Dissemination of the sustainable wastewater technology of constructed wetlands in Tanzania
ZEIN2011Z097

IR 4

Presentation:
Introduction Constructed Wetland Technology

Dar Es Salaam, 28th – 29th November 2013

Rob Van Deun
(Thomas More Kempen)

VLIR UOS South Initiatives 2011-2013
Promoter: Thomas More Kempen University College
Local Partner: University of Dar Es Salaam, WSP and CW Research Group

Constructed Wetlands Introduction

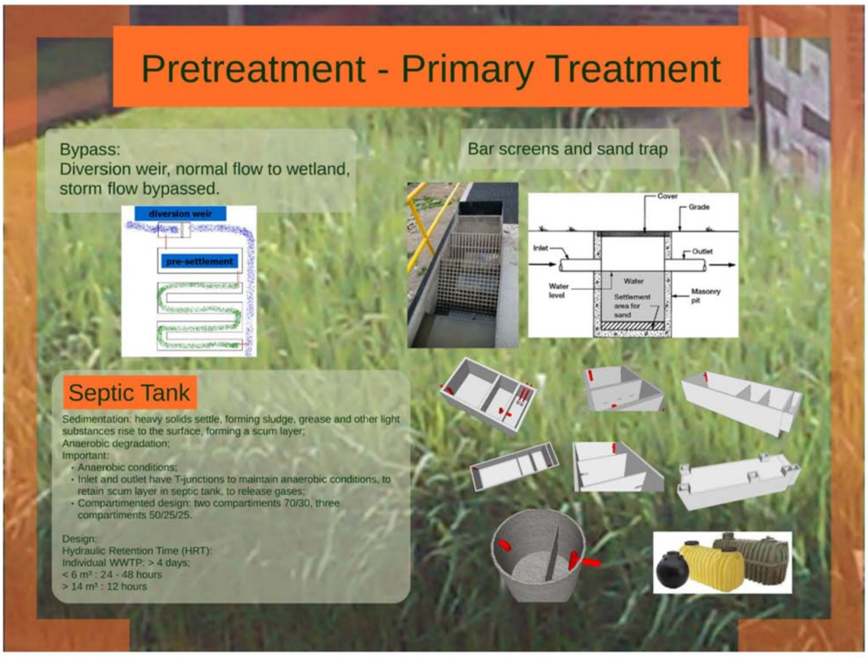
Rob Van Deun
Thomas More University College

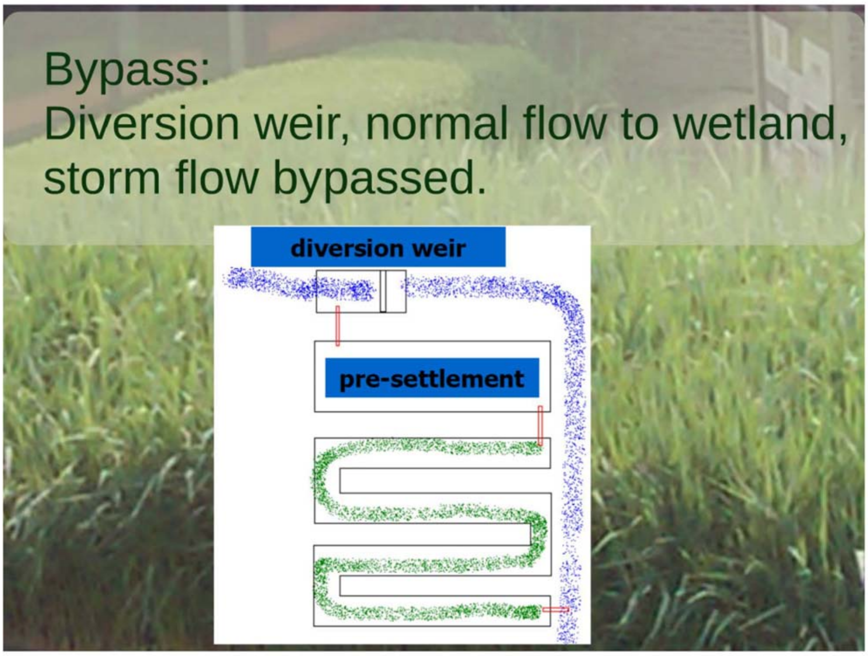
University of Dar Es Salaam, College of Engineering
28th – 29th November 2013
Dar Es Salaam Tanzania

vliruos SHARING MINDS, CHANGING LIVES

South Initiatives
VLIR UOS
Brussels Belgium

THOMAS MORE


Pretreatment - Primary Treatment
Bypass:
Diversion weir, normal flow to wetland, storm flow bypassed.
diversion weir
pre-settlement
Bar screens and sand trap
Cover
Grade
Inlet
Outlet
Water level
Water
Settlement area for sand
Masonry pit
Septic Tank
Sedimentation: heavy solids settle, forming sludge, grease and other light substances rise to the surface, forming a scum layer;
Anaerobic degradation;
Important:
• Anaerobic conditions;
• Inlet and outlet have T-junctions to maintain anaerobic conditions, to retain scum layer in septic tank, to release gases;
• Compartimented design: two compartiments 70/30, three compartiments 50/25/25.
Design:
Hydraulic Retention Time (HRT):
Individual WWTP: > 4 days;
< 6 m³ : 24 - 48 hours
> 14 m³ : 12 hours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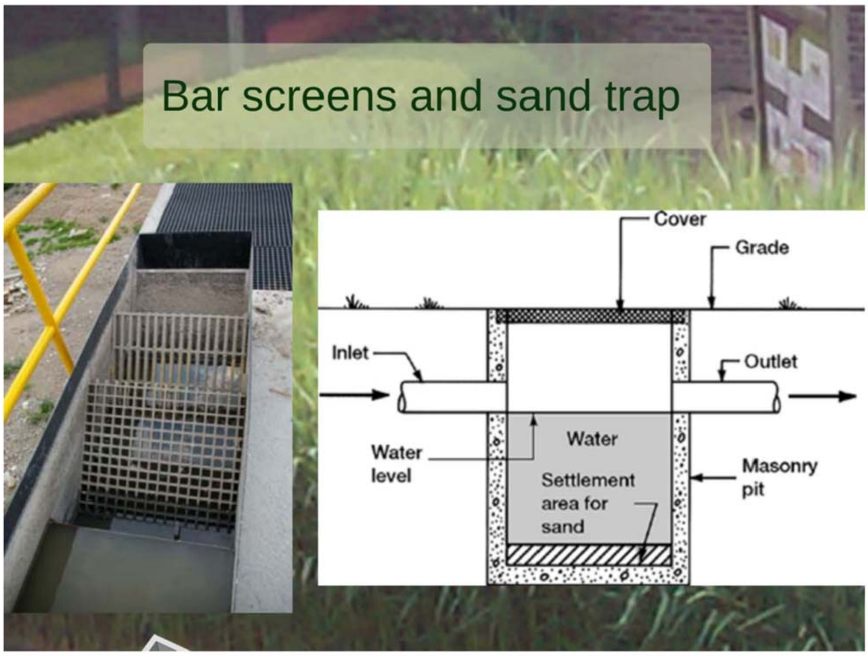
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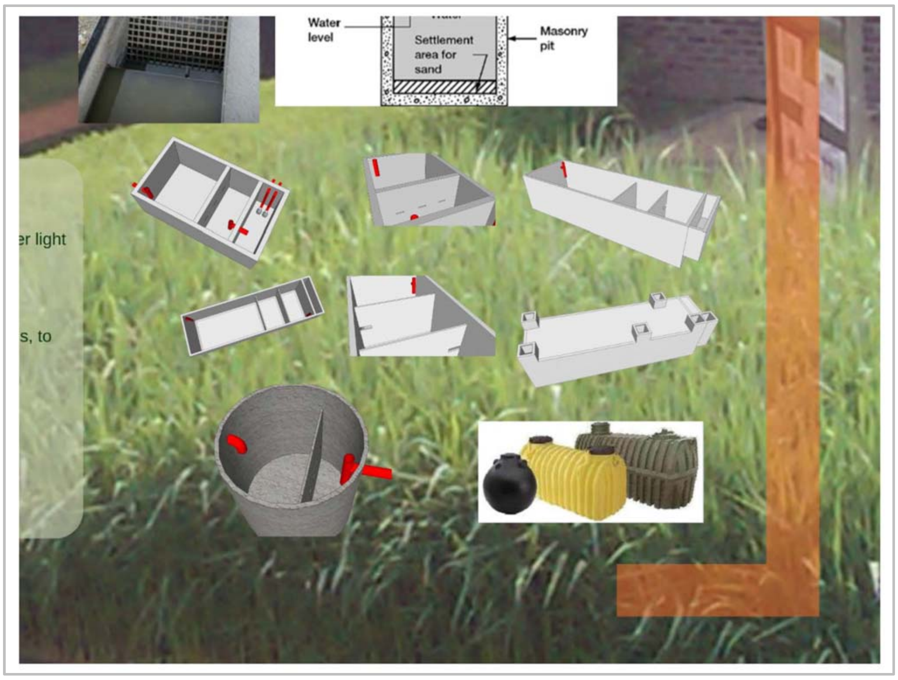
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Free Water Surface FWS
Free water surface wetlands are made up of ponds or channels.
Water flows through the system at a relatively shallow depth. The wetlands can include densely vegetated areas or open water areas. If emergent macrophytes or rooted submergent macrophytes are used, a suitable substrate is needed to support the vegetation.
Since the water flows through the system at low velocities, particulates and suspended solids will settle in the wetland. The wetland vegetation can enhance this sedimentation.
The microbial communities attached to the vegetation and suspended in the water column, will be responsible for the removal of soluble organic compounds. The degradation can proceed both aerobic and anaerobic.
Nutrient removal is mainly based on plant uptake. But nitrogen can also be removed by ammonia volatilization and nitrification and denitrification. Nitrifiers grow attached to the roots which provide oxygen. If the wetland is densely covered with macrophytes, oxygen diffusion to the water is limited thus decreasing the dissolved oxygen level. Anaerobic conditions will prevail.
Free water surface CW's are often used as tertiary treatment, polishing stage.
Design:
FWS CW's with emergent macrophytes:
Rule of thumb: 10 - 20 m² per p.e.
Depth of the water column: between 10 and 50 cm.
FWS CW's with floating macrophytes:
Rule of thumb: 10 - 20 m² per p.e.
Depth of the water column: between 25 and 75 cm.
The flow velocity should be less than 0.15 m/s.
Design models: First Order Plug Flow Reaction Kinetics
• Easier and often cheaper to design and build than other CW;
• Greater aesthetic value and wildlife habitat availability.
• Require more land than subsurface flow systems for the same pollution reduction;
• Pose a greater risk of exposure to pathogenic organisms and other harmful contaminants.

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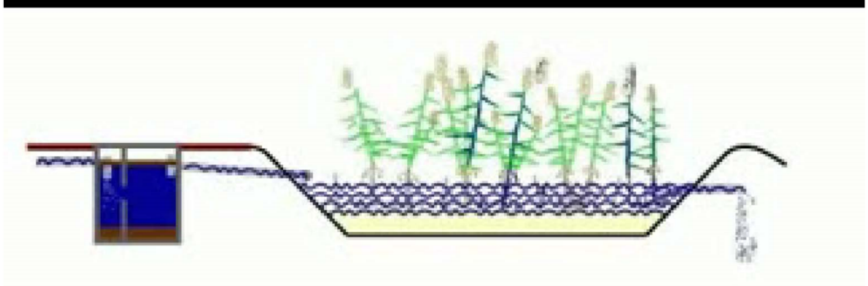

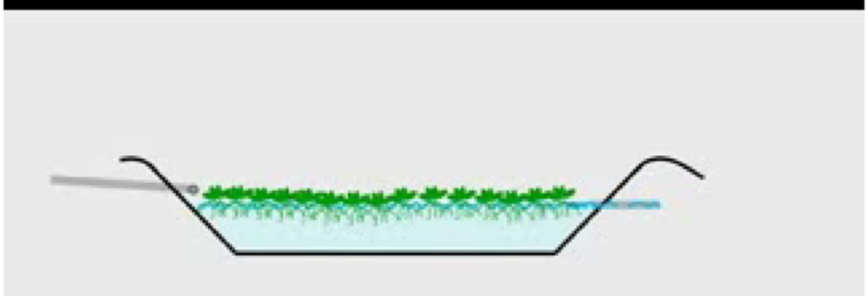

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FWS CW's with floating macrophytes:
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Depth of the water column: between 25 and 75 cm.
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Design models: First Order Plug Flow Reaction Kinetics

Kadlec & Knight: *plug-flow first order k-C* model*

Treatment Wetlands. R. Kadlec & R. Knight. CRC Press Boca Raton FL 1996

First order removal model : removal rate is proportional to pollutant concentration

$$A = Q \ln [(C_i - C^*) / (C_0 - C^*)] / k_A$$

Q = average wastewater flow (m³/d)
A = wetland area
C_0 = outlet concentration (mg/l)
C^* = background concentration (mg/l)
C_i = inlet concentration (mg/l)
k_A = first order areal rate constant (m/d)
q = hydraulic loading rate (m/d)

$$k_A = k_{20}\,\theta^{(T-20)}$$

k_{20} = first order areal rate constant at 20°C (m/d)
Θ = temperature coefficient for rate constant

k_{20} and Θ : Kadlec and Knight: **FWS**

Parameter	$k_{A,20}$ (m/yr)	$k_{A,20}$ (m/d)	θ	C*, mg/l
BOD	34	0,0932	1.00	$3.5+0.053C_i$
TSS	1000	2,7397	1.00	$5.1+0.16C_i$
Org-N	17	0,0466	1.05	1.5
NH4-N	18	0,0493	1.04	0
NOx-N	35	0,0959	1.09	0
Tot-N	22	0,0603	1.05	1.5
Tot-P	12	0,0329	1.00	0.02
Fecal Coliform	75	0,2055	1.00	300 cfu/100ml

Reed: First order plug flow kinetic model **FWS**

Natural Systems for Waste Management and Treatment, 2nd ed. S. Reed, R. Crites, and E. Middlebrooks.

Volumetric temperature dependent based constants

$$\frac{C_0}{C_i} = e^{-K_T.t} \qquad A = [\,Q\,(\ln C_i - \ln C_o)\,] / [\,K_T.d.n\,]$$

A = wetland surface area, m²
Q = average flow rate, m³/d
D = water depth, typically 0.1- 0.5 m
n = wetland porosity, typically 0.65-0.75
C_o = effluent BOD mg/l
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K_T = temperature dependent, first order rate constant d^{-1}
t = retention time, days

$$K_T = K_{20}.\theta^{(T-20)}$$

Process	K_{20}	θ
BOD removal	0.678	1.06
NH4 removal nitrification	0.2187	1.048
NO3 removal denitrification	1.000	1.15
Pathogen removal	2.6	1.19

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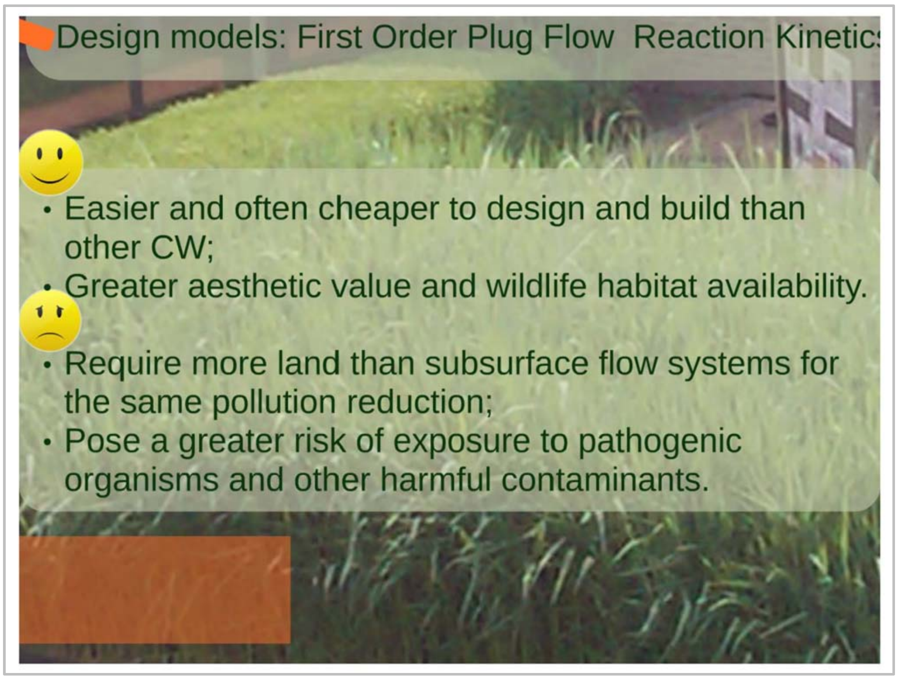
Diversion Weir
Presettlement pond
Reed ditches
Inlet Settling Zone
Floating and Emergent Plants
Submerged Growth Plants
Floating and Emergent Plants
Outlet Zone
Pretreated (Lagoon) Influent
Width (W)
Length (L)
Depth (H)
Variable Level Outlet
Zone 1 Fully Vegetated D.O. (-) H ≤ 0.75 m
Zone 2 Open-Water Surface D.O. (+) H ≥ 1.2 m
Zone 3 Fully Vegetated D.O. (-) H ≤ 0.75 m
EPA, 2000



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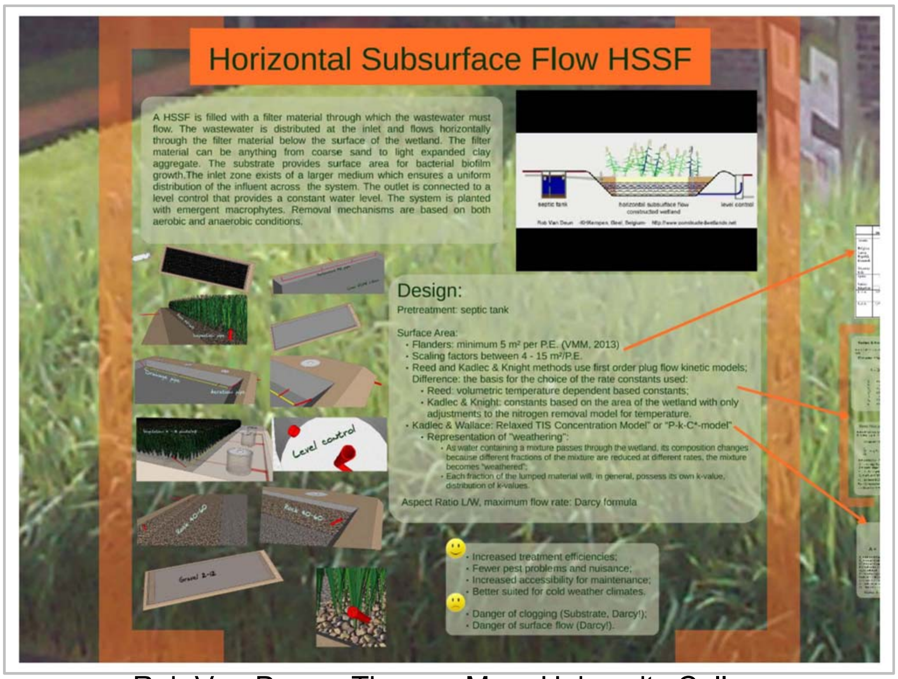

Horizontal Subsurface Flow HSSF
A HSSF is filled with a filter material through which the wastewater must flow. The wastewater is distributed at the inlet and flows horizontally through the filter material below the surface of the wetland. The filter material can be anything from coarse sand to light expanded clay aggregate. The substrate provides surface area for bacterial biofilm growth.The inlet zone exists of a larger medium which ensures a uniform distribution of the influent across the system. The outlet is connected to a level control that provides a constant water level. The system is planted with emergent macrophytes. Removal mechanisms are based on both aerobic and anaerobic conditions.
septic tank
horizontal subsurface flow constructed wetland
level control
Level control
Design:
Pretreatment: septic tank
Surface Area:
• Flanders: minimum 5 m² per P.E. (VMM, 2013)
• Scaling factors between 4 - 15 m²/P.E.
• Reed and Kadlec & Knight methods use first order plug flow kinetic models; Difference: the basis for the choice of the rate constants used:
• Reed: volumetric temperature dependent based constants;
• Kadlec & Knight: constants based on the area of the wetland with only adjustments to the nitrogen removal model for temperature.
• Kadlec & Wallace: Relaxed TIS Concentration Model" or "P-k-C*-model"
• Representation of "weathering":
• As water containing a mixture passes through the wetland, its composition changes because different fractions of the mixture are reduced at different rates, the mixture becomes "weathered";
• Each fraction of the lumped material will, in general, possess its own k-value, distribution of k-values.
Aspect Ratio L/W, maximum flow rate: Darcy formula
• Increased treatment efficiencies;
• Fewer pest problems and nuisance;
• Increased accessibility for maintenance;
• Better suited for cold weather climates.
• Danger of clogging (Substrate, Darcy!);
• Danger of surface flow (Darcy!).

Horizontal Subsurface

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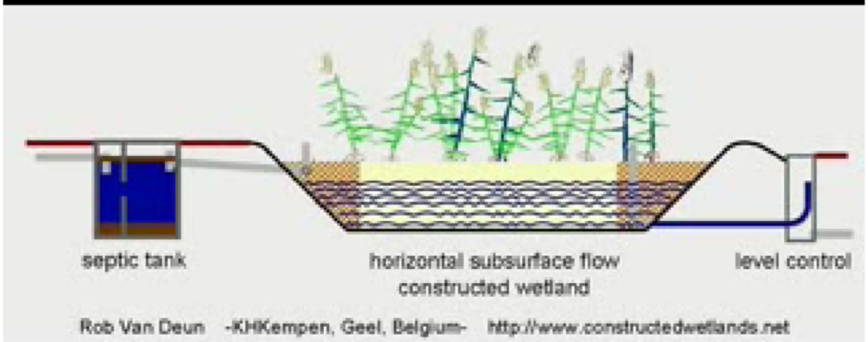

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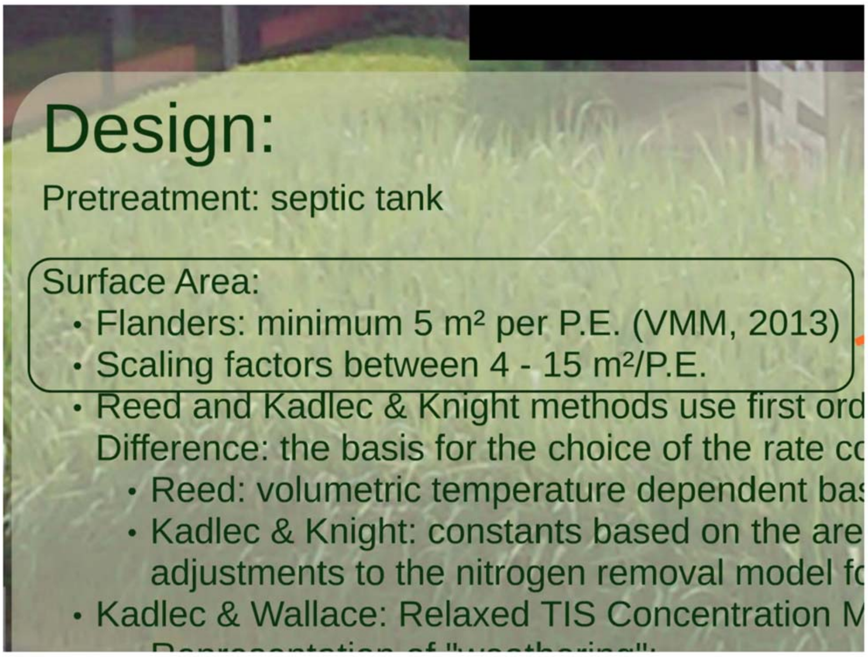
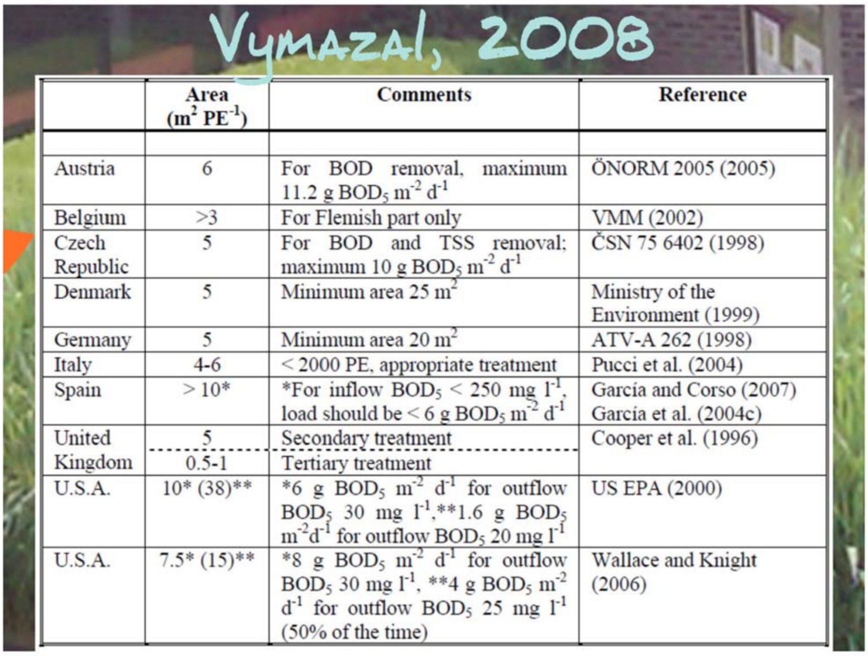
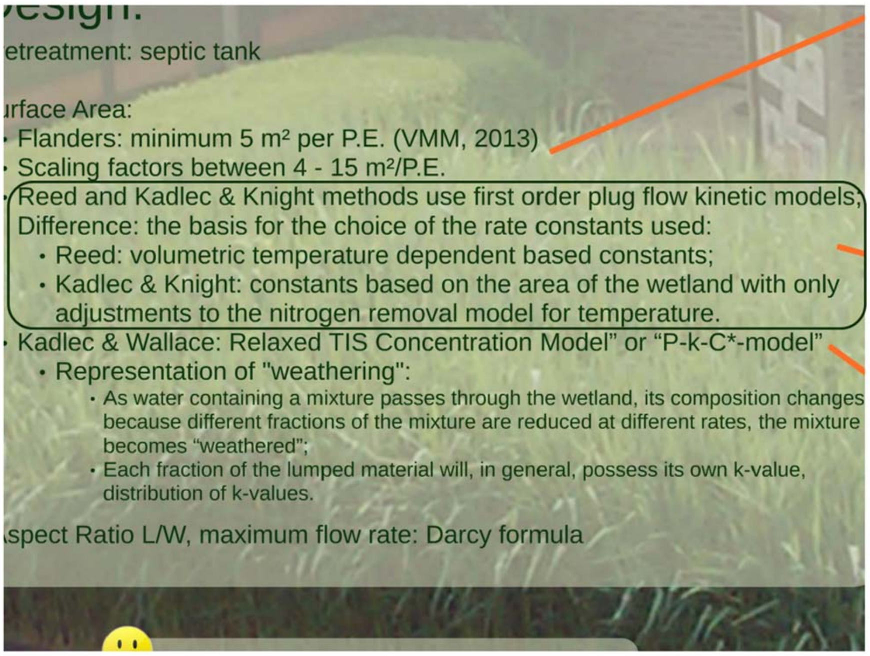




	Area (m^2 PE^{-1})	Comments	Reference
Austria	6	For BOD removal, maximum 11.2 g BOD_5 m^{-2} d^{-1}	ÖNORM 2005 (2005)
Belgium	>3	For Flemish part only	VMM (2002)
Czech Republic	5	For BOD and TSS removal; maximum 10 g BOD_5 m^{-2} d^{-1}	ČSN 75 6402 (1998)
Denmark	5	Minimum area 25 m^2	Ministry of the Environment (1999)
Germany	5	Minimum area 20 m^2	ATV-A 262 (1998)
Italy	4-6	< 2000 PE, appropriate treatment	Pucci et al. (2004)
Spain	> 10*	*For inflow BOD_5 < 250 mg l^{-1}, load should be < 6 g BOD_5 m^{-2} d^{-1}	García and Corso (2007) García et al. (2004c)
United Kingdom	5	Secondary treatment	Cooper et al. (1996)
	0.5-1	Tertiary treatment	
U.S.A.	10* (38)**	*6 g BOD_5 m^{-2} d^{-1} for outflow BOD_5 30 mg l^{-1},**1.6 g BOD_5 $m^{-2}d^{-1}$ for outflow BOD_5 20 mg l^{-1}	US EPA (2000)
U.S.A.	7.5* (15)**	*8 g BOD_5 m^{-2} d^{-1} for outflow BOD_5 30 mg l^{-1}, **4 g BOD_5 m^{-2} d^{-1} for outflow BOD_5 25 mg l^{-1} (50% of the time)	Wallace and Knight (2006)

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kA = first order areal rate constant (m/d)
q = hydraulic loading rate (m/d)
kA = k20 θ(T-20)
k20 = first order areal rate constant at 20°C (m/d)
Θ = temperature coefficient for rate constant
k20 and Θ : IWA (2000): HSSF
Parameter | kA,20 (m/yr) | kA,20 (m/d) | θ | C*, mg/l
BOD | 117 | 0,3205 | 1.057 | 3.0
TSS | 43,3 | 0,1186 | 1.00 | 6.0
Org-N | 35 | 0,0959 | 1.05 | 1.5
NH4-N | 34 | 0,0932 | 1.05 | 0
NOx-N | 50 | 0,1370 | 1.05 | 0
Tot-N | 10 | 0,0274 | 1.05 | 1.5
Tot-P | 9,1 | 0,0249 | 1.097 | 0
Fecal Coliform | 100 | 0,2740 | 1.003 | 200 cfu/100ml
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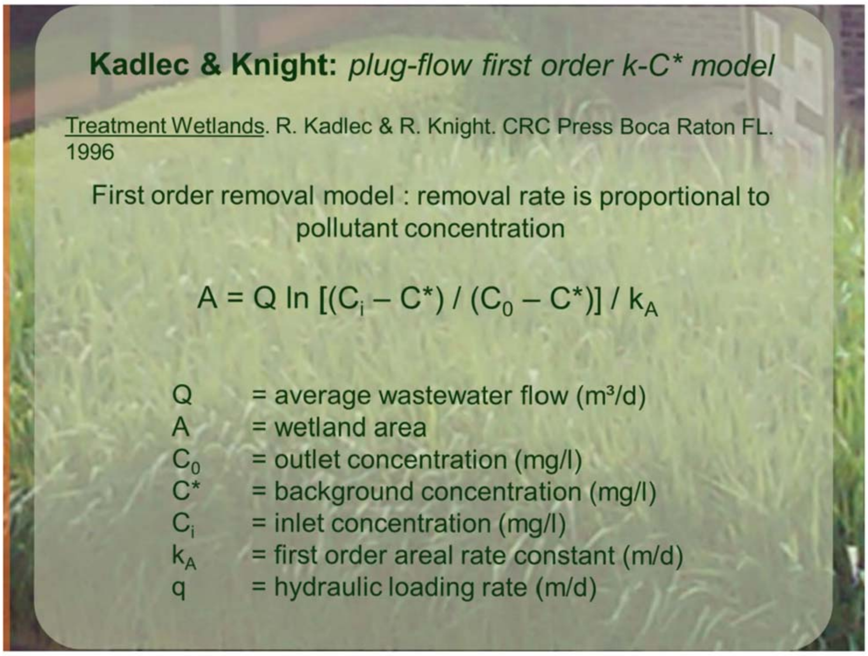
Co/Ci = e^(-KT t)   A = [Q (lnCi – lnCo)] / [KT.d.n]
A = wetland surface area, m²
Q = average flow rate, m³/d
D = water depth, typically 0,6 m
n = wetland porosity, dependent on media selected, 0.28-0.45
Co = effluent BOD mg/l
Ci = influent BOD mg/l
KT = temperature dependent, first order rate constant d-1
t = detention time, days
KT = K20.θ(T-20)
Process | K20 | θ
BOD removal | 1.104 | 1.06
NH4 removal nitrification | KNH | 1.048
NO3 removal denitrification | 1.000 | 1.15
KNH = 0.01854 + 0.3922(rz)^2.6077
KNH = nitrification rate constant at 20°C, d-1
rz = fraction of HSSF bed depth occupied by root zone, (0 to 1)
(According to Wallace root depth of Phragmites = 0,6 m (???)
if reed bed depth <0,6m → rz = 1)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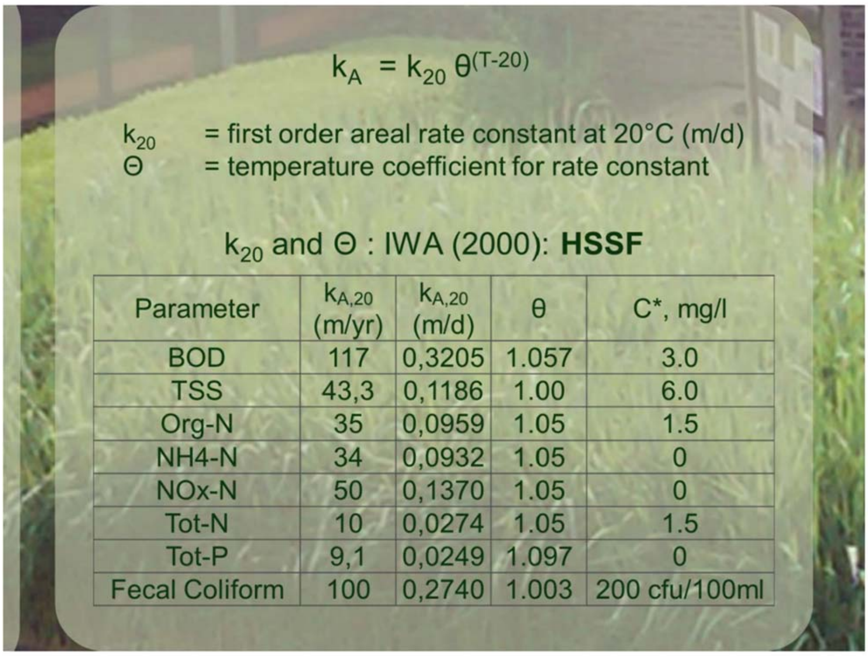
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$$K_T = K_{20} . \theta^{(T-20)}$$

Process	K_{20}	θ
BOD removal	1.104	1.06
NH4 removal nitrification	K_{NH}	1.048
NO3 removal denitrification	1.000	1.15

$$K_{NH} = 0.01854 + 0.3922(rz)^{2.6077}$$

K_{NH} = nitrification rate constant at 20°C, d^{-1}
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(According to Wallace root depth of *Phragmites = 0,6 m (???)*
if reed bed depth <0,6m → rz = 1)

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  - Representation of "weathering":
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Aspect Ratio L/W, maximum flow rate: Darcy formula

- Increased treatment efficiencies;
- Fewer pest problems and nuisance;
- Increased accessibility for maintenance;
- Better suited for cold weather climates.

Danger of clogging (Substrate, Darcy!);

PkC* - model

$$A = \frac{P^*Q * \left(\frac{C_o - C^*}{C_i - C^*}\right)^{(-1/P)} - (P^*Q)}{k}$$

C_i = inflow (influent) concentration (mg/l)
C_o = wetland outflow (effluent) concentration (mg/l)
C^* = wetland equilibrium background concentration (mg/l)
k = first-order, area-based rate constant (m/yr), which varies depending upon pollutant
P = weathering factor that takes into account the estimated number of hydraulic tanks-in-series (TIS-model) and the number of component compounds for a particular parameter (dimensionless)
A = wetland area (square meters (m^2)
Q = flow (cubic meters per year (m^3/yr)

Kadlec & Wallace, "Treatment Wetlands", 2009

TABLE 16.11
Summary of First-Order Rate Constants for Selected Parameters

Kadlec & Wallace, p618

C_i (mg/L)	BOD *Tertiary* 0–30 mg/L	BOD *Secondary* 30–100 mg/L	BOD *Primary* 100–200 mg/L	BOD *Super* >200 mg/L	Ammonification ORG-N	Nitrification NH_4-N	Denitrification NO_x-N	TKN	TN	TP	FC
FWS											
P	1	1	1	1	3	3	3	3	3	3.4	3
*C**, mg/L	2	5	10	20	1.5	0	0	1.5	1.5	0.002	40
30th percentile *k*, m/yr	16	16	23	54	10.7	8.7	18.5	6.1	6.6	4.5	49
50th percentile *k*, m/yr	33	**41**	36	189	**17.3**	**14.7**	**26.5**	**9.8**	**12.6**	**10.0**	**83**
70th percentile *k*, m/yr	79	67	112	439	27.4	45.1	33.6	13.6	24.2	16.7	177
HSSF											
P	3	→ 3	3	3	6	6	8	6	6	*	6
*C**, mg/L	1	→ 5	10	15	1	0	0	1	1	*	0
30th percentile *k*, m/yr	36	24	15	21	8.8	5.2	32	4.8	4.7	*	56
50th percentile *k*, m/yr	86	→ **37**	25	66	**19.6**	**11.4**	**42**	**9.1**	**8.4**	*	**103**
70th percentile *k*, m/yr	224	44	44	114	38.0	18.8	73	14.6	14.2	*	181
VF											
P	6	→ 6	6	6	6	6	6	6	6	*	6
*C**, mg/L	0	→ 0	0	0	0	0	0	0	0	*	0
30th percentile *k*, m/yr	22	40	53	48	24.0	23.9	20.3	14.2	4.1	*	76
50th percentile *k*, m/yr	63	→ **56**	76	71	**27.2**	**52.8**	**40.8**	**33.1**	**5.2**	*	**112**
70th percentile *k*, m/yr	105	79	122	93	37.5	97.3	85.0	47.0	10.3	*	201

* = insufficient data to determine parameters.

FWS			
P	1	1	1
*C**, mg/L	2	5	10
30th percentile *k*, m/yr	16	16	23
50th percentile *k*, m/yr	33	**41**	36
70th percentile *k*, m/yr	79	67	112
HSSF			
P	3	→ 3	3
*C**, mg/L	1	→ 5	10
30th percentile *k*, m/yr	36	24	15
50th percentile *k*, m/yr	86	→ **37**	25
70th percentile *k*, m/yr	224	44	44
VF			
P	6	→ 6	6
*C**, mg/L	0	→ 0	0
30th percentile *k*, m/yr	22	40	53
50th percentile *k*, m/yr	63	→ **56**	76
70th percentile *k*, m/yr	105	79	122

BOD-removal						
emperature	10	10	15	15	°C	
Vater Depth	0,4	0,6	0,4	0,6	m^2	
Kadlec	236	236	179	179	m^2	
Reed	562	375	420	280	m^2	
PkC*	756	756	756	756	m^2	50th percentile
Q = 15 m^3/d	Porosity = 0.3					
Ci = 400 mgO2/l	Co = 25 mgO2/l					

adjustments to the nitrogen removal model for tem

- Kadlec & Wallace: Relaxed TIS Concentration Model"
  - Representation of "weathering":
    - As water containing a mixture passes through the wetlan because different fractions of the mixture are reduced at becomes "weathered";
    - Each fraction of the lumped material will, in general, pos distribution of k-values.

Aspect Ratio L/W, maximum flow rate: Darcy formula

- Increased treatment efficiencies;
- Fewer pest problems and nuisance;
- Increased accessibility for maintenance;
- Better suited for cold weather climates.

Darcy formula

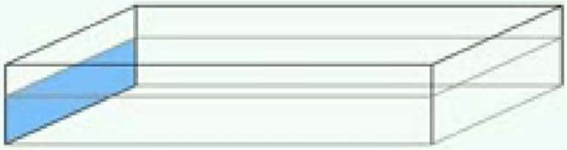
$$Q = K_S.A.s$$

- Q = Flow Rate m^3/d
- K_S = Hydraulic Conductivity
- A = Cross Sectional Area
- s = Hydraulic Gradient

Hydraulic gradient: slope of the water surface in the flow system

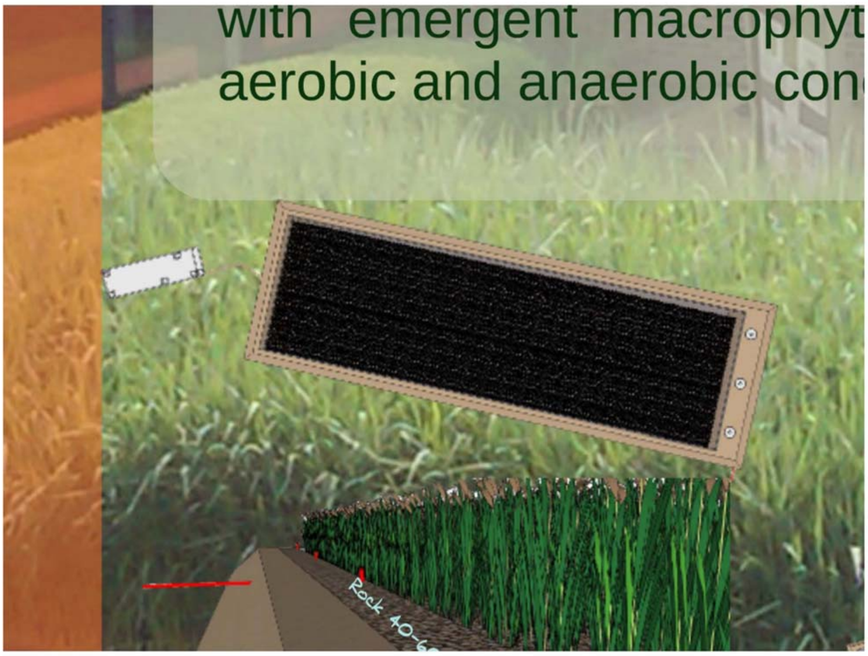
Crites, Middlebrooks, Reed «Natural Wastewater Treatment Systems», 2006

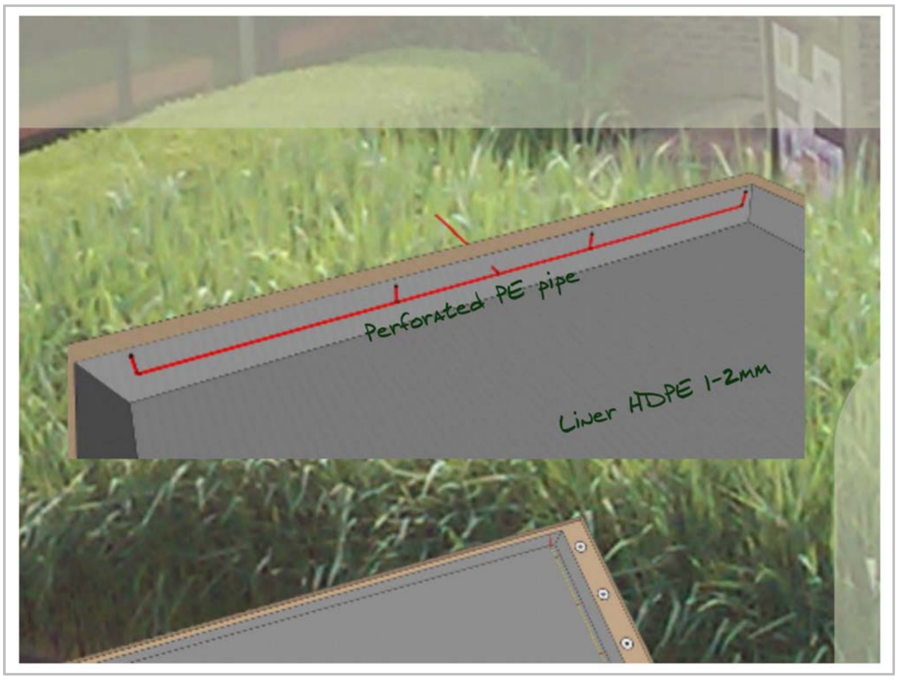
Media Type	Effective Size (D_{10}) (mm)	Porosity (n) (%)	Hydraulic Conductivity (m/d)
Coarse Sand	2	28-32	100-1000
Gravelly Sand	8	30-35	500-5000
Fine Gravel	16	35-38	1000-10000
Medium Gravel	32	36-40	10000-50000
Coarse Rock	128	38-45	50000-250000

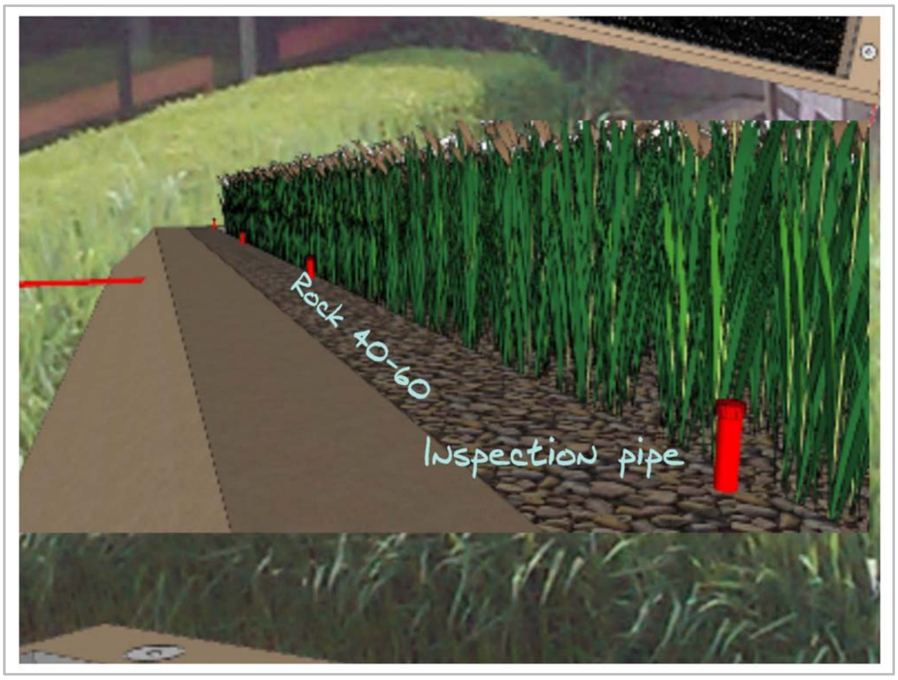


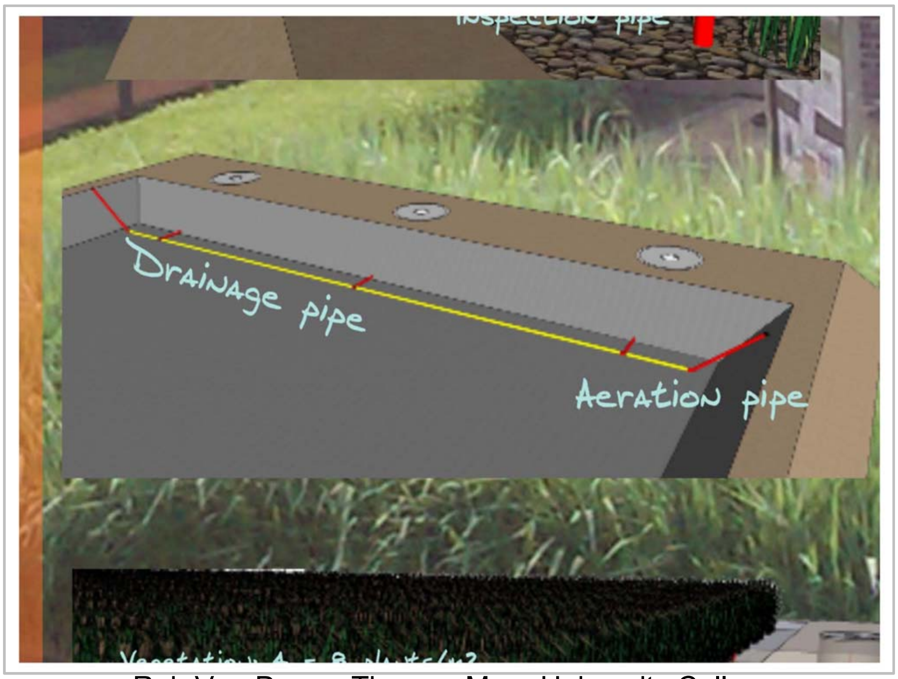
Design Flow Rate: 15 m³/d
Surface Area: 400 m²
Hydraulic Conductivity: 3500 m/d

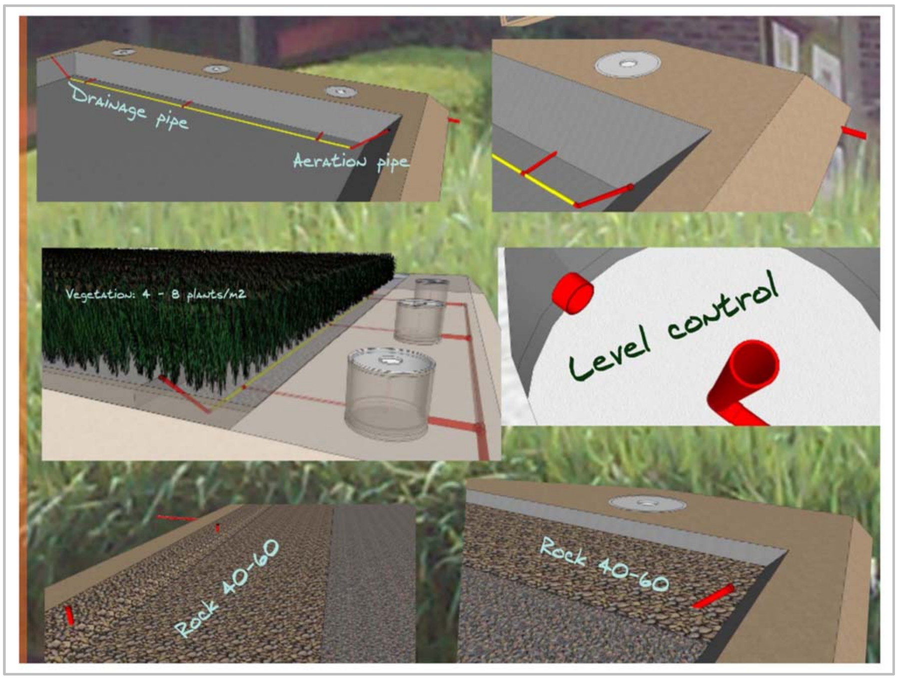
Hydraulic Gradient (m/m)	Wetted Depth (m)	Length (m)	Width (m)	L/W Ratio	Max. Flow Rate (m³/d)	Hydraulic Retention Time (d)
0.00125	0.45	40	10	4/1	19.7	3.6
0.0025	0.90	40	10	4/1	41.0	7.18
0.0025	0.40	40	10	4/1	35.0	3.20
0.0025	0.45	20	20	1/1	78.8	3.6
0.005	0.90	20	20	1/1	315	7.2
0.0011	0.45	45.8	8.73	5.3/1	15.02	3.60

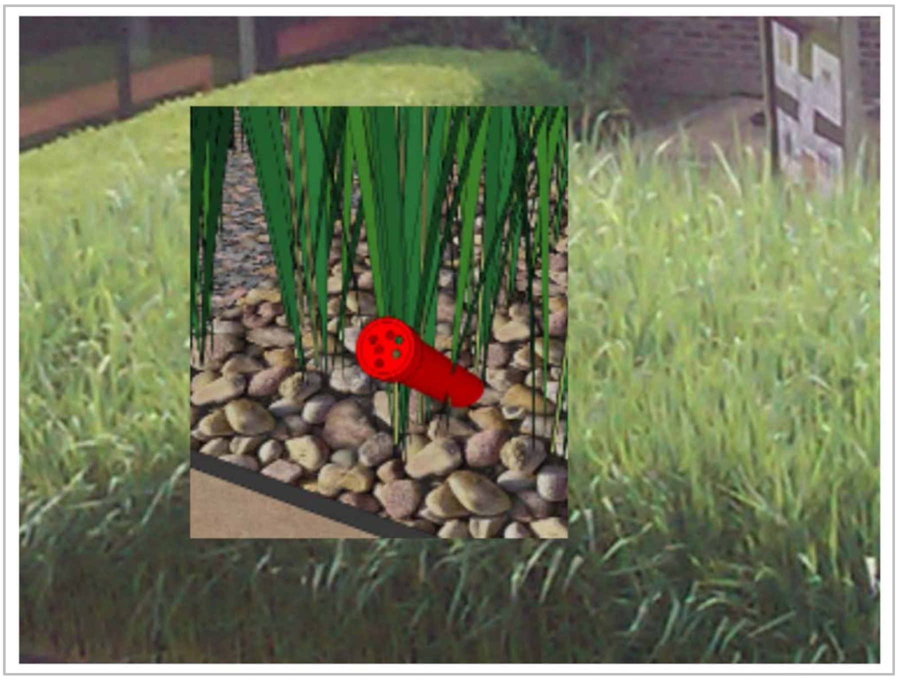



Perforated PE pipe
Liner HDPE 1-2mm


Rock 40-60
Inspection pipe

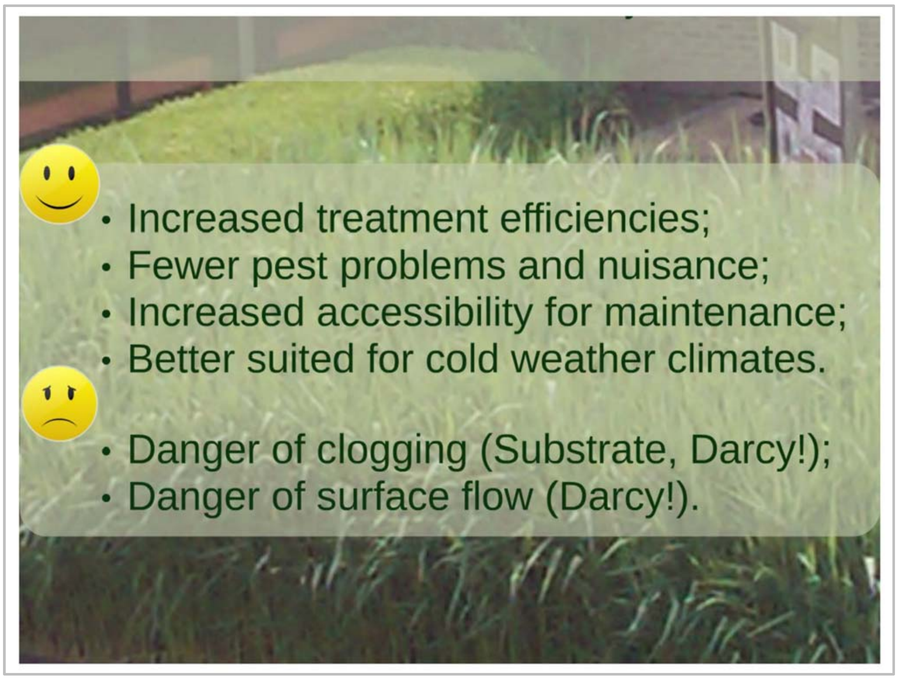

Drainage pipe
Aeration pipe

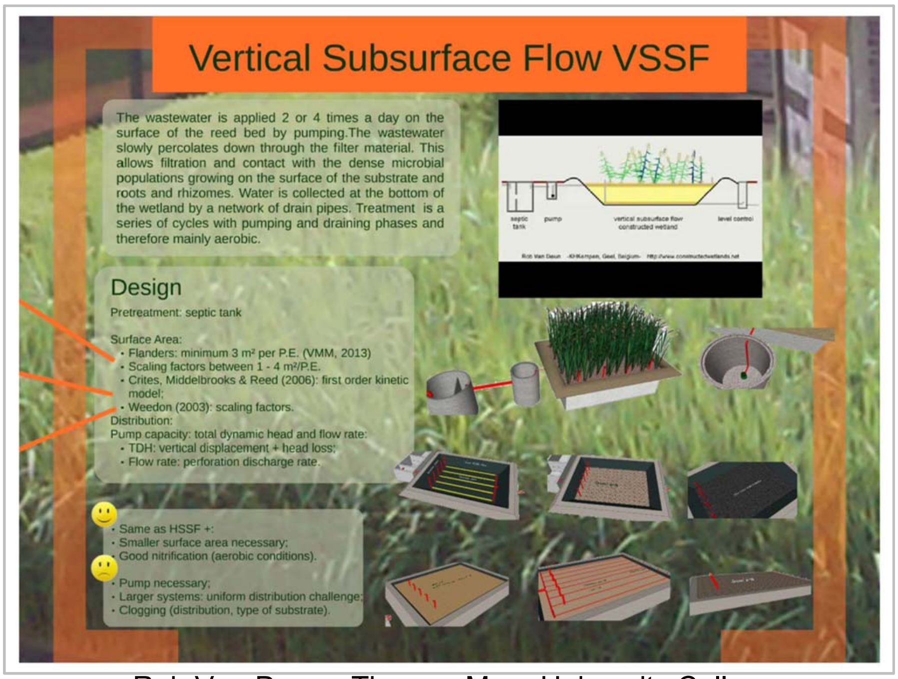

Drainage pipe
Aeration pipe
Vegetation: 4 - 8 plants/m2
Level control
Rock 40-60
Rock 40-60




Vegetation: 4 - 8 plants/m2
Level control
Rock 40-60
Rock 40-60
Gravel 2-12


Gravel 2-12

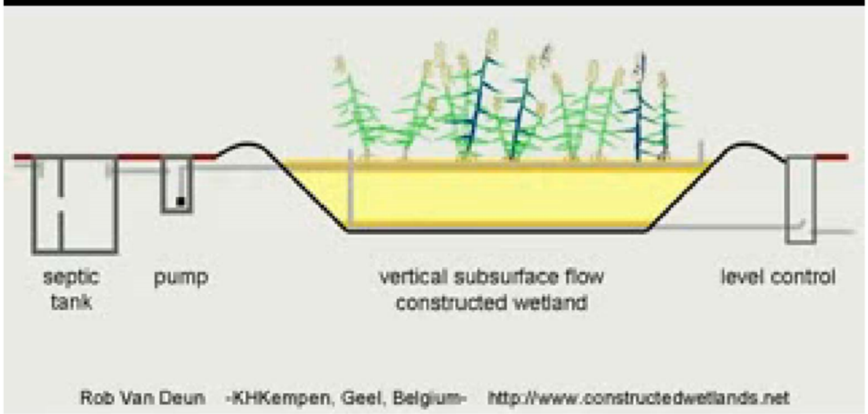

• Increased treatment efficiencies;
• Fewer pest problems and nuisance;
• Increased accessibility for maintenance;
• Better suited for cold weather climates.
• Danger of clogging (Substrate, Darcy!);
• Danger of surface flow (Darcy!).


Vertical Subsurface Flow VSSF
The wastewater is applied 2 or 4 times a day on the surface of the reed bed by pumping.The wastewater slowly percolates down through the filter material. This allows filtration and contact with the dense microbial populations growing on the surface of the substrate and roots and rhizomes. Water is collected at the bottom of the wetland by a network of drain pipes. Treatment is a series of cycles with pumping and draining phases and therefore mainly aerobic.
Design
Pretreatment: septic tank
Surface Area:
• Flanders: minimum 3 m² per P.E. (VMM, 2013)
• Scaling factors between 1 - 4 m²/P.E.
• Crites, Middelbrooks & Reed (2006): first order kinetic model;
• Weedon (2003): scaling factors.
Distribution:
Pump capacity: total dynamic head and flow rate:
• TDH: vertical displacement + head loss;
• Flow rate: perforation discharge rate.
• Same as HSSF +:
• Smaller surface area necessary;
• Good nitrification (aerobic conditions).
• Pump necessary;
• Larger systems: uniform distribution challenge;
• Clogging (distribution, type of substrate).

Vertical Subsurfa

The wastewater is applied 2 or 4 times a day on the surface of the reed bed by pumping.The wastewater slowly percolates down through the filter material. This allows filtration and contact with the dense microbial populations growing on the surface of the substrate and roots and rhizomes. Water is collected at the bottom of the wetland by a network of drain pipes. Treatment is a series of cycles with pumping and draining phases and therefore mainly aerobic.

Design



Design

Pretreatment: septic tank

Surface Area:

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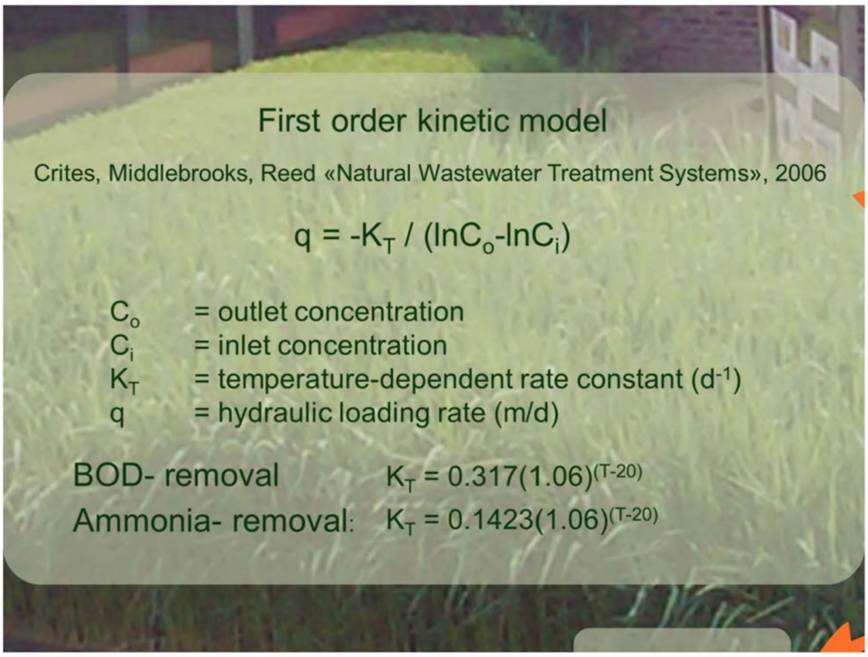
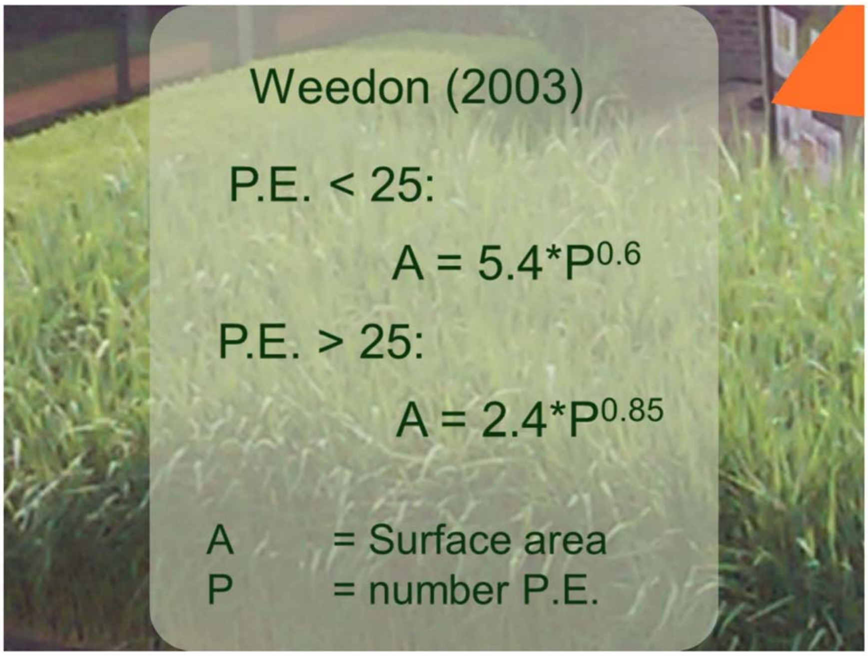
Distribution:

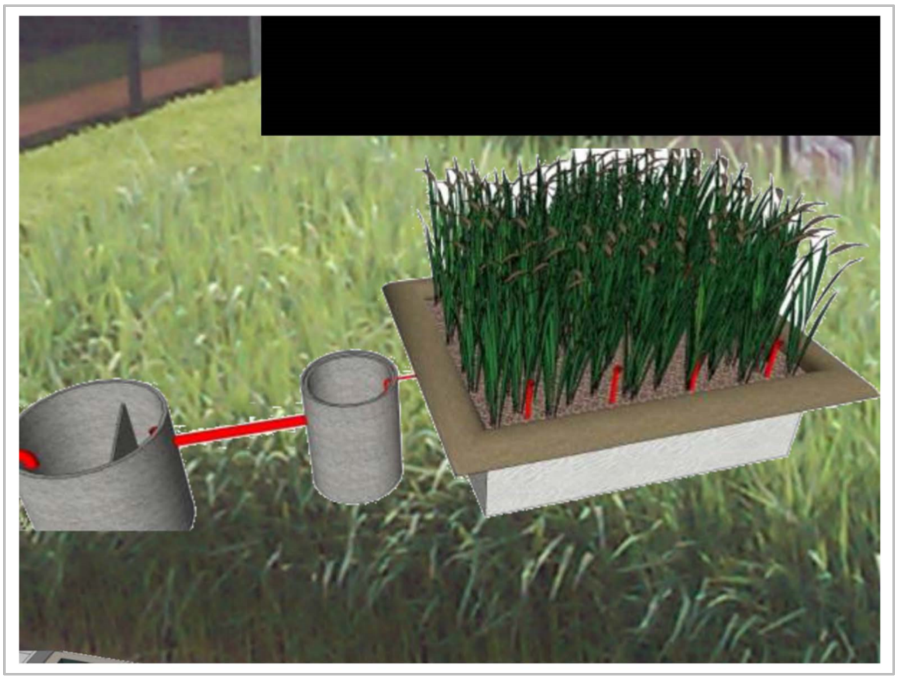
Pump capacity: total dynamic head and flow rate:

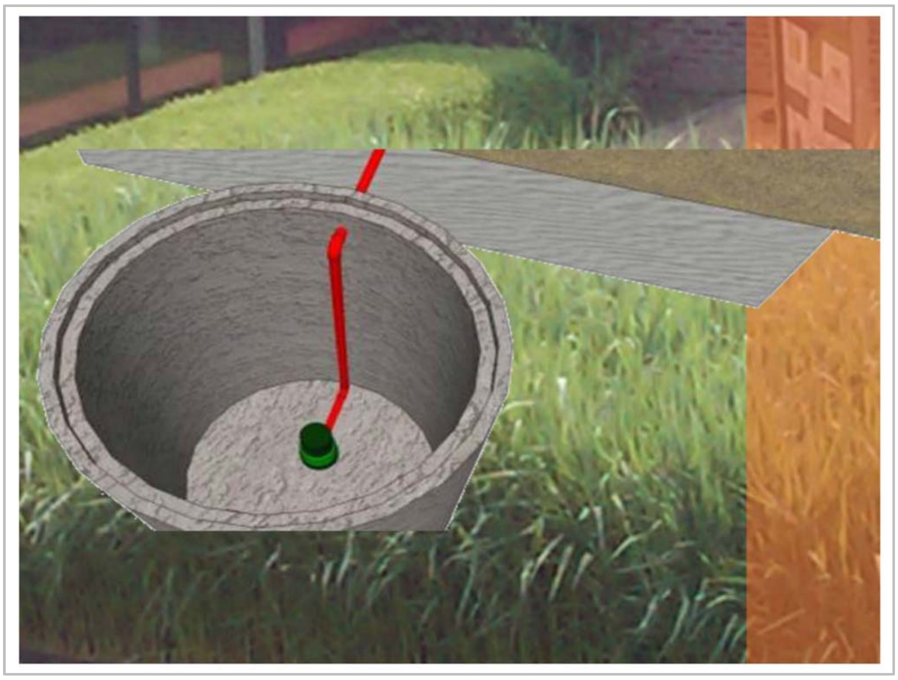
- TDH: vertical displacement + head loss;
- Flow rate: perforation discharge rate.

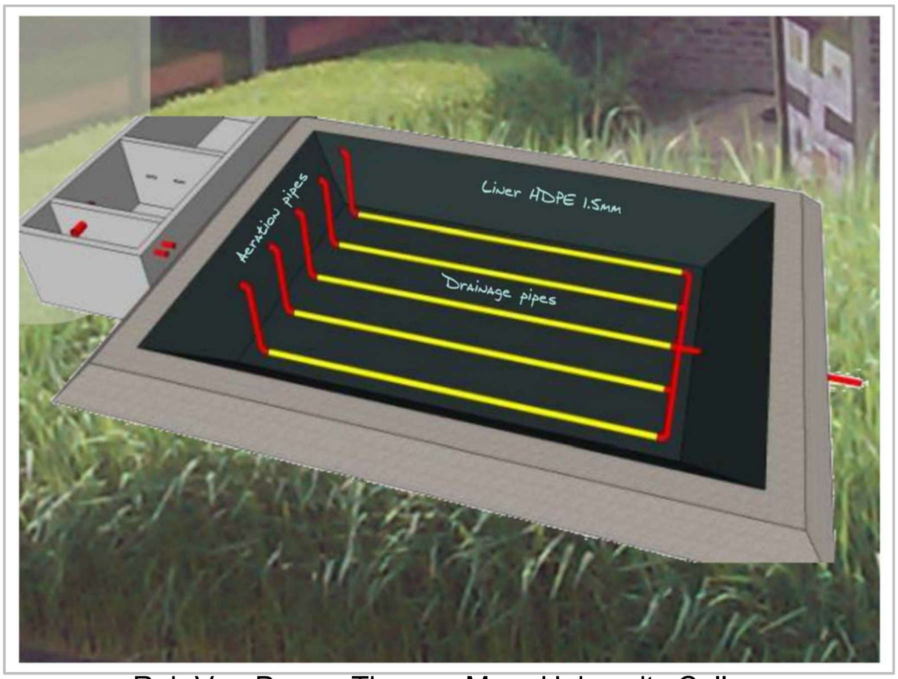
Source	Country	m²/P.E.	Comment
Cooper et al. 1996	U.K.	1	BOD only
Cooper et al. 1996	U.K.	2	BOD and NH4-N
Boutin and Liénard 2003	France	2,5	Two stages
Fehr 2003	Germany	4	
Brix and Johansen 2004	Denmark	3	95% BOD reduction
Molle 2005	France	2	1.2 in 1st stage, 0.8 in 2th stage, COD<60
ÖNORM 2005	Austria	4	
DWA 2006	Germany	4	
Langergraber et al. 2006	Austria	4	

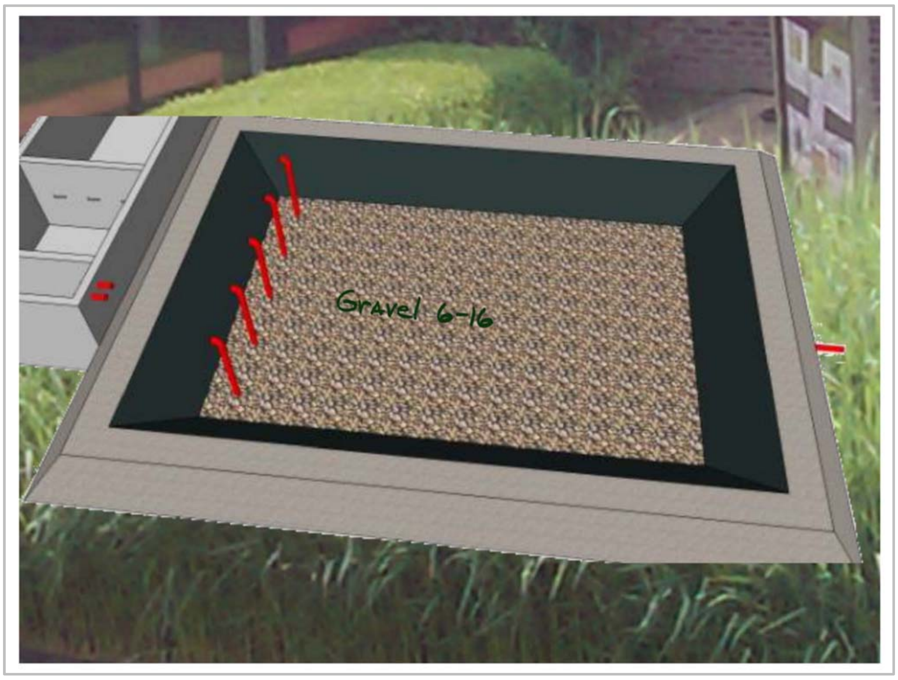


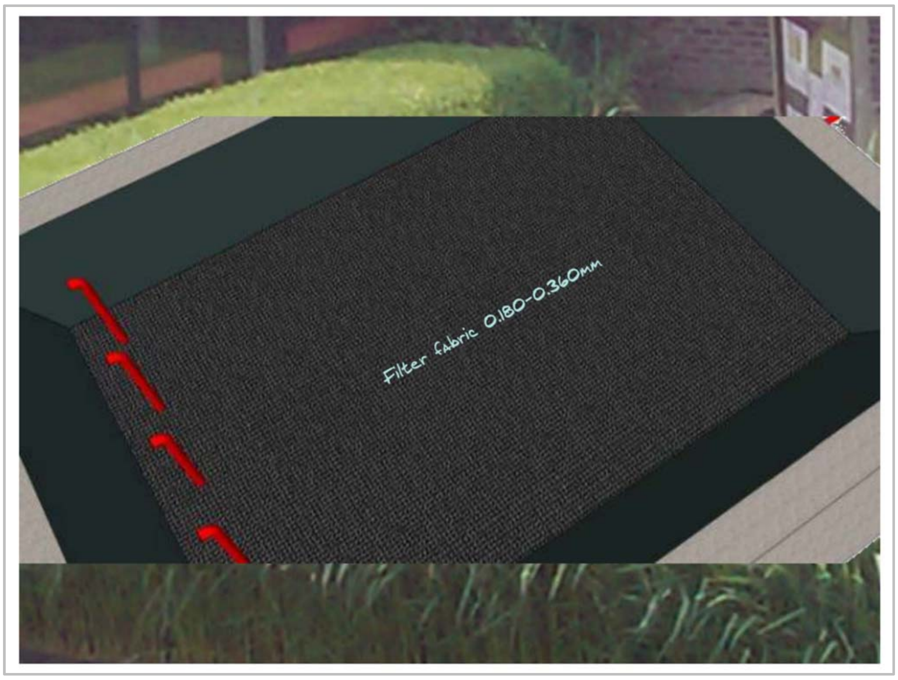


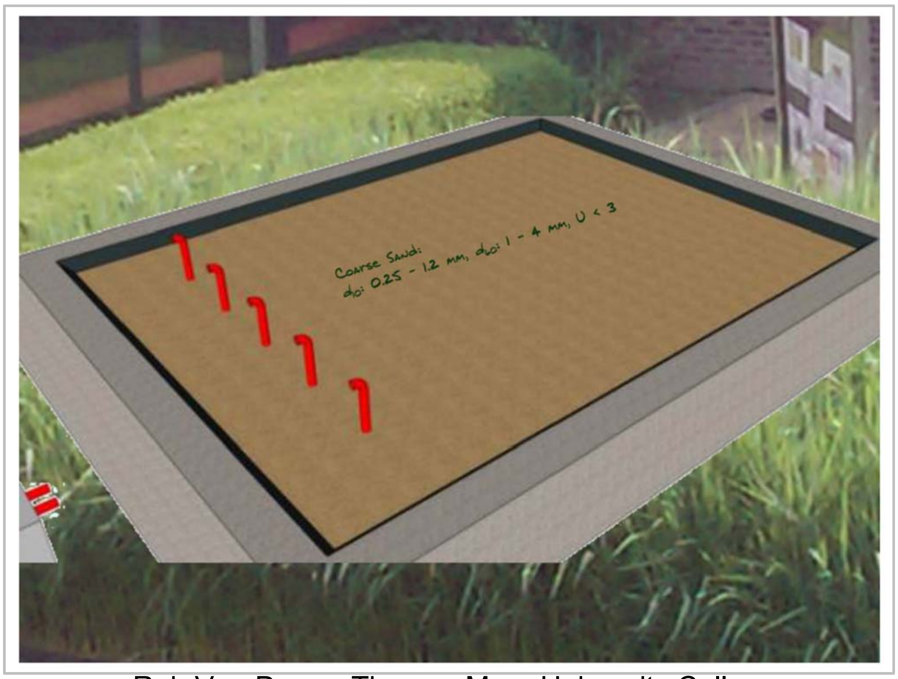


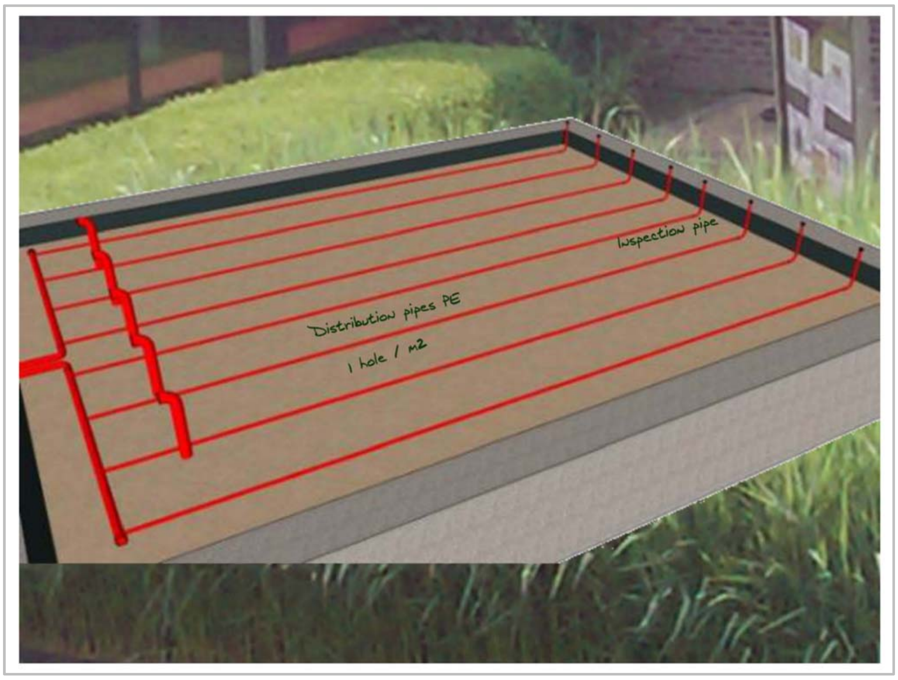


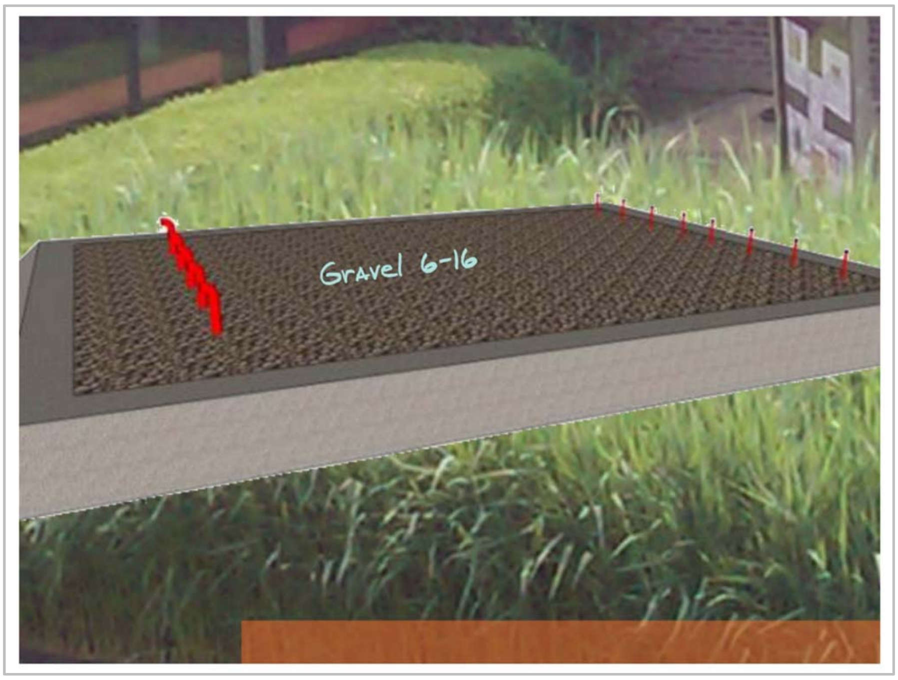

Aeration pipes
Liner HDPE 1.5mm
Drainage pipes

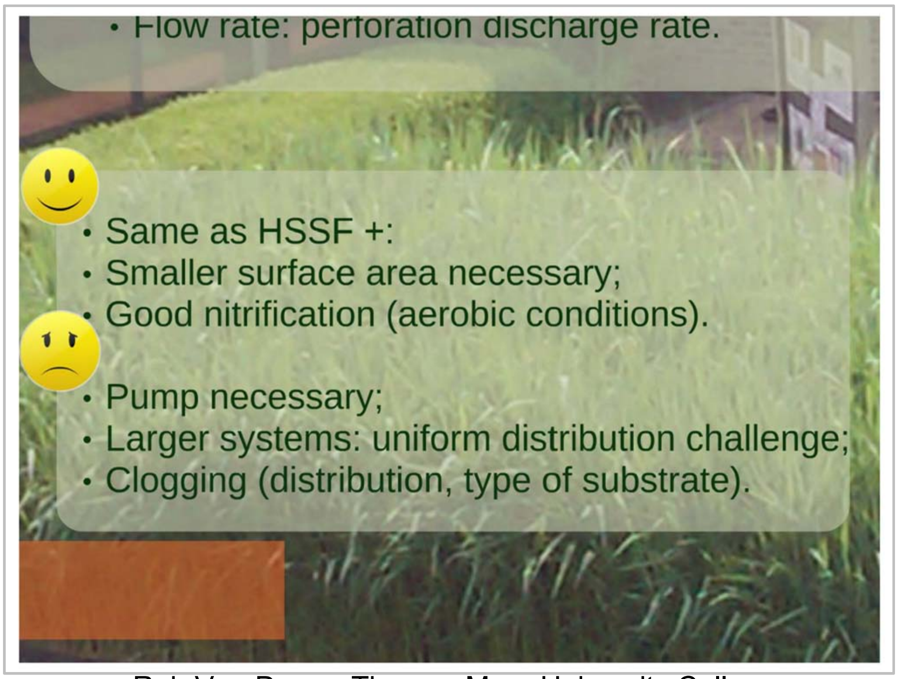

Gravel 6-16


Filter fabric 0.180-0.360mm

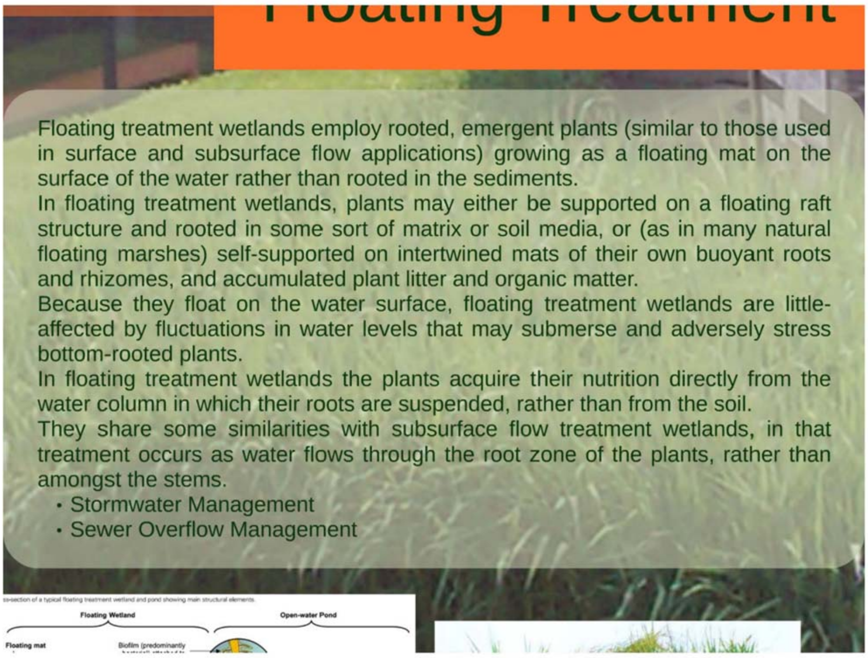

Coarse Sand:
d10: 0.25 - 1.2 mm, d60: 1 - 4 mm, U < 3

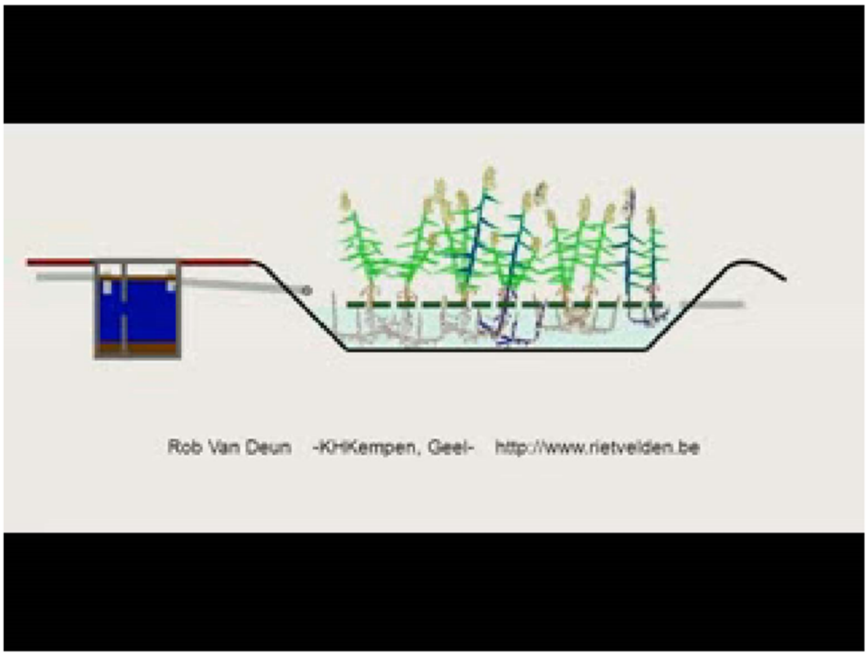

Distribution pipes PE
1 hole / m2
Inspection pipe


Gravel 6-16

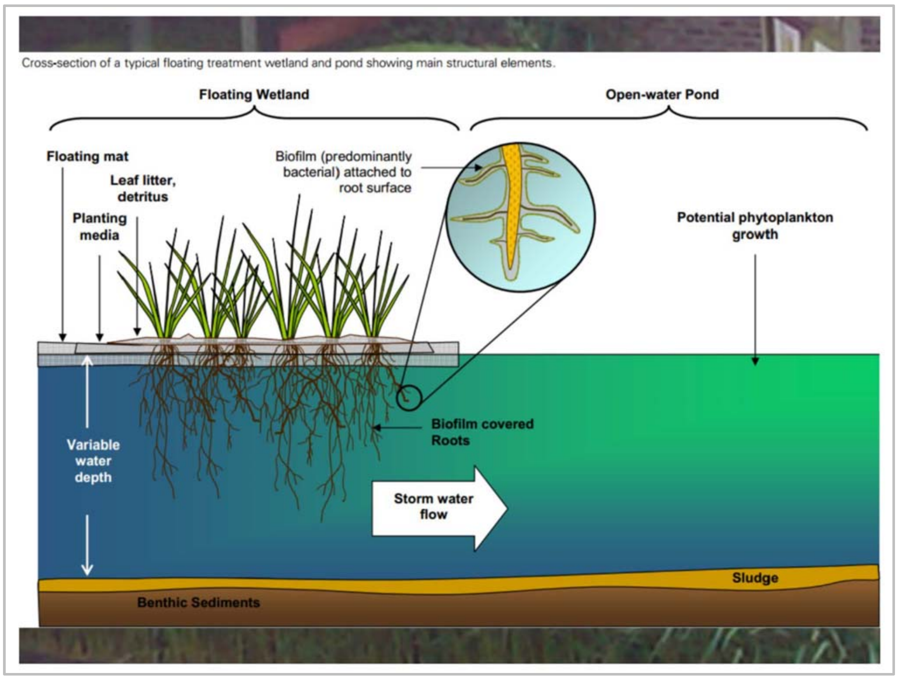

• Flow rate: perforation discharge rate.
• Same as HSSF +:
• Smaller surface area necessary;
• Good nitrification (aerobic conditions).
• Pump necessary;
• Larger systems: uniform distribution challenge;
• Clogging (distribution, type of substrate).

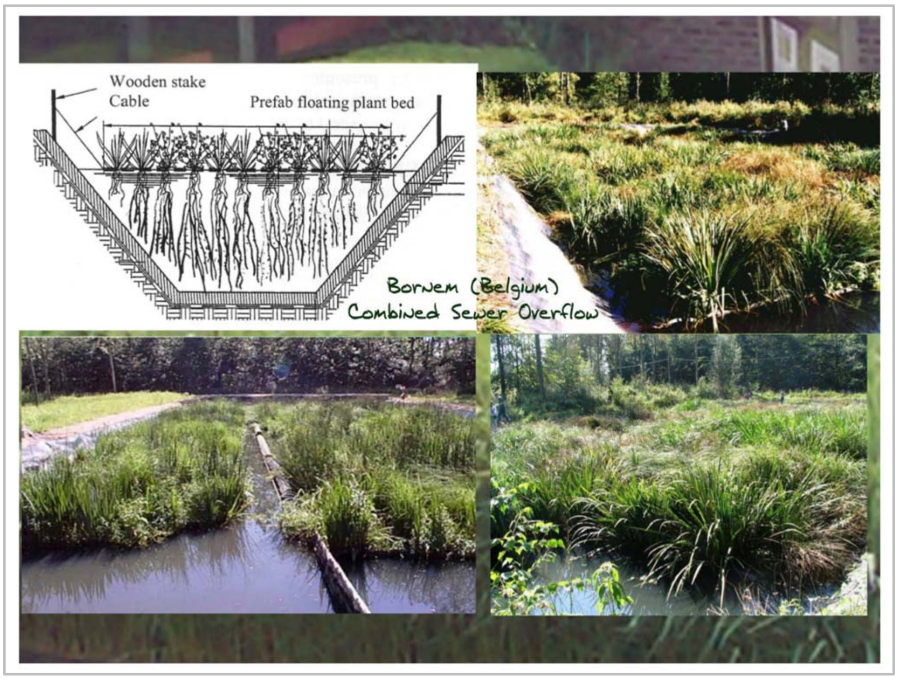

Floating Treatment Wetlands
Heathrow UK


Floating treatment wetlands employ rooted, emergent plants (similar to those used in surface and subsurface flow applications) growing as a floating mat on the surface of the water rather than rooted in the sediments.
In floating treatment wetlands, plants may either be supported on a floating raft structure and rooted in some sort of matrix or soil media, or (as in many natural floating marshes) self-supported on intertwined mats of their own buoyant roots and rhizomes, and accumulated plant litter and organic matter.
Because they float on the water surface, floating treatment wetlands are little-affected by fluctuations in water levels that may submerse and adversely stress bottom-rooted plants.
In floating treatment wetlands the plants acquire their nutrition directly from the water column in which their roots are suspended, rather than from the soil.
They share some similarities with subsurface flow treatment wetlands, in that treatment occurs as water flows through the root zone of the plants, rather than amongst the stems.
• Stormwater Management
• Sewer Overflow Management

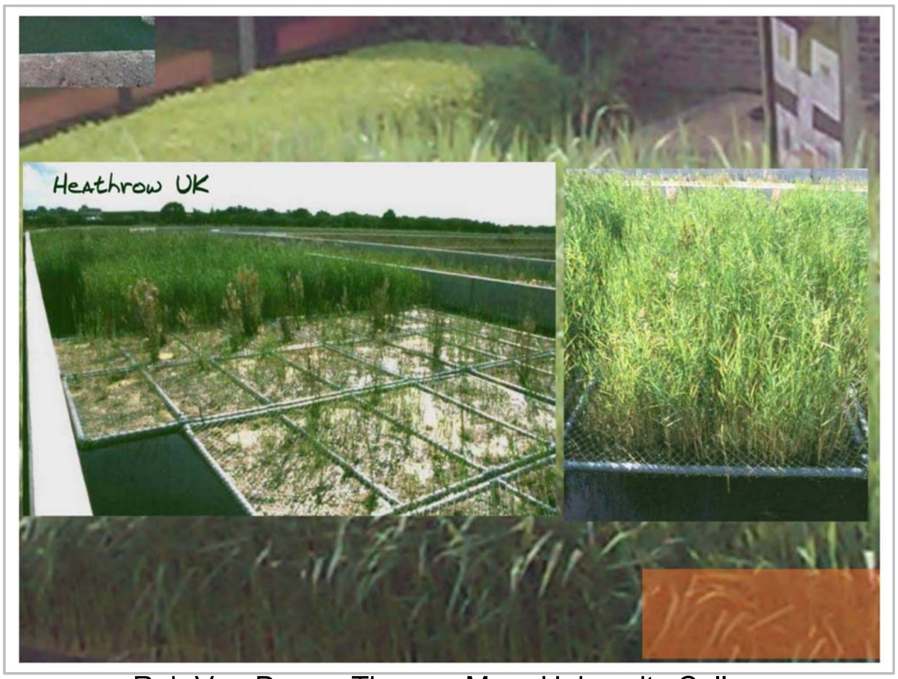

Rob Van Deun -KHKempen, Geel- http://www.rietvelden.be


Wooden stake
Cable
Prefab floating plant bed


Cross-section of a typical floating treatment wetland and pond showing main structural elements.
Floating Wetland
Open-water Pond
Floating mat
Leaf litter, detritus
Planting media
Biofilm (predominantly bacterial) attached to root surface
Potential phytoplankton growth
Variable water depth
Biofilm covered Roots
Storm water flow
Sludge
Benthic Sediments


Wooden stake
Cable
Prefab floating plant bed
Bornem (Belgium)
Combined Sewer Overflow


Heathrow


Heathrow UK


Rob Van Deun, Thomas More Kempen University College, Belgium

VLIR-UOS
Mailing address: VLIR-UOS | PO box 103 Elsene Naamsepoort | 1050 Elsene | Belgium
[e] info@vliruos.be

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Dissemination of the sustainable wastewater technology of constructed wetlands in Tanzania

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Promoter:
Thomas More University College | Kleinhoefstraat 4 | 2440 Geel | Belgium
[e] rob.van.deun@thomasmore.be

Local Partner:
University of Dar es Salaam, College of Engineering and Technology (CoET)
Waste Stabilization Ponds and Constructed Wetland Research and Development Group (WSP-CW)
University of Dar es Salaam | P.O. Box 35131 | Dar es Salaam | Tanzania
[e] knjau30@yahoo.com