge deposits are retained on the filter surface.

Engineering a saturated bottom layer essentially serves to:
- improve the treatment of total nitrogen by establishing an anoxic zone, which is a vital prerequisite to denitrification;
- improve performances on organics decomposition by adding further denitrification-driven use of carbon;
- trap any residual TSS and thus guarantee an effluent TSS discharge of under 25 mg/L, which is a vital prerequisite for UV modules to work.

1.2.3 Second stage

The basic tropical wetland treatment chain has just one treatment stage, but a second treatment stage can be added when permit limits on effluent quality levels are severe. There are several workable types of process technologies.

■ Non-saturated vertical-flow filter

A second-stage vertical-flow filter works to the same sizing principles as for the first stage (section 3.2, p.37), but with the following loads applied: hydraulic load 0.37 m/d, 70 gDCO/m²/d, 20 g BOD_5/m²/d, 30 gTSS/m²/d and 15 gTKN/m²/d.

However, the feed system network changes, as it uses elevated headers slotted with 8 mm-plus diameter holes (Figure 8).

Feeding is done in batches, just like for the first stage.

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Figure 8. *Feeding on second stage of the Mansarde Rancée (Martinique) facility before planting, February 2014.*

Compared to a first-stage filter (subsection 3.5.2, p.42), there are differences in design composition of the three gravel layers:
- filtration layer: 30 cm of sand (0,25 < d_{10} < 0,4 mm, d_{60}/d_{10} < 5) ;
- transition layer: 10–20cm of 3/10mm gravel;
- drainage layer: 10–20cm of 20/60mm gravel.

A second vertical-flow stage enables more advanced **ammonium removal** (>90%) while also delivering **low effluent levels of TSS** (<25 mg/L) and COD (<90 mgO_2/L). However, the fact that good quality sand is in short supply in the French overseas departments may cap the number of vertical-flow second-stage filters implemented. This configuration can be a good option for shallow-bedrock sites, where it can be integrated as a pair of 60cm-deep filters, and with the right gradient, the technology can even work gravitationally for advanced aerobic treatment.

■ Horizontal-flow filter

In horizontal-flow filters, the filter bed matrix is totally water-saturated.

The effluent is distributed across the depth and width of the filter by a distribution system situated at one end of the basin, from where it then takes a mainly horizontal flowpath through the substrate. Feeding is practically continuous most of the time, and there is a low organic load input moving through a relatively big surface area (Figure 9).

The treated effluent outflows through an underdrain situated at the opposite end of the filter, buried into a layer of drainaway stone. This pipe connects to a recharge line that serves to set the depth of the overflow, and consequently the depth of water in the cell* to keep it saturated. Water level has to be held to around 5 cm below the media surface. This helps counter preferential overland flows, and thus delivering a homogenous flow path.

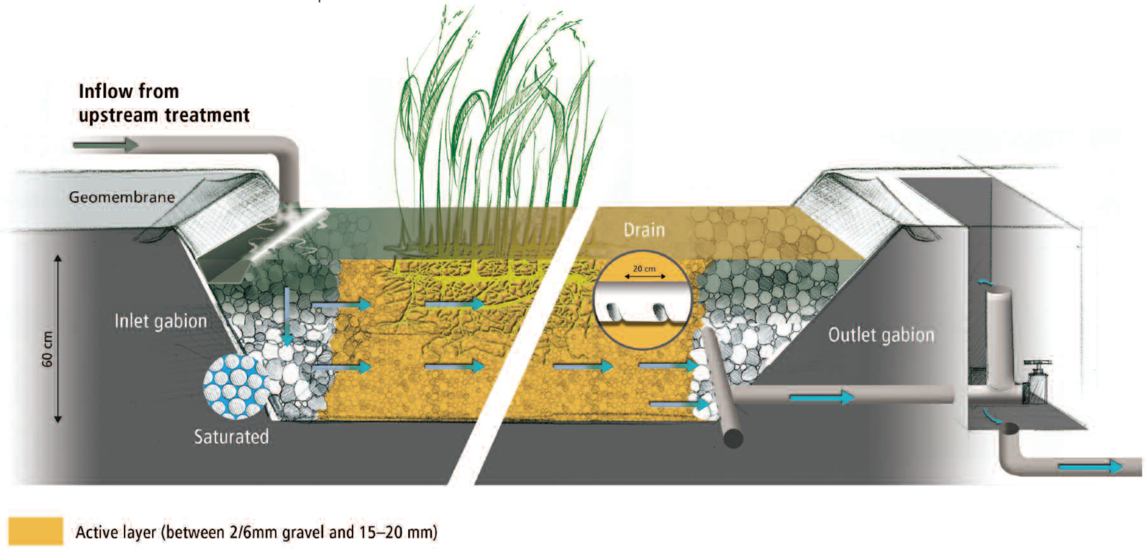

Figure 9. *Schematic illustration of a horizontal-flow filter (artwork by Saurel for AFB).*

The horizontal-flow filter must be preceded by a primary treatment. It has been tested in combination with a clarifier at Mayotte (on the Totorossa treatment unit), but the filter quickly clogged as the community was lax with clarifier O&M. This experience clearly shows the fragility of horizontal-flow filters, especially when they are preceded by a primary treatment that is sensitive to load variations (particularly rainfall episodes). However, if preceded by a vertical-flow filter, a properly-sized horizontal-flow second stage can prove to be a good option. Here we only detail this second combination, which is a more reliable option, especially in tropical geographies where intense rainfall-surge events can trigger big hydraulic overloads.

As the filter media is saturated, there is relatively little input of oxygen, essentially by diffusion from the surface but also, to a lesser extent, by oxygen release from the plant root-zone, i.e. the rhizosphere effect. These conditions will create an oxygen-deprived habitat in which an appropriately-adapted microbial flora develops. Anoxic digestion processes then enable these bacteria to reduce nitrates into nitrogen gas (denitrification).

A horizontal-flow second stage can enable full denitrification (if carbon is not limiting) and thus reduce total nitrogen **proportionally to the fraction that gets nitrified. It completes the treatment of dissolved carbon and TSS (<25 mg/L).**

■ Very-low-load simple trickling filter

The Taupinière treatment unit in Martinique has a very-low-load simple trickling filter as second-stage system. The trickling filter itself is a 150cm-high bed of 20/60mm volcanic rock. The feeding system comprises of two networks of pipework holed with ports and laid out in a staggered zig-zag pattern (Figure 10). Feeding is rotated between the networks, by pulsed batches volume equivalent to a 3 cm flush, every 5 minutes. This pulse-feeding mode helps shear off the surplus biofilm growing on the blocks. Down in the bottom bed, built-in cells can set aside a zone in which the treated effluent can be split from the secondary sewage, which gets removed between one and four times a day and redirected back to the filter influent line.

The trickling filter is sized at very low load: with 150m²/m³ specific-surface-area media stacked 1.5m in depth, the areal load density is 3.5 g BOD_5/m²/d.

This type of process infrastructure involves high oxygen input, enabling very advanced treatment of reduced nitrogen (TKN <10 mg/L). Its compact footprint (at just around 0.1m²/PE) and the fact that it eliminates the need to use sand make it an attractive option.

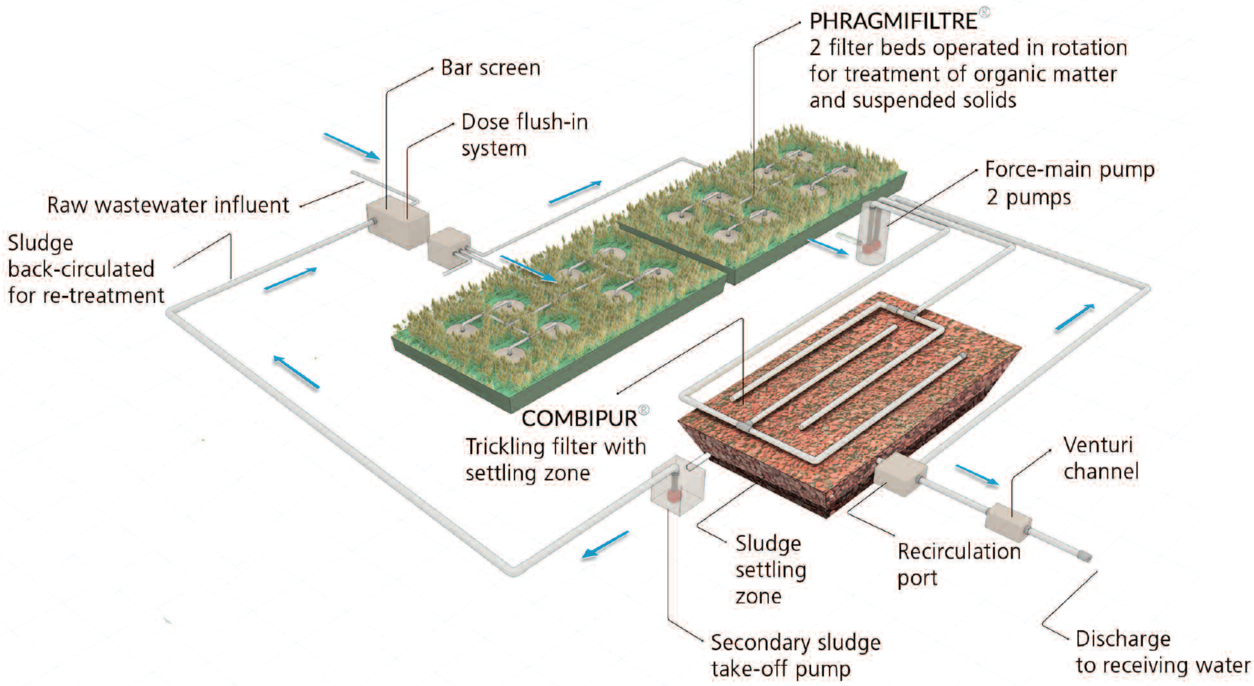

Figure 10. *Low-load trickling filter used as second stage technology (source: CombiPur system).*

1.3 Contaminant-removing processes and system control

This section details the various processes involved in wastewater treatment by a CW, and how to run the system while maintaining the conditions vital to sound service, running and performance.

1.3.1 Physical retention and sewage sludge management

Raw wastewater is flushed onto the filter surface. The particulate organic matter fraction gets retained at the filter surface by a physical filtration mechanism. The sludge layer that progressively forms is packed with microorganisms that quickly mineralize the organic matter.

This layer grows 2.5 cm thicker every year in mainland France, which, over time, helps steadily improve system performances (physical retention, biological activity). However, sludge accumulating on the filter surface disrupts the flow of wastewater through the filter and the gas exchanges between outside air and inside filter matrix. There are three components that help counter this clogging effect—one short term, one mid-term, and one long term:

- mechanical action on the sludge layer by the stems of the plants maintains continuous hydraulic conductivity and enables gas transfer in system (section 1.4, p.19);
- rotating between the different filters accommodates rest-phase periods that are crucial for mineralization of the organic matter accumulated during the feed-mode phase;
- emptying the organic deposit accumulated on the filter surface, which has to be done once the organic deposit has built up to around twenty-odd centimetres (every 10-15 years in practice in mainland France).

In tropical areas, organic matter gets mineralized at a far faster rate, so much so that it has not yet been possible to accurately gauge sludge accumulation rate over time through the monitoring campaigns conducted to date. One thing is for sure - it is far less than on the mainland, and this has repercussions on all three sludge management operations:

- the mechanical role of reedbed vegetation is still a fundamental function, but as the sludge does not get as thick, it should be possible to add lower-stem-density plants to the list of candidate plant-species;
- the faster organic matter mineralization rate shortens the rest-phase period needed between two feeding cycles. With a rest phase lasting just as long as a feed phase, only two filters need to be set up in parallel (instead of three in the conventional system practiced in mainland France);
- the interval to desludging is stretched, potentially to over 15 years.

Figure 11. Desludging operation in French Guiana on Bois d'Opale 1. This sludge can be reclaimed for use in agriculture (Epnac, 2014).

Physical retention at the filter surface is a pivotal step in the treatment process, and it accounts for the bulk of TSS removal in the system. The particulate fraction of the organic carbon pollution is trapped and retained at the surface of the filters, and accounts for over a third of COD load. Particulate forms of nitrogen and phosphorus are also retained.

Lastly, it is in this layer that the system traps and retains certain micropollutants (Choubert, 2011).

1.3.2 Biological treatment and aeration

CW are part of a family of biological treatments that use attached-growth biomass. The biomass grows on the filter-media gravel, where it conglomerates to form a slimy matrix dubbed biofilm. This biofilm is an organic mat composed of extracellular polysaccharides secreted by the contaminant-removing bacteria. It serves as bacteria-habitat interface. Dissolved organic matter/nutrients simply penetrate the biofilm by diffusion along a concentration gradient. Vertical flow CW are aerobic systems - the bacteria inside them use dissolved oxygen as substrate for their metabolism. The filter hosts several different types of bacteria. The first few centimetres host the bulk activity of heterotrophic bacteria that degrade the organic carbon. Their thriving metabolic activity enables them to outcompete the autotrophic bacteria that break down ammoniacal nitrogen via slower processes, and thus get relegated deeper down.

Maintaining aerobic conditions inside the filter is crucial, and it is done by intermittent feeding with large volumes of wastewater. These pulsed batch flushes spread the water across the whole surface of the filter. As this water wave infiltrates, it squeezes out a part of the oxygen-stripped air contained in the bed and replenishes it by convection. Bed aeration is further aided by surface-downflow diffusion or filter-base upflow diffusion *via* the air-piped underdrain network. Volume of the pulsed batches and density of the aeration–drainage pipework network are the key design parameters that will determine the infrastructure's aeration capacities.

The biofilm grows in the interstitial space between the grains making up the filter bed. When conditions are right, it develops a continuous growth that starts to clog the filter deep down. Just like for control of surface-layer deposits, the rest-phase periods are crucial for regulating the organic matter inside the filter. The first forty centimetres of the filter (and the sludge blanket) are where most of the organics entering the system get treated. It also oxidizes part of nitrogen load. Phosphorus gets used for bacterial metabolism at 1-2% of the mass of BOD_5 used.

Autotrophs and heterotrophs

This is an important distinction, as it separates organisms on the basis of whether they can self-produce organic compounds from inorganic gases or minerals (the autotrophs, like nitrifying bacteria) or whether they are dependent on organic carbon substrates (the heterotrophs). Nitrifying bacteria are chemoautotrophs - they produce their organic matter from the carbon found in air but use the chemical - reaction energy they recover from the oxidation of ammonium to nitrite to synthesize all their necessary organic compounds.

1.3.3 Nitrogen treatment, filtration, and thickness of the filter bed matrix

Given that there is a bigger depthwise stratification of autotrophic bacteria, it is possible to vary the depth of the filter layer between 30 and 80 cm according to the nitrification goals targeted. At upwards of 60 cm, it is recommended to run an intermediate aeration network through the middle of the active layer, to ensure aeration by diffusion in the mid-filter bulk.

Installing a saturated bottom layer (subsection 1.2.2, p. 13) will help maximize total nitrogen treatment by pushing denitrification, at a reasonable extra investment cost. The build involves increasing the depth of the drain-out layer so as to be able to establish a saturated zone using an upturned elbow for recharging the bottom of the filter (Figure 7). The anoxic conditions necessary for denitrification will establish in the saturated zone. It is then the absence of available carbon source that may limit denitrification.

There are a number of possible filter configurations depending on the effluent levels required. **Depth of the filtration layer can be adjusted to advance nitrification and, to a lesser extent, TSS retention. Installing a saturated zone will enable denitrification of oxidized forms of nitrogen while guaranteeing under-threshold effluent TSS** (<25 mg/L) and COD. The challenge here is to adapt the depths of the non-saturated and saturated layers in a way that delivers optimal treatment performance, especially on total nitrogen.

Whatever options and configurations are chosen, effluent residence time in the system is still relatively short (less than 24h) and does not enable pathogen die-off (removal of 2 to 3 log units max).

1.4 Role played by the vegetation

Uptake by the vegetation

Although the figures vary between species, plant tissue absorbs 20–200 g of nitrogen per square metre per year, plus 3–15 g of phosphorus. One PE corresponds to the daily production of 15 g total Kjeldhal nitrogen and 2.5 g total phosphorus. At a sizing ratio of 0.8 m^2/PE, the, metabolic uptake by wetland plants would account for no more than 2.9% of *direct* nitrogen treatment and no more than 1.3% for phosphorus in direct.

Here, the role played by the vegetation has been split from the role played by the contaminant-removing processes. This is a conscious move, as in the systems described here, the plants help maintain the conditions needed for the contaminant-removing processes, but without directly participating in them.

The main role of the plants on these vertical-flow constructed wetland filters fed with raw wastewater is a mechanical action that prevents the organic sludge that forms on the filter surface from getting clogged. Wind swaying the plants will move the stems, thus creating channels in the sludge layer (Figure 3, p. 11). These channels enable wastewater to infiltrate and enable gas transfers between outside air and inside filter matrix. Good even stem growth across the whole filter surface (unlike tufting) with a good high strand density offer the right foundations to support optimal gas transfers and thereby maintain the contaminant-removing capacities of the filters.

The root-system of the plants secretes organic compounds (plant root exsudates*) and small amounts of oxygen. Root-surface hairs host the development of a denser and more diverse bacterial flora than in the rest of the filter. In the saturated systems (horizontal-flow filters), these bacteria play a non-negligible role in effluent treatment performance (Gagnon, 2007).

The plants support microbial diversity inside the filter, but they have only negligible impact on the treatment process in vertical-flow filter systems.

Wastewater treatment by the CWs described here is thus driven by the microbial biomass contained in the media filter and not by the plants for which uptake for metabolism remains negligible. This makes commercial terms like 'phytosanitation' an abuse of language.

1.5 Water purification performances of CW in tropical-zone geographies

Projects undertaken in the French overseas departments, with AFB backing, served to monitor seven facilities (Table 1). A hundred-odd 24hr-composite performance assessments with flow-proportional sampling have been compiled so far.

Table 1. *Features and characteristics of the tropical-climate-zones pilot facilities*

Name	Department	Capacity	Technology	Commissioned	Number of performance monitoring	Mean load rate (% nominal load)	
						Organic	Hydraulic
Hachenoua	Mayotte	110 EH	1 stage : 2 CW NS 80 cm filtration layer	April 2006	16	53 %	65 %
Bois d'Opale 1	Guyane	300 EH	1 stage : 2 CW NS 0 and 100% recirculation	May 2010	9	33 %	139 %
Bois d'Opale 2	Guyane	480 EH	1 stage : 2 CW NS 100% recirculation	March 2012	13	29 %	169 %
Mansarde Rancée	Martinique	1 000 EH	1st stage : 2 x 3 NS/S 2nd stage : 2 x 2 NS CW	January 2014	3	10 %	16 %
Taupinière	Martinique	900 EH	1st stage : 2 x 2 NS/S CW 2nd stage : Low-load TF	November 2014	31	84 %	98 %
Les Mangles	Guadeloupe	120 EH	1 stage : 2 NS/S CW	October 2015	17	4 %	15 %
Champ d'Ylang 2	Mayotte	190 EH	1 stage: 2 NS CW 30cm filtration layer	November 2015	7	81 %	105 %

NS: non-saturated; NS/S: non-saturated/saturated; TF: trickling filter.

Load rates calculated for applied loads of 350 g COD/m²/d and a flush of 0.37 m/d, which equates to a sizing ratio of 0.8 m²/PE

** Terms flagged with an asterisk * are defined in the glossary found at the back of this guide.*

The wetland systems have been designed with a ratio of 0.8 m²/PE, which equates to an applied loading of 350 g COD/m²/d and a hydraulic load of 0.37 m/d on the filter in operation.

The mean organics load rates may sometimes be low, but the hydraulic loads tend to be high, or even very high. The conclusions drawn from investigations on this panel of wetland amenities are taken as representative of a normal loading level.

First we describe and benchmark the characteristics of the raw wastewater against data from observations on small rural communities in mainland France.

Then, given the observed imbalance between the organic loads and hydraulic loads received by the facilities, discussion turns to address the wet-weather factor and its consequences for the filters. To conclude, CW performances are presented here at two levels of analysis: first per process (non-saturated vertical-flow filter and a non-saturated/saturated vertical-flow filter), then at treatment chain level as a whole, based on the variant CW configurations monitored in the French overseas departments.

Nominal hydraulic load applied on filter in operation

It is normalized and expressed as water depth (m), as it corresponds to a volume (m³) applied on a surface area (m²). The sizing ratio of these CW is 0.8 m²/PE. As the two filter cells are operated in rotation, the applied load is actually only ever effective on one of the two filters, i.e. 0.4 m²/PE.

For the hydraulic load, this equates to:

$$\frac{0{,}15\ m^3/d}{0{,}4\ m^2/EH} = 0{,}37\ m/d$$

To refresh the memory, the calculations consider that volume of wastewater produced per PE is 150 L/d, i.e. 0.15 m³.

1.5.1 Characteristics of household wastewater in the French overseas departments, and the wet-season factor

Table 2 gives a roll-up of the entire dataset of results from raw water analyses in the French overseas departments. Nature of the influent to the facilities varies widely, which is a hallmark characteristic of decentralized sanitation for small communities. In dry weather, the influents have slightly higher concentrations than observed in rural mainland France (Mercoiret, 2010). In wet weather, however, the influents are more diluted. In both cases, raw domestic wastewater loads measured in the French overseas departments are in the standard range of concentrations observed in mainland France, and can comfortably be handled and treated by the CW.

Table 2. *Characteristics of wet-weather and dry-weather raw wastewater in the French overseas departments, and comparison with dry-weather data on small rural communities in mainland France (Mercoiret, 2010)*

		BOD_5 (mg/L)	COD (mg/L)	TSS (mg/L)	TKN (mg/L)	TP (mg/L)	Hydraulic load ratio - wet-weather/ dry-weather
Dry weather (n=73)	Max	680	1 394	700	130	23.4	
	Mean	**319**	**674**	**281**	**83**	**10.7**	
	Min	32	92	28	33	2.7	
	SD	*195*	*340*	*175*	*25*	*4.0*	
Wet weather (n=15)	Max	580	1 051	519	87	11.2	4.4
	Mean	**209**	**449**	**223**	**40**	**5.7**	**2.8**
	Min	30	109	49	7	1.7	1.9
	SD	*178*	*307*	*148*	*27*	*2.8*	*1.2*
Small mainland communities (n=10,275)	Max	1 230	2 930	2 100	223	39.2	
	Mean	**265**	**646**	**288**	**67**	**9.4**	
	Min	5	30	2	1	0.2	
	SD	*171*	*395*	*226*	*35*	*5.3*	

A look at the table confirms that wet weather substantially dilutes influent loads: Nitrogen and phosphorous get diluted two-fold, whereas organics get diluted just 1.5-fold and TSS just 1.2-fold. This asymmetrical effect of rainfall episodes on dilution of different pollutant is a perfectly conventional and well-known pattern, explained by the fact that stormwater runoff picks up mainly mineral and organic matter (hydrocarbons on road surfaces, etc.).

The wet-weather/dry-weather ratio shows that hydraulic load demand more than doubles during rainfall episodes on average.

How often and how big are these hydraulic overloads? How do the filters react to these rainfall-surge events?

In 'normal' load scenarios, over the course of the year, there will only be a handful of rainfall episodes (2%) liable to impact filter performance on nitrogen. In more complex load scenarios (organics overload, recirculation), this proportion can climb to 15% (Figure 12). These proportions should obviously be revised according to quality of the network and local rainfall figures.

To dig deeper

Figure 12 was plotted from the daily records of hydraulic loads at the Taupinière facility (Martinique) between 01 January 2015 and 31 May 2017. The filters are operated without recirculation and the upstream network is a new build. This monitoring effort served to investigate the hydraulic loads received by the facility and study frequency and scale of rainfall episode-triggered surges.

At the start of the study, organic load received by the facility was low (at around 30% of nominal organic load), but it increased later on, when one of the filters was partitioned into two and only one half of the cell was kept running. This reconfiguration made it possible to study facility performance at low load (32%, start-up phase), in normal conditions (85% of nominal organic load, dosed onto the whole filter surface) and in heavy overload (164% of organic load, all channelled onto the partitioned filter).

Flowrate and filter-surface recordings throughout operation were used to compute the daily flush applied. The flushes calculated were then ranked in ascending order. As they all share the same frequency of occurrence, the cumulative frequency curve charts the dispersion of flushes applied and serves to visualize how often the thresholds are overstepped.

Prost-Boucle & Molle (2012) assert that when daily flush climbs over a 75 cm/d, the nitrification processes start to wane. The curves show that at a 'normal' load regime, 15% of events overstep the nominal hydraulic load, of which 2% overstep the ceiling limit beyond which nitrification processes may be impacted. The frequencies are a lot higher for organic overload: 95% of events overstep the nominal hydraulic load, of which 15% overstep the ceiling limit beyond which nitrification processes may be impacted. A recirculation rate of 100% corresponds to double the load applied on the in-feed-mode filter, and thus, in hydraulic terms, to what is observed on the filter during organic overload.

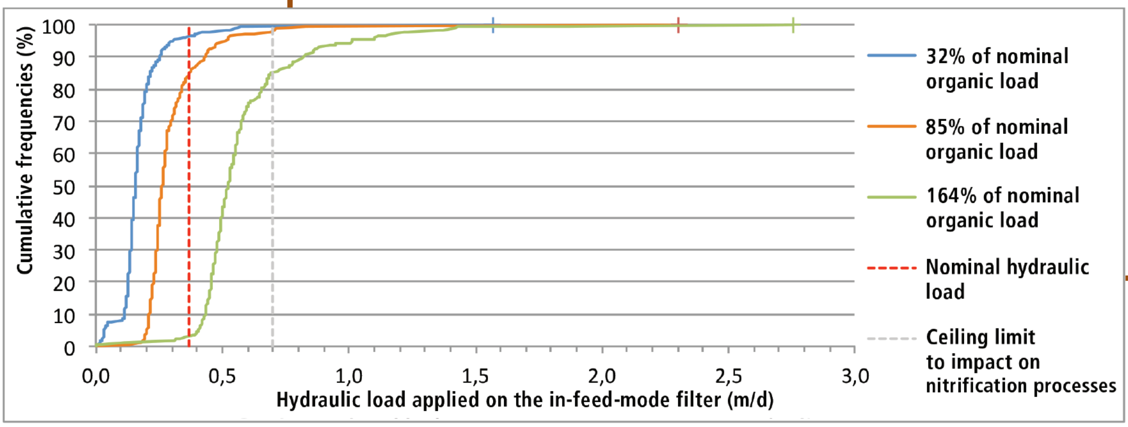

Figure 12. *Distribution of hydraulic loadings on the filters at the Taupinière facility (Martinique) between 1/01/2015 and 31/05/2017. Bars mark the peak values recorded for each series.*

On 28 September 2016, tropical storm Matthew made landfall on Martinique. Data recorded by the Taupinière facility gave a picture of how a CW filter responds to extreme shock climate conditions.

The rain gauge records showed that 88.6 mm of rain fell between 13:00h on the 28th and 03:00h on the 29th. On that day, filter in operation received a flush of 2.39m, i.e. more than seven-fold nominal loading. In normal routine operation, treated water gets pumped from the filter outflow to the trickling filter. However, the flowrate of the pumps was undersized for when tropical storm Matthew hit, and the filters experienced a big upcharge. Maximum water depth in the pump well peaked at 3 m, which corresponds to twenty-odd centimetres of water sitting on the filters, as illustrated in Figure 13. The facility then emptied slowly, and by 24 hours after the cyclone had passed, the facility had returned to normal serviceability.

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Figure 13. *Recharge of the Taupinière facility filters during tropical storm Matthew. It is the facility's second-line filters that are not yet in service, and so not replanted, as the system is under-loaded.*

The only collateral damage registered on the treatment facility was to the plants (Figure 14). The CW cells are therefore ready and able to absorb the hydraulic overloads caused by tropical storms. To avoid filter recharge and facilitate a return to normal functionality as soon as rainfall stops, it is recommended to equip the filter with a bypass if water level needs to be lift-pumped before tertiary treatment.

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Figure 14. *Wetland vegetation on the in-service filters of the Taupinière facility, in the wake of tropical storm Matthew. On the left, in the foreground, the Cyperus alternifolius had just been thinned and harvested, and so resisted the storm well. In the background, Heliconia psittacorum was hit hard, particularly by the strong winds, but managed to recover. On the right, the Costus spiralis plants, which were already suffering before the storm, never managed to recover afterwards.*

Assessment of wastewater inflows to the French-overseas CW shows that:

- raw wastewater loads measured in the French overseas departments are in the standard range of concentrations observed in rural mainland France;
- in rainfall episodes, the influent flowrates are two-fold higher on average;
- for facilities that are loaded as designed (>70% of nominal loading), it is not rare for hydraulic loading to approach the limits beyond which nitrification processes may be impacted;
- the CWs are ultimately able to handle tropical cyclones passing over, despite receiving flush loadings more than seven-fold nominal loading.

1.5.2. Performances of the various constructed wetland processes in tropical-climate geographies

Section 1.2 introduced the various different CW configurations, which in fact encompass two process categories:
- the all-non-saturated vertical-flow CW (NS vfCW), which work to all-aerobic processes;

- the non-saturated/saturated vertical-flow **CW (NS/S vfCW), which on top of aerobic processes also mobilize anoxic processes hosted** in their anoxic zone. All performances reported further down keep this distinction between treatment process technologies, and are discussed first at process scale - thus at filter level - before a second section extending to treatment chain level (at facility scale).

Table 3 reports the raw influent and treated effluent concentrations along with the corresponding removal rates for all the main water quality parameters, and for both CW process technologies (NS and NS/S). Figure 15 collates the full performance-values dataset and charts the process-by-process dispersion of concentrations measured over the course of the performance assessment campaigns, in cumulative percentiles format.

Table 3. *Roll-up of the analyses led on filter inflow and filter outflow samples (1st stage only)*

	NS CW (n=45)											
	Raw water (mg/L)				Treated water (mg/L)				Removal			
	Max	**Mean**	Min	*SD*	Max	**Mean**	Min	*SD*	Max	**Mean**	Min	*SD*
BOD_5	560	**245**	30	*163*	90	**17**	3	*16*	98 %	**90 %**	74 %	*6 %*
COD	1240	**585**	109	*296*	184	**75**	23	*32*	96 %	**83 %**	50 %	*10 %*
CODf	671	**244**	36	*135*	114	**50**	15	*22*	93 %	**75 %**	45 %	*12 %*
TSS	648	**263**	49	*165*	81	**28**	3	*20*	99 %	**86 %**	35 %	*12 %*
TKN	123	**65**	7	*32*	45	**16**	2	*11*	98 %	**68 %**	12 %	*23 %*
$N\text{-}NH_4$	120	**52**	6	*31*	35	**13**	0	*9*	100 %	**68 %**	4 %	*26 %*
$N\text{-}NO_3$	1.5	**0.7**	0.45	*0.34*	66	**21**	0.1	*16*				
TN	124	**66**	7	*33*	74	**36**	11	*17*	75 %	**42 %**	2 %	*18 %*
TP	23.4	**10.2**	1.7	*4.8*	11.3	**4.9**	1.3	*2*	91 %	**46 %**	2 %	*26 %*

	NS/S CW (n=48)											
	Raw water (mg/L)				Treated water (mg/L)				Removal			
	Max	**Mean**	Min	*SD*	Max	**Mean**	Min	*SD*	Max	**Mean**	Min	*SD*
BOD_5	680	**344**	32	*205*	60	**12**	2	*10*	98 %	**93 %**	68 %	*5 %*
COD	1394	**696**	92	*371*	196	**85**	15	*46*	94 %	**85 %**	66 %	*7 %*
CODf	558	**241**	74	*116*	97	**59**	9	*28*	91 %	**72 %**	12 %	*15 %*
TSS	700	**282**	28	*175*	70	**15**	3	*12*	98 %	**93 %**	64 %	*5 %*
TKN	130	**85**	31	*25*	51	**18**	3	*14*	96 %	**79 %**	39 %	*15 %*
$N\text{-}NH_4$	110	**64**	21	*21*	44	**16**	2	*13*	97 %	**76 %**	24 %	*19 %*
$N\text{-}NO_3$	9.32	**0.71**	0.01	*1.28*	75	**13**	0	*17.3*				
TN	131	**85**	31	*25*	66	**29**	13	*14*	86 %	**62 %**	19 %	*16 %*
TP	20.7	**9.3**	2.7	*3.6*	11	**5,6**	0,7	*3*	88 %	**42 %**	-4 %	*26 %*

n: number of datapoints; Max: max value; Min: min value; Mean: mean value; SD: standard deviation.

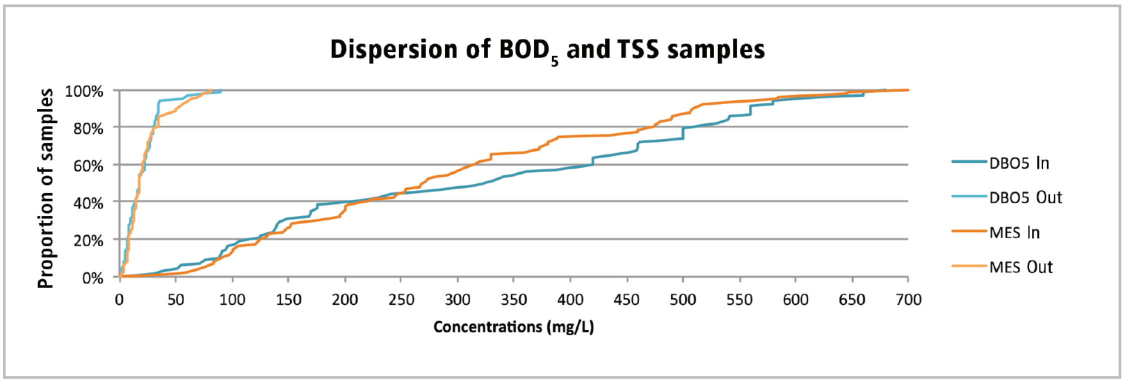
Despite the wildly variable quality of the wasteload influent to the facilities, pollutant removal is substantial and stable for organic carbon (83% for NS systems and 85% for NS/S systems), TSS (NS=86% and NS/S=93%) and organic nitrogen (NS=68% and NS/S=79%).

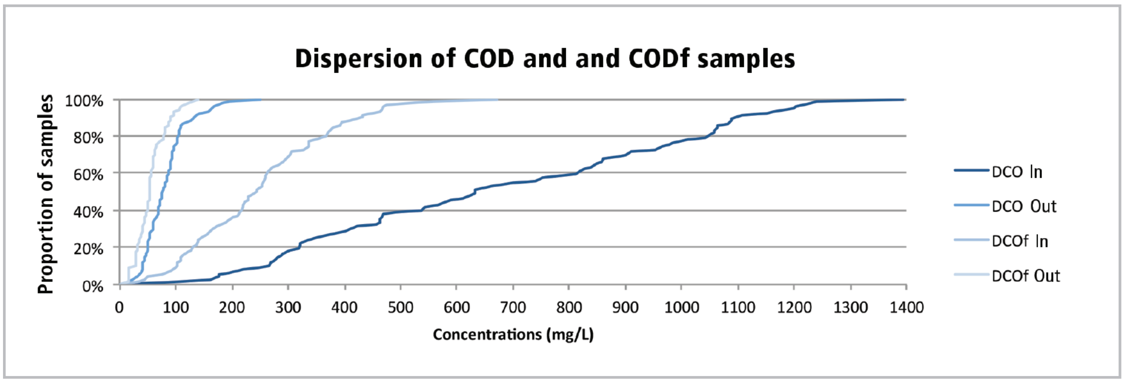
There is a clear performance differential between the systems: a saturated bottom layer enables a slight gain in carbon removal but brings reliable performance for TSS and strongly improves performance for nitrogen (+20% on TN).

Throughout the measurement campaigns, effluent levels never once overstepped the quality thresholds (minimum performances stipulated in the national decree of 21 July 2015 or by special prefectoral order).

Discharges from the in-feed-mode filter also remained below the maximum permissible concentrations[2] for facilities of over 2,000 PE, except on BOD_5 for three high-strength-load assessments upstream of the second stage at Taupinière.

2- *Maximum permissible oncentrations pursuant to the decree of 21 July 2015. See section 2.1 for a recap of the regulatory requirements.*





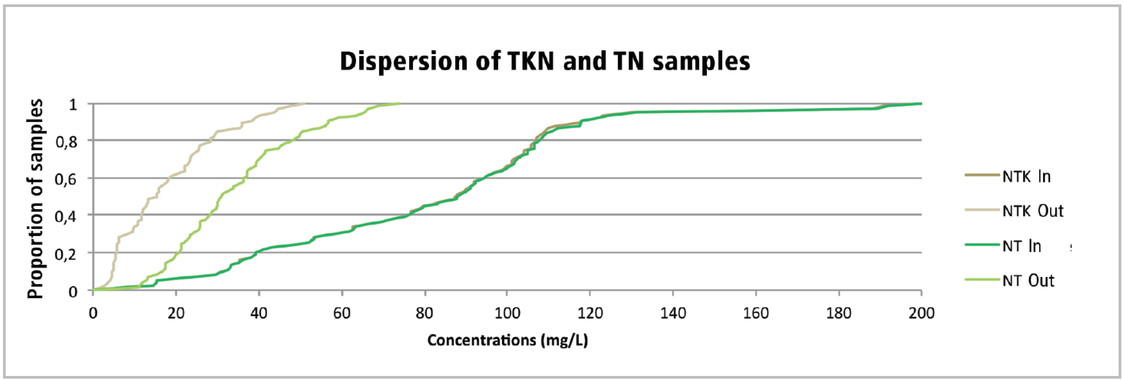


Figure 15. *Sampling dispersion–concentration curves.*

The surface reduction design ratio between the French mainland and the tropical-zone geographies (section 1.1, p.12) prompts the question of where the system's meets its limits: did the more compact footprint come at a cost of less performance or less robustness? The graphs in Figure 16 plot loads treated against loads applied on filter in operation, which serves as a basis for assessing quality of treatment as a function of loads applied.

For COD and TSS, the load values obtained so far do not point to limits of the filters, as the performances continue to remain stable, even at over nominal loading. For TKN, however, performances visibly start to decline at upwards of 30 g/m²/d. TKN removal remains over 60% at up to 50 g/m²/d, but could fall under at any higher loads.

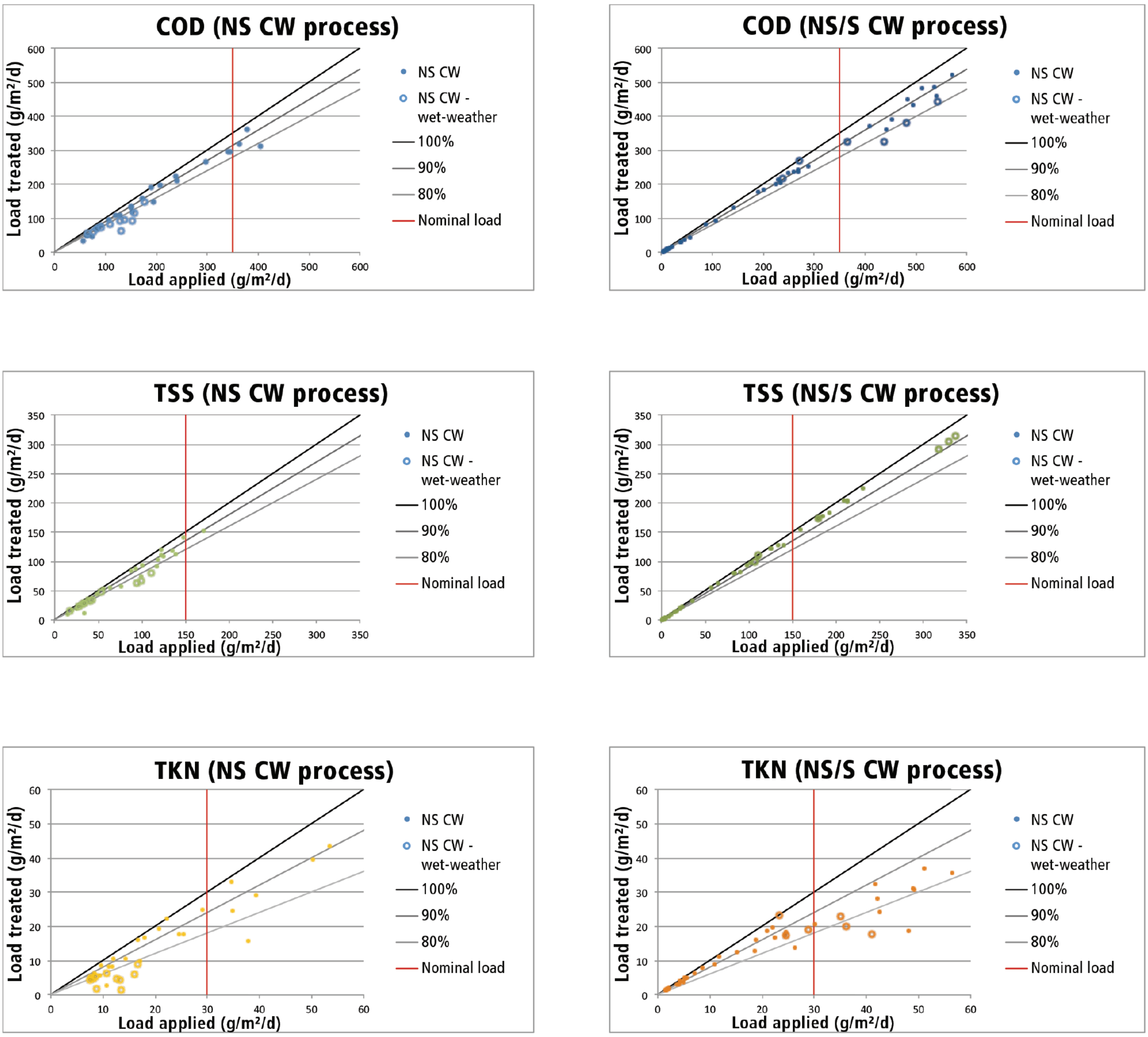


Figure 16. *Loads treated plotted against loads applied for COD, TSS and TKN water quality parameters for the two CW process technologies (NS and NS/S). The greyed-out curves plot the guidance values for pollutant removal efficiencies.*

These same graphs also capture the impact of wet weather events and the allied hydraulic overloads: regardless the load applied, the least-efficient performances are always registered during rainfall events. There are essentially two reasons to explain this pattern: First of all, and as shown in Table 2, rainfall episodes dilute the sewage. It is impossible to maintain high treatment efficiency with diluted sewage, as the process would need to drop to concentrations so low that they fall below the biological or chemical limits. Furthermore, the hydraulic overloads not only strangle the gas exchanges between outside air and inside filter (long ponding*) but also shorten wastewater residence time in the system. Hydraulic overloads push the system towards its limits.

No real difference between processes emerges from these graphs. The loads received by the non-saturated vertical-flow CW facilities start lower and stay lower than the nominal load. Inside this comfort zone, both processes deliver excellent performances. It is doubtless once outside this comfort zone that differences would have emerged. Note too that the non-saturated vertical-flow CW facilities show mixed performances on TKN, but the sample of systems studied is too small to reasonably draw any firm conclusions.

The design rules for the tropicalized CW treatment scheme guarantee a stable level of treatment, even if the system is put under organic overload (up to 165% of nominal load at Taupinière). This means there was still room to further shrink the filter surface footprint. However, during heavy rainfall episodes, the CWs - just like other treatment schemes - experience a dip in pollutant removal efficiencies, as the concentrations are lower. To keep performances high even during hydraulic overload, the choice was made to not go beyond a ceiling of 0.8 m²/PE.

1.5.3 CW performances at wetland-system scale

Now that we have described the performances of each of the two processes, it is informative to assess the performances of the treatment schemes in the wider CW landscape, i.e. for the various different CW variants or in hybrid process configurations.

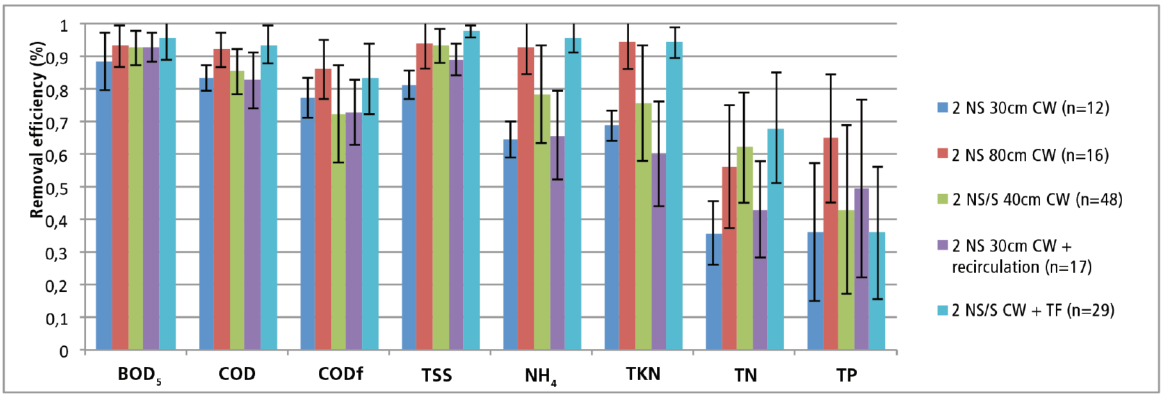


Figure 17. *Performance comparison between the various constructed wetland (CW) configurations. The vertical black bars chart uncertainty (standard deviations). NS: non-saturated; NS/S: non-saturated/saturated; TF: trickling filter.*

Phosphorus treatment

None of these configurations was purpose-designed for phosphorus treatment. However, the sludge layer does trap the particulate phase, while treatment of the dissolved fraction remains limited to bacterial metabolism (around 2% of the BOD_5 load removed) and adsorption processes on the media-filtration material. The gravel does not regenerate its adsorption capacities, which decline over time. Performances on phosphorus may start out strong in the first few months (or even years) of the facility's life in service (>70%), but will later decline and plateau somewhere around a stable 30–40%.

Figure 17 plots removal performances for the main water quality parameters in the different configurations studied in the French overseas departments. The in-series two-stage vertical-flow filters configuration (2 NS/S CW + 2 NS CW at Mansarde Rancée) has been excluded from the analysis on the grounds that the data is unrepresentative as the load rate to the facility is too low (just 10% on average).

Treatment of organic carbon is excellent whatever the configuration employed (removal rate over 80%)

However, the non-saturated vfCW with a shallow filtration layer retained less TSS than the other configurations. With minimal removal performances well above 75%, the minimum performances stipulated in the national decree of 2015 are comfortably delivered. Installing a saturated bottom layer or a deeper layer of filtration media delivers very stable performances, at over 90% in general. For nitrogen removal, nitrification is limited at 50–60% with the most straightforward configurations. Increasing the depth of the filtration layer and installing a mid-filter aeration drain substantially improves nitrification. The saturated bottom layer plays host to anoxic processes and denitrification, and more advanced total nitrogen removal.

These results warrant a degree of perspective, given the small number of facilities or, for certain configurations, 24hr-composite-samples studied (there is only one facility equipped with an 80cm filtration layer). The two-stage configurations manage to maintain advanced effluent quality levels: 90% removal on BOD_5, COD, TSS and TKN, or 20 mg/L BOD_5, 125 mg/L COD, 30 mg/L TSS and 8 mg/L TKN. Removal performances on the second stage are not quite as good as on the first stage, but are still integral to achieving severe effluent quality goals.

To dig deeper

Compared to the figures recorded in mainland France, the performances obtained by a NS vfCW with a 30cm filtration layer are comparable to the performances obtained by the first stages of CWr systems - all filtration layer depths included (Molle *et al.*, 2005, Morvannou *et al.*, 2015). The 80-cm configuration demonstrates equivalent removal rates, and even superior rates for TKN, to the conventional French two-stage treatment schemes on the mainland.

Lastly, the one-stage NS/S configuration delivers comparable performances to mainland France for organic carbon and TSS and slightly higher levels for TKN and TN (Morvannou, *et al.,* 2017).

Design engineering: treatment-level objectives, loads applied, and strategy

2

The process of designing a wastewater treatment plant starts by siting the waterbody into which treated water is discharged, as it dictates the quality goals for the treated effluent. The effluent quality levels required will direct which kind of treatment scheme to build. Below is a decision matrix that may help engineers navigate their choice between the different CW variants. The population to hook up to the network and the planned pace of scale-up will dictate the infrastructure's treatment capacity, its layout, and whether phased project staging is the way forward.

2.1. Effluent quality levels

2.1.1 Regulatory requirements

Outside of any further requirements imposed by the receiving watershed, the minimum effluent quality levels required are laid down by the decree of 21 July 2015. Table 4 is an excerpt of Annexe 3 of the decree setting out baseline-minimum performances for wastewater treatment plants that need to treat a raw wasteload of 1.2 kg/j BOD_5 or more (which equates to a 20 PE load).

The performance goals are reported in concentration values or efficiency values. However, over what are called 'maximum permissible concentrations', the performance record is declared non-standards-compliant regardless of the allied pollutant removal efficiencies. If a performance record is declared non-standards-compliant, then the facility will need to complete (and pass) a number of further assessment campaigns before the end of the year to become re-compliant.

Table 4. *Minimum treatment performances required in France for water quality parameters BOD_5, COD and TSS as defined by the decree of 21 July 2015*

Parameter	RAW ORGANIC WASTELOAD received by the facility, in kg/d of BOD_5	MAXIMUM CONCENTRATION TARGET, average daily load	MINIMUM EFFICIENCY GOAL, average daily load	MAXIMUM PERMISSIBLE CONCENTRATION, average daily load
BOD_5	< 120 ≥ 120	35 mg (O_2)/L 25 mg (O_2)/L	60 % 80 %	70 mg (O_2)/L 50 mg (O_2)/L
COD	< 120 ≥ 120	200 mg (O_2)/L 125 mg (O_2)/L	60 % 75 %	400 mg (O_2)/L 250 mg (O_2)/L
TSS	< 120 ≥ 120	/ 35 mg/L	50 % 90 %	85 mg/L 85 mg/L

The French regulations do not lay down any obligations on nitrogen and phosphorus treatment for facilities serving under 10,000 PE capacity (600 kg/d BOD5), even though they are unlikely to be found in sensitive areas. Depending on the fate of the treated effluent, the water security authorities [Service de police de l'eau - 'SPE') have the power to set more severe effluent quality levels in the prefectoral order for the treatment facility's permit to operate.

2.1.2 Receiving watershed

The treated effluent outfall into the environment (surface water body, ravine, marine outfall, groundwater infiltration, etc.) is what the SPE takes as starting point for defining the effluent quality levels required.

This is a tricky issue to negotiate, as the effluent quality levels dictate the pollutant removal efficiencies that the plant is required to reliably deliver. It is always the latest contaminant removal percentages or mg/L figures that are the toughest - and the most expensive - to achieve. Very stringent effluent quality levels will have direct repercussions on the cost of the project. If the community is setting ambitious treatment-level goals, it may be preferable to explore alternation siting and layout options for the facility to find a less sensitive receiving watershed that will come with less severe effluent quality levels. In certain cases, it is even smarter for the community to revise its sanitation zoning plan so as to requalify certain zones for decentralized on-site sewage facility (OSF) coverage. For further information, readers are advised to consult the memo released by a MEDDE-Epnac taskforce (2015) working on definitions of effluent quality levels.

Certain objectives may have knock-on effects on other parameters. In the French overseas departments, given that beaches are nearby and that tourism is pivotal to the local economy, there are often extra treatment objectives for pathogen die-off. With the exception of lagooning, effective pathogen elimination often relies on implementing a tertiary treatment, which in most cases means a UV disinfection process. For UV treatment to prove effective, the effluent TSS concentrations have to be under 25 mg/L. To keep effluent TSS levels at such a low level, the treatment scheme has to be purpose-adapted (see Table 5 further down). This means that extra investment cost for a pathogen-die-off treatment is not just for the UV module but also for the more advanced TSS removal needed.

2.2. Choosing the right CW treatment scheme

Table 5 gives a roll-up of the key information input that will help engineers navigate their choice between the different CW variants according to their project-site constraints. The variants covered are basically those that have been assessed so far in French overseas departments.

The simplest basic configuration is two filters set up in parallel on one stage with a 30cm filtration layer. It will meet the minimum requirements stipulated in the decree of 2015 for facilities serving communities of less than 2,000 PE. It is not the solution best geared to serving intermittent-activity populations (self-catering units, schools, and so on) where regular absence of influent wasteloads will stress the plants, and it cannot accommodate a UV-module disinfection treatment as it cannot reliably keep effluent TSS concentrations below 25 mg/L on a permanent basis.

Table 5. *Roll-up of the information dictating which constructed wetland (CW) variants to set up*

CW variants	Standalone electricity (excluding topography constraints)	Combined sewer	Intermittent activity	Footprint of the treatment infrastructure	Minimum guaranteed treatment performances: % removal (threshold concentrations, mg/L)				Pathogen die-off (UV module disinfection)
					COD	TSS	TKN	TN	
2 FPV NS with 30 cm of first filtration layer	✓	✓	✗	0.8 m²/PE	75 % (125 mg/L)	80 % (50 mg/L)	60 % (40 mg/L)	20 % (60 mg/L)	✗
2 FPV NS with 30 cm of first filtration layer + recirculation	✗	✓ (daily flush < 70 cm)	✓ (can hike the electricity bill)	0.8 m²/PE	75 % (125 mg/L)	85 % (30mg/L)	60 % (40 mg/L)	20 % (60 mg/L)	✗
2 FPV NS/S with 30 cm of first filtration layer	✓	✓	✓	0.8 m²/PE	85 % (125 mg/L)	90 % (25 mg/L)	60 % (40 mg/L)	50 % (50 mg/L)	✓
2 FPV NS with 80 cm of first filtration layer	✓	✓	✓ possible with recirculation	0.8 m²/PE	90 % (100 mg/L)	90 % (25 mg/L)	80 % (15 mg/L)	20 % (60 mg/L)	✓
2 FPV NS/S stage + NS stage	✓	✓	✓ possible with recirculation (hydric stress on the second stage)	1.6 m²/PE	90 % (75 mg/L)	95 % (15 mg/L)	90 % (6 mg/L)	70 % (35 mg/L)	✓
2 FPV NS/S stage + TF stage	✗	✓	✓	0.9 m²/PE	90 % (75 mg/L)	95 % (15 mg/L)	90 % (6 mg/L)	70 % (35 mg/L)	✓
2 FPV NS stage + HF stage	✓	✓	✓	1.8 m²/PE	85 % (125 mg/L)	90 % (25 mg/L)	70 % (20 mg/L)	70 % (35 mg/L)	✓

✓ = possible ✗ = not possible

Adding a recirculation loop serves to ensure reliable effluent TSS levels and thus meet the minimum requirements stipulated in the order of 2015 for facilities serving communities of more than 2,000 PE (<35 mg TSS/L), but it does need to be equipped with a lift pump. If hooked up to a combined sewer system, the recirculation rate has to be made readily adjustable if rainfall hits, so as not to compound wet weather-driven hydraulic overload.

However, the recirculation loop will guarantee that the wetland stays wet even when population activity is only intermittent. Recirculation rate has to be carefully adjusted, as during these periods of inactivity, electricity is no longer used for effluent treatment but for watering the filter-bed plants. Performances on TSS, although improved, are still not good enough for a UV module to function as intended.

However, installing a saturated bottom layer can take the system below the 25 mg/L TSS threshold and thus host effective disinfection via a UV module. The anoxic zone eliminates the nitrates content and improves the quality of the treated effluent in terms of total nitrogen. When there is no incoming effluent inflow, the plants can still tap into the saturated zone for water, which means the facility can be safely left at a standstill.

Increasing the filtration layer depth to 80 cm with an aeration drain installed mid-filter at 40 cm can achieve 90% removal and 100 mg/L for COD, 85% and 15 mg/L for TKN, and take the system below the 25 mg/L threshold for TSS.

A second stage may prove necessary in order to guarantee very low treated effluent load levels. Here again, there are multiple configurations possible - not all of which have yet been tested. Installing a saturated bottom layer under 80cm of filtration-layer media, for instance, looks a promising solution that may well deliver excellent performances: 90% COD removal, 90% TSS removal, 85% TKN removal, and 60% TN removal.

To dig deeper

Note that for this NS/S 80cm CW configuration, as the denitrification process uses up organic carbon, it is not impossible that the very advanced removal of organic carbon removal by the non-saturated part of the filter could result in a denitrification-limiting C:N ratio.

2.3. Estimation of wasteload demands

The loads received by the facilities are generally less than 50% of the nominal design loads, both in the French overseas departments and in mainland France. This state of events stems from misestimated load demands and overestimated community population-growth projections.

Estimating load demands is a tricky exercise, including for private real-estate development contractors even though they have the exact number of housing units involved. Oftentimes the project engineer has no way of knowing the load because the network has not yet been built. As the lifespan of a CW facility is at least 25 years, the estimation is based on built housing stock and the demographic boom forecasted by the French statistics agency INSEE, which projects a net all-French-overseas population growth of 34.6.% between 2011 and 2030 against just 5.1% for the net all-France population (Richez, 2011). These forecasts do warrant a degree of caution, since in 2016 the population of Martinique actually shrunk by 1% whereas the INSEE forecasts 7.5% growth between 2011 and 2030.

Beyond these demographic projections, in an effort to get more reliable estimations of load demands, a good starting point is to revise the distinction between inhabitant and population equivalent and the correction coefficients used to define service capacities for small community amenities (schools, hotels, and so on), and then to go back over phased project staging options offered by CWs.

2.3.1 Definition of PE pollutants production in tropical French areas

Wastewater-facility treatment capacity is expressed in population equivalents (PE). The EU wastewater treatment directive of 21 May 1991 defines one PE as the "organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day".

Actual pollution load released per capita varies with context but is between 40 and 50 g BOD_5/d. The MEDDE's urban wastewater directive guidance (Morin *et al.*, 2013) works on the premise that "in small-community not connected to any industrial activity, one inhabitant produces 40 g of BOD_5/d". Under these conditions, **assimilating inhabitant to PE would, in practice, effectively oversize the facility by 50%.**

The same applies in the French overseas departments, prompting the 'Intercommunal water and sanitation authority—Mayotte' (SIEAM) to define the PE–*mahorais* (PE*m*), where 1 PE*m* = 0.75 PE. While the PE*m* at least has the merit of addressing the inhabitant–PE differential, it also adds confusion by giving the impression that there is a proven difference in organic load produced by someone living in Mayotte and someone living in mainland France.

Mercoiret (2010) databased over 10,000 24hr-composite performance assessments on 2,700 facilities serving communities of less than 2,000 PE in mainland France. She computed a number of ratios (e.g. COD/BOD_5) that carry the advantage of being representative of raw wastewater in rural communities yet relatively independent of facility loading rate. If we reapply these ratios to the definition of PE, then it becomes possible to define the loads equivalent to one PE for each of the various pollutant items (Table 6).

This same research is currently being repeated based on the full dataset of regulatory-compliance self-monitoring records produced in the French overseas departments since 2012. Our database numbers over 9,500 24hr-composite performance assessments recorded on every single facility built in the French overseas region*. Our data serves to define the tropical-region PE as a whole, and is not necessarily representative of raw wastewater in rural communities (as the sample also accounts industrial effluents from bigger urban clusters).

The lifestyle patterns of certain ethnic-group communities is also a relevant factor, especially in French Guiana or Mayotte where certain communities (connected to the centralized sewerage network) continue a tradition of washing clothes and cooking outdoors, which means these effluent streams go uncollected. Design-office engineers

Table 6. *Comparison of French-mainland PE vs tropical-region PE for small communities (<2,000 PE). The figures used are the rounded values—the actual calculated values are given in brackets (mainland-France data borrowed from Mercoiret, 2010)*

Parameter	BOD? (gO?/d)	COD (gO?/d)	TKN (gN/d)	NH? (gN/d)	TP (gP/d)	TSS (g/d)
Mainland rural-community PE	60	150 (157.2)	15 (15.5)	11 (11.5)	2.5 (2.1)	75 (72)
Tropical-region (all-sizes) PE	60	125 (127.5)	15 (13.5)	11 (10.25)	2.5 (1.85)	75 (66.9)

planning for particularly specific communities are encouraged to mobilize their insider knowledge of the field and its peoples to adapt the coefficients to fit the pollutant wasteload estimates to the real-world picture.

Apart from the COD value for which the mainland-France PE–tropical-region PE differential is more than 20%, the deviations are small and not significantly different given the sampling dispersion. This is, of course, perfectly normal, as human metabolism is exactly the same wherever you are.

However, different patterns of consumption can lead to variations for chemical-source pollution (COD, TP). The mainland-to-tropical differential for COD is almost certainly underestimated due to the fact that the tropical-region PE assessment is based partly on composite samples taken from urban-area facilities that also integrate chemicals-heavy industrial effluent. It thus emerges that the population of the French overseas departments produce more chemical-source pollution that in rural mainland France.

2.3.2 Correction coefficients for infrastructure sizing

The policy memo of 22 May 1997 governing decentralized sanitation systems gives correction coefficients as a function of the type of facility (Table 7). As no fresh study has been conducted since, these same coefficients continue to apply today for estimating pollutant loads on basic small community amenities. **They are guidance-only values that the project engineer needs to adapt to their real-world picture on the ground.**

Table 7. *Correction coefficients used for assessing the service capacity of small community amenities, borrowed from the policy memo of 22 May 1997*

Parameter	Correction coefficient
Permanent user	1
School (boarding), barracks or rest-home	1
School (half-board) or similar	0.5
School (residential) or similar	0.3
Hospital, clinic, etc., per bed (counting nursing staff and operations staff)	3
Factory staff (per 8h shift)	0.5
Office workers, shop workers	0.5
Hotel-restaurant, guesthouse (per room)	2
Hotel, guesthouse without restaurant (per room)	1
Campsite	0.75 à 2
Casual users (place of public use)	0.05

Trade organizations may be ready to provide other reference frames like this for certain specific activities.

2.3.3 Phased project staging periods

When estimated load demands are plagued by a catalogue of uncertainties (demographic projections, speculative sewer-system connections, new tourism business taking off), the project can be packaged into several phases so as to realign the investment as and when needs change.

CW can easily be reconfigured (Figure 18):
- by creating a second stream*, running parallel to the first, which requires reworking the distribution infrastructure capacity or installing automatic valving for dose-feeding the two streams;
- by only creating one of the two filters initially planned, and partitioning it. The hard partition can be permanent or modular (brick wall, corrugated sheet, etc.)—the important thing is to make sure the filtration layers in each half are hydraulically separated, so that the rest-phase periods really are 100% rest. The feeding system will also need pipe-splitters so that the filter cells can be rotated.

Whatever solution gets adopted, it is important to set aside the landholding needed for later extension.

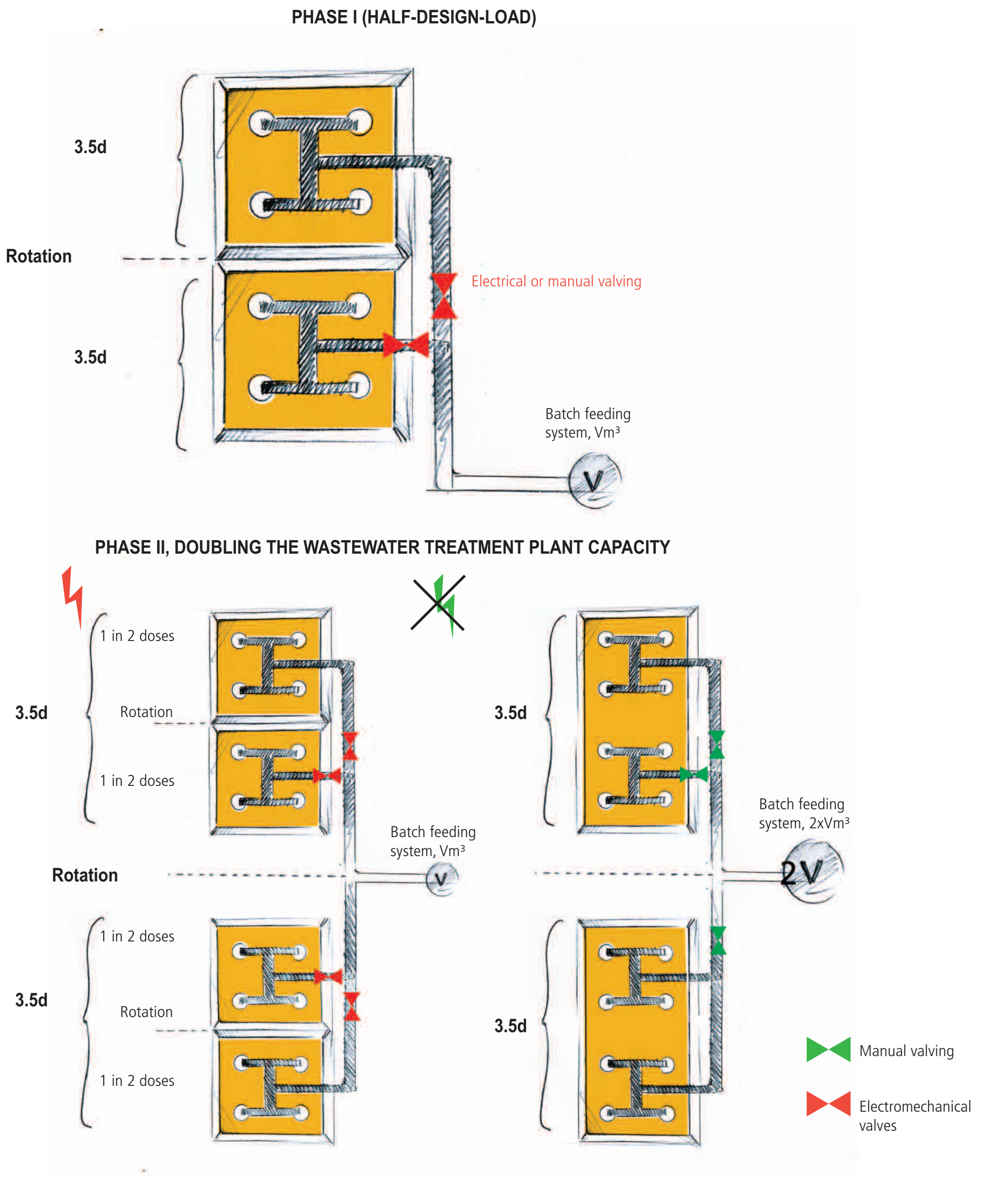


Figure 18. *Phased staging of a constructed wetland (CW) project by partitioning or adding a new stream.*

Likewise, once the filters have been constructed, it is possible to put only part of the infrastructure into service, which will help save on operational expenditure.

For a relatively modest investment cost, each cell can be partitioned using corrugated sheet and the feeding system can be flanged to shut off the redundant feeding headers (Figure 19).

It may be practical to take measures to control the spread of adventives* into the plant community on the redundant filters. In French Guiana, a virgin filter cell can become a thick woody forest in the space of a year. Even if plant life is slower to grow in the other French overseas departments, it is good practice to cover the non-service filter with permeable geotextile sheet and to run regular monitoring and routine maintenance if necessary. Leaving unwanted plants to colonize the filter will compromise the filter once in service by strangling wetland-plant growth due to competition with residual adventives and the root systems and seeds they leave behind.

Figure 19. *Partitioning—example at the Taupinière facility (Martinique). In the foreground, the filter has been partitioned using corrugated sheeting. A flange has been fitted to shut off the redundant feeding headers designed to serve the half-filter that is not yet in service. In the background, the cells that make the facility's second stream are not yet in service and have not yet been planted.*

Design rules and materials

3

Once the engineer has settled on a treatment scheme, the next step is to define the characteristics of its system components using sizing ratios. These sizing ratios give the filter surface area that will be used to calculate volume of the feed-line works, composition of the distribution and feeding network, and composition of the drainage network. This same section also gives the material characteristics used in each set of works.

3.1. Protecting the infrastructure

Whatever CW variant is selected, it will be fed with raw wastewater, so there is no need for pre-treatment of the influent household wastewater. An influent screening system is still essential, though, to protect the infrastructure and make sure there is nothing to block flowpaths through the plant. Indeed, it is actually a regulatory compliance requirement[3].

In theory, influent through-flow in the bar screen should be between 0.3 and 1.2 m/s to prevent heavier debris getting deposited in the channel and stop large floatables like plastic bottles getting through.

In practice, the bar screen can be installed on the feed-line channel, where it can be manually-cleaned or automatically-cleaned or, if the system uses pump-station feeding, integrated into the station (basket screen). Choice of electromechanical hardware needs to factor in the climate constraints, as wearable and oxidizable parts tend to degrade prematurely in tropical environments. Shielding against exposure to sunlight and water will always pay off in the long run.

In any case, the screening system is to be built to the following specifications:
- a **20–40-mm screen** (if bar gap is 20 mm, the bar screen must be automatically-cleaned);
- equipped with **a bypass channel to offtake the influent if the bar screen gets clogged**;
- provided with a gap-adapted manual-cleaning rake;
- and a **screenings drainer basket** and dumpster.

[3] *Article 22 of the decree of 21 June 1996..*

3.2. Sizing the filters

3.2.1 Sizing ratios

CW sizing is scaled based on the loadings that the filter in operation can accept. The sizing ratio used is 350 g COD/m²/d on the filter in operation. The code-permissible influent loads are stipulated in Table 8. These ceiling values equate implementing filters with an area requirement approaching 0.4 m²/PE for standard domestic wastewaters.

Note, however, that the sizing is **based on applied loads, not on surface area requirement per PE.** Directly applying the surface-area criteria can result in a mis-sized facility if the loads have different characteristics (which will be the case if the local community hosts a specific activity, for instance). Therefore, if the data is available, the design engineer should cross-check the surface requirements given by the ratios against each of the parameters, especially hydraulic load which can reach very high values in the French overseas departments (subsection 1.5.1, p.21).

Table 8. *Sizing-code loads on the in-feed-mode filter of the free-draining first-stage vertical-flow filter*

Parameter	TSS	COD	BOD_5	TKN	HL (m/d)
g/m²/d	150	350	150	30	< 0.75

The hydraulic load limit relates to regular loads (including clear water intrusion and recirculation) and is unrelated to weather-driven flushes (storm events, for instance). Prost-Boucle & Molle (2012) showed that at over 75 cm/d, nitrification performances decline in the winter season. Even in tropical climate conditions, it is good advice to adjust the filter surface area to keep daily flush applied on the filter under this limit. With added recirculation, the volume of recirculated water needs to be accounted for as part of the hydraulic load to the filter in operation.

Project sizing examples

Example 1: creation of a housing development

The owner of a 40-home housing development project, theoretically to house 180 residents, plans to install an on-site CW sanitation system. As the effluent network has not yet been built, a measurement campaign is impossible, so sizing will be based on the definition of PE and the theoretical mean effluent output data (subsection 2.3.1, p.32), i.e. 45 g BOD_5/person/d

180 persons × 45 g BOD_5/person/d ? 8,100 g BOD_5/d

8,100 g BOD/$_5$d ÷ 60 g BOD_5/PE/d ? 135 PE

135 PE × 0.8 m²/PE ? 108 m²

Without hard field data, the sizing based on the theoretical values points to building two 54 m² filters for a total surface filter-area footprint of 108 m².

suite

Example 2: reprocessing of an activated sludge
Finding repeated reports of sludge leaching on one of its treatment facilities, a local council plans to replace one of its activated sludge processes by a CW. The mean values from the latest monitoring campaigns are: 220.8 m^3/d, 344.6 mg COD/L, 163 mg BOD_5/L
344.6 mg COD/L × 220.8 m^3/d ? 76,088 g COD/d
76,088 g COD/d ÷ 350 g COD/m^2/d ? 217.5 m^2
Based on total daily maximum COD wasteload, the system needs two cells at 217.5 m^2. Next, the engineer needs to check that this surface area is appropriately scaled for treatment of all the other water quality parameters.
163 mg BOD_5/L × 220.8 m^3/d ? 35,990 g BOD_5/d
35,990 g BOD_5/d ÷ 150 g BOD_5/m^2/d ? 240 m^2
220.8 m^3/d ÷ 217.5 m^2 ? 1.02 m/d
220.8 m^3/d ÷ 240 m^2 ? 0.92 m/d
220.8 m^3/d ÷ 0.75 m/d ? 294.5 m^2
In our case example here, the combination of an imbalance (COD/BOD_5) together with significant dilution of the effluents (suspected clean water infiltration/inflow), the sizing obtained based on COD flux is under-equipped to treat the BOD5 load and under-equipped to accept the hydraulic loads. It is the limiting-factor parameter (here, hydraulic load) that dictates the sizing. In our case here, the recommended practice will be to bed two 295 m^2 filters.

3.2.2 Construction practices

There are two main construction practices: concrete-formwork cells or excavation-and-fill. Cost efficiency imperatives will more often than not swing the decision towards excavation-and-fill. As axcavation-and-fill makes embankments, it creates a slightly bigger footprint. The surface calculated is the surface area at the highest point of the media material packing the filter. The sloping embankments mean that the filter surface gets smaller with as it goes deeper. In certain configurations (deep filtration layers, saturated bottom layer), the side-slope gradient should be made as high as possible, especially if the filters are small, to keep a substantial volume for autotrophs to thrive in or for the anoxic zone.

The bank slope is 3 × horizontal for 2 × vertical if fitting a geomembrane liner—the ideal ratio would be 1 for 1, but feasibility-wise all depends on the quality of the undersoil.

Concrete-formworked cells carry the advantage of adding a hard barrier preventing outside adventives from invading inside the filter.

3.2.3 Freeboard

Freeboard, defined as the distance between the high-point level of the upper filter topsurface and the high-point level of the filter bank, is to be designed to accommodate two objectives:
- hold surface sludge up to 20 centimetres deep;
- contain the flushes applied during wet weather events. In the rainier regions of mainland France, the filters handling rainfall influx (combined sewers) have 70-cm freeboards to minimize the number of annual overflows (Arias Lopez, 2013).

A 70-cm freeboard is recommended practice in the tropics, as it will minimize the number of annual overflows even when the system has been long-serving and built up a 20cm-deep sludge blanket at the surface.

To save on earthworks costs, the same one excavated basin can be made to accommodate both the filters parallel (Figure 20), in which case the filters will be separated by a partition wall, itself anchored into the excavation sides shoring the filter embankments. The partition wall has to be absolutely impermeable to prevent any filter-to-filter transfers and thus preclude any interference in the rest-phase periods. Ideally, the belowground section will equal the depth of the filtration layer, with an overhead freeboard of at least 70 cm. Transition layer, drainage layer, and the aeration and draining pipework can serve the two filters together.

The top of the partition wall must at least reach the freeboard level.

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Figure 20. *Partition wall separating two filters inside the same cell. Note that it could have been stacked a little higher (20–30 cm) to accommodate a higher freeboard. Champ d'Ylang 1 facility, at its inauguration in November 2015, on Combani commune (Mayotte).*

3.3. Distribution infrastructure and feed-system network

To ensure that the filter-media bed is well re-oxygenated and the raw wastewater is evenly distributed across the filters, feeding is done at a substantially higher flowrate than the influent flowrate. This feeding by batches is delivered from a batch feeding system that holds the incoming effluent until it fills to a fixed volume then quickly ejects it at a fast flowrate towards filter in operation via the distribution-system headers.

3.3.1 Pulsed dose characteristics

Depending on the site topography and technical engineering (Table 5), the filter can be fed by gravity flow or be pressure-dosed by a force-main pump. Either way, the pulsed doses are to meet specific characteristics, as given below:

- a volume corresponding to a 2.5–5cm flush distributed all across the entire in-feed-mode filter. At below 2.5cm, the pulsed dose will fail to cause ponding and the influent will not distribute evenly. At over 5cm, the doses can hang around in the batch feeding system for long enough to start giving off objectionable nuisance odours. Likewise, if preferential flows through the filter become too strong, the infiltration rate will increase, which will undermine removal performances. With feeding driven by a lift-pump, the volume of the doses needs to account for the ullage volume of the distribution pipes that will backwash into the well when the pumps stop;

- an instantaneous flowrate greater than 0.5 $m^3/h/m^2$ of filter in operation. This flow rate is designed to self-clean the distribution pipes and evenly distribute the dose flush.

As large-capacity facilities have bigger filter-bed surfaces to flush, the doses have to be flushed in at very high flowrates. The appropriate equipment is expensive. One way to cut the cost is to set up several treatment-stream lines in parallel, but all served by the same one distribution infrastructure. This will mean that the filter surfaces dosed are smaller, and so dose volume and flowrate are also divided by the number of streams. The flipside is that the plant will need to be equipped with a system of console-controlled electromechanical valves to switch the doses between the streams, or with several pumps in the lift pump station (at least one pump per stream) all working in rotation. There is no change in the filter feed-resting phases (3.5 d/3.5 d).

Electromechanical valving leaves the filter less robust. A project owner opting for this technical solution will need to have competently-skilled personnel ready to jump in if any of this hardware goes out of action.

3.3.2 Feeding by gravity flow

There are three types of gravity-flow devices: self-priming siphon, ball-valve flushers and float-valve flushers. However, ball-valve flushers are ruled out of use for raw wastewater (but can be used for the second stage).

The chosen device is set up in a dose tank sized to hold the targeted flush volume. The capacity is determined by the instantaneous flowrate that the device is gauged to deliver and that is calculated integrating downgradient pipework head loss. The dose flush has to be fully emptied to prevent a build-up of deposits on the tank floor. Different types of dose-flushing systems have been installed in the French overseas departments. All are fully functional, and the wear parts have all been replaced at regular intervals corresponding to the manufacturer's guidelines. The system can be hooked up with a mechanical dose-flush meter, which helps keep count of the number of doses flushed daily for monitoring.

3.3.3 Feeding by a lift pump

The filters may have to be dosed by a lift pump station when site topography or a recirculation loop so dictate, in which case the station is equipped with two pumps operating in rotation. A set of valves is to be fitted so that if one pump breaks down, the filters are still dose-rotated. As a rule, the pumps are triggered by float switches. Minimum diameter of the pumps and distribution pipes is DN80. The ullage lost in the distribution pipes, which return-backwashes into the well after each dose flush, has to be factored in when setting the pump-switch water levels in order to discharge the right volume onto the in-feed-mode filter.

Fitting check valves could be an option, but one that carries the drawback that influent may be hang around in the piping for a long time between rotations.

Recording time pump functioning is a useful add-on to the pumps, and once they have been calibrated they can fairly precisely gauge the volumes pumped (although an assessment of this type does not qualify as 'measurement' following the decree of 21 July 2015; subsection 5.4.2, p.63).

3.3.4 Distribution and feeding network

To optimize the spread of effluent load distributed onto the filter surface, the number of feeding points is determined to ensure there is at least one for every 50m² of filter. For geometric reasons, the feeding point are generally paired, or even in 4s. An anti-scouring plate* is installed under each feeding point to off-slough the wastewater inflow and protect the filter-media bed (Figure 21).

Each type of dose delivery system requires a different header-system network.

Feeding by gravity flow uses a network of elevated (overground) headers, which is entirely inspectable and dismantlable. It has to be built in HD-PE, or even stainless steel, for UV resistance.

Feeding by a lift pump can use buried (through-ground) distribution pipes. Only the terminal section has to be UV-protected, the rest can be built in PVC. The network is generally laid in a double-H format, with progressively narrowing pipe up to a minimum of DN100 in diameter. This kind of network is engineered to fully empty out at each dose pulse, thus preventing stagnation, organics build-up, risk of clogging, and nuisance odours. Raw wastewater can be made to circulate at a flowrate of over 0.6 m/s^{-1} (self-cleansing velocity) at every point.

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Figure 21. *Elevated headers with the anti-scouring sheet (at left) or buried headers mid-feeding (at right).*

3.4. Network of aeration and drainage pipes

Each end of the drainage network vents out to the atmosphere via 90° tubes topped with a vent cap. This is the path taken by the air contained in the bed when a dose batch flushes it down, and it is this same network that also hosts diffusion-driven upflow transfers from the bottom of the filter (Petitjean *et al.*, 2011), hence named aeration–drainage network, as it serves both functions.

It is composed of PVC tubing (except for the vents and vent caps above the filter), gauged at least DN100 in diameter, notched with 1cm-wide down-facing slits over a third of the tube circumference, and spaced at 10cm intervals (Figure 22). Right-angle elbows are *not* good practice. High-resistance-grade (CR8/SN8: resistant to 8 kN/m^2) PVC tubing will minimize the risks of damage during heavy maintenance operations (desludging). Agricultural-grade drain pipes are not to be used as the holes are too small.

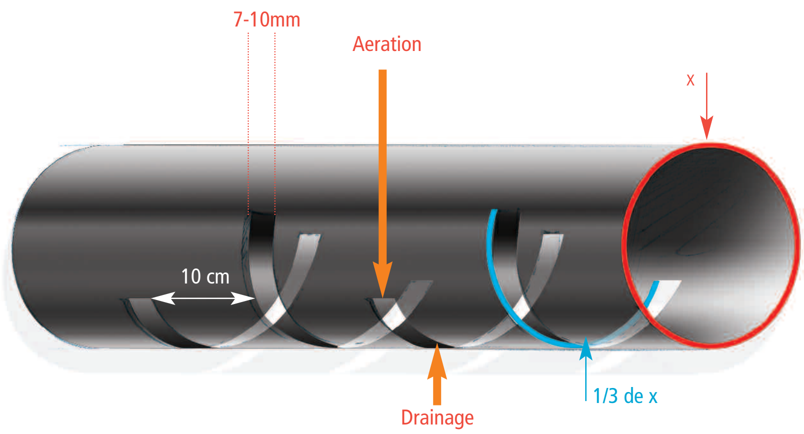

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Figure 22. *Schematic illustration of aeration–drainage pipework.*

The bottom of the filter, which underpins the network's main collector system, has a slope gradient greater than 0.5%. Some configurations (NS/S and filtration layer >50 cm) are engineered with intermediate aeration networks through the stages that have exactly the same characteristics to increase filter-bed aeration.

Drain-line density is calculated based on surface area of the filters and must be greater than 0.25 linear m per m² of filter area.

3.5. Sealing and sealing materials

The filter-media bed composed of different-graded gravel layers is sealed from the undersoil by a synthetic (geomembrane) or natural (compacted earth) envelope.

3.5.1 Artificial sealing, natural sealing, and infiltration

The filter base is generally sealed over with a synthetic liner, which has to be opaque, UV-resistant, and puncture-resistant (rhizomes and media/materials), which means the geomembrane has to be sandwiched between a pair of geotextile liners.

Guidelines issued by CFG—the French Committee for Geosynthetics (1991) give minimum recommended thicknesses for the membranes according to their build material, i.e. 1mm for PVC and PP (polypropylene), 1.5mm for HD-PE, and 1.14mm for EPDM. Bitumen should not be used as rhizomes can force through it. These guidelines are further elaborated by the *Laboratoire des Ponts et Chaussées*/Setra (2000) which gives detailed design code on how they should be webbed and how seams should be lapped in civil-engineered works or pipe runs. The geomembrane is to be fitted by ASQUAL-certified installers, especially for welding the membrane-to-membrane seams.

The geomembrane has to cover the banks to at least as high as the freeboard line, and anchored at the crest. The open-air-side parts of the membrane lining the excavation sides should be shielded against direct sunlight with a layer of protective gravel. Recommended practice is to design a gas drainage system underneath the geomembrane together with a set of context-driven system measures to deal with a rising watertable.

3.5.2 Filter packing materials

Quality of the filter materials is absolutely crucial for a long-serving system. All media installed should be homogeneously grain-sized and pre-washed until mineral fines (d<63 µm) content is less than 3% by bulk. Any excess fines can irreversibly clog the system deep down. The use of crushed bulk gravel or volcanic material aggregates requires close attention to ensure homogeneous grain-sizing with no fine minerals. The manufacturer must provide the characteristics (grain size, hardness, limestone composition [expressed in $CaCO_3$]) and source of the material and a layering plan (layer thicknesses).

Toughness of the filter media aggregate is a factor, as aggregate material being hauled to site and bedded in the filter will collide together and undergo different crush pressures. It the aggregate is too friable, the grain size will get smaller and the fine materials fraction will get too big. The media material can undergo substantial change in quality between quarrying and the moment it is in place. This is why it is advised to rewash the material before it gets sited, washing it several times over if necessary until fine sand no longer drag out with the washwater. The Los Angeles test (NF 1097-2—coarse-grained aggregate) and the micro-Deval test (NF 1097-1 - fine-grained aggregate) are used to determine aggregate toughness and disintegration resistance. Their grading scale runs from 0 (extremely tough) to 100 (extremely friable). Engineers are advised not to select any materials that are rated over 35.

Water, especially acidic water, dissolves the calcium carbonate content, which progressively undermines the toughness of the material. Nitrification processes can also have this same effect. Calcium carbonate content is capped at 20% by bulk mass.

The CWs are composed of three layers of gravel stratified by a grain size that increases from top to bottom:

- filtration layer. It handles the bulk of treatment by enabling physical retention of solid particles and by serving as substrate for the growth of contaminant-removing biomass. It is between 30 and 80 cm thick depending on the process variant employed (Table 5, p.30). At upwards of 60 cm, it is recommended practice to run an intermediate aeration drain through the middle of the filtration layer. It is to be connected to the aeration network, and with down-facing slits. The filtration layer is composed of 2–6 mm gravel with a uniformity coefficient (Cu) of less than 5;
- transition layer. This intermediate layer prevents the finer grains in the filtration layer from migrating into the drainage layer. The grain size of this 10–20-cm thick layer is defined based on the grain size of the filtration layer and the following grain-size transition rule, borrowed from Terzaghi's principle:

$$d_{15} \text{ transition layer} \leq 5 \times d_{85} \text{ filtration layer.}$$

It is sandwiched between upper and lower layers whose grain sizes generally lead to 5/20 mm gravel;
- drainage layer. This layer is traversed by the aeration and drainage pipes that collects and evacuates the treated effluent. It is this layer that accommodates the 0.5% slope gradient at the bottom of the filter. If there is no saturated zone, it will be 10–20cm thick. For the NS/S variant, it will be 10–20 cm thicker than the depth of saturation. It is composed of 20–60mm course-grade gravel. Terzaghi's principle, as set out above, again applies here.

3.6. Sizing horizontal-flow filters

The design guidelines for horizontal-flow CW in tropical-region geographies are based on two schemes: one tied to hydraulics and the other tied to pollutant biodegradation.

3.6.1 Hydraulics

The hydraulic sizing of horizontal-flow CW should be simple but in fact throws up a number of issues that can lead to drastic changes in operating conditions - and even wholesale system failures.

The emergence of surface flows is the hallmark example. Surface flows have been observed in most of the countries that have pioneered this type of infrastructure (USA, UK, Denmark), particular when attempting to use the native soil in place (Germany).

Although not the perfect solution for the hydraulic conditions in horizontal-flow biofilters, Darcy's equation is often used to determine the cross-sectional area of hydraulic flow (width and depth) needed in the filter for water to flow through the pore spaces inside the filter-media bed.

It is written as follows:

$$q = \frac{Q}{As} = -k_s \frac{dH}{dx}$$

where:
q: influent flow as a ratio of sectional area, m/d
Q: volumetric flowrate, m^3/d
As: sectional area, m^2
dH/dx: hydraulic gradient, ad.
ks: saturated hydraulic conductivity of the media, m/d

Every horizontal -flow filter is going to clog over time as it slowly accumulates recalcitrant organic matter, inert TSS deposits, precipitates, biomass growth or dense root-system development… The net result is that the media loses porosity, and therefore permeability. The hydraulic sizing of the filter consequently has to plan for this clogging process to avoid preferential surface flows over time, which is the cue to plan in the influence of clogging on the permeability of the media. When the horizontal-flow filter is located downstream of an upgradient first-stage vertical-flow wetland, design needs to integrate a 10-fold drop in saturated hydraulic conductivity from start to finish. In practical terms, this will mean having to implement a gradient of media running from 3/6 mm grade to 15/20 mm grade.

3.6.2 Pollutant biodegradation

The sizing tied to pollutant removal efficiencies entails setting the residence time of influent in the filter system to guarantee al level of treatment efficiency. As width and depth are already governed (by hydraulic sizing), the only parameter left to work on is length of the filter. Several different models have been put forward for this purpose, the most popular today being the k-C model*. It is based on a first-order (k) pollutant decay and a background concentration tied to a backwashed pollution flux and a plug flow. Although admittedly imperfect, it does allow an approximation of the in-filter residence time to engineer for a target effluent quality level.

$$\frac{C - C^*}{C_{in} - C^*} = \exp(-k_V \tau)$$

where:
C and C*: concentration (in: in-load) and background concentration (C*) of a given pollutant, g/m^3
kv: bulkstream rate constant of degradation of a pollutant J-1: residence time, J

The effects of temperature on the rate-constant kv can be expressed by an Arrhenius-type equation:

$$k_T = k_{20} \cdot {}^{(T\text{-}20)}$$

When installed downstream of a first-stage non-saturated vertical-flow CW, a surface of 1 m²/PE can achieve effluent contents of under 25 mg BOD_5/L. This configuration has not been tested as part of our system projects for the overseas departments, so there is no way to guarantee that this sizing scheme is optimized for tropical climate.

Interested readers are invited to refer to more specialized literature to appropriately adapt the sizing criteria (Dotro *et al.*, 2017).

4 CW - Which plants for tropical areas?

The plants, via their mechanical action, are integral to the CW process. *Phragmites australis* is used in both mainland France and abroad, but is not naturally found in the tropics, where it carries strong invasiveness risk. Tropics-adapted CW design thus hinges on selecting endemic native species that can replace *Phragmites australis*. A study that was set up specifically to address this issue has served to evaluate a hundred-odd species (Lombard-Latune & Molle, 2016). The conclusions of the final report can be found below.

The research to find a substitute had to first lay down a clear statement of the needs. Selection criteria were then defined based on this master statement of needs. These criteria serve to make sure the plants selected are suitably adapted to the unique biotope involved in biofilters, the mechanical role required of the reedbed vegetation, and the ecosystem (in terms of balance of the community of species) set to host the wetland filters.

The CW environment itself imposes some requirements:

- ability to thrive in a non-saturated good-drainaway sand-gravel substrate;

- ability to tolerate substantial inputs of crude organic matter, possibly including transient periods of an oxygen-deprived habitat;

- ability to tolerate hydric stress: sharp swings between feed-mode phases

(>400mm/d for 3.5 days) and rest-mode phases (3.5 days without input);

- capable of thriving in direct sunshine (no shade).

The functional role expected also imposes a non-negotiable set of intrinsic characteristics:

- perennial non-woody;

- fast and even growth to rapidly colonize the filter surface without 'tufting' which would shrink the effectively-active filter surface;

- rhizome-system plants, ideally developing dense rhizomes packed in the first 50 cm into the filter bed;

- not considered as invasive, and not producing large numbers of seeds (to minimize dispersal);

- growing to over 60 cm in height and stem diameter between 0.5 and 2 cm to combine good strong mechanical effect with easy manual thinning and harvesting*;

- leaves, bracts or other aerial foliage organs must not catch rainwater, to preclude any sanitary risks tied to mosquitoes and similar weed risks;

> **Plant growth cycle**
>
> The plant growth cycle defines as a series of life-stages in plant development. These stages can be grossly classified into four 4 phases.
>
> • Vegetative growth, from the germination of a seed or the emergence of a shoot in the case of vegetative propagation. This phase lasts until the plant has reached a level of development enabling it to produce enough energy to reproduce.
>
> • Flowering, which the phase where plants enter sexual vegetative reproduction.
>
> • Setting or fruit-setting, which leads to the production of a seed egg.
>
> • Senescence, where the plant, having fulfilled its reproductive function, starts slowly dying.

- not be an irritant or an intoxicant during harvesting.

Local status of the species is another factor to internalize:

- the plants must not carry a risk of invasiveness;

- the plants must not be protected species.

4.1 Results of the study

Starting out from these required criteria, a hundred-odd different species were studied in greater depth. First, a desktop review phase served to rule out the majority of the candidate plants. Second, pilot trials were set up to compare the plants on the main sources of CW-induced stress, i.e. hydric stress and anoxic stress. Third and last, we assessed the full-scale real-world behaviour of the remaining species in response to competition with adventives (the technical term for "weeds"), their growth cycle and their in-filter development, which served as grounds for discussion on the thinning and harvesting intervals they would need.

The best-candidate plants belong to three different botanical families: the Zingiberales, the Cyperaceae and the Poaceae.

4.1.1 The Zingiberacae

The Zingiberacae are a relatively narrow botanical order of plants that are only found natively in the tropics. The order has eight families spanning just a few dozen species. Some of these species are cultured as ornamentals and have a large number of cultivars*. *Heliconia psittacorum* is thought to count over 1,200.

The five species that proved best adapted to hydric and anoxic stresses during the pilot-trial phase all belong to this order, which thus appears to be a prime candidate. As this prime-candidate order is also relatively small, the study endeavoured to be fairly exhaustive (Figure 23).

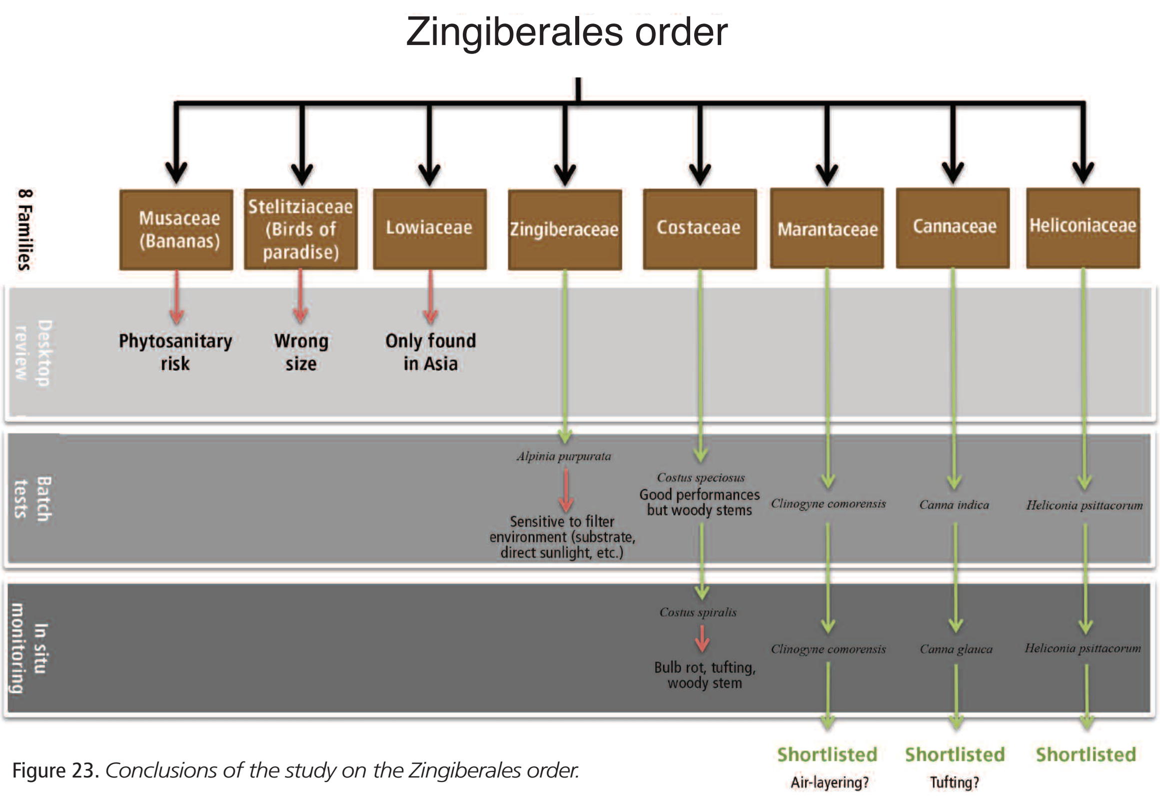

Figure 23. *Conclusions of the study on the Zingiberales order.*

The Zingiberacae contain eight families. Three of these families were ruled out for different reasons: phytosanitary risk (Musaceae: the banana group), size (Strelitziaceae: the traveller's tree) or geographic boundaries (Lowiaceae: only really found in Asia). After further studying representatives of the five families left, two families were ruled out:

- the Costaceae (*Costus spiralis et Costus speciosus*), due to being undercompetitive on the filter beds and having rhizomes that were oversensitive to stagnant water;

- the Zingiberaceae (*Alpinia purpurata*) which failed to survive the local filter-bed conditions (sunshine, substrate).

After this study, the representatives of the three last families left proved the most promising candidates moving forward. They are characterized by relatively slow development compared to the other species assessed, which has the advantage of needing fewer harvesting operations—the major O&M task in terms of time budget. The flipside is that they are slower to establish/colonize and may require hand-weeding to help get established during the start-up phase. Once these families are established, their thick foliage generates throws a dense dark shade over the ground, which is what makes them very competitive plant that leave little room for adventives.

These three candidate families are listed below.

■ *Heliconia psittacorum*, from the Heliconiaceae family (Figure 24).

Development may be slow but it compensates by better distribution over the filter-bed surface. It appears currently the best alternative for use in tropicalized CW. However, it is also genetically closer to the banana tree than the other two families, which means it could ultimately turn into a reservoir for pathogens or pests and thereby make it a significant phytosanitary risk for nearby banana plantations. According to the Martinique's regional federation for pest control (Fredon), the Heliconiaceae have risk potential and should not be planted at less than a kilometre from a banana plantation. The Cannaceae, in contrast, present little risk and so should be the preferred option in such cases.

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Figure 24. *Filter bed planted with Heliconia psittacorum.*

■ *Canna indica* and *Canna glauca*, from the Cannaceae family.

They grow in very dense stands, and are more akin to tufting than the others, which makes them less attractive than *Heliconia*. However, there are recommended for CWs in close proximity (<1km) to banana plantations. Filter beds planted with *Canna indica* in Martinique and Guadeloupe suffer caterpillar invasions from November to January every year, whereas Mayotte (*Canna indica*) and French Guiana (*Canna glauca*) have had no such problems (Figure 25). The invasions do not visibly pose a threat to plant survival in the filter beds, but they almost certainty hamper plant development.

© Cotram assainissement

Figure 25. *Caterpillar invasion on Canna indica at the Mangles facility (Guadeloupe).*

■ *Clinogyne comorensis* from the Marantaceae family.

It is fairly fast-growing, but the stem, which bear the flower sets, has a tendency to propagate by air-layering (Figure 26), which could generate a risk of forming a ground-layer 'mat'. The plant is endemic to Mayotte, where it is considered as an endangered species, and so wetlands filters could provide it with a value-adding niche.

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Figure 26. *Air-layering on Clinogyne comorensis. Air layering, or 'marcotting'*, is a propagatability found in the stems of certain plants that boast epidermal meristematic cells cells capable of differentiating into root tissue in contact with soil.*

These plants confer extra robustness to the system as they readily adapt to broad spectrum of conditions (ability to tolerate both hydric stress and anoxic stress) yet require relatively little maintenance (demanding waterweed harvesting only every 18 months).

However, they will require help to get established during the start-up phase to minimize competition from adventives. The vegetative growth cycles could not be ascertained but are definitively more than 12 months. Recommended practice is to perform thinning and harvesting every year, just before the tropical cyclone season, or before the dry season in French Guiana, where Heliconia presents on the facility suffered lodging in the wake of tropical storm Matthew, so preventive thinning and harvesting ahead of the cyclone season would protect the vegetation against violent winds.

4.1.2 The Cyperaceae

The Cyperaceae - or 'sedges' - are a large family of plants (5,000-plus species) known the world over, mainly found in warmer climate zones. They belong to the *Poales* order. The three species studied dealt with hydric stress in a way that, although not as good as the Zingiberacae, was nevertheless comparable to that of the other plants used to date on filter beds in tropical-region geographies (whose problem was more a tendency to present variegated 'tufting' rather than any real incompatibility with the CW habitat itself).

■ *Cyperus alternifolius* and *Cyperus involucratus*.

Depending on the botanical classification system used, these two species are qualified as distinct or as one and the same variety. There is little to no real difference between the two. Both are relatively fast-growing, and their foliage quickly covers the whole filter bed, limiting the development of ground-level adventives. After a few months, a thick litter forms on the ground. They need two harvesting campaigns a year in order, to maintain a good strand density, and remove all of the plant matter produced.

■ *Cyperus papyrus* is not as dense as *C. alternifolous/involucratus*.

However, it grows higher stems and appears to better tolerate anoxic conditions that its cousins. The literature reports its use on sludge drying beds (for the treatment of sewage sludge and septage). Certain botanists claim that tit carries a non-negligible risk of spreading outside the filter beds and there warrants tight monitoring. It has not, as yet, been shortlisted for use on CW.

The Cyperaceae tested have proven to be a promising candidate substitutes for CW, even though they are less equipped to deal with extreme shock climate conditions that the Zingiberacae. They need less maintenance at start-up, but more regular harvesting down the line. They have tougher stems and thus require purpose-adapted hand-tools like hedgecutters for harvesting.

4.1.3 The Poaceae

The Poaceae, or 'grasses', also belong to the Poales order. They account for an estimated 20% of all vegetation on planet Earth and count over 12,000 species, making them the 5th largest plant family on Earth. The handful of species evaluated so far do not appear to demonstrate highly-evolved stress response mechanisms.

Phragmites australis is member of the Poaceae, so there will be some species better adapted than others.

This family of plants is characterized by very fast growth, which can be an asset.

■ *Arundo donax* and *Echinochloa polystachia* looked attractive as they are fast-growing and form dense strands. However, their growth cycles were so short (3-4 months) that the frequency of harvesting should have been upped (three times per year) to maintain a reasonably substantial density. However, the bigger problem encountered came from their over-affinity for the filter media, as they vary quickly migrated out of the filters. They spread by layering, which means they colonize faster and form a very dense mat of interknotted stems that blocks out any kind of mechanical action on the sludge layer. They should never be used, as even with firm management and maintenance, they still carry a risk of invasiveness.

■ *Thysanolaena maxima* grows into tufts, which is counter to our purpose.

■ *Brachiaria decumbens* is a tropical forage plant. It is too small to have a mechanical action on a thick sludge layer, it is also relatively stress-sensitive.

None of the Poaceae tested were ultimately selected as candidates. However, the order is so large that there are surely as-yet-unstudied species that hold promise, particularly when looking at systems designed to integrate sustainably with farming (fodder plants).

4.2 Plant catalogue for CW in the French overseas departments

The plants selected as lead candidates for CW in the French overseas departments based on the this study are catalogued in Table 9.

Table 9. *Roll-up of the species selected as candidates for constructed wetlands (CW) in the French overseas departments*

Heliconia psittacorum	***Canna indica, canna glauca***	***Cyperus alternifolius/involucratus***
Heliconiaceae family, Zingiberales order	**Cannaceae family, Zingiberales order**	**Cyperaceae family, Poales order**
 © Irstéa	 © Irstéa	 © Irstéa
Very even growth, progressive colonization of the entire filter bed	Slight tendency to tuft Slow colonization of the entire filter bed	Fast growth but slow colonization of the entire filter bed Tufting
Moderate strand density: up to 250 stems/m²	Moderate strand density: up to 250 stems/m²	Very high strand density: up to 600 stems/m²
Very very competitive against adventives	Very very competitive against adventives	Very competitive against adventives
Needs help to establish: weeding out adventives for a 3-month periods, once or twice per month Annual harvesting, before the tropical cyclone season	Needs help to establish: weeding out adventives for a 3-month periods, once or twice per month Annual harvesting, before the tropical cyclone season	Does not need help for nursery plants to establish harvesting every 6 months to thin out dead stems and encourage colonization of the entire filter bed
Notes and comment There are 1,200-odd cultivars, leading to chronically uneven growth (even inside the same filter beds!). Opt for the smallest cultivars. Genetic overlap with the banana tree creates plant health risks if the CW is sited within 1 km of a banana plantation	Note and comment *Canna indica* in both Guadeloupe and Martinique suffered caterpillar invasions from December to March. The plants are not decimated, but they are weakened.	

5

Cw - Implementation, operation, maintenance

This final section is a synthesis of the experience and feedback gained to date on CW implementation, operation and maintenance in tropical-areas. It details the incidents that have hit the works causing varying degrees of damage. It also illustrates the different phases in the life of the filter beds, along with examples of treatment scheme-appropriate metrology for regulations-compliant self-monitoring.

5.1 Implementation of CW

5.1.1 Feedback from the field—construction

The completion of the CW project hinges on the quality of the build media. As there is no second stage to build, problems with sand procurements can immediately be ruled out. That said, the filter media needed do have fairly specific characteristics (subsection 3.5.2, p.42), which may prompt quarries to adapt their output. Réunion got its first CW completed in 2016, and they are now CW in each of the French overseas departments, so there must be materials procurement solutions available.

Note, however, the project owner is planning a grain-size analysis on top of the information it gets from the suppliers. If material delivered is too far out-of-specification, it is wise to press the quarry to produce a new batch of filter media.

Lastly, it is vital to give the media an on-site pre-wash before laying it in the filters, as crushed bulk can suffer in transport, producing fine particles that need to be eliminated.

The filters are built to last, so the build process needs to be properly thought out and carefully sequenced.

Piling mineral media onto the bed infrastructure is a major risk, as heavy stacking will cause faster clogging deep down and drastically shorten their useful life. This is why the filters have to be shielded against runoff (Figure 27).

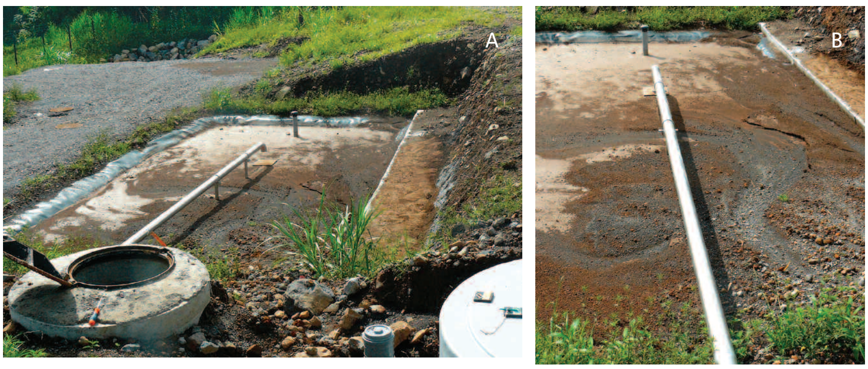

Figure 27. *Sloughed sludge on the constructed wetland (CW) at Salazie, Réunion.*

The geomembranes, even if they have been woven with protection against UV degradation, still stand to gain from being shielded against direct sunlight, typically with a layer of gravel. It would then be smart to plan one or more accessways to the filter surface for ongoing operation and monitoring.

Depending on the size of the cells, some kind of surfaced roadway needs to be arranged on at least one side to enable access to machinery for filter desludging operations.

5.1.2 List of documents to file and tests to be performed by the architect

Here we give a non-exhaustive, guidance-only list of the documents to file and tests to be performed by the constructor over the course of construction and the CW facility start-up phase (Table 10). The document called "Guidance on framing special technical specifications for constructed wetlands" (technical support agency to the Ministry of Agriculture's decentralized services, 2007) is a precious source of further input for completing these tests.

Tableau 10. *List of documents to file and tests to be performed by the architect during the facility start-up phase.*

	Manufacturer paperwork	Focus	Allied test
Media	Characteristics, layout, and layering procedure	Geomembrane: supplier record, thickness, mechanical properties (for geotextiles: tensile strength and elongation, puncture resistance)	Verification of membrane-to-membrane seams, leaktightness test
		Gravel: supplier record, grain-size, hardness, fines content, granulometry analysis cross-check	On-site pre-wash before laying, flatness check after laying
Pipework and channelling	Characteristics, implementation schedules and procedure, technical and hydraulic design calculations	Feed-system network: supplier record of the pipework characteristics, implementation schedules, handbook for pipework cleaning	Verification of the pipe-splitter systems (equivalent head flow at all feeding headers) Visual inspection of the piperuns
		Drainage network: supplier record of the pipe characteristics, piping diagram and photos of the drainage groundwork, implementation schedules	Drain tests, visual inspection of the drains
Mechanical and electromechanical hardware	O&M manuals, factory acceptance logs, electrical compliance test reports, technical and hydraulic design calculations	For all hardware: evidence of their fitness for the project environment based on their characteristics, compliance with rules on fitting and service, mode of operation in response to process malfunction	
		Gravity-flow feeding infrastructure: mode of operation, frequency and form of maintenance	Pump/siphon calibration, flowrate measurement
		Valving and electromechanical valving: frequency and form of maintenance	
		Vannes et électrovannes : fréquence et mode d'entretien	Valving leakage and operability tests
Plants	Layout and planting procedure	Name and source of the species (supplier), rationale for the species chosen, planting density, frequency of thinning–waterweed harvesting, detailed plantation schedule during the bedding-in period (hand-weeding, watering), best window for planting	Assessment of bed-in rate at 1 and 3 months

5.1.3 Major incidents that impacted the facilities

Looking back at the ten years of follow-up data in our possession, only two incidents have had big impacts on the operability of the CW monitored.

The first was caused by laterite* ingress into effluent collection network upstream of the facility. One, the network was in disrepair, with nearly 50% clean water infiltration/inflow, and two, there was evidence that several local users had hooked up their own plot drainage networks directly into the mains network branch boxes.

However, the filters fail to retain mineral fines at the filter surface, especially when there is little or no sludge blanket, so fines accumulated at the filter surface and partially penetrated down into the filter-media bed, leading to clogging (Figure 28). The blanket has been desludged to regain an acceptable through-flow permeability, but the in-bed accumulation deeper down can only properly be dealt with by thoroughly washing or replacing the filter media.

This experience demonstrates how it is vital to keep close checks on potential influx of laterite to the filter (*via the* piped service or by surface runoff from the facility plot); extra vigilance is needed during works phases.

© Etiage Guyane

Figure 28. *Bois d'Opale 1 filter clogging caused by laterite.*

The second incident had far less dramatic effects for the system infrastructure.

A particularly strong tidal surge in Martinique flushed seawater into the effluent collection network via the overflow on an inspection port that was not equipped with a check valve. The plants on the in-service filter were unable to cope with the salinity and died off in the space of days (Figure 29). Despite a thinning–waterweed harvesting effort, the plants struggled to recover. The incident had zero consequences on filter operability, and only required a re-plant of the bed.

In both cases, the root cause of impact on facility operation was poor-quality infrastructure, and infrastructure quality is the owner's responsibility.

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Figure 29. *Thysanolaena maxima die-back at the feeding headers, Mansarde Rancée facility (Martinique).*

Note that certain wetland residents can alter its operability, such as reptiles like iguanas that may nest in the filters and end up lodging vegetation under their bodyweight. Again, this process needs to be resolved by thinning and harvesting the plants before they start decaying on the filter surface.

5.2 The different phases of filter functionality

Over the course of their life in service, CWs can experience up to five different phases of functionality: start-up, normal function, degraded functionality, desludging, and definitive clogging/plugging.

5.2.1 CW planting and start-up

The plants are planted at a density between 4 and 8 plants/m² depending on how fast the selected species grows (Table 9) and the load expected at facility start-up. The plants are bedded with their root plug, which facilitates the start of growth. If start-up is suspected to coincide with very low loading, then a layer of compost can be added as it will act as a mulching material for the young seedlings, maintaining good soil-level humidity and improving inflow spread on the filter surface. Depending on the quality of the compost, it may leach out some TSS, or even slightly taint the water (humic acids). Even if these effects are only transient, it is still important to work with a compost that does not contain too many fines - the ideal solution is to sieve it out and only keep the fraction greater than 1 mm. The first few monitoring campaigns at Taupinière, where the vegetation had been installed with compost, found non-negligible levels of COD leaching (no biodegradable). The phenomenon only lasted a few months.

If there is a gap in time between plantation and commissioning the facility to service, the vegetation will need to be watered at regular intervals to help the plants grow.

The start-up phase is a period during which vegetative growth must be closely monitored without fail. If the facility is underloaded, the plants may struggle to grow. If the plants are suffering hydric stress, then it will be necessary to maintain routine rewatering with clear water (recirculation is possible) or, with an NS/S treatment scheme, to increase saturation level to as high as possible. The filters still have to be rotated at 3.5 days in feed mode and 3.5 days in rest mode. If the facility is starting up at near-nominal load, the plants will not yet be ready to effectuate their mechanical role, so ponding may happen. Check that any ponding does not become too problematic: the filters must not be under surface water too long during rest-mode phases. If such is the case, then scarifying the sludge blanket will help facilitate infiltration.

Either way, work to weed out adventives needs to be scheduled at least once a month until the planted vegetation has densely colonized all of the filter beds. Once stand density has reached 100 stems per m², there should be no further need for intervention, unless invasive species weed their way into the plant bed and start to take over. In every one of the French overseas departments, there are creeping plants that have an annoying tendency to 'lodge' the vegetation in place, a final stage of mis-maintenance that should be avoided at all costs.

5.2.2 Normal function

In the normal-function phase, the filters are dosed in rotation at a cycle of 3.5 days on/3.5 days off. Normal filter maintenance becomes routine. The surrounding strips are cleaned every 2 months, and any weeds inside the filter beds are to be ripped out at more regular intervals, as and when needed.

Thinning and waterweed harvesting aims to rid the wetland of any and all dead plants and maintain a good strong stand density on top of the filters. Guideline intervals for each species can be found in Table 9, p.51. Harvesting is a task that can eat up a lot of time, so it is smart and serious to use professional equipment such as hedge-trimmers or brushcutters. It is equally vital to rid the filters of all the cut biomass produced, as if not, it can prove so slow to decay that it may end up clogging the filter surface. Once plants have been allowed to grow back, it becomes very difficult to control them. It is because of this reason that certain wetland operators prefer to cut the plants back one by one and remove them as they go along, rather than hack everything down and end up facing a huge mass of difficult-to-remove biomass. Harvesting is a normal routine O&M task and does not require any change in the facility's regular operational programme. The plants grow back in the space of a few weeks.

5.2.3 Degraded functionality

Degraded functionality corresponds to the facility's minimal functionality in the wake of system trouble (breakdown, power outage, and so on). It is usually planned into the facility design programme.

CW can operate entirely by gravity flow, site topography permitting, with manual valving, which serves as a backstop against catastrophic failure. A lift pump is a vital prerequisite, but it does have to be sited at the filter influent to make sure that there is nothing to block the flowpath through the plant if infrastructure is out of action. In degraded functionality mode, performances on organic carbon (COD, BOD5, TSS) are dependably maintained, but performances on nitrogen may well be affected.

5.2.4 Desludging

When the sludge blanket has thickened to 20 cm, the filters start to lose hydraulic conductivity, thus decreasing air–gas exchanges. This makes it necessary to desludge the blanket. As this sludge blanket is heavily mineralized, it is also stabilized (non-fermentable). The Epnac taskforce has produced a guide to collecting, sampling and analyzing CW organic deposit ready for reuse in agriculture as a fertilizer (2014). The guidance details the tasks to do.

If the feeding system is elevated (overground), it can be taken down before worksite machinery can step in. Desludging can be done by a backhoe loader equipped with a relatively sharp-bladed (not serrated) ditcher bucket. Machinery is only allowed as far as the perimeter of the filters, as actually encroaching on the filters would compress and compact the beds and could damage system infrastructure, particularly the aeration and drainage pipework. Consequently, access ways should be designed and planned to ring the filters.

The plant biomass has to be harvested out before the desludging phase. Plant regrowth comes directly from the rhizomes contained in the residual sludge layer and in the first few centimetres of the filter bed matrix, which is why plants chosen are rhizome-system plants.

Ruling out curative operations to remediate problems caused by mineral matter ingress into the flowlines (see subsections 5.1.1 and 5.1.3), none of the CW in the French overseas department have ever been desludged. These items come from field experience in mainland France. Other than the sludge accumulation rate which has yet to be determined for the tropical-region zone, in principle there is no difference with mainland-France conditions, so the same guidelines should equally apply.

Ingress protection rating IP68

The ingress protection rating (IP68) is an international standard enclosure protection rating published by the International Electrotechnical Commission.
It classifies and rates the degree of protection provided against ingress by solid foreign bodies (sand, dust, insects, bugs and other small creatures), liquids (water and other fluids), mechanical impacts and corrosive gases.
The format of the rating, set by standard IEC 60529, is IP68, where the first digit 6 indicates that the equipment is completely dust-tight and the second digit 8 indicates that the equipment is completely water-tight when immersed at 1 m or more depth.

5.2.5 Irreversible clogging

With time, all CW systems will tend to clog naturally. Diligently completing the facility O&M tasks will help postpone the process, whereas accidents (mineral media getting into the system), poor-quality build materials (proportion of mineral fines >3%) or mismanagement (failing to stick to the rotation schedule) will tend to accelerate it.

The longest-running CW in operation in mainland France is currently over 30 years old and has only needed sludge stabilization twice...

5.3 O&M of wetland amenities in tropical-climate zones

A Guide to operating constructed wetlands can be found on the Epnac website, but it is not specific to tropical-zone geographies. To address this gap, feedback from wetland operators in the French overseas departments has been compiled here. The specificities of operating CW in tropical-zone geographies mainly revolve around protection of the electromechanical hardware and maintenance of the vegetation.

5.3.1 Tropicalization of the amenities

The construction and operation of CW in tropical areas involves choosing media and material that is appropriately adapted to tough climate conditions. High heat, sunlight and humidity are all factors that can shorten the lifespan of amenity hardware, and so all metering, monitoring and control devices have to be rated IP68 (i.e. adequately tropicalized). The service life of the amenity hardware can be increased by adding further protective measures, typically:

- shielding the flowmeters, electromechanical value cables, outside metering instruments, control consoles, etc., against direct sunlight (Figure 30A). The electromechanical valves, pressure reducers and power cables are the parts that will need changing most often. Indeed, the pneumatic valves in particular have caused serious operational problems, requiring intervention work every six month on average over the course of the three-year 'Attentive' project. The main root-cause problem identified is pressure fluctuations in the tap water supply network.

- it is also recommended practice to fit some kind of aeration in all confined spaces: switch cabinet, mechanical room, and so on (Figure 30B).

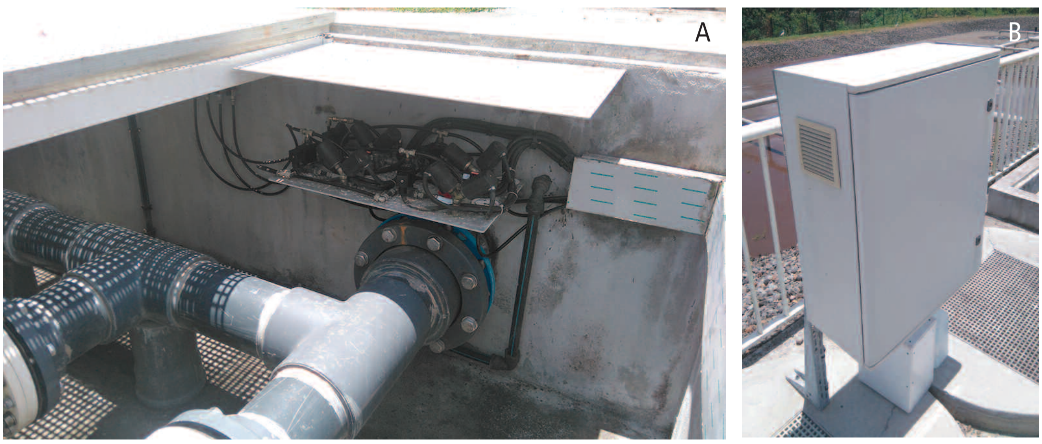

Figure 30. *A) Shielding the electromechanical valves against direct sunlight. B) Aeration on an electrical enclosure.*

5.3.2 Routine maintenance of the vegetation

■ Inside the filters

The routine maintenance needs of the in-filter vegetation depends on the plant species chosen (Table 9, p.51). The in-filter facility O&M tasks are described below.

■ After planting or following sewage sludge stabilization: curb the growth of adventives by selective hand-weeding. Task interval varies from once a week to once a month depending on type of plant, maturity of the system, and other factors, but once stand density has reached around a hundred stems per m^2, this effort is no longer needed as the plants selected will be competitive enough to establish without outside help.

■ The facility manager should use each visit to visually check the health of the on-filter vegetation. Any adventives slowly weeding their way into the plant bed need to be promptly weeded out by hand-uprooting,

■ and it is good practice to execute harvesting every year before the cyclone season, whatever the bed-plant species used, and certain species will need a repeat harvest before the year is out.

Using appropriate equipment (hedge trimmers rather than shears) can get the work done in half the time. The plants are cut at around 15cm from the top of the sludge layer, and it is essential to remove all plant biomass harvested from the filter rather than leaving it to litter on the filter surface where it is liable to cause surface clogging. Some operators cut Heliconia back by sweeping through with a machete, which makes it quicker to clear the cut biomass from the filter surface.

Routine maintenance inside the filters is absolutely crucial for a long-serving system, but the task itself may put off operators who are used to more conventional structures. Good filter maintenance requires an understanding of the importance of the plants and their growth. Certain tasks, like harvesting, can be dull and dirty work without the right tools and equipment. **Facility managers are strongly advised against calling in outside contractors for routine maintenance inside the filters, which is a normal routine O&M task.**

■ Around the facility

Vegetation in and around the entire facility needs regular maintenance (roughly once a month) to not become overgrown: greenspace should be mown, trees pruned, and all green biomass picked-up and cleared out to an approved green waste stream.

Good perimeter maintenance spans the access ways and the fencing but also all embankments and verges found on-site. The embankments that shield the filters and bund them against stormwater runoff warrant special attention.

The adventives that are hardest to remove from inside the filters more often come from outside the filters. Good perimeter maintenance thus plays its part in preventing problems caused by filter colonization by weeds.

5.3.3 Roll-up of the to-do list

Table 11. *Roll-up of the to-do list for operation and maintenance of 100-PE and 800-PE constructed wetlands (CW) (Cotram data)*

List of operations	Frequency	100-PE CW		800-PE CW	
		Time per task (min)	Total/year (hours)	Time per task (min)	Total/year (hours)
Control-check on float tanks, exercising the valves	twice/week	5	8	5	8
Cleaning the bar screen	once/week	10	8	10	8
Filter health check and routine maintenance, hand-weeding	once/week	60	48	180	144
Complete the CW logbook	once/week	15	12	15	12
Routine maintenance of greenspace around the filters	once/month	60	12	180	36
Cleaning inspection ports and float tanks	once/month	60	12	90	18
Flush-out and inspection of the first-stage (and second-stage) header-system networks	twice/year	60	2	150	5
Check sludge depth, check geomembrane integrity	once/year	30	0,5	60	1
Harvesting	once/year*	240	4	960	16
Sludge-take-off from the first stage	once/10 years	960	1.5	1440	2.5
Total hours per year			108		250.5

**Depending on species planted (section 4.2, p.50).*

5.3.4 Feedback from the field—French Guiana

Étiage - French Guiana is currently running or performance-monitoring seven constructed wetlands, the oldest one since back in 2010. The main O&M task is routine maintenance of the wetland vegetation. After several years of performance monitoring, the conclusion is black-and-white: wetlands built cut-to-fill with a geomembrane liner are a lot more maintenance-heavy than CW built formworked in concrete cells which are a lot less prone to adventives. Thorough waterweed harvesting should be done at the end of the dry season in French Guiana, and a second repeat (or partial) harvesting operation at the end of the rainy season may prove necessary depending on its intensity and whether the plants are prone to falling under the weight of water.

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Figure 31. *Naturescaping a CW in a housing development in French Guiana.*

Étiage—French Guiana recommends keeping tabs on lift pumps via off-site e-monitoring or on-site checks at least once a week.

For the smaller-scale CW (serving <100 PE), the best way forward is a filter rotation scheme using manual valves to ensure a technician is regularly deployed on site.

Few reptiles, if any, have been found on the CW. The personal protective equipment (PPE)* needed is more for the ants that can get aggressive during weeding or harvesting operations (boots and gloves are indispensable attire for anyone setting out to work on the filters).

The vegetated filters do not produce any kind of odour, and are highly valued by residents—even when they border onto their homes—as they flower beautifully (*Heliconia psittacorum*) and can even look like a stroll garden (Figure 31).

5.4 Self-monitoring and regulatory compliance

The objective of self-monitoring is to check and maintain treatment-system performances. It is framed under French legislation laid down by the decree of 21 July 2015. This section gives a roll-up of framework, also drawing on the 'technical brief to the decree', for on-site sanitation systems serving under 10,000 PE capacity.

Self-monitoring for regulatory compliance is the facility manager's duty. It spans the entire sanitation system, i.e. both the sewerage collection and the wastewater treatment plant (WWTP). If there are several facility managers engaged in the same system, then it is the WWTP facility that takes responsibility for data and records coordination, roll-up and reporting.

5.4.1 Recordkeeping

Self-monitoring for regulatory compliance is a scheme built around filing two documents that combine the results of self-monitoring measurement campaigns, whose intervals that depend on facility's capacity.

The first document sets out the characteristics of the system and details how self-monitoring is organized. It will be the "logbook" when treatment capacity is less than 2,000 PE, otherwise it will be the "sanitation system self-monitoring manual".

The second document is the "record of sanitation system performance" which gives a roll-up report of the self-monitoring results.

Templates can be found on the ministry authority's decentralized water and sanitation services portal[4].

4 Go to http://assainissement.developpement- durable.gouv.fr/services.php (accessed 14/06/2017).

■ Logbook (<2,000 PE)

The sewerage collection and wastewater treatment plant facilities concerned are to draft and keep a logbook split into three sections covering at least (regulatory minimum) the following items.

1. Sanitation system—Description, O&M, management:

1.1. Sanitation system—Plan and description, including the complete list of non-household connections to the sewerage collection system;

1.2. Sanitation system—10-year programme of facility operation

1.3. Sanitation system—Internal organization arranged for the system manager(s).

2. Sanitation system—Organization of the self-monitoring programme

2.1. Self-monitoring records—System frame

2.2. Self-monitoring records—Rules for reporting data

2.3. Self-monitoring records—List of nodes equipped or fitted out, and hardware used;

2.4. The methods used for regular time-boxed monitoring;

2.5. Sanitation system—Internal organization arranged for the system manager(s).

3. Sanitation system—Performance monitoring

3.1. Sanitation system—Log of interventions dated and signed off;

3.2. Self-monitoring records—Information and results

3.3. Self-monitoring records—Results of measurements received for permitting non-household wastewater discharges into the effluent collection system;

3.4. Sanitation system—List of major events (breakdown, one-off situations, etc.)

3.5. Sanitation system—Annual performance roll-up report;

3.6. Roll-up of alerts registered;

3.7. Documents corroborating the intended destination of the sludge.

The logbook and any rewrites are forwarded to the regional water authority [*Office de l'eau*] and the French water security agency [*Service de police de l'eau*; SPE-DEAL] for information purposes.

■ Sanitation system self-monitoring manual (≥ 2,000 PE)

This is a manual that is drafted as groundwork to monitor the sanitation-facility infrastructure and the water body receiving the treated effluent discharge. The project owner uses it to give an in-depth description of the internal organization arranged, the methods planned for operation, inspection and analysis, the location of measurement points and sampling points, the rules and practices for reporting data, the independent organizations commissioned to handle all or part of the monitoring effort, and qualification process for people engaged in these arrangements.

The manual specifies:

1. The reference methods of standards employed for implementing and running the self-monitoring-scheme hardware.

2. The qualifiers associated to implementation of the "SANDRE" data exchange platform format;

3. The performance goals for effluent collection and treatment as laid down in the prefectoral order granting the sanitation system permit to operate;

4. The treatment-scheme infrastructure, inventorying all stormwater discharge (name, size, location of the facility and the associated effluent outfall(s), and name of the receiving water bodies).

This manual is filed with the *Office de l'eau* [regional water authority], which conducts an appraisal of the manual and forwards its appraisal on to the *SPE* for validation. The manual is updated at appropriate intervals and held on-site ready for consultation by the appropriate government agency officials.

■ Record of sanitation system performance

At the start of the year, the sanitation system facilities draft a roll-up record of year-round performance, and forward it to the *water offices* and the *SPE* before 1 March.

Systems serving less than 200 PE do not have self-monitoring to complete for regulatory compliance. Between 200 and 500 PE, the record of performance is to be submitted every 2 years, which coincides with the schedule of 24hr-composite-sample self-monitoring. From 500 PE and upwards, the performance records are to be submitted every year.

This annual record of performance is a roll-up document that reports on all of the data collected and compiled for regulatory-compliance self-monitoring and detailed in the subsections below. It includes:

1. A record of spills and discharges into the natural habitat (date, frequency, duration, volumes and, where relevant, the pollution loads discharged);

2. Evidence for the management of sanitation-system waste (waste produced by desludging work, sand, fats and oils, screenings refuse, sludge produced, and so on);

3. Information on amount and management practice for any external influxes (quantity and quality): septage, off-site sludge, lixiviates*, industrial effluents, etc.;

4. Energy consumption and reagent inputs;

5. A recap of all major events and incidents registered at the facility (maintenance operations, operational trouble, one-off situations, etc.);

6. A year-round roll-up of the results from 24hr-composite-sample self-monitoring over the previous year;

7. A record of all self-monitoring-scheme hardware inspections led by the project owner;

8. A record of all new permits to discharge to the sewerage collection system issued over the year and all follow-through action on permits currently held;

9. Inputs for the sanitation-system performance diagnosis (to be done every 10 years; see article 12 of the decree of 21 July 2015);

10. Critical analysis of sanitation-system operability;

11. A self-assessment of sanitation performances against the decree of 21 July 2015;

12. The list of further works tabled for a future date, including the period of work where and when known.

The annual self-monitoring programme must be organized to articulate a schedule of measurement operations, which must be representative of the features of the urban cluster sanitation system (seasonal activities). The project owner is to file the programme with the SPE and the *Office de l'eau* before 1st December of the previous year.

The project owner also files these same agencies with the self-monitoring results within 30 days of recording them, via the current online data exchange scenario defined by the French national agency for water data and reference datasets (SANDRE).

If any one of the limit-cap values defined by the decree of 21 July 2015 or by the prefect is overstepped, the agency tasked with handling local control is to be immediately notified. The project owner is also to comment the root causes of any limit-value violations as well as the corrective action implemented or tabled for implementation.

5.4.2 Metrology and self-monitoring practice

The self-monitoring assessment schedules are recapped in Table 12 and Table 13.

■ Flowrate measurements

Table 12. *Flowrate measurements (measure and frequency) deliverable for regulatory-compliance self-monitoring (decree of 21 July 2015)*

WWTP	Obligations
< 500 PE	Estimates of facility influent or treated effluent flowrates
≥ 500 and < 2,000 PE	Measurements of facility influent or treated effluent flowrates
≥ 2,000 PE	Measurements and records-reporting of facility influent or treated effluent flowrates

■ Water quality parameters and self-monitoring schedule

The 24hr-composite performance assessments deliverable for regulations-compliant self-monitoring cover the following parameters: pH, flowrates, T°, TSS, BOD_5 and COD and, according to the effluent quality levels required, NH_4, TKN, NO_2, NO_3, TP. Analysis of samples is to be performed by a laboratory with the requisite accreditation pursuant to the French Environment Code (except for flowrate, T° and pH measurements).

Table 13. *Water quality analyses (parameters and frequency) deliverable for regulatory-compliance self-monitoring (decree of 21 July 2015)*

Capacity	Self-monitoring schedule
< 200 PE	No obligation
≥ 200 and < 500 PE	Once every two years
≥ 500 and < 1,000 PE	Once/year
≥ 1,000 and < 2,000 PE	Twice/year
≥ 2,000 and < 10,000 PE	Daily: flowrates Monthly: pH, MES, DBO5, DCO four times/year: TKN, NH_4, NO_2, NO_3, Ptot

The difference between estimated and measured flowrate is explained in detail in the technical comment to the decree of 21 July 2015, part 2: self-monitoring of decentralized sanitation system. A measurement comes from a standardized device that has been installation-verified. At the scale of small communities, this will mean:

- electromagnetic flowmeter installed on the pipework as per the manufacturer's guidance and appropriately calibrated;

- ultrasound or bubble-gauge flowmeter, paired with a control flume with or without threshold (Venturi or equivalent), appropriately installed and serviced.

Pump running time on pump station combined with pump flow rate calibration only gives a flow rate estimation. As pump capacity varies with load on the pump, this estimate has to be coupled with the measurement of water column depth to upgrade the estimate to a measurement. Likewise, a mechanical dose-flush meter combined with the volume of each dose flush only gives a flowrate estimate, not a measurement as understood by the regulations.

6 Conclusion

The French overseas departments have acute sanitation issues to deal with. Governed by the same regulatory framework as mainland France (WFD and UWWT directives), they are trailing well behind in terms of efficient and effective sanitation system, whereas local challenges for the environment (which concentrates the bulk of the nation's biodiversity), health–hygiene standards, economy, property development and social fabric all demand swift development of sanitation infrastructure.

Once of the major bottlenecks has been under-adequate technologies under-adapted to the specific geocontext of the DOM—the French overseas departments. This design guideline to sizing constructed wetlands for tropical area reviews a decade of research in the five DOM to adapt a technology that has already been tried, tested and proven in temperate-climate zones. The lessons learned are based on intensive scientific monitoring on seven different CW treatment facilities and a specific study on which plants to choose.

This research was useful to build and validate design guidelines adapted to tropical geographies. These design guidelines guarantee the same balance between efficiency and robustness that has proven so successful in mainland France, but with a more compact footprint made possible by the higher mean temperatures in tropical climate zones. There has been special focus on handling wet-weather rainfall loads, which is one of the weaknesses of conventional conventional processes in tropical settings. Actions are ongoing that may bring changes to the design code featured in this guide, both in choice of plant species and optimization of the treatment scheme.

Throughout the performance monitoring campaigns, effluent levels never once overstepped the required quality thresholds. Even the most basic configuration delivers performances that go further than the regulatory-required minimum (removal rates of 75% for COD, 80% for BOD_5, 80% for TSS and 60% for TKN with effluent concentrations below 125 mg COD/L). CW can be adapted, according to needs and constraints, to effectively deliver over 95% organics treatment, 100% nitrification, or 70% total nitrogen treatment.

The vertical-flow constructed wetlands presented here are fed with raw water and will co-treat both wastewater and sludge, which means they also offer a solution to the problem of treatment by-products which are tricky to manage in the French overseas departments.

The compact footprint of the tropical-zone wetland process not only enable it to compete with conventional processes in space-squeezed settings but also makes it competitive at above the economic capacity threshold in mainland France (5,000 PE). CW thus span a very broad capacity range, from semi-decentralized projects for isolated housing developments and rural communities up to medium-sized urban communities.

One of the keys to the success of CW in mainland France is that once built, ongoing operability is simple. With little electromechanical hardware - or even none at all and therefore no electricals to manage if site topography is right -, there are no complex operation and maintenance tasks and little risk of operational trouble. Routine maintenance of the vegetation is more of a constraint in tropical-climate regions, where it represents the owner-manager’s main task

The design guideline featured in this guide, which has been put together through research led in the context of French overseas regions, can be used in all tropical-zones.

Glossary 7

Anti-scouring That protects against scour (excavation caused by swiftly moving inflow of water)

Adventives Weeds, unwanted plants, or unwanted plant species.

Dose Volume of water corresponding to a 2.5–5cm flush distributed all across the entire filter surface. This dose is delivered onto the filter with a faster rate of flow than the rate of infiltration into the bed, thus causing ponding, which ensures that wastewater is evenly distributed on the filter and guarantees optimal renewal and recycling of the air inside the filter media.

Cell Subdivision of a filter bed that has been partitioned. Depending on the context, may count as just one of the two filters making up a treatment stage.

Cultivar A given plant variety will count a number of cultivars, each purpose-cultured after selective for a desirable characteristic.

Root exudates Liquids secreted from a plant's root system (for defensive, symbiotic, or other roles).

Waterweed harvesting CW management task that involves cutting the plants growing on the filters back down to around 20 cm from the ground and harvesting the biomass produced.

Stream For big treatment units, it may prove better to set up a series of small-cell units working in parallel than one big treatment train, in which case a stream corresponds to one small-cell unit.

Ponding Temporary clogging or plugging at the filter surface, which materializes as ponds or pools.

Laterite Rusty-red or brown soil, with a high iron oxide content, that is formed by the weathering of parent rock in tropical-climate areas. Residual liquid left by soil water (or stormwater) percolating through a material that contains a soluble fraction.

Lixiviate or percolate Residual liquid left by soil water (or stormwater) percolating through a material that contains a soluble fraction.

Air layering ('marcotting') Method of vegetative propagation of numerous plant species by rooting a part of the aerial stem to graft to the parent plant.

Overseas region French overseas

Lodging Plant damage caused by the effects of rain, wind or parasites, bending and flattening the stems near ground level.

8 Acronyms and abbreviations

AFB	French biodiversity agency
OSSF	On-site sewage facility
C	Carbone
CANGT	*Communauté d'agglomération du Nord Grande Terre* - an urban community division in Guadeloupe
BOD_5	Biochemical oxygen demand at 5 days
WFD	Water framework directive
COD	Chemical oxygen demand
CODf	Chemical oxygen demand–filtered
DEAL	French-Overseas directorate for the environment, planning and housing
UWWTD	Urban wastewater treatment directive
DOM	French overseas department
PE	Population equivalent
PE*m*	Population equivalent-mahorais (Mayotte)
PPE	Personal protective equipment
Epnac	Assessment of new sanitation processes for small and decentralized communities
Fredon	French regional federation for pest control
CW*r*	Constructed wetland reedbed
CW	Constructed wetland
vfCW	Vertical-flow constructed wetland
hfCW	Horizontal-flow constructed wetland
INSEE	French National Institute of Statistics and Economic Studies
IP	Ingress protection rating
Irstea	French national institute of science and technology research for the environment and agriculture
H_2S	Hydrogen sulphide
TF	Trickling filter
MEDDE	French ministry for ecology, sustainable Development and Energy
TSS	Total suspended solids
N	Nitrogen
NH_4	Ammonium
NO_2	Nitrite
NO_3	Nitrate
TN	Total nitrogen
TKN	Total kjeldhal nitrogen
NS/S	Non-saturated/saturated
ODE	*Office de l'eau* - a french regional water authority
Onema	French national agency for water and aquatic environments
pH	Potential of hydrogen
PP	Polypropylene
LP	Lift pump
TP/P_{tot}	Total phosphorus
PVC	Polyvinyl chloride
SANDRE	French national water data and water standards authority
SICSM	Intercommunal water authority - Central and south Martinique
SIEAM	Intercommunal water and sanitation authority—Mayotte
WWTP	Wastewater treatment plant
SPE	French water security agency
T°	Temperature
UV	Ultraviolet

9 List of figures, tables and box-insets

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Cite as
Lombard Latune R & Molle P, 2017.
Constructed wetlands for on-site wastewater treatment in the tropics.
Guidelines on sizing tropicalized systems.
French Biodiversity Agency, *Guides and protocols* series, 72 pages

ISBN online pdf: 978-2-37785-090-7

Translation
Team Irstea, from French version © AFB, October 2017

Publishing
Véronique Barre, Béatrice Gentil-Salasc

Artwork and graphic design
Béatrice Saurel

Printing
IME by Estimprim

This guide is designed as a toolkit to support both clients and contractors in the design and completion of a constructed wetland (CW) project for on-site wastewater treatment.

The French overseas departments ('DOM') all have acute sanitation issues to deal with. One of the major bottlenecks is that the process technologies have been under-adapted to the specific geocontext of tropical regions.

The design code featured in this guide, which has been put together through research led in the French overseas regions, can be used in all tropical-zone geographies.

This guide reviews a decade of research in the five DOM to adapt a technology that has already been tried, tested and proven in temperate-climate zones. The lessons learned are based on intensive scientific monitoring and a specific study on which plants to choose.

This research has served to build and validate structural-code sizing standards adapted to tropical geographies, where the objective is a more compact footprint but still guaranteeing a good working balance between efficiency and robustness. Efforts have focused on vertical-flow constructed wetlands. These integrated systems can be fed directly with raw wastewater, thus delivering a valuable solution to the problem of sewage sludge management—a tricky issue in island settings.

There has been special focus on handling wet-weather rainfall loads, which is one of the weakness of conventional processes in tropical settings. Scientific monitoring has demonstrated that CW reliably and dependably deliver the regulatory-required performances, and even go further: advanced treatment of organics, 100% nitrification, and even 70% total nitrogen removal.

The compact footprint of the tropical-zone wetland process not only enables it to compete with conventional processes in space-squeezed settings but also makes it competitive in settings serving medium-sized urban communities.

The guide starts with a primer on the processes at work in these wetland infrastructures and the performances of the different processes studied, before going on to set out the key considerations when planning an on-site sanitation project. It thus spells out:

- the characteristics of wastewater from small communities in the French overseas departments;
- a recap of the rules for determining effluent level;
- the technology options dictated by local constraints and any phased staging to complete;
- precise design code and sizing standards for construction;
- the different in-stream plant species suitable for use;
- details of the routine operation and maintenance and monitoring tasks needed for optimum facility management.

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