Introduction to vertical flow wetland pilots

Günter Langergraber
Institute of Sanitary Engineering and Water Pollution Control

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Günter LANGERGRABER
IWA Fellow

@ BOKU University

- Head, Institute of Sanitary Engineering and Water Pollution Control
- Deputy-Head, Department of Landscape, Water and Infrastructure

@ IWA (International Water Association)

- Co-Chair, IWA Cluster on “*Nature-base Solutions for climate resilient water and sanitation management*” (IWA NbS Cluster) from 2025
- Chair, IWA Specialist Group on “*Resources Oriented Sanitation*” (2023-2025 and several terms before)
- Co-Chair, IWA Task Group on “Mainstreaming the Use of Treatment Wetlands (2015-2019)
- President, Austrian IWA National Committee (from 2025)

Background

- Dissertation (2001, BOKU University): Development of a simulation tool for subsurface flow constructed wetlands
- Habilitation (2012, BOKU University): Towards a more sustainable implementation of sanitation systems

Overview

- Introduction to wastewater treatment
  - Composition of wastewater and main treatment processes
  - Legal requirements
- Treatment wetland main types
- VF wetlands
- Examples of large / beautiful treatment wetlands
- Summary

- VF wetland pilots
  - Design, filter material, artificial/synthetic greywater, loading of the pilots

Introduction

- Collected but **untreated or poorly treated faecal sludge and wastewaters** can discharge organic substances, nutrients and hazardous substances in considerable amount into surface and subsurface water bodies.
- Urban and rural developments, connected to the sewer systems and to wastewater treatment plants with inappropriate treatment technology, are the **most important contributors of surface water contamination via point sources**.
- Access to water and sanitation is a **human right**
- UN Sustainable Development Goal 6 (**SDG 6**) on "Clean Water and Sanitation"
  - **Target 6.2.** (achieve access to **safely managed sanitation systems** for all) and
  - **Target 6.3.** (improve **water quality** by reducing pollution)

Introduction
Definitions, composition of wastewater, main processes

- Household wastewater = blackwater and greywater
  - Blackwater: Urine, faeces and any cleansing material mixed with water and flushed down in the toilet
  - Greywater: Wastewater from households excluding wastewater from toilets

- Main constituents of wastewater and main removal/transformation processes
  - Organic matter: BOD_5, COD ➔ org. C + O_2 → CO_2 + H_2O
  - Nutrients: Nitrogen (NH_4-N and organic N) and Phosphorus (PO_4-P and organic P)
    - N removal: Nitrification $NH_4^+ + O_2 \rightarrow NO_3^-$ & Denitrification: $NO_3^- \rightarrow N_2$
  - Microbial contamination

Introduction
Definitions, composition of wastewater

Parameter	Unit	Urine [1]		Blackwater[1]		Greywater [1]		Raw wastewater (A131) [2]
Volumetric flow	L/(E·d)	1,5	- [3)]	8 – 50 [4]	-	75	- [3)]	150
BOD_5	g/(E·d)	5	10%	37	67%	18	33%	60
COD	g/(E·d)	10	10%	50	52%	47	48%	120
TS	g/(E·d)	-		61	82%	13	20%	70
TKN	g/(E·d)	11	85%	12	92%	1	8%	11
P	g/(E·d)	1,0	50%	1,5	75%	0,5	25%	1,8

1) Median values, 2) 85 percentiles, 3) dependent on toilet used, i.e. amount of flushing water, 4) huge variation dependent on system used

Comparison of loads and flows per person (adapted from DWA-A 272, 2014)

Introduction
Legal requirements

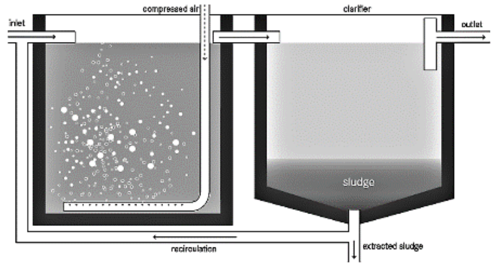
Parameter		AT **	AT - 1.AEVkA (1996) *				EU - UWWTD (2024) >1'000 PE *	
		≤ 50 PE	51-500 PE	501-5'000 PE	5'001-50'000 PE	>50'000 PE	All areas	Sensitive areas
BOD_5	(mg/l)	25	25	20	20	15	25	25
	(%)	-	-	95 (> 1'000 PE)	95	95	70-90	70-90
COD	(mg/l)	90	90	75	75	75	125	125
	(%)	-	-	85 (> 1'000 PE)	85	85	75	75
NH_4-N	(mg/l)	**10** (> 12°C)	**10** (> 12°C)	5 (> 12°C)	5 (> 8°C)	5 (> 8°C)	-	-
Total N	(%)	-	-	-	70 (> 12°C)	70 (> 12°C)	-	10 mg/l (10 - 150'000 PE) 8 mg/l (> 150'000 PE) 80 %
Total P	(mg/l)	-	-	2 (> 1'000 PE)	1	1	-	0.7 (10 - 150'000 PE) 0.5 (> 150'000 PE)

* More stringent effluent requirements possible for sensitive receiving waters
** No specific regulation for ≤ 50 PE

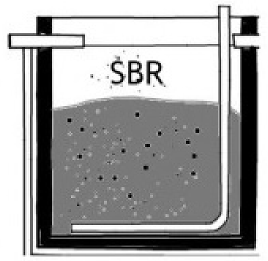
Introduction

Technologies for (rural) wastewater treatment

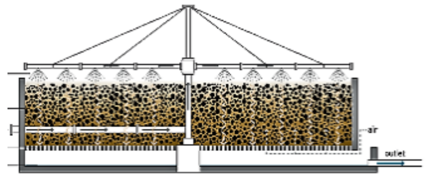
- **On-site collection with off-site treatment**
  - Cesspits (with transport to next WWTP or faecal sludge treatment unit)
- Soil as recipient of treated (or partially treated or untreated) wastewater
  - Soak pits, leach fields, etc.
- Solutions with less than secondary treatment
  - Septic tanks, etc.
- **Solutions with at least secondary treatment**
  - Technological solutions with suspended biomass (e.g., conventional activated sludge plants, SBR – Sequencing Batch Reactor, MBR – Membrane BioReactor)
  - Technological solutions with fixed biomass (e.g., Trickling filter, RBC – Rotating Biological Contactor, filtration systems)
  - Nature-based solutions (e.g., treatment wetlands)



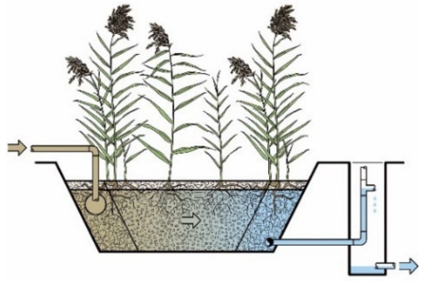
Conventional Activated Sludge (CAS)



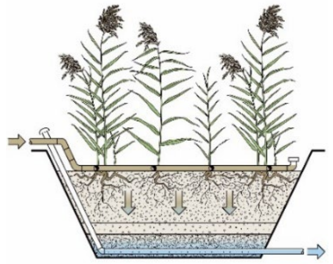
Sequencing Batch Reactor (SBR)



Trickling filter



Horizontal flow (HF) wetland



Vertical flow (VF) wetland

Treatment wetlands

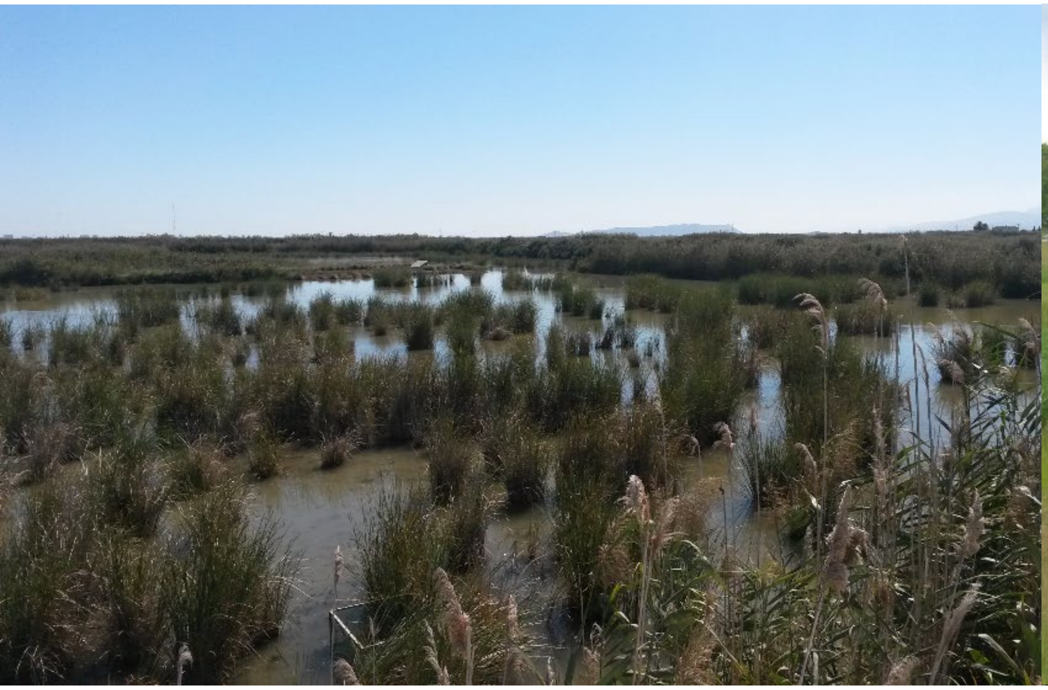
Natural wetlands are those wetland areas that exist in the landscape due to natural processes rather than having been created either directly or indirectly as a result of anthropogenic influences.

Constructed wetlands are man-made systems that are designed to mimic many of the conditions and/or processes that occur in natural wetlands.

Purpose of constructed wetlands:

- Restored wetlands: Areas which were formerly natural wetlands
- Created wetlands: Non-wetland areas which have been converted
- **Treatment wetlands**: Artificially created wetland systems designed to provide a specific water treatment function

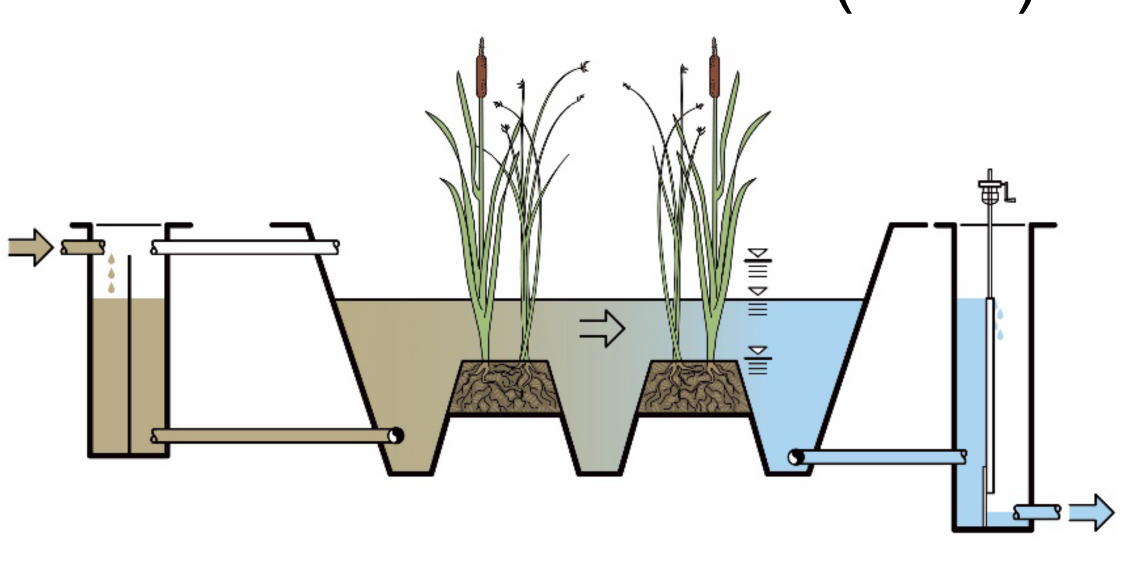
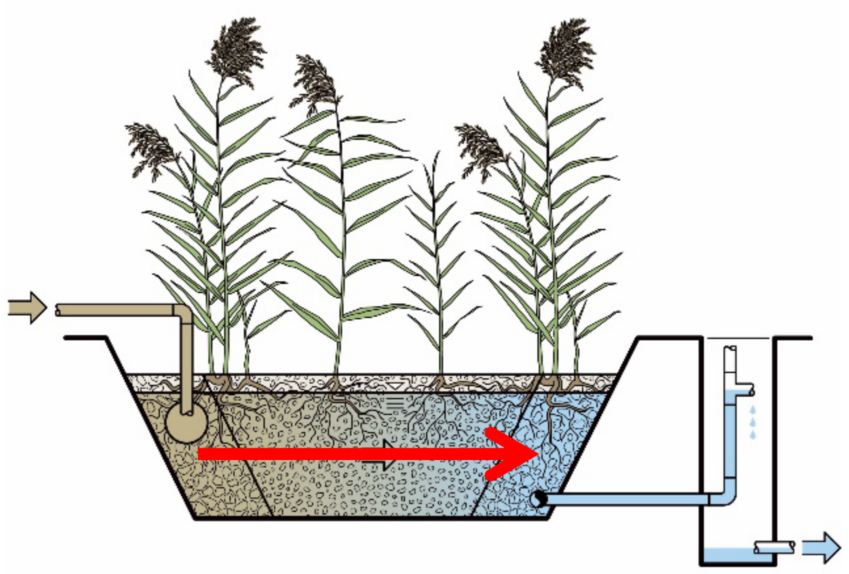
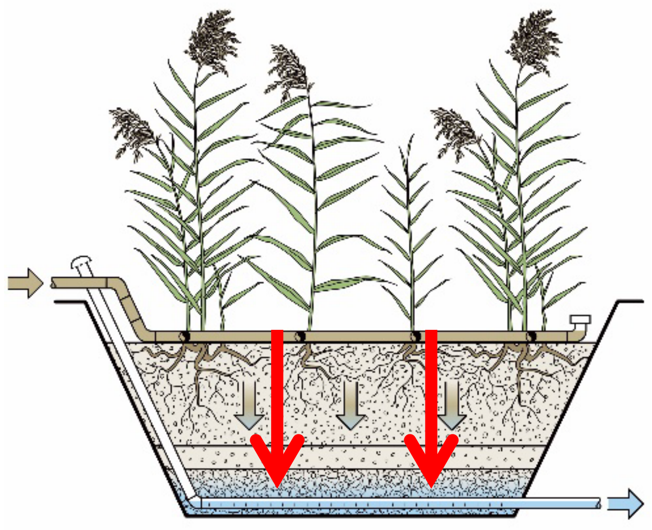
Treatment wetland main types




Free Water Surface (FWS)

Horizontal Flow (HF)

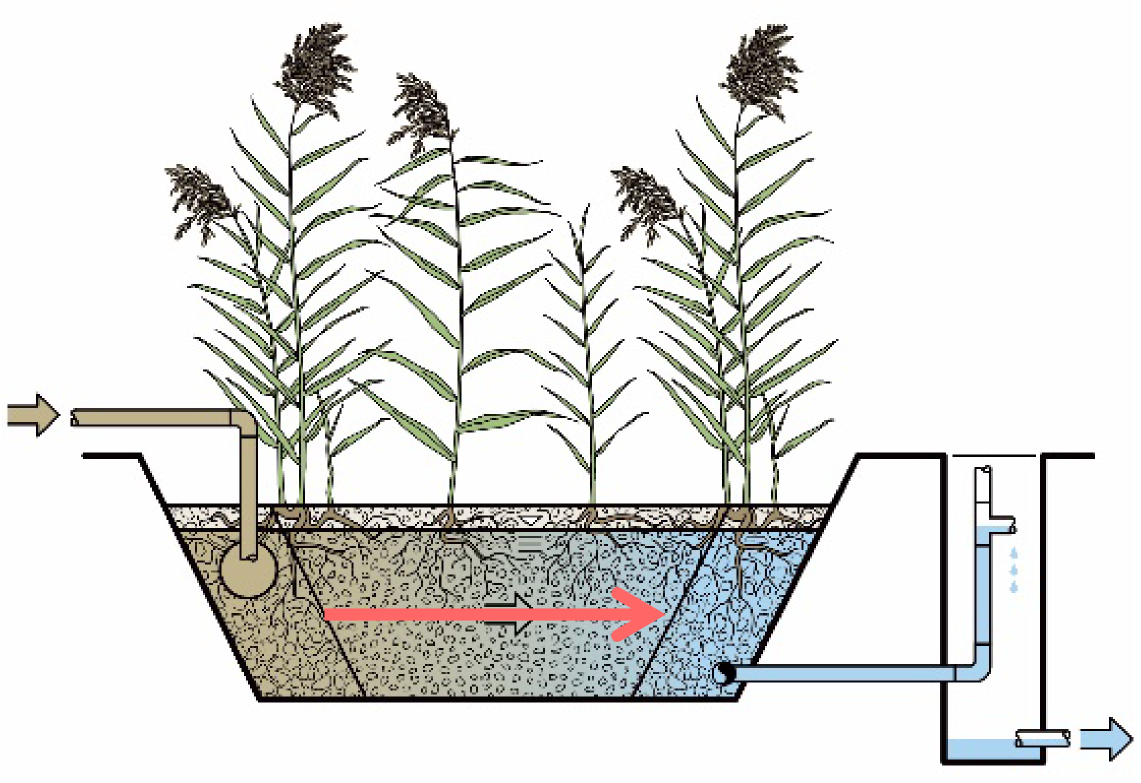
Vertical Flow (VF)
with intermittent loading

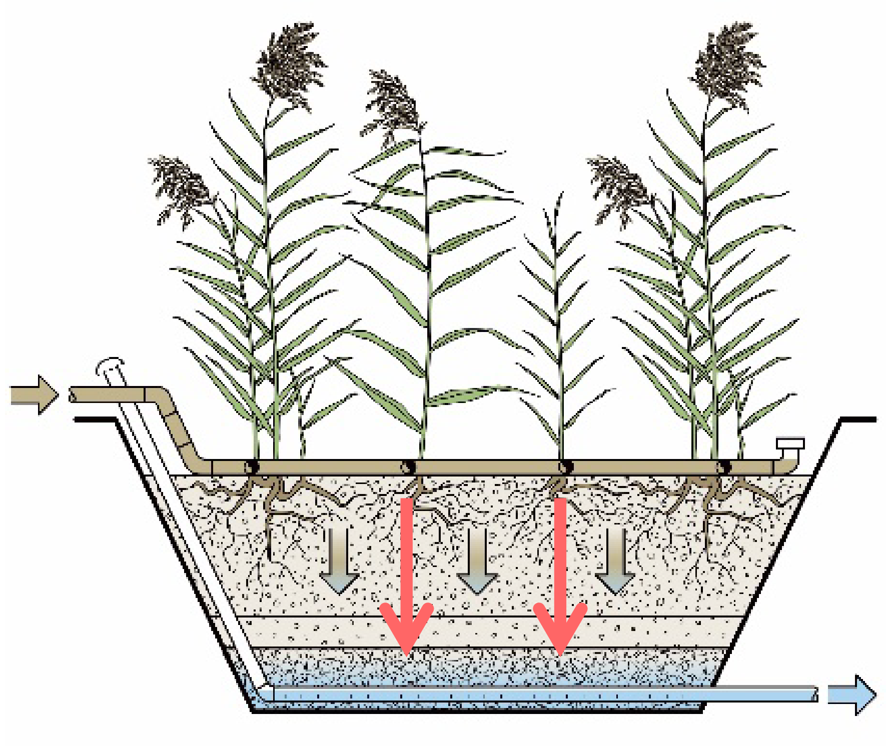
Dotro et al. (2017): *Treatment Wetlands*; https://doi.org/10.2166/9781780408774.

Treatment wetland main types

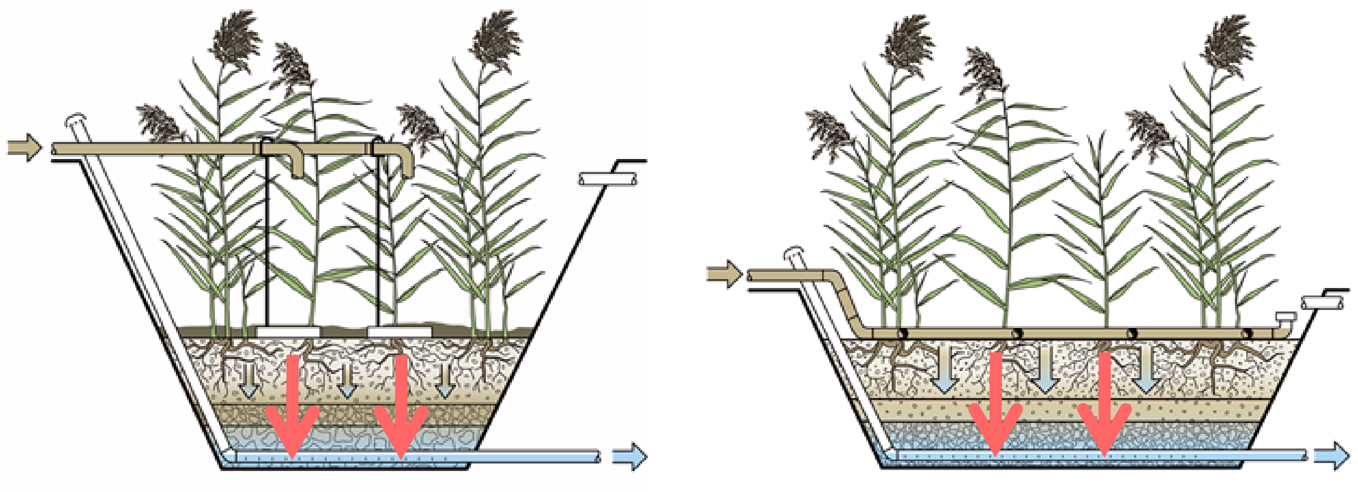
Horizontal flow (HF) wetland



Vertical flow (VF) wetland



French VF wetland



For primary treated wastewater

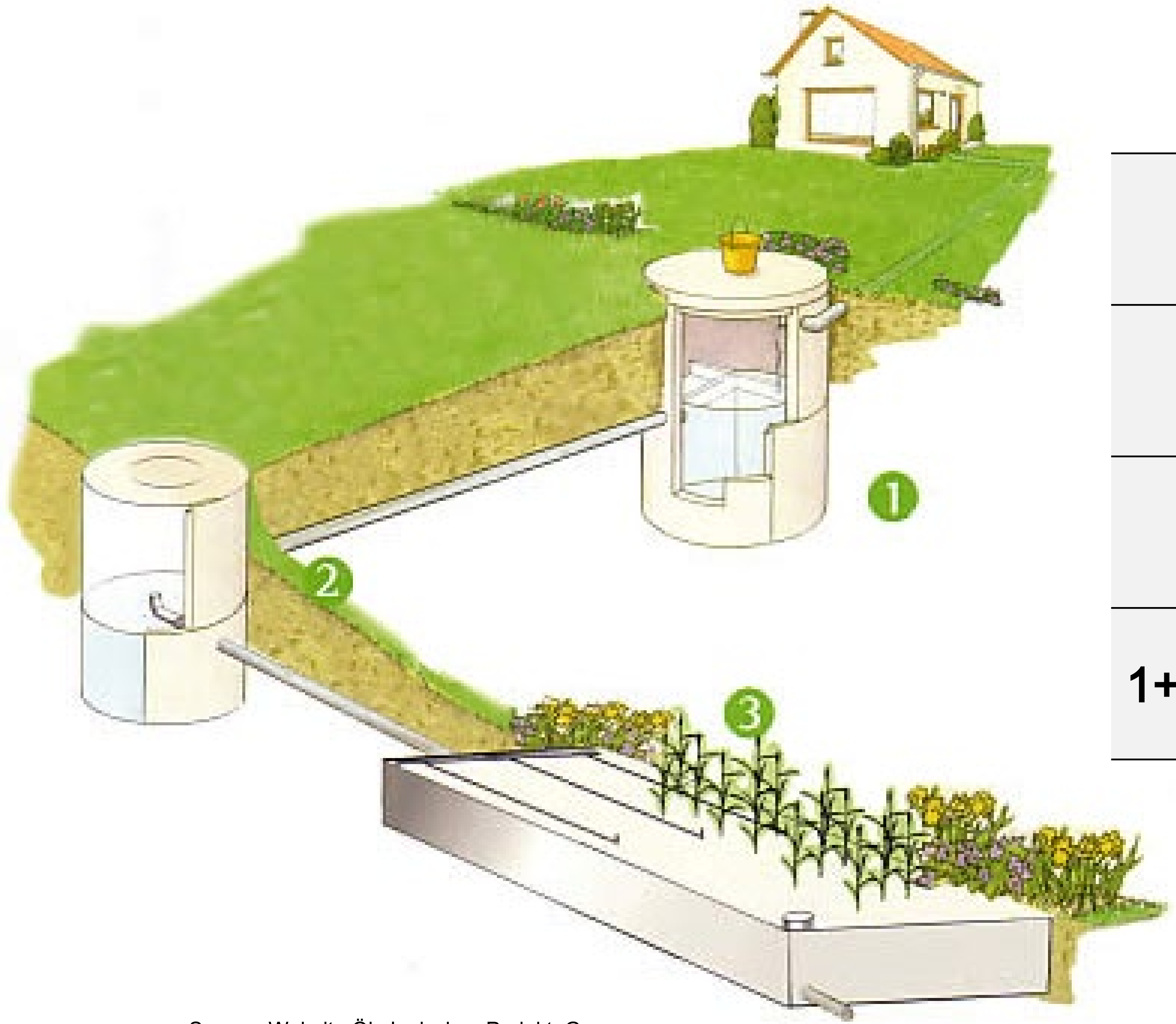
Primary treatment unit required
Regular emptying sludge from PTU is essential

For raw (screened) wastewater

2 VF wetlands in series
Integrated sludge and wastewater treatment

adapted from Dotro et al., 2017, Treatment Wetlands., IWA Publishing, London, UK, 172p; https://doi.org/10.2166/9781780408774.

VF wetland



Source: Website Ökologisches Projekt, Graz

1	Primary treatment, e.g. septic tank	Mechanische Vorreinigung
2	Intermittent loading tank	Intervallbeschickungs-schacht
3	VF bed	Vertikal durchströmter bepflanzter Bodenfilter
1+2+3	**VF wetland**	**Pflanzenkläranlage**

Treatment wetland main types

Main application, land requirement and typical removal efficiencies of the main wetland types (adapted from Dotro et al., 2017)

Wetland Type	HF	VF	French VF	FWS
Treatment step (main application)	Secondary	Secondary	Combined primary and secondary	Tertiary
Land requirement [m^2 per person]	3.0 – 10.0	1.0 – 5.0	2.0	> 10
Total suspended solids (TSS)	> 80%	> 90%	> 90%	> 80%
Organic matter (BOD_5, COD)	> 80%	> 90%	> 90%	> 80%
Ammonia nitrogen	20 – 30%	> 90%	> 90%	> 80%
Total nitrogen	30 – 50%	< 20%	< 20%	30 – 50%
Total phosphorus (long term)	10 – 20%	10 – 20%	10 – 20%	10 – 20%
Microbial indicators	2 $\log_{10}$	3-4 $\log_{10}$	3-4 $\log_{10}$	1 $\log_{10}$

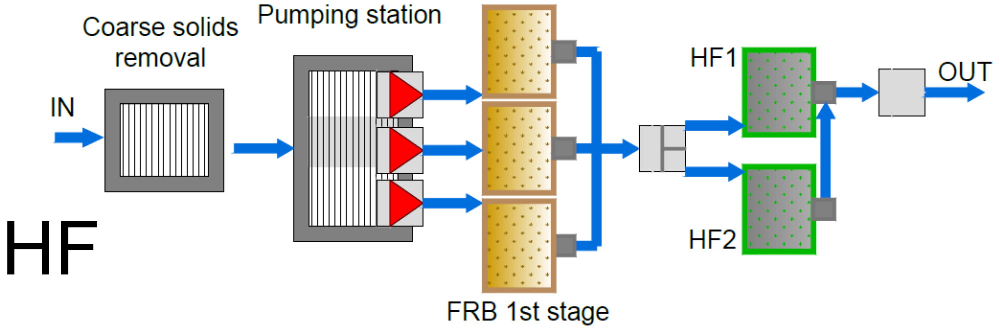
Dotro G., Langergraber G., Nivala J., Puigagut J., Stein O.R., von Sperling, M. (2017): *Biological Wastewater Treatment Series, Volume 7: Treatment Wetlands*. IWA Publishing, London, UK.; https://doi.org/10.2166/9781780408774 **- available as an Open Access eBook**

Treatment wetland main types

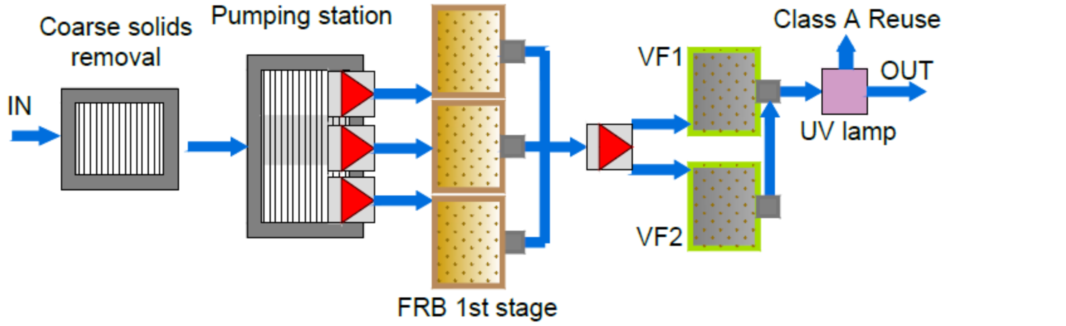
VF = Vertical Flow bed
HF = Horizontal Flow bed
FRB = French Reed Bed = 1st stage of a French VF wetland
FWS = Free Water Surface wetland

TW design of TWs related to anticipated reuse of treated water

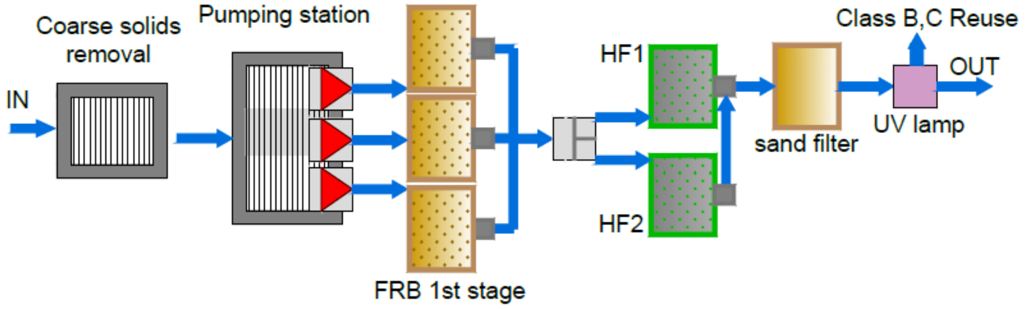
1. Discharge, no reuse: FRB + HF



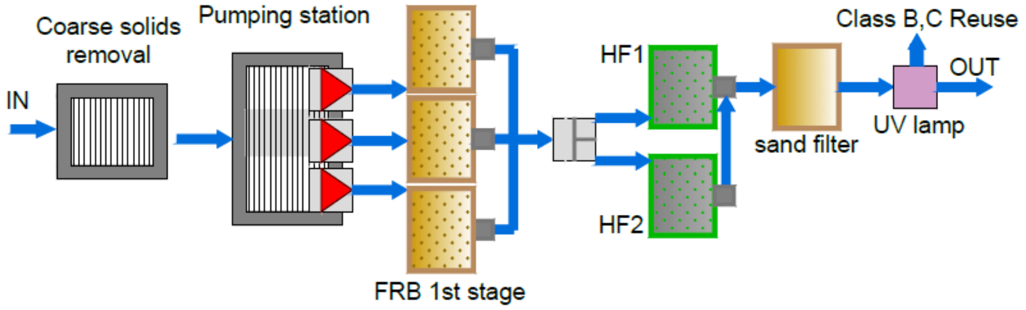
2. Reuse, **class A**: FRB + VF + UV lamp



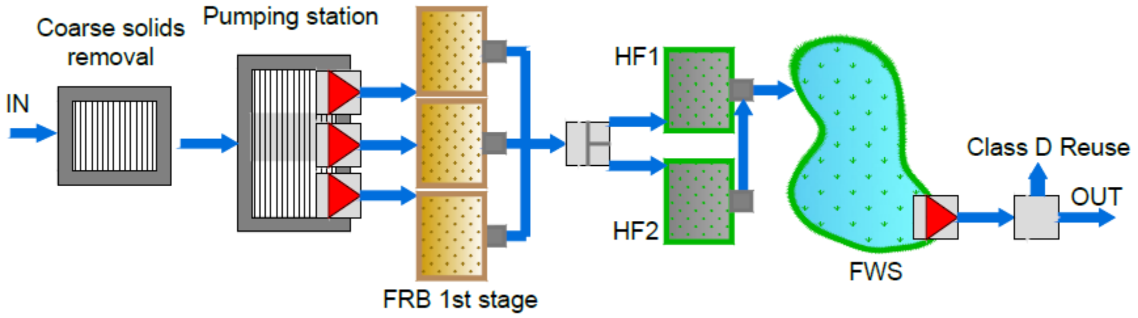
3. Reuse, **class B**: FRB + HF + sand filter + UV lamp



4. Reuse, **class C**: FRB + HF + sand filter +UV lamp



5. Reuse, **class D**: FRB + HF + FWS



IRIDRA, SHUKALB & BOKU (2022): Draft of the Project Document and Technoeconomic Notes (Deliverable D3)

Treatment wetlands
Role of plants

- **Physical effects:** roots provide surface area for attached micro-organisms; root growth maintains the hydraulic properties of the substrate; vegetation cover protects the surface from erosion and shading prevents algae growth; Litter provides an insulation layer on the wetland surface (especially for operation during winter).

- **Uptake:** 1) nutrients: plays a minor role for common wastewater parameters compared to the degradation processes by micro-organisms. 2) heavy metals and special organic compounds: different plant species can play a major role to enhance the treatment efficiency.

- **Release:** plants not harvested → release during decomposition; Some plants: release of organic compounds (which can be used for denitrification) or oxygen (e.g. reeds – but too little compared to O2 demand of wastewater).

- other functions not directly related to the treatment process

Vertical flow (VF) wetlands

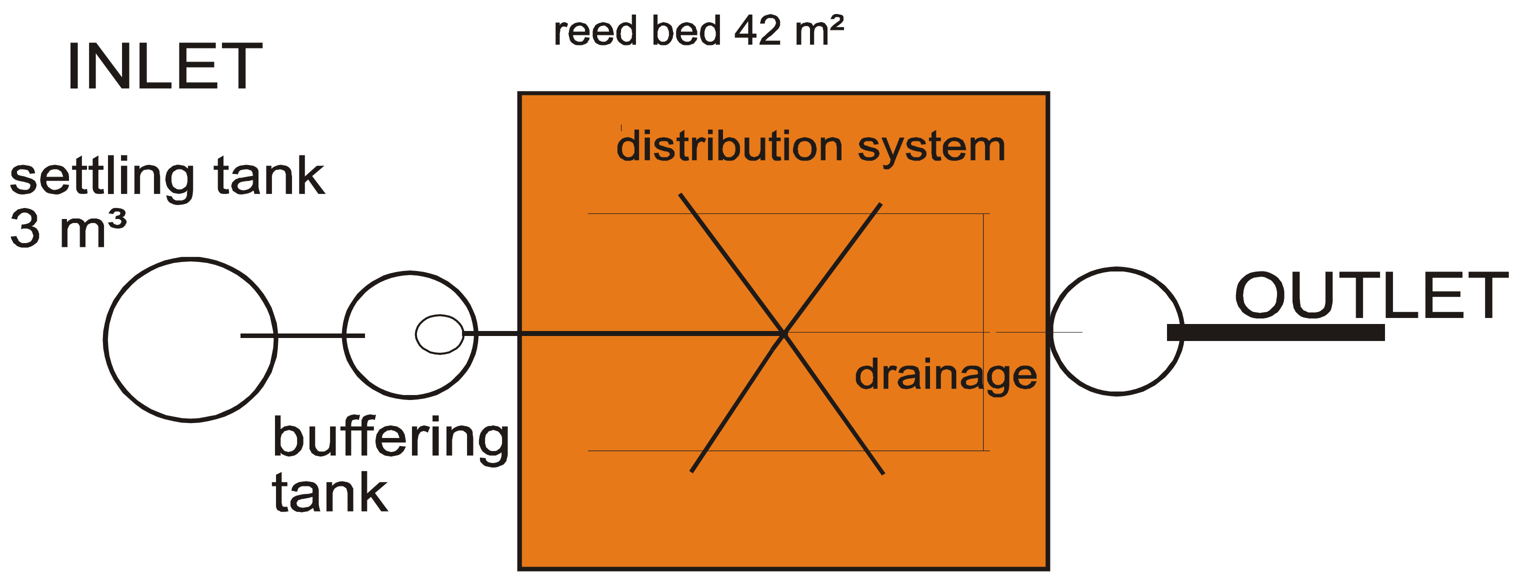
Development in Austria

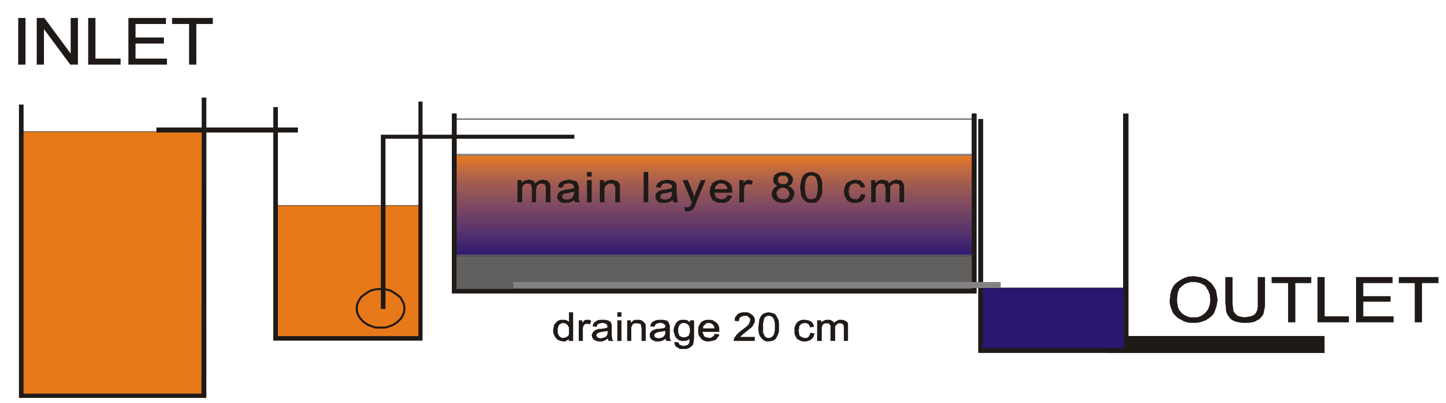
- In 1990, the legal requirements changed and requested now nitrification for all sizes of treatment plants. Consequently, the research focus changed to the development of **VF sand based wetlands with intermittent loading**.
- 1990: first VF wetland for 8 PE constructed
- 1997: First version of Austrian design guideline (ÖNORM B 2505, 1997) – for VF wetlands: 5 m² per PE
- 2009: Update of Austrian design guideline for VF wetlands: **4 m² per PE**
- Today: almost 6‘000 TWs (= VF wetlands) in operation
  - most of them 10-20 PE, largest one 500 PE

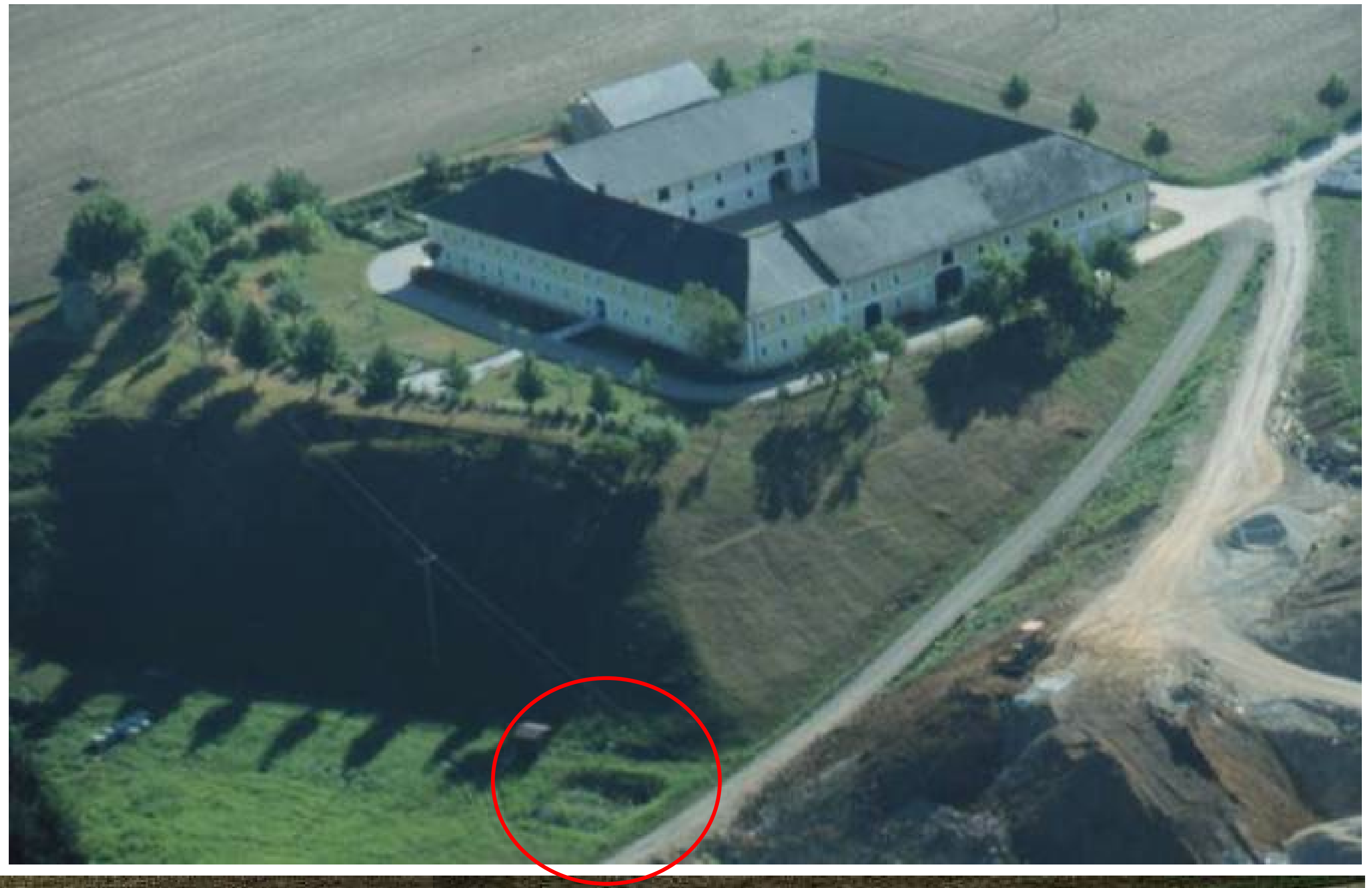
Vertical flow (VF) wetlands

Case study VF wetland Schillhuber, Wolfern, Upper Austria

- First VF wetland in Austria;
- 5m²/PE, design size 8 PE
- constructed 1990, in operation since 1991







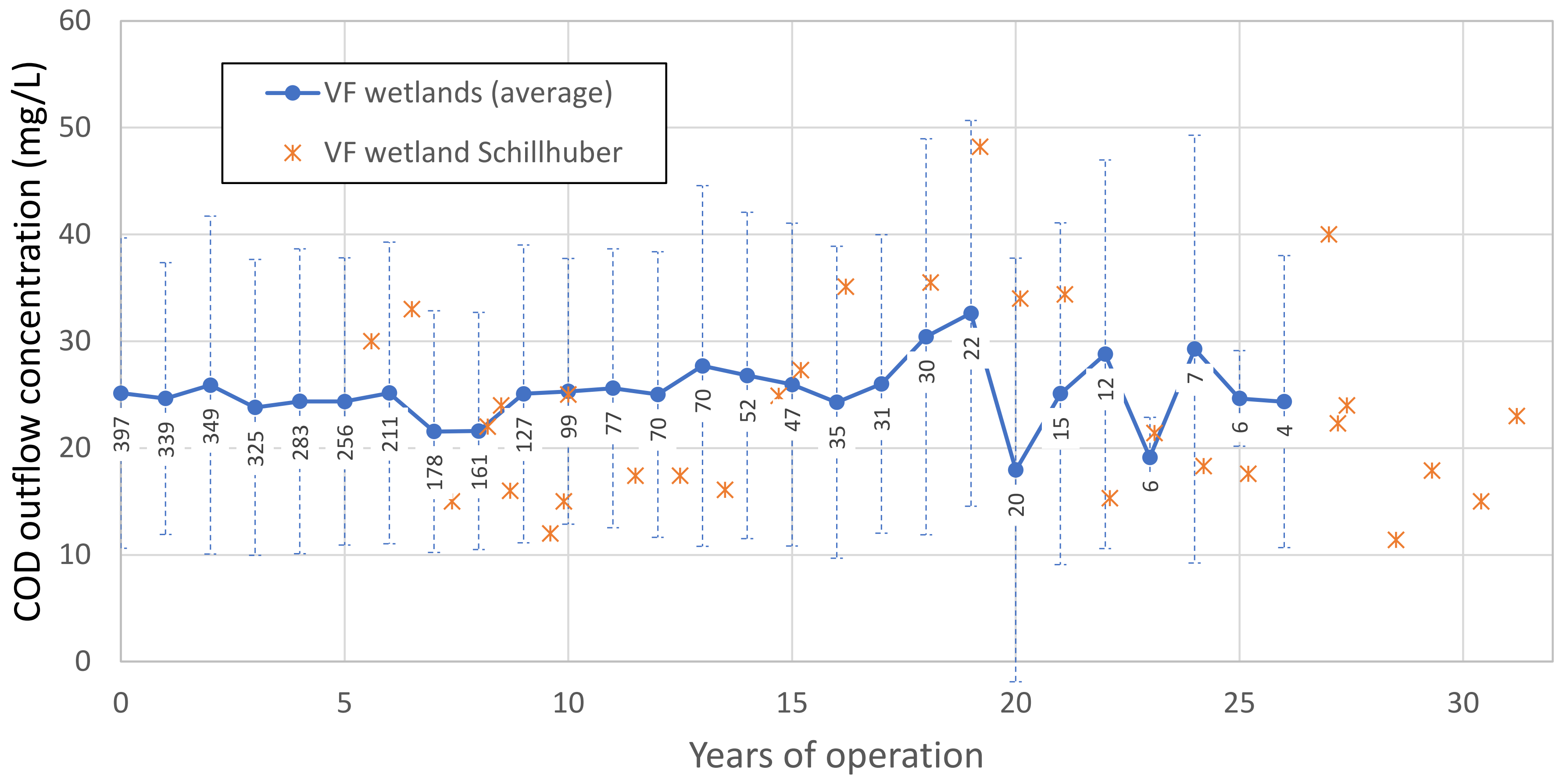
Vertical flow (VF) wetlands

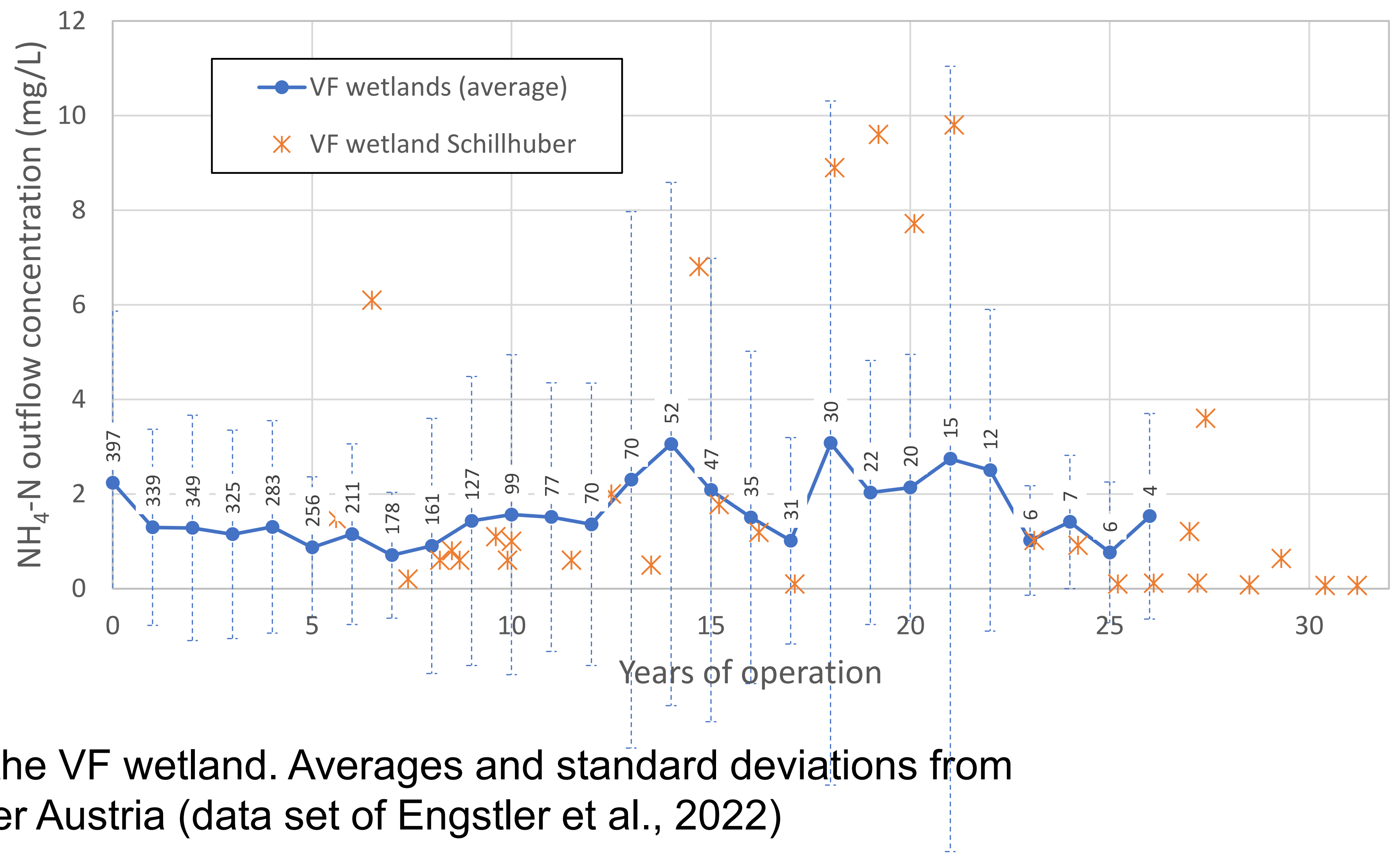
Case study VF wetland Schillhuber, Wolfern, Upper Austria

- hydraulic loading (November 1991 to June 1999): 26 mm/d → 87 % of design load (30 mm/d)

Parameter	**Influent** in mg/l	**Effluent** in mg/l	**Removal** in %	**Effluent 2013-2018*** in mg/l
COD	485	34	93	16
BOD_5	173	3	98	5
TOC	149	12	92	
NH_4-N	60	2.4	96	0.9
TN	75	48.8	35	
TP	11	5.0	55	* external monitoring

Vertical flow (VF) wetlands

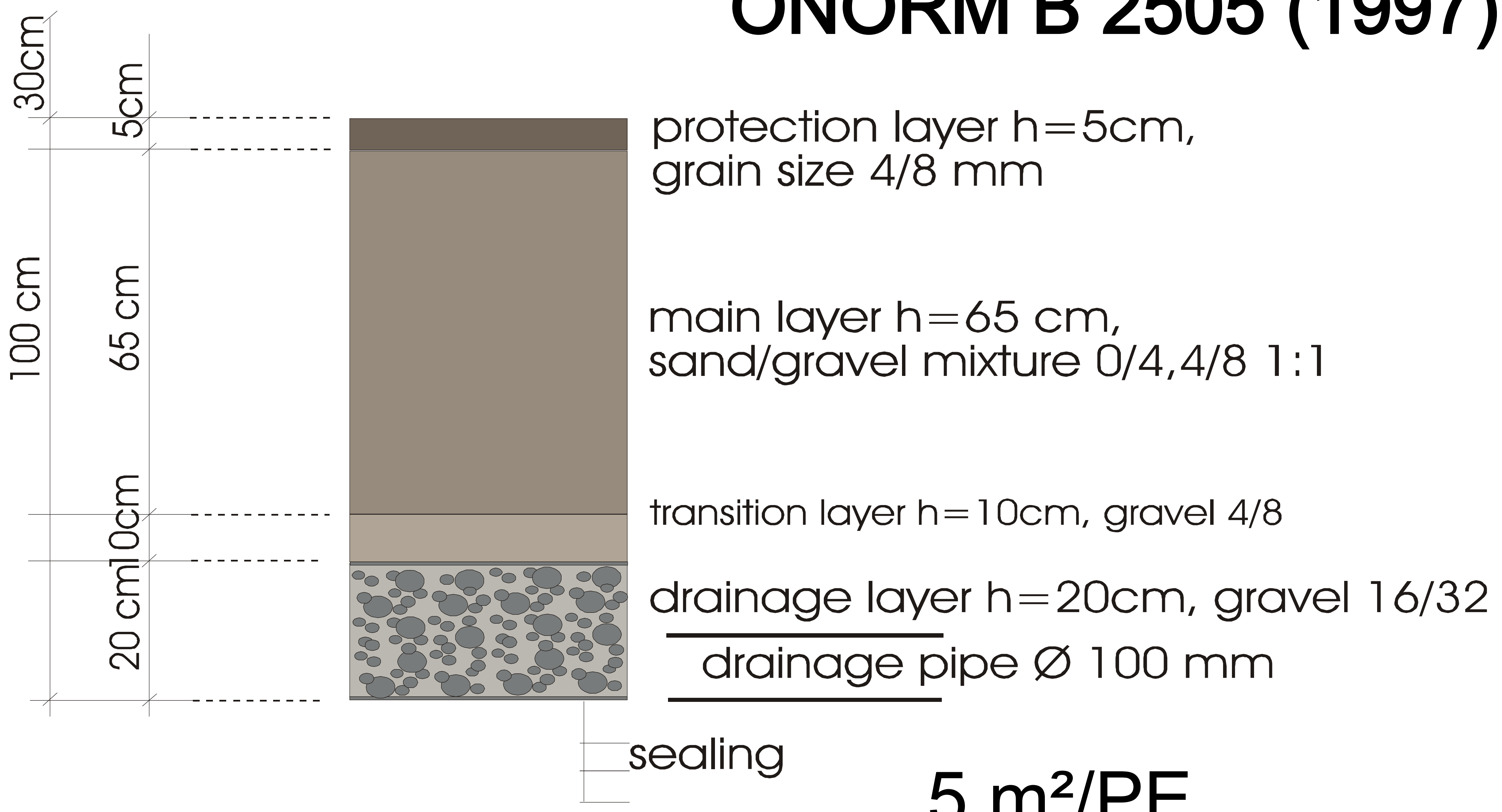




COD and NH_4-N outflow concentrations vs. the age of the VF wetland. Averages and standard deviations from external monitoring of VF wetlands in Upper Austria (data set of Engstler et al., 2022)

Vertical flow (VF) wetlands

Austrian design standard for VF wetlands (ÖNORM B 2505)

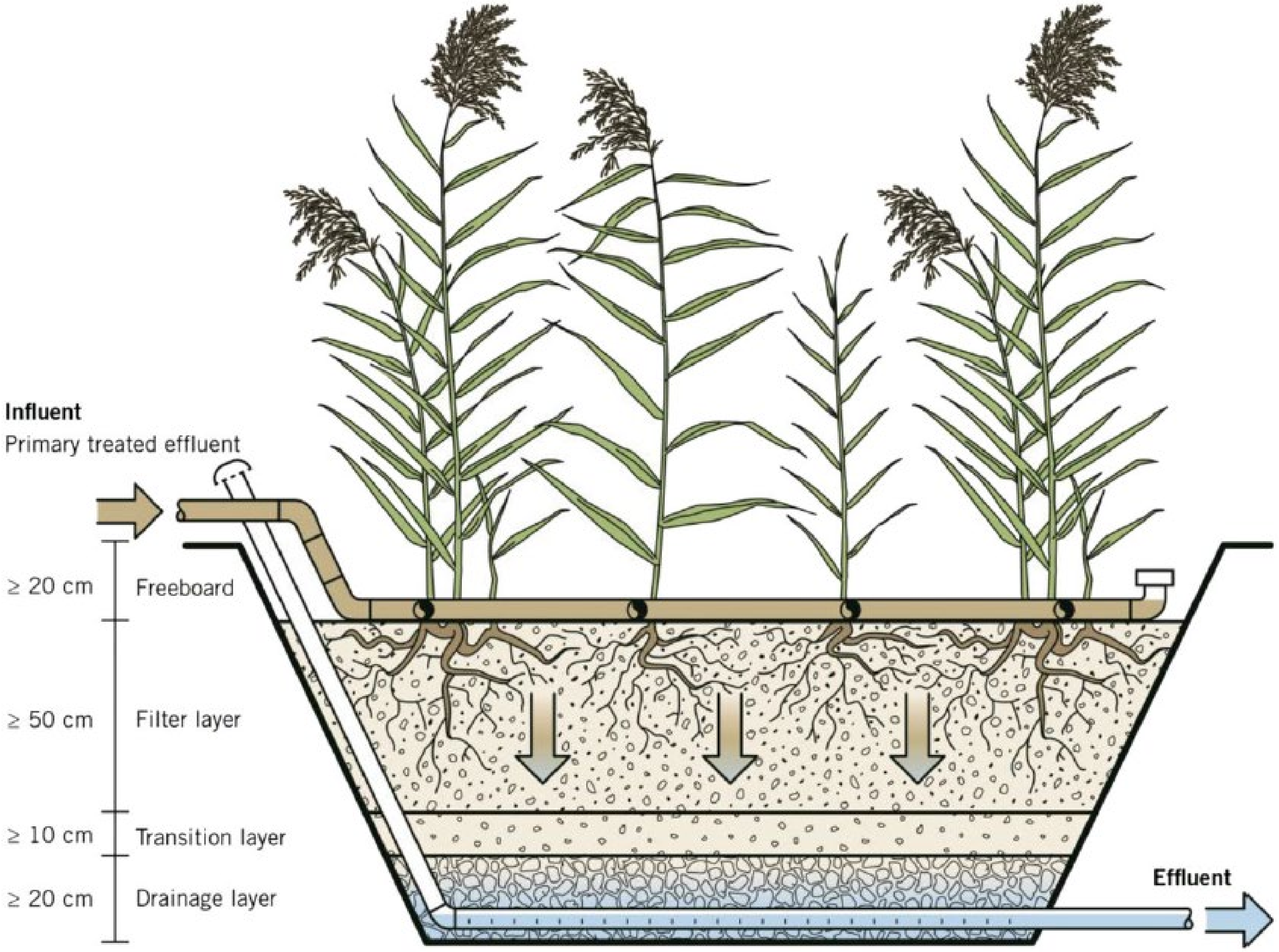


ÖNORM B 2505 (1997)	ÖNORM B 2505 (2009)
	Main layer h = 50 cm Sand 0.06/4 mm
5 m²/PE	4 m²/PE

Vertical flow (VF) wetlands

Design of VF wetlands

- VF wetlands with intermittent loading are designed to eliminate NH_4-N and organic matter
- Main factors determining the treatment performance of VF wetland (Pucher and Langergraber, 2019):
  - the filter material of the main layer (grain size of material, filter depth),
  - the loading of the VF wetland (loading interval, volume of single doses, resting periods),
  - the loading rate (hydraulic and organic loading rates), and
  - the distribution system (number of openings in distribution pipes per m² of filter surface).

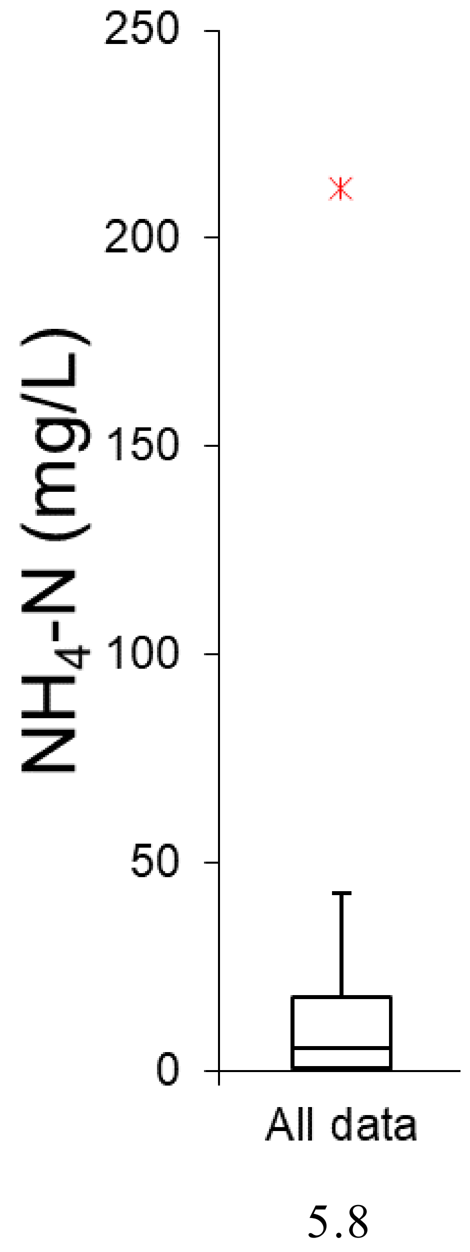


Schematic of a typical VF wetland with intermittent dosing

Dotro et al. (2017)

Pucher and Langergraber (2019): *Water Sci Technol* 80(2), 265-273; https://doi.org/10.2166/wst.2019.268.

Vertical flow (VF) wetlands



Box-plots of annual averages of outflow ammonia nitrogen concentrations of VF wetlands with different filter media for the main stage

GR = gravel; main = VF wetland used as main treatment stage, pol. = VF wetland used as polishing stage

Data source: VF wetland performance data from the dataset Kadlec and Wallace (2009), *Treatment Wetlands, 2nd edition*

Wallace et al. (2026, in preparation) *Treatment Wetlands, 3rd edition.*

Vertical flow (VF) wetlands

Operation & maintenance

- *Primary treatment*: The sludge from the primary treatment unit must be removed in order to prevent sludge drift to the VF beds. The emptying interval depends on the volume of the primary treatment unit, but sludge should be removed at least once a year.
- *Intermittent loading*: After some years, the rubber part of some siphons can get porous, which allows wastewater to seep continuously and thus only one part of the VF filter is loaded.
- *Distribution pipes*: In order to prevent freezing of wastewater in the pipes of the distribution system, it is essential that after a loading no water stays in the pipes. This needs to be checked at least in fall and after removing wetland plants.
- *Weeds*: During the first year, weeds should be removed until a mature cover of wetland vegetation is established.
- *Wetland plants*: Wetland plants should be cut every two to three years either in spring or in fall. If they are cut in fall, the plant material should be left on the filter surface to provide an insulation layer to the forthcoming winter.

Examples of large/beautiful treatment wetlands

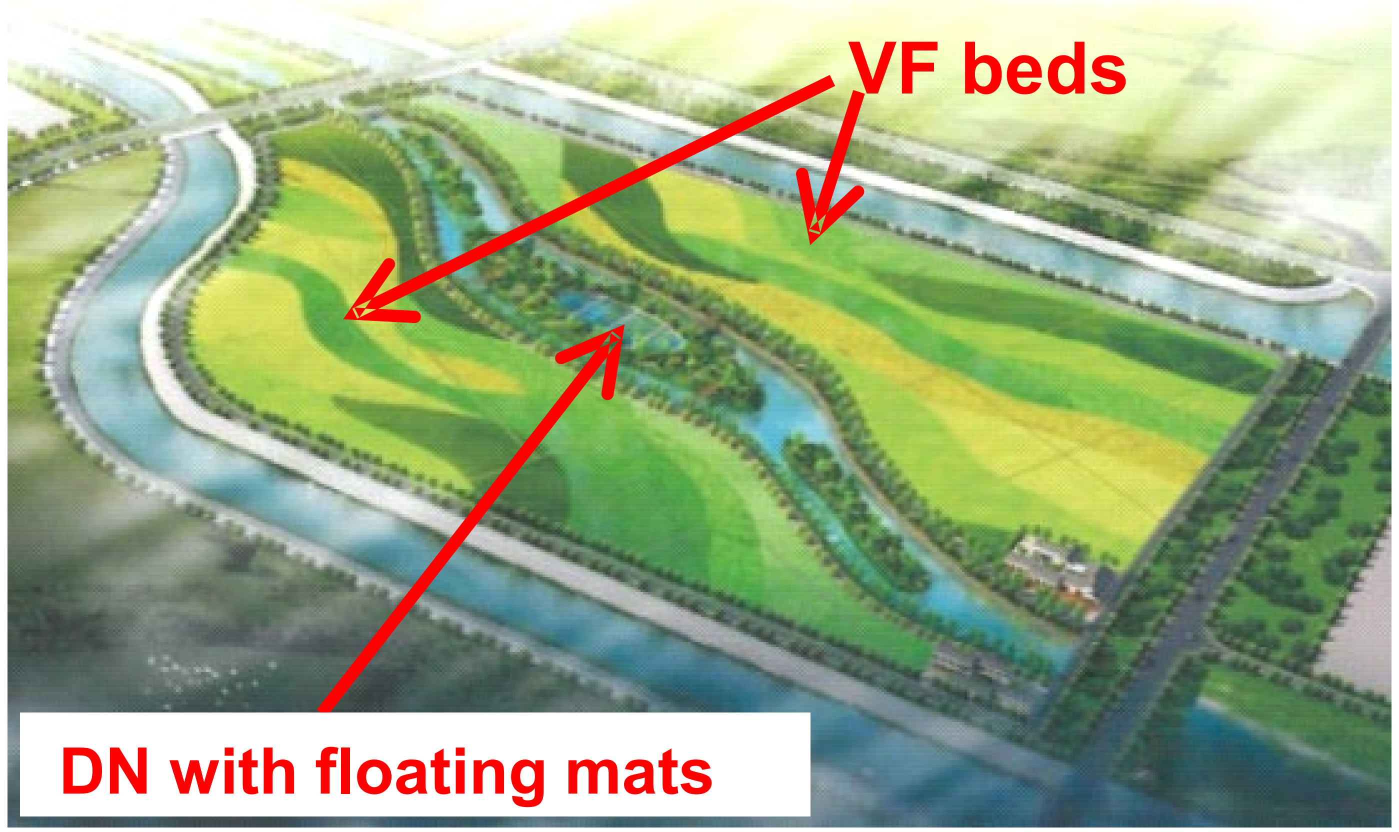
1) Orhei Treatment Wetland, Moldova - 20'000 PE, raw wastewater

- French VF wetland for treating raw wastewater
- 35'000 m² (Surface area)
- 2000 m³/d (with max. of 2700 m³/d)
- Start of operation in October 2013
- Energy consumption: 0.4 kWh/m³ water treated (AS: 1.75 kWh/m³)

Water 21 (Oct 2014), pp.28-30

Examples of large/beautiful treatment wetlands

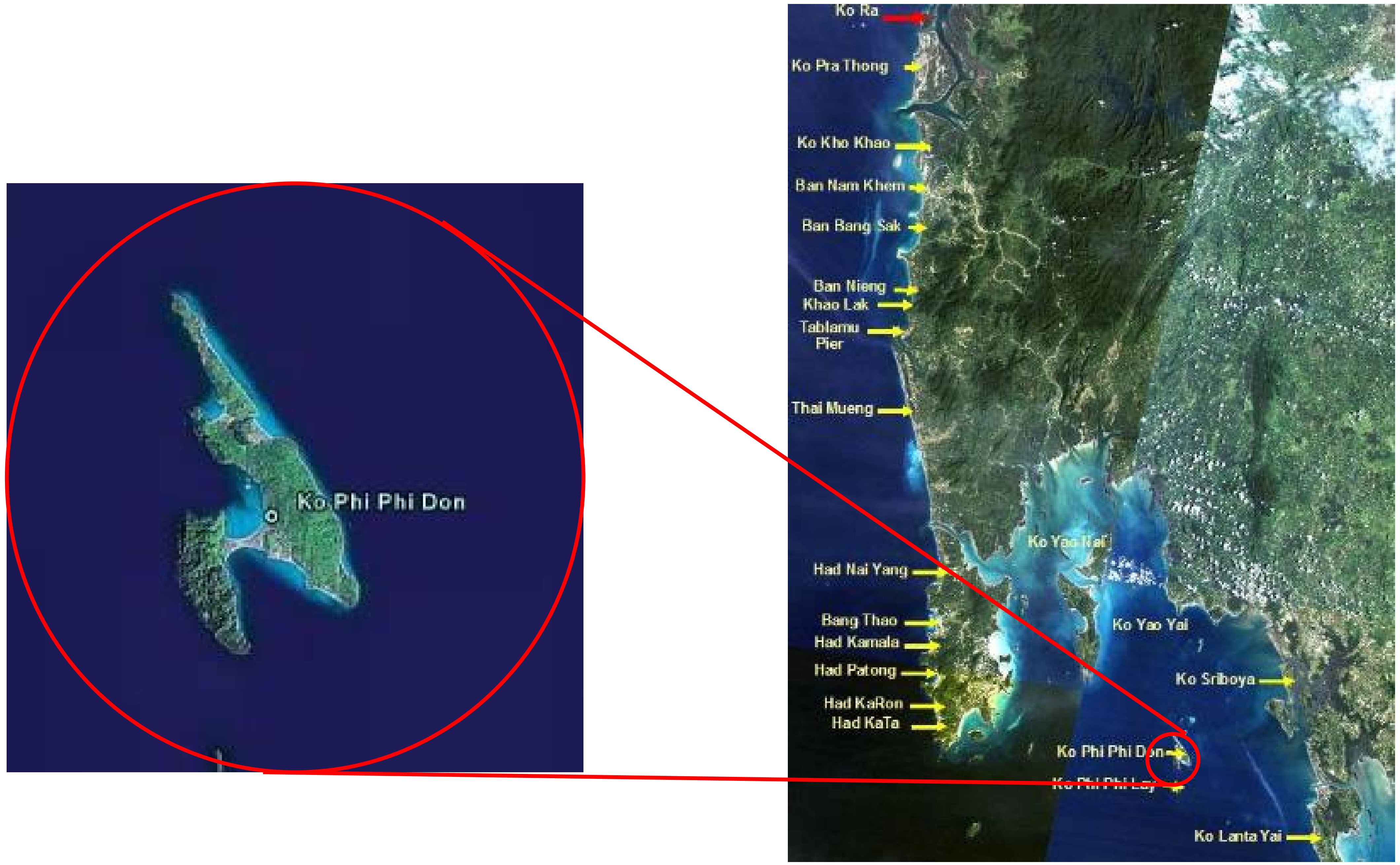
2) Yanling TW, Gonguan, PR China, 100'000 m³/d - Tertiary treatment



- built and operated by Shenzhen Biyuan Environmental Technology
- in operation since 2010
- total area of 25 ha
- denitrification step with floating mats, the water flows with gravity to the next treatment steps, i.e. VF beds surface flow wetland
- total area of VF beds = 180'000 m² subdivided in 60 smaller beds)
- total VF bed area is divided in 4 areas (each with 15 beds) that can be loaded separately

Examples of large/beautiful treatment wetlands

3) “Butterfly Wetland” @ Phi Phi Island, Thailand



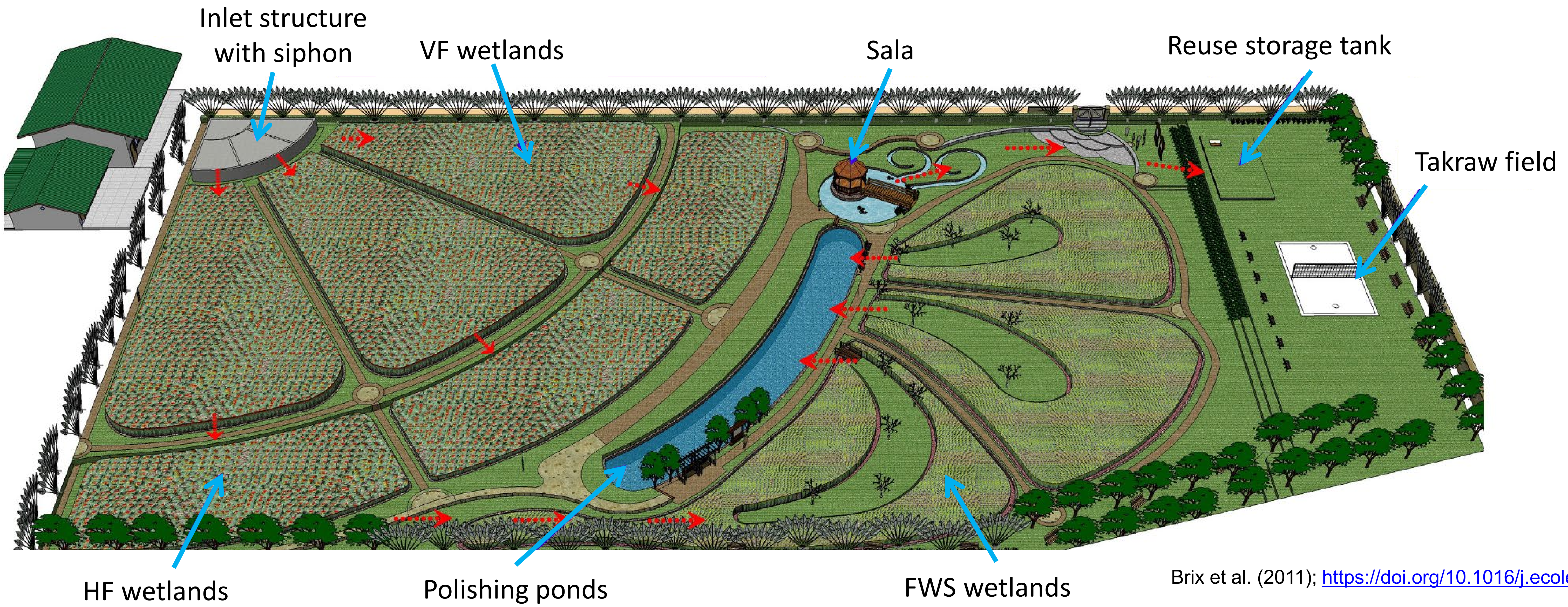
Examples of large/beautiful treatment wetlands

3) “Butterfly Wetland” @ Phi Phi Island, Thailand

Loading: 400 m^3/day mixed black and greywater

Total Area: 6000 m^2;

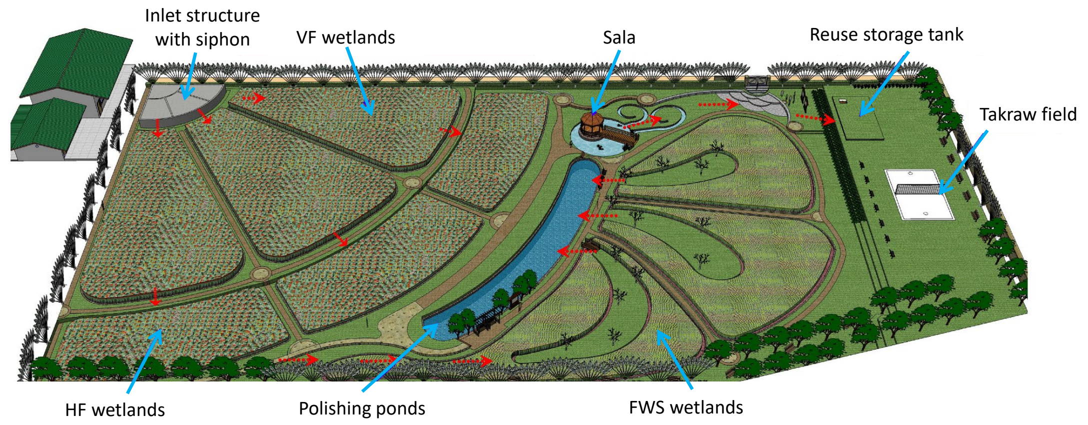
VF Area: 2300 m^2; HF/SF Area 1500 m^2; Pond Area 200 m^2



Brix et al. (2011); https://doi.org/10.1016/j.ecoleng.2010.06.035.

Examples of large/beautiful treatment wetlands

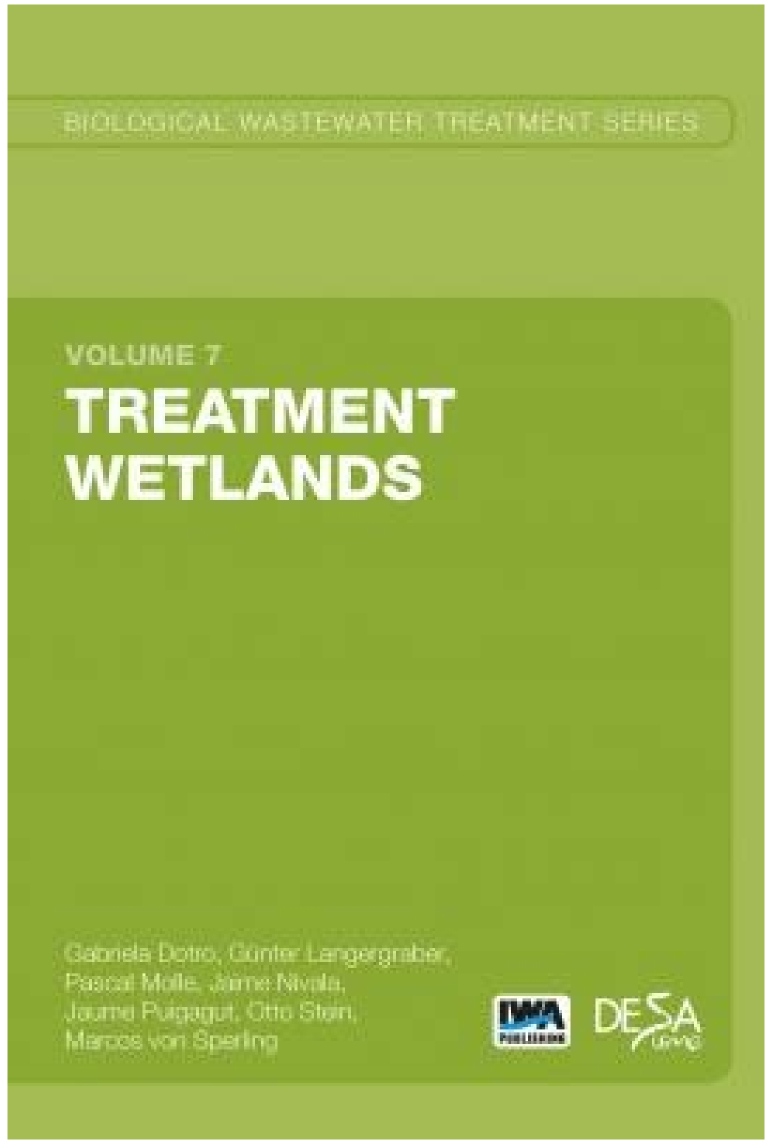
3) "Butterfly Wetland" @ Phi Phi Island, Thailand



Start of operation: 2007
Terminated ?

Brix et al. (2011); https://doi.org/10.1016/j.ecoleng.2010.06.035.

Resource material



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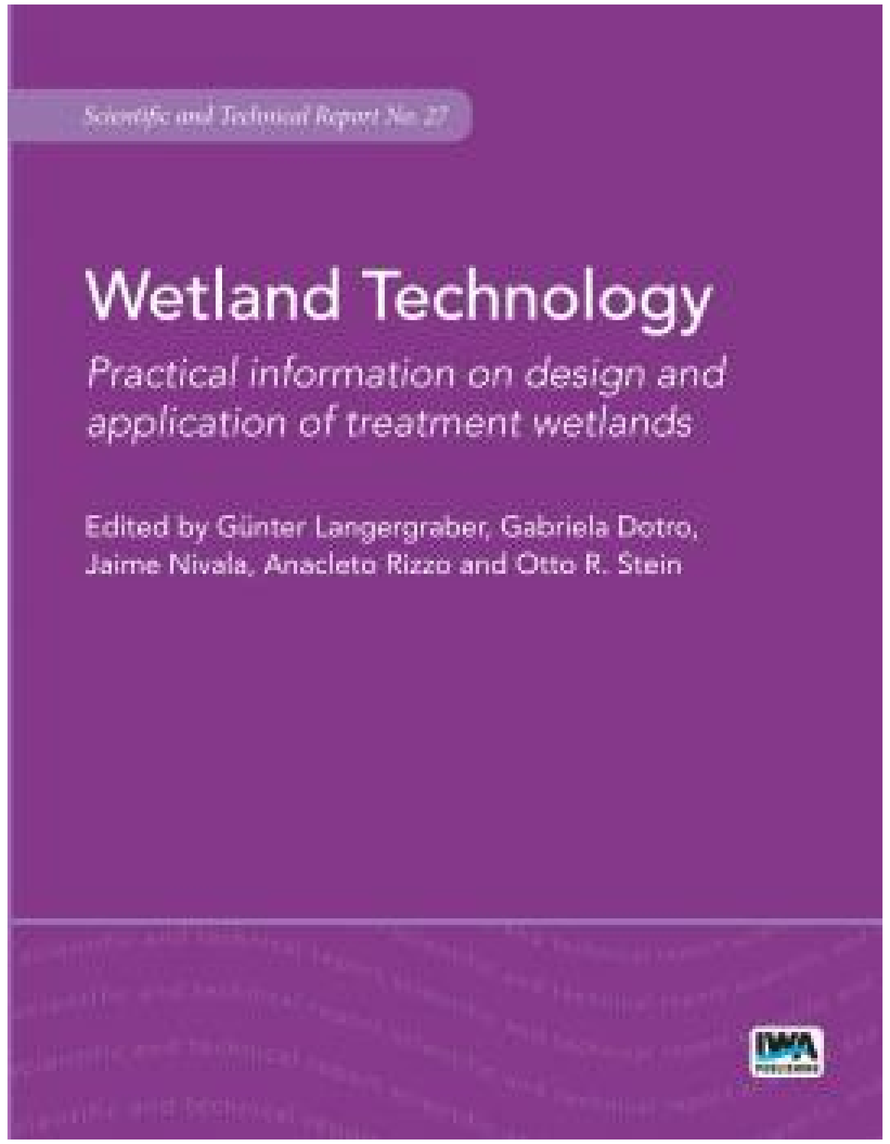
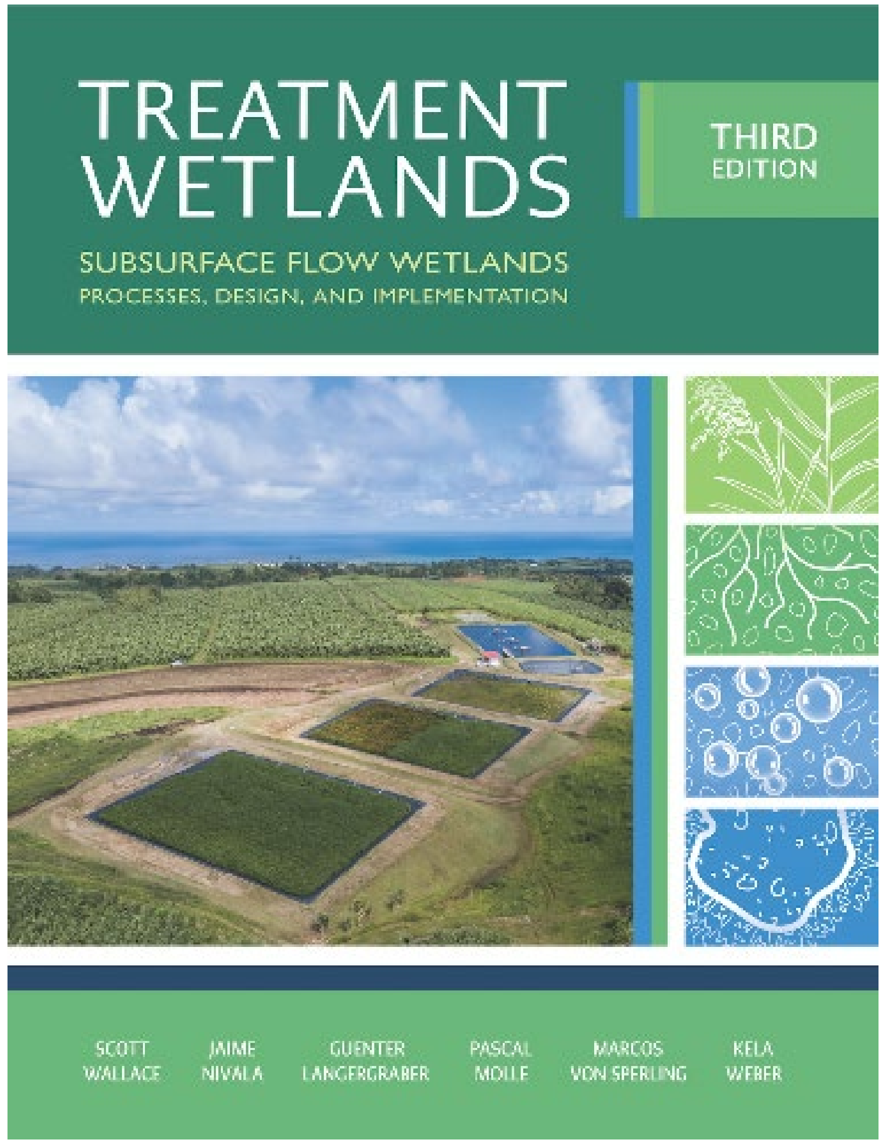
Available also in Spanish and Hindi.



Langergraber, G., Dotro, G., Nivala, J., Rizzo, A., Stein, O.R. (Eds., 2019): Wetland Technology: Practical information on the design and application of treatment wetlands. IWA Scientific and Technical Report No.27, IWA Publishing, London, UK, 164p. https://doi.org/10.2166/9781789060171.

Available also in Spanish and Hindi.

Coming soon!



Wallace, S.; Nivala, J.; Langergraber, G.; Molle, P.; von Sperling, M.; Weber, K. (2026): Treatment Wetlands – Subsurface flow wetlands: Processes design and implementation. CRC Press, Boca Raton, FL, USA; ISBN 978-1-138-61526-7.

Will be available also in Spanish and Chinese.

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D-CLEAN

"Improving Water Quality in the Danube River Basin: Nature-based Solutions for Sustainable Wastewater and Stormwater Management in Small Settlements"

01.04.2025 – 31.03.2028

The D-CLEAN project aims to address the pressing issue of **wastewater** and **stormwater** pollution in the **small settlements** in Danube River Basin by **rising awareness, building capacity**, and **identifying, testing and showcasing practical solutions**. Our aim is to **improve water quality** within the DRB by **promoting the use** of sustainable WW and SW management practices resilient to climate change and providing stakeholders with the **necessary tools**.

D-CLEAN pilot regions

Sava River Basin *(Serbia)*
- Regional development agency Srem
(Regionalna razvojna agencija Srem)

Drava-Mura River Basin *(Croatia)*
- Međimurske vode d.o.o. Čakovec

Tisza River Basin *(Hungary)*
- Middle Tisza District Water Directorate (KÖTIVIZIG)

Lower Danube *(Romania)*
- National Administration "Romanian Waters" (Administrația Națională "Apele Române")
- Romanian Water Association

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Summary

Are treatment wetlands an appropriate solution (for rural areas)?

- Yes, treatment wetlands in general and VF wetlands in particular are an excellent solution as they
  - achieve (if properly designed, constructed & operated) the same (if not a better) treatment level as technical solutions;
  - can be designed to deliver different effluent water quality tailored do the anticipated reuse;
  - have lower operation and maintenance requirements and thus costs compared to technological solutions; and
  - achieve a stable and robust treatment performance also over a long operational time (> 30 years).
- However, for treatment wetlands (as for any wastewater treatment technology) proper operation, monitoring and maintenance is key for well-functioning.

VF wetland pilots

Showcase the functioning of treatment wetlands (VF wetlands) in schools

- pilot systems with **different filter media** to show the importance of filter media for the treatment performance
- **artificial/synthetic greywater** for hygienic reasons

MSExcel® file for calculations: **Materials-VF-pilots.xlsx**

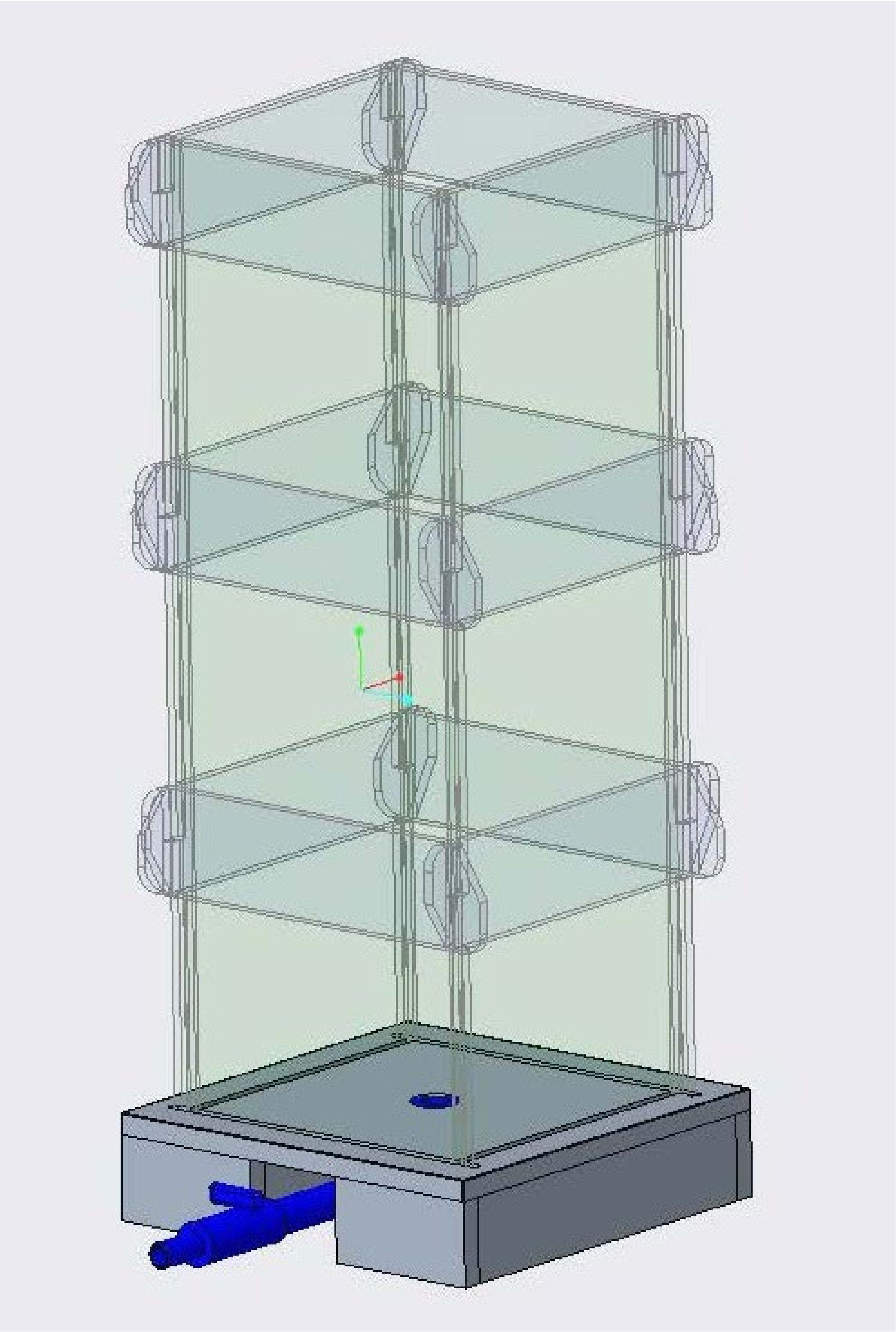
VF wetland pilots

1) VF filters

- Filter layers

Layer	Depth	VF 1	VF 2
Main filter layer	50 cm	0.06 - 4 mm	1 - 4 mm
Intermediate layer	10 cm	4 - 8 mm	4 - 8 mm
Drainage	10 cm	16-32 mm	16-32 mm
Organic loading rate (g COD/m²/d)		max. 20	max. 80

- Courser filter material → higher organic loading rates are applicable, i.e., more (waste)water can be treated → less surface area required, but treatment performance lower



Dimensions:
- 30 cm x 30 cm = 0.09 m²
- Height: 1 m

VF wetland pilots

Artificial/synthetic greywater

- based on Pucher et al. (2022) http://dx.doi.org/10.1016/j.scitotenv.2022.157842
- Measured concentrations (n=27)

Parameter	Unit	Influent			
		Mean	Min	Max	SD
COD	($mg.L^{-1}$)	382	270	580	59
TOC	($mg.L^{-1}$)	88.9	55.4	152.0	25.4
TNb	($mg.L^{-1}$)	11.74	9.00	18.00	2.20
NH_4-N	($mg.L^{-1}$)	6.67	3.84	12.00	1.49
NO_3-N	($mg.L^{-1}$)	0.22	0.05	0.91	0.20
Turbidity	(NTU)	26.82	16.80	45.80	5.80
Temperature	(°C)	18.8	10.1	25.4	3.9
O_2	($mg.L^{-1}$)	4.31	1.16	10.15	1.64
O_2 sat	(%)	45.8	12.8	83.2	14.7
µS	($\mu S.cm^{-1}$)	750	584	833	55
pH	(−)	7.96	7.45	8.90	0.43

Table 3
Recipe for the synthetic greywater used.

Products	$g{\cdot}L^{-1}$
Ammonium chloride	0.029
Cleaning agent	0.106
Dishwashing soap	0.132
Dishwasher tabs	0.13
Salt for dishwasher	0.1
Liquide laundry detergent	0.311
Fabric softener	0.147
Shampoo + shower gel	0.552
Conditioner	0.161
Toothpaste	0.03
Hand wash soap (liquid)	0.114

VF wetland pilots

Loading of the filters

- COD inflow concentration: 400 mg/L
- Surface area 0.09 m²

Parameter	VF1 (0.06 - 4 mm)	VF2 (1 - 4 mm)	Unit
Organic loading rate	20	80	g COD/m²/d
Hydraulic loading rate	50	200	L/m²/d = mm/d
Volume of greywater	4.5	18	L/d
Loading			
Morning (30%)	1.4	5.5	L
Lunch (20%)	0.9	3.5	L
Evening (50%)	2.2	9	L

VF wetland pilots

MSExcel® file … inputs / results

Sand / gravel for VF wetlands

sand / gravel	1.5	kg
Surface area:	**0.3 x 0.3 m²=**	
Drainage	**16/32 mm**	
Intermediate layer	**4/8 mm**	
Filter layer	**0.06/4 mm**	
	1/4 mm	
Required Materials		
Gravel	**16/32 mm**	
Gravel	**4/8 mm**	
Sand	**0.06/4 mm**	**70 kg**
Sand	**1/4 mm**	**70 kg**

Greywater volume

Concentration greywater		400	mg COD/L
	VF filter 1	**VF filter 2**	
	0.06/4 mm	**1/4 mm**	
OLR	20	80	g COD/m2/d
HLR	50	200	L/m²/day
Inflow	**4.5**	**18**	**L/day**
Inflow total		**22.5**	**L/day**
Operation	4	4	days
Volume	18	72	Liter
Volume total		90	Liter
Volume rounded		100	Liter

Greywater preparation

Recipe for the synthetic greywater (Pucher et al. 2022)

Greywater			
Products	***g/L***	***g per***	
		100	***Liter***
Ammonium chloride	0.029	2.9	
Cleaning agent	0.106	10.6	
Dishwashing soap	0.132	13.2	
Dishwasher tabs	0.13	13	
Salt for dishwasher	0.1	10	
Liquide laundry detergent	0.311	31.1	
Fabric softener	0.147	14.7	
Shampoo + shower gel	0.552	55.2	
Conditioner	0.162	16.2	
Toothpaste	0.03	3	
Hand wash soap (liquid)	0.114	11.4	

VF wetland pilots

Main filter layer	0.06-4 mm (1-4 mm)	50 cm
Intermediate layer	4-8 mm	10 cm
Drainage layer	16-32 mm	10 cm

What happened on Monday

VF wetland pilots

VF wetland pilots

VF wetland pilots

VF wetland pilots

1-4 mm	0-4 mm
20 L/day	5 L/day

Results (samples taken on third day, i.e., Thursday)

	Inflow		Outflow 1 (1-4 mm)		Outflow 2 (0-4 mm)	
Parameter	expected	measured	expected	measured	expected	measured
COD (mg/L)	400	305	50	107	< 20	106
NH_4-N (mg/L)	10	14.8	> 1	5.2	< 0.1	0.04

Merci BOKU

Günter Langergraber, Priv.-Doz. DI Dr.
Senior Scientist

University of Natural Resources and Life Sciences Vienna
Department of Landscape, Water and Infrastructure
Institute of Sanitary Engineering and Water Pollution Control
Muthgasse 18, 1190 Vienna, Austria

T +43 1 47654-811 11
E: guenter.langergraber@boku.ac.at
W: https://boku.ac.at/lawi/isig