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

IR 4

Design example:

Horizontal Subsurface Flow Constructed Wetland
for a
Secondary School in Tanzania

Rob Van Deun
Thomas More University College
Department Agro- and Biotechnology

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

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1 Description

- Full boarding secondary school in the Southern highland region of Tanzania;
- 600 pupils, 100 persons staff;
- Wastewater is collected and pre-treated in septic tanks;
- Design flow rate: 35 m^3 per day;
- Peak factor: 1.7, maximum flow rate 59.5 m^3/day;
- Average annual temperature: 18 °C.

2 Wastewater Characteristics

Influent Horizontal Subsurface Flow Constructed Wetland (HSSF):

Biochemical Oxygen Demand	200	mg O_2/l
Organic Nitrogen	60	mg N/l
Ammonia Nitrogen	60	mg N/l
Nitrate Nitrogen	45	mg N/l
Total Nitrogen	60	mg N/l
Total Kjeldahl Nitrogen	60	mg N/l
Total Phosphorus	15	mg P/l
Fecal Coliform	1000000	cfu/100ml

Effluent HSSF:

Biochemical Oxygen Demand	30	mg O_2/l
Organic Nitrogen	15	mg N/l
Ammonia Nitrogen	15	mg N/l
Nitrate Nitrogen	20	mg N/l
Total Nitrogen	15	mg N/l
Total Kjeldahl Nitrogen	15	mg N/l
Total Phosphorus	6	mg P/l
Fecal Coliform	10000	cfu/100ml

3 Design Approaches Horizontal Subsurface Flow Constructed Wetlands

3.1 Pre-treatment

- Bar screen;
- Septic tank:
  - Minimum Hydraulic Retention Time 24 hours;
  - Two compartments: first compartment 75% of total volume;
  - Length/Width ratio: 3/1.

3.2 First Order model according to Reed

Source: Natural Systems for Waste Management and Treatment, 2nd ed; S. Reed, R. Crites, and E. Middlebrooks; 1995; McGraw-Hill.

First order removal model, the removal rate is proportional to the pollutant concentration. The Reed model is based on volumetric loading and temperature dependent rate constants.

$$\frac{C_o}{C_i} = e^{-K_{TV} . t}$$

$$A = [\ Q\ (\ln C_i - \ln C_o)\ ]\ /\ [\ K_{TV}.d.n\ ]$$

C_O = Effluent concentration pollutant (mg/l)
C_i = Influent concentration pollutant (mg/l)
K_{TV} = Temperature dependent rate constant (1/d)
t = Hydraulic Retention Time (d days)
A = Wetland surface area (m²)
Q = Average flow rate (m³/d)
d = Mean water depth (m)
n = Wetland porosity (decimal fraction)

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

K_{20} = First order rate constant at 20°C (1/d)
θ = Temperature coefficient for rate constant
T = Temperature (°C)

Process	K_{20}	θ
BOD removal	1.104	1.06
NH_4^+ removal (nitrification)	K_{NH}	1.048
NO_3^- removal (denitrification)	1.000	1.15

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

K_{NH} = Nitrification rate constant at 20°C (1/d)
rz = Fraction of HSSF bed depth occupied by root zone (decimal fraction, 0 to 1)

3.3 First Order kC* model according to Kadlec & Knight

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

First order removal model, the removal rate is proportional to the pollutant concentration. The Kadlec model is based on areal loading and temperature dependent rate constants.

$$\ln [(C_0 - C^*)/(C_i - C^*)] = - K_{TA} / q \qquad q = Q / A$$

$$A = Q \ln [(C_i - C^*) / (C_0 - C^*)] / K_{TA}$$

C_O = Effluent concentration pollutant (mg/l)
C_i = Influent concentration pollutant (mg/l)
C^* = Background concentration pollutant (mg/l)
K_{TA} = Temperature dependent rate constant (1/d)
q = Hydraulic loading Rate (m/d)
A = Wetland surface area (m^2)
Q = Average flow rate (m^3/d)

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

K_{20} = First order rate constant at 20°C (1/d)
θ = Temperature coefficient for rate constant
T = Temperature (°C)

Process	K_{20} (m/d)	θ	C^* (mg/l)
BOD	0.3205	1.057	3.0
TSS	0.1186	1.00	6.0
Org-N	0.0959	1.05	1.5
NH_4^+-N	0.0932	1.05	0
NO_x-N	0.1370	1.05	0
Tot-N	0.0274	1.05	1.5
Tot-P	0.0249	1.097	0
Fecal Coliform	0.2740	1.003	200 (cfu/100ml)

3.4 PkC* model according to Kadlec & Wallace

Source: Treatment Wetlands; R. Kadlec & S. Wallace; 2009; CRC Press.
Comparison of free water and horizontal subsurface treatment wetlands; R. Kadlec; 2009; Ecological Engineering 35 159-174.

Representation of "weathering", relaxed TIS concentration model or PkC* model. 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. This results in a distribution of K-values.

$$\frac{C_o - C^*}{C_i - C^*} = \frac{1}{(1+(k/Pq))^P}$$

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)

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)
q = Hydraulic loading rate (m/y) = Q/A
A = Wetland area (square meters (m^2)
Q = Annual flow rate (m^3/yr)

Process	P	C^* (mg/l)	k (m/yr, 50^{th} percentile)
BOD (Super C_i>200mg/l)	3	15	66
BOD (primary 100<C_i<200mg/l)	3	10	25
BOD (secondary 30<C_i<100mg/l)	3	5	37
BOD (tertiary 0<C_i<30mg/l)	3	1	86
Org-N (ammonification)	6	1	19.6
NH_4^+-N (nitrification)	6	0	11.4
NO_x-N (denitrification)	8	0	42
TKN	6	1	9.1
Total-N	6	1	8.4
Total-P	6	0	6
Fecal Coliform	6	0	103

3.5 First Order model according to Njau (Tropical conditions)

Source: Effect of diffusional mass transfer on the performance of horizontal subsurface flow constructed wetlands in tropical climate conditions; K. Njau, L. Gastory, B. Eshton, J. H. Katima, R. Minja, R. Kimwaga, M. Shaaban; 2011; Water Science and Technology 63.12

First order removal model, the removal rate is proportional to the pollutant concentration. The Njau model is based on volumetric loading and rate constants dependent on mass transfer (velocity).

$$\frac{C_o}{C_i} = e^{-K_m \cdot t}$$

$$A = [\ Q\ (\ln C_i - \ln C_o)\ ]\ /\ [\ K_m . d . n\ ]$$

C_O = Eflluent concentration pollutant (mg/l)
C_i = Influent concentration pollutant (mg/l)
K_m = Mass transfer dependent rate constant (1/d)
t = Hydraulic Retention Time (d days)
A = Wetland surface area (m^2)
Q = Average flow rate (m^3/d)
d = Mean water depth (m)
n = Wetland porosity (decimal fraction)
K_m = Mass transfer dependent rate constant (1/d)

$K_m = c.\ u^{\beta}$ $\quad u = Q / (W.d.n)$

c, β = Constants
u = velocity (m/d)
Q = Average flow rate (m^3/d)
d = Mean water depth (m)
n = Wetland porosity (decimal fraction)
W = Width (m)

Process	c	β	
BOD	0.123	0.87	
NH_4^+-N	0.004	1.00	for u < 2.4 m/d
	0.051	0.81	for u > 2.4 m/d
NO_3^--N	0.017	1.20	
TKN	0.048	0.94	

3.6 Hydraulic Design – Darcy Formula

For a given geometry and substrate of the constructed wetland, the Darcy formula should be used to calculate the maximum flow rate to prevent overland flow.

$$Q = K_S \,.\, A_c \,.\, s \qquad A_c = W \,.\, d \qquad s = \Delta H / L$$

Q = (maximum) Flow Rate (m³/d)
K_S = Hydraulic Conductivity (m/d)
A_c = Cross Sectional Area (m²)
s = Hydraulic Gradient (m/m)
W = Width (m)
L = Length (m)
A = Wetland surface area (m²)
d = Mean water depth (m)
ΔH = Head differential

4 Design Horizontal Subsurface Flow Constructed Wetland

4.1 Design HSSF using design model acc. Njau

Since the first order rate constant is dependent on the velocity of the wastewater in the system, a long, narrow wetland will guarantee the best result. But to avoid overland flow the wetland should be designed with a minimum width or maximum length based on the Darcy formula.

Rearranging and combining the formulas for surface area, velocity and rate constant according to Njau and the Darcy formula, results in a formula to calculate the maximum length.

$$L = \left[8.13 \times (\ln C_i - \ln C_O) \times (K_s \times \Delta H / n)^{0.13}\right]^{(1/1.13)}$$

This maximum length should be taken into account when determining the necessary surface area following the Njau model.

4.2 Design example BOD removal

4.2.1 Results

	Reed	Kadlec kC*	Kadlec PkC*	Njau	
C_i	200	200	200	200	mg/l
C_O	30	30	30	30	mg/l
Q	35	35	35	35	m³/d
Peak Q	59.5	59.5	59.5	59.5	m³/d
T	18	18	18	18	°C
d	0.5	0.54	0.54	0.5	m
n	0.35	0.35	0.35	0.35	

K_S	3000	3000	3000	3000	m/d
ΔH	0.1	0.06	0.06	0.1	m
C*	NA	3.0	15.0	NA	mg/l
P	NA	NA	3	NA	
K_T or K_m or k	0.983	0.287	66	1.7919	d^{-1} or y^{-1}
A	**386.2**	**242.4**	**760.9**	**211.6**	**m²**
W	**12.5**	**12.4**	**21.7**	**9.2**	**m**
L	**31.0**	**19.5**	**35**	**23.0**	**m**
Max. Flow Rate	**60.3**	**62.0**	**60.4**	**60.0**	**m³/d**

4.2.2 Construction data – Comparison between models

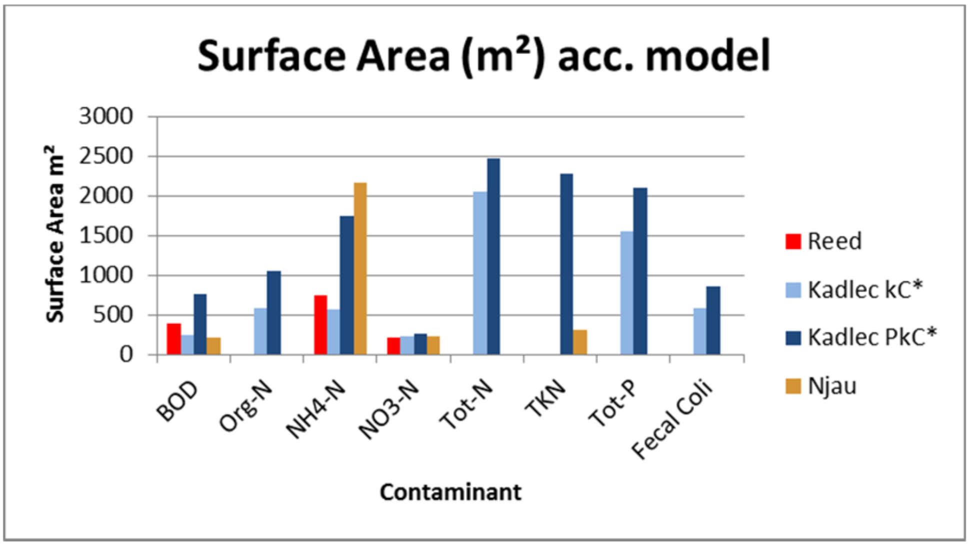
	Unit	Reed	kC* Kadlec	PkC* Kadlec	Njau
Surface Area	m²	386,2	242,4	760,9	211,7
Height Gravel Inlet	m	0,6	0,6	0,6	0,6
Height Gravel Outlet	m	0,6	0,6	0,6	0,6
Height Distribution Pipe	m	0,6	0,6	0,6	0,6
Height Outlet	m	0,5	0,54	0,54	0,5
Wetted Depth (mean)	m	0,50	0,54	0,54	0,50
Length	m	31	19,5	35	23,0
Width	m	12,5	12,433	21,741	9,2
Hydraulic Retention Time	d	1,93	1,31	4,11	1,06
Flow Rate (max.)	m³/d	60,3	62,0	60,4	60,0
Liner Surface Area	m²	510,8	335,9	921,4	306,0
Length Liner	m	33,7	22,2	37,7	25,7
Width Liner	m	15,2	15,1	24,4	11,9
Geotextile	m²	463	300	860	269
Length Inlet Zone (Rock)	m	2	2	2	2
Length Outlet Zone (Rock)	m	1,5	1,5	1,5	1,5
(Total) Rock (density 1.7)	tonnes	43	43	77	32
(if) Gravel (dry, density 1.6)	tonnes	331	193	659	173
Vegetation	#	2317	1455	4566	1270

5 Comparison of performances according to the different models

5.1 Calculated surface area for different contaminants

The calculations are based on the influent and effluent characteristics proposed in chapter 2: Wastewater Characteristics.

Surface Area m^2	BOD	Org-N	NH4-N	NO3-N	Tot-N	TKN	Tot-P	Fecal Coli
Reed	386	NA	741	214	NA	NA	NA	NA
Kadlec kC*	242	590	574	228	2065	NA	1550	594
Kadlec PkC*	761	1060	1748	260	2472	2282	2108	859
Njau	212	NA	2171	237	NA	320	NA	NA



5.2 Characteristics of the HSSF

The characteristics of the HSSF listed in this table were used to forecast the treatment results according to the different first order models. The results were calculated for different flow rates.

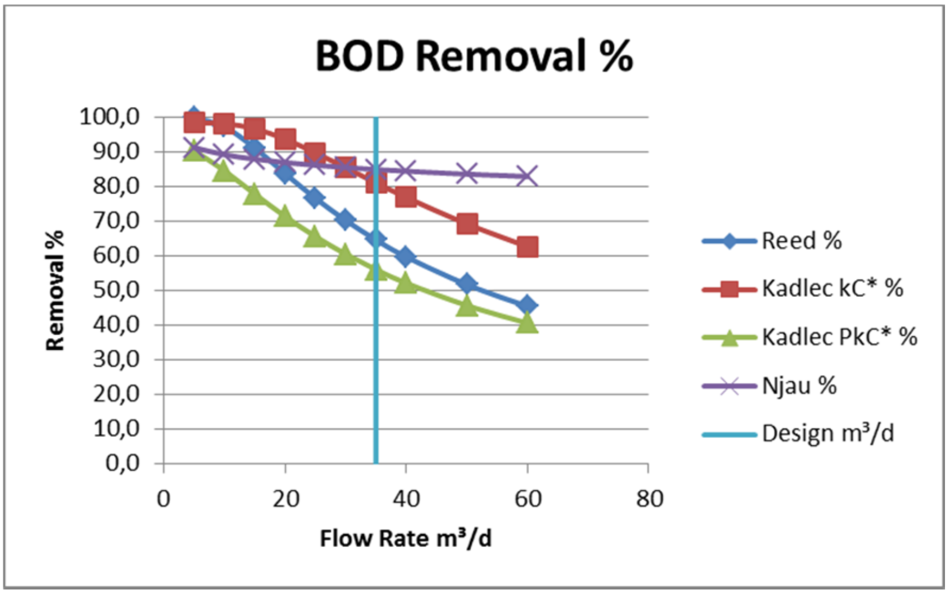
Design Q	35	m^3/d						
A	212	m^2	W	9,2	m	L	23,0	m
d	0,5	m	A_c	4,6	m^3	rz	1	
ΔH	0,1	m	s	0,00434	m/m			
n	0,35		K_S	3000	m/d			
T	18	°C						

5.3 Comparison theoretical performances HSSF according different models

5.3.1 BOD removal

Flow Rate m³/d	HRT days	BOD IN	**BOD OUT Njau**	**BOD OUT Reed**	**BOD OUT Kadlec kC***	**BOD OUT Kadlec PkC***
5	7,42	200	**17**	**0**	**3**	**19**
10	3,71	200	**21**	**4**	**3**	**31**
15	2,47	200	**24**	**15**	**6**	**44**
20	1,86	200	**26**	**29**	**11**	**57**
25	1,48	200	**27**	**43**	**18**	**69**
30	1,24	200	**29**	**56**	**26**	**79**
35	1,06	200	**30**	**67**	**35**	**88**
40	0,93	200	**31**	**77**	**43**	**96**
50	0,74	200	**33**	**93**	**58**	**108**
60	0,62	200	**34**	**105**	**71**	**119**

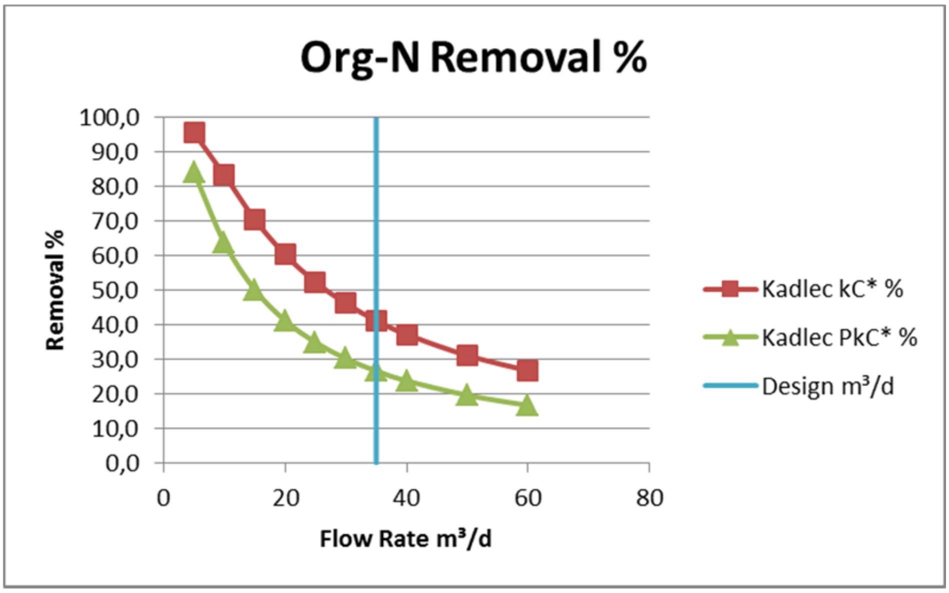
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %	100,0	97,9	92,3	85,4	78,5	72,2	66,6	61,7	53,6	47,3
Kadlec kC* %	98,5	98,3	97,1	94,5	90,9	86,8	82,6	78,6	71,1	64,6
Kadlec PkC* %	90,4	84,7	77,9	71,5	65,7	60,6	56,1	52,2	45,8	40,7
Njau %	91,3	89,3	88,0	87,0	86,3	85,6	85,0	84,5	83,7	83,0



5.3.2 Organic Nitrogen Removal - Ammonification

Flow Rate m³/d	HRT days	Org-N IN	**Org-N OUT Kadlec kC***	**Org-N OUT Kadlec PkC***
5	7,42	60	**3**	**10**
10	3,71	60	**10**	**22**
15	2,47	60	**18**	**30**
20	1,86	60	**24**	**35**
25	1,48	60	**29**	**39**
30	1,24	60	**32**	**42**
35	1,06	60	**35**	**44**
40	0,93	60	**38**	**46**
50	0,74	60	**41**	**48**
60	0,62	60	**44**	**50**

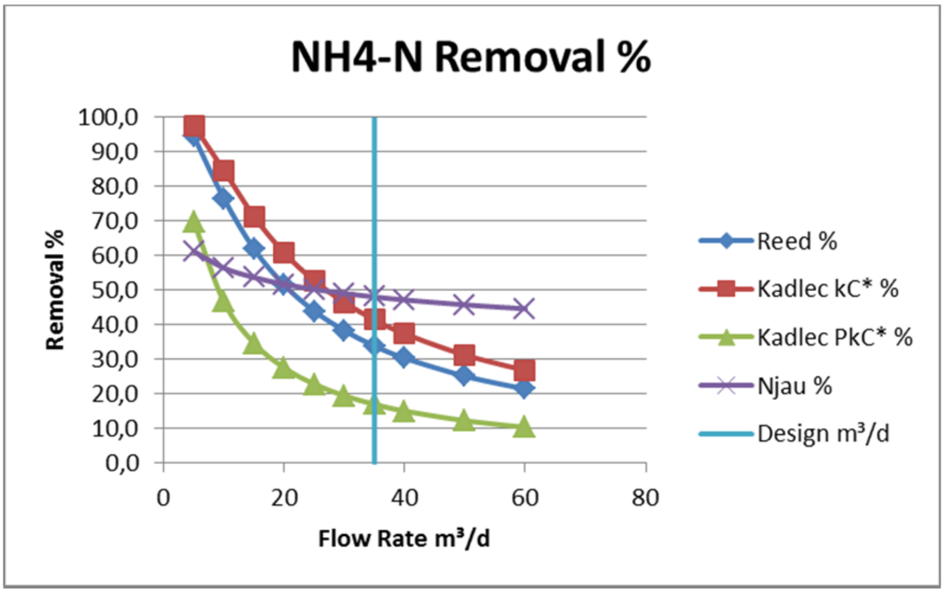
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %										
Kadlec kC* %	95,4	83,3	70,5	60,3	52,4	46,2	41,3	37,3	31,2	26,8
Kadlec PkC* %	84,1	63,7	50,2	41,2	34,9	30,3	26,7	23,9	19,7	16,8
Njau %										



5.3.3 Ammonia Nitrogen Removal – Nitrification

Flow Rate m³/d	HRT days	NH4-N IN	**NH4-N OUT Njau**	**NH4-N OUT Reed**	**NH4-N OUT Kadlec kC***	**NH4-N OUT Kadlec PkC***
5	7,42	60	**23**	**3**	**1**	**18**
10	3,71	60	**26**	**14**	**9**	**32**
15	2,47	60	**28**	**23**	**17**	**39**
20	1,86	60	**29**	**29**	**24**	**43**
25	1,48	60	**30**	**34**	**28**	**46**
30	1,24	60	**31**	**37**	**32**	**48**
35	1,06	60	**31**	**40**	**35**	**50**
40	0,93	60	**32**	**42**	**38**	**51**
50	0,74	60	**33**	**45**	**41**	**53**
60	0,62	60	**33**	**47**	**44**	**54**

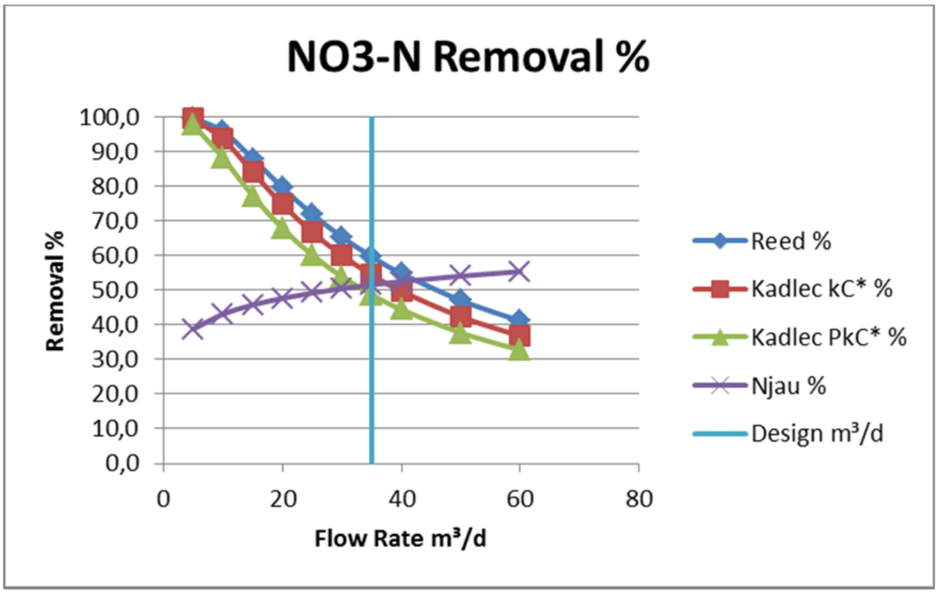
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %	94,5	76,5	61,9	51,5	43,9	38,3	33,9	30,4	25,1	21,4
Kadlec kC* %	97,6	84,6	71,3	60,8	52,7	46,4	41,4	37,4	31,2	26,8
Kadlec PkC* %	69,8	46,6	34,7	27,5	22,8	19,5	17,0	15,1	12,3	10,4
Njau %	61,2	56,4	53,7	51,7	50,2	49,0	48,0	47,2	45,8	44,6



5.3.4 NO_x Nitrogen Removal – Denitrification

Flow Rate m³/d	HRT days	NO_x-N IN	NO_x-N OUT Njau	NO_x-N OUT Reed	NO_x-N OUT Kadlec kC*	NO_x-N OUT Kadlec PkC*
5	7,42	45	**28**	**0**	**0**	**1**
10	3,71	45	**26**	**2**	**3**	**5**
15	2,47	45	**24**	**5**	**7**	**10**
20	1,86	45	**24**	**9**	**11**	**14**
25	1,48	45	**23**	**13**	**15**	**18**
30	1,24	45	**22**	**16**	**18**	**21**
35	1,06	45	**22**	**18**	**20**	**23**
40	0,93	45	**21**	**20**	**23**	**25**
50	0,74	45	**21**	**24**	**26**	**28**
60	0,62	45	**20**	**26**	**28**	**30**

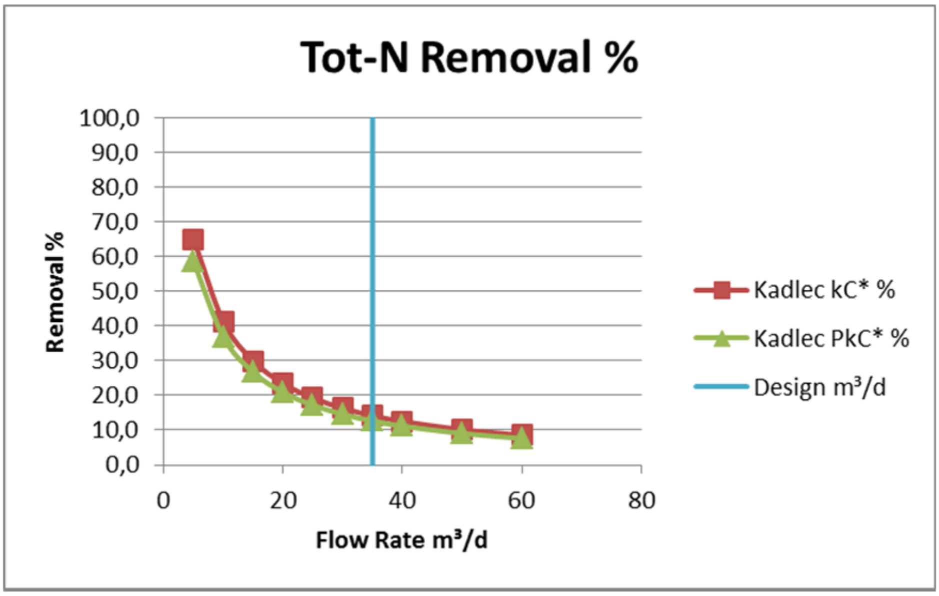
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %	99,8	95,8	88,0	79,6	72,0	65,4	59,7	54,9	47,1	41,2
Kadlec kC* %	99,6	93,6	84,0	74,7	66,7	60,1	54,5	49,7	42,3	36,8
Kadlec PkC* %	97,8	88,1	77,2	67,9	60,2	53,9	48,7	44,4	37,7	32,7
Njau %	38,8	43,1	45,8	47,7	49,2	50,5	51,6	52,5	54,1	55,4



5.3.5 Total Nitrogen Removal

Flow Rate m³/d	HRT days	Total-N IN	**Total OUT Kadlec kC***	**Total OUT Kadlec PkC***
5	7,42	60	**21**	**25**
10	3,71	60	**35**	**38**
15	2,47	60	**42**	**44**
20	1,86	60	**46**	**47**
25	1,48	60	**48**	**50**
30	1,24	60	**50**	**51**
35	1,06	60	**51**	**52**
40	0,93	60	**52**	**53**
50	0,74	60	**54**	**55**
60	0,62	60	**55**	**55**

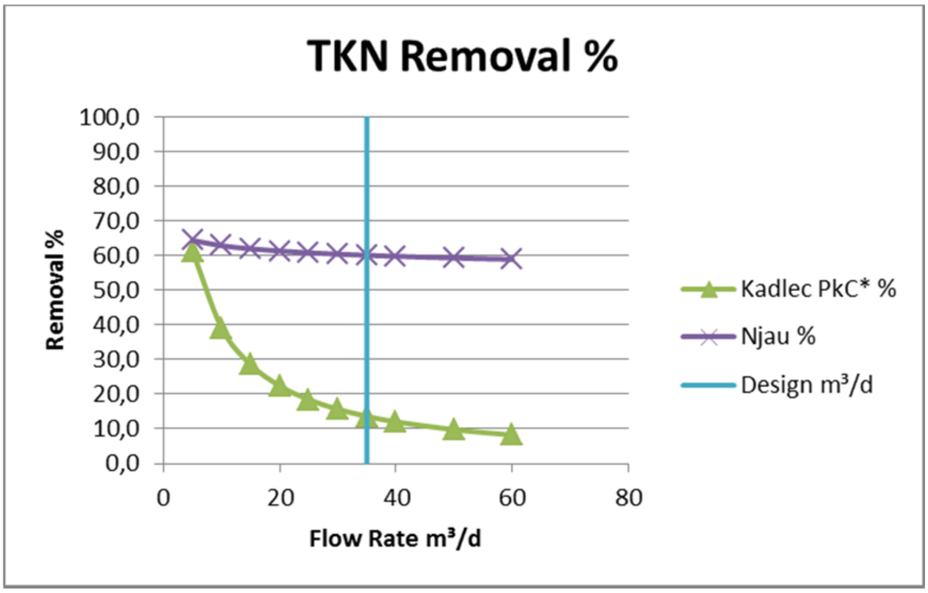
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %										
Kadlec kC* %	65,1	41,3	30,0	23,5	19,3	16,3	14,2	12,5	10,2	8,5
Kadlec PkC* %	58,5	36,8	26,7	20,9	17,2	14,6	12,7	11,2	9,1	7,6
Njau %										



5.3.6 Total Kjeldahl Nitrogen Removal

Flow Rate m³/d	HRT days	TKN IN	**TKN OUT Njau**	**TKN OUT Kadlec PkC***
5	7,42	60	**21**	**23**
10	3,71	60	**22**	**37**
15	2,47	60	**23**	**43**
20	1,86	60	**23**	**47**
25	1,48	60	**23**	**49**
30	1,24	60	**24**	**51**
35	1,06	60	**24**	**52**
40	0,93	60	**24**	**53**
50	0,74	60	**24**	**54**
60	0,62	60	**25**	**55**

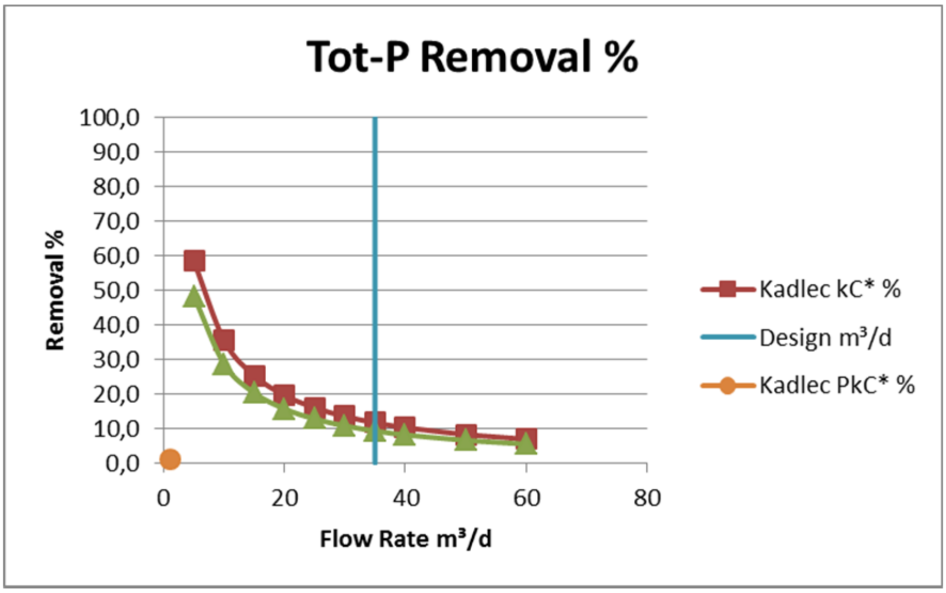
Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %										
Kadlec kC* %										
Kadlec PkC* %	61,2	39,1	28,5	22,4	18,4	15,7	13,6	12,0	9,8	8,2
Njau %	64,4	62,9	62,0	61,4	60,9	60,5	60,1	59,8	59,3	58,9



5.3.7 Total Phosphorus Removal

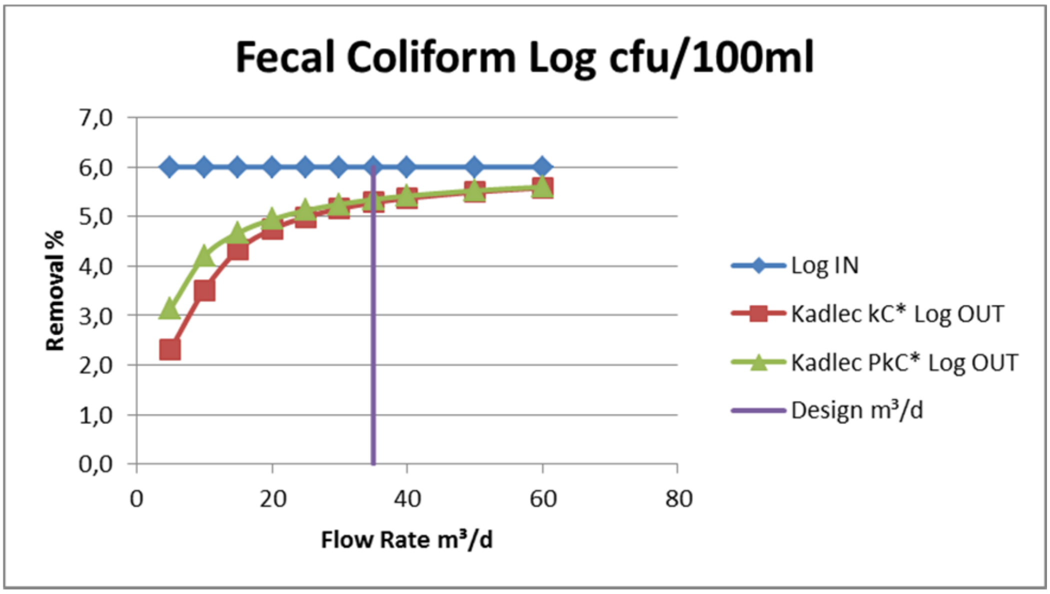
Flow Rate m³/d	HRT days	Total-P IN	**Total-P OUT Kadlec kC***	**Total-P OUT Kadlec PkC***
5	7,42	15	**6**	**8**
10	3,71	15	**9**	**11**
15	2,47	15	**11**	**12**
20	1,86	15	**12**	**13**
25	1,48	15	**12**	**13**
30	1,24	15	**13**	**13**
35	1,06	15	**13**	**14**
40	0,93	15	**13**	**14**
50	0,74	15	**14**	**14**
60	0,62	15	**14**	**14**

Flow Rate m³/d	5	10	15	20	25	30	35	40	50	60
Reed %										
Kadlec kC* %	61,5	37,9	27,2	21,2	17,4	14,7	12,7	11,2	9,1	7,6
Kadlec PkC* %	48,3	28,7	20,4	15,8	12,9	10,9	9,4	8,3	6,7	5,6
Njau %										



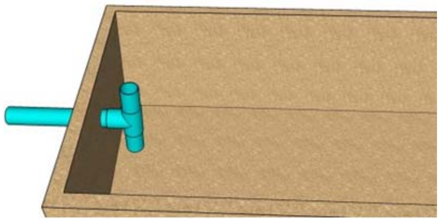
5.3.8 Fecal Coliform Removal

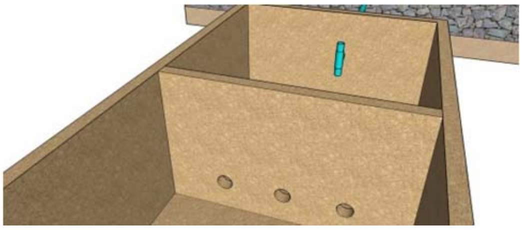
Flow Rate m^3/d	HRT days	Log cfu/100ml IN	**Log OUT Kadlec kC***	**Log OUT Kadlec PkC***
5	7,42	6	**2,3**	**3,1**
10	3,71	6	**3,5**	**4,2**
15	2,47	6	**4,3**	**4,7**
20	1,86	6	**4,7**	**4,9**
25	1,48	6	**5,0**	**5,1**
30	1,24	6	**5,2**	**5,3**
35	1,06	6	**5,3**	**5,3**
40	0,93	6	**5,4**	**5,4**
50	0,74	6	**5,5**	**5,5**
60	0,62	6	**5,6**	**5,6**



6 Drawings different layouts HSSF

6.1 Drawings Septic tank

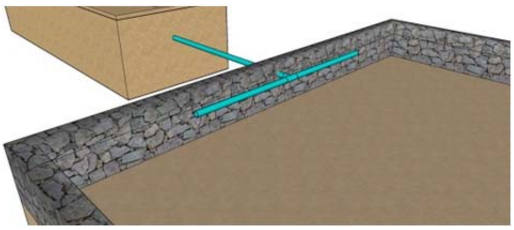


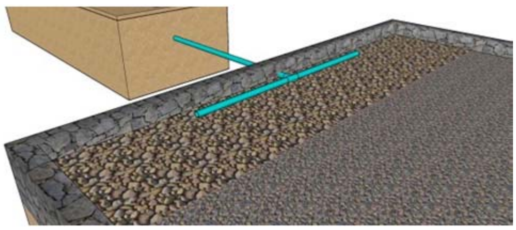


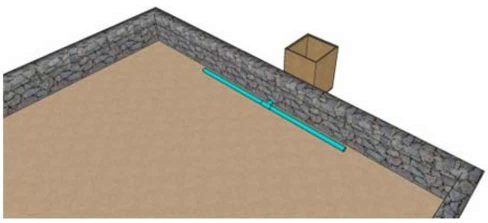
6.2 Layout 1: characteristics

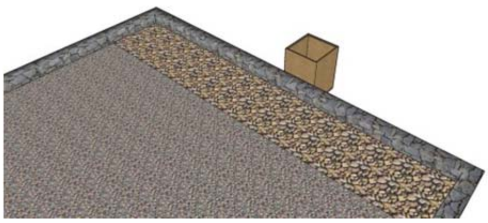
Lining: stone walls and compacted clay.
Distribution wastewater: both ends of a PE or PVC pipe.
Draining of effluent: both ends of a PE or PVC pipe.
Substrates used: inlet and outlet zone: rounded rocks 40-60, filter material: gravel 2-12
Vegatation: for example *Cyperus papyrus*

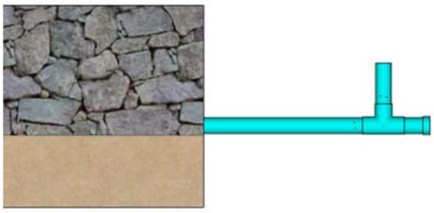
6.3 Layout 1: drawings

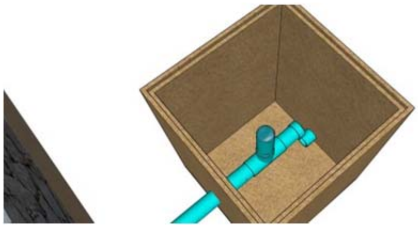


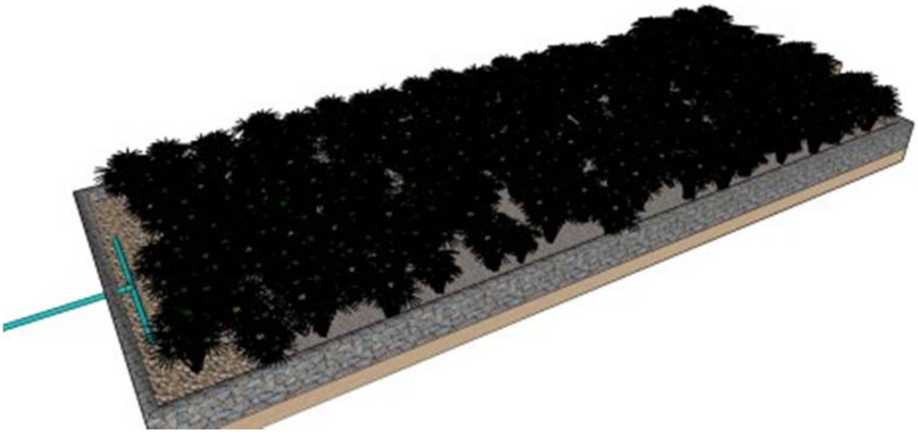








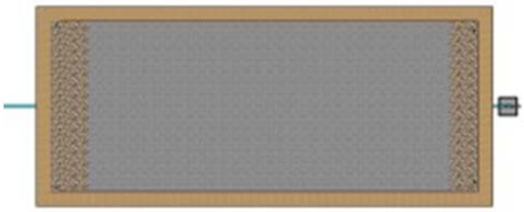


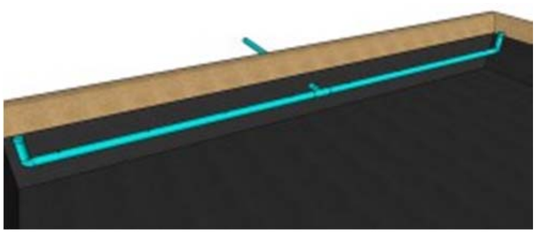


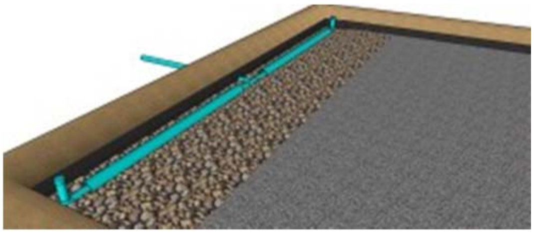
6.4 Layout 2: Characteristics

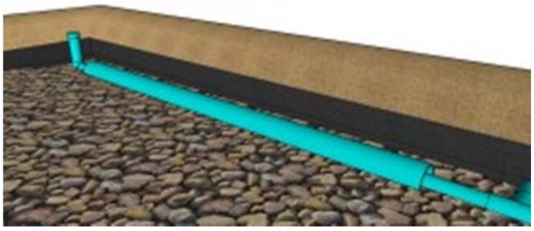
Lining: protective geotextile fabric and HDPE liner.
Distribution wastewater: perforated PE or PVC pipe with inspection pipes at both ends.
Draining of effluent: drainage pipe with aeration pipes at both ends.
Substrates used: inlet and outlet zone: rounded rocks 40-60, filter material: gravel 2-12
Vegatation: for example *Cyperus papyrus*

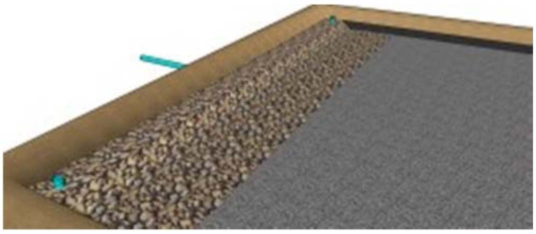
6.5 Layout 2: Drawings

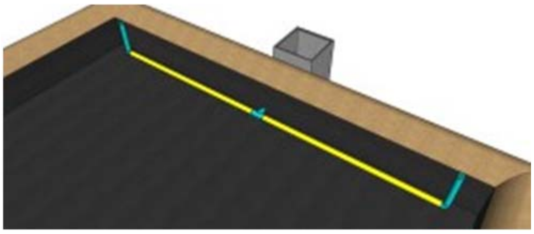


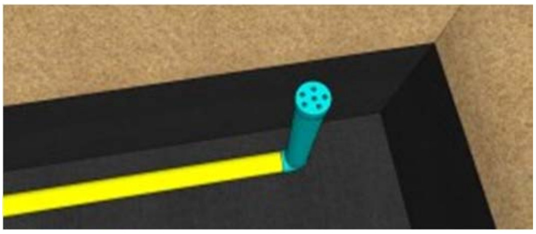


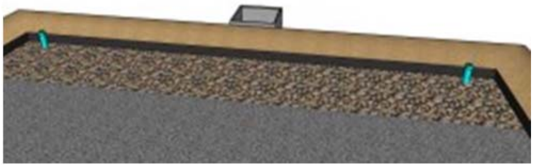


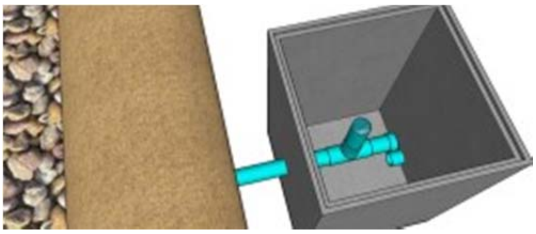


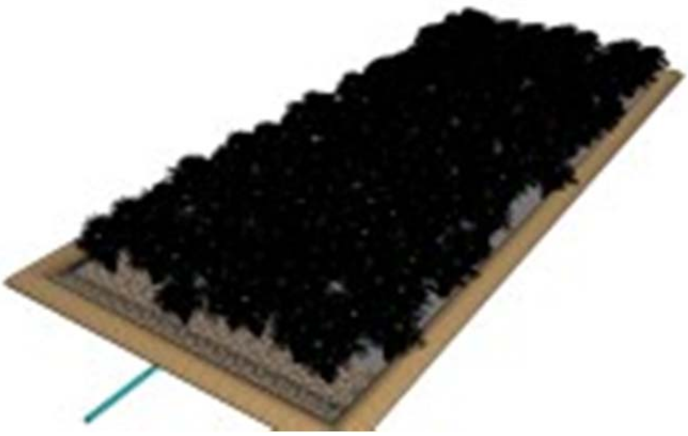












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Programme: **South Initiatives**

Dissemination of the sustainable wastewater technology of constructed wetlands in Tanzania

ZEIN2011Z097

2011-12-01 - 2013-11-30

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